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The Dark Side of the Universe

Outposts and perspectives of astrophysics
and contemporary cosmology

by

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Prologue

Our understanding of the universe is changing. New observation techniques have become operational and the Hubble space telescope, finally cured of its bad eyesight, has revealed unsuspected things. In immense molecular clouds we have discovered star nurseries whose children still attached to their uterus by "umbilical cords". Infra-red telescopes are showing us the universe from an unprecedented angle. We will be able to see things as a whole. We are sailing towards a new world.

Our conception of the cosmos depends on observations. Without them, we would turn in sterile circles playing with equations. Observation bought about the cosmological revolution at the beginning of this century and will provoke the revolution of the now so close twenty-first century.

To account for these new observations, we must improve, and perhaps profoundly modify, our conception of the universe. We have always considered the universe to be made of clumps, hierarchically arranged. Galaxies are clumps of stars, and clusters of galaxies form clumps too. We expected to find bigger clumps, already named "superclusters" but instead we have discovered a strangely hollowed-out universe, structured on a very large scale like Swiss cheese (or rather, to be true to our friends the Swiss, like Emmenthal, since real Swiss cheese, Gruyere, does not have holes).

Galaxies, beginning with own Milky Way, lack the mass to balance centrifugal forces. On the basis of stars brilliant enough to make an impression on the plates of our optical telescopes, these "island universes" should have blown apart long ago and been scattered to the four winds of the cosmos. Something remains to discover which still escapes us -- perhaps stars of very small mass and luminosity, or unknown objects such as new particles. Perhaps what the superstring theoreticians call a "shadow universe", as suggested by John Schwarz of Caltech, Michael Green of Queen Mary College, London, or Nobel Prize winner Abdus Salam (in his contribution on the unification of electromagnetism and the "weak force"). A "shadow universe", they say, is not observable optically but revealing its presence through gravitational effects alone.

Dark matter, the term is everywhere, in all the magazines. Various approaches have been taken to find an invisible phantom which will supply the key to unlock the observations of the last decade. Would this obscure but omnipresent entity, under whatever name, explain the stable galaxies as well as the large gravitational lens effects which are too great for the masses recorded in galaxies and galaxy clusters through optical observations?

What is more fascinating than a mystery? Science would lose its charm if everything were known. New mysteries approach. Questions are much more engaging than answers. Year after year, they drop from the sky with regularity.

We put Hubble in orbit and in just a few months it seems to have rejuvenated our universe! Holy Hubble! We are going to have to begin thinking again and try to understand afresh.

Astronomy has acquired a new tool -- the gamma-ray telescope. Neat! It is able to detects flashes coming from every corner of the universe, one a day on average. So what object, what phenomenon is responsible for these strange signals?

Another new puzzle for theoreticians.

How do the quasars, now counted in the thousands, function? What fantastic source of energy knocks around the center of the Seyfert galaxies to make these active galaxies reel like amusement park rides?

We are also scrutinizing the universe's distant past through theory and using ever more sophisticated means and. What did the first moments of the universe look like? Do these questions have a meaning or are they badly formulated?

Borges said that science was the most elaborate form of fantasy literature.

In workshops the world over, forges resound. The superstring theoreticians dream of a "theory of everything". A single equation that everyone could wear on a T-shirt, as Leon Lederman, director of Fermilab in Chicago, optimistically announces. Hawking predicts "the end of physics". Some dream of unifying the four fundamental forces and of finally building the theoretical machinery to give an answer to every question.

In brief, we in the scientific community are frankly not bored.

First Part :

A Walk Around the Flat

The non-relativistic universe

The sky, humanity's first book.

Have you ever considered that the beautiful summer sky above you is the same one your most distant ancestors contemplated? For the Egyptians, it was the stomach of the goddess Nout. To help embalmed pharaohs guard this vision during their voyage into the beyond, they carved it in the marble of sarcophagus covers. Babylonian astronomers, who gave us the seven-day week, the sixty-minute hour and the sixty-second minute (their numerical system was in base sixty), sought to decipher the destiny of kings by contemplating from their Ziggurats the Great Bear, Orion, or the Perseid cluster, which appeared then just as we see them today.

In the Bible, God replies to Job (chapter 38, verses 31-33):

Can you tie the bonds of the Pleiades or untie the cords of Orion, make the signs of the Zodiac appear in their season, lead the Bear with its children? Do you know the laws of the heavens?

The sky was humanity's first book.

When the celestial vault expands.

We learn in books that the universe is measured in billions of light-years. But let us be frank: such numbers mean strictly nothing -- one might as well describe the city of San Francisco to an ant. Humanity's universe is its horizon. The mental scale of distance, for a plain dweller, is ten miles. He carries it around with him. The mountain dweller sees further. He knows that those promontories over there are far away, for he has been there and it took many hours or days of walking to get there.

Our time scales also follow our experience. Hours, days, weeks are familiar to us. Years are already beyond the time-horizon. Frankly, what do a millisecond and a billion years mean to you? Strictly nothing.

We have precise ideas only of what we can grasp or travel through. Binocular vision allows us to locate objects with relative precision up to about fifty feet distant. But look at the errors made by people riding in a car who try to guess the height or judge the distances of two objects of unknown size. To be able to judge greater distances, to "see further", we have to change our position. A one-eyed person does not have that capacity. He judges distance by the speed of displacement of close objects relative to the background, the phenomenon known as parallax. We will return to this later and see how, at the end of the nineteenth century, it allowed the first measurement of stars' distances to be made.

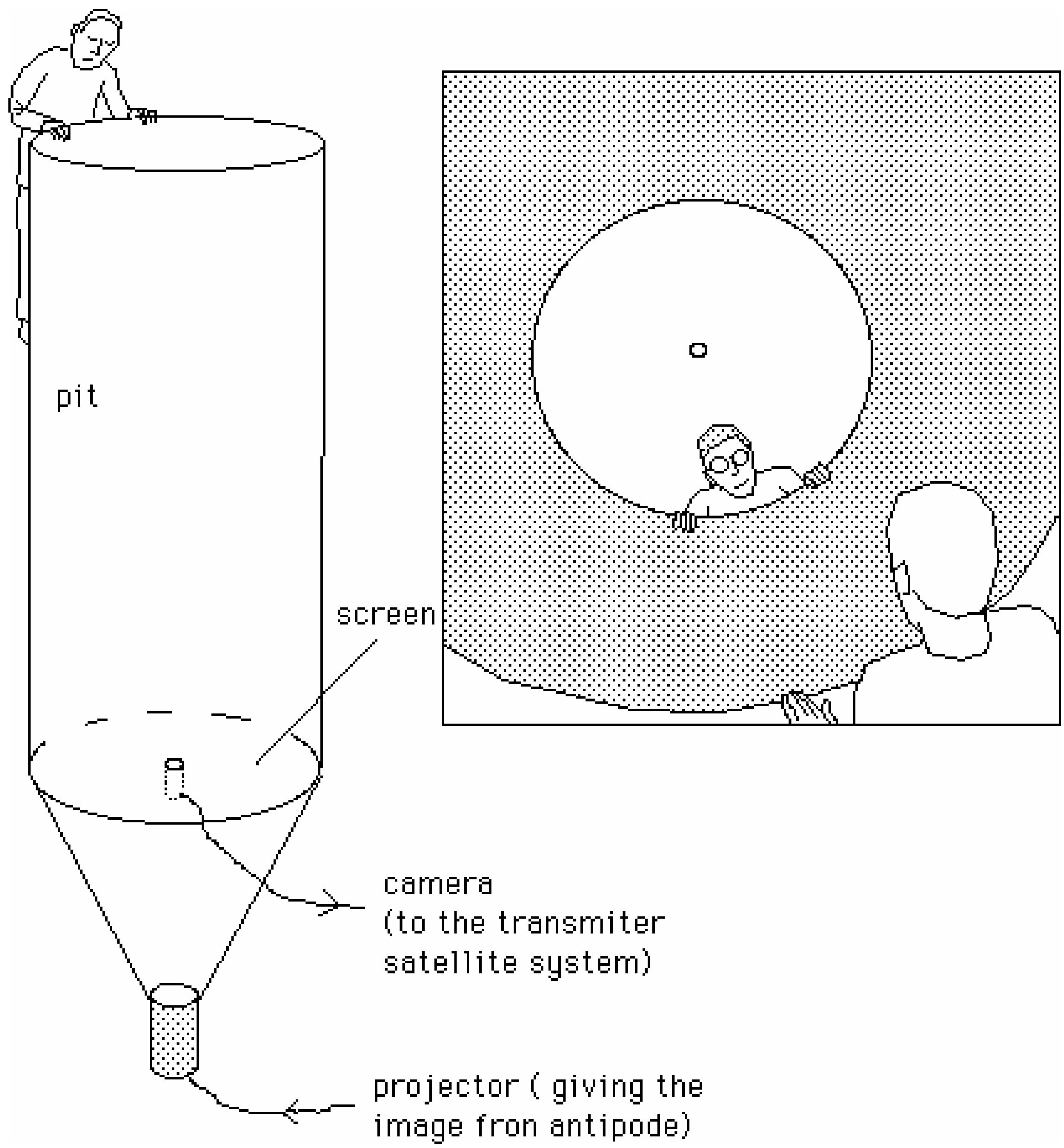
Go out of doors and observe the moon. How far away is it? Admit that you do not have the least idea. It is only "beyond the furthest hills and mountains". Our mental conception does not go beyond several dozen miles. To comprehend a road a thousand miles long we have to follow it on a map. In this respect we are hardly more advanced than cavemen. Still worse, we have lost our original reference-points. No one, or hardly anyone, walks or travels by horseback any more. So these standards, engraved into the minds of our ancestors -- a day's journey by foot or on horseback -- no longer serve us. Today we get into an airplane and open a book; when it's finished we have changed scenery, season and time.

For us the Earth is always flat. Only sailors, who saw ships' masts descending below the horizon, had a primitive notion of its curvature. It might resemble, let us say, a slightly rounded buckle they carried around.

One day I had a telephone call from a man in the antipodes. We talked for ten minutes and then I had a strange feeling -- this man was upside-down! He would fall into space. Blood must be rushing to his head. I shared my feeling with him and immediately he too began to have the same malaise.

For the first time in my life I was conscious that the Earth might really be round.

Let us say we dug two wells located at each other's antipodes. At the bottom of each we place a screen with an image from a television projector. They would also be equipped with cameras at the bottom, turned upwards. It would then be possible, through a satellite link, to project onto the screen at the bottom of one well the image received from the other's camera.



By leaning over the side we would thus be able to perceive the "antipodians", to look through the Earth, and they could see us. If the wells were placed in the centers of two villages, their inhabitants would come to realize little by little that the earth is not really flat. Or at least they would no longer imagine it as just a thick slab with two sorts of inhabitants, those above and those below.

Only astronauts really know that the Earth is round.

Let us say I pick up a telephone and call a friend twenty thousand miles away. While I am rushing off to lunch, he is still in nightshirt. Incomprehensible. All this remains terribly abstract for us. Who is capable of knowing another's time as well as his own? Who is conscious in their mind of the slow rotational movement of the terrestrial globe? Who sees the day devour the night? Each time I ask myself such questions I have to imagine an orange lit by a candle but I can never remember in which direction I should make it turn.

Who is aware of the Earth's rotation? Nobody.

When you see the Sun crossing the sky, do you imagine for a single second that this motion is only apparent, that it is due to the Earth's rotation about itself? Not for a moment. It also is "ten miles away, " just behind the horizon, barely more. We imagine it "as big as a mountain", but no one succeeds in conceiving its true dimensions. The proof is that I cannot remember its exact diameter and have to look it up in a book.

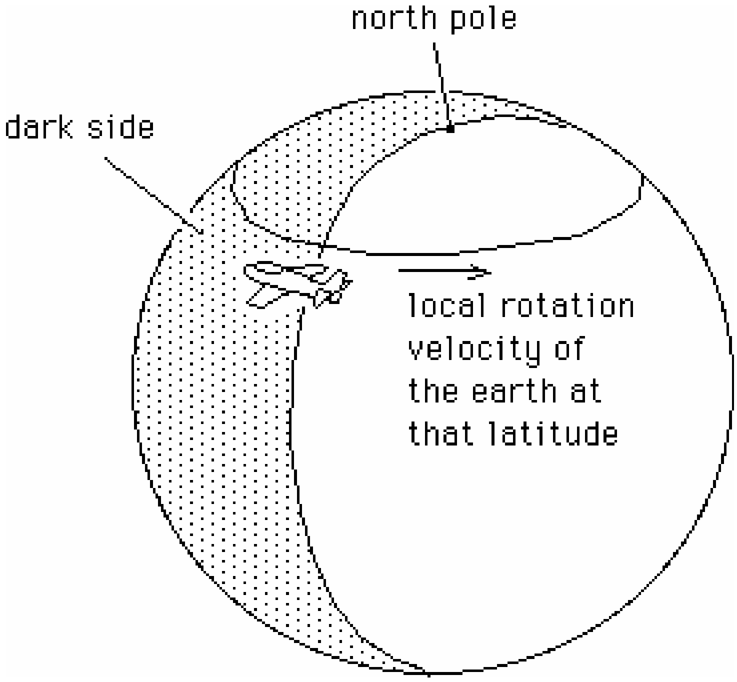
Americans and Russians are more familiar with the problems of jet lag than Europeans, because their countries are spread over several time-zones. But ask an Englishman or an Italian what time it is in Tokyo or San Francisco...

"Wait, it's later... no, earlier. Oh, I don't know any more".

"And when you travel westward, should you put your watch forward or back?"

"Well, I ... "

At the end of the fifties a jet plane, flying at a high altitude, succeeded in flying so fast in a westerly direction that its speed was equal and opposite to the local speed of terrestrial rotation.



Strange impression -- the pilots were flying at "constant time". They merely had to stop their watches. They had "stopped time".

I knew a Japanese industrialist who traveled endlessly; one day he had had enough of being at the wrong time wherever he went. What did he do? (The story is like an oriental fairy tale). He simply decided to bring his time with him. He fitted out his sumptuous personal liner with living quarters and a meeting room and put a clock on the wall which he vowed not to touch. The cabin's windows were closed (though not the pilot's fortunately) and only artificial light indicated whether it was day or night. When "day" came, he lit his interior candelabra which he extinguished when he went to bed, in blissful ignorance of what might be going on outside his plane.

As for his co-workers in different offices located all over the planet, they had to accommodate themselves to meetings at inconvenient hours, often the middle of their night, to which their CEO arrived as fresh as a cucumber.

We learn rules, memorizing them as best we can. Do not call Professor Nakajima between this and this hour, or else you will drag him out of bed and look like a fool. The instantaneousness of communications takes us by surprise. On Earth, with the telephone, it is the present for everyone.

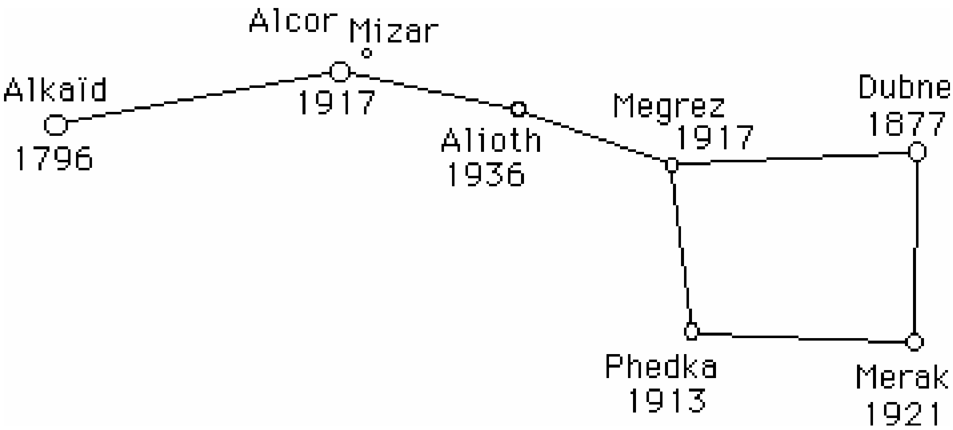
Writing fascinates me. It allows us to hear the words of people dead for hundreds of centuries. Often, while reading the text of a Greek author, I catch myself thinking, "How can it be that this man can speak to me, seem so present and share his humor to make me laugh out loud when his bones have long ago turned into dust?"

Once letters arrived by boat and brought with them an impression of past. The fax has overturned this aspects of the missive. It is amazing to realize that at the moment one hears the printer sputter someone at the other end of the planet, inclined at an angle of twenty-six degrees, "walking on walls" or completely upside-down, is watching their own fax machine to see whether the pages are going through correctly. However, the other way around, things are not always the same. Sometimes, after having sent a fax, I am surprised not to receive an immediate reply from my correspondent, forgetting that they are probably sleeping peacefully.

We no longer know who is when.

However we know, or at least we have learned in books, that information, electronic or radio-electric impulses, is not propagated at infinite speed. Nor is light. The moon appears to us as it was a second ago, the Sun as it was eight minutes previously. In the sky, the present does not exist. There is only the past. Certain stars we see might have disappeared a thousand years ago so the concept of actuality loses its meaning.

In 1987 it was announced that a supernova had just exploded in the Magellanic Cloud. Adjusting their telescopes, astronomers wanted to miss nothing of the spectacle but the play had already been performed a long time ago. The curtain had long since risen and the star's debris dispersed and, in fact, people were watching "live" an event which had occurred a hundred thousand years ago. Perhaps not a single astronomer asked himself the simple question. If the Earth has become for us "instantaneous", the sky is only an appearance. Even the constellations are deceptive. No star in the Big Dipper is the same age as the others. In contemplating it, we are watching a composite show with the most "recent" of its stars showing a sixty-year-old face to us and the furthest appearing such as it was two centuries ago.



The dates of emission of the light from the different stars of the Big Dipper which reached Earth in 1996.

Our ancestors were ignorant of all this. Our progress in telecommunications has given us a unique perception. But light's relative slowness will soon reverse this feeling.

Recall that delightful rolling and jolting garbage-can named Lunokhod, which the Russians placed on the lunar soil. One man piloted it from his console at Baikonur with two levers, like a battle-tank. Right lever, starboard tracks; left lever, port tracks. Accelerator, brake. Before him, a screen showed what the machine saw hundreds of thousands of miles away. Between the perception of an obstacle to avoid, a simple stone, and the execution of the order to do it there was a two second gap. Luckily Lunokhod did not go very fast. But this temporal displacement would make driving at great speed problematic. Interplanetary piloting means limited speed!

Let us consider the problem Earth-based manual piloting would pose for a vehicle running around the surface of Mars, where the delay would be minutes rather than seconds. Imagine the pilot, bent over his console:

"I see a pebble right before me -- darn! I am already on it. Are the vehicle's feet already in the air? I will only know in a few minutes. Turn, brake? Maybe it's already too late".

In the case of manual piloting at constant speed, guaranteeing the safety of the machine would transform it into a snail. It would be necessary to examine the terrain well before giving any order to go forward, just like someone who tests the ground with a cane before taking a step. We will advance on Mars step by step.

Can you imagine exchanges of radio messages between a terrestrial control center and a Martian mission? Is anyone capable of having a dialogue with someone when they have to wait twenty seconds for a reply?

Jupiter can be seen with the naked eye. It lies in the outer suburbs of the solar system. Perhaps one day miners will collect an interesting ore on one of its satellites, Titan turbinium let us say, but all conversation between him and his wife back on Earth will be impossible because an hour would elapse between each sentence.

Once America, or the Indies, were several months voyage away. Today, thanks to the airplane, one can say, "I'm coming!", even from the other side of the world. But the miner on Titan, if he suspects that his wife is cheating on him, can only say, "In two years I'll be dropping in so watch out!" Spatial and temporal disproportion. Our scientific progress has given us a new conception of the heavens, but the day to day mind does not follow it.

Astronomy is a science of surveying; we will see how humanity has gone from surprise to surprise in this area, each time seeing its domain grow out of all proportion.

Megalomania.

Astronomy on any level is not on our scale. It weighs objects in solar masses. If I tell you the Sun's mass, expressed in pounds, is a number that involves thirty zeros, will that be of any use to you at all?

Moreover, if I had said that it had seventeen or fifty-six zeroes, it would have had exactly the same effect and you would have taken me at my word.

The mass of an electron is not any more comprehensible. The microcosm and the macrocosm are intellectually hostile worlds.

Astronomical temperatures, from the burning heart of a star to the vast frozen stretches of intergalactic space, are just as far beyond us. What can a modern human being conceive in this area? Nothing more than could their distant ancestors : From the cold of a steppe, thirty degrees below zero to the heat of a red hot iron. Ten million degrees or three degrees above absolute zero are unthinkable numbers. But you have to think of them nonetheless.

However, in contrast, human beings do have a good intuition of the void, since they invented nothingness. No void, however complete, could disconcert them since they are capable of imagining an absolute void in their heads, though it would have no meaning for a physicist, as we will see later.

Thus, paradoxically, the only extreme things that people can conceive easily either do not exist, or require qualification. Zero, for example. Nothing seems to want to be truly null in the universe, time no more than space. Quantum physics, as we will see, tends to stop dealing with distances of less than 10^{-33} centimeters (a fraction whose numerator is 1 and the denominator another 1, followed by thirty-three zeros. We will see where this number comes from elsewhere in this book), and periods shorter than 10^{-43} seconds (the Planck time, the time taken by light to cross the above distance).

If we manipulate a very thin sheet of mylar, its thickness, whether a hundredth of a millimeter or a half-micron, will seem the same to us. Conceptually we will assimilate this sheet as a "plane surface". Everything smaller than our power of optical resolution, real or imaginary, is of zero dimension. All objects joined in time and space by intervals smaller than our perceptual capacities form continuous sequences for us. A photograph whose "pixels" we do not discern appears to be an object continuous in space. A film is continuous in time when we know very well that this impression of continuity is only a phenomenon of retinal persistence.

Astronomical numbers are also beyond conception. Ten sheep, a hundred sheep, a thousand sheep, fine. They are numerable. Ten million sheep -- nonsense. A galaxy contains a hundred to a thousand billion stars. But I could have said fifty thousand billion stars -- it would have been the same.

Let us be clear -- there are two approaches in science:

- Align equations and numbers, which become games with ideograms. Certain people are excellent at such games and are able to content themselves with their intellectual nourishment. We call them mathematicians. People who believe that the universe is entirely constituted of ideograms are called schizophrenics.

- Try to forge for oneself an intuition of intangible, incommensurable things. There you and I act alike. Commensurable, etymologically, is said of sizes which have a common measure.

You seek the commensurable as soon as you leave your mother's womb when your hands and, above all, your mouth become your basic standards. For a newborn, nothing over three inches is comprehensible. Comprehensible and prehensible together -- what one can put in one's hands.

Afterwards we pass to the arms and we imagine groups of objects, atoms, which we could clasp, that is to say take in our arms. We reflect with fistfuls, armfuls. We bring everything back to our primordial reference, our body, our perceptual system. What we do not feel in our hand has zero mass. Everything which moves at less than a millimeter a second is immobile. And so on.

When things "go beyond us" we bring them back instinctively to our scale. For me, a galaxy, at least the "mental galaxy" I have in my head, is a sort of swarm of gnats with a diameter of several feet at most. My universe is contained in a hangar. A superstring is no finer than a hair. If not, my intuition falls through my fingers, like sand.

So we will use the same approach.

Astronomy, just like the microscopic physics of the "so-called elementary particles", brought immense surprises for humanity. At the dawn of this century great men of science, like the Frenchman Berthelot, refused to envisage the existence of atoms, simply because they could not be seen with the naked eye. Inversely, astronomy and cosmology have brought a constant enlargement of the human representation of the cosmos. The boundaries of the cosmos have been cast to the four winds. Even God, who we used to imagine seated peacefully on the clouds, has taken refuge in a sphere of Planck's diameter even for those who continue to look for Him.

In order that things stay familiar to us we must mentally bring them down to human scale or else they remain incomprehensible, still in the etymological sense of the term. We will do as Gulliver did : When things are minuscule, we will make them larger, or shrink ourselves to observe them better, which amounts to the same thing. When they are gigantic, we will do the opposite. We will accelerate or slow down clocks, to the scale of the cosmos or of atoms. Either this or we will understand nothing. We will transform at will atoms and galaxies into baby peas.

But watch out. The universe is only a vast theater of shadows, on the scale of the microcosm or macrocosm. It is Plato's cave, especially when the eye sees what the hand cannot reach.

To close this little chapter, I will tell you a personal anecdote, perfectly true. I spent the first years of my life in a little town, all of whose streets and houses I knew. I left it when I was seven, having memorized everything, packing memories as in a suitcase. I returned forty years later, by chance. But everything had changed. The wall I had fallen from when I broke my leg, which I had imagined very high, reached to my shoulder. My parents' house seemed to have shrunk by half. Vaguely disturbed, I ran to see if the same phenomenon had affected my aunt's house. The distance between them now seemed ridiculously short to me, it had had shrunk, like a headhunter's trophy. The same for the village square. The same for everything. I wondered whether time had not also changed its speed, if things flowed at the same rhythm. But we cannot travel in time, if we could we might be in for some surprises. The observation of a clock's balance-wheel by the eyes of a newborn baby or the eyes of an old person are perhaps very different things.

We said that the sailors used the image of a rounded buckle, bounded by the horizon, during their voyages. In growing up we borrow the vehicle of our body, which has variable geometry. We drag around in our head our biological clock. But, as we will see, even ideas change, in the course of this eternal voyage called science.

We can in fact perceive nothing without conceptual eyeglasses. When I lean on a table with my hand, I cannot pass through it. I have the impression of fullness. In fact my finger and the table are both great voids, with just a few atoms here and there. It is the play of electromagnetic forces which prevents the two swarms of atoms from passing through each other.

Look at the stars. They seem immobile but in fact are moving at five miles per second. For millennia people believed that they were suspended from the celestial vault like candles.

I believe that the universe is like this or like that because I observe things through my telescope. There again I use conceptual eyeglasses. If we take them off, we are blind. But perhaps these objects do not truly exist. Perhaps they are only images, Who knows?

In sum, Science, an organized system of beliefs, is never anything but a way of saving face. I like this phrase of Borges a lot, perhaps science is only the most elaborate form of fantasy literature.

An error that lasted thirteen centuries.

I will tell you the story of an error that lasted thirteen centuries. Aristotle (384-322 BC , Greek philosopher and preceptor of Alexander the Great) had laid down a certain number of principles. Today we call them working hypotheses, or axioms.

- What was eternal, imperishable, should move according to a circular trajectory, because only the circle had no beginning nor end.

- As for the perishable, it moved according to straight lines, which, as everyone knows, have a beginning and an end.

Therefore stars, perfect objects, assimilated to gods, could only move circularly.

In addition movement necessarily had a propulsive cause. According to him objects could move only if a force acted on them. It suffices to communicate an impulsion to a supermarket cart to know that this is not true. But if Aristotle saw you do it, he would give you his own interpretation -- eddies of air, visible when dust is present, were pushing your cart. Similarly, he thought, eddies appear at the bow of a vessel forging ahead, maintaining its movement.

- The proof, he said, is that when the eddies cease, the boat stops!

During this epoch, before inertia had been discovered, people considered this demonstration to be irrefutable.

Claudius Ptolemy, a Greek astronomer living during the second century AD, was tempted for a moment, he confesses, by heliocentric vertigo when he was revising his doctoral thesis, the Almagest. But once more Aristotle's shadow was watching. In comparing the falls of a rock and a feather the master had showed that heavy bodies were submitted to forces with more intensity than light ones. If the Earth moved, Ptolemy told himself, it must be subject to a force, a sort of weight. However as human beings and everything else on the planet would also bathe in this force field, the Earth would have taken off and people left hanging helplessly in space.

The idea of the sky's immobility, even relative, would not have entered anyone's mind. It was quite evident that stars progressed according to circular trajectories. A glance at their image on a photographic plate after a long exposure gives convincing evidence. Only the Pole star does not move, planted like a shining nail on the celestial vault, the axis of the world.

As for planets, they move in relation to the stars and seem to go their own way. Some go fast, others take their time. They follow a common route called the zodiac. Even the Sun moves against this stellar background.

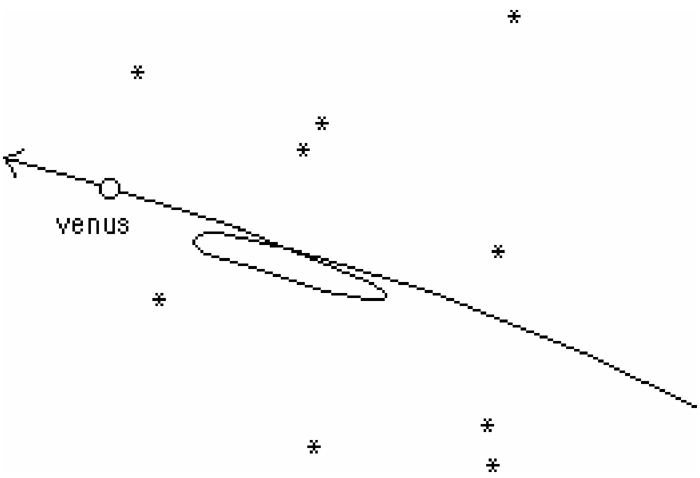
You will say -- how can we tell, since when present it is so bright that it extinguishes all the stars. But astronomy was born in Babylon, a country where the sky is clear and moreover is fairly low in latitude. It was therefore possible to note, just after its disappearance, the constellation against which it appeared, whose stars then lit up like flashlights. In a land clouded with twilight mist and at a latitude where sunset is interminable, such as Norway, this identification would have been more problematic.

Close to the equator, for example in Kenya, where the nights are so beautiful, the Masai see the day-star dive vertically and sunsets last only several minutes.

However, even the Sun was locatable on this planetary cycle-track with its twelve assigned boundaries, the zodiacal constellations, and it could be seen to move along it with clockwork regularity during the course of the year (and because there were seven visible heavenly bodies - the Sun, the Moon, Mercury, Venus, Mars, Jupiter and Saturn, they decided that the week would have seven days and that Sunday would be "the day of the Sun").

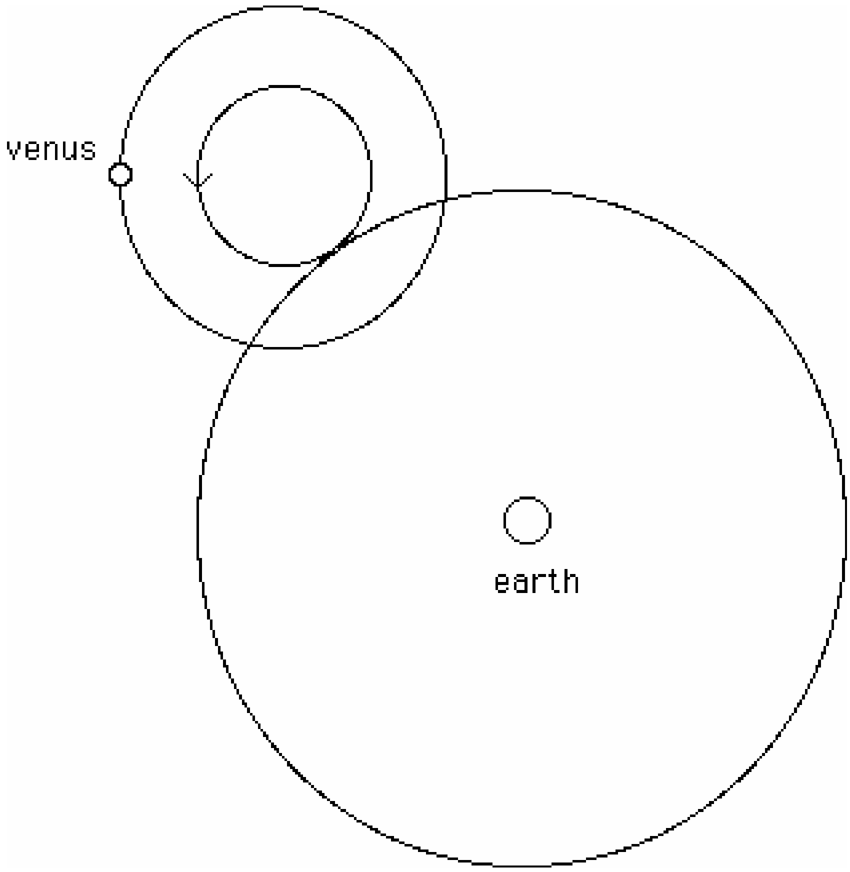
These heavenly bodies moved as they pleased. It would not have occurred to anyone to interrogate the gods on their choice of displacement speed. Finding the position of the Sun, Saturn, Jupiter, Mars or the Moon posed no problem. The Sun could be found on its planetary cycle-track.

Let us mark the different planets' trajectories, supposed to be approximately circular, on a map centered on the Sun. As months and (terrestrial) years go by, with the Earth as the point of observation, we will be able to confirm that these so-called planets have trajectories inscribed irregularly on the sky's depths. In other words, the measured aiming angle between Earth and the planet does not change regularly with time because of to the movement of the point of observation -- the Earth itself. Sometimes the planets seem to come to a halt against the celestial vault and then make a retrograde movement, as if they had forgotten something, before once more taking up what would have seemed, for an observer living in Ptolemy's time, to be their normal course. This is true for example for Mars, the point of departure for Ptolemy's reflection. But it is easier to illustrate this phenomenon for the planet Venus.



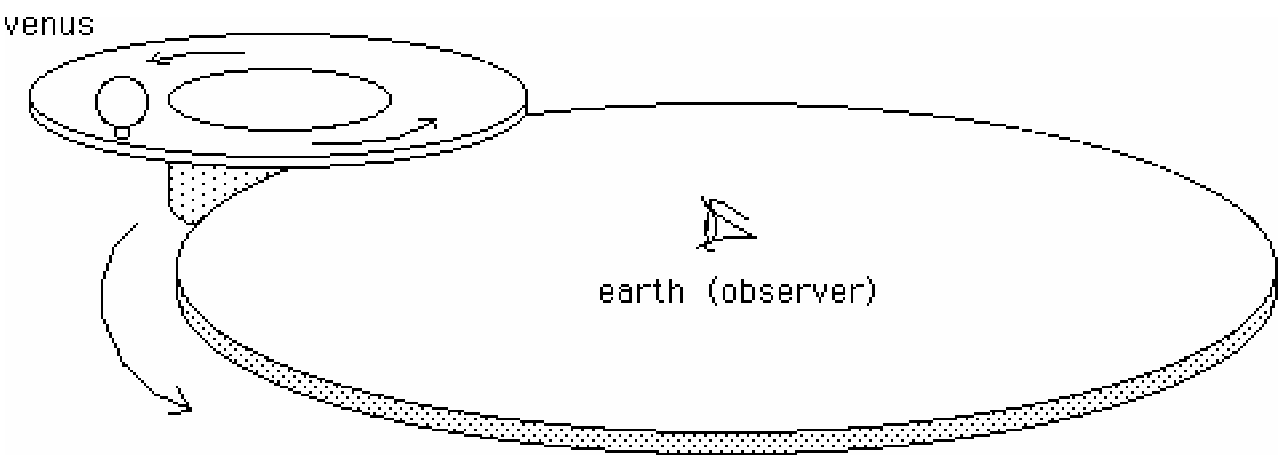
Trajectory of Venus, standing out against the stellar vault.

Reflecting on this singular trajectory of Venus, Ptolemy wondered how to integrate it with the principle of the circle, the foundation of the thought his master Aristotle. Answer : Combine the movement of *two* circles. See the following picture.



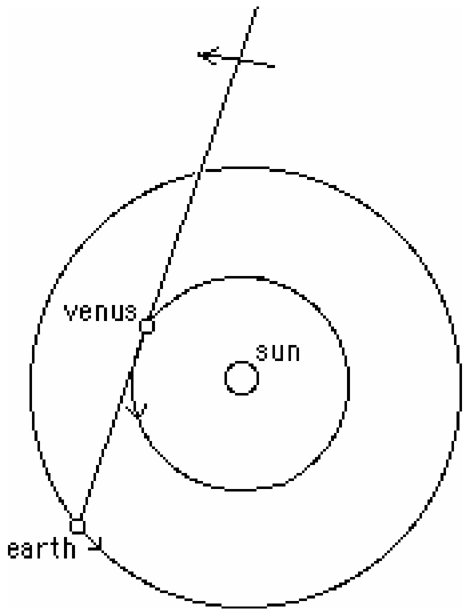
Ptolemy's model : one circle rolling on another.

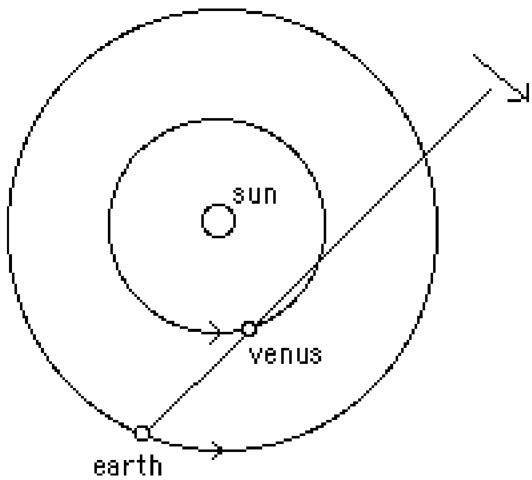
In perspective, we obtain this:

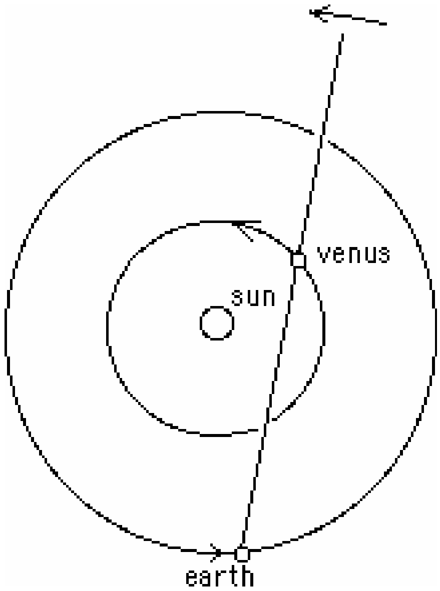


Under these conditions, for an observer located at the center of the celestial mechanism, the object "Venus", borne along by this sauntering and rotating plate, would indeed make outbound and return trips in relation to a fixed decor functioning as its background. The circular myth was safe.

In fact, it was not until discovered thirteen centuries later, when Copernicus and Kepler entered the scene, that this capricious trajectory of Venus was shown to be due to it following a heliocentric trajectory closer to the Sun than that of the Earth. This also makes its orbital period shorter. The following figures explain this apparent effect of retrograde motion:





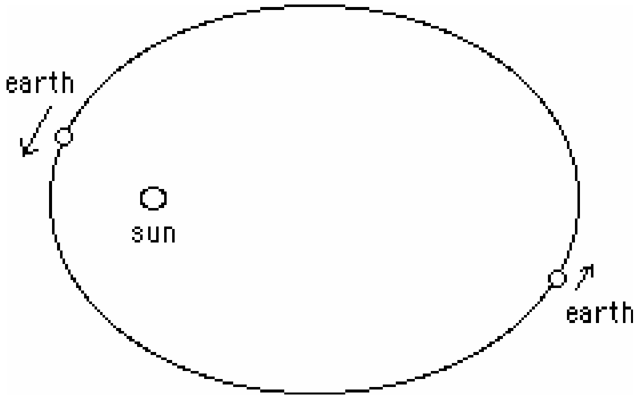


***Three successive positions of the Earth and Venus explaining, for an observer on Earth, the apparent retrograde motion of Venus against the background of the sky*.**

We know now that this model was false and can wonder how it managed to last so long. In fact it worked very well and constant efforts were made to perfect it. Every deviation from prediction could easily be explained by adding another circle, both for Venus' trajectory or that of any other planet. Thus this (purely phenomenological) description had potentially unlimited precision. If Copernicus and Kepler had not entered the story, our modern computers might be predicting with extreme precision the apparent position of heavenly bodies by using, for example, a million circles. When the model was finally abandoned, astronomers had already reached forty-eight, which caused the young King of Spain, during his initiation into this technique by his tutor, to one day say :

- If God had consulted me before creating all this, I would have recommended something simpler.

Kepler showed that the planets' trajectories did not describe circles centered on the Sun, but ellipses, the solar star occupying one of the focal points. The laws of celestial mechanics eventually explained why, as Kepler had revealed, planets accelerate when they approach the Sun (perihelion) and, opposedly, slow down as they approach their apogee (aphelion).



Variations in the Earth's speed in its elliptic course around the Sun (the eccentricity has been exaggerated).

Those attempting to calculate using circles centered on the Sun found themselves unable to take into account the variation of speed over the trajectory, whereas Ptolemy's circles meshed according to perfectly oiled mechanics.

This present work cannot give an exhaustive history of astronomical ideas; instead we have preferred to highlight certain significant facts. Our goal is to treat contemporary astronomy and cosmology, their problems and possibly solutions. With human cognitive procedure as a backdrop, it will include some mistakes from trial and error. In every epoch, even ours, we are exposed to such risks of error.

Ptolemy's system found new support from Danish astronomer Tycho Brahe (1546-1601), a contemporary of Kepler. After observing that the further away a light source, the weaker its gleam, he conjectured that feeble stars should therefore be further away than bright stars like Sirius and used this argument to refute any possibility of movement of the Earth's. He said, in effect, that if the Earth orbited the Sun, and not the reverse, we should observe a phenomenon of parallax. But we do not. Therefore the Earth must be immobile.

What is parallax?

Look at your index finger held at arm's length and, at the same time, a background such as the wall of your room. If you first close one eye, then the other, you will be modifying your "observation point" so that your finger will seem to move in relation to the background. Tycho reasoned that if the Earth moved, the bright stars, which he supposed in principle close by, should move in relation to the stars of the sky behind, the weaker ones.

First error -- the brightest stars are not automatically the closest. The reverse is very often the case -- stars emitting small amounts of light are very close, while supergiants are thousands of light-years away. Second error -- in thinking that the stars were situated at distances comparable to those of the planets, Tycho was miscalculating by a factor of ten thousand. Parallax was real, but totally unobservable to the naked eye. However Tycho could not know this. The effect was only revealed in the nineteenth century by the German Friedrich Bessel (German astronomer, 1784-1846), using a photographic plate. See Appendix 4 .

So with the aid of a very "rational" argument, founded on false premises, he arrived at an erroneous conclusion, though a very impressive one for the people of his times.

One single message, light.

Each branch of science has its own sources of information. In some we can make both observations and laboratory experiments, in others experiments are impossible. Sciences which deal with living beings mix observation and experiment. A medicine, a synthetic protein, a surgical operation, are experiments. In history and paleontology, to the contrary, there is no experimentation, since it is impossible to travel into the past. Physics and chemistry are playing-fields where observation, analysis, modeling, and experimentation alternate. Modeling results in ranges of prediction, which sometimes lead to very spectacular open-air experiments which can be enjoyed by everyone, such as the early hydrogen bomb tests. Their incontestable results seem to make the restrictive framework of the laboratory room pale into insignificance.

If we except the astronauts' incursions onto lunar soil, astronomy bases its knowledge on the analysis of light and, more generally, of all the radiation it receives from the outer reaches of the cosmos. It is a sort of photography. As a general rule, astronomy considers that it has little chance of actually touching the object of its study except in the case of the planets, which one day we will eventually visit, either by sending people or using robots.

Before we went to the moon, though automatic probes had already made analyses *in situ*, we had no certainty about the exact composition of the Earth's companion. Until the very last moment speculation was rife and I even remember a newspaper headline saying "And what if it's cheese?"

We know today that the moon is definitely not a piece of cheese. With time all the inner, solid planets will be visited, as will the asteroids in transit. Probes will plunge into the atmospheres of Jupiter and Saturn while transmitting the results of their analyses by radio. As for the Sun, we have to content ourselves with watching it from afar.

But what riches can be found in the analysis of radiation?

First of all angular coordinates, a system of reference against the background of the sky. We also measure the quantity of light captured, betting on the idea that this is inversely proportional to the square of the distance separating us from the source. If we believe that, it gives us a sufficiently exact idea of its nature, of its radiant power (what one calls its absolute magnitude) and we can then complete this angular sighting by a judgment of distance. This allows us to situate the object in three dimensions, with more or less precision. The decoding of a parallax effect allows an evaluation of the distance of sufficiently close objects. We will see later how other standards of distance, the Cepheids, allow measures to be made of mind-boggling distances -- 55 million light-years in 1995.

The Doppler-Fizeau effect allows the measurement of radial velocity, that is to say the projection of the object's speed with respect to ourselves on the "line of sight". Spectrum analysis brings information on chemical composition and temperature of the source. This is complemented by an assortment of new observations in other ranges of wavelength -- infra-red, X-ray, gamma-ray. These rays, absorbed by the earth's atmosphere, escaped our observation until the advent of spatial astronomy.

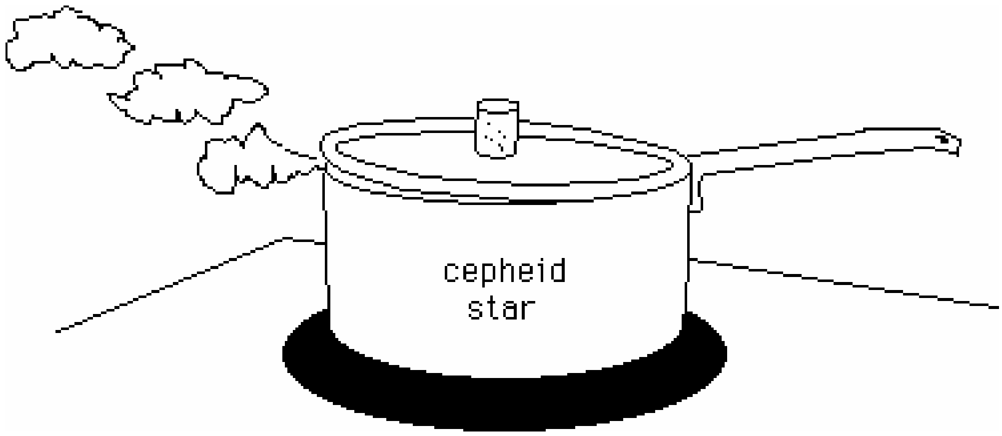
Each time the sky draws back
the known universe expands.

At the end of the nineteenth century the German Bessel (already cited, see the details of the measurement method in Appendix 4) made the first measurement of stellar distance. It was a surprise. The closest stars are fantastically far away, ten thousand times farther than the planets at the confines of our solar system's. While the light emanating from Pluto takes about an hour to reach us, Bessel's discovery showed that the time taken by stellar light should be counted in years.

There were many discoveries made at the turn of the nineteenth and beginning of the twentieth centuries and each brought answers to age-old questions.

A word in passing about the Cepheids. These are pulsing stars, which function like cooking pots whose cover lifts up at regular intervals to let a puff of vapor escape.

Let us examine a Cepheid in the process of contracting. The temperature and pressure at the core increase. At its heart the process of fusion, liberator of energy, starts to race -- the star becomes more radiant. But this "puff of heat" immediately provokes its expansion which brings about a cooling of its central furnace. The expansion then stops and it begins a new contraction. And so on.



This mechanism (though at the time people knew nothing of how a star functioned) was discovered in 1912 by Henrietta Leawitt, who showed that the largest Cepheids, the most radiant, had the longest periods. It was possible to measure the distance of a certain number among them, in our near stellar neighborhood, by the parallax method.

Ms. Leawitt used this method to measure the distance of a large number of Cepheids. From this and by measuring the energy captured by the telescope (apparent magnitude), she was able to calculate the quantity of energy they were really sending out (absolute magnitude).

She derived an empirical law relating their frequency of oscillation to their power of radiation. It now became possible to deduce the distance of a Cepheid by measuring its period of variation (it is situated much too far away to use the parallax method) and the quantity of light received,.

The parallax method, like binocular vision, had a very limited range. The Cepheids were going to push back the gates of heaven to unimaginable distances.

In 1802 the Englishman William Herschel (1732-1822), one of the pioneers of modern astronomy, had been the first to claim that the "Milky Way", which crossed our night sky, was in fact an enormous grouping of stars (two hundred billion) seen in cross-section, whose more populous center was located in the direction of the constellation Sagittarius. If the object appeared to us like a wedge, it was because we were inside it.

But telescopes did not show only stars. Objects were distinguished on the plates which were designated under the name of "nebulas". Some were had no form, others appeared as spherical or elliptical masses, others still ultimately resembled immense spiral vortexes.

Some people believed these objects to be of relatively modest size and situated within the Milky Way. Others imagined them as immense and outside it. It was the astronomer Edwin Hubble who settled the matter in 1924, by identifying a Cepheid in the Andromeda galaxy and determining immediately its distance relative to us -- 2.2 million light-years.

Thus what we were calling the Universe was not just a grouping of stars (our galaxy) containing different types of "nebulas", but a grouping of galaxies.

Astronomers began to catalogue them using Andromeda and other relatively close galaxies to develop new standards of distance, relying on the photometric method. The universe began to unfold in all its immensity, totally inconceivable for the human mind.

We discovered that there existed "galaxies of galaxies", clusters like that of Virgo containing individuals numbered in thousands. And relatively recently we have come to understand that these galaxies are arranged around immense "bubbles" whose average diameter is of the order of a hundred million light-years.

From this point, these are the sorts of distances we will be envisaging.

Spectroscopy is the key component of modern astronomy. Newton was the first to show that solar light was composed of different colors whose mixture produced what we call "white". But he did not realize that it was not diffracted by a prism into a sort of continuous rainbow but rather into rays. The Germans Kirschoff, Fraunhofer and Bunsen, the inventor of the burner which bears his name, made essential discoveries. Every heated body emits light and this light, when dispersed with a prism, produces a characteristic spectrum. As two bodies with the same spectrum do not exist this becomes a means of identifying them, not only in the laboratory, but also at a distance. We discovered with amazement that we could analyze stars' atomic compositions in complete tranquillity without any need to travel there. We found that they were mainly composed of hydrogen but also various other sorts of atoms.

A little anecdote : It was found at this time that the Sun contained an unknown substance, identified as always by its spectrum, which was baptized "helium" (from helios, in Greek -- the Sun). It was only later that they discovered helium also existed on Earth.

This latter discovery led people to think that the cosmos might have no center, that the same phenomena could take place at considerable distances, obeying the same laws and putting into play the same basic mechanisms. Once people believed that the Earth was the center of the world, then the Sun until spectral analysis revealed that it was just another star of an extremely banal and common type. There were plenty of others like it in our galaxy, the Milky Way, and in other galaxies which had been "resolved into stars" by powerful means of observation And there were galaxies everywhere.

We did not find any exotic substances in these stars, just the hundred or so atoms classified by the Russian Mendeleiev in his celebrated table. In other galaxies we found stars of the same type as those of our own Milky Way. It began to seem evident that the universe is the same everywhere. Everywhere we looked we found the same substances and in rather limited number. The laws of physics should prevail just as surely a billion light-years away as they do on Earth.

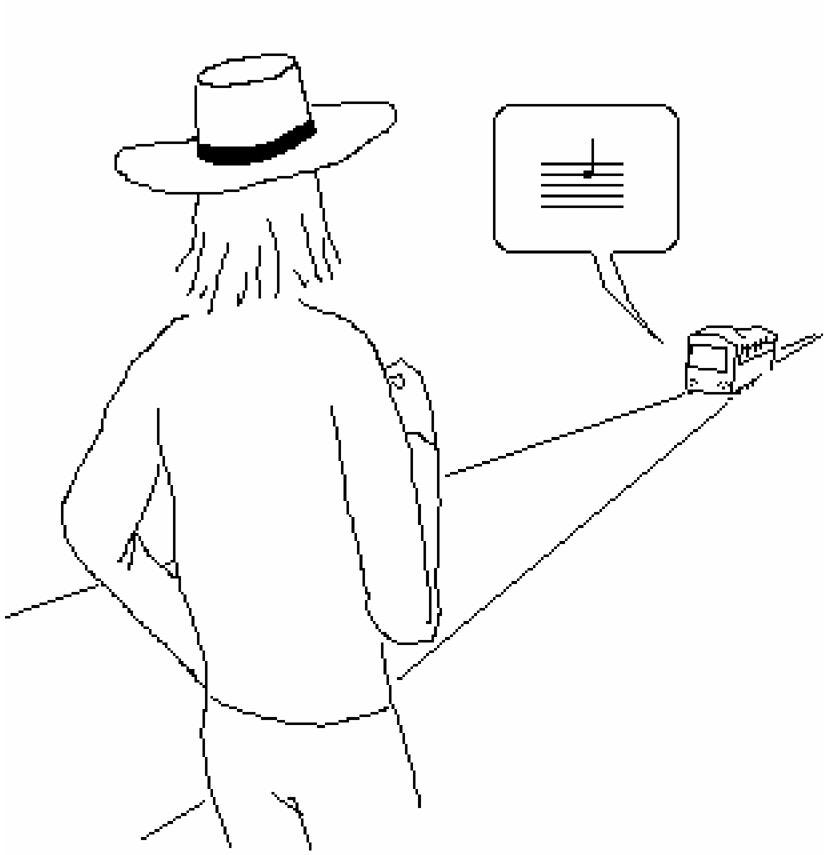
This was a lucky thought as we had just discovered what those laws were as well as a number of constants :

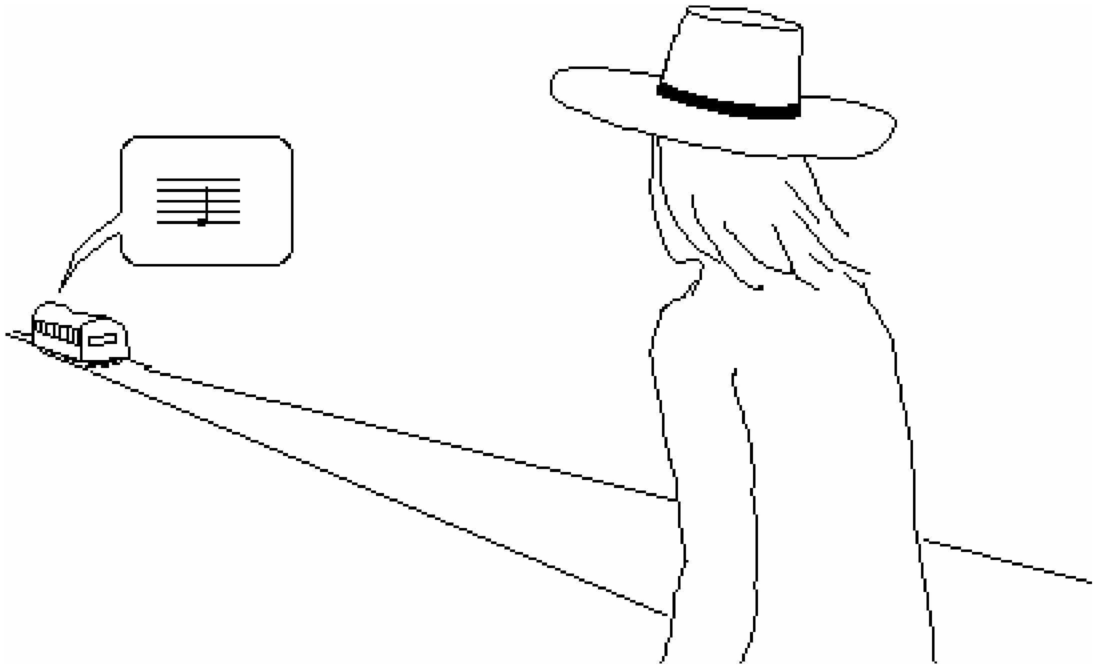
- That of gravitation, G , already known, but whose measurement had been refined (6,67 10^{-11} MKSA)
- The speed of light, c (3 10^{8} m/s)·
- Planck's constant, h (6,63 10^{-34} MKSA system)
- The masses of the elementary particles, (mass of a proton or neutron : 1,67 10^{-27} k)
- The elementary electric charge, e (1.6 10^{-19} coulomb) .

With the availability of such tools, we began to attack light-years, the goal being to put the cosmos into a box, to finish with its exploration and comprehension once and for all. There was a generally optimistic mood.

We were going to "understand everything". It was all just a question of equations, of "initial conditions" and calculation techniques.

A word in passing on the Doppler-Fizeau effect. In the days when level crossings were common, they have almost vanished in wealthy and large cities, rail-cars crossed them hooting gaily so that everyone was aware of the sudden lowering of the sound's frequency at the moment its source went by.



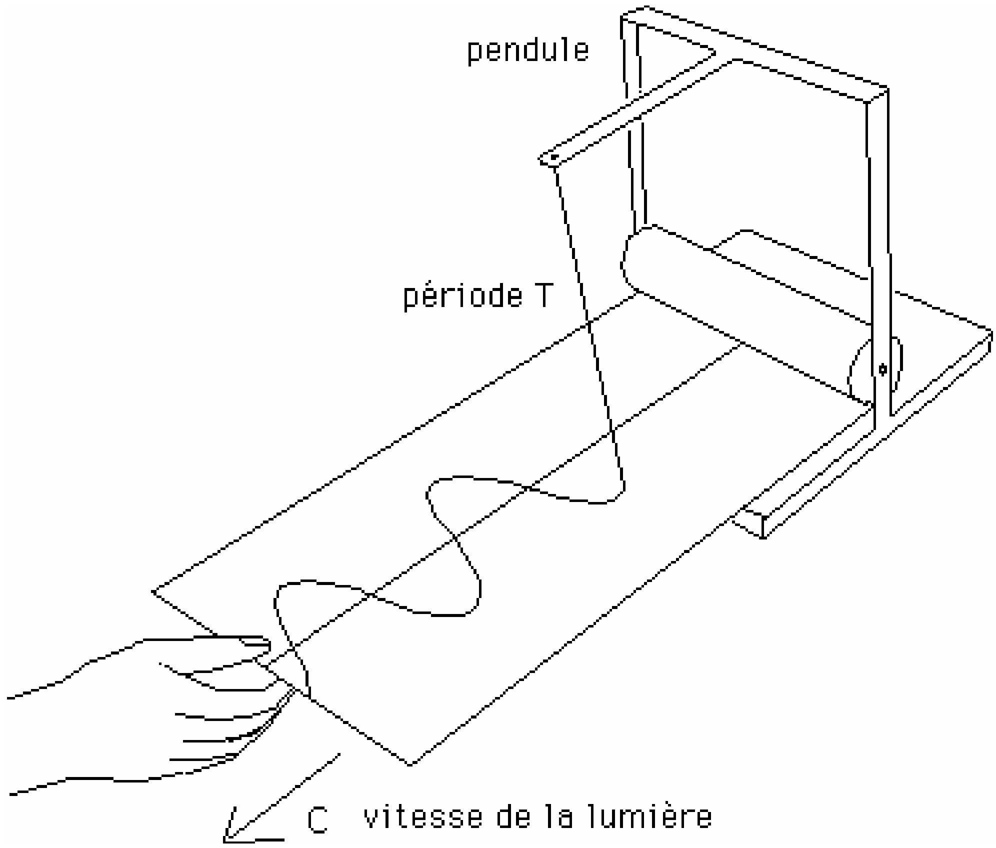


The Doppler-Fizeau effect.

(Hippolyte Fizeau, 1819-1896. French physicist who made the first direct measurement of the speed of light.

We could try to explain everything and vulgarize everywhere. With the help of an infinite variety of pictures we could try to bring matters within the reach of those who cannot deal with equations. But that is not our primary goal.

But let us make an exception for this old classic. Let us imagine that the light reaching our eye, or our measuring instrument, is a piece of paper which we pull at constant speed of ... 186,000 miles per second. This paper is on a roller set at some distance and on a fixed support. A oscillating pendulum carries a pen which thus draws a pretty sinusoid on the paper.



For these waves, from one peak to the other, the wavelength is l. The time which light takes to propagate is :

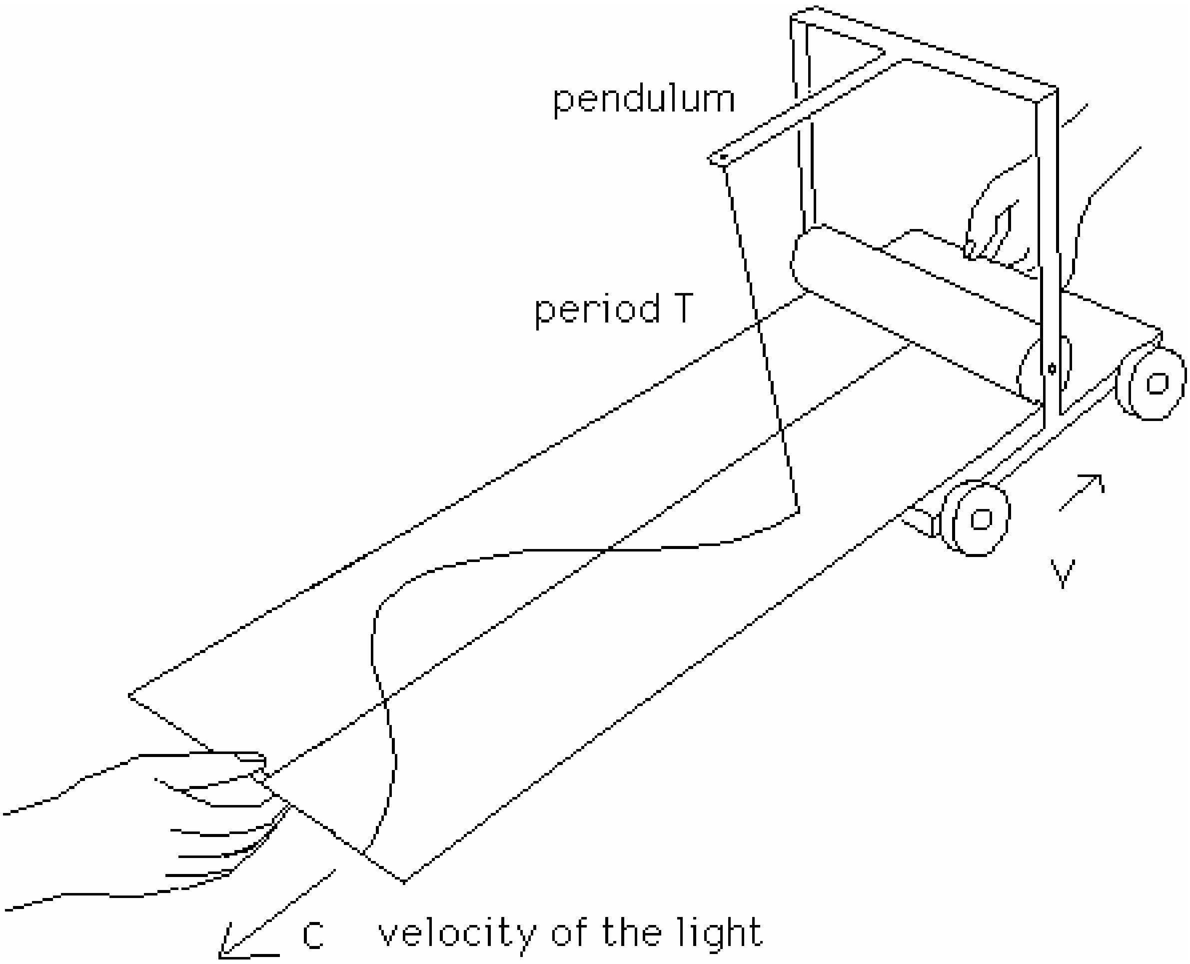
$$\tau = \lambda/$$

And its inverse:

$$\nu = 1/\tau$$

is the light's frequency.

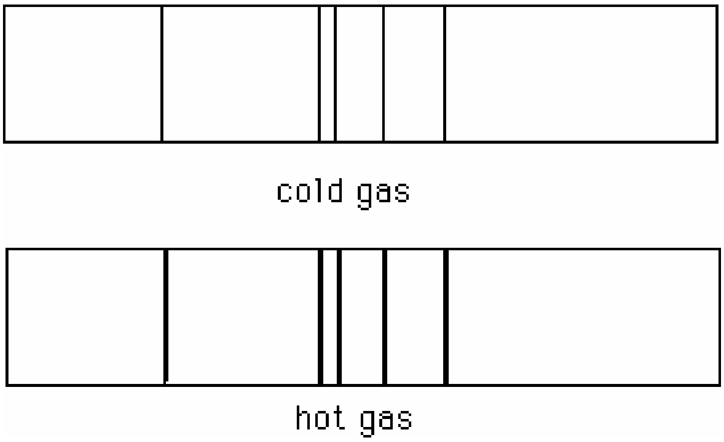
Now let us place this oscillating system on a runner and imagine that a hand pushes it towards the observer at speed V. The wavelength will decrease and the frequency will increase.



Inverse the operation : the hand will now pull back the runner at speed V. This time the sinusoid will be elongated.

If we know the radiating object's nominal frequency and measure the Doppler effect, we will then be able to deduce its speed of recession or approach, even at a considerable distance. By this means it was established that the stars move in all directions, like the molecules of a gas through thermal agitation. In a galaxy the speed is generally around three to thirty miles per second, according to the star type.

Each atom of a stellar shell is in itself a mini-radiation source. Let us suppose schematically that these atoms radiate only on a single frequency. We would have a spectrum with a single line (Sodium possesses a vary marked line. It emits also in other frequencies, but mainly in this one). The radiating gas is always hot. The atoms making it up are alive with thermal agitation. Therefore each one, at each moment, will produce a Doppler effect. The various contributions from different atoms, some moving away at a given moment while others are approaching, widen the spectral line.



Widening of the spectral lines due to atoms' thermal agitation.

This allows direct measurement of the average speed of thermal agitation and therefore of the atoms' average kinetic energy:

$$\frac{1}{2} m V^2$$

where m is the mass of the atom. We can then obtain the absolute temperature value of the gas. By definition it is equal to the energy plus a coefficient (Boltzmann's constant k = 1.38 10^{-23} and the exact relation is $3/2\ kT = 1/2\ m V^2$). In this way we learned that stars have very varied temperatures, our sun being far from the hottest (The surface temperature of stars covers a wide spectrum -- from 3000 to one million degrees Kelvin. Stars with temperatures between 20,000 and 50,000 degrees are the most common).

All this information -- chemical composition, temperature, speed -- was concealed in light.

Nevertheless there are disappointments -- stars so "small" at their distance from us that even our best telescopes can do no better than our eyes. Under the best magnification they stay sadly pointlike.

A telescope does magnify, however. If you have access to one with a ten-inch mirror in not too turbulent air, you will be astounded to see that you can read the fine print on a sack of manure five hundred yards away, or count the strands of a telephone wire and the pebbles strewn on a neighboring hill.

But to see the surface of a star, even that of a supergiant which could engulf the solar system, forget it. Even with the most powerful astronomical instrument in the world.

The stellar furnaces deliver up their secrets.

For centuries people hardly asked themselves why the Sun (or the stars) shine. For our ancestors the Sun was only one heavenly body among all those which kept their rounds under the celestial vault. Its presence and absence set the rhythm of the alternation of day and night but no one imagined that the stars, tiny bright points, could also be "suns". The discoveries of Bessel and the invention of spectroscopy transformed these pale heavenly bodies into a burning and varied bestiary.

With time people came to understand that the day-star was pouring "something" onto our planet's surface which heated our atmosphere and oceans. It was setting immense masses of air into movement and allowing plants to synthesize the oxygen we breathe and manufacture our basic foodstuffs. We call this thing energy.

Since the time of Archimedes of Syracuse in Sicily (287-212 BC), people knew how to concentrate the Suns rays with the aid of vast bronze mirrors, reportedly to the point of being able to set the sails of distant enemy vessels on fire (The Sun pours on to the surface of the Earth an energy equal to one kilowatt per square meter).

We will show that this energy can exist in many forms, all inter-transformable (This principle was enunciated in 1847 by the German physicist Hermann Von Helmholtz). Since bodies brought to a high temperature emit

light it made sense that the stars shine, but where do they draw their energy from?
Numerous hypotheses were submitted. In 1810 the astronomer Herschel suggested that the Sun might be an immense block of incandescent carbon, but the idea was too primitive and rapidly abandoned because in such a case the heavenly body could not have burned more than ten thousand years. Helmholtz and the English physicist Lord Kelvin then considered that stars, like our sun, could draw their energy from a phenomenon of contraction due to the effect of gravitational forces. In contracting, they would heat up and this increase in heat would be accompanied by the release of energy in the form of radiation (The existence of planetary magma, like on Earth, is linked to this phenomenon. When the dust particles constituting the "primitive nebulae" condensed by colliding with one another, their kinetic energy was transformed into heat). However quickly became clear that this could not account for such an enormous hemorrhage over so long a time (In 1904, when studying the radioactivity of the mineral pitchblende, the physicist Ernest Rutherford, investigator of the atom, showed the age of his sample to be 700,000 years. People concluded that the Sun must be at least as old, which was a lot longer than traditional dating, such as that of the Bible for instance. Later estimates established by paleontology put the age of the Earth in billions of years).

With the beginning of the century came the discovery of atoms, radioactivity, and then, just before the Second World War, fission and fusion. Atomic nuclei were shown to be made up of nucleons -- protons and neutrons (only discovered in 1932 by the Englishman Chadwick). The Englishman Eddington was the first to consider that stars' cores might be fantastically hot with temperatures reaching millions of degrees. Many of his contemporaries, incapable of imagining such infernos, were disconcerted by his assertion. While theoretical models from quantum mechanics made it possible to envision fusion reactions between protons, the fact that both particles have the same electric charge meant that because of their mutual repulsion theoreticians to propose mind-boggling temperatures for fusion to take place -- ten billion degrees. In 1929 Fritz Houtermans and Robert Atkison, using the "tunnel effect" a quantum trick discovered the year before by Gamow, showed that the fusion of protons was possible at "only forty million degrees".

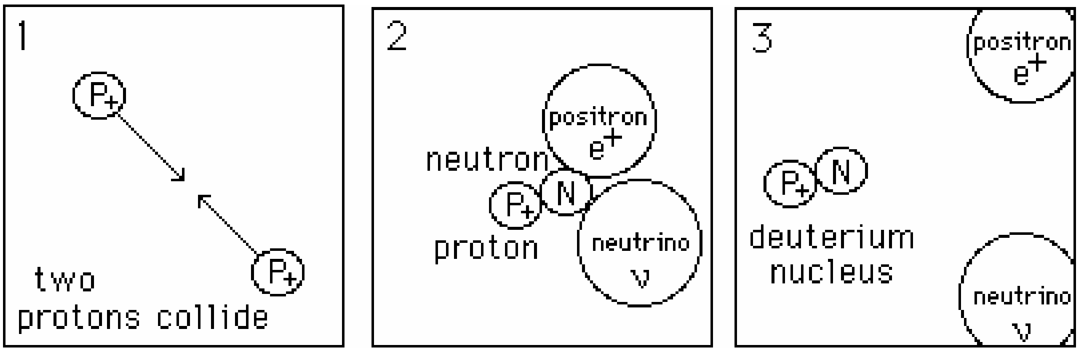
In quantum mechanics, the position and energy of a particle cannot be perfectly determined. Gamow, exploiting this idea, showed that a small, but not non-existent probability existed that the proton was "already" in the interior of the nucleus and susceptible to interact with it. He found that this phenomenon was sufficient to allow the appearance of fusion reactions, though the proton, slipping surreptitiously into the interior of the nucleus in the manner of a conjurer, did not have sufficient energy to pass over this potential barrier itself.

The evening he had this intuition, Houtermans took a young woman for whom he had tender sentiments for a walk under the starry sky. "How wonderfully they sparkle!" she exclaimed. "Yes", her companion replied, "and as of today, I know why!" Despite the effect of this announcement, the young lady nevertheless ended up preferring the co-author of the discovery, Atkison.

Today scientists believe they just about understand what goes on inside stars. For the Sun, whose core temperature is fifteen million degrees, it is the proton-proton connection which dominates.

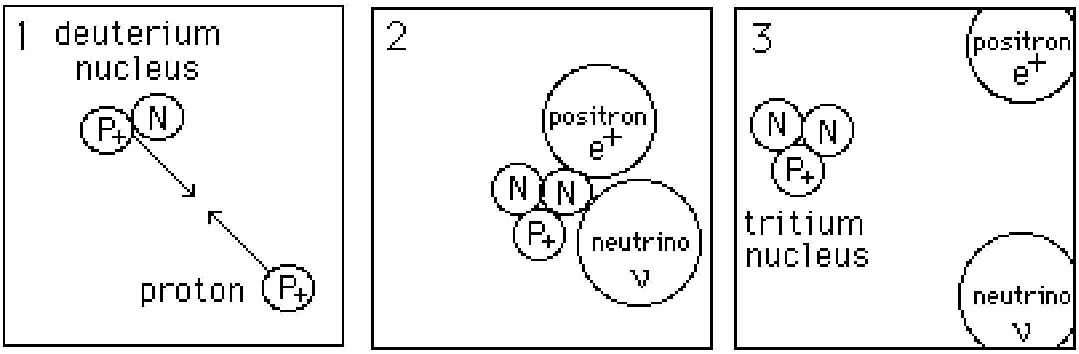
The proton-proton pathway.

Two protons enter into collision. One of them is immediately transformed into three objects -- a neutron, an anti-electron and a neutrino. The last two fly away leaving just a proton-neutron combination, that is to say a deuterium nucleus, an isotope of hydrogen, with the same charge.



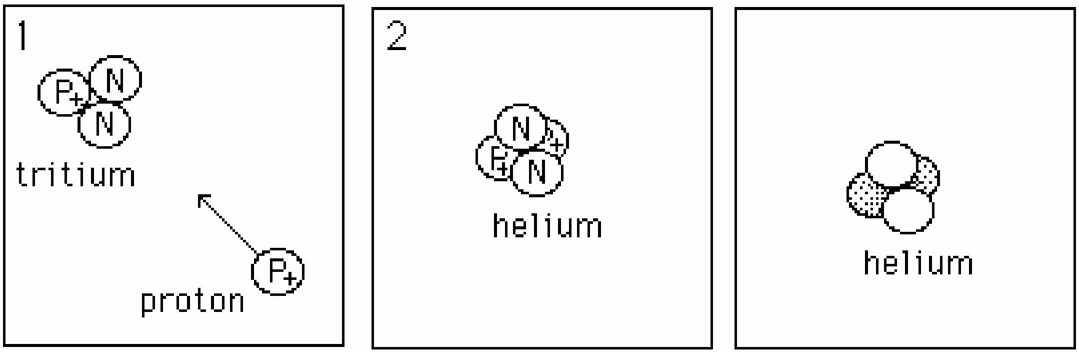
The proton-proton process. First stage creation of a deuterium nucleus.

This is the first stage of the proton-proton connection -- subsequently the deuterium nucleus, in colliding with a new free proton, is transformed into tritium by the same mechanism. The proton which had tried to intrude into the nucleus is transformed into the same neutron-positron-neutrino trio, with the last two flying instantaneously away.



Proton-proton process. Second stage Creation of a tritium nucleus.

A new proton then arrives on the scene, which intrudes into the tritium nucleus but without giving rise to this process of proton conversion into a neutron-positron-neutrino group. The object's electric charge then increases by one unit and the nucleus becomes one of Helium.

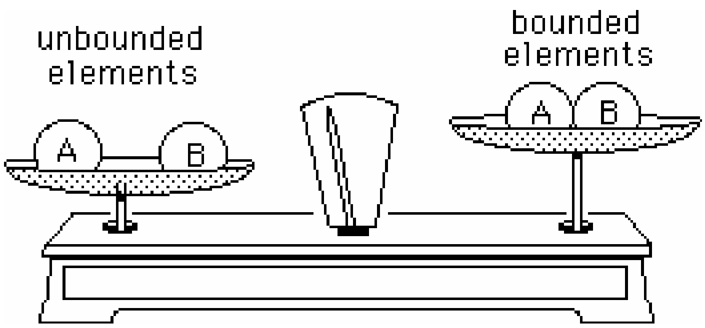


Proton-proton process.
Creation of a helium nucleus.

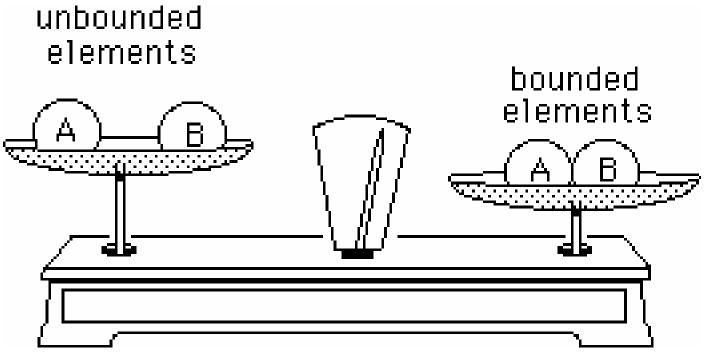
Helium has a tetrahedral structure similar to the little piles of balls staked up ready for use beside cannons. Such a compact structure, so stable. A good "nuclear ash" for this reaction.

If either a nuclear or chemical reaction synthesizing a composite A-B is exo-energetic, the composite's mass will be less than the sum of its components A and B, the difference corresponding to the liaison energy. If the reaction is endo-energetic, on the other hand, and its synthesis requires an outside supply of energy, the product's mass will be greater.

For chemical reactions, this variation in mass is tiny, but nevertheless quite real. We can schematize this in the two following drawings:



Exo-energetic reaction (nuclear or chemical) The mass lost during the liaison between the two components reflects the energy discharged.



Endo-energetic reaction (nuclear or chemical) The acquired mass reflects the liaison energy added to the reaction.

The nuclear fusion reactions cited above are exo-energetic, producers of energy. The energy comes from the transformation of a part of the mass, according to Einstein's relation:

$$E = mc^2$$

In the case of synthetic endo-energetic reactions, when there is an exterior energy supply, this is converted into mass according to the same relation. All this applies equally, at a smaller scale, to the world of chemistry.

Where two hydrogen nuclei fuse to give a deuterium nucleus, the loss of mass is of the order of seven per thousand. The deuterium nucleus weighs less at rest then than the sum of the rest masses of the two colliding protons. The energy resulting from the mass' transformation is divided between the different "reaction products" -- the deuterium nucleus, the anti-electron and the neutrino.

The Sun emits neutrinos, which we have succeeded in capturing on Earth. They traverse it without hindrance (they hardly interact at all with matter). As for anti-electrons, the surrounding matter annihilates them, their mass being converted into gamma rays which are absorbed by atoms and re-emitted in other frequencies. This energy diffuses very slowly towards the Sun's exterior through an interminable succession of photon absorptions and re-emissions by the star's components. The reader will be doubtless very surprised to learn that the energy takes about a century to arrive at the Sun's outer surface! But the conservation of this energy for such a long time within the Sun's bowels allows it to maintain its internal pressure and avoid collapsing on itself.

Nuclear reactions are merely a "chemistry of nuclei".

Fission, for example, is an autocatalytic "spontaneous dissociation" -- the neutrons emitted start other fission and create a chain reaction if the density of uranium atoms and the volume containing them are sufficient. If not, the neutrons emitted by reason of the basic instability of U239 leave the metal without colliding with one of their neighbors. From this comes the notion of "critical mass".

Even in this somewhat peculiar "chemistry" we preserve the concepts of classical chemistry.

The solar neutrino deficit.

It was long time before we were able to measure the neutrino flux. There are three kinds of neutrinos :

- Electronic neutrino
- Muonic neutrino
- Tauonic neutrino.

They are supposed to be zero-mass particles (like the photon) and as these neutrinos interact very weakly with matter, it that it has been very difficult to measure the rare interactions that occur. To do so, huge tanks were built and filled with water before being surrounded by a multitude of detection devices. One of the biggest systems, called Kamiokande, is in Japan.

But when the count of neutrinos began scientists became very puzzled : half of them were missing. Today, this is still an open question, an unsolved problem. Moreover quantum mechanics is unable to give any explanation to this solar neutrino deficit, nothing. Some researchers (Foot and Volkas, Berezhiani and Mohapatra, Physical Review 1995) have suggested that half of the energy carried by neutrinos could correspond to "mirror neutrinos", traveling in some "mirror universe".

Quantum mechanics theory also predicts a certain ratio between the different kinds of neutrinos but here again measurements show a 50% difference from theoretical predictions.

What does it mean ?

It means that we don't really understand how our solar star, the Sun, works.

But let us return to classical theories.

The carbon cycle.

When the star's core has a temperature somewhat above fifteen billion degrees, another reaction begins and takes over from the proton-proton pathway. Discovered by Hans Bethe, a German immigrant living in the United States, in 1938, it is called the "carbon cycle". The idea is simple enough to understand. An ordinary carbon nucleus composed of twelve nucleons, six protons and six neutrons, is bombarded by protons, hydrogen nuclei. It swallows four of them, successively. In the course of doing so it transforms two of them into neutrons. The protons transmute, as already seen in the preceding proton-proton pathway, into groups:

Proton --> Neutron + anti-electron + neutrino.

This conversion process can only take place inside a nucleus. It requires energy, which is taken from the nucleus' total mass. A proton in a free state could not decompose in this way, simply because its mass is less that that of a neutron. In the above equation there is therefore more mass on the right side than the left.

In contrast a neutron, in a free state, would decompose spontaneously, giving a proton and an electron, at the end of 10^9 seconds. A neutron which is not part of a nucleus in an unstable particle.

In the reactions in question the proton's conversion is instantaneous. As a general rule, the emission of anti-electrons (or electrons, this type of reaction also being possible) by a nucleus is called beta-disintegration. Many unstable nuclei act like this, with shorter or longer periods.

With its fourth proton stashed away, the "carbon" spits out the whole, that is to say a helium nucleus (two protons plus two neutrons, which corresponds to what is called alpha radio-activity).

During this process carbon C^{12} "changes name". After it swallows the first proton it is called "isotope of nitrogen N^{12} (seven protons, six neutrons)". Beta-radioactivity transforming the swallowed proton into a neutron, it transmutes into carbon C^{13} (six protons, seven neutrons). A new change of identity. It then becomes oxygen O^{14} (seven protons, seven neutrons). The collision with the fourth proton should have transformed it into a nucleus possessing eight protons and eight neutrons but this unstable nucleus ejects the four intruders as a block (a helium nucleus) and once again becomes ... carbon C^{12}, ready for a new cycle.

Let us draw a the diagram of the carbon cycle (the number of protons at the top, the number of neutrons at the bottom). P^1 represents the proton (hydrogen nucleus).

$C^{6}_{6} + P^{1}$ ---> N^{7}_{6} (nitrogen isotope)

N^{7}_{6} ---> C^{6}_{7} (carbon isotope) + e^{+} + ν

C^{6}_{7} + P^{1}---> N^{7}_{7} (nitrogen isotope)

N^{7}_{7} + P^{1}---> O^{8}_{7} (oxygen)

O^{8}_{7} ---> N^{7}_{8} (nitrogen isotope) + e^{+} + ν

N^{7}_{8} + P^{1} ---> X^{8}_{8} (unstable) --> C^{6}_{6} + He^{2}_{2} (helium) + γ

The carbon is recycled.

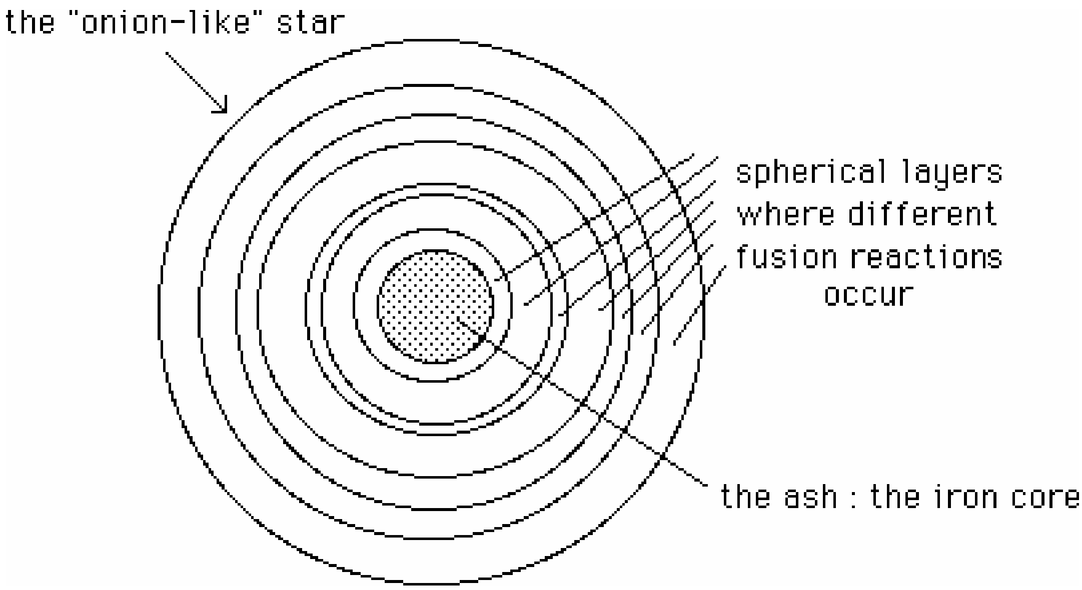
In the carbon cycle energy is liberated in the form of very short wavelength gamma rays (the symbol g in the previous reaction), absorbed by the star's elements and reemitted in other wavelengths.

Helium can fuse in its turn if the temperature is higher. For that the core temperature of the star must attain one hundred million degrees. Two heliums (four protons, four neutrons) give berylium (eight protons, eight neutrons). In absorbing a new helium nucleus the berylium transforms into carbon (six protons, six neutrons).Theoreticians have calculated numerous possible fusion reactions. They are at work in very massive stars (some known stars have a mass equal to a hundred times that of the Sun). We will now describe the fate of these "space spores".

The fate of massive stars : supernovae.

These stars consume their hydrogen in ten million years (a twentieth of our galaxy's period of revolution). The giant then has a million years to live. The helium, brought to a temperature of one hundred and seventy million degrees, fuses in its turn to form carbon and oxygen. When the helium is consumed, the star begins to collapse again. At that stage it is then a thousand years from its end. During this period its core temperature climbs in stages. A thousand years from the end the star's core is at seven hundred million degrees. At less than a year its temperature reaches two billion degrees.

The synthesized iron acts then like slag and falls to the center of the star where it accumulates.



The supernova furnace : a sort of onion where specific nuclear fusion reactions take place in each different temperature and pressure layer. The "ash", the synthesized iron, falls to the center.

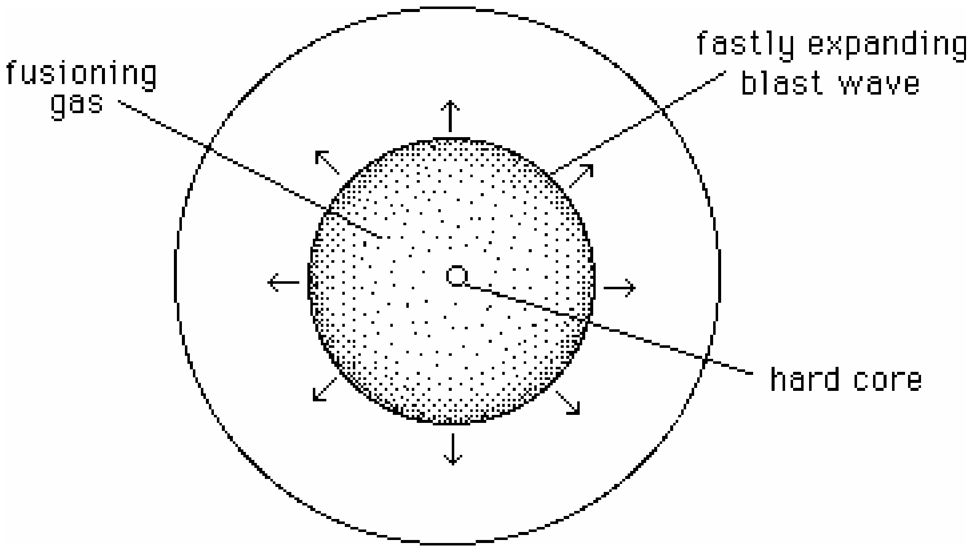
For the star, significant fusion reactions are those which produce energy and so allow it to fight against collapse due to the forces of gravity. From this point of view iron is not at all "profitable", it cannot provide exo-energetic fusion reactions. It just accumulates in the center of the star as a useless ash.

As the different elements are progressively transformed into iron and the slag piles up, the stellar furnace produces less and less energy until eventually it becomes unstable.

We can compare a star to a cheese souffle, whose weight tends to flatten it. So long as it receives heat, it conserves its form. This heat is the energy issuing from the nuclear fusion reactions. Without it, the souffle must inevitably collapse.

The iron atoms are destroyed within the star's iron core and their mass transformed into an enormous nucleus. The prevailing pressure there becomes such that the protons cannot "exist". All those present in the iron nuclei are transformed into neutrons. However this mass of closely packed neutrons can endure a much higher pressure than could a simple iron sphere. They finally say "stop!" and the atoms converging towards the star's center begin to bounce back violently from this incompressible object. The rebound creates a detonation wave, which traverses the star, setting it ablaze as it passes, to reach its outside surface in just a few hours.

A normal shock wave traverses a gas "passively". A detonation wave is a shock wave which is self-propelled by combustion reactions in a chemical milieu. In a stick of dynamite for example the element's chemical transformation takes place because of the detonation wave traversing it. We then no longer say that it burns, but that it explodes.



Gas rebounding against the central nucleus gives birth to a detonation wave which inflames the star's total mass.

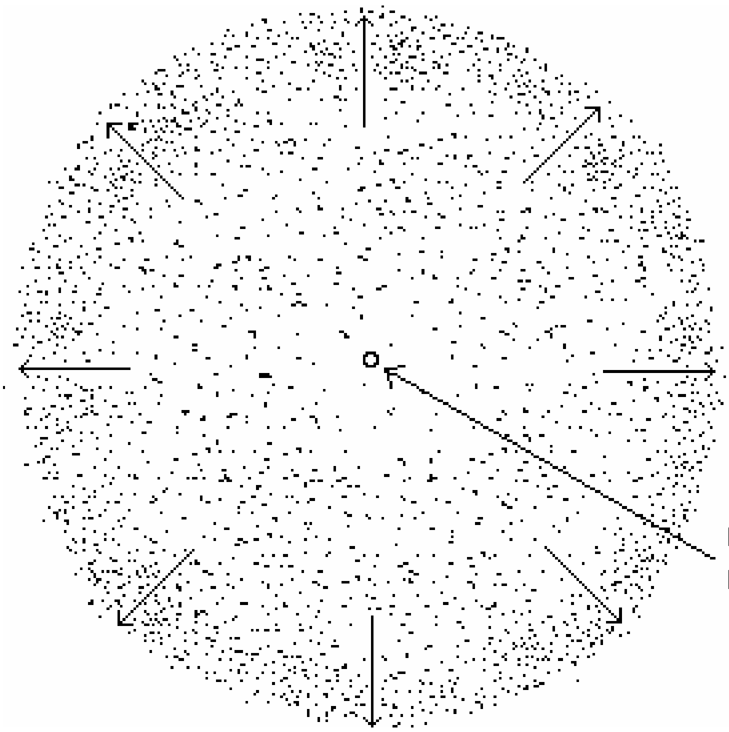
These fusion reactions give birth to not only all the "possible" (stable) atoms of the Mendeleiev table, but also to a multitude of disintegrating radioactive nuclei, with longer or shorter half-lives.

The radioactive atoms present in the terrestrial crust, like radium or uranium, are simply the elements synthesized in a supernova explosion, but endowed with half-lives sufficiently long to reveal their existence well after the creation of the Earth.

These fusion reactions are accompanied by a formidable emission of neutrinos which carry away 99% of the energy released and go off to the ends of the galaxy. If we compare a supernova explosion with a bank robbery and the energy produced to the star's energy-treasury, we could say that the neutrinos act like nimble accomplices who succeed in infiltrating the space between the nuclei and then escaping at the speed of light without incident, clutching their portion of the booty. Other forms of energy are slower in leaving the rapidly expanding star. Thus photons of all energy levels are absorbed, reemitted, reabsorbed and reemitted many, many times, until finally the energy can radiate freely into the surrounding space. This explains why the first signal recorded by astronomers from the 1987 supernova explosion was a packet of 19 neutrinos which set off detectors 18 hours before the supernova revealed its presence through a formidable increase in luminous radiation.

But, historically, it is the increase in magnitude of the star which will attract the astronomers' attention. The correlation with the recording of the 19 neutrinos was only established afterwards.

The detonation wave not only compresses the gas, provoking fusion reactions, but also makes it expand. The star's debris will remain visible in the form of a shell for thousands of years.



The supernova's debris disperses while a central residual object subsists : a neutron star.

A remark about the initial value of the mass.

The result of the process depends on the initial mass of the star. Here, we deal with a star whose mass in 20 solar masses. Then the calculations give a neutron star as residual object.

But if the initial mass of the star is smaller than 8-10 solar masses, at the end of its life, and after a somewhat violent period, it becomes a white dwarf, not a neutron star.

Nowadays we know that stars with masses up to 100 solar masses exist. However we don't know what could happen when their fusion fuel is burnt.

What happens to stars whose masses are at an intermediary value, say

10 solar masses < M < 20 solar masses

What is the impact of their initial rotation velocity and initial magnetic field ?

There is no clear answer to the question. We have to rely on schematic models :

- The stars which give white dwarfs
- The stars which give neutron stars.

The case of the neutron star is interesting. As we said, suddenly there is a lack of fuel and the material of the star undergoes a fast free fall towards the central hard iron core. When the material hits the core it is strongly compressed and its temperature and density increase. If the density becomes important enough, electrons no longer have enough room to survive and so are absorbed by protons, each couple being transformed into a neutron plus a neutrino :

$$P^{+} + e^{-} \longrightarrow N + \nu$$

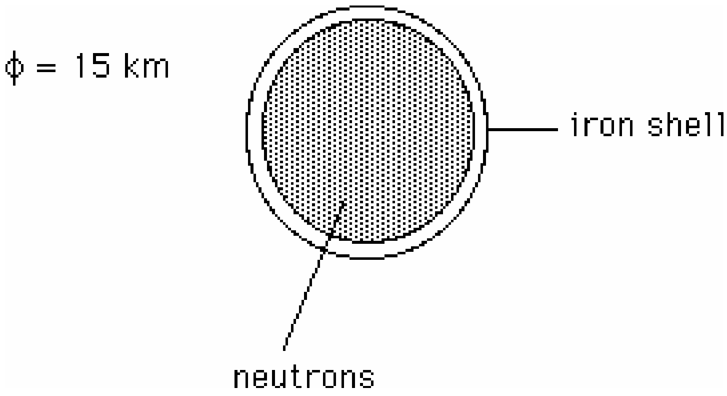
The neutrino carries energy. But due to its extremely weak interaction with matter, it can escape the object completely, which thus ensures the dissipation of energy so that there is no pressure increase or rebound.

But if the level of compression is not high enough, this process cannot occur and the energy cannot be dissipated. Then the object just explodes.

Some specialists think that in certain conditions, no residual object could survive the final process.

But let us return to stars of 20 times solar mass.

A central object subsists, a neutron star, formidably dense (ten million tons per cubic centimeter). It resembles a fruit, whose pulp is made up of packed neutrons and whose skin is an iron cover about a hundred meters thick.



A neutron star.

The weight at such a star's surface is crushing although the star itself is minute. If a starship equipped with some means of canceling out the frightful gravity landed on it and a passenger opened the door to step onto the star, he would be immediately transformed into ... an iron coating,

These residual objects are bizarre. However their existence was proven in 1967 by Jocelyn Bell and Anthony Hewish, who directly observed not only neutron stars but also their effects.

When an ice-skater pulls back her arms to her body she begins to act like a spinning top. Every contracting body does the same thing to conserve its rotational energy, called its "kinetic moment".

The neutron star came about from the contraction of a vigorously rotating object. The contraction was such that the top now has to turn at great speed, up to a thousand revolutions per second.

In addition neutron stars have a very strong magnetic field whose poles do not necessarily coincide with its axis of rotation. Stars' magnetic geometries are complex and we are only just beginning to study those of the Sun with accuracy.

The interaction between this revolving magnetic field and the star's environment transforms it into a kind of lighthouse. More precisely a radio-beacon, since its electromagnetic wave emission is located within the radio range.

When Bell and Hewish picked up these modulated signals for the first time they believed that extraterrestrials were trying to communicate with us. Their technology would have had to be very advanced for the signal to be so intense a such a distance and aimed at our solar system with a certain precision. In the ensuing months the two researchers found several other "pulsars" and it quickly appeared improbable that so many civilizations had agreed together to try to communicate with us. The hypothesis of messages from extraterrestrial civilizations was therefore rapidly abandoned.

Today we know of several hundred pulsars.

In a neutron star the neutrons fill all available space, but stand the enormous pressure of gravitational force. This is possible if the mass of the object is lower than a critical mass (about 2,5 solar masses) but nobody knows what would happen if the mass increased to a point where the neutrons themselves would become incapable of resisting the phenomenon of compression. Some people think that the object would then become what is called a black hole.

We will return to this theme later.

Two anecdotes.

The idea that stars can explode was proposed for the first time in 1931 by Fritz Zwicky, at a Caltech conference. Two years later, with his colleague Walter Baade, he published a paper through the American Physical Society affirming that massive stars explode in galaxies every hundred years on average, in particular in our Milky Way, and that the phenomenon could last twenty days or so. Zwicky claimed that the star in question could then become a hundred million times brighter than the Sun. A fantastic prediction it seemed and the idea was greeted with sneers and smiles.

"Come on, Fritz, the cosmos is quiet. You only have to look at the sky".

I had the opportunity twenty-five years ago to take a boat cruise with this unusual man, now deceased. Zwicky viewed the universe like a pyromaniac and had the mental capacity to stretch his scale of temporal perception to millions of light-years. In listening to him one was taken beyond the limits of imagination and began to feel as if living with the rhythm of the cosmos itself. Zwicky was a passionate visionary but his strong personality brought him the enmity of several colleagues. He thought more quickly and further than others, like a mutant, and was aware of it. Everything about the man was extra-normal. People said that in his youth he did push-ups with one arm in the university cafeteria while challenging his audience to do the same. He reacted forcefully to criticism by calling his detractors "spherical bastards", a concept he invented to describe people whose stupidity was invariant from all angles.

He had ideas in all areas, from technology to the most sophisticated theoretical speculations.

When the Russians were winning all the laurels in the conquest of space, Americans pulled out their hair and wondered : "Gee, what can we do that the Russians haven't done already?"

The former had already put their first satellite in orbit, Sputnik, which was followed by a dog, Laika, then a man, Gagarin.

"I've found it", Zwicky said, "we will be the first to send objects beyond the earth's gravity!"

"But how? This means attaining a speed above the earth's escape velocity -- seven miles a second. No rocket is capable of getting to such a speed".

"There is another way".

"What?"

"An explosive. We pour metal balls into a hollow tube and when one of our Aerobee rockets has climbed high enough and is outside the earth's atmosphere, we ignite the explosive. The balls will be shot off in every direction at much greater speed. Some them will necessarily escapee behind the earth's attraction and, with a little luck, we will see some of them even as far as the Sun!"

The idea was approved and carried it out. The press announced that the Americans were the first to send objects outside the earth's attraction thus to creating the first artificial meteorites.

In 1937 Zwicky finally managed was to film an explosion of these space spores in a galaxy four million light-years away. Five months later he produced evidence of a second explosion. By the time of his death he had recorded 280 supernovae. Today, almost a thousand have been observed. But the idea took hold only slowly within the scientific community.

The second anecdote refers to the first observation made "close by". On February 24 1987, a twenty-year-old Canadian astronomer, Ian Shelton, could not believe his eyes when, after developing a negative taken with a modest telescope equipped with 25-centimeter-diameter mirror, he discovered an abnormally luminous star in our closest neighbor, an irregular galaxy named the Magellan Cloud which practically nudges our own. He observed "live" the death of a star located some seventy thousand million light-years away, or, in other words, which took place .. seventy million years ago. It was a star with a mass twenty times that of the Sun.

This supernova phenomenon, although statistically it happens every century, just as Zwicky predicted, is practically unobservable in our own galaxy. Massive stars are virtually all located in the galaxy's diametrical plane, where dust obscures observation considerably. Only Tycho Brahe, in 1582, and Kepler, in 1604, have had the luck to observe one of these violent star-deaths with the naked eye.

In 1987, as soon as the news of the Magellan galaxy supernova observation became known, all available instruments of observation were pointed in its direction. We were thus able to capture 19 neutrinos in all, in eight in the United States, in Cleveland, Ohio, and eleven in Kamioka, Japan.

When a supernova explodes, neutrinos take 99% of the energy of the explosion with them.

The event happened, as we have already said, eighteen hours before the supernova itself became visible.

In fact these devices were not designed to detect such sudden puffs of neutrinos but to try to reveal the spontaneous, hypothetical decomposition of a proton. In order to do so, many detectors were placed in vast subterranean pools of water and at great depth in order to render them insensitive to the flux of cosmic rays falling onto the terrestrial surface. However the proton did not want to cooperate, to the great disappointment of scientists, but it happened that these same detectors were capable of recording so massive a bombardment of neutrinos, estimated at a hundred million particles per square centimeter of the earth's surface and of extremely brief duration -- ten seconds or so at the most (as the recordings testify).

One year after the explosion the satellite Solar Max picked up a gamma ray emission from the object, which revealed the radioactive decomposition of unstable elements synthesized during the cataclysm. This fitted in with a theory proposed a year before by the Burbridges, husband and wife, Fowler and Fred Hoyle. The supernova model was thus brilliantly confirmed.

For decades scientists have hoped to detect gravitational waves. Since gravitation is an extremely weak force (10^{39} times weaker than the electromagnetic force), it required really cataclysmic events causing such great movements of matter for the ultra-sensitive detectors (large metallic blocks whose tiny deformation was measured) to be able to register anything. Unfortunately, just at the moment when the supernova in the Great Magellan Cloud exploded, every detectors that had been built on Earth was either being revised or undergoing technical modifications! Their owners really bit their fingers and it was decided that from then on, two detectors would always remain operational in case anything happened. It was a little late to think about it -- the laws of statistics indicate that it might be several centuries before the next observable supernova appears.

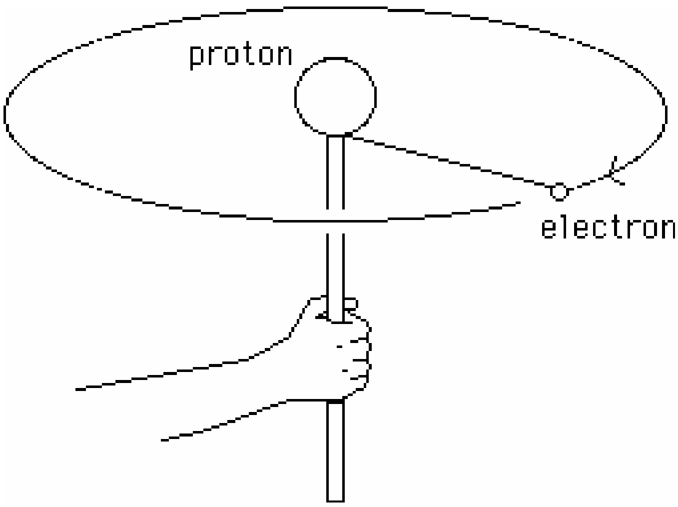
Quantum digression.

In the above drawings concerning the proton-proton fusion pathway, the electron is represented by a circle larger than that surrounding the proton. The reader perhaps said to himself, "hmm, the author simply wanted to make space for all the letters in the word 'electron'", as everyone knows that the electron, 1850 times lighter than the proton, is "smaller". However this is only the result of our mental iconography which believes that a greater condensation of matter should automatically be larger. Paraphrasing Aristotle, we could enunciate the following principle:

--As far as elementary particles are concerned, what is heavy is big and what is light is small.

In fact ... it is exactly the opposite, as we will see.

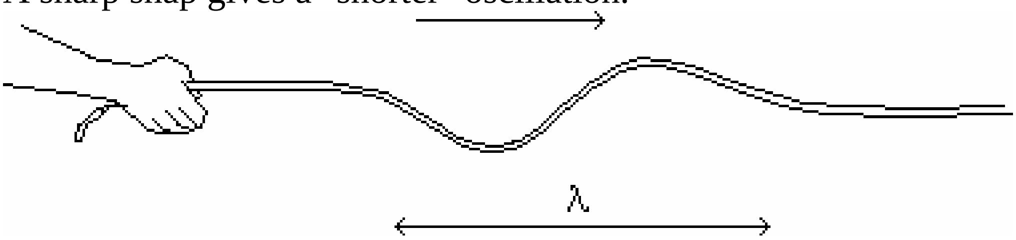
Our mental model of the hydrogen atom resembles a billiard ball fixed to a stick. A marble revolving around it is attached by a string which is supposed to represent the electrostatic attraction (the proton and the electron, having opposite charges, attract one another) and to counteract centrifugal force.



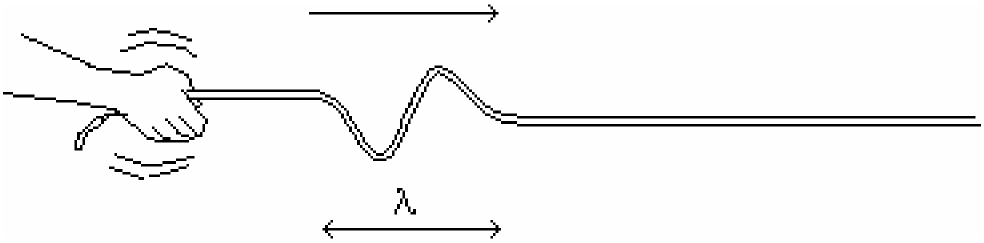
Our mental model of the hydrogen atom : a little electron turning around a big proton.

The image is naive. The particles are neither billiard balls nor glass marbles. They are wave packets.

Take a rope and shake it. You will set off one or several oscillations. You might notice that the more energy you put in, the shorter is the wavelength. A sharp snap gives a "shorter" oscillation.



If we shake the rope softly we create an oscillation with a long wavelength.



A sharper snap, putting more energy, will create an oscillation with a shorter wavelength.

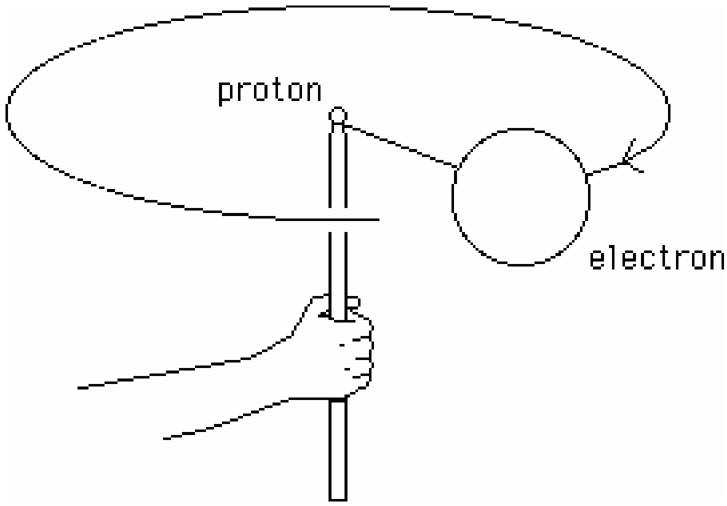
In quantum mechanics one can associate a characteristic Compton wavelength to a particle of mass m:

$$\lambda_c = h/mc$$

which we can use to determine the order of a particle's spatial extension.

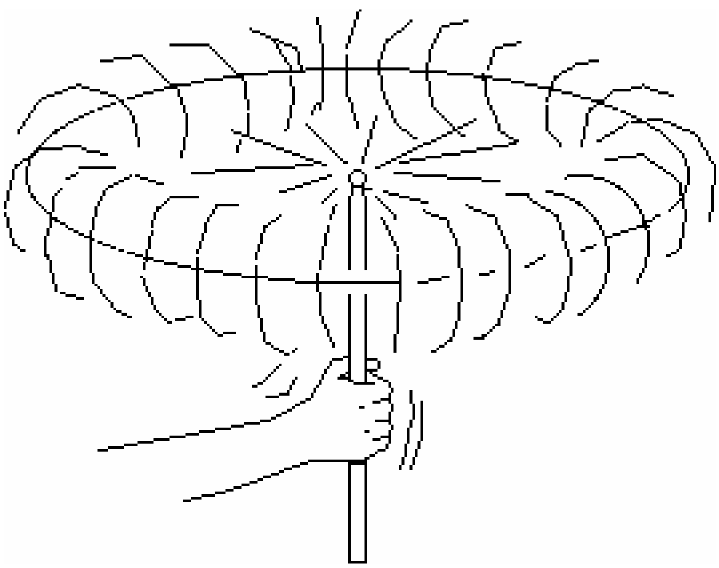
h and c being absolute constants, we see that size varies inversely to mass. Therefore the heavier one gets, the smaller one is? We will have to modify our model of the hydrogen atom, replacing the billiard ball with a ball of lead and the electron with a polystyrene sphere.

The proton's mass is 1850 times larger than that of the electron. Therefore, from this point of view, the proton is "1850 times smaller" than the electron.



Second model : the electron is this time larger than the proton.

But we are still far from quantum reality. All this shows simply to what extent we are still using naive images in our minds. Things will change when we finally decide to teach quantum mechanics in kindergarten.
In fact, the electron occupies no particular place around the proton. To suggest this it would have to turn fast enough to show that it cannot be localized it in space.



By making the "electron-ball" turn very fast your eye can no longer localize it in space.

In addition the electron cannot use any old orbit. But, to know more, look at Appendix 8.

The scenario of a star's life.

We have presented the most spectacular history above, that of a very massive star, a mass exceeding the Sun's by eight to nine times. We consider such massive stars to be "problem stars".
Below them we find a whole range of possible evolution, depending uniquely on the heavenly body's initial mass. Of course, very old, primitive stars were formed from what was then the "primitive soup" of the cosmos, that is to say 75% hydrogen and 25% helium. Where did this primitive helium come from? From a primordial nucleosynthesis, the universe itself having functioned in its infancy as a single star, synthesizing helium through a proton-proton path.

Today "secondary stars" are being born, collecting the heavy elements already synthesized in massive stars, and functioning like spores. Spectroscopically speaking, we distinguish ancient from more recent stars by their being poor in metals.

This said, the variation in composition has little effect on stellar destiny, the initial mass being always mainly composed of the hydrogen-helium mixture.

Stars are formed in gas clouds by condensation. Falling onto one another through gravitational instability (a theme which will appear in detail later), the atoms acquire kinetic energy which is transformed into heat, which increases pressure. This internal pressure opposes the star's collapse. For the star to create temperature and density conditions in its center sufficient to set off the first nuclear reactions (around seven hundred thousand degrees), the heat from condensation must be able to escape. The star radiates then in the infra-red, for a longer or shorter time period. The ignition of a massive star, for example, takes place rapidly -- in the order of a thousand years.

Certain proto-stars, which have masses less than a tenth of the Sun's, do not succeed in igniting because the core temperature never attains the threshold temperature of seven hundred thousand degrees. In that case they develop into unobservable "black dwarves" the size of a planet. Stars with masses comparable to the Sun's may be considered the standard stars of galaxies.

When this mass of hot gas has become a veritable star, a "cruising speed" is reached. Massive stars have a high carburation regime. Small stars are peaceful embers and can stay in that state for a period of time far exceeding the age of the universe itself. The lifetime of a small dwarf is estimated at a hundred billion years, ten times the age of the universe.

Stars with a core temperature less than or equal to fifteen million degrees function via the proton-proton pathway. For those with the higher temperatures, massive stars in particular, the carbon cycle dominates. They burn their hydrogen at both ends, in "only" ten million years, and come, as we have seen, to cataclysmic ends.

These types of stars all have different roles to play. Stars of the solar type (and we are increasingly coming to believe that this is a general phenomenon) surround themselves with a cortege of planets. If one of these is situated at a distance where water is neither in a state of ice or vapor, life can begin and develop, the star around which the planet orbits furnishing the necessary energy.

But certain forms of submarine life do not use solar energy as their basic source but the energy which emanates from submarine fumaroles of volcanic nature at great depths. We do not know if these living beings migrated to these abysses or whether they were born there and have never known the light of day.

Massive stars serve to fabricate the atoms needed for life to create itself. The sole use of dwarf stars for the moment, be they white, brown, or black, is to serve astronomers as candidates making up the so-called "dark matter", a subject which will be discussed later.

How have theoreticians been able to test the validity of all these models? Did they wait for these stars to evolve before their eyes? That would be rather a waste of time. At the end of the nineteenth century astronomers had the inspired intuition that the great variety of stars before them, classified by their spectra, represented not so much different stars as a small number of star families in different stages of evolution.

On the scale of cosmic phenomena, even the most rapid (except for rare supernovae, the exception to the rule), the ridiculously ephemeral human being is in perpetual "freeze frame". The movements of the planets are the only phenomena on the scale of his short life. However, with so many snapshots of similar events before his eyes, he can, like Sherlock Holmes, find the pathway of stellar evolution.

Despite the fantastic distance separating us from these objects and the impossibility of examining their burning entrails, through theoretical models and calculations, and well before having reconstituted the phenomenon "in the laboratory" (the hydrogen bomb), we have nevertheless been able to pierce the secrets of the stars,

The galaxies : a theoretician's nightmare.

We evidently cannot discuss all the discoveries made at the beginning of this century. We have yet mentioned Special or General Relativity for fear of losing ourselves in this vast forest of new ideas.

Theoreticians had remarkable successes with stars. They were able to interpret observational data and develop fruitful models. Of course, the evolution of stars, excepting the paroxysmal supernovae, is not on the ephemeral human scale. However, as we have said, it was rapidly understood that in fact groups of seemingly different stars represented successive evolutionary states of the same object.

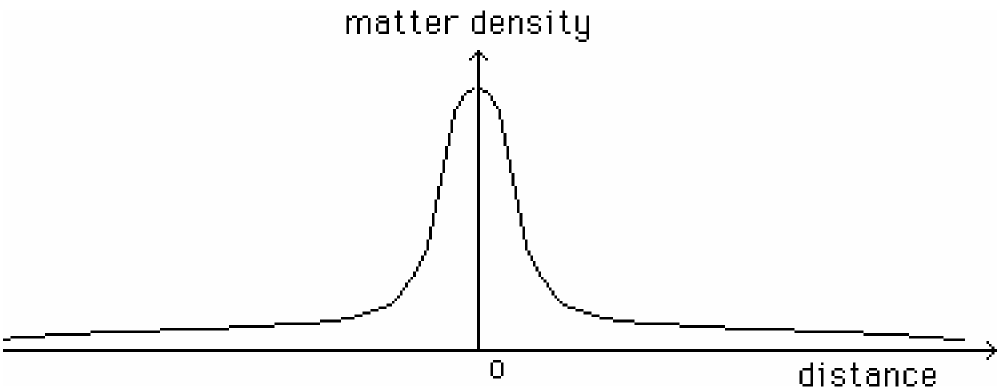
The same strategy was brought to bear on galaxies. There were all sorts, all forms, with or without interstellar gas, with a bar, without a bar, with arms, without arms, in the shape of car steering-wheels, etc.

Therefore the construction of a model describing not only the actual state of galaxies but also their evolution over of billions of years required a logic that would link all these different objects to reveal their formation, evolution, and final destiny.

The place to begin, as for the stars, was through observation.

With photometry we are able to determine the distribution of a galaxy's mass. The stars form a halo, a sort of ellipsoid, flattened a little and denser towards the center. The density profile had therefore the shape of a "bell curve".

The density of light emitted by stars, deduced by photometry, varies generally as the inverse of the fourth power of the distance from the center.



Characteristic appearance of the matter density in a galaxy, as a function of the distance from the center.

On the other hand, gas present in spiral galaxies forms a very flat shape -- a sort of pancake, of almost constant thickness, confined to the neighborhood of the central plane. This medium is fairly unhomogeneous and lumpy, made of clouds whose individual masses range from ten to a hundred solar masses. Precise cartography of interstellar gas distribution only began with the invention of radio-telescopes which are able to capture wavelengths specific to this milieu, as opposed to the neighboring stars.

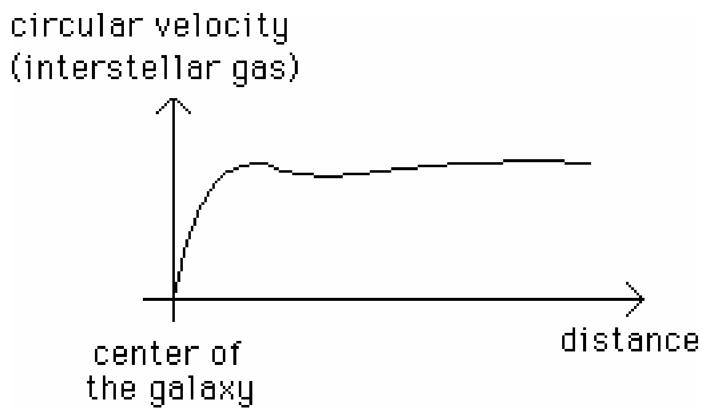
The gas was estimated to represent about ten per cent of the total mass, the rest being made up of stars. Gas density is fairly constant over distance and falls to zero rather abruptly at the galactic periphery.

The clouds' "residual velocities" relative to each other are fairly low, several kilometers per second, or about a hundredth of their orbital velocity around the galaxy. As stated above, the gas, orbiting in the field created by the stars, has a dynamic like the "rings of Saturn", with quasi-circular orbital trajectories.

It is possible to determine this circular orbit profile by observation using the Doppler effect. But let us remember that this can only give a projection of speed on the light of sight. But used in conjunction with the spatial position of a galaxy's central plane and a simple trigonometric calculation, it is sufficiently to deduce the component of circular rotation.

Determining the profile was not easy. I still remember when the "error bars" were considerable and theoreticians said to themselves, "Gosh! We can really pass any old curve within that!"

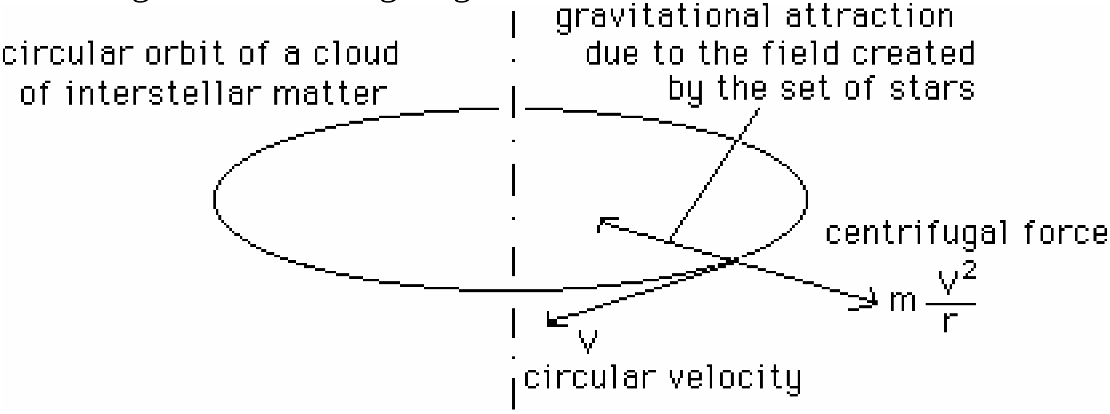
But this improved decisively with time. Gas rotation curves have the following general appearance:



Typical appearance of the rotation curve of interstellar gas orbiting in a galaxy's central plane.

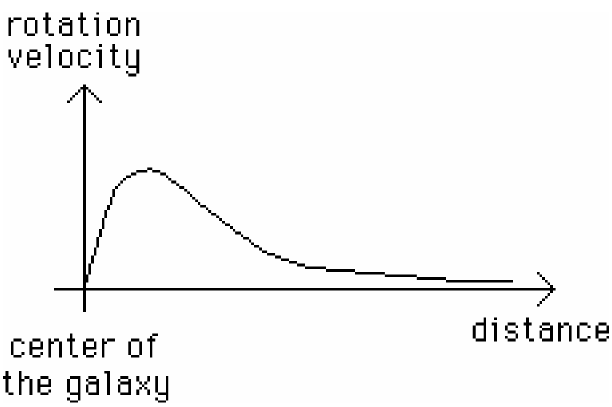
In the neighborhood of the center, a similar movement occurs to that of a "solid body", shown in the curve's linearity here. This is often followed by a sort of bump and finally the speed makes a very characteristic landing. Where the curve breaks off there is simply no more gas.

We might logically expect that this measured speed profile reflects centrifugal forces balancing the force of attraction due to the halo of stars according to the following diagram:



Schema of forces. Balanced circular orbit

Based on observed spatial distribution of star masses, here is what astronomers obtained:



Theoretical circular orbital speed, corresponding to a centrifugal force counterbalancing the field created by the stellar halo mass.

As we can see, there are not only quantitative (the measured speeds are higher) but also qualitative differences (the measured speed does not tend towards zero at the periphery; far from it).

What is true for the interstellar gas is equally true for the stars. Our sun also an almost circular trajectory in the galaxy's central plane, ambling at 230 kilometers per second. By all logic centrifugal force should have flung it off long ago, along with its cortege of planets. But we seem to be still here. Something must be ensuring the galaxies' cohesion, accounting for the observed form of the circular orbital speed curve.

The lack of mass is not negligible. The galaxies do not possess half, even a tenth of what they should need to hold the stars and interstellar gas in leash.

Hence the concept of missing mass.

A pure theory, a model needed elaboration. Theoreticians began working in this area in the twenties. At first glance the "elliptical" galaxies, where gas was practically absent, seemed easier to model. Their stars were very ancient, with less variation in mass than spiral galaxies, which contain many young and massive stars.

Since these galaxies contain a thousand billion stars we can usefully liken them to a sort of gaseous mass. But what an odd gas. The molecules of the air we breathe are moving at four hundred meters per second. They do not go very far; at the end of a very brief journey, their average free run, they hit a neighbor, every ....ths of a second (their average free run time). The air you breathe is a milieu in collision.

"Star gas" is not. Nor is two stars hitting one each necessarily a real collision. The time taken for an effect to be felt on a star's course by a near neighbor has been calculated. The distance being in the order of the size of our solar system. The time about 10^{17} years. One with seventeen zeros. Ten million times the age of the universe. Thus, in galaxies, stars move in superb ignorance of one another. They are "unconscious" of their neighbors' presence and "perceive" only a "smooth field". The gravitational field's alteration by each star could be compared to tiny depressions created by lead shot rolling around on a foam mattress. Each shot "would believe that the mattress surface is curved and concave, but perfectly smooth. The probability of a piece of shot entering into another's mini-depression would be practically nil.

All this is extremely annoying, because colliding gaseous ensembles are fundamentally different from non-colliding ones. The first can be described by equations invented in the nineteenth century by Navier and Stockes, which are tried and tested -- planes fly, furnaces function, etc. For many years now we have known how to use these equations to create piles of solutions. Once equations were manipulated by hand and brought many beautiful things. Today we have become lazier and tend to use the computer. But the mechanics of colliding fluids reached its maturity a long time ago an the age of empirical experiment has long been over. When we wish to build an airliner or a supersonic fighter, we can calculate the flow from A to Z, with a precision sufficient to rule out surprises. Everything is mastered -- aerodynamic forces, turbulence, heat flow and shock waves.

The mechanics of non-colliding fluids ... does not exist.

The galaxies constitute what is called "auto-gravitating" systems, which complicates the problem still further. They orbit in their own gravitational field.

Mathematically we say that this gives the solutions a forcibly non-linear character.

They are described by two very beautiful equations.:

-The Vlasov equation
-The Poisson equation.

Only for the sake of esthetics, breaking with my mrinciples, I cannot resist to show them to you :

Vlasov : $$\frac{\partial f}{\partial t} + \mathbf{V} \cdot \frac{\partial f}{\partial \mathbf{r}} - \frac{\partial \Psi}{\partial \mathbf{r}} \cdot \frac{\partial f}{\partial \mathbf{V}} = 0$$

Poisson : $$\Delta \Psi = 4 \pi G \rho$$

For over half a century this system has been like a safe whose combination we did not know. The greatest minds, such as the celebrated English astrophysicist Eddington or the Indian Nobel prize-winner Chandrasekhar, have unsuccessfully attacked the problem.

Don't think that one can derive ex nihilo a beautiful solution to such an equation through adding, subtracting, or dividing, as a non-mathematician might imagine who finds himself in difficulty when confronted with a system of two simple linear equations.

In the present case, the only possibility is to say, "Let us take a solution of such and such form..". and to particularize the solution according to this or that intuition. For this particular case, mathematicians adopt a solution called "elliptic" whatever it really resembles. At this stage, this choice consists of "injecting" the solution (the form of the function f present in the Vlasov equation) into a system of two equations. The matrix then explodes like a hand-grenade and vomits a disgusting system of twenty-one partial derivative equations, which in addition is non-linear, that is to say of the most hermetic species.

A single partial derivative equation is already in itself something rather terrifying. But twenty-one, you can imagine!

The derivation of this solution comes down to determining the value of twenty-one parameters (as many as there are equations, as it should be). You do not have to understand it; think of it as an oriental fairy tale.

Now, miraculously, the first twenty equations can be solved. We see interesting elements appear, extremely useful pieces of information in the area of velocity fields and their distribution in the galaxy. There remains just the twenty-first equation. Suspense. And there, oops!, everything unravels like a sweater, just when we thought we had prevailed. The moment we put the last card on the house, the whole edifice suddenly tumbles down.

Let us suppose that we write the twenty-one parameters on which the solution depends as follows:

$$a_1, a_2, a_3, a_4, ..., a_{19}, a_{20}, a_{21}.$$

The last solution gives, in a final tweak of the nose :

$$(a_1^2) + (a_2^2) + (a_3^2) + (a_4^2) + ... + (a_{19}^2) + (a_{20}^2) + (a_{21}^2) + (a_{22}^2) = 0$$

whose single solution is:

$$a_1 = a_2 = a_3 = a_4 = ... = a_{19} = a_{20} = a_{21} = 0.$$

All the parameters are ... zero. Our beautiful solution disappears in a puff of smoke. In the mathematical sense, "it does not exist". Clearly, if the system admits a solution, it is not of this type.

The reader might say that if that one does not work, mathematicians will just have to try others. Alas no one has any idea what to try. We have never found any other than this, back in the twenties, and it is unworkable. Sixty-one years later we have not taken one step further. The "galactic dynamic", from a theoretical angle, remains just assembly of two words, a substantive and an adjective. It simply does not exist. It is quite obvious that we do not have a model of a galaxy and no astrophysicist can tell you otherwise. As far as representing galaxies is concerned, we have not got any further than did the earliest and most primitive empirical experiments.

The strange world of galaxies ...

Since theory is unable to tell us anything, let us turn to the data. In general there are three types of galaxy:

- The "ellipticals" : containing in the order of a thousand billion stars.
- The spirals : containing in the order of a hundred billion stars.
- The "dwarves" : less than ten billion stars.

In the ellipticals gas is rare, or even practically absent. They are made up of ancient stars, ten billion years old and more.

Let us be clear from the start -- we do not know how galaxies are formed. There are competing models, between which we do not know how to choose. Nevertheless we constantly speak about young and old stars so how can we make this distinction?

As we have said above, stars function with the universal fuel known as hydrogen. (Plus a certain percentage of equally primitive helium, which we will come to later when discussing cosmology and the "standard model".) Second generation stars exist, stars which have gathered up the debris from the explosion of more massive stars. They are rich in metals, detectable by spectroscopy. Very old stars are made up solely of the primitive hydrogen and helium and are poor in metals.

Elliptical galaxies are constituted by stars poor in metals. We deduce from this that they are ancient objects, whose age is in the order of ten billion years or more.

Does this mean that spiral or dwarf galaxies are more recent? No, because they contain stars just as poor in metals and just as ancient as those in elliptical galaxies. When were these galaxies formed, and how? We do not know. There are two diametrically opposed theories. Some think that galaxies, condensations of matter, were first formed into objects and then fragmented into stars; others believe the opposite, that is to say that groups of hundreds of thousands of stars were formed first, then these "mini-galaxies" grouped together to form spiral and elliptical galaxies.

Only the observation of a proto-galaxy in the course of formation could give us a clearer view of the matter but we have never detected one, which leads us to think that galaxies are very old objects, almost as old as the universe itself.

Stars seem to be born in bunches within the clouds of interstellar space. The Perseus cluster is an example of a cluster of young stars, on the way to dispersion.

As we have said above, these proto-stars have a latency phase, before nuclear reactions begin in their interiors. They are clumps of gas raised to a temperature of several thousand degrees, and which therefore radiate in the infra-red, before cooling off slowly. This cooling off allows them to contract and increase their core temperature up to the threshold temperature of fusion reactions, seven hundred thousand degrees.

The terrestrial atmosphere absorbs infra-red. So there is no hope of comfortably observing these proto-stars from the ground. In theory we should get more access these interesting proto-stars thanks to the space telescope ISO which is specially equipped for infra-red observation.

In 1993 the space telescope Hubble detected small dark spots against the luminous background of the immense gas cloud called the Orion Nebula, located 1500 light-years away. They were called "proplyds" and identified as proto-stars surrounded by proto-planetary systems. Astronomers think that they are very young stars, still surrounded by an opaque dust shell. Infra-red examination of their surface temperature will tell us more. Other, still more recent and very spectacular pictures seem to show proto-stars, or proto-stellar masses, in the course of leaving their immense uterus but still tied to it by a sort of "umbilical cord".

Astrophysicists have something to chew on therefore but as yet, we have no picture of a "proto-galaxy", a galaxy in formation, either nearby or far away. Recent images of galaxies located at mind-boggling distances, more than ten billion light-years, suggest that the formation of such systems may be very ancient. Without observational data, however, we can only indulge in untrustworthy speculation.

What applies to stars in galaxies applies equally to clusters of galaxies. Did these immense condensations of matter appear before or after the birth of galaxies? Impossible to judge.

Why are massive galaxies poor in residual gas? There are different theories. In any case, a galaxy is a sort of oven. Stars heat the residual, the interstellar gas. Ancient stars, which make up the elliptical galaxies, must have been young once. In such a cry-baby galaxy radiation must have been very intense and perhaps this heated up the residual gas which had not condensed into stars. Temperature means speed of thermal agitation. This speed might have become higher than the "escape velocity" of a galaxy's gravity so that it was perhaps it stripped of its gas. Gone forever.

We know that galaxies bathe in a very hot gaseous environment made up of very rapid atoms, too rapid to be captured by galaxies but not dense enough to cool down by themselves through radiation because of collisions between atoms. Perhaps this is the primitive gas which massive galaxies have dispersed and "evaporated" beyond their clusters.

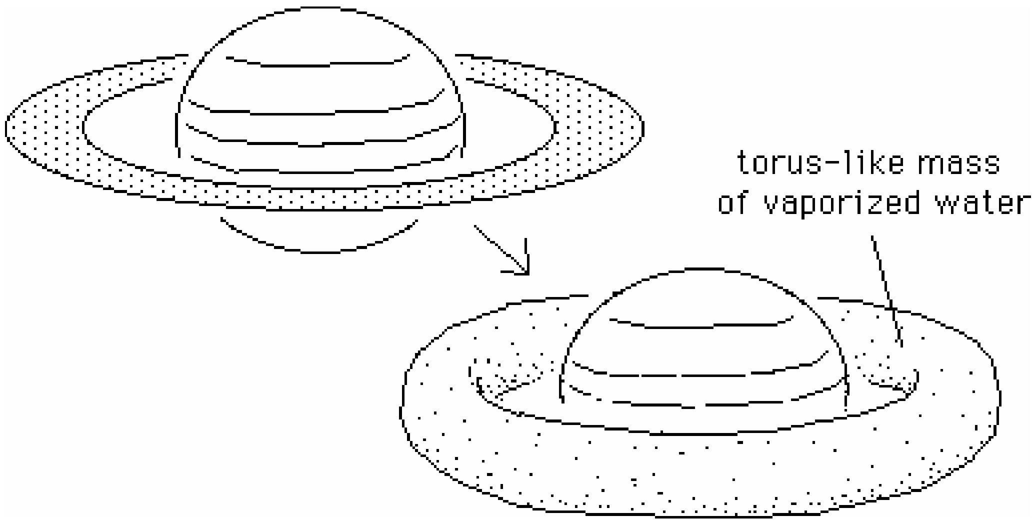
Less massive galaxies, the spirals, would on the contrary have conserved their gas even after their first infant wails. After having been "kept at a distance" by the intense flow of radiation (the "radiation pressure"), the gas would have fallen back to form a flat disk.

But these are only some theories. There are dozens of others.

Interstellar gas "metabolism".

The reader can nevertheless understand what regulates the shape, the spatial extension of cosmic objects. The rings of Saturn form an ultra-flat system made up of blocks of "dirty ice" of varying dimensions and quasi-circular movements. They have no "agitation velocity" and are endowed with almost zero "residual velocities".

It is logical to think that initially this sub-system was a water vapor mass in the shape of a torus. In fact, if you could heat the rings of Saturn with a powerful infra-red lamp, for example, the blocks would vaporize and the freed molecules would take on this toroidal form.

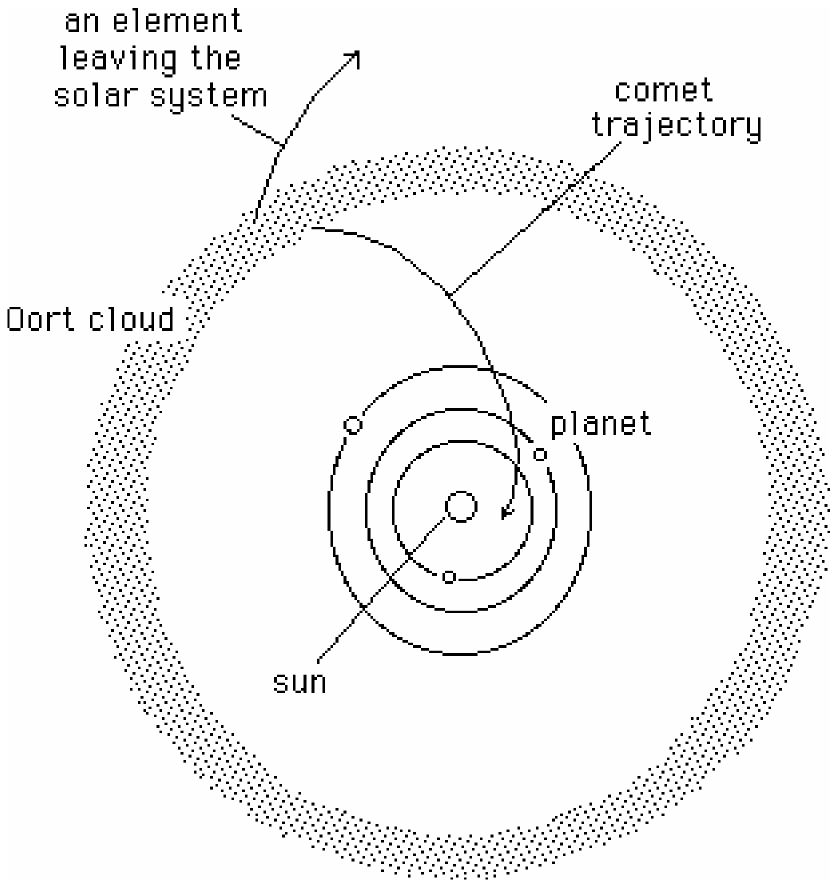


What would happen if we vaporized Saturn's ring.

The heating would not modify the ring's distance in relation to the planet because it would not alter its rotational motion and, therefore, its centrifugal force. If continued, the heating could be such that the molecules would take off from the planet, "evaporating".

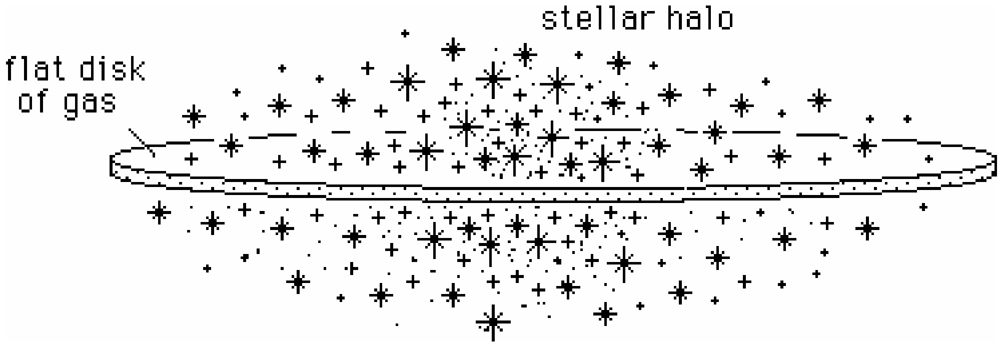
Inversely, when we stopped applying heat, the gaseous mass would begin to cool down through radiation. Its molecules would begin to collide losing a little energy with each collision. They would lose speed. The inverse scenario would take place. The gas would flatten out, ice-blocks would form and the rings, the ultra-flat system, would reconstitute itself.

It should be noted that the solar system itself seems to possess a formation analogous to Saturn's rings, the "Oort cloud", is also made up of dirty ice-blocks. Comets originate in this distant cloud. It should be weakly collisional. Occasional interactions between blocks cause some of them to accelerate and take on more eccentric trajectories, that is to say to leave our solar system completely, while others plunge towards its center and become comets.



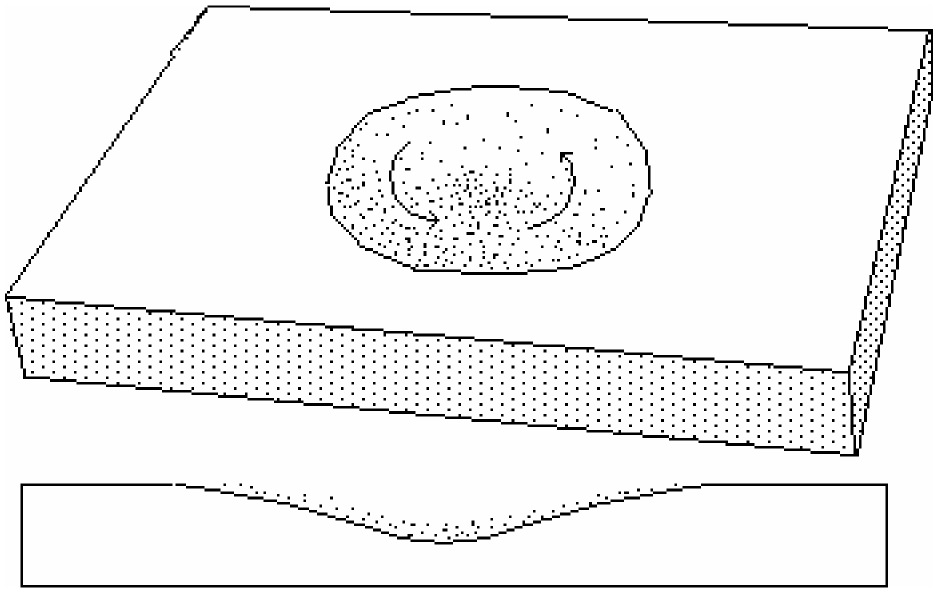
The hypothetical "Oort cloud", from which comets fall from time to time. (Schematic)

In the same manner, interstellar gas has a structure of the Saturn rings type, orbiting not around the stellar mass but across it, in the gravitational field created principally by stars.



Schematic representation of a galaxy: a fine layer of gas, orbiting in the gravitational field created by the stars.

It is possible to give another didactic image of interstellar gas dynamics from the simple point of view of gravitation. We can model gravitational attraction as a hollow formed in a foam mattress from the pressure exercised on it by the stars (a sort of heavy layer). Gas would circulate in this hollow like minute marbles, following circular trajectories:



The dynamic of interstellar gas : buck-shot orbiting quasi-circularly in a hollow (the field of attraction of stars).

In passing, this takes us back to the problem of missing mass. What we measure is the rotational speed of the gas. We deduce the "shape of the hollow" (the gravitational field) from a count of the stellar population and the hollow is not hollow enough -- gas should normally escape (just like for the stars themselves).

If new, very hot stars (and explosions of supernovae) did not constantly appear and maintain the temperature of the gas, it would cool down and create something resembling Saturn's rings -- an ultra-flat disc. The addition of energy prevents the gas from deflating.

What we call a homeostasis arises. The gas acts like a cistern. When it cools down, the gas condenses through "gravitational instability" lumps together and forms new stars which re-inflate the gaseous mass. In reality it is a little more complicated because a spiral wave runs through the gas (which we will treat later) which serves to detonate star synthesis.

By multiplying the density of matter by the square of the speed of agitation, we obtain a quantity which is called the pressure. This is the "internal pressure" which prevents the gas from flattening out on the central plane.

On the other hand, just as the phenomenon of viscous braking does not diminish the rotation speed, rotation cannot converge towards the center of the system. Even if the stars ceased to play their role, the system would only flatten out, like Saturn's rings.

Thus, even though currently without a complete theoretical description of galaxies, we can nevertheless comprehend certain mechanisms at work within them.

From a stellar point of view a spiral galaxy is an ensemble of two populations, which we call the "disc" and the "halo population", a distinction introduced in 1950 by the astronomers Walter Baade and Bertil Lindblad. The disc population is the young stars born in the gas layer along the central plane. The agitation speeds of the gaseous masses and of these young stars are both low, of the order of several miles per second. The halo is made up of older, more rapidly moving stars.

In the halo, we find what are called globular clusters (in our galaxy they number five hundred), which are in fact "mini-galaxies", which can contain up to five thousand stars (such as in the famous Hercules cluster).

As we have said, as a general rule stars form a non-collisional medium. They only interact within their groups at birth while still close together. Perhaps you have used a computer program simulating an "n-body problem". You place objects on your screen with given masses and speeds and watch them twirl around each other. This is a good way to see how some encounters accelerate certain objects and give them an impulsion beyond the escape velocity which catapults them out of the system. The effect is all the greater when the objects' masses are dissimilar (we use this phenomenon to accelerate our space probes, making them brush planets, like Jupiter, as otherwise we would not be able to give them a speed sufficient to allow them leave the solar system).

Small clusters are unstable and stars born there (as in the Perseus cluster) disperse relatively rapidly (dispersal time is proportional to the mass of the cluster). Every star in a galaxy was once in a cluster, some of which have fallen apart. The only truly stable systems are the two-body ones, two stars orbiting around their common center of gravity. Half of the stars you see in the sky are such systems, in general binary. The others are "celibate" stars. *Menages a trois* have no future in space. Sooner or later a member of the trio will acquire enough speed to go off and seek its fortune elsewhere. A vain project, however, given the probability of meeting a new companion, as we have said (average time for such a meeting -- ten million times the age of the universe).

Large clusters also evaporate, but very slowly, because the required escape velocity is higher. It explains why such enormous clusters, like the Hercules cluster for instance, have survived until now. They are distributed almost spherically; this "sub-system" is considered to be a "fossil" of the galaxy in its primitive state (Idea due initially to the astronomers D. Lynden-Bell, O. Eggen, and A. Sandage and published in 1962 in the Astrophysical Journal.) made up of the oldest known stars. The globular clusters group together between ten and a hundred thousand stars.

Stars do not interact among themselves but with the masses of instellar gas they traverse or brush, some of which have masses equivalent to a hundred thousand times that of the Sun. Then, depending on how they enter the gaseous mass, they might be subjected to an accelerating impulsion. A tiny space probe gains speed when it approaches a planet as massive as Jupiter. In a similar way, in the course of time young stars stationed in the neighborhood of the central plane accumulate random speed increases and are progressively ejected from the "disc". Thus, as they age they tend to rejoin the more ancient stars, those of the halo, which form an almost spherical or lightly flattened whole. So we do not see just two very marked populations, the primitive stars of the halo and the young stars of the disk because between them lies a whole spectrum of stars in the midst of leaving the second population to join the first.

This kettle of fish makes a rather complicated soup.

In the following pages we would like to give you an idea of a galaxy like our own. As we have said, numbers concerning distance and time are not really meaningful. The Milky Way has a diameter of a hundred thousand light-years but what does that mean? Nothing, probably.

Let us reduce it to the size of a pea. Its closest neighbor will then be at a distance of about a yard, which gives an idea of the cosmos' "filling".

Change the scale and give it a diameter of a yard. Imagine it to be in the room, in front of you. What will you see? A diffuse mass, in a more or less flattened ellipsoid shape with a marked central condensation. Two hundred billion stars, almost a gas. The gas disc will resemble an inch-thick pancake. It is striated by its spiral structure, or by circular formations, or by both at the same time. In some galaxies the spiral will seem to continue to the center, in others the arms will join together as a "bar". This type of barred spiral structure is very common.

If we do not speed up time, the system will appear to be completely immobile. A galaxy revolves on itself once every hundred million years or so. One turn earlier -- the age of the dinosaurs. A comparison of its lap-time with the estimated age of the universe tells us that galaxies have made just several dozen revolutions since their birth.

Imagine that you are holding a lever which allows you to progressively accelerate time. The first slight push on the lever will not show you the galaxy turning, but something unexpected appears right away. Supernovae explode every hundred years on average, a very rapid rhythm on the scale of this monster's rotation period. If you have made a millennium equivalent to a second, there is already a veritable crackling occurring before your eyes. Ten stars will explode every second and their scintillation, very brief, will be quite visible. We can compare it to signal flashes. The mini-explosions provoke disorder among these space pachyderms, the interstellar gas clouds, whose graininess you barely perceive. Approaching your galaxy and observing it this time through a lens, you will see that the gas is as inconstant as the clouds of the sky when seen on accelerated film. The supernovae perpetuate disorder like little fire-crackers exploding in an eider-down

Before your acceleration lever reaches the point of finally showing the monster turn, the scintillations will have melted into one, continuous sparkle.

Ten million years equal one second. The huge wheel turns, like a vortex. And just like water in a bathtub outlet, the center turns fastest.

Our description stops there, for we do not yet know how a galaxy's arms evolve, lacking an ad hoc theoretical handle.

Let us return to our normal scale, return to Earth and go back to normal time. Everything freezes, immediately.

A galaxy is an immense void, comparable to that separating gas molecules. If we wanted to find a comparison for stars, it would be necessary to imagine several dozen ants strolling around on the territory of the United States. The time they would require to eventually to meet each other is comparable to that required for two stars to do the same.

Several years ago the Voyager probe began a cruise which will take it to the closest stars ... in thirty thousand years time! Terrestrials, proud of this exploit, could be compared to inhabitants of San Francisco contemplating a bottle brought to the Golden Gate by the play of the current and exclaiming to one another, "There it is, on its way towards Japan!"

Definitely, all this is beyond us.

Galaxies are grouped in clusters, the richest having thousands of them. like a big box of peas poured into a swimming pool. A cluster of galaxies is similar to a gas but with a much smaller number of molecules, more like a swarm of bees. These bee-galaxies twirl around, like molecules in a gas and like stars in a galaxy. Clusters are also auto-gravitating systems. Measurement of the Doppler effect gives us information about their agitation speed -- from two to four hundred miles per second. Is that a lot; is that little? The question seems to make no sense. Relative to what?

Hmm.... two to six hundred times smaller than the speed of light. They move at a resolutely non-relativistic speed. But it is important to understand the cluster's dynamics. Counting the galaxies it contains enables us to determine its escape velocity at which a galaxy can depart, like a space probe surpassing 7 miles per second which will allow it to leave the Earth forever. But a new unwelcome surprise awaits, just as in the case of galaxies. The clusters' escape velocity, deduced from their mass, is greatly inferior to that of the population's individuals. Logically these clusters should have dispersed a long time ago. But they are still there. An invisible something is holding them prisoner. What is it? The answer is in part 2 of this work.

A galaxy's stars make up a perfectly non-collisional whole. This is not the case for clusters. Meetings between galaxies are possible. They do not travel fast (relative to the distances separating them) but they are big (as we said -- peas a yard apart). In atlases we find "galaxies in interaction" which are visibly entering into one another. Observation completes theoretical prediction.

We note in passing that these collisions have a rather singular character. While galaxies can really collide, in effect their stars cannot. If you want to picture a collision between two elliptical galaxies, imagine two swarms of mosquitoes crossing one another without any hitting each other.

Does that mean that such encounters are without effect? No, and simulations on giant computers have explored different possible scenarios, with varying relative masses and speeds. One large galaxy can absorb another... galaxies are potential cannibals. Or a small galaxy can become a larger galaxy's satellite.

The most important interaction takes place at the level of the clouds, which are themselves collisional. The encounter is then violent and accompanied by a shock wave. The two objects' relative speeds are in effect well superior to those of the atoms in the clouds.

In a gas, the speed of sound (collisional phenomenon) is very close to the speed of thermal agitation.

If the collision is not frontal, the galaxies, in scraping against one another, can mutually communicate rotation. This is a possible explanation for the origin of the rotational motion of galaxies.

A phenomenon which it will be necessary to revisit in the context of cosmic expansion. In the past the galaxies were closer to one another and interacted more frequently.

Another phenomenon, which we will look at in detail later on, is an instance of the macrocosm meeting the microcosm. In the air we breathe molecules can possess three types of energy. First, their translational, kinetic energy, linked to their thermal agitation speed (1200 feet per second). This is their

$$1/2 \; m \; V^2$$

Then their rotational energy. Molecules of oxygen, nitrogen and carbon dioxide spin about themselves like tops, and this represents energy.

There is finally a third, vibratory mode. Liaisons between atoms are elastic. Certain molecules possess many modes of vibration.

These energies are transformable into each other. Thermodynamics teaches us that when molecules encounter one another, the entire energy tends to be distributed into these three modes indifferently. We call this the equipartition of energies. When this state is realized, it corresponds to thermodynamic equilibrium.

But there is a leak -- radiation. If we imprison an air mass at ordinary temperature in an imaginary, perfectly transparent receptacle, and place it in a "zero temperature furnace", the gaseous mass will cool down, radiating in the infra-red. Energy will dissipate. A gas will only keep its temperature if the exchange balance with its surroundings (other gaseous masses or the receptacle) is zero, or if it is well isolated.

The problem's variables are familiar. A cluster of galaxies will tend towards this state of thermal equilibrium, simply because collisions are occurring, whence the rotations. But what does the third mode correspond to?

The phenomenon is still not perfectly mastered and we will come back to it later. What matters here is to grasp its essence. These convulsions of gas initiate the birth of new stars whose radiation will lose itself in the cosmos. The process is a dissipative one.

On certain summer nights, in warm waters, plankton comes up to the surface. If you agitate the water with your hand, you will cause light to shine. Galaxies react, when they are disturbed, like these tiny animals.

Gravitational instability.

Why is the cosmos not simply uniform? Why these structures and not others? For what reason are there condensations of matter at all?

At bottom, why do atoms not hold themselves sagely at a distance from one another, each submitting to the whole of its neighbor's forces whose sum would be nil?

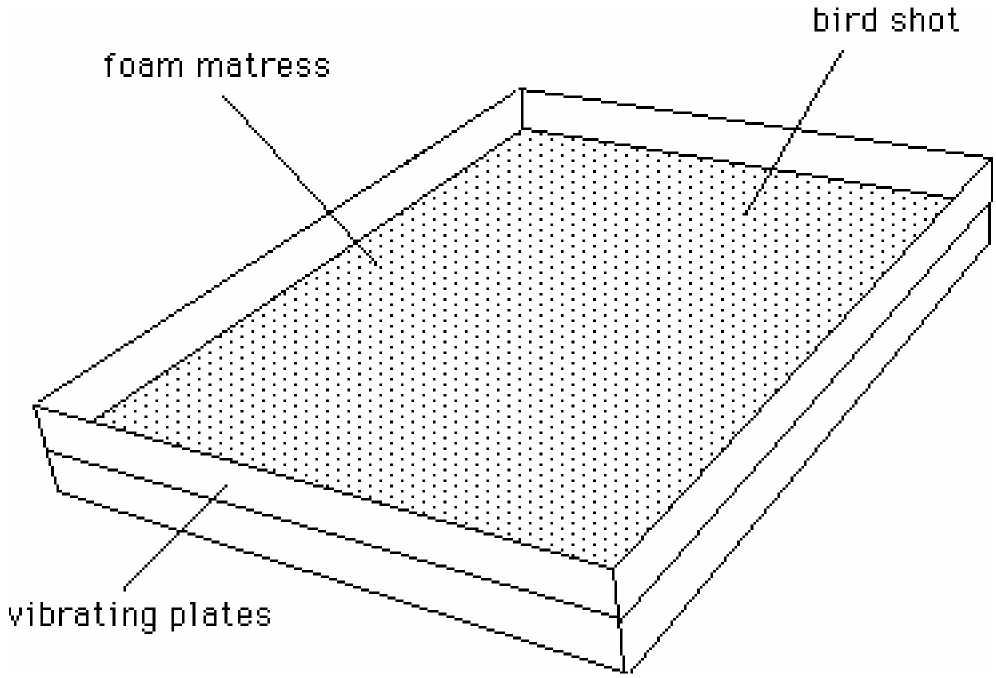
When I was a kid I never missed an aviation meeting. Such presentations of new airplanes always attract gatherings of the curious. With the spectacle in the air, they could contentedly stretch out on the airfield's grass, a sandwich or a can of beer in hand, and in a generally rather homogeneous distribution.

One day curiosity caused a rather singular phenomenon. There was a pause in the program and people began to get bored. A hundred thousand bored persons is not nothing. The sky stayed desperately empty; there was nothing to watch.

Suddenly a gathering formed. People were intrigued. Something interesting must have happened at the crowd's heart. They converged rapidly towards the human concentration. I too of course. The density of people soon reached a high value. People pushed each other to see better. In the midst of the human mass I reached the formation's attractive center. It became more difficult to escape the migration. We were elbow to elbow, carried by the flow. Suddenly a man, who was trying desperately to start a reverse movement, and who was visibly coming from the center of attraction, cried, "Stop, in the name of God! There is nothing, do you hear me, nothing to see". We were converging towards pure nothing.

Atoms are curious and tend to converge towards the first concentration that comes along, even if there is nothing special to see. To illustrate this we will utilize a didactic model. Imagine a foam mattress. Under this mattress, install a refrigeration system which allows you to harden it (supposing that it hardens when cooled). When it is smooth like a wooden plank, you place buck-shot on top, quite uniformly. Then you turn off the refrigeration, giving the mattress back its suppleness, and wait to see what happens. The shot distribute itself into dips. These will be located anywhere, randomly, if the mattress material is perfectly homogeneous.

In this model, the shot is at first immobile. It is "cold". There is no thermal agitation. We could create some by placing vibrating plates along the sides which to communicate energy to the shot which would then be transmitted from neighbor to neighbor in turn, through collisions.



Our foam mattress with vibrating plates covered with small buck-shot.

We could build something of the sort with certain flat loud-speakers. We could also put a plate of glass on top, to prevent the shot from jumping overboard. Having done this we could regulate at will the "temperature" of this kind of two-dimensional gas. It would simply be proportional to the square of the shot's average agitation speed.

What would happen?

Agitating the shot in every direction would have the effect of opposing their tendency to assemble in the dips. Heating this "gas" would make the dips disappear. But reducing the shot's state of agitation would make them reappear.

A certain amount of time is needed for dips to be formed, for shot to assemble there and then to attract its little comrades. The heavier the shot, or the more numerous, the faster will dips appear. We call this an accretion phenomenon. It does not depend on the size of the depressions which tend to form.

We cover the mattress with shot corresponding to a certain density of matter ρ in grams per square inch. The dips will form in a time t which depends on this density.

In astrophysics this accretion time is proportional to the inverse of the root squared of the density of matter ρ. See annex 1 .

Let us take a depression having a diameter D. The shot has a speed of agitation V. Therefore it crosses the depression in a time:

$$t = D/V.$$

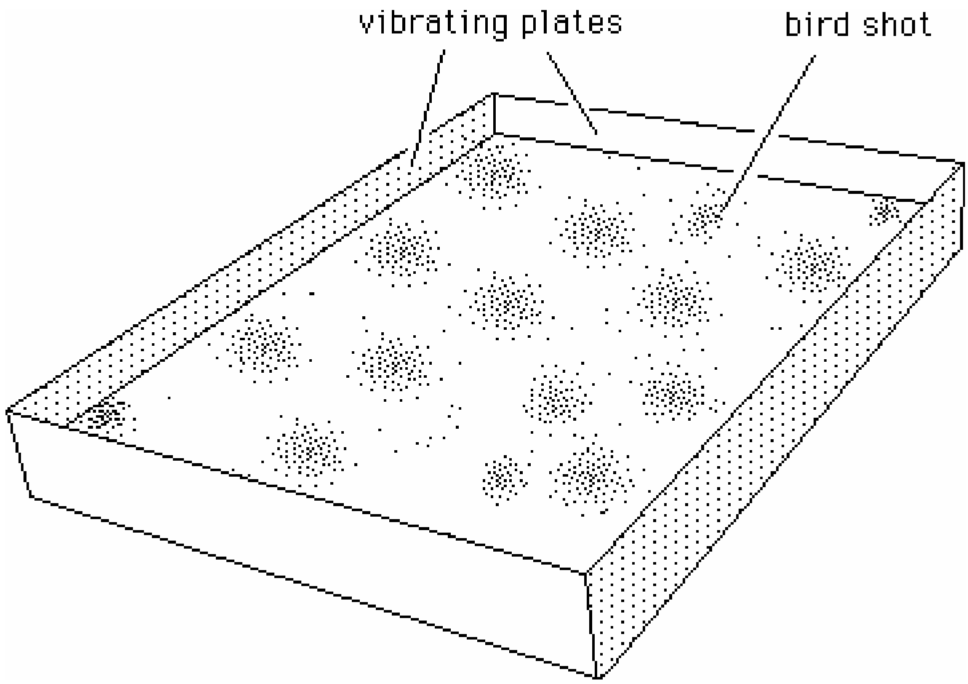
This is also the time which the shot takes to leave this type of depression, or, if we prefer, the time taken for all accidental condensation of matter to disperse naturally by simple thermal agitation.

If this time is less than the time t of depression formation, the depression cannot be formed. Even before it had begun to be formed, the shot which would have served to create would already be gone to restart the same housekeeping elsewhere. Therefore, for a given density of shot ρ on the mattress, and for its equally fixed agitation speed V, the depressions which can form will be those such that:

$$\tau < D/V.$$

This is to say that the will only be formation of those depressions which have a diameter superior to:

$$V\,\tau.$$



If this quantity is superior to the size of the mattress -- no depressions or dips at all.

This reasoning was made for the first time by the Englishman Sir James Jeans and this quantity is called the Jeans distance.

Concretely it is written $L_j = \frac{V}{\sqrt{6 \pi G \rho}}$ where V is the velocity of thermal agitation and ρ the local density of matter.

It is an extremely powerful tool of reflection. Let us take an elliptic galaxy for example. This is a homogeneous medium, at least "macroscopically speaking". Stars are not distributed in packets. In this galaxy there is volume-mass r. Atoms or molecules move at a speed V. If the cloud is relatively homogeneous, it is because its Jeans distance is superior to its spatial extension.

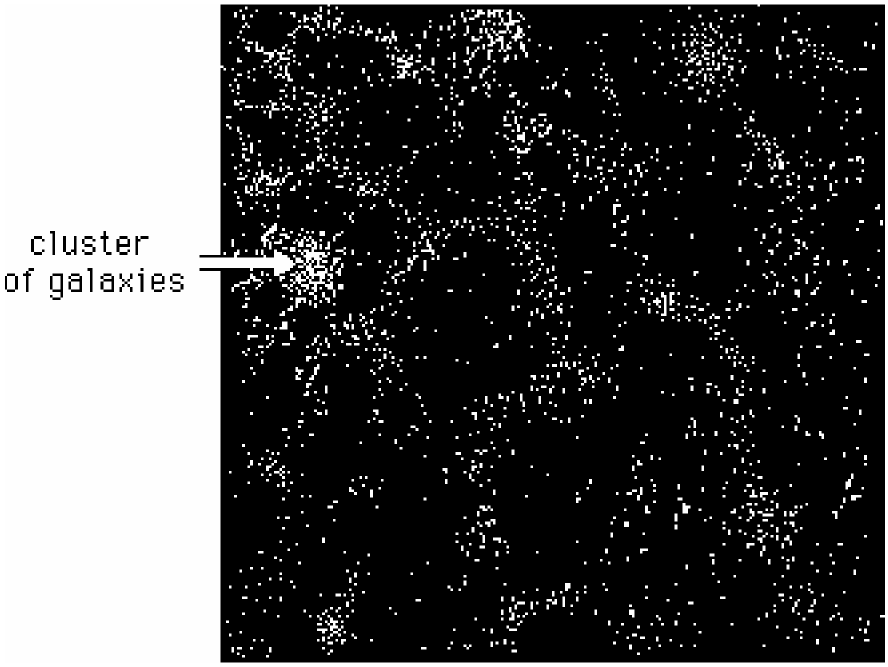
But what determines the diameter of such a condensation of matter? It will be in equilibrium if the force of gravity, which tends to contract it, is balanced by the force of pressure, which tends to dilate it. Calculation shows that this happens when the diameter is very close to the Jeans distance.

Interstellar gas is made up of large clumps. These move relative to each other at a speed V. This pancake corresponds to an average density r', smaller than that of the clouds, because a certain void exists around it. From these two quantities we can calculate a new a Jeans distance and find ... the thickness of the gas layer.

We understand now how our "cistern" (the clouds of interstellar gas, for example) functions. Molecules or atoms of gas collide, creating a loss of energy through radiation. Their speed of agitation diminishes as a result. The Jeans distance decreases and becomes smaller than the cloud's dimensions and this then tends to fragment and produce ... stars.

These stars emit radiation, which is absorbed by atoms and molecules, increasing their heat. This means that their agitation speed increases. The Jeans distance once again becomes equal to that of the cloud. Fragmentation and synthesis of stars stop.

Armed with this concept, astrophysicists expect in all logic that this "hierarchical fragmentation" phenomenon should reproduce itself on every scale. There will be "clusters of clusters of galaxies" which have already been baptized "superclusters". But the results of observations at very great distances revealed a totally different structure -- lacunary. Matter, on the scale of billions of light-years, is assembled around great empty bubbles, like soap bubbles joined together. Clusters are in fact the "knots" of this formation, comparable to points where different soap sheets run together. Different mechanisms were therefore necessary, which we will discuss later.



Map of the spatial distribution of galaxies

Any guiding thread ?

Our discussion has been referring to relatively recent discoveries, dating from the end of the sixties. As the reader is being initiated into the great contemporary problems of astrophysics and cosmology, inseparable from our quest for the knowledge of matter, time, and simply what we call the real, they have the right to wonder, "What is this discussion's main thread?"

Surely not the chronology of events. The tree of knowledge does not grow straight, nor does it have only one trunk. It is not comparable to a genealogical tree -- it is a forest growing like an anarchy of ideas, arising in the course of the centuries without the least logical connection and with different, interlacing logical structures. Sometimes someone jumps unbelievably far into the future. Sometimes observations suddenly bring down an entire conceptual edifice which had been regarded as definitive.

In Alexandria, Egypt, in the second century before Christ, there lived at a man named Eratosthenes (Greek philosopher, 284-192 BC). His voyages occasionally took him to Syrena, where the great Aswan Dam is now. This is in the Northern Hemisphere.

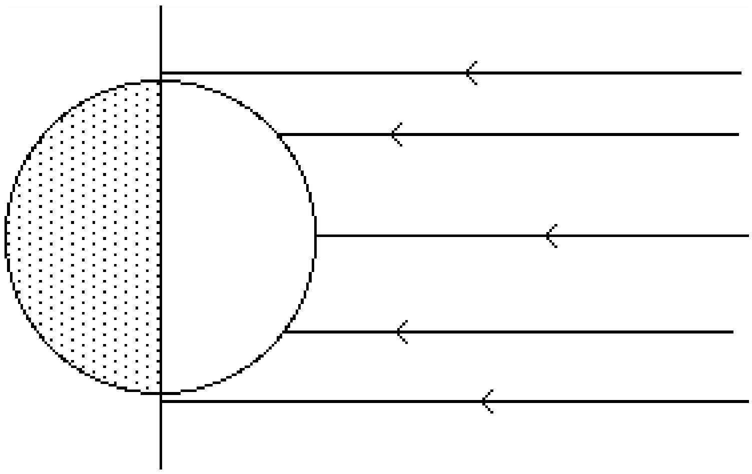
The maximum height which the Sun can attain in the sky depends on the latitude you inhabit. Its angle of sight is the greatest on the day called the summer solstice, and least on the winter solstice. This leads to a whole variety of rather disconcerting situations if we forget that the Earth is round. At very high latitudes, beyond the polar circle, the Sun plays games with us. On the summer solstice it does not set, while on the winter solstice it resolutely refuses to rise, like a hibernating bear.

When we witness such spectacles we find ourselves up against the primitive geometric vision of the flat Earth. In our heads, let us not deceive ourselves, it is still so. The proof is that you have to make painful mental efforts or use a paper and pencil to follow everything I have just told you. We live on the terrestrial surface like flies on a wall.

A few years ago I made a transpolar flight to Moscow. I experienced the strange phenomenon of jet lag. One entered a plane, stayed there for twelve hours, and then, on leaving, everything was upside-down. I felt bizarre, like someone who had gotten off on another planet. The best thing to do was to ignore as much as possible my own body's signals and try to live according to the other's rhythms, as quickly as possible.

During this flight I had not slept. I had seen the Sun drop to the horizon, fairly quickly. I expected it to set. Oh no. After a moment's hesitation, it began to climb. I had to take paper and pencil and draw some figures to convince myself that this was normal after all and there was no point in bringing this odd fact to the crew's attention.

The Earth's axis is not perpendicular to the plane of its orbit, the ecliptic. The deviation is 23°. If it were zero, only the equatorians would see the Sun pass at the zenith, vertically from where it is seen, every day. For the pole dweller it would be permanent daylight, or at least a type of dawn-twilight lasting all day and year, since the Sun's trajectory would be tangent to the horizon (more precisely, the pole dwellers would only see half of the solar disk forever).



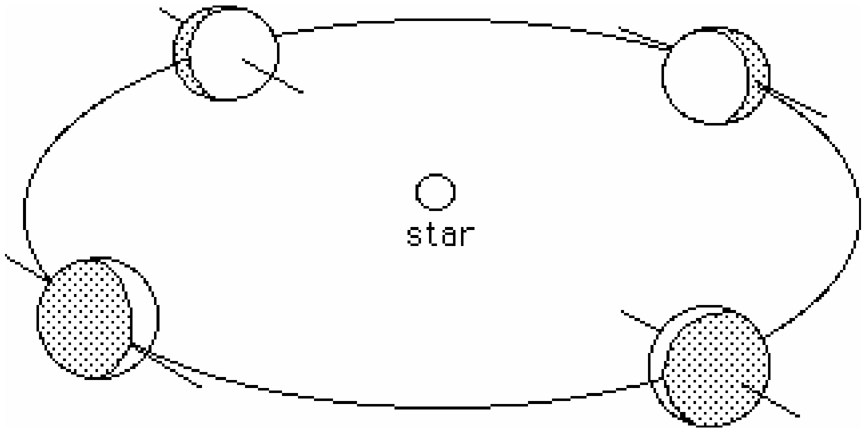
An imaginary planet whose axis of rotation is perpendicular to its plane of rotation about its star.

A planet in this configuration exists very probably in the universe; its inhabitants are ignorant of the concept of seasons. For them the equinox lasts the whole year, since the days and nights are equal in length whatever the latitude, except for the pole dwellers.

The maximum height of their solar star at noon would simply depend on their residence's latitude. If they disembark one day here, they would be doubtless very surprised to find that this height varies over the course of the year, conditioning the temperature and climate.

Why not imagine an even more bizarre planet, whose axis of rotation is located on its plane of rotation?

Quickly, close this text and give me the answer.



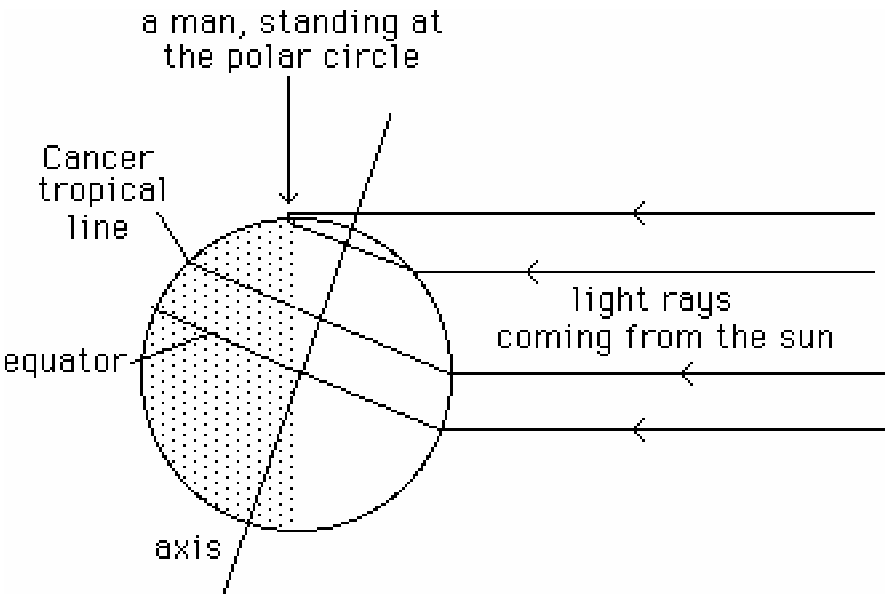
A planet, orbiting around a star whose axis is located on its orbital plane.

The polar circles would become the equator. The situation would be inverted. If the axis of rotation pointed towards the star, for the people in one of the hemispheres it would be "endless day", while the others would never see their sun rise. Then it would be the equatorians who would know that sort of mixture of dawn and twilight.

By the way, notice that one planet of the solar system corresponds to this configuration : Uranus. But :

- The "year" of Uranus corresponds to 84 years of our Earth.
- There are no inhabitants on Uranus.

Let us return to the Earth. Its axis of rotation is inclined 23° relative to the perpendicular to its plane of rotation around the Sun. Its surface is then divided into five regions.



Summer, for the inhabitants
of the northern hemisphere.

Within the polar circles, at a latitude above 90-23 = 63º (in the north), or less than 67º (in the south), there are periods when the Sun disappears below the horizon, when day no longer appears, only night. Symmetrically, inverse periods also exist, when the Sun does not set. We call this the midnight sun. On the northern polar circle, on June 21 the Sun dawdles above the horizon, refusing to pass below. On December 21, same behavior, but below the horizon. The sun refuses to rise.

Between the polar and tropical circles, the so-called "temperate" zones, the Sun never rises to the zenith.

All this, the reader will say, is well known and I have not come here to take so elementary a course in astronomy. But are you capable of answering, on the spot, the two following questions?

- I live in the northern hemisphere. I park my car in a lot at ten in the morning. I would the shadow of a nearby tree to fall right on my car at noon. Where should I park it?

A moment of reflection. In which direction does the Sun turn? That's easy. But what should you do if you lived in the southern hemisphere? The same thing ... or the opposite?

Quick, answer :

In the southern hemisphere shadows turn in the opposite direction.

But let us return to this fellow Eratosthenes. One day he goes to Syrena, Aswan, and it so happens that this place is located practically right on the tropic of Cancer. He leans over the curb of a well, at just the right time, the summer solstice, and discovers with surprise that the Sun lights up the well's bottom perfectly. The heavenly body must be exactly at the zenith.

Now, at Alexandria this could not occur. The Sun did not climb as high at noon on the summer solstice. Knowing its maximum angle, measured with an obelisk, and knowing the distance separating Alexandria from Aswan (a million steps!), our man calculated the Earth's radius with an error of fifteen percent, in the second century before Christ!

I will not insult you by showing you the calculations, worthy of a young high school student.

But Eratosthenes did not stop there. Observing an eclipse of the moon, when the terrestrial curvature is profiled for a short time on the lunar body's surface, he quickly grabbed a piece of parchment. Aware that the Sun's rays are propagated in a straight line, and understanding from earlier eclipses that the Earth was a sphere and not a sort of flat disk, as certain of his contemporaries believed, he made a sketch which allowed him to measure the Moon's radius compared with that of the Earth. Knowing its "apparent diameter", and using a simple proportionality, he calculated the Earth-Moon distance with again a rather good approximation.

This knowledge was lost, for centuries. The Earth became flat again. Nevertheless, does one not find in the Bible:

.... tasting joys without end, rejoicing in His terrestrial globe.

Proverbs 8 : 31

... it is He who sits above the Earth's globe.

Isaiah 40:22

Conversely, in 1900 Lord Kelvin estimated that science was now complete and that "everything was only a question of precision in the calculations". Previously, in 1796, the Frenchman Laplace had come to the same conclusion, advocating a complete determinism:

- *If we knew with precision the initial conditions of each element of the universe, their position and speed, it would then be possible to determine with precision the entire future of the universe.*

A prediction which would brutally break down with the coming of quantum mechanics and Werner Heisenberg's uncertainty principle (see Appendix 8).

The history of astronomy is strewn with similar facts and it is not easy to follow a logical train. Thus, at the turn of the century, Michaelson's experiment demonstrated the invariance of the measurement of the speed of light, whatever the speed of the laboratory (the laboratory being, in this case, the Earth). This obliged theoreticians to totally revise their view of space and time, a work neatly condensed into a publication of 1915 by Albert Einstein.

If we kept the chronology of events, we would now have to discuss Special Relativity or quantum mechanics, but we would risk losing our reader on the way.

We will therefore continue to use the tools we forged at the beginning of this work, and reserve the right to improve them later.

Discovery of cosmic evolution.

In the twenties the sky was populated accordingly with immense "island universes", containing from a hundred to a thousand billion stars.

We knew that they developed, were born and died but it never entered anyone's head that the universe itself could change. When the inventors of the new science called "cosmology" applied themselves to elaborating models of universes, at first they aimed for a stationary state (the first model imagined by Einstein was stationary).

Hubble, detecting a Cepheid with the aid of the powerful Mount Palomar telescope, had shown that the Andromeda galaxy was another group of stars, located 2.2 million light-years away. Measurement of the Doppler effect revealed something else -- Andromeda was falling literally on top of us (see Appendix 5), as were other nearby galaxies.

But speed measurements soon showed that this was only a turbulent movement of the "local group". At a distance, on the contrary, the galaxies were all leaving us and turning red.

When an object moves away, as we have seen above, the wavelength we receive and measure increases. The inverse phenomenon occurs when the object is approaching. What approaches becomes blue; what moves away reddens -- the frequency of blue light is higher than that of red light.

Galaxies were slipping towards the red, a phenomenon called "red shift", customarily designated with the letter z. This is the measured increase in wavelength divided by that from a nominally identical source, immobile relative to the laboratory.

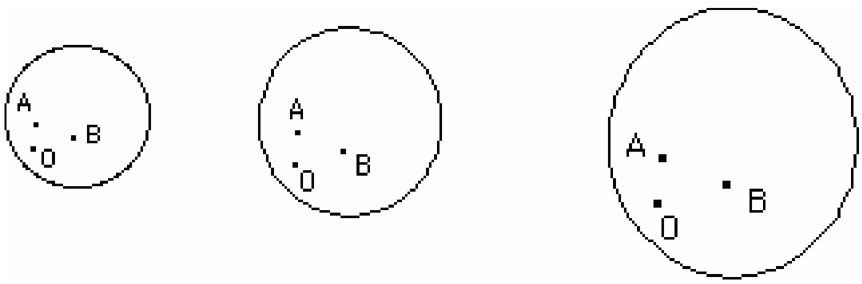
Astronomers had identified numerous galaxies, classified them by type, and estimated their absolute magnitude - the amount of light they were sending out. This enabled them to determine their distance, the quantity of light varying as the inverse square of their magnitude. Hubble then showed that their distance was proportional to the red shift z, itself proportional to their speed of recession.

The slope of this straight line is what is called the Hubble constant Ho. (See appendix 4).

The Hubble law.

The Hubble law's linearity rapidly lead astronomers to conclude that the phenomenon was due to the Doppler effect and that the universe was in a state of expansion. When a gas expands, every observer sitting on one of its molecules effectively perceives such a velocity field.

Suppose you inflate a balloon. Previously, you have put some marks on it, with a pen. Let us figure three points : O , A and B. An observer of this "flatland" is supposed to live in O and to observe how the distances OA and OB grow.



In the initial conditions, suppose :

OA = 5 cm

OB = 10 cm

After ten seconds, we get :

OA = 15 cm

OB = 30 cm

Then we can measure the velocities V_A and V_B, with respect to the point O, supposed to be steady.

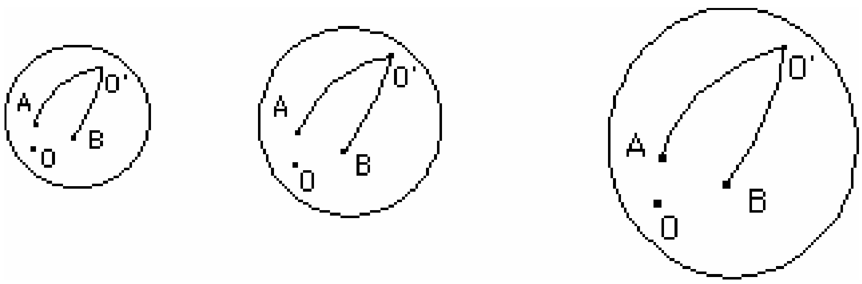
$$V_A = \frac{(15 - 5)\ cm}{10\ seconds} = 1\ cm/s$$

$$V_B = \frac{(30 - 10)\ cm}{10\ seconds} = 2\ cm/s$$

We find that the velocity V_B is twice the velocity V_A. Normal : The initial distance OB was twice the initial distance OA.

We have figured out some sort of 2d Hubble's law of velocity : The velocity of an object is proportional to its distance to the observer.

We could put the observer in another point on the balloon, in O', for example :



If we perform distance measurements from time to time and compute the velocities, with respect to the new steady point O', we will find the same thing : the velocity is still proportional to the distance to the observer, wherever he is.

In a expanding universe everybody thinks he's at the center of the world.

In 1917 Albert Einstein constructed a first model of a stationary universe (to which we will return later) using what is called the "cosmological constant L". Hubble's discovery completely invalidated his work and he was extremely vexed. All theoretical cosmology was thereafter founded on an extremely complicated "field equation". It was a perfectly unknown Russian, Friedman, a mathematician and glider pilot, who negotiated with style a non-stationary solution. Einstein, annoyed, then exclaimed --

- If I had known that the universe was not stationary, I would have found it before him.

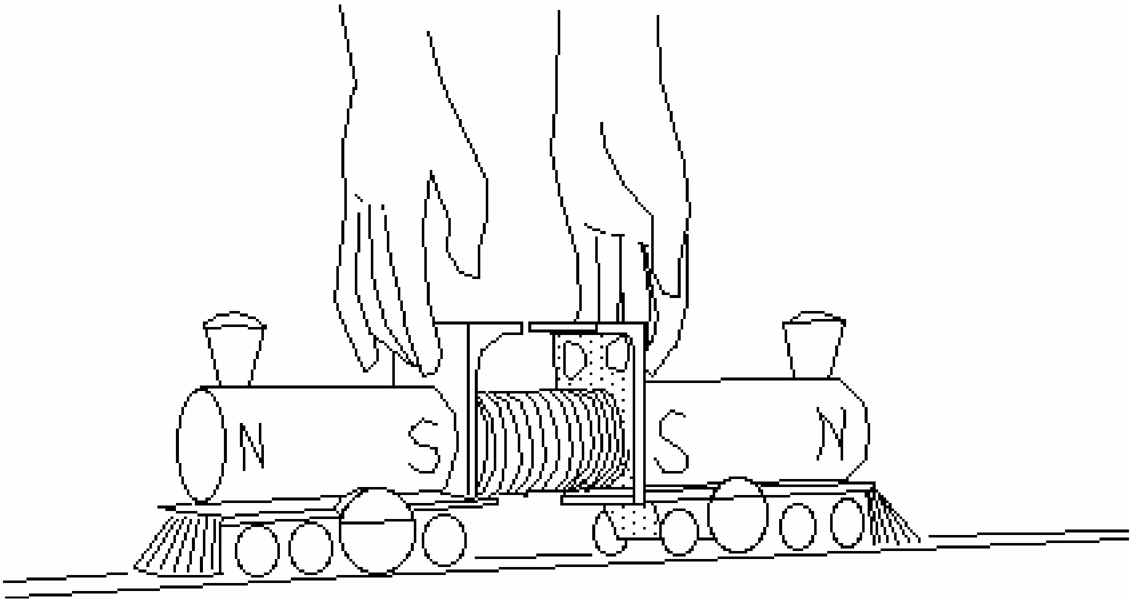
"If..".., as the Lacedaemonians used to say.

Friedman's universe models.

We will discuss curvature, relativity and field equations further on. For the moment we have no need to. Imagine! An Englishman named Milne, with his colleague MacCrea, showed that a few lines of calculus could retrieve this non-stationary equation without curved space, without relativity, with ... Newtonian concepts, as developed in the nineteenth century. General Relativity, within reach of a high school student.

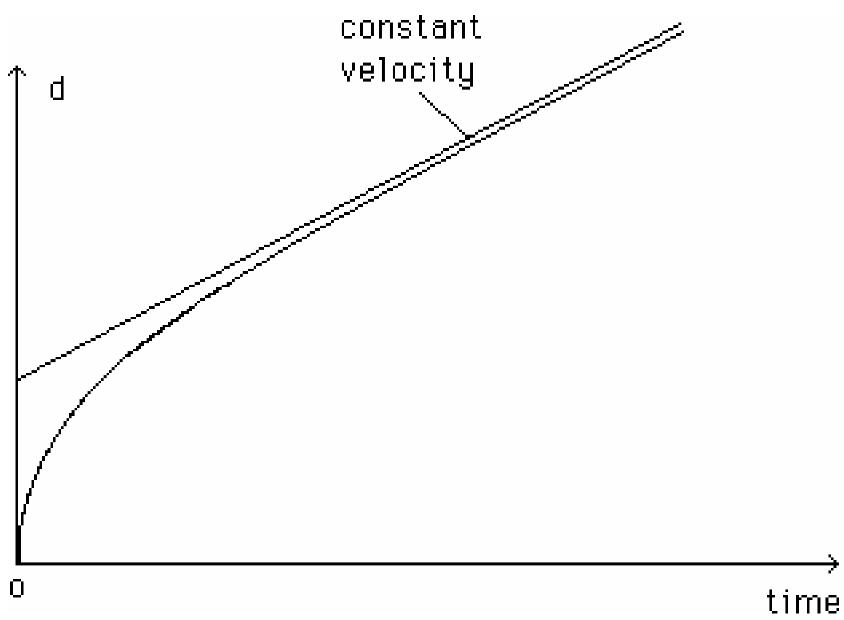
We refer the curious reader to Appendix 1.

We will content ourselves with giving an idea of the phenomenon through a very simple model. If you explode a grenade, the initial energy will be pressure. If the grenade explodes in a vacuum, its fragments will separate at constant speed but at that point the force of gravity intervenes, braking the expansion. We can simulate this with two runners on wheels, a spring and two magnets. We first fix the magnets on the boards in such a way that they attract each other. Then we compress the spring and let go.



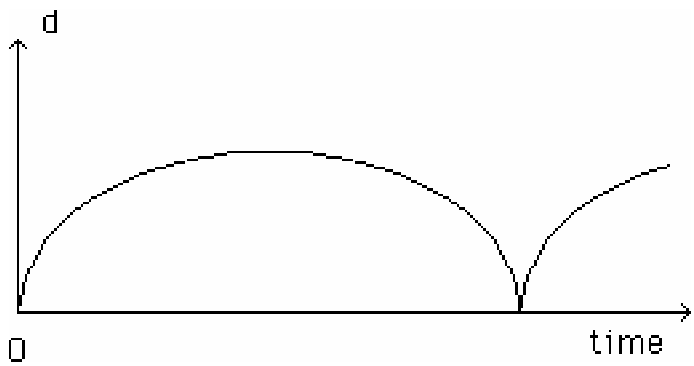
If the magnets were not there, as soon as the spring is released the runners would fly away at constant velocity. But the magnets tend to brake this movement. Let us call the distance between the two runners d and make it zero at the initial moment.

If they are weak magnets, after a certain distance their action will no longer be felt, and will become negligible. The velocity will then become constant and the curve will tend to become a straight line:



The magnets are weak : the runners end up moving apart at constant velocity.

Second case: the magnets are much stronger and succeed in bringing the runners back against one another:



The magnets are powerful enough to bring the two runners into contact with one another.

An intermediate situation exists where the magnets are not powerful enough to reverse the movement but their action continues nevertheless to be felt, even at an infinite (or let us say, very great) distance. The curve will then have a parabolic appearance. It is this type of solution which is described in Appendix 1, corresponding to what is called the Einstein-De Sitter model.

We can place these three developments on one graph.

The three curves correspond to Friedman's three models. The distance d represents the distance between galaxies, for example, or two clusters of galaxies, supposed to be immobile in relation to the background of space (they are called then "comobiles").

In cosmology, the force of gravity, playing the role of the magnets, is linked to the density of matter r. Cosmologists are interested to know which law the universe follows. Will it continue its expansion indefinitely, or on the contrary fall back onto itself, after having experienced a phase of maximum expansion?

On the graph we have marked the present. Towards the past the curves are very close together, but diverge in the distant future. Everything depends then on a critical density which has the value

$$\rho_c = 10^{-29} \text{ grams per cubic centimeter.}$$

If the actual density of the universe is greater, we have a maximum expansion, an oscillating model. If it is less, or equal -- indefinite expansion. It is very difficult to determine this density. If we base ourselves on what can currently be measured, it is very far below the critical value. But it is possible that the majority of the mass contained in the universe is escaping observation (so called dark matter), a subject which will also be taken up later.

However, whatever the final model, the three have something in common. A moment would occur when distances between the elements of the universe were nil. Thus the theme of the Big Bang. This idea took time to make its way in the scientific community. If we agree to take seriously such models, it becomes evident that the universe in its distant past would have had to be at the same time both very dense and very hot. When we compress a gas (the cosmos is modeled after a gas), it heats up. It was therefore necessary, to unpack what is called the "standard model", to reconstruct the universe's history, step by step.

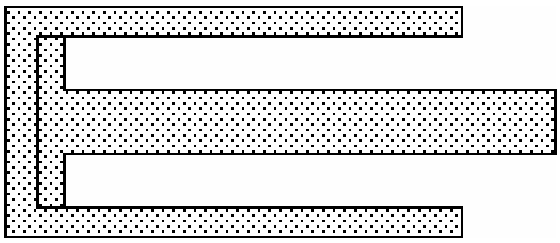
That said, the reader has the right to pose the question:

- Do galaxies follow this movement of expansion?

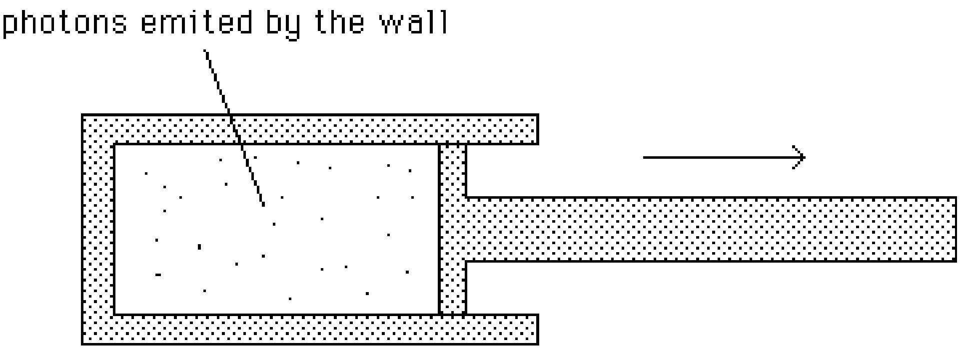
The answer is no. The content of the universe is not being enlarged. But what is this content? Is it the "void"?

What is the void, dear Mister Newton?

Theoretical physics, quantum mechanics, offers an answer. We can try to create a "perfect vacuum" with a cylinder and a piston which we pull away very quickly. The flow through the joint can be made small enough for the number of molecules which succeed in slipping into the available space to be extremely small.



Is this to say that we could, for at least a brief instant, create a perfect or quasi-perfect vacuum ?



No, because the walls of the cylinder radiate. Photons invade the available space at ... the speed of light. Space filled with photons is not a vacuum. Matter and radiation are only two forms of the same entity -- energy-matter. Photons are grains of energy.

A perfect vacuum would be an enclosure from which every trace of molecules and atoms had been eliminated and whose walls had been cooled to a temperature of absolute zero. Then they would not radiate.

Interstellar or intergalactic space does not meet this criterion. As we will see later, its most rarefied regions are filled with photons, which constitute the "2.7K background radiation". They are "elbow-to-elbow". Their wavelength -- a quarter-inch. If we wanted to represent this "spatial void" it would be necessary to think of a lapping, liquid surface where the small wavelets measured five millimeters long and moved at 186,000 miles per second. This "liquid surface" would only be flat if the radiation's temperature equaled absolute zero.

The relation linking this radiation temperature and the photons' wavelength is simple:

$$kT = hc/\lambda$$

where λ is the wavelength (in meters)

k is Boltzmann's constant (1.38×10^{-23})
and h Planck's constant (6.62×10^{-34}).

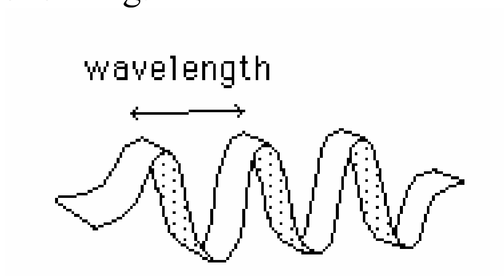
Let us return to the question "who pays the price for expansion". The photons of this "cosmological vacuum" do. Does this mean that they "move away from one another"? The question does not make much sense.

Nevertheless the calculations give an indication -- their wavelength λ grows with the radius R of the universe. Their number stays constant, if we except those which are absorbed by dust or emitted by stars.

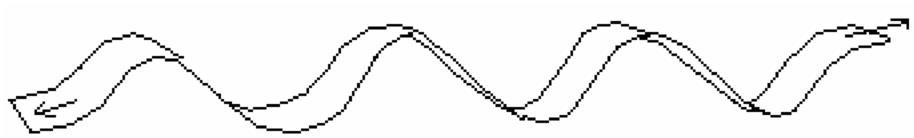
But the universe is extraordinarily transparent, or else we could not have astronomy.

These cosmological photons are a billion times more numerous in the universe than particles carrying mass.

We can then imagine "that the vacuum is in the process of expanding" like a plate traversed by undulations in the course of dilating, their wavelengths doing the same, at the same rhythm. The container and the contained form only one thing.



A portion of "empty" space where the undulations represent cosmological photons.



In the phenomenon of expansion the photons "stretch out" along with the "void". The "cosmological photons'" wavelength λ grows with the dimension of the universe itself.

In this scheme the number of cosmological photons stays constant. We are evidently not speaking of the "accidental photons" emitted by stars or any other radiation process, but rather of primitive photons, infinitely more numerous than these.

The corollary is that these photons lose energy, since this is

$$E_\phi = h\,\nu = hc/\lambda$$

The primitive photons' wavelength grows with time. Their number stays constant, therefore this "primitive photon gas" loses energy, which is after all rather disconcerting. On this level, the cosmos does not function at constant energy.

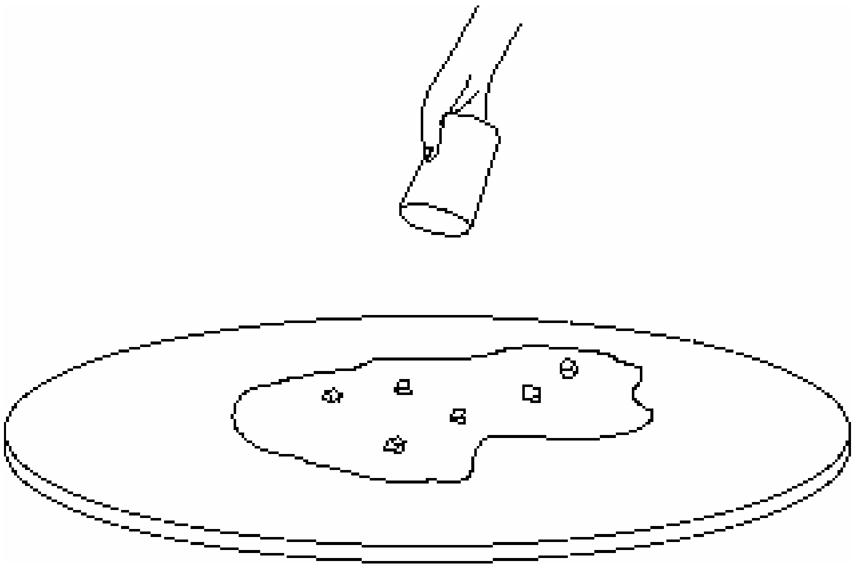
The cosmos has an energy content. One part is in the form of matter, and this energy is mc^2, conserved over time. The other is in the form of primitive radiation, which "devalues".

Today of course, we can neglect the fraction of energy in the second form. With time t it has devalued so much that it is secondary to energy's matter form. But it has not always been so. In the distant past of the universe, previous to t = 500,000 years, energy's radiation form was primary.

For a theoretical physicist, all the universe's "objects" are wave packets. With a particle of mass m we can associate a wavelength, the Compton wavelength, which is written:

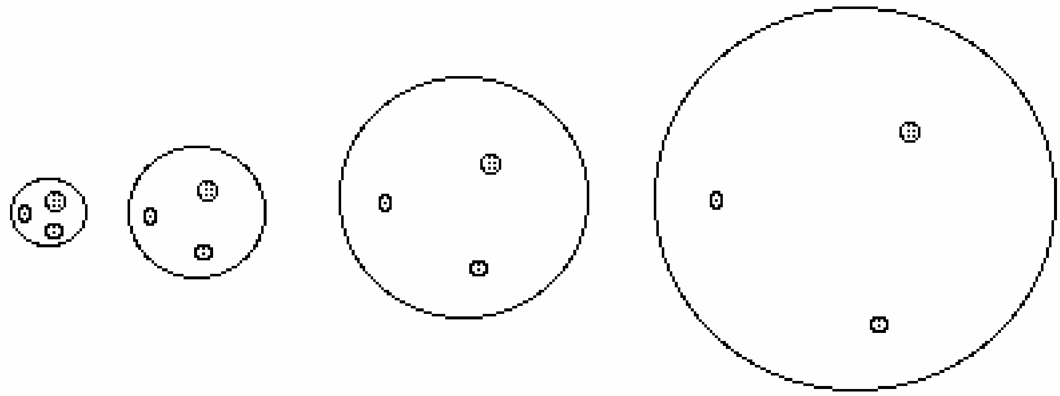
$$\lambda_c = h/mc.$$

In the course of expansion, mass is conserved. Therefore these wavelengths are constant. Photons and mass are only different modes of vibration of the same spatial tissue. To illustrate this difference, we could pour out a glass of water containing ice cubes on a table. The water would represent energy-material in the form of photons. The ice cubes would represent mass. The water would spread out in a pool, on which the ice cubes would drift apart, but conserving their size.



Seen from this angle, matter is frozen space.

People sometimes propose representing the notion of the expansion of the universe as a balloon being inflated. On this we would indicate objects, galaxies, clusters, etc....by spots. But if one represented these objects by drawing them with a marker, the image would be false, for these objects dilate along with the balloon. Now this is not so. To stay closer to the model it would be necessary to stick little confetti on the balloon, themselves not dilating.



Second image of cosmic expansion.

The theme of "decoupling".

We do not know which appeared first in the universe -- galaxies or stars, namely the stellar proto-clusters. Opposing theories exist on these questions and we will not choose one over the other. What we do know, however, is that there was an epoch (t < 500,000 years) when such structures could not exist. The universe was then as hot as an incandescent light filament and its temperature approached three thousand degrees. The hydrogen making it up was for the most part totally ionized, that is to say it was a plasma, a mixture of positively charged nuclei and negatively charged free electrons. This medium was then very strongly coupled to the primordial radiation.

Free electrons interact much more strongly with photons than electrons tied to atoms. This was the coupling's source. Seen from another angle, photons have much more trouble crossing plasmas. The Sun, for example, is a large plasma ball. Photons from its central furnace escape towards the outside. They are quickly absorbed by an atom, which then re-emits another, etc. The photon finally arriving on your retina, or on the telescope's photographic plate, is not the original one from the star's center, but its distant nth generation descendant. Only when photons leave the Sun's surface can they proceed without hindrance. We do not directly observe the Sun's core, only its surface. Optically, the Sun is translucid, not transparent.

Other plasmas exist which resist photons and all radiation with as much vigor. For example, the plasma envelope surrounding a space ship during reentry. As you know, there is a rather long period of radio silence during which no communication is possible with astronauts enclosed in their capsule. Radio waves also travel in the form of photons.

When the universe was less than 500,000 years old, photons forged a path for themselves with difficulty. They were ceaselessly absorbed and re-emitted. We can compare such a medium, optically, to frosted bathroom glass. When we look out to great distances, using classical optical wavelengths, we "look back in time". Each spherical layer on which we focus our attention corresponds to a given epoch. Currently we can "see" to a dozen billion light-years. This is extraordinary. But this returning to the past will one day reach a limit. We will bump up against a layer corresponding to a past so ancient that optical observation is impossible.

Imagine a stack of glass plates. Between two successive plates, flies. The first plates are perfectly transparent. The universe is extraordinarily transparent, we must agree, or else we could not have astronomy -- objects would be fuzzy.

In this model of flies and plates of glass, we can imagine that after a certain distance the latter become frosted. Objects located behind them (the flies) become fuzzier and fuzzier, until at a certain distance we can no longer even identify them.

In the same way the universe hides its most distant past from us but this is not important as behind the frosted glass plates there is nothing to see. That is to say nothing *structured*, for example galaxies or stars. Everything is homogeneous.

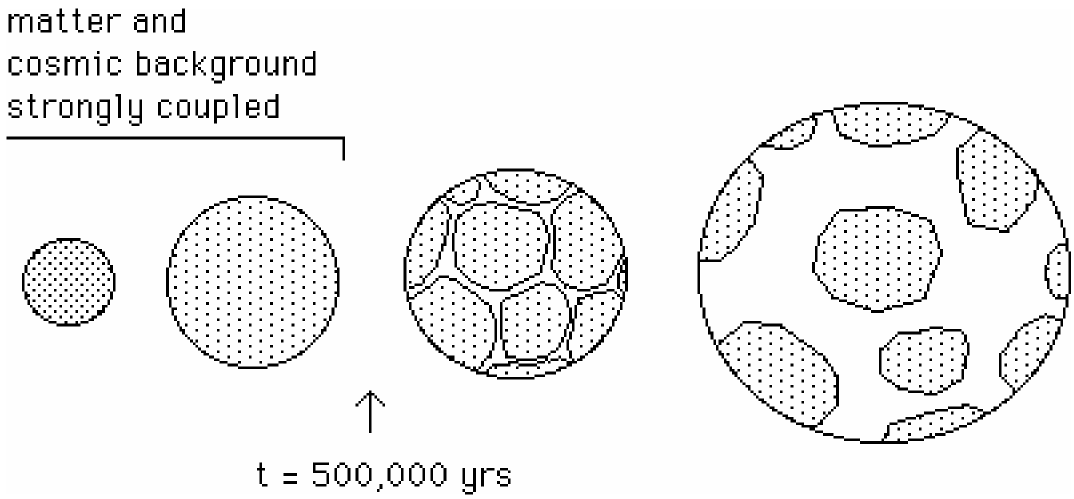
We have said that in this remote epoch ($t < 500{,}000$) the universe was a plasma, strongly coupled to its radiation. In the preceding chapter we have approached the question from the optical angle -- photons cannot traverse this medium without hindrance. They interact too easily with free electrons.

But the phenomenon works in both directions -- matter cannot easily move in the photon gas. This is a rather strange idea because we have trouble imagining light slowing down matter. But during this epoch the photon gas contained as much energy as matter itself; before 500,000 years it contained much more. This radiation was the universe.

The photons totally prevented matter from condensing through gravitational instability. It remained "stuck to this support" as rigid then as a metal plate.

When the universe's temperature fell to less than $3{,}000^\circ$ the free electrons began to quietly orbit around atomic nuclei and left light alone. The universe became transparent. Photons were able to travel tranquilly in a straight line, without obstacle. Conversely, matter was able to form its first condensations.

We have come here to a fairly simple notion of the formation of the first condensations of matter. We think of contractions. But matter has a method of individualizing itself -- by refusing to follow the expansion. In the preceding figure we saw lumps of matter moving further and further apart by conserving their size and their scale with between them the void, "dilated" photons. If we return close to the instant of origin, we obtain the following schema:



The decoupling between matter (stippled) and the background cosmological radiation allows the first fragmentations to take effect.

It is very difficult to mentally represent the universe in its primitive state. It is extremely probable that galaxies and stars were formed very early (since very old stars exist), although astrophysicists are not in agreement as to whether stars were first formed before or after galaxies. In any case at that time galaxies were much closer to one another than they are today. They interacted more strongly; their rotation is perhaps a fossil trace of their primitive crowding.

Ashes of the explosion.

Physicists continued to try to describe the primitive state of the universe according to the theory called the Big Bang. The majority constituent of the cosmos was hydrogen, the simplest atom, made up of one single proton. Going back in time, at around five hundred thousand years after the zero instant, the cosmic temperature should have been in the order of three thousand degrees. The primordial cosmic fluid was completely ionized, transformed into "plasma".

But before?

Before, the temperature should have been even more impressive. It is calculated to vary as the inverse of the universe's characteristic distance, separating two "control particles". Thus the components of the cosmos held more and more vertiginous energy.

The scientific community did not adhere immediately to this neo-biblical vision.

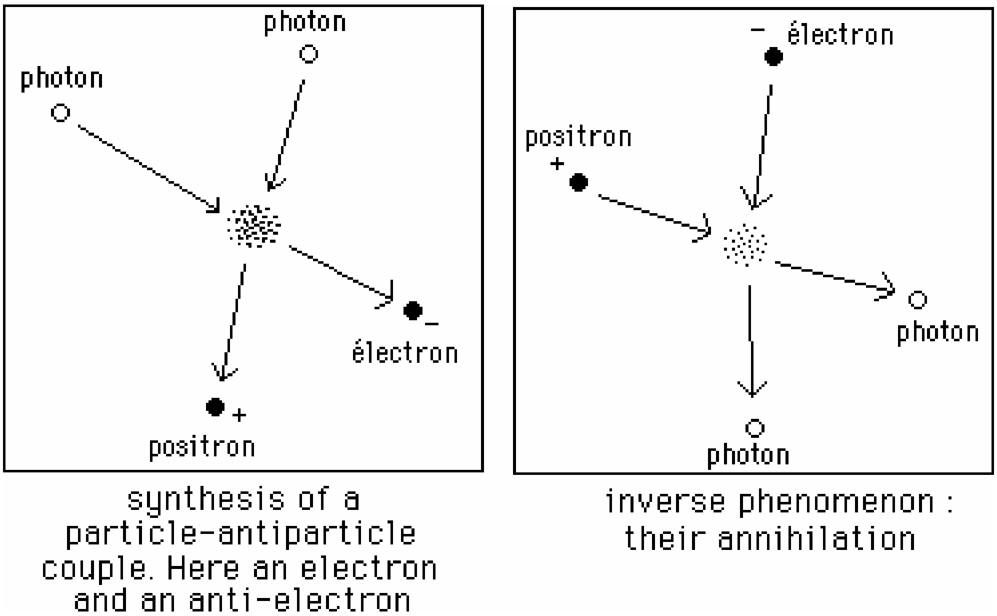
Meanwhile quantum mechanics had made progress. According to this theory, particles are no longer considered to be like little marbles of matter, but rather as "wave packets" linked to a vibratory phenomenon described by Schrodinger's equation, behaving like "a machine for synthesizing particles".

In the thirties, the Englishman Dirac modified the Schrodinger equation by integrating it into Special Relativity, thus founding quantum relativistic physics. He realized that he could elaborate a solution describing a strange object -- a particle possessing the same mass as the electron, but carrying an opposite, positive electric charge -- to which he gave the name of positron. People later realized that other particles could also possess these sorts of "doubles", called "antiparticles".

As is normal in the face of novelty, the idea of such an object was greeted with skepticism. However, over time, it became necessary to surrender to the evidence. Antimatter existed without a doubt. It was found in sprays of "cosmic rays", then through experiments mounted in high energy accelerators.

Charged particles wind in spirals in a powerful magnetic field. The winding direction depends on the field's direction and on the particle's charge. The gyration ray (Larmor ray) is determined by the mass. On the anti-electron pictures, its trajectory, quite visible, is seen to curve with the same gyration ray as that of the electron, but in the opposite direction. Therefore, as predicted, it clearly has a positive charge.

When matter and antimatter meet, annihilation occurs. The product of the mutual destruction is two photons. But the reverse reaction exists as well -- two sufficiently energetic photons, colliding, can make a particle-antiparticle couple.



Creation and annihilation of pairs of particles of matter and anti-matter.

At this stage, the reader has the right to ask a question: "Why don't photons annihilate themselves in turn?"

The answer is simple -- the photon is its own anti-particle and there is no anti-photon.

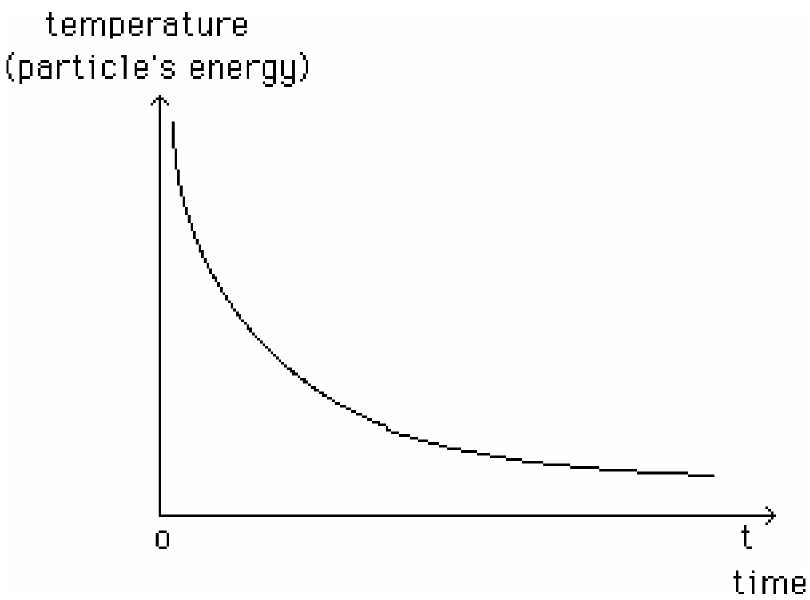
The calculations lead then to a particular description of the universe, with an extremely turbulent infancy. As the Nobel Prize winner S.

Weinberg said in his celebrated popular work The First Three Minutes, "In the beginning" the universe was filled with "all sorts of radiation".

This means that the universe's contents moved at either the speed of light (photons) or very close to it. In these conditions collisions between very energetic photons would continuously produce particle-anti-particle couples, heading off to be annihilated a little later.

But the brutal expansion of the "cosmic fluid", as depicted in the preceding curve, was accompanied by just as brutal a fall in temperature, therefore by definition in the particles' energies, which it measures.

This temperature of the "cosmic oven" happens to obey a very simple law. It varies as the inverse of d.



Change in particle energy as a function of time.

Thus the photons' energy lowered rapidly and they were no longer able to produce particle-anti-particle pairs.

In order that photons be able to give birth to particles of mass m, their energy hn = k T must be equal to mc^2.

They could not compensate for the losses due to annihilation (which were not influenced by the reduction of the ambient temperature). The result was a frantic depopulation, leaving a mixture of a great number of photons issuing from annihilation in the place of turbulent matter-antimatter.

According to the standard model, at the end of the first hundredth of a second, temperature of the photon gas had fallen to less than a hundred billion degrees, which prevented all creation of new proton-anti-proton pairs. Later annihilations decimated the electron-anti-electron pairs. This hecatomb ended at t = 13 seconds, when the temperature of the cosmic fluid was no more than three billion degrees K.

This cosmological Wounded Knee left only one matter or antimatter particle in a billion.

Good, said the theory's adversaries, which had been baptized the Big Bang, where are these primitive photons now?

They were finally found, entirely by chance, in 1964. The Americans had constructed an antenna in the shape of a hearing trumpet in order to listen to radar echoes reflected from a metallic balloon thirty yards across, the Echo satellite. But the antenna began to receive a signal even before the experiment had even begun,.

Penzias and Wilson at first believed that these parasitic signals came from pigeons roosting in the antenna's horn. They chased them away but the signal continued. When every hypothesis for the malfunctioning of the apparatus had been eliminated (Penzias and Wilson, tired of seeing the pigeons continually return to this strange nest, finally ate them), the evidence became inescapable. The antenna was detecting radiation of half-inch wavelength and isotropic, that is to say with the same intensity in all directions.

The wavelength corresponded to photons radiated out by a "black body" at very low temperature -- 2.7 degrees absolute.

The Big Bang partisans triumphed. The radiation temperature corresponded to their predictions. It was clearly the signature of the famous primordial photons from the original explosion, which expansion had "cooled down" to such a low temperature, in conformity with their calculations.

The link between the "radiation temperature" (expressed in degrees Kelvin) and the frequency of the photon is extremely simple. If k is the "Boltzman constant" and h the Planck constant, it is simply a matter of

$$h \nu = k T.$$

Where we lose half of the universe on the way.

But an inexplicable problem remained. The matter-antimatter annihilation had left one couple in a billion subsisting. The rest had been converted into photon pairs. Whatever the score, as much antimatter as matter should have subsisted after such a holocaust. Therefore it should be possible to observe both. But this was not the case.

Matter changes. When the temperature of the cosmic mixture was close to a billion degrees, hydrogen nuclei combined to give helium (four nucleons -- two proton and two neutrons). The entire universe acted like a sort of natural hydrogen bomb.

When the temperature falls below two hundred million degrees, however, this primordial nucleosynthesis freezes. Result of the procedure -- 75% hydrogen, 25% helium.

When the temperature falls below three thousand degrees, that of an incandescent light's tungsten filament, the electrons, which had existed until now in a free state, begin to orbit around nuclei. The universe ceases to be "ionized". Now photons interact strongly with free electrons, not with bound electrons, orbiting around nuclei. The universe therefore becomes transparent, as discussed above.

Gravitational instability then brings these atoms together in vast herds. In these sorts of nurseries stars are born which will then fabricate new atoms in their core.

But antimatter should do the same, produce anti-helium, anti-stars, anti-atoms.

Could this anti-world exist in the middle of our own? Let us examine the hypothesis. If our galaxies were made half of stars and half of anti-stars, of diffuse gas and anti-gas etc., it would not stay unnoticed. The encounter between gaseous matter and antimatter would give rise to not very discrete annihilations, accompanied by powerful radiation, unmistakably detectable by our astronomers. This does not happen.

People thought then that galaxies and anti-galaxies could cohabit, the first being made of matter and the second of antimatter.

Alas, these island universes, made up of hundreds of billions of stars, move slowly in the bosom of clusters, at some two to four hundred thousand miles per second. Collisions are rare, but they do occur (see Appendix 5). In telescopes we observe "galaxies in interaction" in contact with one another. The probability for matter and antimatter galaxies to meet or graze is high, during a time lapse of a dozen billion years -- the age of the universe and of galaxies.

The problem changes scale. If this has happened somewhere in the vast portion of the cosmos accessible to our observation, the powerful radiation linked to annihilations would not pass unnoticed. But we do not observe it. There is no indication that anti-galaxies exist. A dilemma.

For fifty years people tried everything. Models intended to justify a separation between two worlds, that of matter and antimatter, collapsed like houses of cards.

We have to follow the evidence -- we have lost on the way half of the universe, which is not nothing! Missing persons are noticed: Will anyone capable of furnishing information relative to this disappearance please contact the nearest theoretical physicist in his locality.

Nature is decidedly quite puzzling. In offering us the 2.7° K radiation, this ash of a primordial explosion, it gave support to a fairly seductive model. Now, in revealing to our eyes the primordial antimatter, it has produced a new riddle for scientists.

We will see later what they have thought up, since the end of the sixties, to try to answer this imponderable question.

The mysterious quasars.

From time to time, observations bring up a fact supporting a theory and unfortunately, fairly often, the opposite occurs.

The celebrated quasars were discovered for the first time in 1960 by a student from the American observatory at Pasadena, Thomas Matthews, who suggested to his boss, the astronomer Jesse Greenstein, that it might be a hydrogen cloud displaying a very strong red shift.

-- You are completely crazy, Greenstein answered. That would put them at considerable distances and given the quantity of light they send us and their tiny size, it would mean that objects the size of a large star were putting out as much radiation as an entire galaxy!

Matthews did not insist. One year later the Dutchman Maarten Schmidt dared this interpretation and it brought him the Nobel Prize.

Their red shift can go up to five, which puts them, according to Hubble's law, at distances in the order of a dozen billion light-years, at the confines of the cosmos.

But we do not know of any which have a red shift less than 0.1, which signifies that the closest quasars are at a billion light-years away from us, and therefore, since distance is also time, certain astronomers think this phenomenon ended billions of years ago for an unexplained reason. However the reasoning is incomplete. We have counted 5000 quasars within ten thousand light-years cubed. Let us suppose that we have counted them all. Then, within a thousand light-years cubed there would only be, statistically speaking, five to observe.

Since their apparent diameter is minute, they would be very small, the size of the solar system (or a large star of our Milky Way : the largest stars have the size of our solar system, as far as Mars. The smallest a diameter comparable to that of the Earth). Whence their name -- quasar, quasi stellar object (abbreviated QSO).

If they are so far away, they are fabulously powerful and radiate as much energy as an entire galaxy; they are five billion times more brilliant than a star.

Energy source -- unknown.

Appearance -- compact objects, ejecting very hot gas at a relativistic speed, in general in two lobes, diametrically opposite, sometimes one only. Today we have observed more than five thousand of them.

Subsequently it was shown that certain were located in the center of a gaseous formation resembling a galaxy.

The astronomer Seyfert had already discovered galaxies whose nucleus seemed to have exploded and which were also emitting burning gas in a system of jets. We tend today to think that the Seyfert-type galaxy and the quasar are similar, the second being simply more condensed in space.

Why do galaxies explode? One more mystery.

This one deepens to the extent that we discover "naked quasars", isolated, without galactic formations around them.

But it is possible that this is because the quasar is too luminous for the peripheral formation to be observed.

The enigma of "gamma flashes".

From the time of the cold war the Americans placed in orbit satellites furnished with receptors for detecting gamma rays, such as are produced during the ignition of a thermonuclear bomb. Such explosions are rare. Today we undertake them more discreetly, beneath the earth. So the astronomers said to the military, "Since your satellites are useless, lend them to us".

Tired of war, they accepted and the satellites were turned towards the sky. They detected very brief, but extremely intense and frequent "flashes"

-- one per day on average, emanating not from our galaxy's central plane, but from every direction in space.

Origin -- a total mystery. A new puzzle for theoreticians.

A universe younger than the stars it contains ?

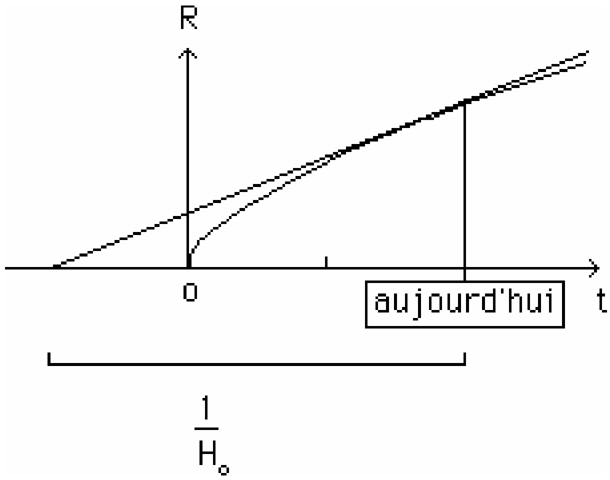
The discovery of the 2.7°K background radiation, by Penzias and Wilson, had been an outstanding event in the elaboration of the Big Bang theory. Up to very recently, this model served to determine the age of the universe. In the standard model, everything turns around the determination of the Hubble constant H_o, the slope of the "Hubble law", the relation of recession to distance.

H_o is evaluated classically in kilometers par second per megaparsec. A megaparsec represents 3,26 million light-years.

The age of the universe is deduced as follows:

$$\text{age of the universe} = 2/3 \;\; 1/H_o.$$

See on this topic Appendix 4. The expansion curve allows this property to appear geometrically.



Expansion and the Hubble constant.

If we choose the so called Einstein-de Sitter model, where $R \approx t^{2/3}$ we easily find : R'/R = 1/t

Models of stars had given very powerful results, not only explanatory, but also predictive.

Confident in the knowledge they had acquired of stellar phenomena (the life-history of stars, supernovae, neutron stars), astronomers determined the age of the oldest stars and found it to be fifteen billion years. The light they emitted was measurable and from it we were able to deduce the quantity of hydrogen "burned" each second to produce this energy. Knowing their "fuel reserves", their lifetime was deduced through simple proportionality. If our galaxy's oldest stars attained such respectable ages, it was indispensable that other determinations fit with this number, which implied a value of the Hubble constant close to 50 (in kilometers per second per megaparsec.)

Astronomers were not all in agreement on the law to apply. Whence a certain fuzziness in the determination of the age of the universe deduced from observations made on distant objects, that is to say in the determination of the Hubble constant H_o.

You have surely already heard conference attendees say, "Assuming that the universe is, let us say, twelve to fifteen billion years old...".

A fuzziness betraying the persistence of uncertainty in the assessment of distance. But it should accord well with the age of old stars. Whence the systematic attempt to increase this age as much as possible.

If astronomers had been able to observe Cepheids in distant galaxies, the precision of distance measurement would have been much greater and limited error to around five percent. Until the entry into operation of the Hubble space telescope, this was not possible. Once it had been cured of its visual problems and could be used correctly, the results came in.

In '94 and 95 the telescope's piercing eye allowed the measurement of different galaxies, situated at distances from forty-eight to fifty-five million light-years, in which Cepheids could be localized and targeted. A spectacular shortening of distances resulted and, correlatively, a revision down of the age of the universe -- eight to ten billion years, instead of fifteen, which the journal Nature announced in September 1995.

The universe became then ... younger than the stars it contains!

And Nature concluded, in its September 1995 issue, it was necessary to very seriously entertain the idea of revising our conception of the cosmos. We will see later how certain adjustments of the standard model can nevertheless deal with this contradiction.

Second Part.

Everything is relative.

In the first part we hardly spoke at all of Relativity. We even managed to introduce the Friedman models of the universe, like rabbits from a hat, without recourse to it (see Appendix 1).

Relativity comprises two parts --

-Special Relativity
-General Relativity.

In principle the two are intimately linked.

Special Relativity takes account of the rather singular behavior of light, which upset people so at the turn of the century -- its speed in the vacuum is an absolute invariant and does not depend on how the measurement is made, in particular on the speed at which the experimenter and his laboratory are moving. It also links together the four dimensions, three of space and one of time, in an intimate manner. Time ceases to be an independent variable.

General Relativity transforms forces into effects due to the curvature of space.

As usual, it is entirely possible to popularize Special Relativity by having recourse to a model,. But, in order not to overload this exposition, we have placed that part in Appendix 1, where the reader will find their demand satisfied, at least we hope so.

In physics a technique exists called passage to the limit, or approximation. The plane tangent to a sphere is very close to its surface if the sizes under consideration are sufficiently small compared to its radius, or its perimeter. If you ask a surveyor to measure your property's surface, they will not take the Earth's curvature into account.

Similarly, when physicists make calculations involving objects moving at a small speed relative to c, they will not use relativistic formulae. They will suppose in particular that all the phenomena they are trying to describe march to the beat of a universal time t, dear to Mister Newton, "our everyday time".

It was this double technique of approximation which Milne and MacCrea used in 1934 to reproduce general features of General Relativity, namely the Friedman models. They neglected the curvature of space, supposing that forces acted at a distance with infinite speed, and described all phenomena through an independent time t.

We will now focus on problems of the curvature of space and sever space from time, that is we will describe all phenomena using a time t, supposed to be universal.

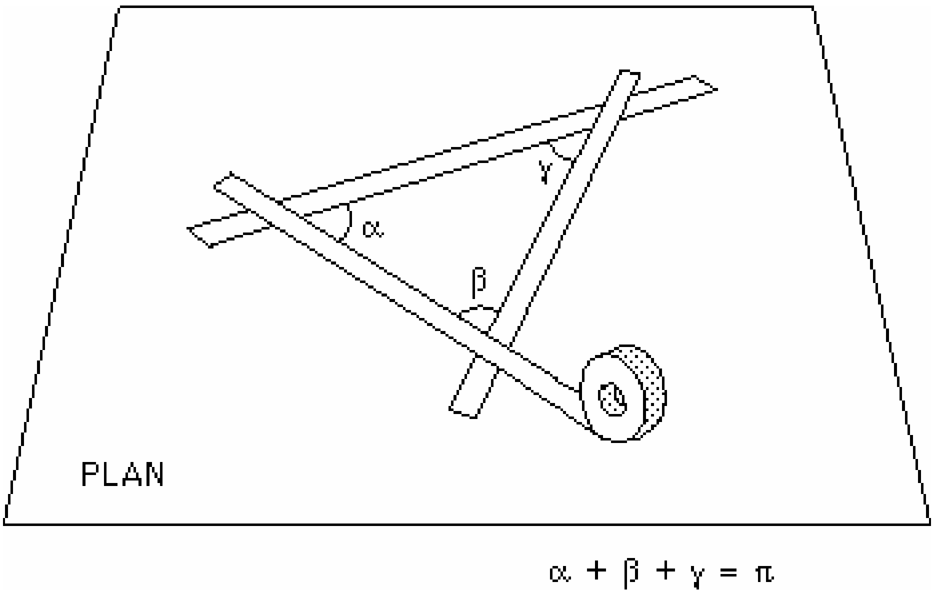
General Relativity.

1 - Curvature.

The geometrical context of General Relativity is quadridimensional. This amounts to saying that we have reduced the study of cosmic phenomena to that of a hypersurface of four dimensions. To enable a non-initiate to understand all this could seem a desperate gamble. so we will first remove time from all this, as if with a pair of tweezers, and aim for an understanding of a hypersurface of three dimensions, already somewhat delicate. We will analogize from basic two-dimensional models -- surfaces.

We will therefore transport ourselves to a universe whose spatial portion comprises only two dimensions, a surface.

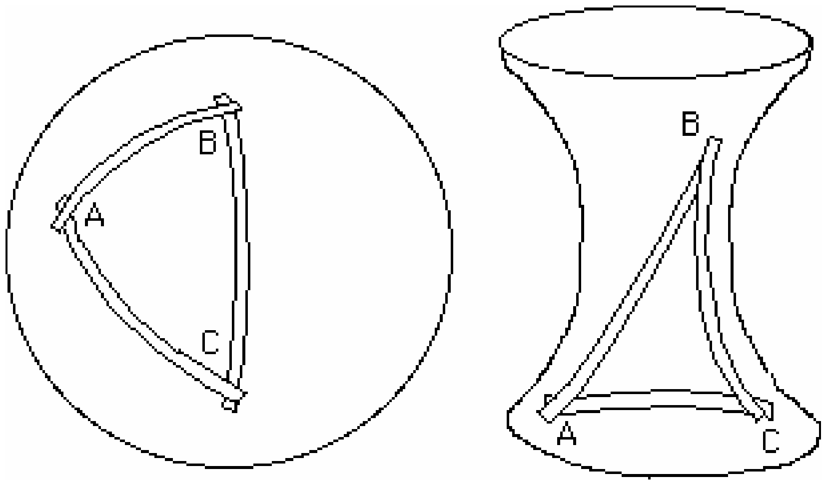
A Euclidian surface is a surface where Euclid's theorems apply, where, for example, the sum of the angles of a triangle is p, or 180^{o}. We are accustomed to construct these triangles on a plane, using a ruler to draw straight lines. We will change tools and this time use adhesive tape. The tape must be applied to the surface with caution, without creases so that it will make a line identical to that that we would have obtained with our classic school ruler.



How to draw straight lines on a plane without a ruler and with scotch tape.

The act of doing so also allows us to highlight a fundamental concept, that of the *geodesic* of a surface. You can stick this tape onto a plane, but also onto absolutely any surface whatever. In the plane the geodesic lines will be identical to what we have previously called "straight lines". But, from now on, we would prefer to consider them more generally as "the geodesics of the plane".

In drawing such geodesics on curved surfaces, we will be able to create some strange triangles.



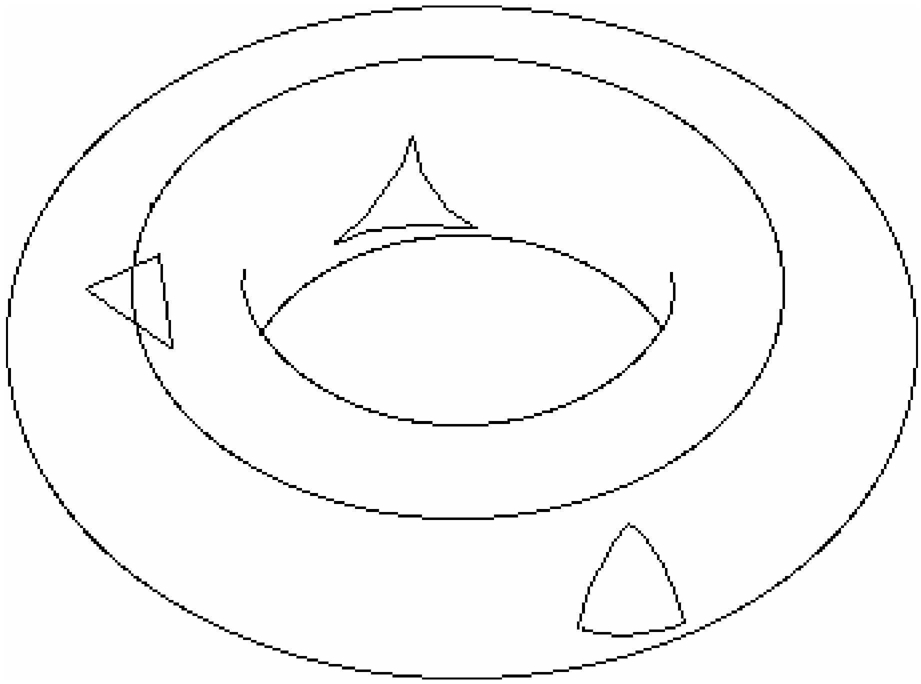
Geodesic Triangles drawn on a surface with positive curvature (a sphere) and on a surface with negative curvature.

A rapid measuring will show us that in the case of the sphere, the sum of the angles exceeds 180°, while in the case of the second surface, it's the reverse that is true. The test is sufficient enough for us to conclude that these surfaces *are not planes,* not *Euclidian* surfaces, since Euclid's theorem no longer works.

When the sum of the angles of a triangle on a surface exceeds the "Euclidean sum", that is to say 180°, we say that it has a positive curvature. In the reverse case we say that this curvature is negative.

We say that a flat, Euclidean surface, displays zero curvature.

But a surface can display variable curvature, according to the region under consideration. The simplest example is the torus.



On the exterior of the torus : positive curvature
In the vicinity of the circular notch : negative curvature in the vicinity of the "flank" :
zero curvature.

2 - Curvature and energy

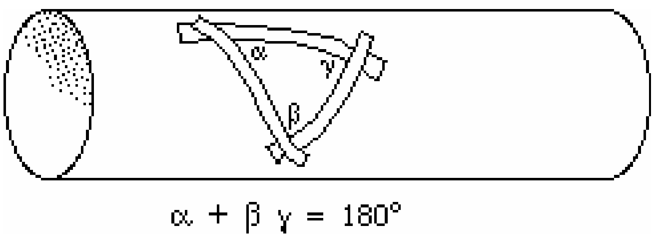
We move to a "thought experiment" involving blacksmiths. Every smith knows that he can deform sheet iron by heating it. Heating causes an object to dilate locally. If we heat a flat, uncurved sheet of iron with an acetylene torch, we will see a blister appear, that is to say a region with positive curvature. Conversely if our smith had before him a flat sheet, uniformly heated to red-hot, and directed a flow of cold air over a region, the metal would contract and it would constitute a region of negative curvature.

Therefore:

- *Dilation is equivalent to increase in curvature.*
- *Contraction is equivalent to decrease in curvature.*

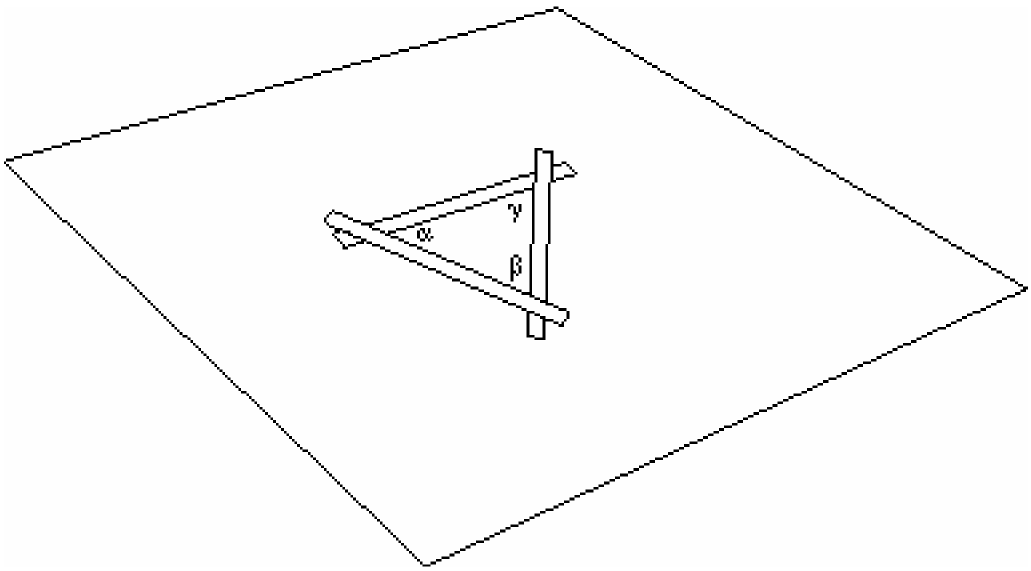
We see the link curvature-energy content being drawn.

But everyone doesn't have a forge, sheet iron and a portable blow torch so let us consider a second thought experiment, easier to imagine. This time take a cylinder. You will doubtless be astonished to learn that it is a Euclidean surface everywhere, with zero curvature, as long as we define the curvature as we did above, with a piece of scotch tape. Using a protractor you can confirm that the sum of the angles of a triangle is always equal to p (180^{o}).



A cylinder is a Euclidean surface.

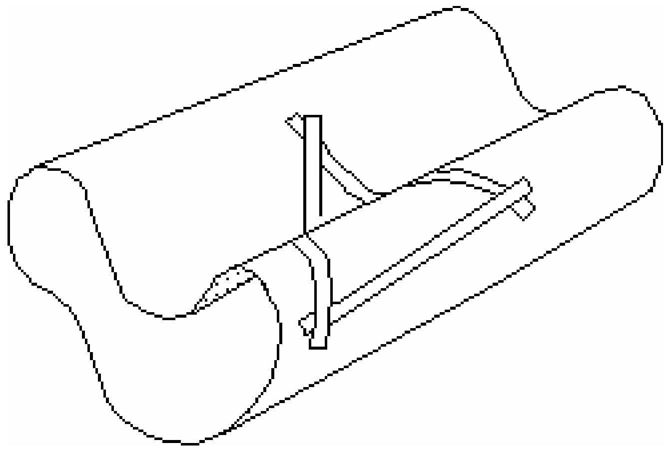
But you can also cut your cylinder along one of its generating lines, for example, and lay it flat, like this:



The cylinder, laid flat.

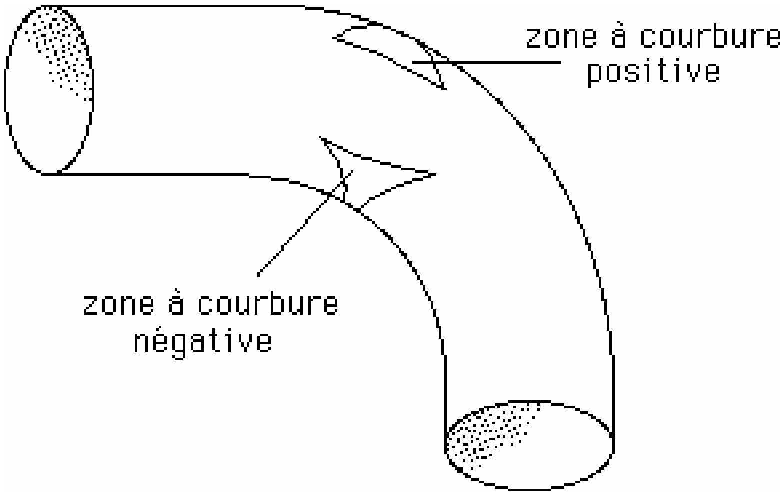
The situation becomes clearer. As a general rule, every geodesic drawn on this cylinder will be transformed into a "straight line", after "being laid flat".

A cylinder is moreover an object which can take very varied forms. You can for example twist it like this:



In drawing geodesics with your adhesive tape you will again produce, after "laying it flat", the plane's straight lines.

Let us take up again, after this digression, our "ordinary" cylinder, supposing it to be made of metal. It is then possible to heat it up on one side and cool it on the other, diametrically opposite side. We can easily imagine that it will be deformed as follows, appearing on one side with positive curvature and on the other with negative.



A curved cylinder.

This allows us to grasp the key concept of General Relativity:

Curvature equals energy.

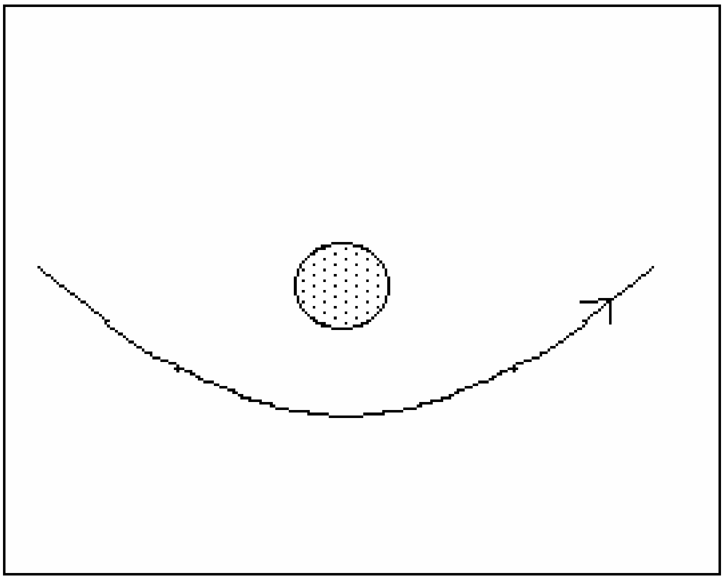
In General Relativity every point-mass is a "grain of energy", according to the equation:

$$E = mc^2$$

Why curved space?

In the classical view, before the birth of the General Relativity model, we had a flat, Euclidean, empty space, peopled here and there by particles. These interacted at a distance through different forces (gravitational, electromagnetic).

Let us concentrate on the force of gravity. A heavenly body, like the Sun, can be equated to a concentration of matter, of atoms. Now let us imagine a test particle penetrating the Sun's gravitational field. It will follow a particular curved trajectory (in the absence of a gravitational field, the trajectory will be rectilinear).

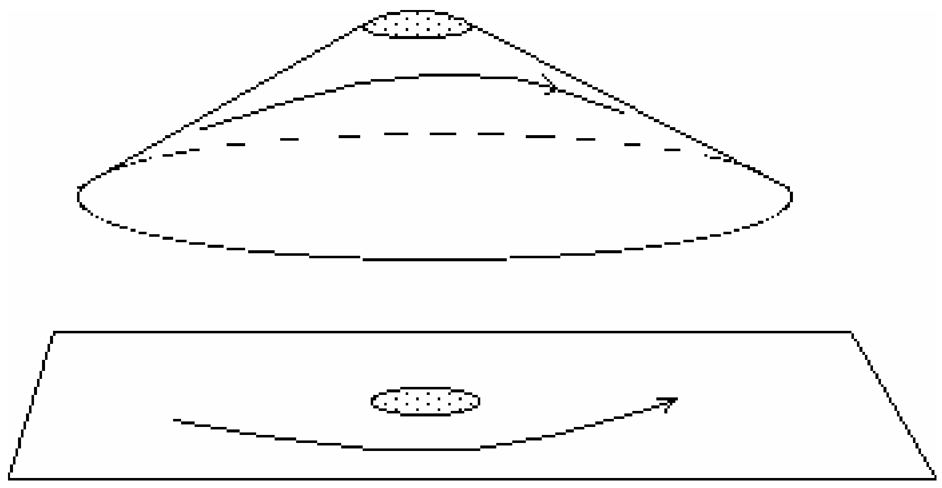


Trajectory of a test mass
in the Sun's vicinity.

Taking up again the idea presented above, we translate this into geometrical terms, that is to say replace mass and attractive force with curvature.

The Sun (represented by the stippled area) is a concentration of matter, supposed to be uniform. We imagine it in two dimensions, as a spherical cap, which we will complete with a cone frustrum. This, like our cylinder just now, is "without curvature". We will use our adhesive tape to draw a geodesic on its surface (see figure).

Projecting this onto a plane, we recreate the preceding figure. Whence another key idea of General Relativity -- we identify the regions containing matter with portions of curved space, and other regions with fragments of surfaces, either curved or Euclidean (without curvature).



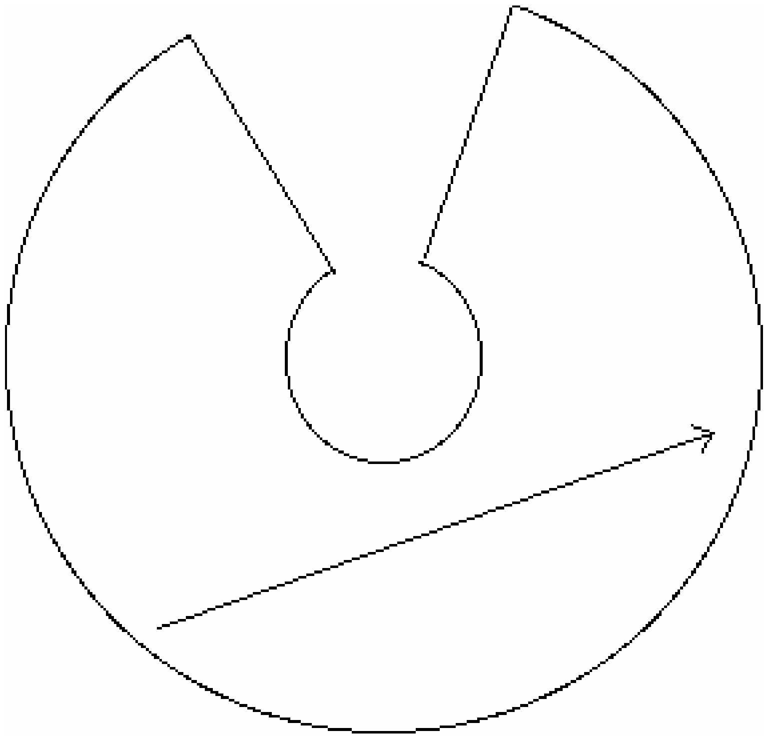
Representation of a trajectory following a geodesic of a space with curvature (blunt cone).

Trajectories are geodesics then. Forces have disappeared and have been replaced by geometry, according to the schema:

Matter = curvature
Trajectory = geodesics

In the preceding example a spherical cap had been coupled to a cone frustrum. Like the cylinder, this is without curvature. If you doubt this for an instant, lay the cone frustrum flat after having drawn a geodesic on it, (see the next figure).

The cone, like the cylinder, can be laid flat. This surface is called developable.

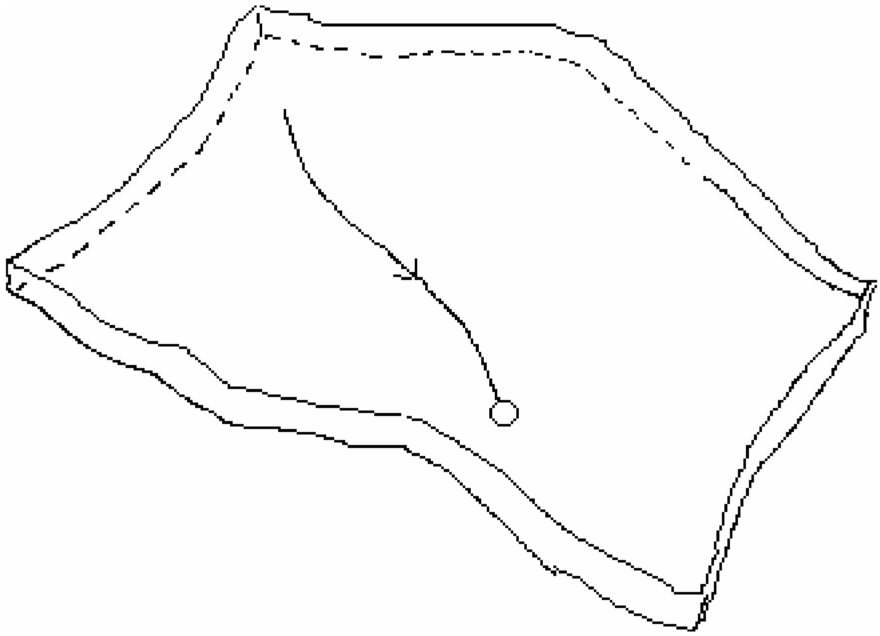


The cone frustrum is laid flat. The test particle's trajectory becomes a straight line.

General Relativity transforms our vision of the universe, turning it into a hypersurface where we alternately find regions with and without curvature (Euclidean). Of course, the concept of a "three-dimensional surface" is a little difficult to apprehend.

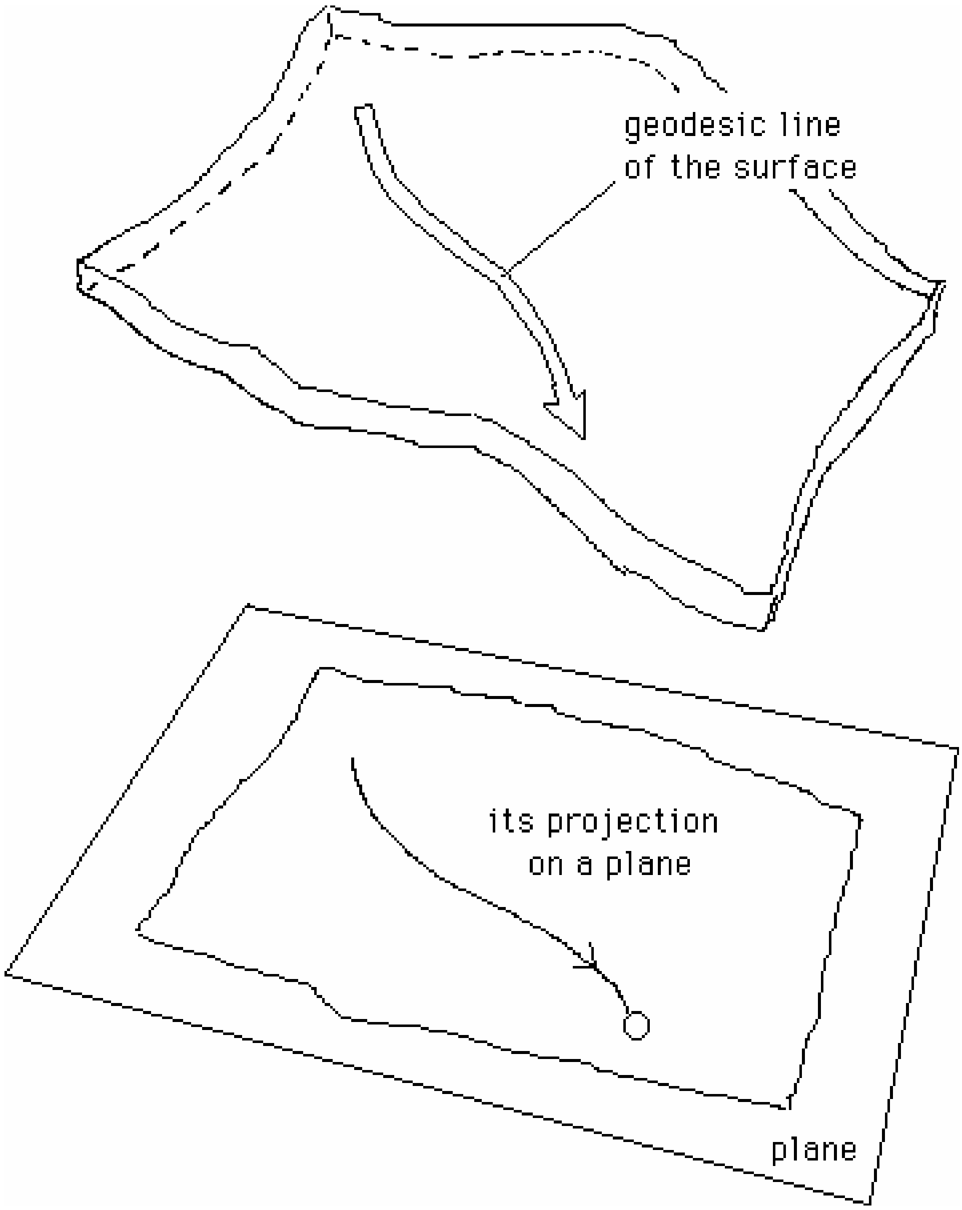
Some years ago NASA had the idea of placing a billiard table of Plexiglas on board the space station Skylab to entertain the astronauts. The project was eventually abandoned. To prevent the balls from flying around the station at the first touch of the billiard cue, their room for maneuver was limited by two perspex plates. The billiard table, like the players, would be weightless but the balls would have nevertheless followed rectilinear trajectories, progressing in straight lines, the geodesics of the plane.

Let us imagine that the billiard table had been warped, like this:



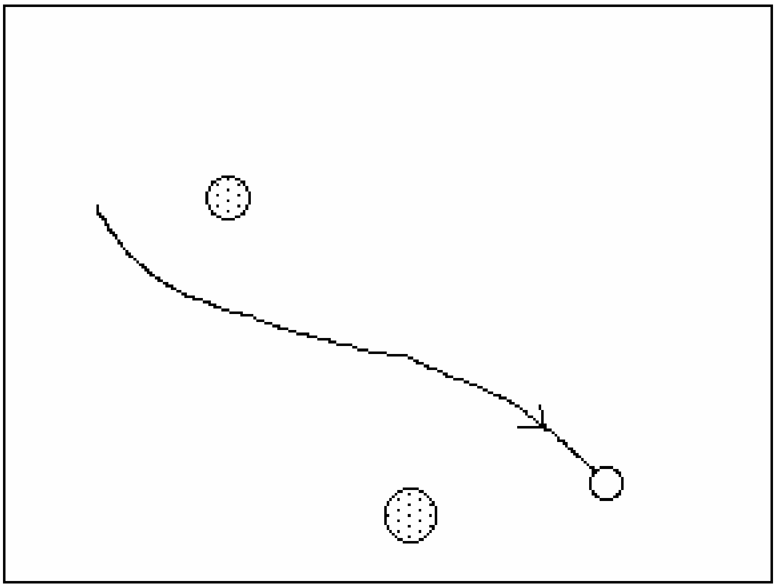
Trajectory of the ball in a spatially curved billiard table.

The balls, always constrained to move between the two Plexiglas surfaces, would in this case have followed non-rectilinear, sinuous trajectories. The laws of mechanics indicate that the trajectories are the geodesics of the surface.



The geodesic on a curved billiard table and its flat projection.

We can imagine another type of billiard table, flat this time but on which objects would affect trajectories (for example in charging the balls and obstacles electrically).



An object moving in a force field created by other objects.

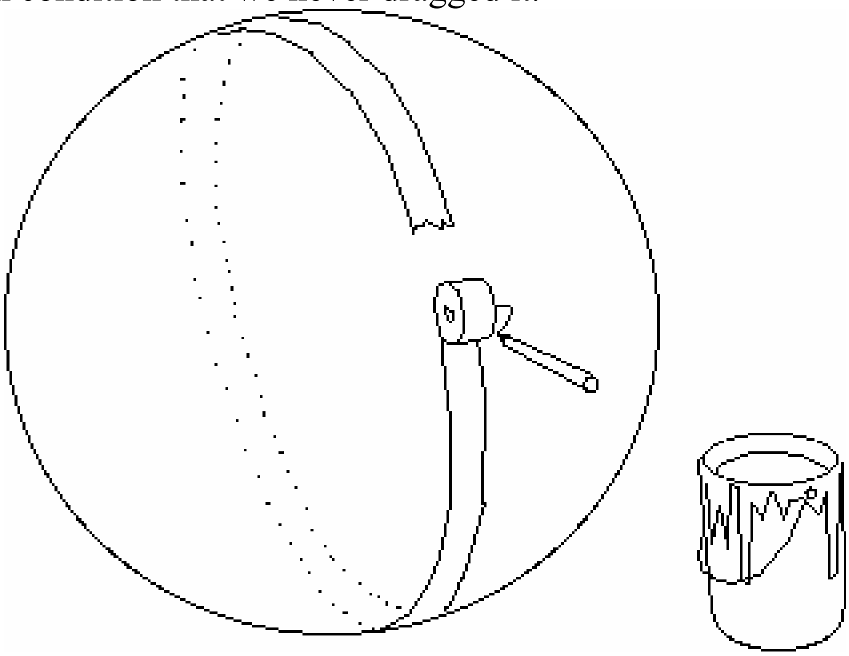
We could then arrange for the ball's trajectory to be the same as on our curved billiard table. We return here to the theme of the equivalence between forces and effects due to curvature.

The white ball is a "test particle" moving in a "force field" somewhere in the cosmos, one created by two asteroids for example,. We suppose that the particle moves on a plane containing the two asteroids. Its trajectory would be somewhat affected by the presence of these two attractive objects. We could however construct a curved surface such that one of its geodesics, after projection, is identical to this trajectory.

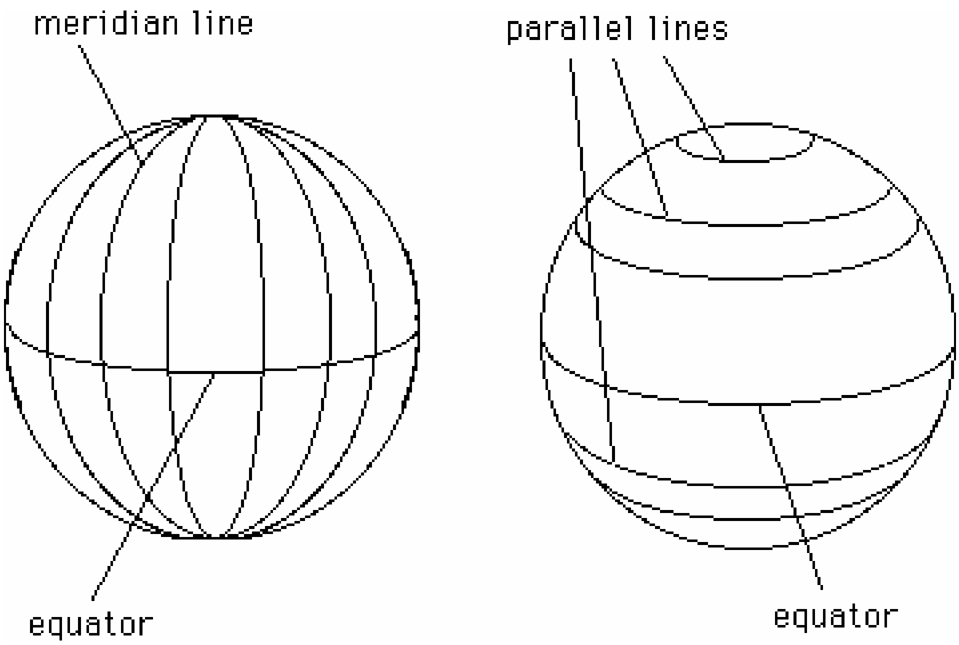
The universe, plunged into an absolute time, is a hypersurface of three dimensions. For the student of General Relativity, forces no longer exist. All trajectories are geodesics. But how to imagine the geodesics of a three-dimensional space? What could be likened to our "adhesive tape"?

We have to replace it with objects resembling tent poles, strung along next to one another.

In two dimensions, on a surface, the adhesive tape allows us to go "neither to the right, nor to the left" (which would make creases). We note in passing that we could also have drawn these geodesics with a "paint roller", on condition that we never dragged it.

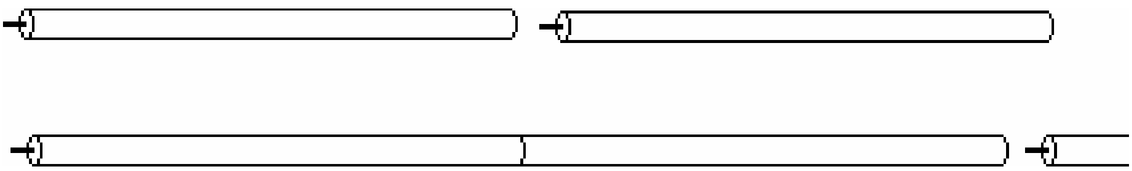


With a paint roller we draw a geodesic of a sphere, one of its "great circles".



A sphere's equator and meridians
are great circles, not parallels.

Let us return to our 3d tape, that is to our tent poles, which allow us to construct geodesics on a three-dimensional hypersurface. Here they are:



The set of tools for creating 3d geodesics.

If space is Euclidean, these straight lines will simply go off to infinity and will be for us, with our "mental Euclidean representation" (the only one we have in our heads), just ordinary straight lines in 3d space.

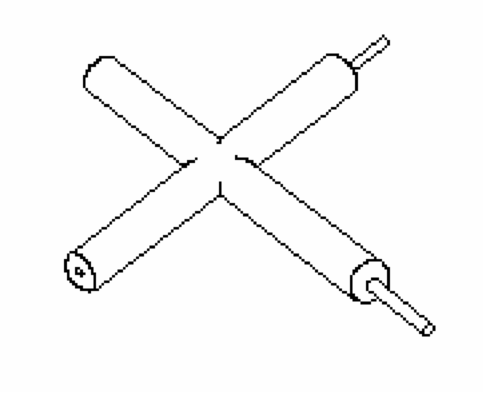
But if space is curved, things will be different. We will be able to have spaces with positive curvature. To test this curvature we could draw immense triangles made up by such geodesics. If the curvature is zero, the sum of the triangle's angles will be 180^o. If it is positive, the sum will be greater than 180^o. Less if it is negative.

At this stage we can begin to imagine that space can be "hyperspherical", closed in on itself.

If we take geodesics on a 2d sphere, starting from any point, they resemble meridians issuing from a pole which, as every knows, converge at the opposite pole, its antipode.

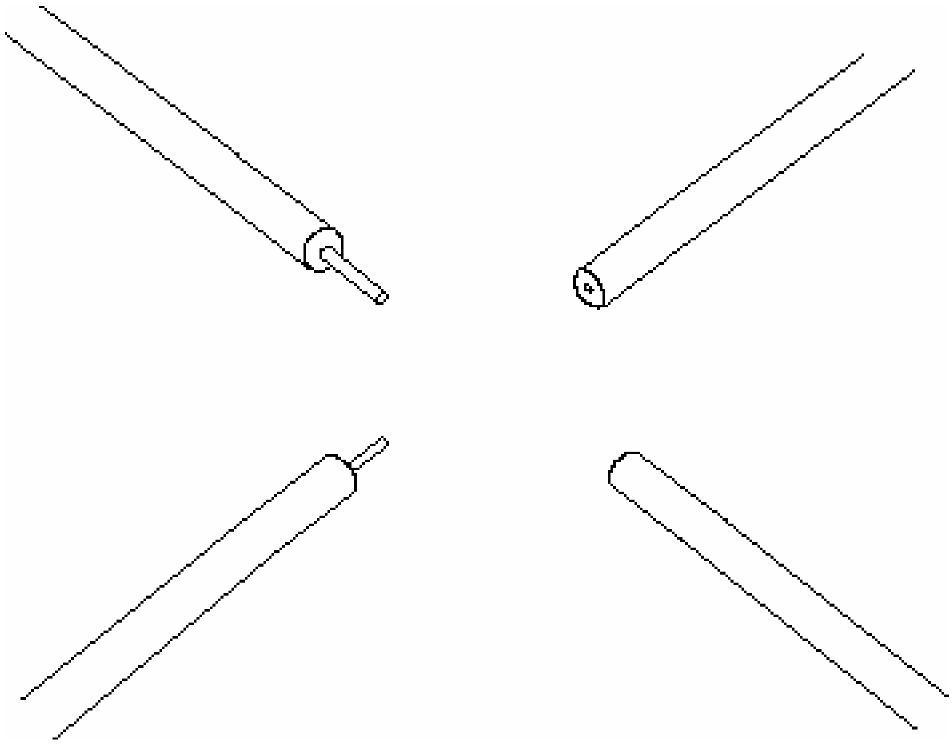
Geodesics coming from any point, in a three-dimensional hyperspherical space, head in all directions like the spines on a sea-urchin and refocus at the antipode.

We can locate the antipode of a point in three-dimensional space through a part like this:



The part for the crossing
of two 3d geodesics.

It would be enough then to join the geodesic's elements and, at the antipode, we would obtain this:



Convergence of the geodesics

at the antipode.

It would only remain to put in another cross-bar to make this antipodal point concrete.

A little time is needed to habituate oneself to such oddities, but we can succeed in doing so. Evidently a hyperspherical space has a finite volume, just as a sphere has a finite surface.

In what follows, this idea of a closed space will be useful to help the reader understand the Einstein field equation.

The universe changes. It curves, uncurves. We can model this by imagining a surface with a certain temperature distribution. At each point the temperature would modulate the object's dilation, therefore its local curvature. Globally, it would dilate.

The physicist could study this surface's behavior through a field equation:

$$\mathbf{S} = \chi\, \mathbf{T}$$

S is a mathematical object, which we will not describe, called a tensor. Its analysis would furnish the local curvature.

T is another tensor, which represents the local density of thermal energy.

χ is what is called the Einstein constant. Its value is of little importance.

This is a *local* equation, and signifies:

Curvature = heat.

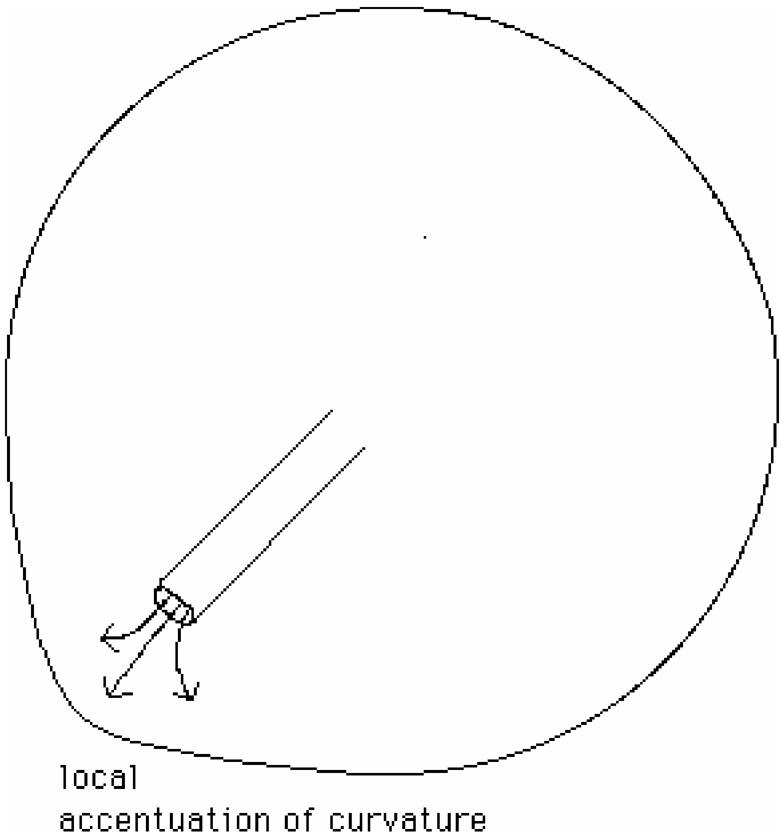
Without entering into details, the reader can easily conceive that such an equation might permit the physicist to calculate the change of the surface with time. If **T** were the same everywhere (if temperature in the "sheet metal" were the same at every point, at a given instant), the surface would have constant curvature. It would be a simple sphere in a state of dilation. A sphere displaying a curvature varying from one point to another could be made of a material which does not diffuse heat, possessing a thermal conductivity close to zero.

Albert Einstein followed the same approach in conceiving of the universe as a hypersurface whose behavior similarly depended on a field equation, expressing the equivalence:

Local geometry = density of matter-energy.

Another object exists obeying a field equation, the soap bubble. Its geometry is determined by the prevailing difference in pressure at every point between interior and exterior. If this is constant, the bubble takes the form of a sphere.

But we can imagine placing inside this bubble devices altering locally the pressure difference. We can for example imagine a straw blowing air against the bubble wall. The bubble would deform.



The soap bubble and straw.

The bubble's local geometry would express the relation:

Curvature = exterior-interior pressure difference.

Of course the cosmological problem should be formulated in four dimensions and not three. The cosmologist's universe is a four-, not a three-dimensional hypersphere.

In fact the problem has been formulated and the solution found. We note that the four-dimensional hypersurface describes the change of the universe over time. Three-dimensional cuts give an instantaneous view of the universe at a given moment.

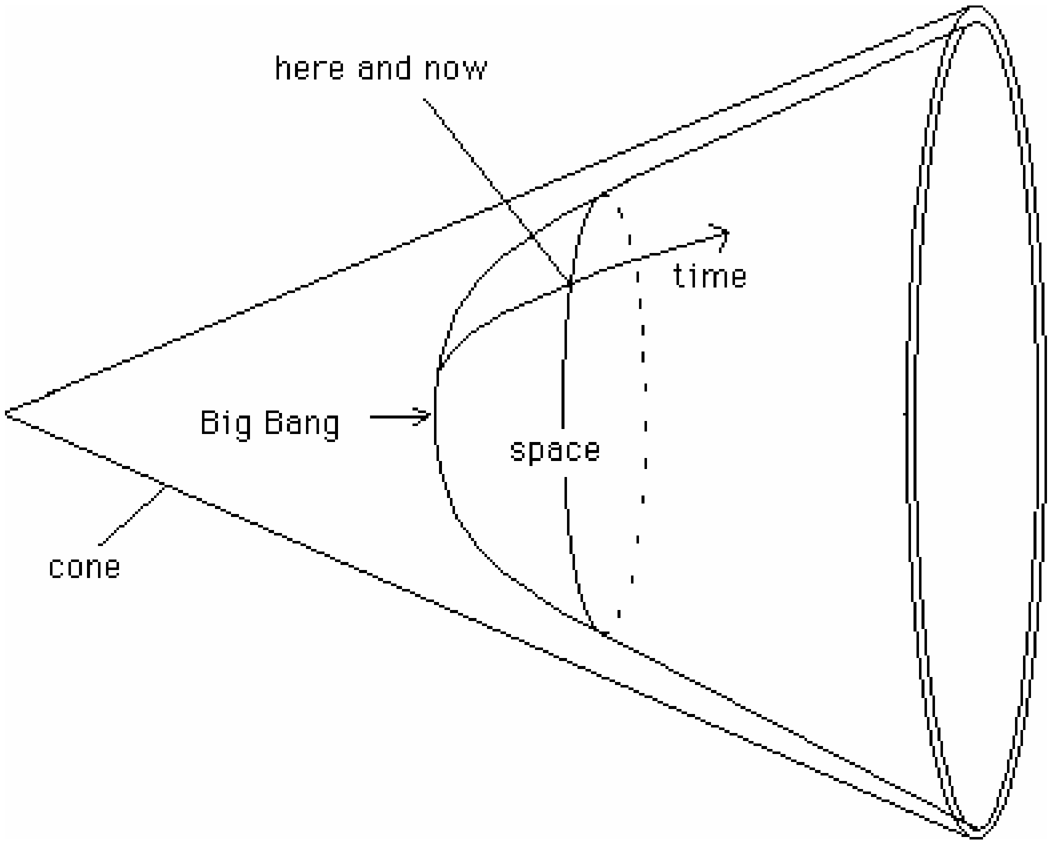
5 - 2d representation of Friedman's solutions.

We can only manipulate or represent with drawings two-dimensional surfaces. Therefore if we want to envisage a space-time, it as well can only have two dimensions -- one for time and a single one for space.

A one-dimensional space is a line, a curve. There again, it is more convenient to imagine space being closed in on itself. We will represent it as a circle changing over time.

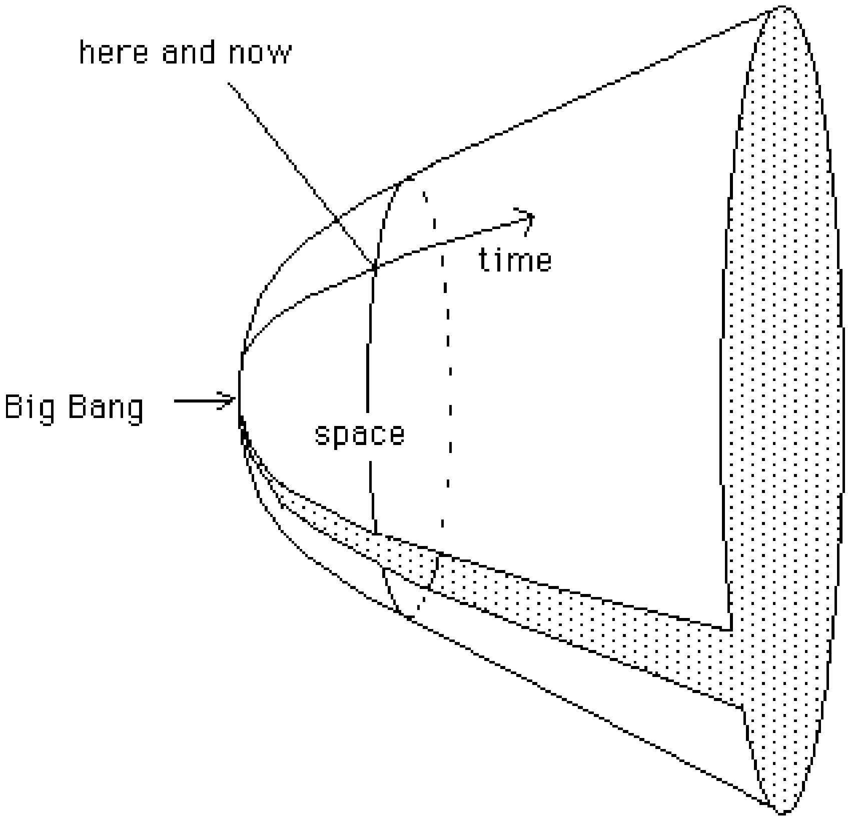
A universe in expansion will start from a point, the Big Bang, where space is reduced to ... zero. The increase of the circle's perimeter will illustrate its expansion. The surface's meridians will be called world lines. They represent the spatio-temporal trajectory of an object immobile with respect to space itself (we say: comobile).

In the following drawing, corresponding to the Friedman model called Hyperbolic, the space-time surface tends to become tangent to a cone, which signifies that the circle's radius grows linearly according to t, a curvilinear abscissa measured on the surface's meridian from the origin.



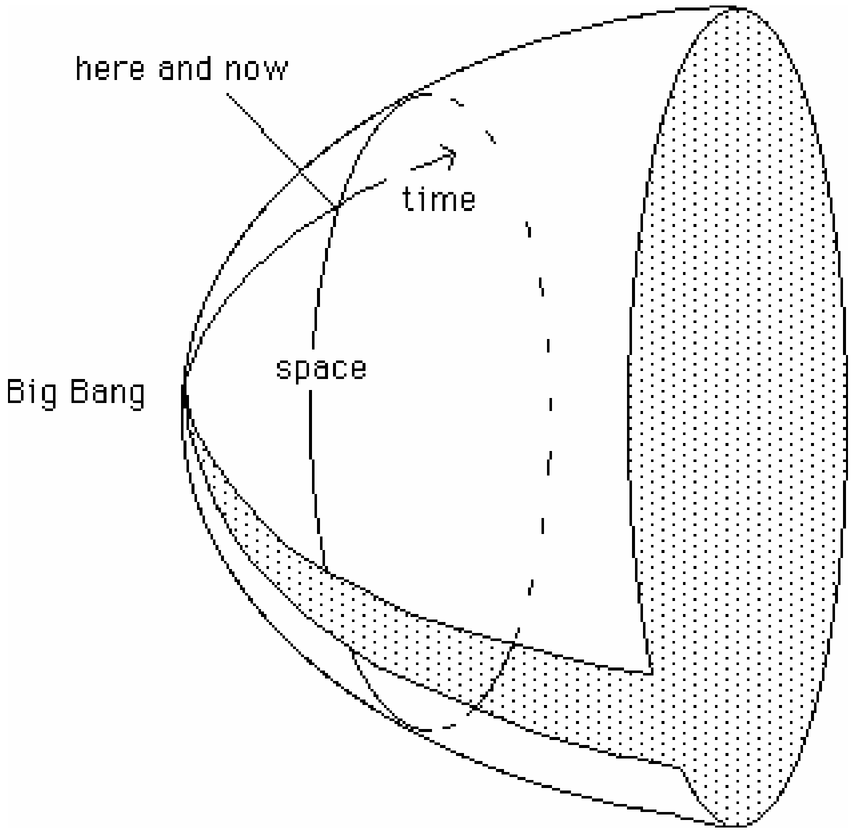
2d geometrical representation of the first space-time corresponding to the Friedman solutions.

In fact this space is open and infinite both towards the future and spatially. The perimeter 2pR is only there to orient us. If we wanted to depict space's non-closure on itself, we could for example make a cut like this:



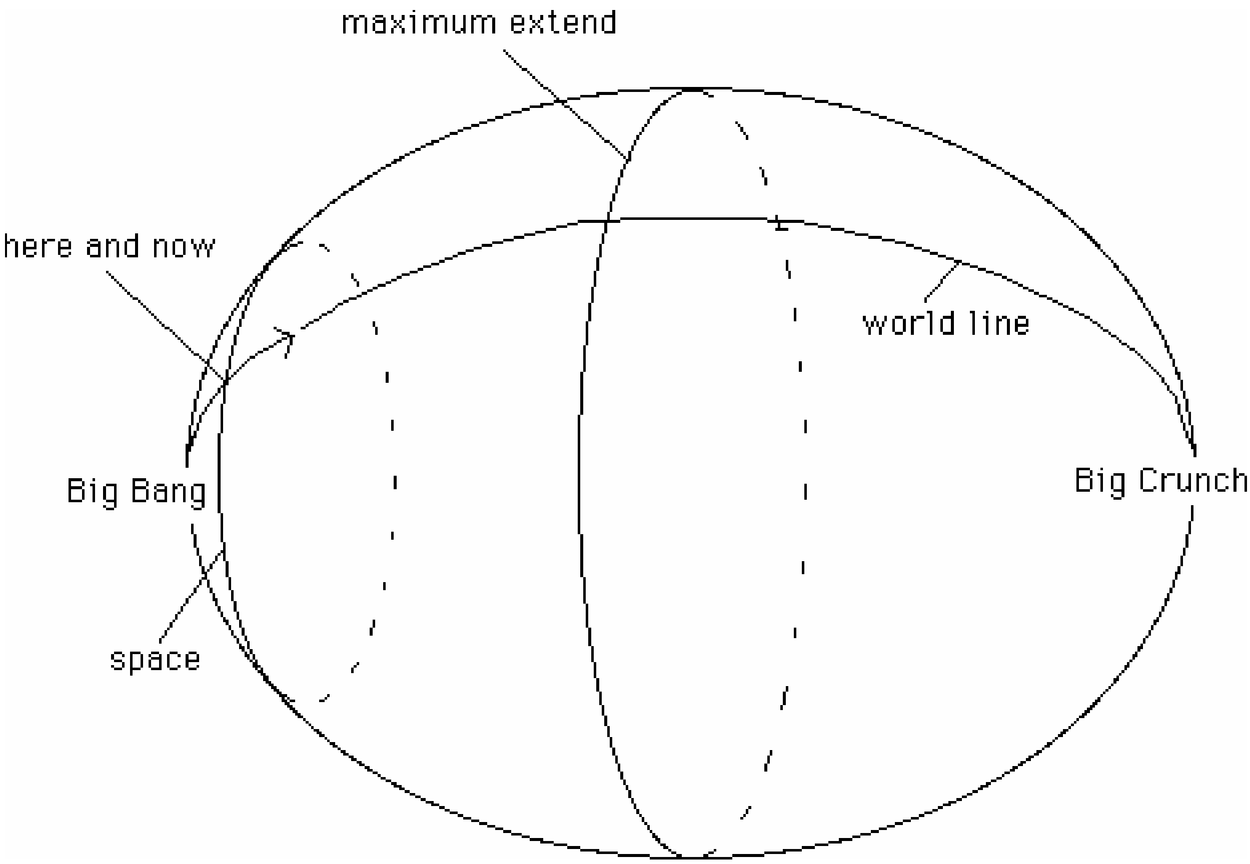
2d representation of the hyperbolic open Friedman model

The parabolic model can be represented in the same way. The space-time surface then has the form of a revolving paraboloid.



2d representation of parabolic Friedman space-time.

But we know that there exists a third solution, called elliptical, where space, after having known a phase of maximum extension, shrinks back to a new singular situation called the Big Crunch. We would then have this:



2d geometric representation of
the elliptical (closed) Friedman model.

As stated above, we do not know how to make a choice between the three models. The third poses a serious problem for us concerning the future of the universe in the very long term. If we represent the appearance of lumps of matter at different scales by a segmentation of "circle-space", we should then conceive that cosmic history plays backwards. What would become of the stars and galaxies? We haven't the faintest idea. Similarly we cannot identify the moment when expansion will stop and contraction begin.

At the end of such lengths of time, numbered perhaps in years with a one followed by I don't know how many zeros, only a very clever person could describe the content of the cosmic soup.

Einstein's frustrations.
The cosmological constant.

Einstein had therefore, in 1917, invented this beautiful field equation:

$$\mathbf{S} = \chi\, \mathbf{T}$$

Looking for a stationary solution, he did not succeed in finding one where **T** would be non-zero. Now this "tensor" **T** describes none other than the contents of the universe in matter-energy. So that Einstein's stationary universe stayed desperately empty, contradicting his initial idea -- that the content determine the geometry.

He went to the French mathematician Elie Cartan, who said to him:

- Your equation is not in the most general form. I have another to propose to you:

$$\mathbf{S} = \chi\, \mathbf{T} - \mathbf{g}\, \Lambda$$

The fat letters represent what we call the tensors, but we will not risk opening this "box". Too complicated.

The tensor **g** is in particular the "metric tensor", the true unknown of the equation and yet to be determined, the tensor **S** being calculated on the basis of this one.

In any event the new equation contained a constant Λ .

At the price of this cobbling, which Einstein considered later as the greatest error of his life, he could construct a stationary model of the universe. But what might be the physical signification of such a quantity?

Matter (tensor **T**) produces curvature (positive). It expresses its auto-attractive character. Placing a minus sign before the second member, with a positive constant Λ, made it seem as if something were opposing the attractive effect. Whence the name given to this constant, this effect. It is:

The repulsive power of the vacuum

Physically, Einstein's stationary model could be summarized as follows :

Matter, auto-attractive, tends to collapse the universe onto itself. Very luckily the repulsive power of the vacuum opposes it and creates a situation of equilibrium.

The corresponding value of this constant is moreover quite simple in these conditions. If we call the density of matter in the universe ρ, it is:

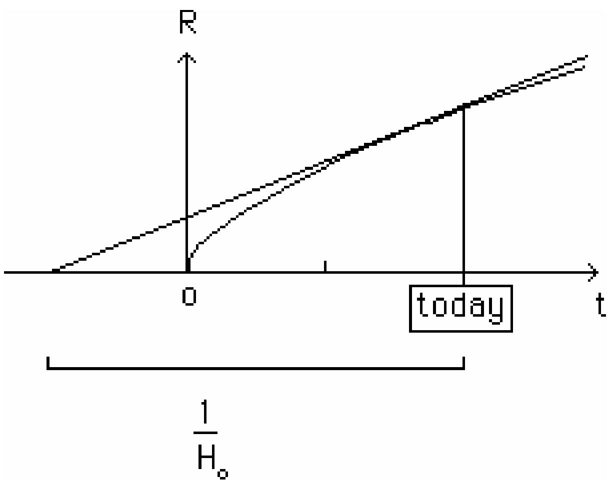
$$\Lambda = 4 \pi G \rho.$$

That is to say ρ with a coefficient (the gravitational constant G).

Later Friedman found a more elegant, non-stationary solution (published in 1922 in the Proceedings of the Paris Academy of Science). Cosmologists amused themselves studying non-stationary solutions, keeping the constant to see what their variables represented in the Friedman solutions. Making it positive had the effect of accelerating the expansion, due to the repulsive power of the vacuum. On the contrary, making it negative made the vacuum attractive.

The problem of the age of the universe.

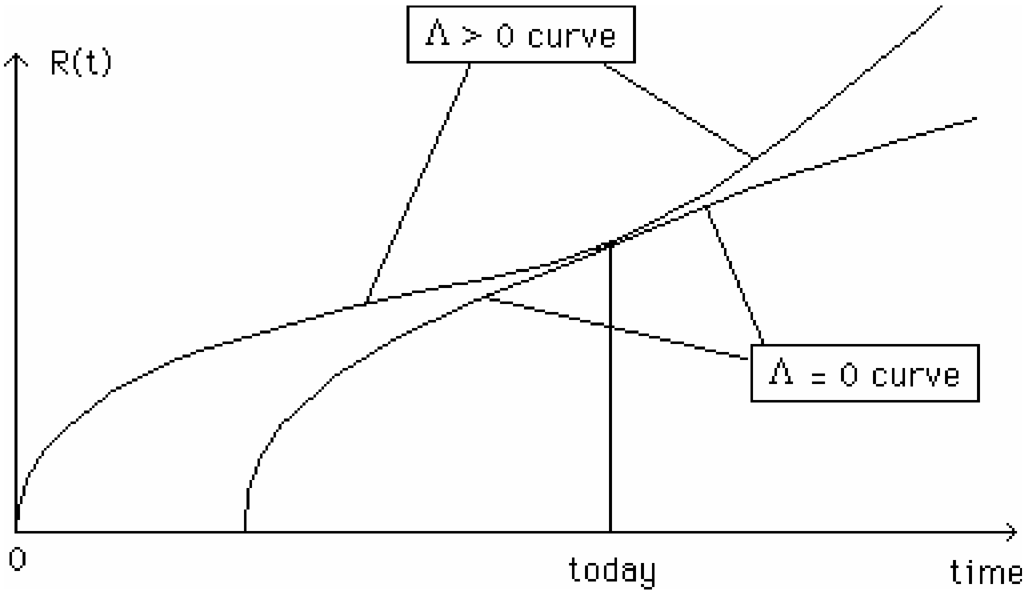
For a long time, not being able to attribute any physical significance to the constant, many people believed that it should be assigned a zero value. A normal reaction, getting rid of an annoyance. But very recently (1995), the Hubble space telescope (see above) gave it an air of reality. Let us return to the preceding case, corresponding to a zero value for the constant L :



where the "Hubble constant" appeared (see Appendix 4). Schematically, as indicated on the figure, the constant's inverse is the length of the segment (on the time axis) taken between the moment we make the measurement (the present) and the point where the tangent to the curve R(t) cuts the axis of the abscissa. The age of the universe is then:

$$A = 2/3\ 1/H_o.$$

In 1993 Hubble's measurements bought values irreconcilable with the estimated age of our galaxy's oldest stars, the ones which belong to globular clusters, whose age was estimated to be close to fifteen billion years. At first the results caused a certain amount of panic among theoreticians. Some suggested returning to the old good cosmological constant Λ . A useful gadget : At first the universe experiences an expansion of approximately parabolic speed with respect to time, then the effect of the cosmological constant, of the vacuum's repulsive power, makes itself felt and the expansion accelerates indefinitely:



Evaluations of the age of the universe with and without a cosmological constant.

In the figure we can see two curves, indicating the law of cosmic expansion with and without a cosmological constant. The astrophysicist, in this middle of the nineties, assigned an adequate value to Λ, it the right size to resolve the contradiction. In the end it seemed that the vacuum did indeed have repulsive power. It remained to find out why.

To sum up, one theoretician said :

- Well, now how to *measure* this cosmological constant?

A few years later things do not look so critical. The satellite Hipparcos gave new distance values for a great number of stars, which, by the way, provided a new calibration for the Cepheids. Fortunately, people found these stars farther than had been imagined before while on another hand, astrophysicists did their best to rejuvenate the grandmother stars, the ones of the globular clusters.

Finally they all reached an acceptable compromise. The cosmological constant was no longer necessary and it was put back in its box. People forgot its "value" and decided to stop talking about it.

The Olbers paradox.

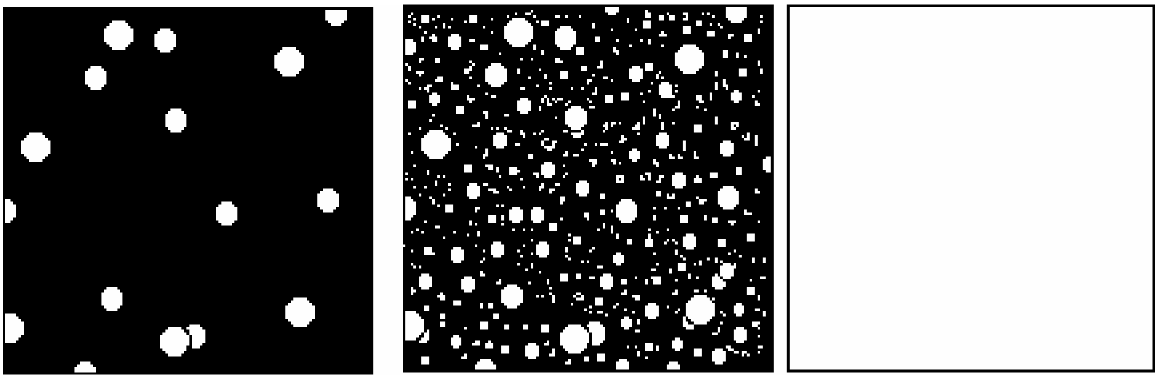
There is a very simple way to ask oneself the questions of cosmology. All you have to do is cross your doorstep in summer and look at the starry sky.

Why is the sky black?

If the universe were infinite and placed before our eyes for all eternity, the view would be unbearable. Why?

Imagine you suspended lights from lines in an enormous airplane hangar. You could use for example lights with frosted glass, looking like spherical globes, shining light uniformly. Your hangar's walls are black and extremely absorbent, to the point that they do not reflect the light they receive. We know how to make such walls, called light traps.

In front of you, you see your lights, white disks against a black background. Even if they are hung at a good distance from each other, providing the hangar is sufficiently long a moment will always come when you can no longer perceive the background.



The Olbers paradox : If vision is carried to infinity, the sky ends up with the appearance of a star's surface.

Every object has what is called a blackbody radiation temperature, even if it is not lit up. Only an object with a temperature of absolute zero emits no radiation. If you go into your kitchen in darkness, and turn out the light while turning on a hotplate, at the beginning you will see nothing, because it radiates in the infrared which your eyes do not perceive. But if you turn up the hotplate, it is possible to bring it into the red range. Then you will see it. Its light will be bearable. If, instead of placing electric lights in your hangar you suspended little red spheres, if you put enough of them the whole of what you saw would seem to your eyes like a large reddish plate, with uniform luminosity. Your retina could stand it.

If the universe were infinite, your sky would resemble a plate with a temperature of six to ten thousand degrees (the average blackbody temperature of stars' surfaces), which would grill your retina immediately. Looking at a simple tungsten filament at three thousand degrees is already unbearable.

Of course, stars are minute objects relative to the immense distances separating them. But the cosmos is immense. Giving a value to its stellar density, it is possible to calculate a spherical radius such that star images would fill the entire field of view.

But if the universe were a three-dimensional hypersphere, could its volume be finite and contain a finite number of stars?

That would change nothing, for light, circling infinitely in this hypersphere, would end up filling the entire visual field. Even a finite, hyperspherical universe would appear "white".

The model of a universe in expansion allows us to resolve the paradox, for then the light of distant stars slides towards low frequencies as their distance grows, due to the Doppler effect. A model for this situation would be objects with blackbody temperatures decreasing with distance until they became invisible. The closest "lights" would send out white light. At a greater distance they would become red. Still further away they would be simple heated filaments radiating in the infra-red, which we could no longer distinguish.

Even if stars did not exist, the sky would not be completely "black". The cosmological radiation would remain, though detectable only by our antennas. We live in a furnace heated to a temperature of 2.7 degrees absolute. If there existed on Earth an animal whose optical system worked at these frequencies, its sky would be of a uniform luminosity.

But what is "mass"?

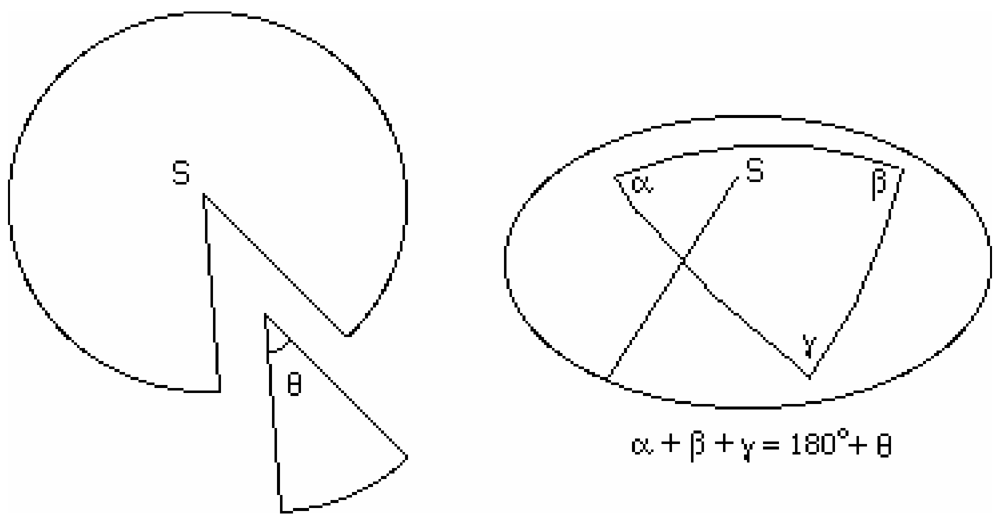
The description given by General Relativity is macroscopic. In this world, particles... do not exist. We do not know how to extract them from the field equation, which furnishes only a smooth geometry, no "wave packets". It is another equation which takes care of this, Schrodinger's. These two equations proudly ignore each other, as though it were a matter of two different worlds or two different representations of the world.

We have said above that matter-energy and curvature have been equated. How could we then represent a point-mass?

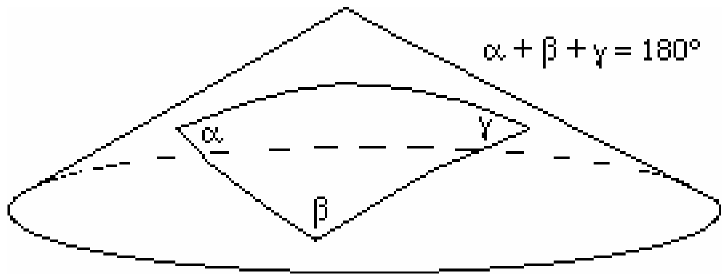
Didactically, through a cone.

Let us take a cardboard disk and make a slice in it forming an angle theta. Gluing together the two sides of the notch forms a cone, on which you can draw geodesics. With these you can compose a triangle. If it contains the cone's pointed end, the sum of the angles will be equal to:

$$180^\circ + \theta$$

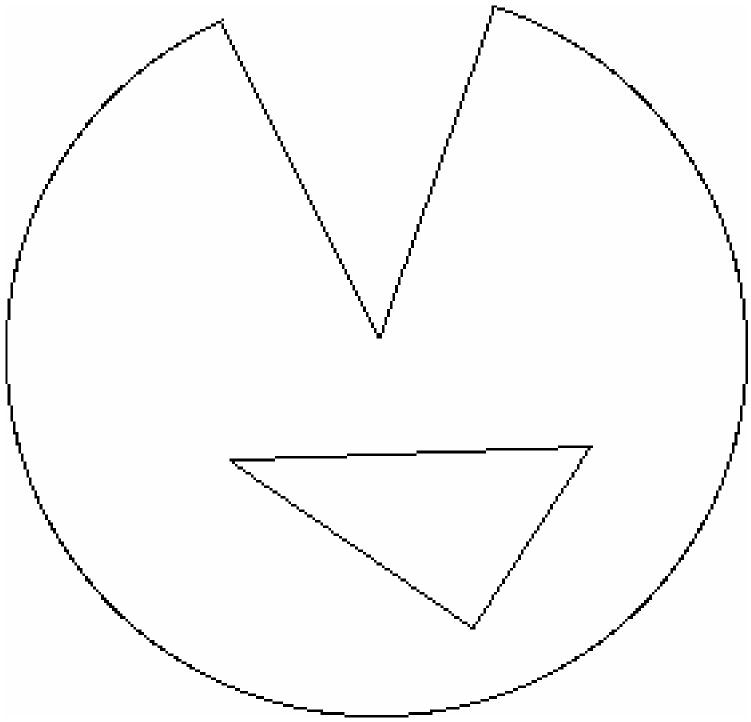


On the contrary, if the triangle does not contain the tip, you will obtain the Euclidian sum -- 180º. The cone's flank is Euclidean "without curvature". Like the cylinder, it is a developable surface. We can lay it flat.



The cone's flank is a Euclidean surface.

If you undertake the operation of laying flat, as we did for the cylinder, you will see that the drawn geodesics become those of a plane, in the classical sense of the term.



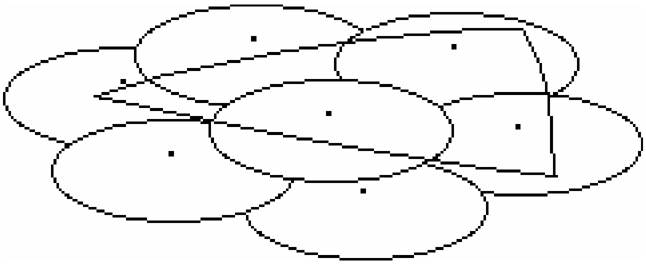
Our cone, laid flat. Geodesics become straight lines. The cone's flank is a fully Euclidean surface.

In this perspective, a point-mass would be a mini-cone fitted into a three-dimensional hypersurface.

The variance from the Euclidean sum is a measure of the "quantity of curvature" contained in the cone's tip.

On a surface these angular curvatures are additive. Imagine that you stick together mini-cones of angles

$$\theta_1, \theta_2, \theta_3, \text{etc......}$$



Several mini-cones stuck to one another.

If you draw a triangle made up of geodesics enclosing a certain number of elementary cone ends, corresponding for example to the angles q1, q2, q3, you will see that the sum of the triangle's angles is:

$$180^o + \theta_1 + \theta_2 + \theta_3$$

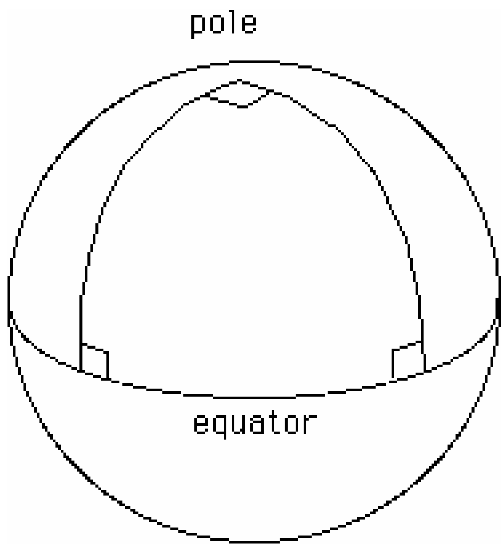
Starting from this notion of "pointlike curvature" concentrated at the tip of each of these cones, we can move to that of a "smooth" surface" by extrapolating to the limit and imagining that a sphere, or any other curved surface, can be constructed with an infinity of mini-cones joined together.

Up to now we have had only a qualitative notion of curvature. Now we obtain a quantitative notion. If our mini-cones pave the surface very closely, the variation from the Euclidean sum will depend on the "quantity of angular curvature" contained in the triangle. We thus arrive at the idea of density of angular curvature (per unit of surface).

The sum of the angles of a triangle drawn on a sphere (a surface of constant angular curvature) will be proportional to its area.

But how do we find the coefficient of proportionality?

On a sphere we can draw an "equilateral triangle rectangle" with two meridians separated by 90^o and a portion of the equator.



An equilateral triangle rectangle.

The sum of its angles is then $180^o + 90^o$. Therefore this triangle contains a quantity of angular curvature equal to 90^o. Its surface represents an eighth of the sphere's surface. The area of a sphere is $4\pi R^2$. My equilateral triangle rectangle's surface is therefore:

$$\pi R^2 / 2.$$

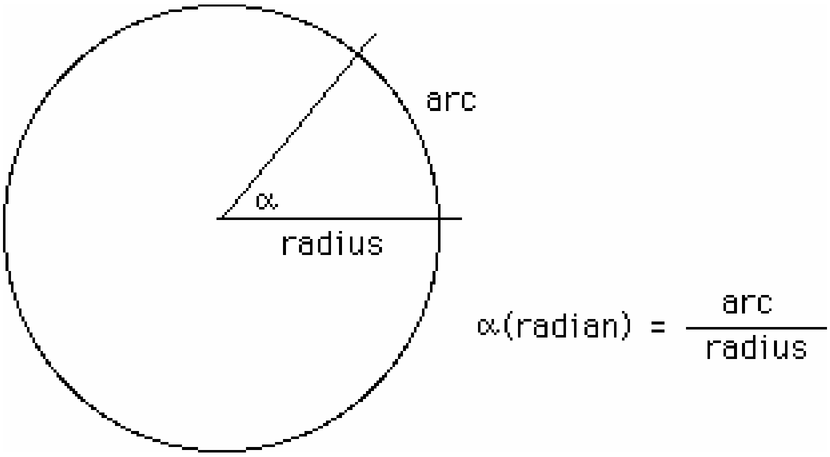
Therefore the sum of the angles of a triangle drawn on a sphere is:

$$\alpha + \beta + \gamma = \pi + \text{area of the triangle} / R^2.$$

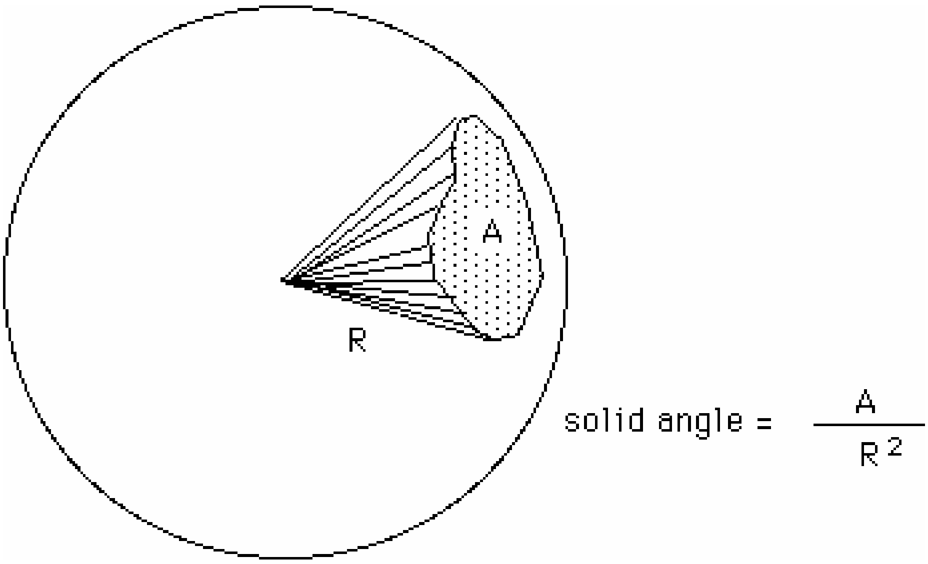
So particles are little atoms of curvature. But how do we measure this "density of curvature" in three dimensions?

Take a cube, a polyhedron with eight corners. From each of these corners three faces emerge. They enclose a certain "solid angle".

How do we define an ordinary angle, measured in radians? It is the length of the arc divided by the radius.



For a solid angle, limited by a conical contour of any form whatsoever, we will use the surface corresponding to the contour intersection of the conical surface with a sphere.



Definition of a solid angle.

In this perspective the eight solid angles at each corner of a cube, placed in a tridimensional Euclidean space, correspond each to a solid angle of $\pi/2$.

In the plane, the sum of the angles of a triangle has the value π. But the sum of the angles of a quadrangle has the value 2π, etc.

Each time we add a corner, we add π.

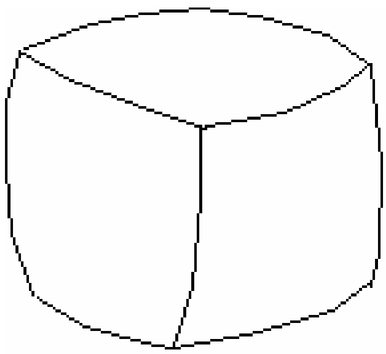
The sum of the solid angles of a cube has the value 4π and this sum stays invariant if we transform the cube into a polyhedron with six faces, moving its corners in any way whatever.

This polyhedron is made up of geodesics. Its faces are themselves a close plaiting of geodesics (just as in flat Euclidean geometry we can consider a plane as made up of an infinity of straight lines).

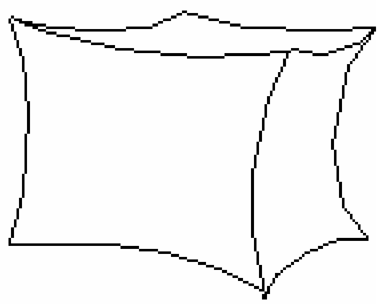
Starting from this idea we can move to a tridimensional curved surface. We place eight points and join them with geodesic arcs. Then we stack new geodesics onto these arcs in such a way as to constitute sheets, which become the equivalent to Euclidean polyhedrons.

If the sum of solid angles exceeds 4π the space has a positive curvature.

If it is less than 4π the curvature is negative.



3d positive curvature



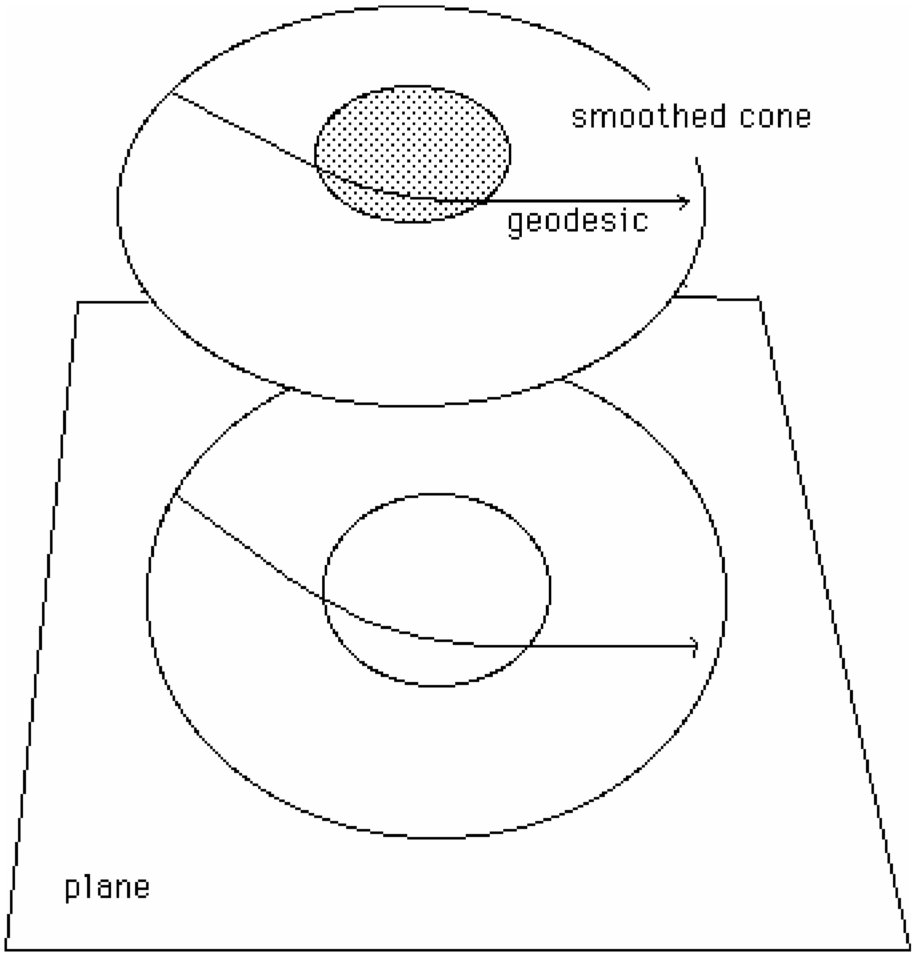
3d negative curvature

If our three-dimensional space has "constant density of curvature", the sum of solid angles will be proportional to the volume contained in this polyhedron, divided by the square of the space's radius of curvature, according to a formula of the same type, which we will not write. The difference is that now we no longer see the radius of curvature R! To "see" it we have to be able to observe the hypersurface containing this cube by plunging it in a four-dimensional space....

We see how we can measure the quantity of curvature contained in a volume (no longer in a surface) and identify it with the density of matter ρ.

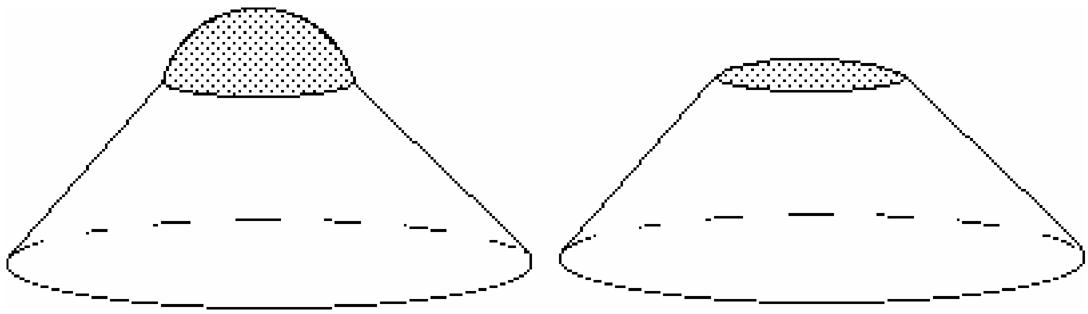
How to describe the curvature within and near the Sun.

We return to our models of two-dimensional surfaces. If we liken the Sun to a sphere of constant density surrounded by a perfect void, its image will be that of a blunted cone, the image which we have already given above. On this surface we can draw geodesics which pass to the side of the spherical cap or cross it. A photon which travels, like every particle, along a geodesic, cannot cross the Sun, but a neutrino can.

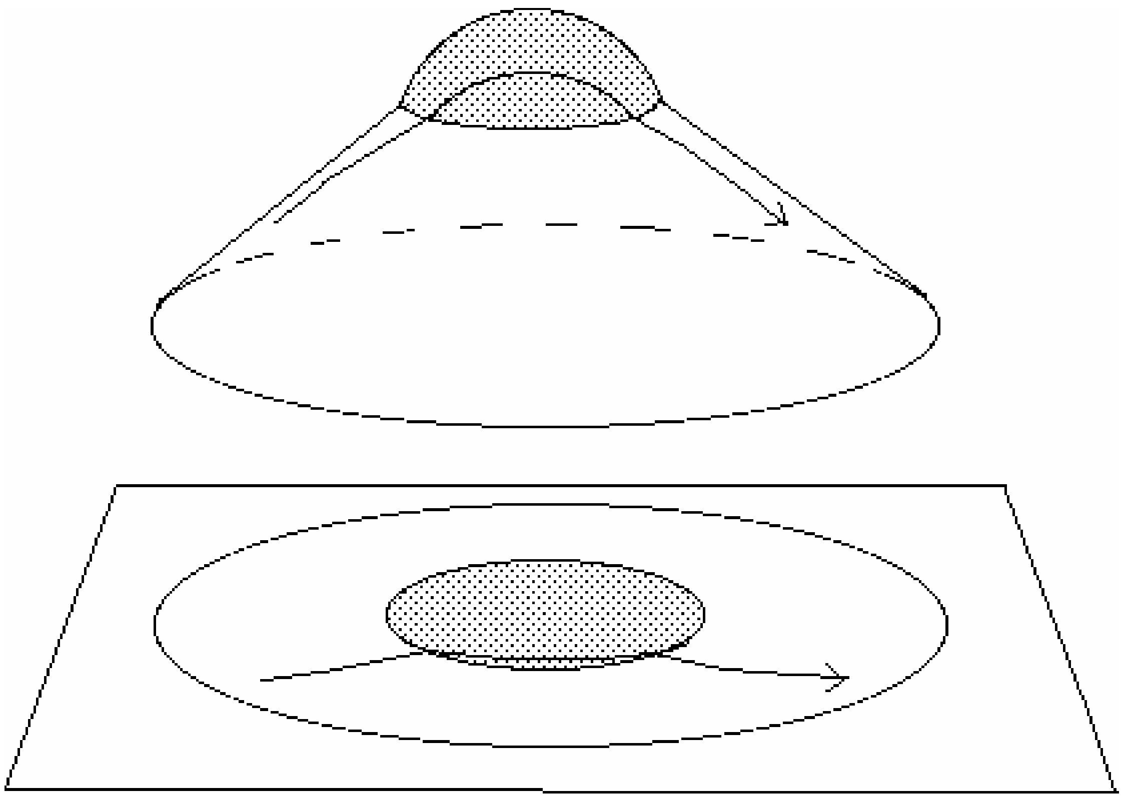


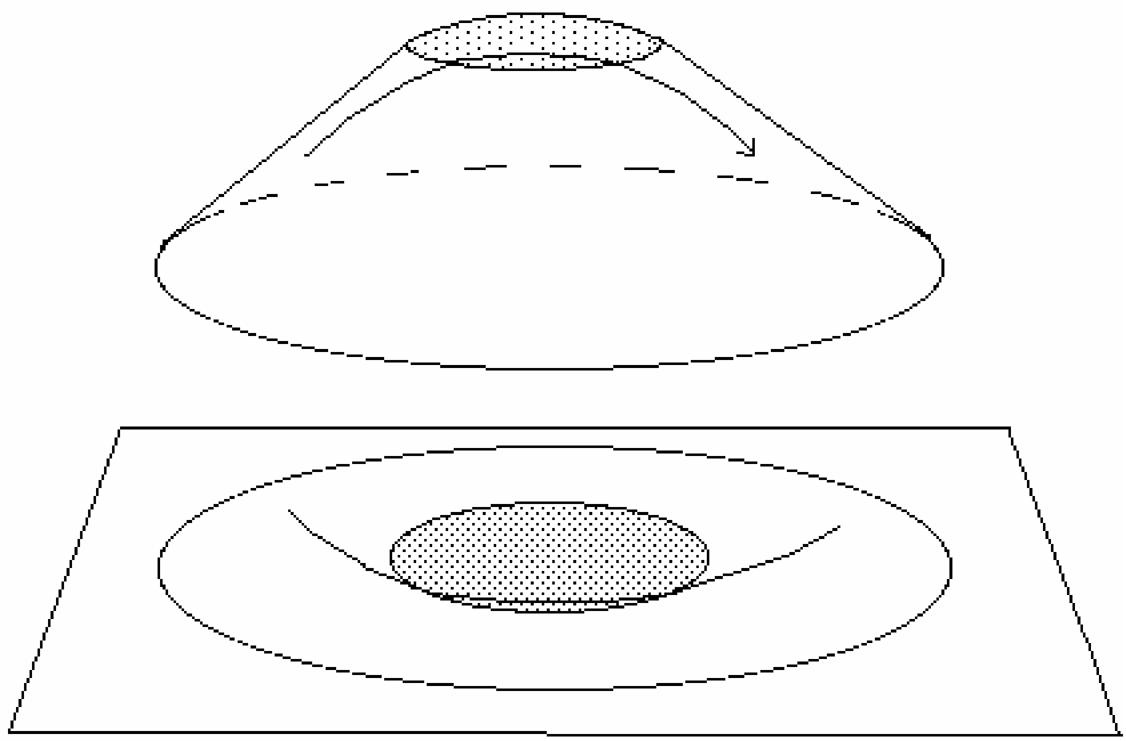
The image of the trajectory of a neutrino crossing the Sun and its Euclidean projection.

In passing: how do we arrange for the spherical cup to connect up perfectly with the cone's frustrum without horrible things, like:



In these conditions, the geodesics get a disagreeable crease:





To avoid this inconvenience and make the tangent planes connect up perfectly, one just has to make sure that the quantity of angular curvature be equal to the cutting angle used to make the cone of the frustrum. If this angle has a value of p/2 we will have to use a cap representing an eighth of a sphere. Now the tangent planes connect up well and there will be no crease in the geodesics when they penetrate the stippled surface.

In General Relativity people are confronted with similar problems. To construct the geometry corresponding to the neighborhood of a star and its interior the mathematician Schwartzschild had to construct two hypersurfaces (of four dimensions) and connect them together along the Sun's surface. The man was inspired. But he was absolutely determined to fight in the war of 1914-18 where he was lost, dying shortly after his return from the front. Einstein was able to put his work to use.

Technically, Schwarzschild represented the interior of the Sun with a tensor **T**, a constant. In the Sun the field equation was therefore:

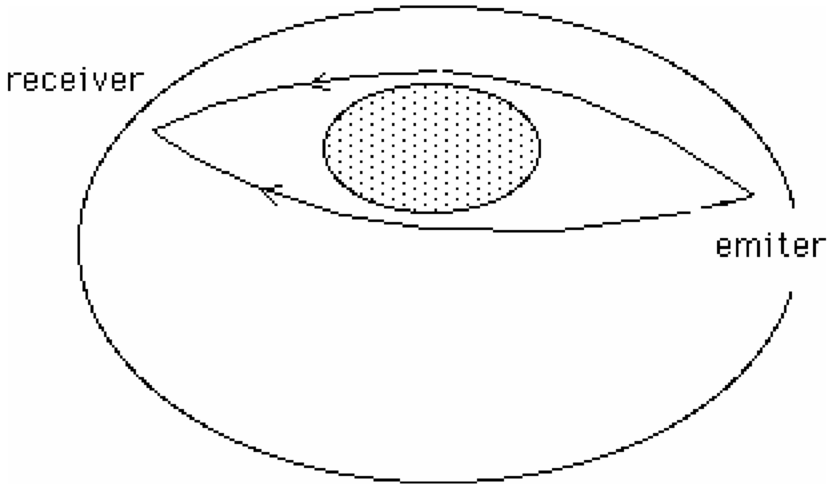
$$\mathbf{S} = 0.$$

The blunt cone model has only didactic value. In truth these cosmological geometries are four-dimensional. Even specialists have difficulty, believe me, in having a geometrical intuition about them.

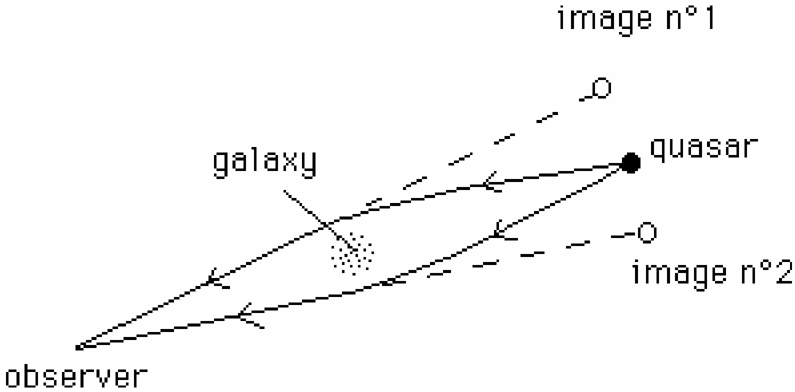
The gravitational lens effect.

The didactic blunt cone model allows us to illustrate an effect predicted by theory, but only actually observed recently.

Photons follow the geodesics of the surface. Therefore one can, with a heavenly body creating a strong enough curvature, obtain this:



One day an astronomer was intrigued. From two different parts of a galaxy he had observed two quasars with the same spectral signature. The idea came to him that this could be two different images of the same object through a "gravitational lens effect". See the following figure:

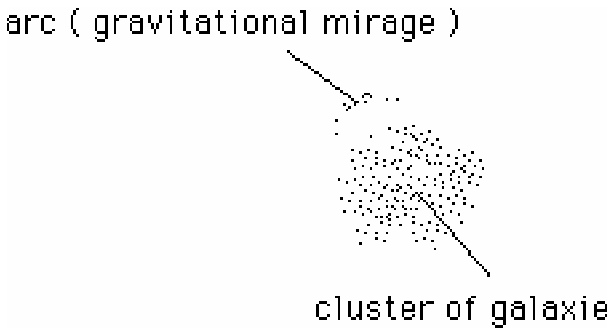


Double images of quasars.

The drawing is schematic.

Subsequently other images were found doubled in this way.

The lens could equally affect light coming from a galaxy, the deflecting object being in this case a cluster of galaxies. A galaxy is not a point-source of light, so its image is deformed in the shape of an arc.



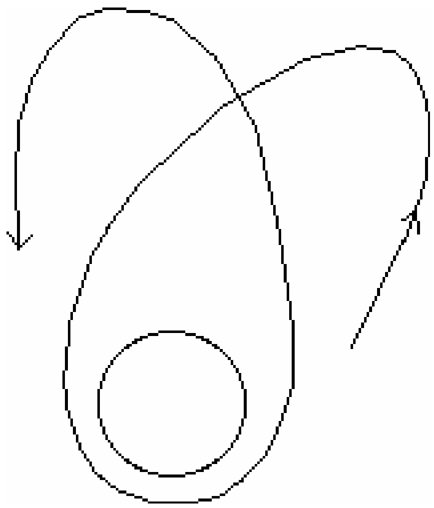
There is only one problem, which will be taken up in the third part of the book -- the mass, evaluated from the light shining from the deflecting galaxy, or deflecting cluster of galaxies, was much too weak to produce such an effect. From ten to a hundred times too weak. Decidedly, at every crossroads of the cosmos we come across the problem of missing mass.

Observational verifications of General Relativity.

The preceding example shows that mass can deflect light, even though in this particular case there was a problem. The problem disappears when we study the deviation of light rays coming from the planet Mercury by the Sun's mass. The theory is the same. But here the calculations are very well confirmed.

General Relativity has other effects in the Sun's vicinity. It creates an advance in Mercury's perihelion (and in general of all the planets, but the effect is easier to observe closest to the heavenly body). It is difficult to explain this in terms of geodesics because it is a typically quadridimensional phenomenon. We can no longer, as we have done up to now, separate time and space. All the planets of the solar system, according to Kepler's law, describe elliptical trajectories, the Sun being located at one of the ellipse's foci. Mercury's trajectory is the most eccentric. It also orbits closest to the Sun, in 88 days.

For Mercury, the perihelion advance effect is weak. If we were to consider an asteroid which had been, for example, captured by a neutron star and orbited around it, the effect would become impressive.



The precession of the (quasi-elliptical) trajectory of an asteroid orbiting around a neutron star, due to a relativistic effect.

Questionable black hole.

In a preceding section we spoke of a stellar evolution model, the supernova, in which the star, at the end of its evolution, would suddenly run out of fusion fuel after having synthesized different heavy elements, including iron, which accumulated in the star's core by simply flowing towards its center (it is the heaviest element that the star can synthesize by fusion); Destabilized, the star brutally collapses on itself. The exterior layers enter into free fall towards the nucleus à 80,000 km/s. The gas accumulates considerable kinetic energy, hits the iron core and compresses it. If the star has a mass around twenty times that of the Sun, the compression of the iron nucleus is such that :

- The nuclei of the iron atoms are split into their components : protons and neutrons.
- Free space becomes so limited that electrons can no longer exist. They therefore combine with protons according to the following reaction :

Proton$^+$ + electron$^-$ -----> Neutron plus neutrino

As we said above, neutrinos very weakly interact with matter and so the energy brought by the compression can be carried away by these same neutrinos which have no difficulty leaving the iron nucleus surrounding them and shooting off in all directions. Because of this process, the compression of the nucleus becomes inelastic compression. There is no rebound. The object that remains becomes a neutron star.

We have also said that if the initial mass of the star was inferior to a mass ten or twelve times that of the sun, there would be no formation of a neutron star but of another object called a white dwarf. Theoreticians are unable to reply to the question of what happens when the star's initial mass is at intermediate values, say between ten and twenty times that of the Sun.

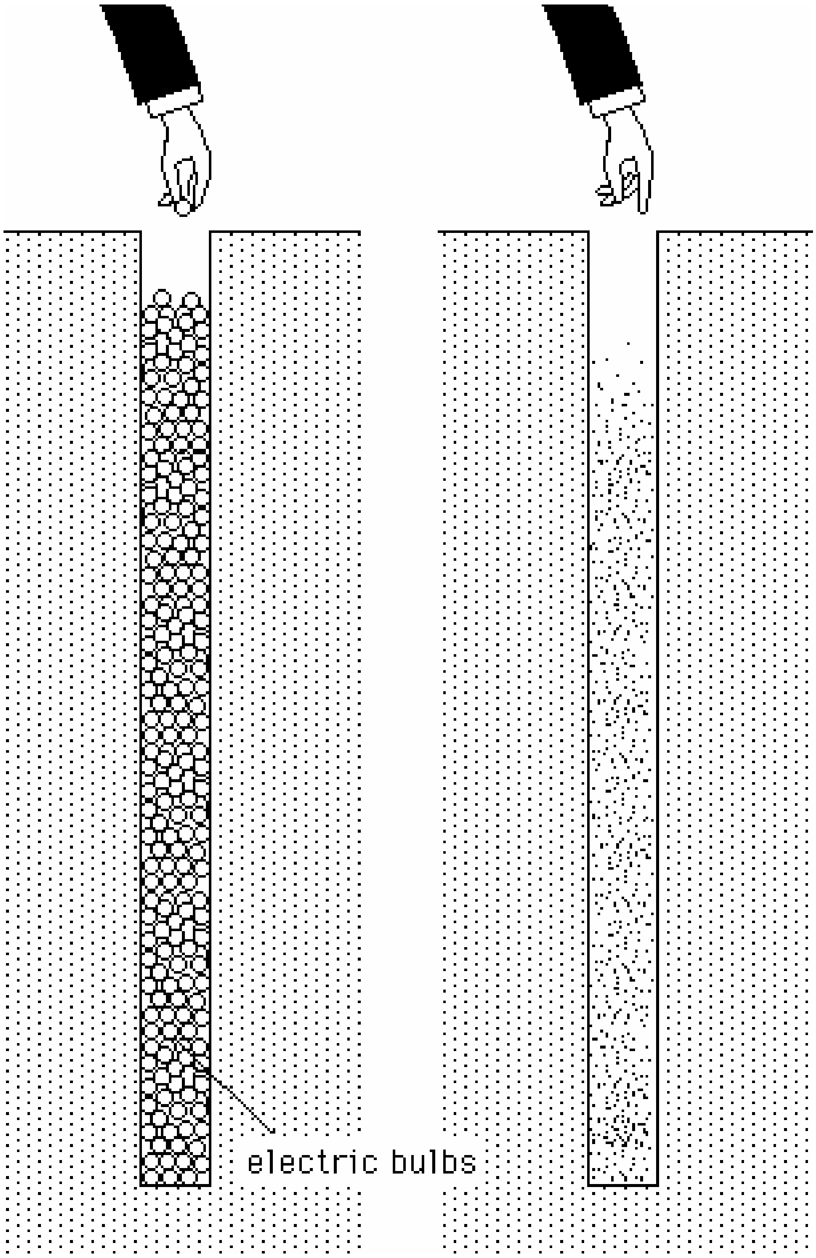
Other parameters also play a role, such as the star's initial rotational movement or the value of its magnetic field, and can have an important effect on the scenario. When the star's mass is below 10 times the mass of the Sun, the phenomenon leading to the formation of a white dwarf is not as brutal as that leading to a supernova. For intermediate initial mass values we can have intense compression of the central nucleus but which gives insufficient density to bring about the transformation of proton-electron couples into neutron plus neutrino. For if neutrinos are not created, then the star cannot evacuate its energy. So that at the end of compression the stellar nucleus will have become fusion plasma raised to a very high temperature, a mixture of protons, neutrons and electrons which would simply explode, creating heavy elements as it did so. Theoreticians do not exclude the possibility that, after an end of life paroxysm, certain stars leave no residue whatever.

We know that extremely massive stars exist, masses reaching one hundred, even two hundred times that of the Sun, whose final evolution we are about to describe.

If we concentrate on the neutron star problem, we might wonder what future such an object could have.

We have already said that there is a maximum value for a neutron star's mass, about 2.5 solar masses If this mass is greater, the pressure applied to the neutrons in contact is so strong that they are unable to resist it. In that case we have no theoretical model to describe a state of matter resulting from the interpenetration of these neutrons. The star could then be compared to a group of grapes in a wine press. After a certain pressure their skins give way and they burst. But in this case it is as if a "group of grapes" with their skins touching remained intact instead of being crushed into " a mass of grape pulp"

Another good image consists of imagining piling up electric bulbs in a mineshaft. Their glass envelopes have limited resistance and it doesn't take much to realize that we will not be able to pile up an infinite number. Sooner or later the pressure will become too great and the bulbs will break. The glass debris will then tumble in free fall.

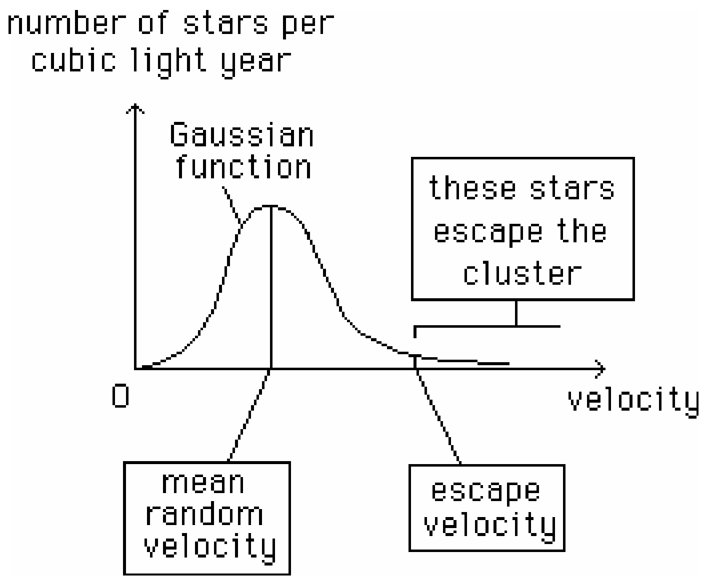


For a neutron star, it's the same. If we go beyond the pressure that neutrons are capable of withstanding, there is no longer anything to oppose a gravitational collapse. But the idea that such a large mass could cave into a space the size of the eye of a needle made physicists' hair stand on end.

The reader might wonder how such a system could be. Isn't nature clever enough to produce neutron stars with a mass lower than the critical value?

Even if it did, other phenomena can increase the mass of neutron stars.

First case : We know that approximately half the stars of a galaxy are in double or even triple systems. In the beginning swarms formed within the lumps making up the material of interstellar clouds. To give an idea, there would be several hundred stars in a typical swarm. These stars would then begin behaving like gas molecules, interacting with each other. That does not mean they collide but rather that they undergo what is called binary encounters. In these binary encounters they exchange kinetic energy. The process tends to create what is called a gaussian velocity distribution :



With very slow objects (on the left) and very fast ones (on the right), the whole being centered around a mean random velocity (which, in a gas, would be the mean thermal velocity of molecules).

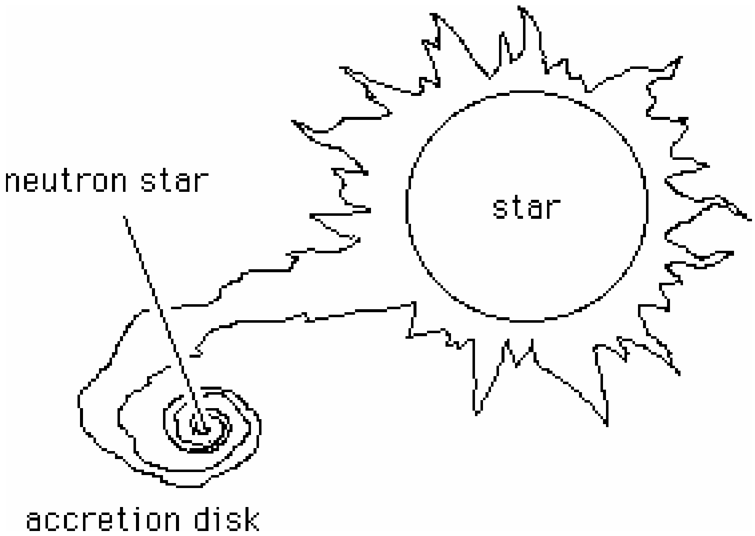
Stars which reach high velocities tend to escape the cluster, for their velocity overcomes its "escape velocity" (see appendix 2), so the clusters "evaporate". The clusters lose their stars. The fewer stars they contain, the more rapid the evaporation. The process thus has a tendency to autoaccelerate. As the escape velocity of an open cluster which loses its stars diminishes, so stars can escape more and more easily.

The lifetime of a cluster is roughly proportional to its mass. A small cluster, an open cluster, containing two hundred stars, would fall to pieces in two hundred million years, equivalent to a quarter rotation of the galaxy on itself (the Sun takes two hundred million years to make its way around our galaxy, the Milky Way). The Sun, whose age is 5 billion years (equivalent two trips round the galaxy), seems to have come from a cluster of this type, all of whose stars are now dispersed throughout the galaxy.

The dispersion phenomenon leaves just small groups of stars. We know of 3, 4 and 5 or more star systems, relics of more important clusters. However any system made up of more than two stars is unstable. Only star couples have stability. Threesomes do not. Through chance encounters in a triple system, one of the partners can acquire a speed allowing it to leave the two others.

This aside has allows us to mention the fact that neutron stars often belong to double systems. They begin as a couple in which one of the stars, the one likely to turn into a supernova, has a mass of around twenty times that of the Sun. Once it has effected its transformation, it throws out the majority of its mass so violently that it is lost into space and the nucleus is transformed into a neutron star. The other star can have any mass.

This second star, like its sister, emits stellar wind (called the solar wind in the case of our Sun). Part of this mass is picked up by the neutron star.



This progressively increases its mass therefore and can thus tend towards the critical value. The emission of matter will only be intense if the star is massive.

Second case :

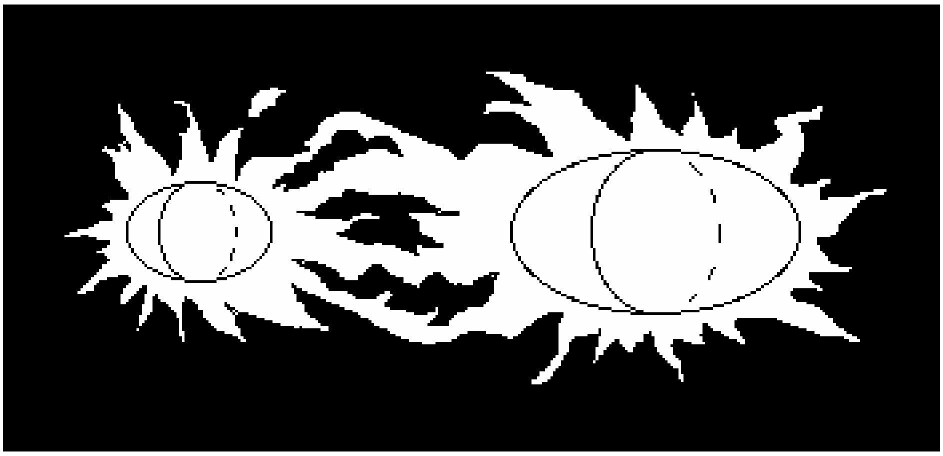
A galaxy such as ours contains about two hundred billion stars of which about half form couples. Among the couples there must be a certain number with masses susceptible to producing neutron stars. It is unlikely that two stars would become supernovae at the same time, but we can end up with a couple of neutron stars. In fact we have already found several examples.

Following their transformation, the two neutron stars would simply revolve around their common center of gravity.

We know of star couples, binary systems, with greatly varying distances between them.

The solar system's dimensions (the orbit of Neptune) are counted in light-years (the distance covered by light in one hour, one billion kilometers). Neptune orbits at 4,5 billion kilometers from the Sun. It is therefore at four and a half light years from it.

If the Sun were associated with a companion star at a few light-hours or light-days distance, it would be a doubtful association. However we do know of stars where the two halves are much closer than that. Indeed, they can be so close that they exchange matter.



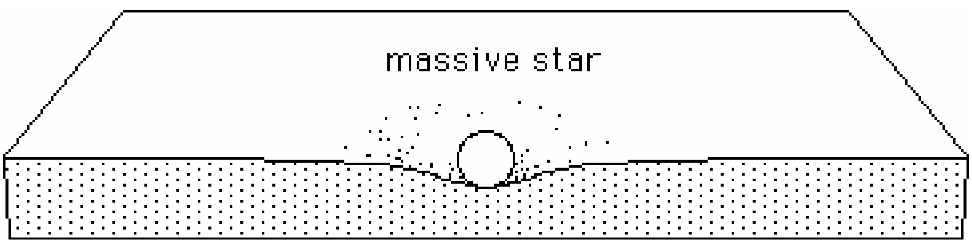
Such stars become deformed and lose their spherical shape. Two pulsars were discovered in 1974 which revolved around each other in about eight hours. Their separation distance is about a tenth of the distance between the Sun and Mercury (six million kilometers) and they have an orbital speed of about 130 kilometers per second.

The general theory of relativity predicts that two sufficiently close and massive bodies, orbiting around each other, emit gravitational waves.

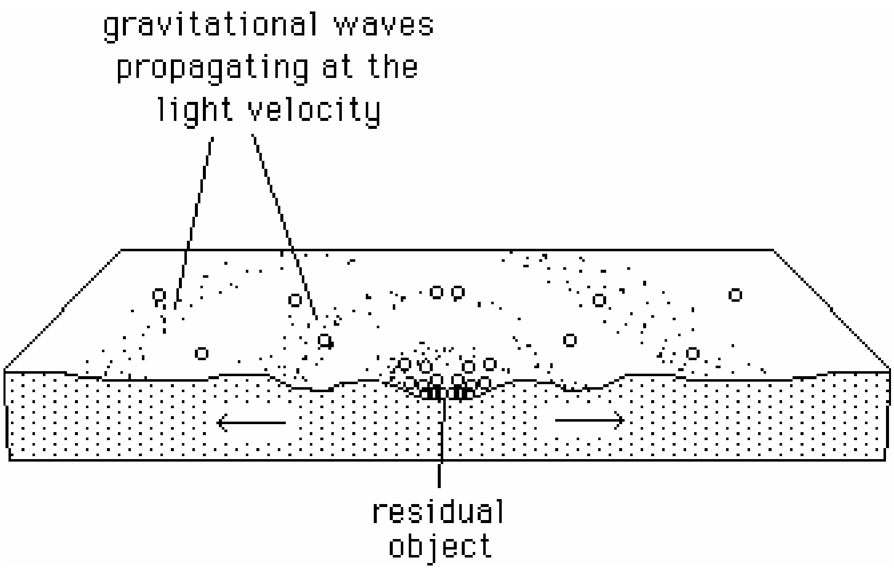
In the section above dedicated to galaxy dynamics we used a model in which masses, symbolized by buck shot, deformed the surface of a foam mattress.

Gravitational waves represent the oscillation that could be produced on the surface of such a mattress. Imagine, for example, the explosion of a massive star which transforms it into a supernova.

Initially the star would create a fairly important deformation of the mattress surface.

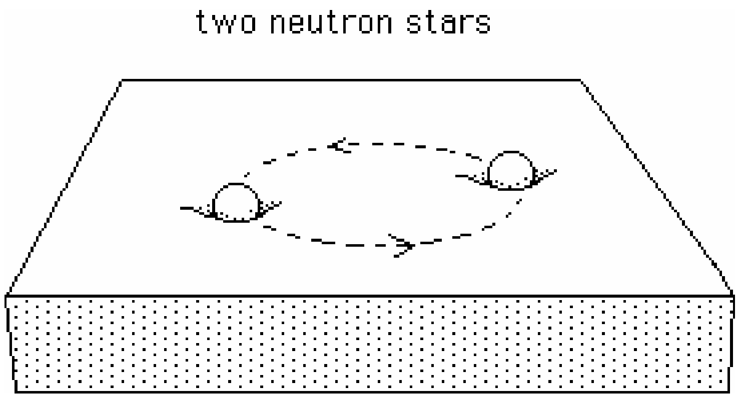


Suddenly the star explodes and disintegrates (except for the residue constituting the neutron star, which represents a tenth of its mass). The dispersion of matter will bring about an "oscillation of the support", of the space symbolized by the mattress.

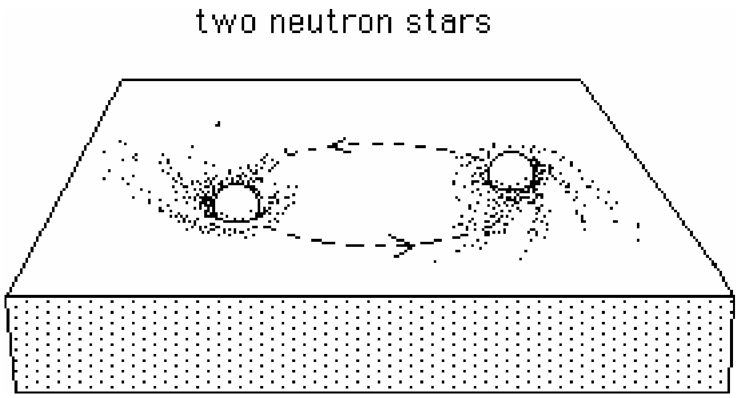


When the Sanduleak star exploded in the Magellan Cloud in 1987, it was an excellent occasion to measure an eventual emission of gravitational waves. But as we have already said, by an incredible coincidence, all the detectors on earth were undergoing revision that day.

Neutron stars rotating around their common center of gravity will also deform the mattress.



If we confer a certain elasticity on the support, we can imagine that as the masses move they create waves similar to the waves created by an object moving on the surface of water.



Some energy is dissipated. The system mentioned above (catalogued as PSR 1913/16) thus loses energy. This is translated into a shortening of its period of rotation (a millisecond every ten years). It's small, but measurable.

The phenomenon also brings the two stars closer together and we have calculated that they will merge in a few hundred million years.

Here then, is a second phenomenon which could allow the fateful critical mass to be passed : the fusion of two neutron stars.

Third case :

This is an even less well modeled situation corresponding to the final destiny of a star whose mass is well over twenty times that of the Sun (we know that stars exist, and are noted in the record books, whose mass is a hundred to two hundred times that of the Sun) .

Obviously their lifetime is short, shorter even than that of stars which become supernovae. They too burn their fusion fuel at breakneck speed. They also discover sudden breakdown followed by rapid collapse onto an iron nucleus. The question to be asked therefore is : "what is the mass of the iron nucleus created by fusion before the star begins its final evolution?"

A priori, extremely massive stars can synthesize iron nuclei whose mass is greater than critical mass : two and a half times solar mass.

When the iron core is compressed, the electrons merge with protons, through the classical schema :

$$\text{Proton}^{+} + \text{electron}^{-} \text{ -----> Neutron plus neutrino}$$

The escape of the neutrinos make the dissipation of energy possible. A neutron star forms at the center but its mass is higher than critical mass and it collapses immediately.

Other scenarii could also lead to such critical conditions. By the way, what is a typical diameter for neutron stars?

In a neutron star, close to criticity, the typical mass-density is :

$$\rho = 10^{15} \text{ g/cm}^3\text{, that is } 10^{18} \text{ k/m}^3$$

The Sun's mass is :

$$M_{\odot} = 2\ 10^{30} \text{ kilos}$$

We write :

$$\frac{4}{3} \pi R^3 \rho = M_c = 2.5 \quad M_{\odot} = 2.5 \times 2\ 10^{30} = 5\ 10^{30} \text{ kilos}$$

We then find a critical radius value R_C equal to 18 kilometers. If the radius of the star is higher, the neutron can no longer stand the pressure and the star collapses.

The neutron stars we observe have lower radii. We consider that a typical diameter for a neutron star is of the order of ten to twenty kilometers.

To bring such an object to the critical point requires successive additions of layers to its surface (such as from the slow contribution of matter from a companion star). When the critical radius is reached, the star implodes.

If the critical point is reached by the merging of two neutron stars, the phenomenon can be far more brutal.

We have indicated several scenarii which could lead to a critical situation, to a mass of neutrons so important that they are unable to go against their own gravitational force which leads to the gravitational collapse of the object.

How do theoreticians treat such a problem ?

We will reply through an imaginary dialogue which could have taken place during the 50's and 60's.

- Tell me John A., astronomers are moaning that they want a theoretical model for the implosion of a destabilized neutron star.
- With such densities it's a relativistic problem.
- I know. We can't use classical fluid mechanics tools as with normal stars.
- We'll have to use the Einstein equation :

$$S = \chi \, T$$

Left : a tensor describing the local geometry of space-time. Right, another tensor describing the local energy-matter content. At the center, the Einstein constant.

&&& Humorous drawing showing perplexed scientists.

- It's magnificent by its simplicity and elegance. Can you tell me by which end you intend to approach the problem?
- Well obviously we must build a non-steady solution to describe the free-fall process.
- Do you know of any non steady solutions to this blasted equation?
- Apart from Friedmann's, which gives us the Big Bang theory, the standard model, no. We don't have any.
- What shall we do then? Tell them we haven't anything to give them?
- Listen John A., if we tell them that well lose all credibility. A theoretician is like God, he has to know how to reply to everything.
- I see a solution.
- What ?
- For example, we've developed a group of two linked solutions to describe the geometry in the vicinity of a star.
- I know. We consider two equations. The first :

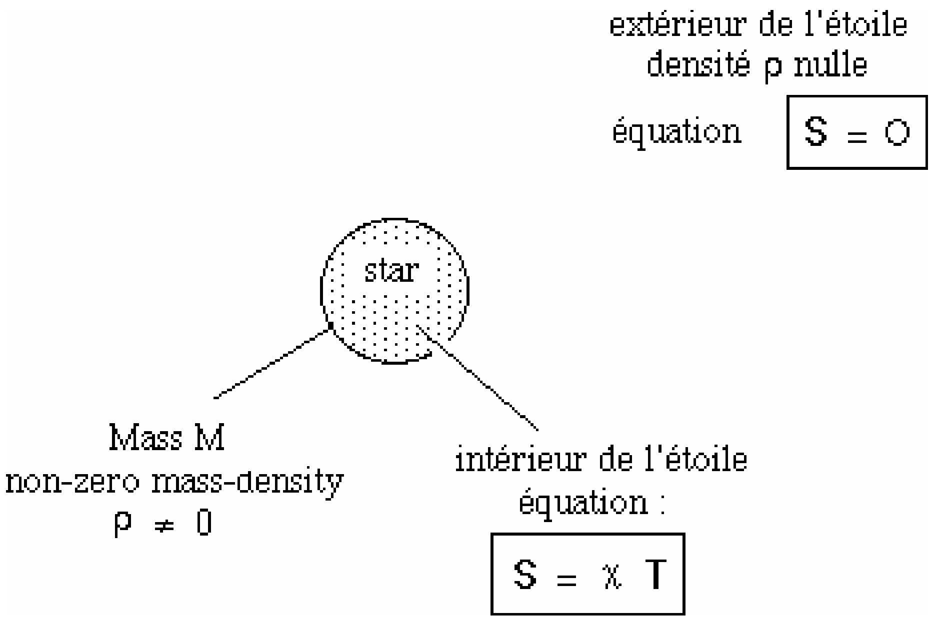
$$S = 0$$

refers to an empty space. The solution was found by Schwarzschild in 1917. Classically, it is called the external Schwarzschild solution. The second member of the equation is zero. (The energy-matter tensor is zero).

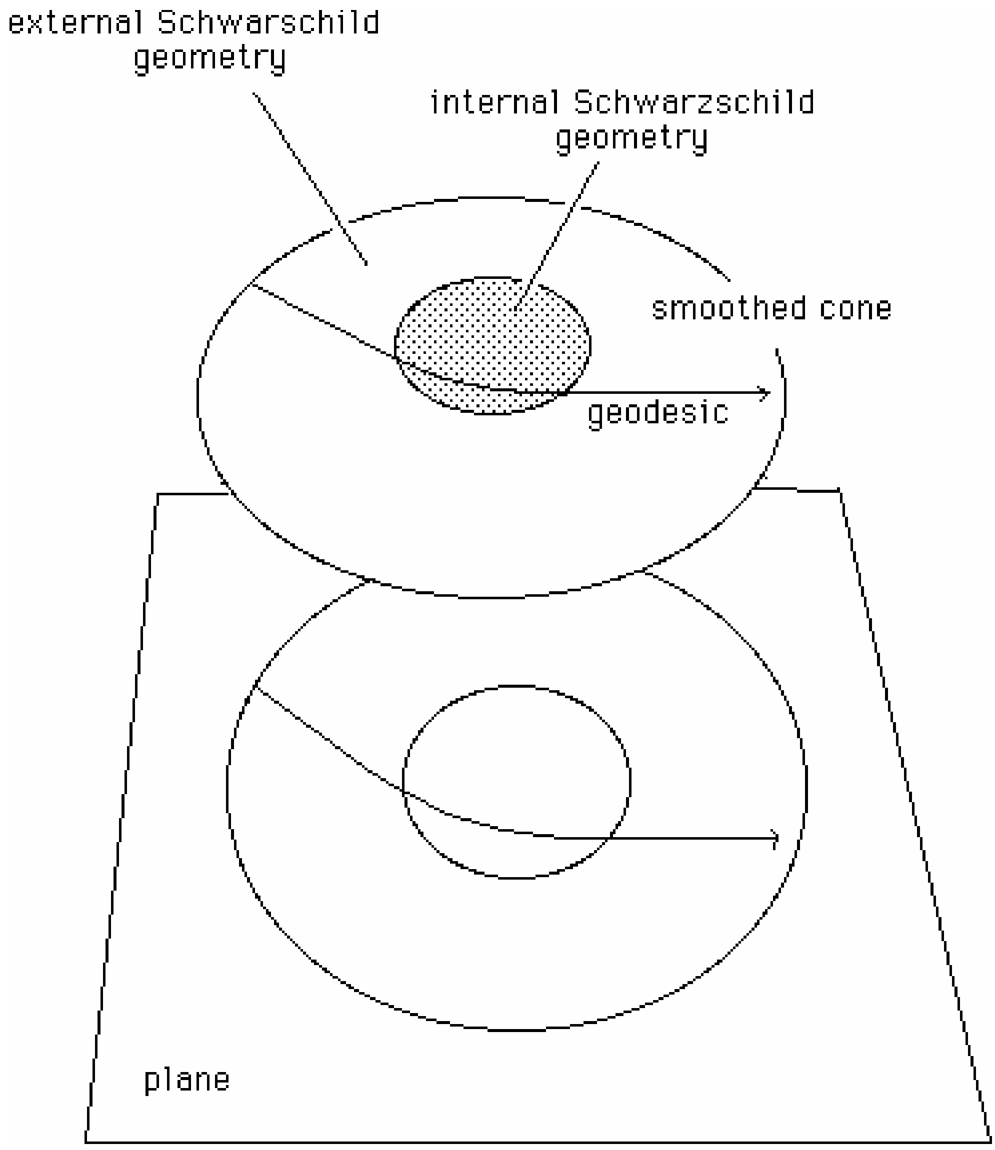
- It means it refers to void, to a portion of space where no energy or matter exist. Then, considering a non empty space, corresponding to the inside of the star, we refer to the Einstein equation with a non-zero right hand :

$$S = \chi\, T$$

- When the tensor **T** is not zero, that is to say an equation describing an unempty part of the universe. To sum up :

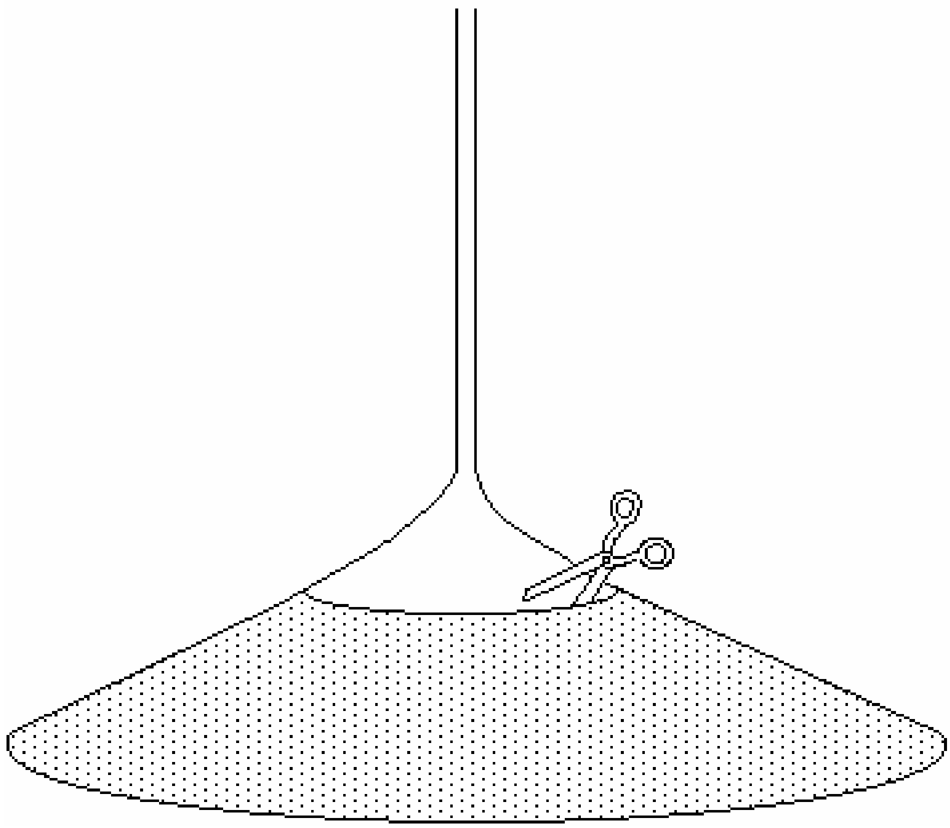


- OK, you get the didactic image of the smoothed cone, evoked above. The spherical cap suggest the interior Schwarzschild solution, the cone's trunk the exterior solution. And we make a mathematical link. But I can't see what you're getting at...

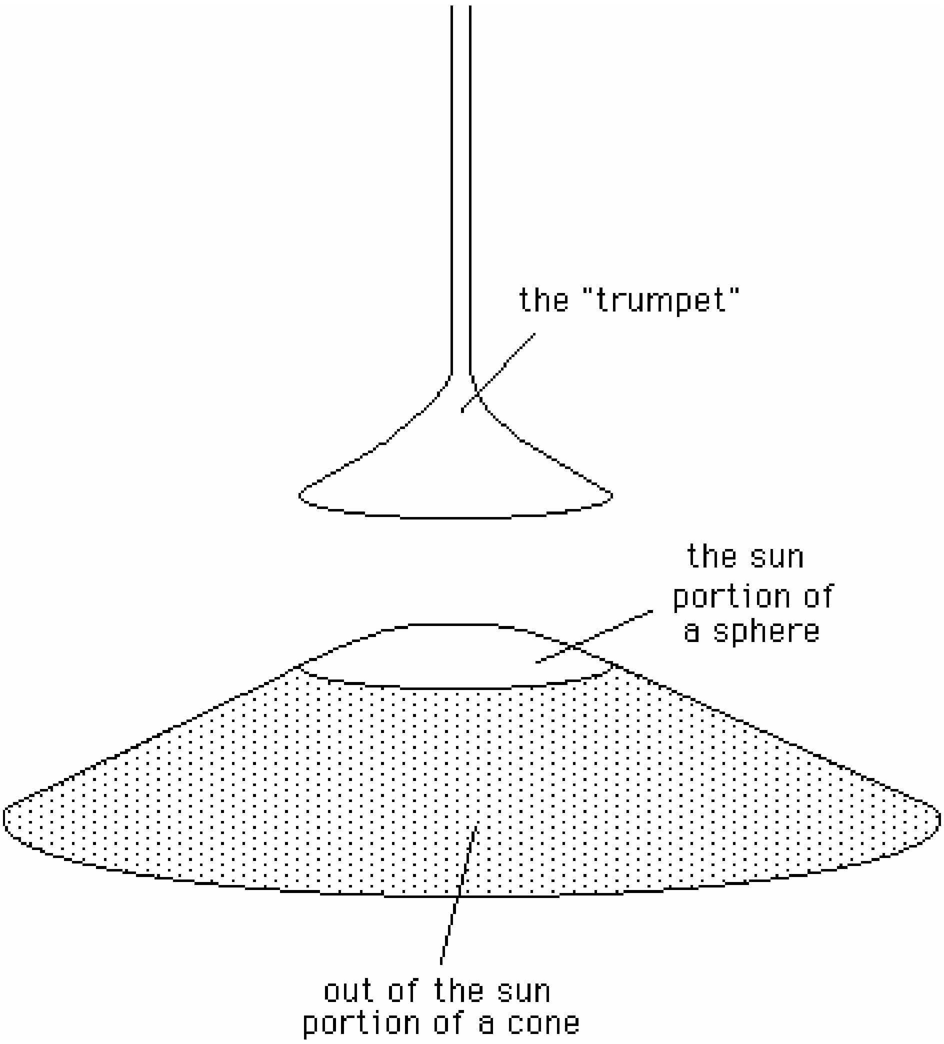


- Notice we use only a portion of the external Schwarzschild solution.
- The one that refers to the outside of the star, when the radial distance to the center of the system is larger than the radius of the star.
- Have you looked at this solution, close to the center ?
- Nonsense ! This solution is supposed to describe an empty space, but, unless I'm mistaken, there is matter inside stars!
- Don't get upset. Let's look at the geometry from a purely mathematical angle.

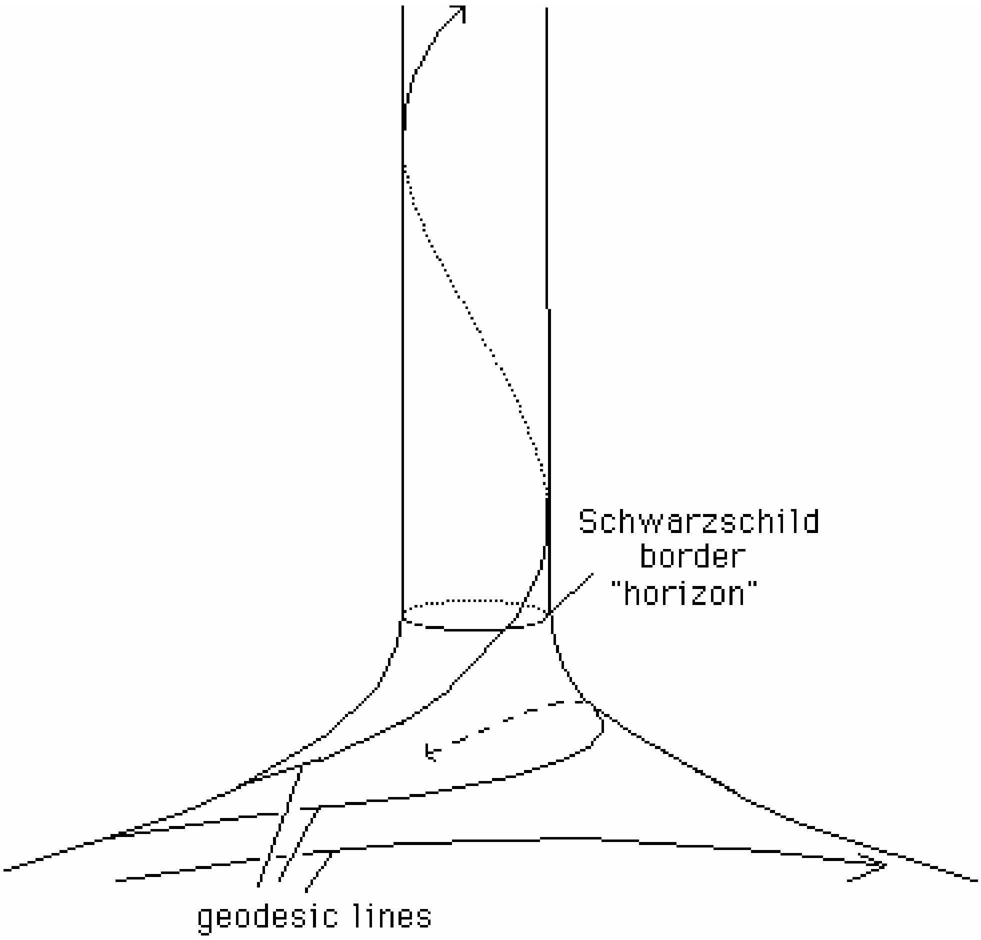
- If you like....
- When we tried to evoke this solution through a crude 2d didactic model, a surface, it looks like part of a cone linked to a trumpet.



- When we describe the geometry outside the star, we remove the central part of the surface and only keep the gray one.

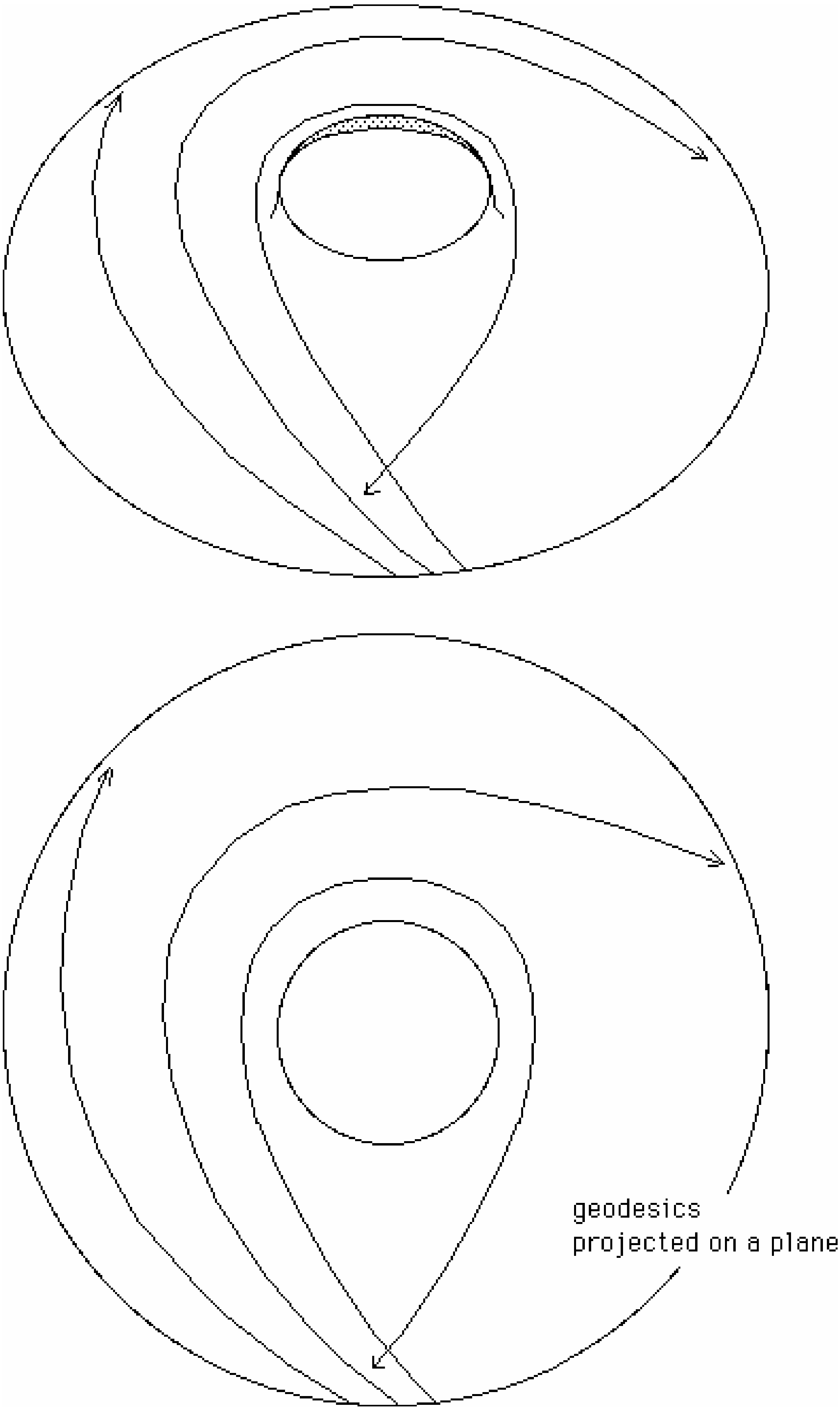


- Then we replace the "trumpet" by a spherical cap. So what ?
- Look at the geodesic curves, close to the trumpet.



- It's a mathematically interesting problem. You could make it an exam subject for your students. They are two different geodesics lines. We find a circular line which represents the link between the tube and the bell of the trumpet. The tube looks like a cylinder. On a cylinder the geodesics are spiral curves. They never return. If a geodesic line cuts the circular link, it enters the cylindrical part of the surface, becomes a spiral, which tends to the infinite, and never returns.

The other geodesics, the ones which do not cut the circular border, look like the ones from a portion of a cone. As the local curvature changes, the geodesics may cut across each other :

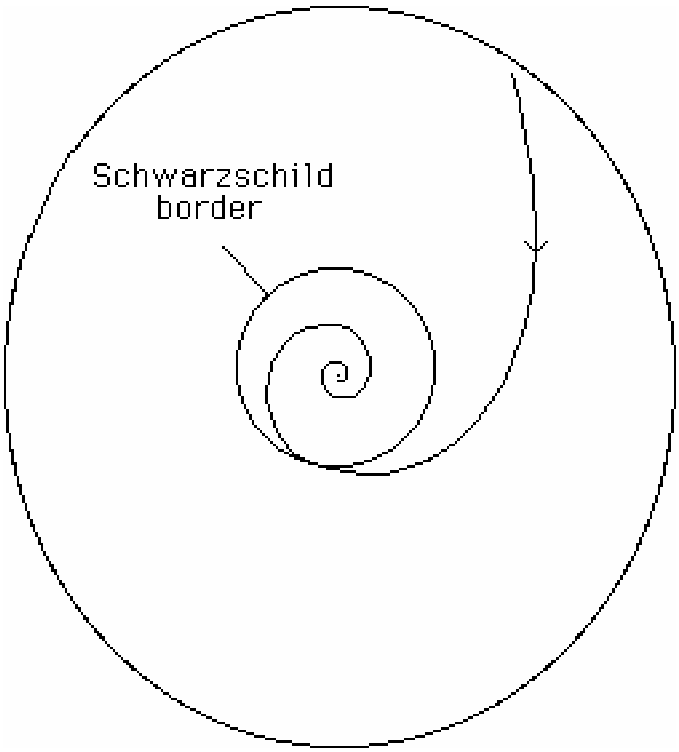

geodesics
projected on a plane

- It makes you think of a collar and someone tying a tie.

&&& Drawing of a man with a tie on his shoulders.

- Well effectively, the geometry is fairly particular. So what ?
- Wait a minute. The tube of the trumpet is not a perfect cylinder. Its cross section tends towards zero at infinity which means that if you look at the flat projections of the geodesics crossing the circle, you will see that they tend towards a central point by spiraling.

&&& Drawing of a man looking



- It's pretty, but where is it leading ?
- Imagine this geometrical solution symbolizes a collapsing neutron star.
- I can't see any neutron star. Where is it? Its the solution to an equation supposed to describe a perfectly empty region of space-time where there is

neither matter nor energy. Furthermore, it's a stationary solution. How can you expect to describe the implosion of an object with a stationary solution, it's crazy !

- Look at the above drawing. It could represent the trajectory of a particle falling towards the central region. By presenting the solution this way, both according to the drawing and mathematically, the particle reaches the center in infinite time in relation to an outside observer.

- And so ?

- And so that leads to a description, a little strange I agree, of the implosion. It really happened. It's true that in the end the two and a half solar masses will find themselves inside a pinhead, but if an exterior observer approaches the problem this way, everything would seem to take place over infinite time. The phenomenon would give a "still screen shot". So I say "I do not feel obliged to describe the result of a process which, for me the outside observer, lasts for an infinite time".

- Such acrobatics. And with their help you manage to describe an unstationary phenomenon with a basically steady solution which, on top of that, describes an empty universe !

- Listen, John A., we don't have anything else. We have to give astronomers something to chew on, otherwise they won't stop bothering us with this problem.

- But what are you going to call it? You have to give names to discoveries otherwise people don't notice them.

- As it's something built from Schwarzschild's solution we could call it a "Schwarzschild object". (historically true).

- Hmmm, not very enticing. It wouldn't be a success.

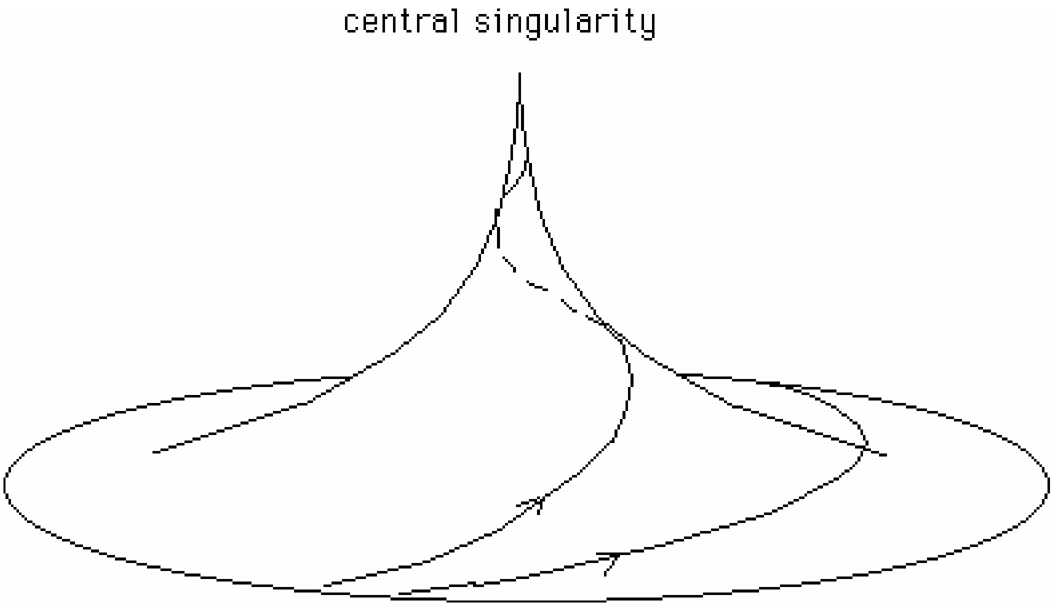
- Why not "Collapsar" ? (historically true).

- Ah, that's better already. But I've got an even better idea? If we look at the previous drawing, where we are looking from above, when an object penetrates into the circle, in the two dimensional representation, it can't get out, right ?

- And in three dimensions the circle becomes a sphere, which I've called the horizon sphere, whose radius is equal to Schwartzschild's radius (see appendix 3). Anything that penetrates into the interior of the sphere can never get out. It's a one-way membrane.

- Hang on,. I've got an idea. We'll call it a black hole.
- Nice name. Even the general public might like that one, who knows.
- Yes, but aren't you worried that someone might discover the trick one day, that it's a stationary solution to the Einstein equation with a second member zero which is supposed to describe a region of the universe where there is neither matter nor energy?
- No chance ! These calculations are frighteningly complicated. No one is going to stick their nose in. Except specialists, our colleagues. And even then, how many are smart enough to see through it? I reckon an object like this will go round the Earth a thousand times. Remember Bikini.
- The name of the atoll where they exploded the atom bomb you mean. It gave its name to some sort of bathing costume didn't it?
- I've no idea, but intuitively I feel that this black hole is destined to have a brilliant career. We can imagine big ones, small ones, giants and tiny ones.
- Yes, but what could it be used for, apart from explaining what happens to neutron stars when their mass becomes greater than critical mass?
- Even in that situation, a black hole is an attractive object, because it curves the geodesic trajectories of particles passing nearby. It gives its own contribution to the gravitational field. It is invisible mass because even the photons unable to get out. And as you know, we've got loads of trouble all over the place. We haven't found enough mass in the galaxies or galaxy clusters. Since the days when Fritz Zwicky pinpointed this problem, we have never understood why the whole thing doesn't just blow up. But all we need to do is fill the galaxies with black holes. We could even put giant black holes at the center of galaxies.
- So, to sum up, black holes could constitute dark matter ?
- Great idea isn't it ?
- Yes, but what bothers me is the mass. Where is it? How are we going to get mass out of a solution which describes an empty universe?
- We just need to put in a central singularity.
- What sort of mathematical look would you give it?
- None. I wouldn't describe it. I'll just say that there's a central singularity, and no one will look any closer.

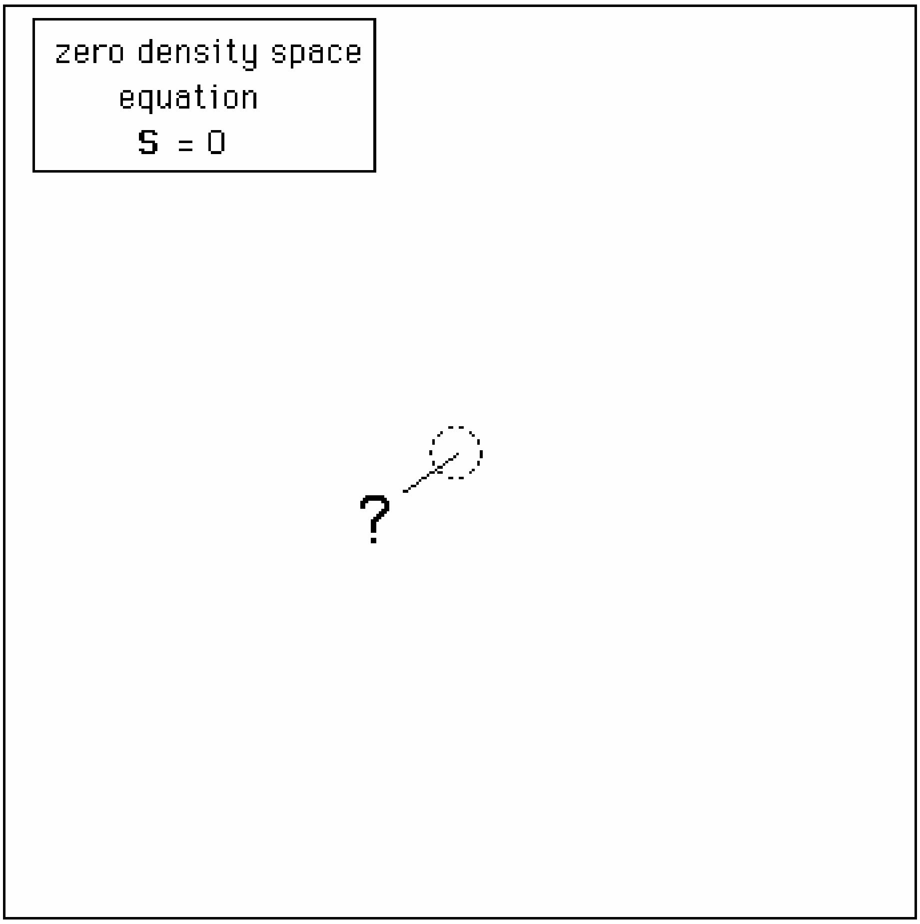
- In any case, if anyone goes into a black hole they can never get out. There is a geometrical way of describing the idea a crude two-dimensional model:



- You can easily see that there are some trajectories which converge towards the singularity and others that don not.
- If I'm following you correctly, that means concentrating all mass at the center.
- In a manner of speaking, yes. It's like with a cone. Outside its singular point, its summit, it's a Euclidean surface, a "plane" (see Geometrical Physics A). The local curvature is zero. The cone's summit is a concentrated curvature point. If we identify curvature and mass, the summit of a cone is similar to a point-like mass.
- in short, your pushing the problem to the center of your object. You say that the geometry obeys the equation :

$$S = 0$$

everywhere, except at the center.

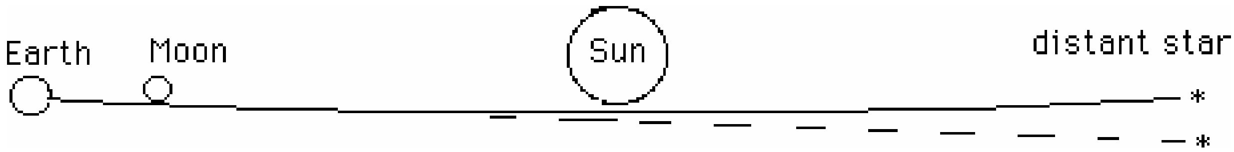


A digression for the science fan.

Through this imaginary conversation between John Archibald and his friend and with the help of a fewc images, we have tried to explain to the reader the problems linked to the black hole theory. But there are far more serious problems than that. In the section entitled Geometrical Physics, an initiation into the application of geometry to physics, we discuss the *metric concept.* Those whose knowledge of mathematics is sufficient might like to refer to this section. The metric is a mathematical concept which concentrates in itself all the elements of the solution to a field equation, such as the Einstein equation. The equation can thus be applied to a universe containing matter locally or to an empty universe?

To build the black hole model theoreticians used the old steady solution of the field equation, devised in 1917 by Schwarzschild, and called "the external Schwarzschild metric", which refers to an empty space, and is

From the metric we can build the geodesic system. All particles follow geodesic lines, including photons. The external Schwarzschild metric gives geodesics corresponding to the trajectories of planets, comets and photons around the Sun, where space is supposed to be extremely rarefied. This allowed the calculation of the precession of Mercury's perihelion or the deviation of light rays from distant stars when they travel close to the sun. Observation of this is only possible during eclipses of the Sun.



An observer is not completely dazzled by the sun during a total eclipse as he is normally. It gives him the chance to observe that presence of the Sun's mass brings about a "slight" bending of a ray of light arriving from a distant star. In relation to the background sky, it will not be in its usual place.

When we consider this metric "close to the center", to "the origin of coordinates", we find a characteristic surface called the Schwarzschild sphere. Inside, the metric becomes pathologic. The radius of this sphere is called the Schwarzschild radius. It depends only on the involved mass M. This characteristic radius is calculated in appendix 3 :

$$R_s = \frac{2GM}{c^2}$$

G is the constant of gravity ($6.67\ 10^{-11}$ MKSA) and c the velocity of light (300,000 km/s). The characteristic Schwarzschild radius, for the Sun, whose mass is 10^{30} kilos, is 2.7 kilometers.

As the radius of the sun is much larger than this characteristic Schwarzschild radius, there is no problem. Inside the sun the geometry is described by another metric, called the "Internal Schwarzschild metric".

When trying to construct a model of a black hole, astrophysicians tried to give the object a physical significance at whatever the cost. Because of this we were obliged to accept mathematical aberrations.

In the section Geometrical Physics A of the website, the metric, as a mathematical object, is briefly evoked. One of its characteristics is what is called its "signature". It is a set of signs. The number of signs depends on the dimension of space. We are supposed to live in four dimensional space-time (x , y , z , t). In this case the signature of our space-time metric would be a set of four signs (+ - - -). This contains all the features of Special Relativity. We know that in such a world the speed v is necessarily lower than a characteristic speed : the speed of light c.

When we get inside the Schwarzschild sphere, in Schwarzschild geometry (Schwarzschild metric) the signature becomes : (- + - -). It means that the speed of the particle speed

$$v = \frac{dr}{dt}$$

where r is radial distance and t time, becomes greater than the speed of light. Inside this strange surface, called the "horizon", the particles become "tachyons".

The relativistic energy of a particle is :

$$E = \frac{m\,c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

if v is superior to c, the quantity below the radical becomes negative. The square root becomes a pure imaginary number. If we want the energy to remain positive, the mass must be a pure imaginary quantity.

No problem, said John Archibald Wheeler, a famous scientist. Let's decide that inside the horizon, r becomes time and t the radial distance. That will solve the problem.

In 1963 the Schwarzschild solution was used as he basis for a new solution by Kerr.

However this solution still referred to empty space. As the new solution was no longer axisymmetrical, Kerr suggested it described a "rotating black hole". It is a little bit more complicated than its predecessors, but the pathologies mentioned above are still there. However nobody cares.

It is astonishing to hear or read specialists who come out with phrases like:

- While we do not yet have formal proof of their existence, today no scientist doubts the existence of black holes.

How to detect black holes?

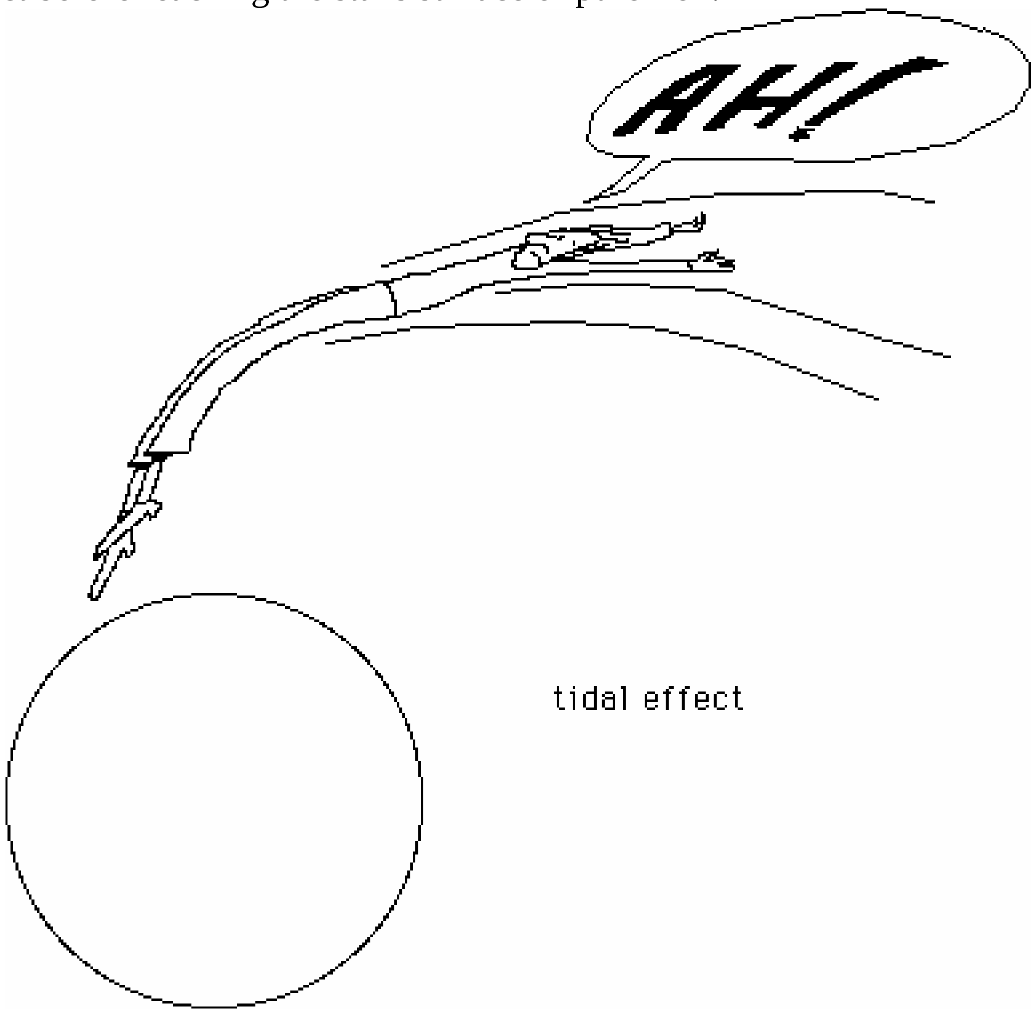
If they do exist, lonely black holes must be very silent objects. After having swallowed everything lying around, such as interstellar gas, they are happy to sit there like idiots with their mouths wide open.

A black hole that eats would be a black hole associated with a sufficiently nearby and emissive star part of whose emitted solar wind it could absorb.

What do we mean by that?

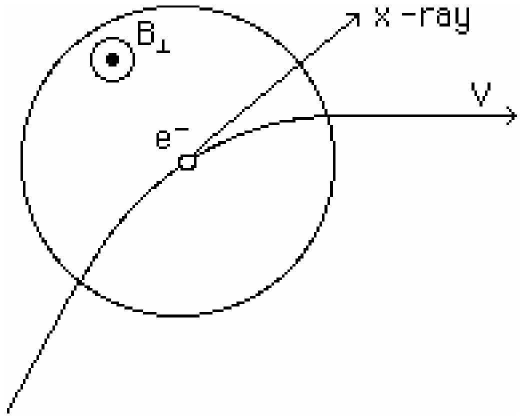
The orbital velocity of a mass, circling around a spherical body, depends on the distance to its center of gravity. A space station orbiting around the Earth at an altitude of 500 km will turn at 7.5 km/s. Imagine that the station is not like those we design nowadays but an enormous city, one kilometer across. The lower and upper parts of the space city will tend to orbit at different speeds, one meter-second apart. The resulting shear constraint effect must be taken into account. Because objects flow freely in space, we tend to think that we can build immense structures without worrying about the stress resistance of the material we use (except those corresponding to a rather brutal arrival of a space shuttle for instance). We find that when we design very large structures, enormous orbiting radio-telescopes for example, we must take this stress into account in order to avoid the risk of deformation.

The denser the object, the more marked the effect. Close to a neutron star the circular orbital velocity is ... 150.000 km/s. When falling in a spiral towards such an object, a space station would be dislocated by the tidal effect before reaching the star's surface of pure iron.



So if black holes do exist, it is not molecules or atoms that they swallow, but fragments of atoms, nuclei and free electrons.

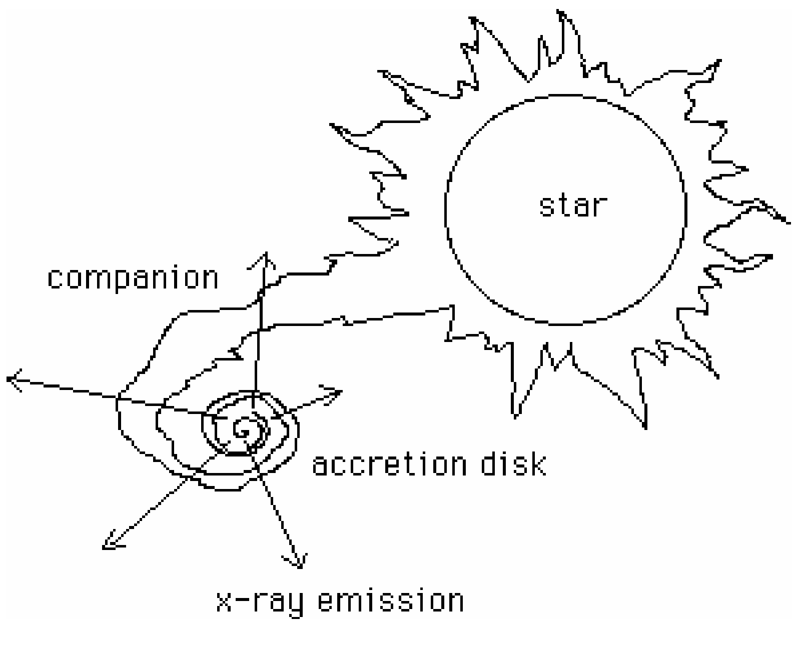
When an electron crosses a region subject to amagnetic field its trajectory is deviated by the field.



An electron penetrates a magnetic field at a speed V perpendicular to the plane of the sheet and pointing towards the reader. It turns and emits X-rays tangentially.

The deviation is accompanied by a tangential emission of X-rays. This is called synchrotron radiation.

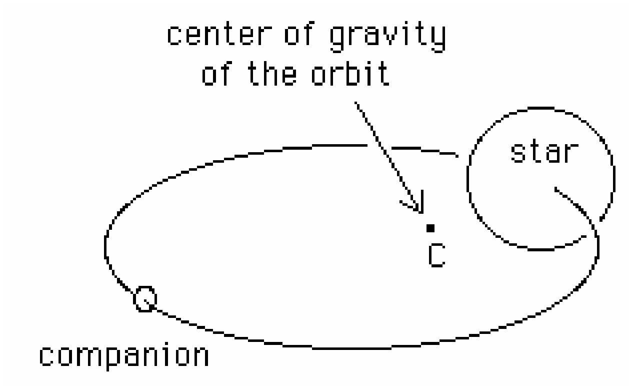
When a "black hole" or a neutron star swallow up matter emitted by companion stars, the matter will circulate in an accretion disk. The movement will be accompanied by a strong emission of X-rays.



However the phenomenon will be the same for a black hole or a neutron star. How then do we differentiate the emission of X-rays from a neutron star from that of a black hole ?

By analyzing the perturbation of the star's trajectory caused by its invisible companion.

Two heavenly bodies orbiting around their common center of gravity.



In analyzing the speed of the two bodies, and knowing the weight of one of them, we can "weigh" the other. See Appendix 6.

Cygnus XI is a double system, containing a visible star whose mass is twenty times the sun's. Its invisible companion emits X-rays. The two heavenly bodies turn around their common center of gravity in 5.6 days. But the star's orbital speed reveals that its partner's mass is greater than the critical mass a simple neutron star could support. It could therefore be a black hole.

Half a dozen objects of this type are now known.

Third Part

Nothing new under the sun?

The first two parts of the book surveyed contemporary knowledge in astrophysics and cosmology. Not exhaustively, of course, to do so would have required hundreds of supplementary pages, with new explanatory models and dozens of drawings.

We contented ourselves with a rapid guided visit, highlighting just this or that aspect. In the section consecrated to General Relativity, the reader was able to appreciate geometry's seductiveness and was perhaps surprised that he could to peek into such sophisticated areas. In the Appendices he will be able to see that a few lines of calculus can get over certain problems, at the price, of course, of some schematization. A model remains a metaphor, which carries meaning, but presents either only a part of reality, or a somewhat distorted view of it. But all in all, perhaps it is better to have a slightly distorted view than no view at all.

In a sense, it is as if we had stuck the wrong glasses on the reader and then taken him off on a visit to the supermarket of science.

In this third part we will travel to the farthest reaches, where science is being made.

The dark matter concept.

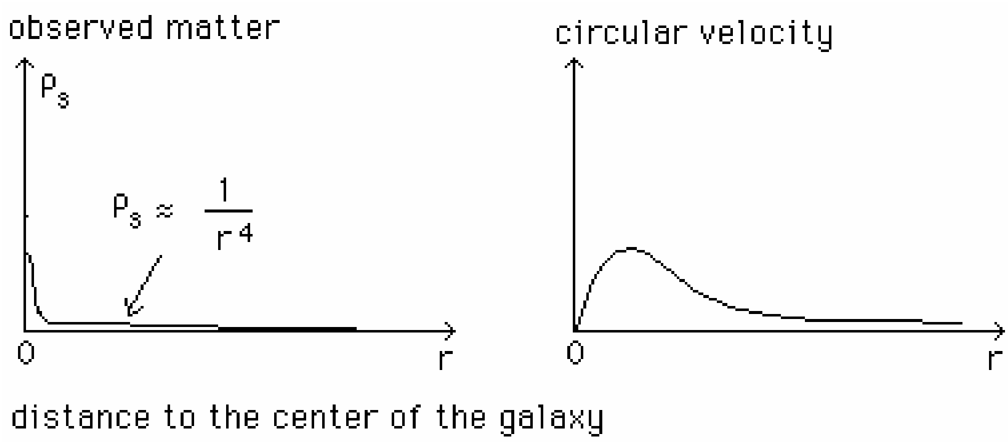
The first part contained a chapter entitled "nothing but light". Until now astronomers have based their knowledge on information sent out by objects themselves, those which radiated. We have seen how the analysis of their message has allowed fantastic progress to be made in astrophysics, enabling it to penetrate even to the heart of stars. More than a half-century ago these same luminous messages allowed us to verify the exactitude of the vision of General Relativity through an analysis of the trajectories of Mercury's light.

Today things are changing. In the last chapter of the second part we gave an example of the model of the still hypothetical black hole. This is the cosmos' first "dark object".

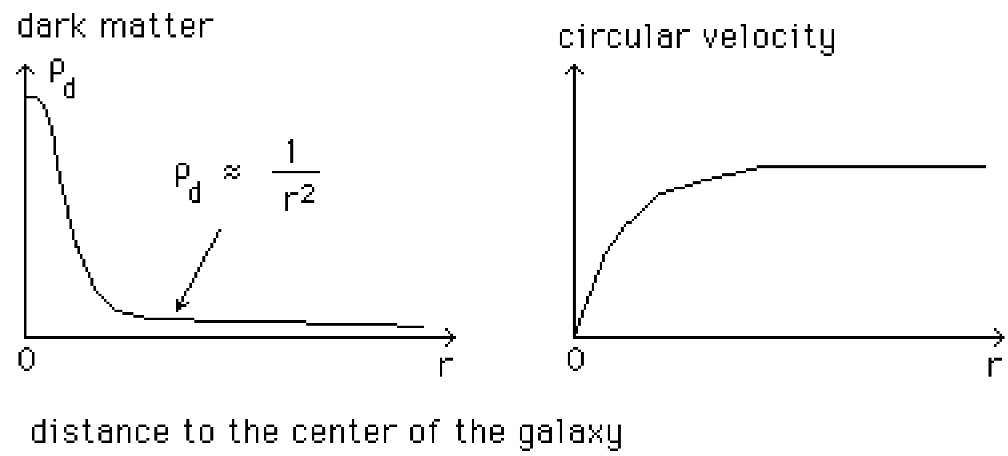
As regards the solar system's dynamics, we had the impression of seeing everything. Stars, planets, the very rarefied interplanetary medium. As regards galaxies and clusters of galaxies, or the structure of the cosmos on a very large scale however, one fact could not be ignored. An ingredient was lacking, or a new concept, something.

The dynamics of our own galaxy cannot be explained with its observed mass. Quantitatively, it is too small for its gravitational attraction to be able to counterbalance centrifugal force. Something else is ensuring the cohesion of our galaxy, and others, something unseen and so far unobserved, whose effect is equivalent to five to ten times the matter of all the stars put together.

The density of stellar matter, based on photometry, varies as the inverse of the fourth power of the distance to the center of the galaxy. However, to account for the profile of the rotational curves of interstellar gas orbiting in circles, we need a halo of matter whose density decreases much more slowly, according to the inverse of the radius' square. Most people think that a massive halo obeying this law could exist, made up of something as yet undiscovered.



On the left, the observed density of matter and on the right, the profile of the corresponding curve of circular orbit.



On the left, the profile of the distribution of hypothetical dark matter and on the right, the corresponding curve of circular orbit (closer to observational data)

If we want to convince ourselves that a halo of dark matter exists in the galaxy, we have to show it.

What would it be made of?

There are several possibilities.

First : The hypothesis of a halo made up of hydrogen atoms at a very low temperature - 2.7^{o} K, the temperature of the "cosmic oven", which would be practically impossible to detect.

Second hypothesis -- conventional objects, stars whose mass is too small to be detected exist in the galaxy. We have no rigid model for the birth of galaxies. It is quite possible, although it needs to be justified theoretically, that they were formed from a considerable number of mini-stars. We have models of stars of all masses. Jupiter can be considered a "failed star", one which has not concentrated enough hydrogen to start nuclear reaction in its center, having insufficient temperature and density (the minimum temperature for ignition is 700,000°). Between Jupiter and the Sun ther is a whole gamut of imaginable types of heavenly body. If the mass is less than a tenth of that of the Sun the star does not ignite. It is merely a type of large Jupiter (whose mass is a thousandth of the Sun's). Between this limit and the Sun there is room for a whole variety of stars whose radiation is too low to be directly detected by telescope -- brown dwarfs, red dwarfs. Such hypothetical objects are called MACHOs (Massive Astrophysical Compact Objects).

How do we find evidence for their existence? First idea -- occultation. Stars are minute objects on the galactic scale, as we have said. MACHOs are even smaller.

Stars never meet each other, but two stars can appear on the same line of sight, the dark one partially occulting the other's light in the background. To collecting evidence of such phenomena we must follow a considerable number of stars over a long period of time, the enterprise being managed by computer. Some years ago astronomers thought they found evidence for some occultation. The results remain uncertain and it will doubtless take a dozen years or so before we can have any certainty, so don't hold your breath.

The second method is what is called the phenomenon of micro-lensing. An object passing before a star curves its light rays slightly. It behaves then as a weak converging lens and slightly increases the star's luminosity, its apparent magnitude. A computer is again needed to follow a great number of stars for a long time.

We saw above that gravitational lens effects, due to galaxies or clusters of galaxies, do not correspond to the figures for their visible mass. One to two orders of magnitude are lacking. Once more an invisible component must be responsible for the observed effect.

On the galactic scale, this could be MACHOs. On the scale of galaxy clusters, however, other hypotheses are possible. Inter-galactic space is poorly understood. If galaxies heated their gas powerfully at their moment of birth, they might have given atoms a speed exceeding the galactic escape velocity so that they no longer fell back. The atoms would go so fast because the medium's temperature is enormous. Many think that galaxies bathe in a hydrogen gas of millions of degrees and that this could constitute an enormous quantity of invisible mass. These atoms would have to collide with each other to reveal their presence. Now intergalactic space can contain immense quantities of matter but ultra-rarefied to the point where collisions between atoms become practically non-existent. So this ultra-hot gas would not radiate. Evidence for it could only be indirect, based on its power to absorb light emanating from the background.

Most people think that dark matter, under whatever form, would also be responsible for the very large-scale structure of the universe -- stringy, forming "plates". Three-dimensional computer simulations, using phenomenal calculating power, determine the quantity required.

The problem of the spiral structure of galaxies.

This is the complement of the general problem of galactic dynamics, which, as we saw above, is still currently in a limbo and lacking an ad hoc theoretical model. To date, all attempts at theoretical modeling of the spiral structure by purely analytic methods have failed. In this field we have only computer simulations whose technique is difficult and which are dependent on a continuing increase in the calculating power of machines. Fortunately they are already extremely rapid. But no one yet knows how to manage a true galaxy, with its hundreds or thousands of billions of point-masses.

Nevertheless, fundamentally, the problem is extremely simple. We introduce initial conditions, that is to say n point-masses, stipulating their coordinates and initial velocities, then we begin the calculation, which proceeds step by step. The distribution of matter allows us to calculate at every point the direction and intensity of gravitational force, created by the attractive power all of the other points. For a certain time we have these point-masses move in this "frozen" field. Then we recalculate it. From the point of view of maximum precision it would be necessary to calculate the action exercised at each step on each object by all the others, that is to say to make n^2 elementary calculations. If we are managing a hundred billion point-masses, that would represent ten thousand billion calculations at each step. Unthinkable.

So we reduce the number of points and use tricks to reduce the number of calculations. We also use computers specially designed for this type of work and into which Newton's laws have been "hard-wired", that is to say integrated into the processor's elementary functioning.

Progress remains slow. For a long time the number of points to be managed and the slowness of calculations limited simulation to two dimensions. We handled "flat galaxies", whose movements were confined to a plane, evidently not realistic. To contemplate calculating a swarm of point-masses moving in three dimensions meant reducing the number of points drastically. Scylla or Charybdis.

Eventually, with the continuing improvement of machines, the first "full 3d" results began to appear.

Where do the so elegant spiral structures come from? They relate essentially to the disk's gas. The contrast in density between arm and inter-arm is roughly one to five. This means that it is a fundamentally non-linear problem. Of course, it is gravitational instability that leads the gas to assemble itself in the form of bars, spiral scarves, or rings. Along the arms the gas fragments form vast clusters, whose span corresponds to the famous Jeans distance (see Appendix 1).

Pure gravitational instability is not the only thing at work. At first, logically, people tried to introduce the spiral structure into the calculation's initial conditions. That didn't last however. An external cause for the phenomenon was required, a tidal effect.

A tide is a resonance phenomenon. The moon influences the Earth as it revolves around it (employing here an image with a fixed Earth.) Ocean basins play the role of resonators. Some are "in tune", others are not. The Mediterranean Sea has its own frequency of oscillation which does not correspond to that of the Moon's passage. Therefore it does not resonate and tidal phenomena are practically non-existent there (and, in any case, masked by the "barometric tides", variations in sea level due to variations in air pressure). Other liquid masses however do react -- the Atlantic Ocean and the North Sea for instance.

Interstellar gas behaves like a sort of gas ocean, ready to react to a solicitation, a gravitational perturbation.

The New Zealander Allard Toomre undertook the first studies in this area. Certain galaxies, like the celebrated formation of the Hunting Dogs, M 51, possess companions.

The galaxy of the "Hunting Dogs", M 51.

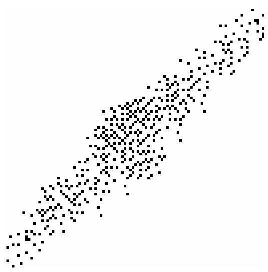
Measurements of velocity showed that the companion, a spherical mini-galaxy, was "passing by" it. An encounter was taking place between two galaxies which Toomre undertook to try and simulate numerically. And then, a miracle, the fat galaxy reacted as expected. Like an octopus it threw out an arm, as if it wanted to capture the object. The New-Zealander interpreted this not as an attempt at capture (the perturbing mini-galaxy, whether in the numerical simulations or in the real case of M 51, ended up moving away), but as a resonance phenomenon, a "tidal effect".

So we have a first explanation of the origin of galaxies' spiral structure -- a transitory tidal effect due to the action of a perturbing object. For the last twenty years several teams, in different countries, have been working intensively on this theme of interaction between two galaxies. In this perspective, however, the phenomenon would be purely "transient".

Moreover not all galaxies have companions, at least not visible ones. Some people suggest that the spiral structure could be linked to an abundance of invisible objects, such as hypothetical giant black holes. Again we stumble on the concept of dark matter as a hypothetical constituent of the invisible mass of galaxy clusters.

Let us leave aside this potential source for a spiral structure, the passage of a perturbing mini-galaxy or hypothetical giant black hole, and return to the results of simulations for an isolated galaxy.

When they introduced spiral structure as a given a priori initial condition, the result of observation, astrophysicists quickly saw it fall apart. The therefore tried the reverse procedure -- make such a structure appear from an object endowed with symmetry of revolution. If the parameters are adjusted conveniently, internal resonance mechanisms can show themselves. In particular, a barred structure appears relatively easily.



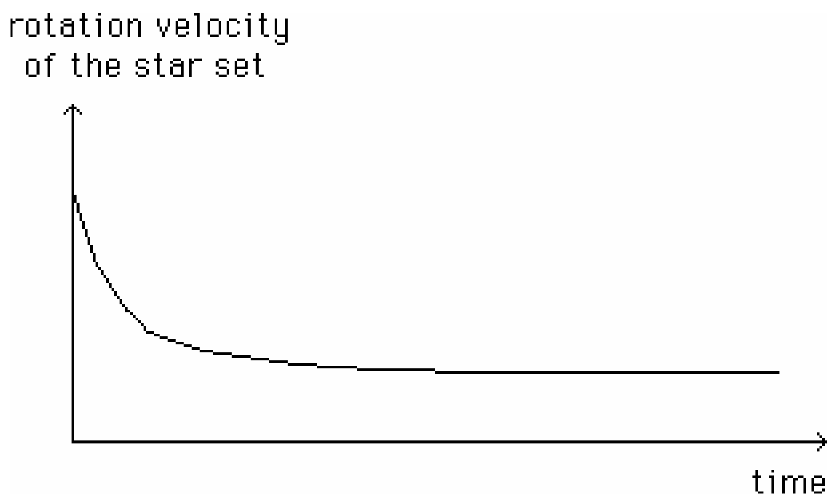
Barred structure, resulting from numerical simulations performed on computer.

In the best of cases this bar carries "mustaches":

A "synthetic galaxy", with bar and "mustaches".

As mentioned above, these inhomogeneities are dissipative structures. Here they tend to communicate speed to certain point-masses, assimilated to stars and in particular, alas, to those which make up the "mustaches". The points then disperse rather rapidly. Our mustaches evaporate and the problem is not resolved.

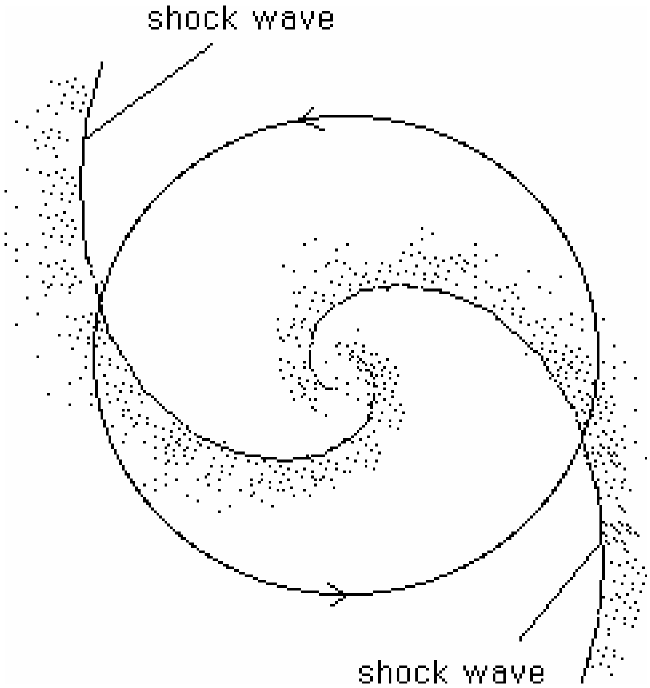
Another approach, that of Sellwood, consists of making two subsystems interact through three-dimensional simulations. The first subsystem is composed of stars and the second, of an immense spheroid "mass of gas" corresponding to the galaxy's missing mass. If a difference in speed exists between the two subsystems (for example if the halo does not turn), dynamic friction results, as predicted by the Indian Chandrasekhar. Sellwood shows that the halo brakes the rotational movement of the stars fairly efficiently. A bar appears. If we represent the rotational velocity of the stellar whole over time, we obtain a curve similar to the following :



Braking of the rotation of stars by a large halo of invisible matter.

The braking is intense in the first turns, then diminishes. We thus come upon another possible cause of galactic inhomogeneities -- a mechanism of internal friction between two subsystems, one visible, the other as yet undetected. This approach is only at its beginning, but looks promising. The adjustment of parameters is very delicate and calculation time long (in three dimensions) but it is not impossible that with time, this type of approach will enable us to solve the problem.

Careful examination of the distribution of matter in the spiral structures of galaxies shows that the spiral arms are configured like ... shock waves, whose front would be located in the arms' concavities. They would turn less quickly than the galaxy, which effectively resembles a braking.



Schematic appearance of density in a galaxy's spiral arms. The circle indicates the direction of rotation of matter.

The high density of gas in the arm's concavity forms a wave-front, analogous to that of a shock wave., Strictly speaking, what we see so brilliantly in ordinary photographs are not stars, but masses of gas illuminated by bunches of young stars being born in these arms.

Look at a bathtub when it is emptying. When the water circles rapidly close to the drain, you see spiral wavelets forming. They are the faithful analogues of shock waves. They appear because the water pours out at a "supersonic" speed in its ultimate phase of the draining. Here, the speed of "sound" is that of the propagation of surface waves on the water. The waves are created by the braking effect of friction of the water on the bottom, which intensifies as the water level becomes lower.

As you can verify, the spiral waves move with a rotational speed much lower than that of the water itself.

Perhaps, in the near future, simulations of dynamic friction between two subsystems, one visible and the other as yet invisible, will enable us to pierce the secret of the spiral forms of galaxies.

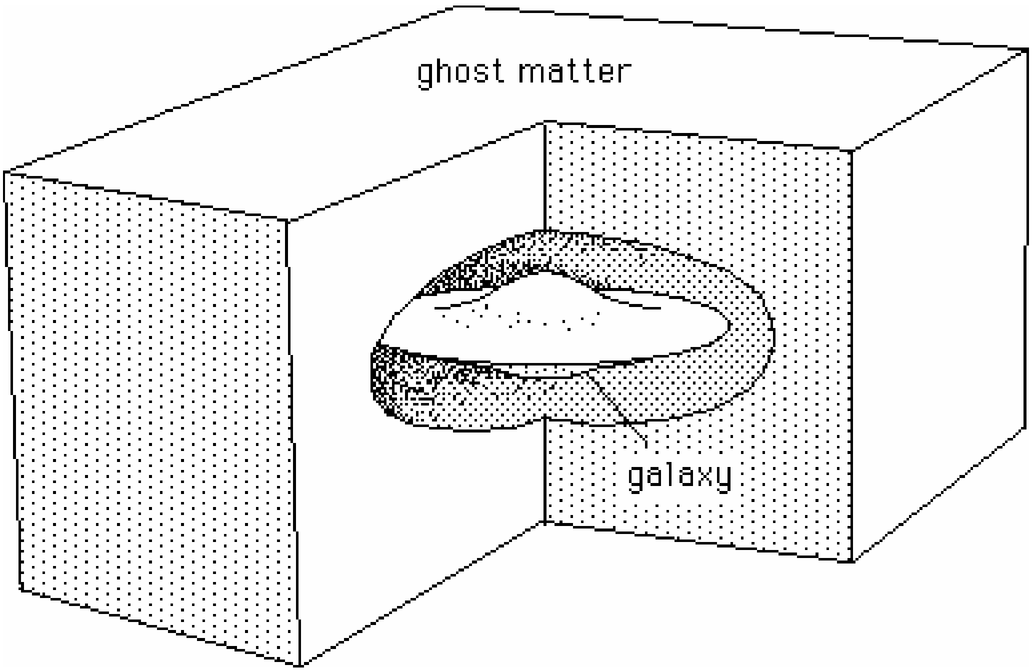
The water in a bathtub does not form a liquid bar. The bar structure is tied to another phenomenon, resonance, which has no equivalent in this analogy.

There is another theory : ours. But it would take too much room to present it in this document. See :

J.P. Petit & F. Landsheat : Matter ghost matter astrophysics 6 : Spiral structure. Geometrical Physics 9, April 1998.

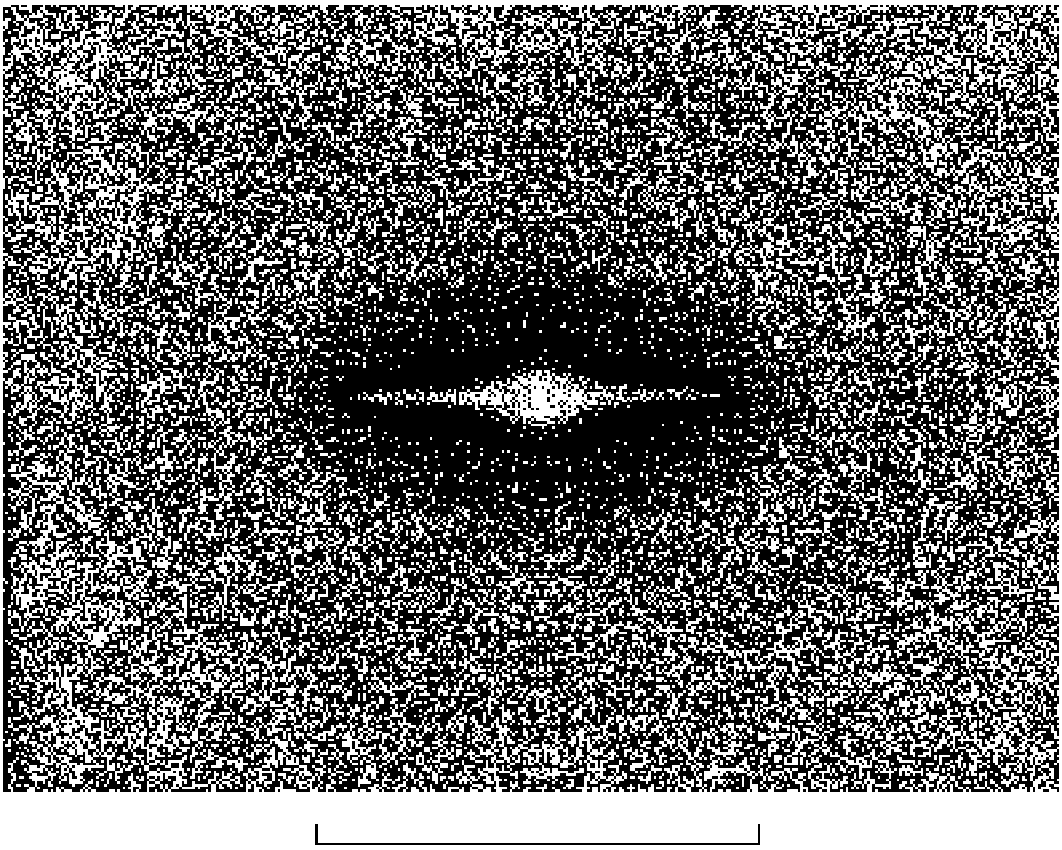
On the website.

Schematically : galaxies are supposed to be confined by some invisible ghost matter which cannot be detected optically. It would interact with ordinary matter only through gravitational force (matter and ghost matter repel each other) so that each galaxy nests in a sort of hole in the ghost matter distribution.

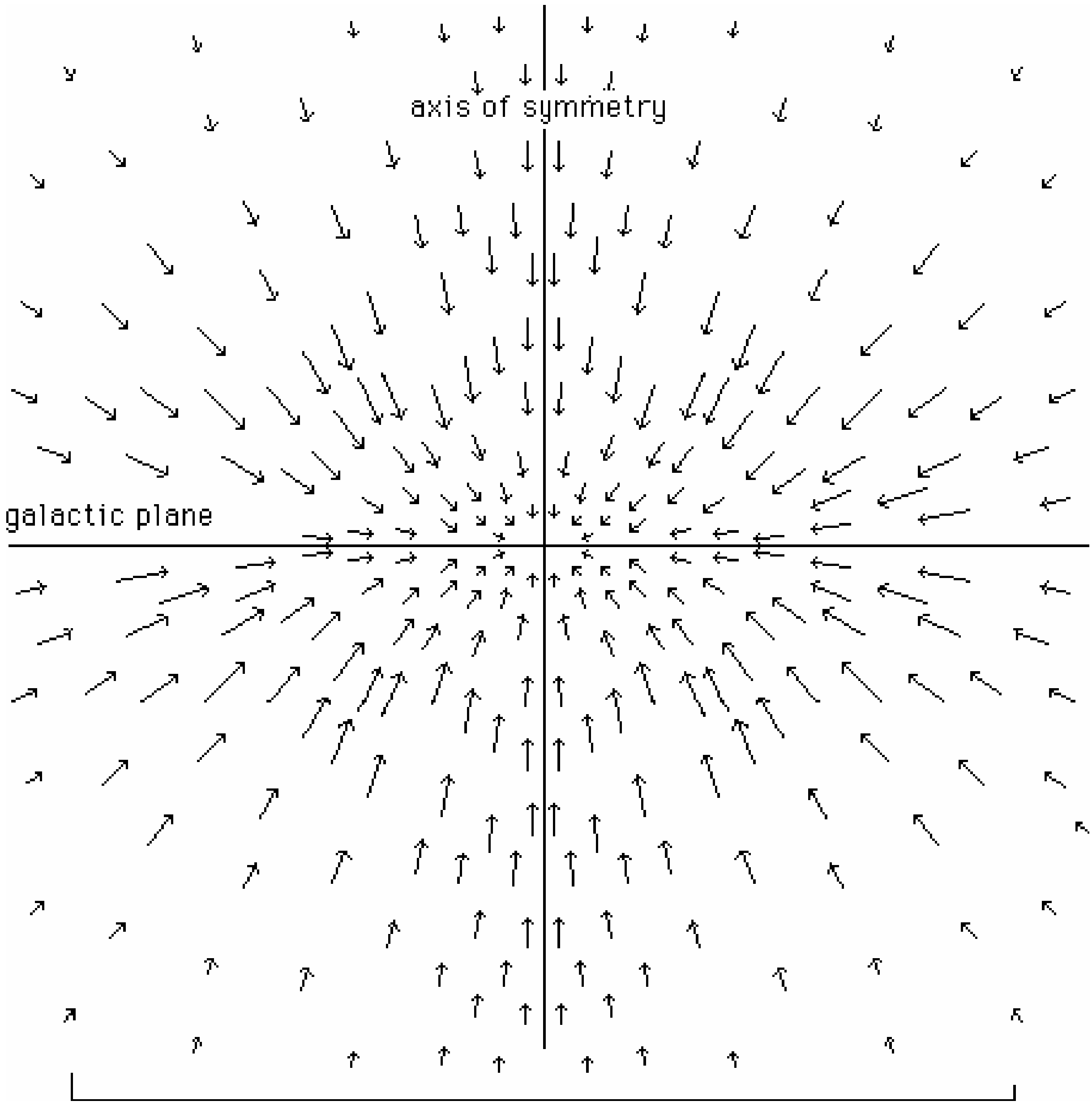


The following illustration is from :

J.P. Petit & Pierre Midy : Repulsive dark matter. Geometrical Physics A,6, April 1998.

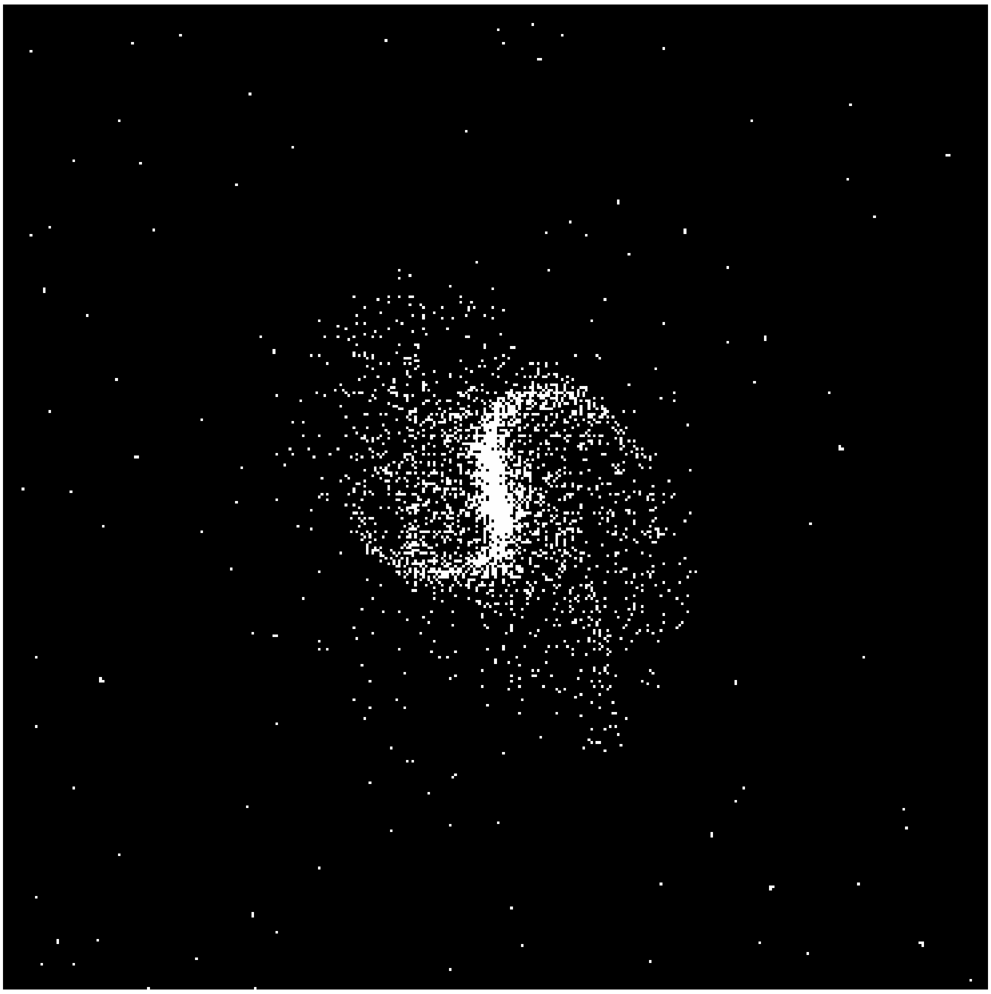


(See the Website). It is not an artist's impression but the result of a computer calculation. We can see the galaxy at the center. It is confined by an environment of repulsive ghost matter around it which prevents its explosion due to centrifugal force. If we ignore the presence of such surrounding ghost matter we get a "missing mass effect". The figure below shows the repulsive force field, due to ghost matter, acting on the galaxy.



This is an alternative theory to the "classic dark matter theory".

In such conditions the spiral structure would correspond to some sort of dynamic friction between matter and ghost matter, plus tidal effects. The next figure, obtained by numerical simulation (see paper), shows a barred spiral.



A crude image showing the friction of coffee on the wall of a cup when stirred :

Other hypotheses on the nature of invisible component so called dark matter.

We have entertained the most conventional hypotheses up to now, with the invisible component of the universe being made up of stars too faint to be detected, or of gas. Theoreticians have other candidates however. Some propose, for example, the existence of massive neutrinos. If they have mass, they can contribute to the gravitational field. On a cosmological scale massive neutrinos could completely revise our current value for the density of matter in the cosmos. They could also explain the phenomenon of missing mass in galaxies and galaxy clusters. The only problem is how to detect this mass.

Steven Hawking thinks that billions of primeval mini black holes could have formed in the early universe. This would be another candidate for invisible mass. But to date, no observation has confirmed his hypothesis.

Superstring theory furnishes another possibility, that of "shadow matter".

This theory has mobilized considerable energy on the part of researchers for the last ten or twenty years. At the moment ten articles a day are being published on the subject.

What is a "shadow particle"?

In the twenties theoreticians were captivated by the attempts to geometrize physics, which had begun with gravitation. At the time only two forces were known -- the gravitational and electromagnetic.

General Relativity handles only the first. This force field is reinterpreted as a geometrical form, as was discussed in the second part of the book. Mathematicians like Herman Weyl in the twenties tried vainly to construct a geometrical context capable of handling the two force fields together but failed. Until the end of his life Einstein himself hoped to create a "unified theory" integrating the two physical phenomena. It was shown later that this is impossible in a quadridimensional context, there is "not enough room" to hold both phenomena at the same time. The suitcase was too small, quadridimensional geometry not rich enough to geometrize mass and electric charge at the same time.

A Pole, Kaluza, then had the idea of adding a fifth dimension. The field equation is still written in the same way:

$$\mathbf{S} = \chi \ \mathbf{T}$$

Instead of "tensors" made up of sixteen parts (four lines and four columns -- four, because four dimensions), there were now twenty-five (five by five).

The tensor **T** is supposed to represent the energy content of the universe. The supplementary parts allow us to insert electromagnetic energy. With these conditions, all that remains necessary is the construction of the solution to such an equation, that is to find the equivalent form of the geometrical tensor **S**. Easier said than done. The theory also brings an additional disconcerting fact. It is possible to associate a characteristic length to this fifth dimension, the Planck length (see Appendix 3), that is 10^{-33} centimeters.

For decades the Kaluza theory remained a curiosity until theoreticians once again took up the idea and began to add piles of dimensions to the universe. They reached ... twenty-six!

Why such a profusion, such inflation? Well to try to describe elementary particles. They have numerous "symmetries" and to account for them it was necessary to increase the number of dimensions in order to obtain a geometry potentially richer in diverse and varied forms.

Certain considerations, which are too long and complicated to treat here, led to a general convergence around ten dimensions. There were now three spatial dimensions, one of time and six additional, "auxiliary" dimensions. Invariably, theory still bestowed on them the same characteristic length -- the Planck length.

Physicists love doing experiments. When they plan one, the first thing they do is to ask what energy should be applied. In quantum physics a particle is associated with a "wave packet". If n is the frequency of the "associated wave", the energy linked to the existence of this particle is h n, where h is Planck's constant.

The higher the frequency, the shorter the wavelength and the greater the energy associated with the wave packet. We have already given a didactic image for this -- the shaken rope.

The wavelength associated with phenomena bringing the supplementary dimensions into play was therefore the Planck length. It was easy then to calculate the associated energy:

$$E = hc/\lambda$$

where λ was the famous Planck length. So, you say, it's just a matter of building an accelerator capable of giving particles such energy. Yes, but unfortunately it would have to be the size of a galaxy. In effect the energy required is 10^{19} billion electron-volts. So far, only God has been able to supply such energy in a unique and, unfortunately, non-replicable experiment called the Big Bang. This inconvenience means that since the theory's birth there has been no point of contact between theoreticians and experimentalists. Nevertheless the former had steely confidence in their approach. Over time, according to them, this representation of the universe should supply a theory of everything. It would be able to integrate into a coherent whole the four known forces of nature --

- Gravitational force
- Electromagnetic force
- The strong interaction, responsible for the cohesion of nuclei
- The weak interaction, responsible for certain processes of disintegration.

No one knows if the theory will bear fruit in a reasonable time. Some think that it is a 21st century science which has landed by accident in the 20 th, a little as if medieval man had suddenly found himself in possession of theoretical tools enabling him to describe controlled fusion.

We will not enter into the debate but the context postulates a fundamental object from which everything flows, in the form of a string. There are partisans of open strings, with two ends, and those of strings closed upon themselves.

A curve can oscillate in a plane in a great number of ways. The superstring people think that a particle is only a given mode of vibration of the superstring. A ten-dimensional space allows a string inhabiting it to contort itself in many ways; theoreticians think that each mode corresponds to a particle.

We do not intend to launch ourselves into popularizing these complicated concepts so we will go no further. What interests us here are their implications for astrophysics and cosmology.

Certain superstring theoreticians think that their model can engender two types of matter -- the familiar type and a shadow matter. Among them we find John Schwarz, professor of theoretical physics at Caltech, Michael Green, of Queen Mary College in London (two of the theory's precursors) and the well known Nobel Prize winner Abdus Salam (for his work on the unification of the "weak force" and the electromagnetic force). They suggest that shadow matter would be utterly extraordinary. It could only interact with our matter through gravitational force and in no other way.

Here are the words of John Schwarz:

The other E_8 symmetry describes a new kind of matter, sometimes called shadow matter, that does not interact, or only interacts extremely weakly with the ordinary matter we are familiar with. If you wanted to construct some science fiction out of this, you could imagine all sorts of galaxies and planets made out of shadow matter that would be completely invisible to us because they would not interact with our kind of light.

So, the amusing possibility is that shadow matter associated with this second E_8 symmetry would be essentially invisible to us because it wouldn't interact with our kind of light.

Those of Michael Green:

One prediction that might come out of these theories is that there should be a whole new type of matter we would not be able to see directly, except for its gravitational effects on us, though particles of shadow matter might exert strong forces on each other.

And those of Abdus Salam:

From superstring theory, some sort of duplicate universe could exist, made of a double copy of matter, which would communicate with us only through gravitational force. Amazingly this invisible universe should determine the manner in which supersymmetry should be broken in our universe. Such a theory should shed light on the problem of what determines some of the mass differences in the visible universe.

There is a lot at stake because, as we can see, Abdus Salam thinks that this structure would be the key to our comprehension of the "spectrum of masses" of elementary particles.

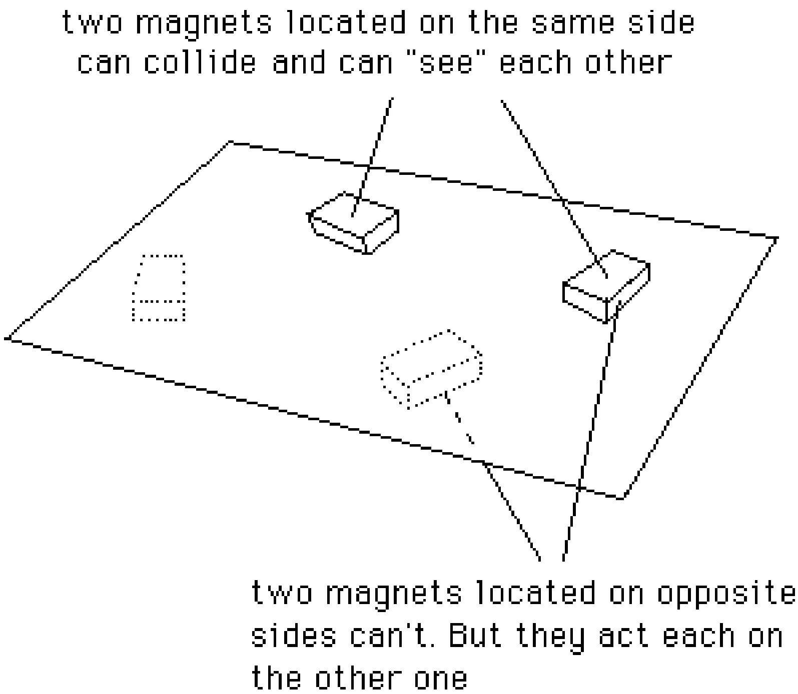
Particles of shadow matter could not combine with ours, nor exchange photons with them. In brief they would be "present but invisible", constituting a shadow universe overlapping our own, revealing its presence only through gravitation.

Imagine a dark room in which you suspend lights. Two types of lights, red and blue, for example. They would be in the same space, but you could not see them at the same time. We might imagine that the inhabitants of the "red" universe are equipped with filtered glasses, which would only allow them to discern this color and not blue light. Reverse situation for the inhabitant of the "blue" universe.

But the lights, moving around, might hit each other. Only ghosts can cross walls so how do we imagine such a situation? By taking away one of the spatial dimensions, transforming it into a plane.

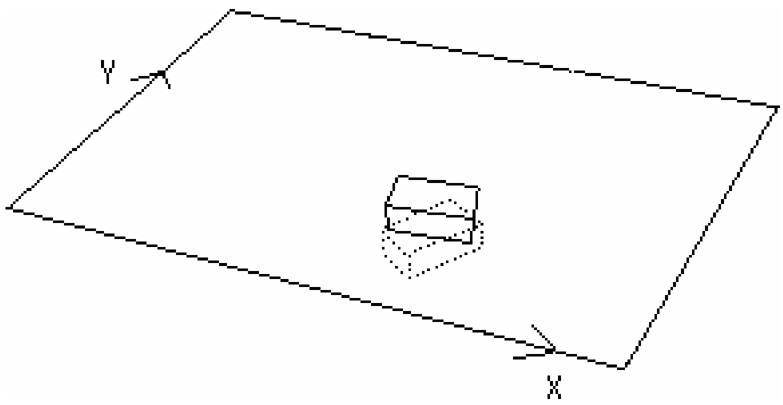
A plane has a front and a back. Normal particles, our own, make their way on one side and the shadow particles on the other. Thus they never meet one another. But gravitational force can act across this opaque plane.

It is easy to create situations where two types of objects can change, exercise forces on each other, but not meet. It suffices to imagine two groups of magnets moving on two sides of a plane:



Two groups of magnets, situated on either sides of a plane.

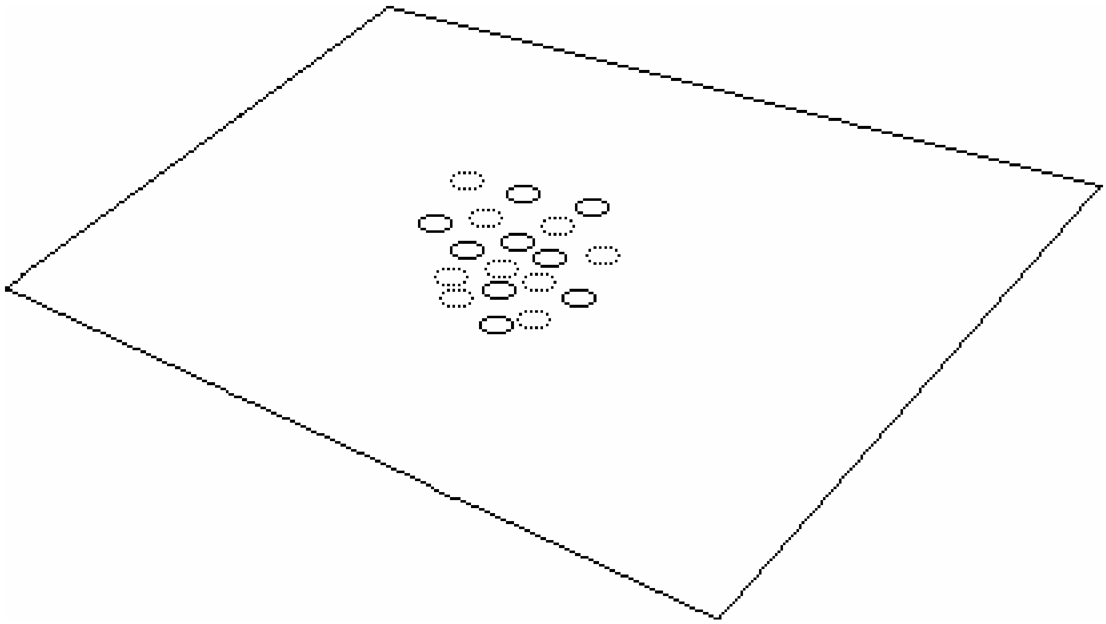
Two magnets can then perfectly well cross each other yet be located at the same place in the plane, at coordinates (x, y).



It is hard for us to imagine such a situation in three dimensions. Nevertheless Michael Green referred to this when saying that if a shadow planet crossed ours, we would not perceive it, except for the resulting gravitational perturbation (high tides, he said). In 1985 the journal Nature published an article in which the authors proposed that the sun might co-exist with a "shadow sun".

This shadow matter could also play the role of a peculiar dark matter, but there would be no question of finding optical evidence for it. It would assure our galaxies' confinement and would contribute to the gravitational lens effect in the vicinity of galaxies and galaxy clusters, etc.

Remaining with the image of a plane, it is possible to show, schematically, what a galaxy and its adjacent shadow galaxy look like:

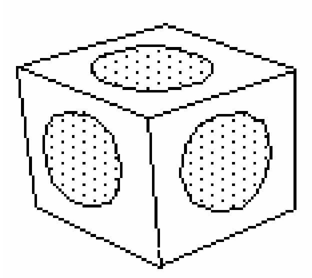


A galaxy and its "shadow galaxy".

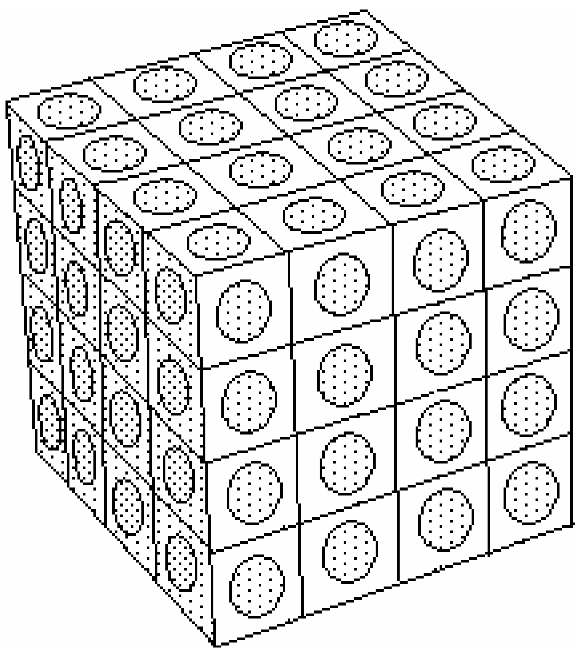
The black disks represent elements of matter and the gray disks shadow matter, located on the plane's other side.

As certain astrophysicists, tempted by the vision born of superstrings men elucubration's, suggest, it would not be a priori impossible that the galactic spiral structure, which we try currently to impute to interaction between the galaxy's visible portion and some hypothetical halo of invisible matter, might be due to its dynamic friction with ... a shadow galaxy!

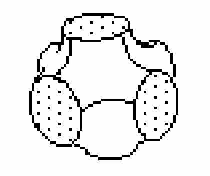
The above figure does not give the impression that the particles and ghost particles could exist in space so let us try a close 3d overlapping. Draw disks on the six faces of a cube and place adhesive on them.



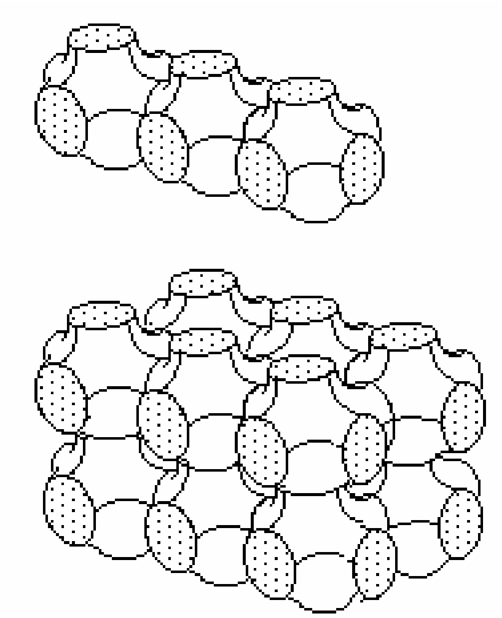
You can stick an infinity of cubes alongside these disks to "pave space".

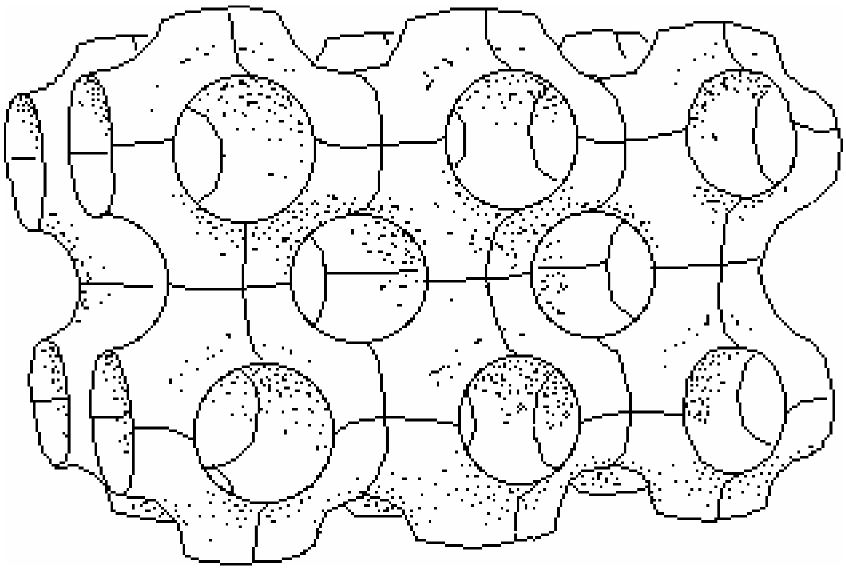


Before attaching these objects to one another, we can take out a bit of matter with a knife to sculpt them into the following form:

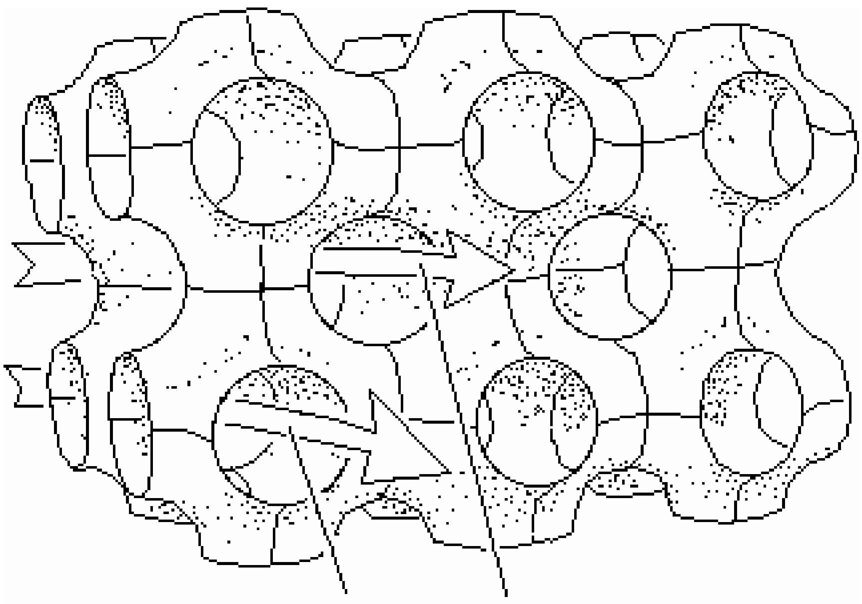


We can still attach the objects with the adhesive disks.



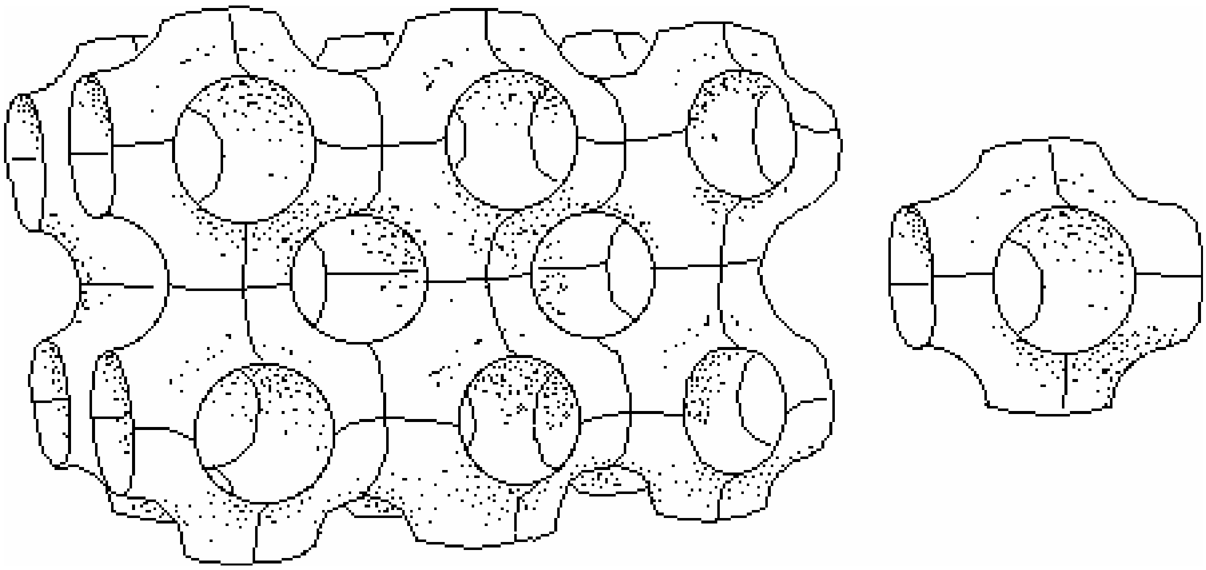


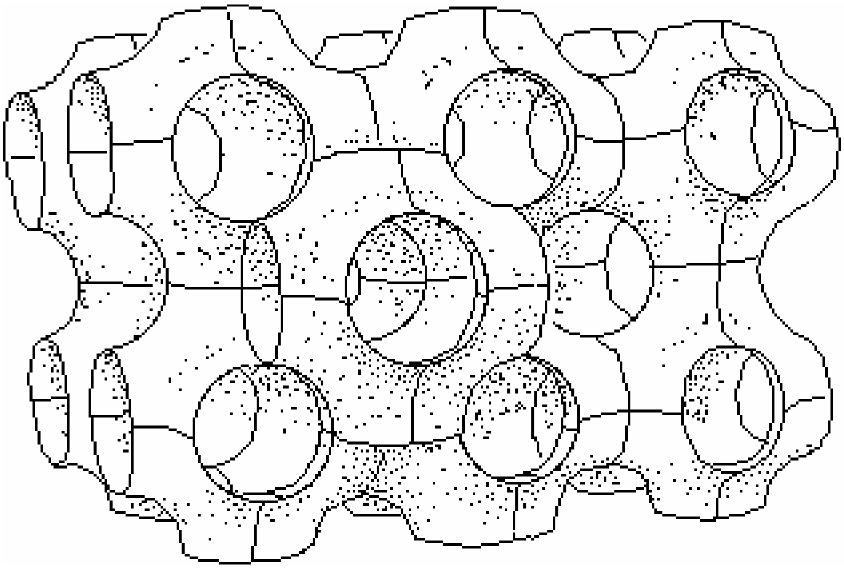
We obtain a "paving" of space with the same periodicity and the same symmetry as the original cubes but this time, with interstitial space.

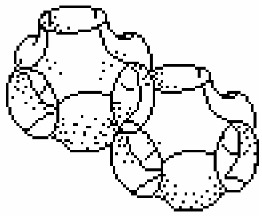


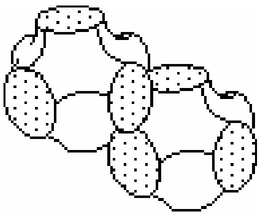
The surface divides space in two. In one space, ordinary matter can move about and in the other shadow matter, without ever meeting in the corridors.

To make it more interesting, let us consider as full what we have been treating until now as "empty". We obtain ... exactly the same thing. The space "inside the surface" has the same topology as its outside, through a simple spatial translation. Look at the following figure. You will see that the element borrowed from the surface's "outside" comes to depend exactly on the latter, the connecting disks leaning on the shoulders of the first structure.

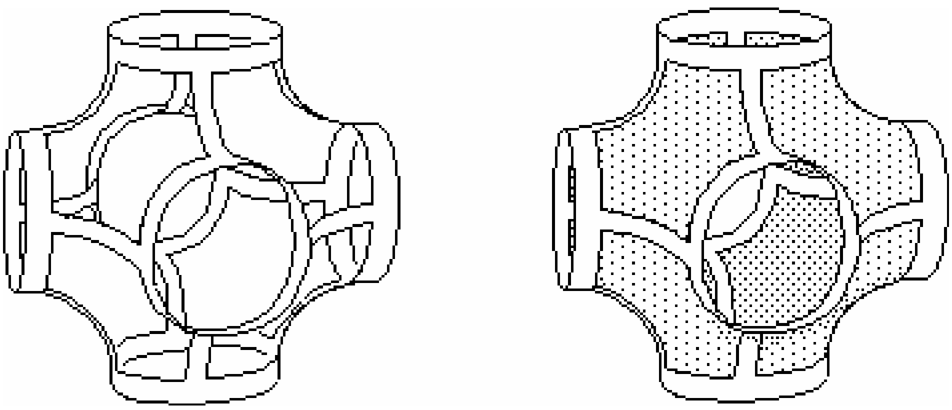








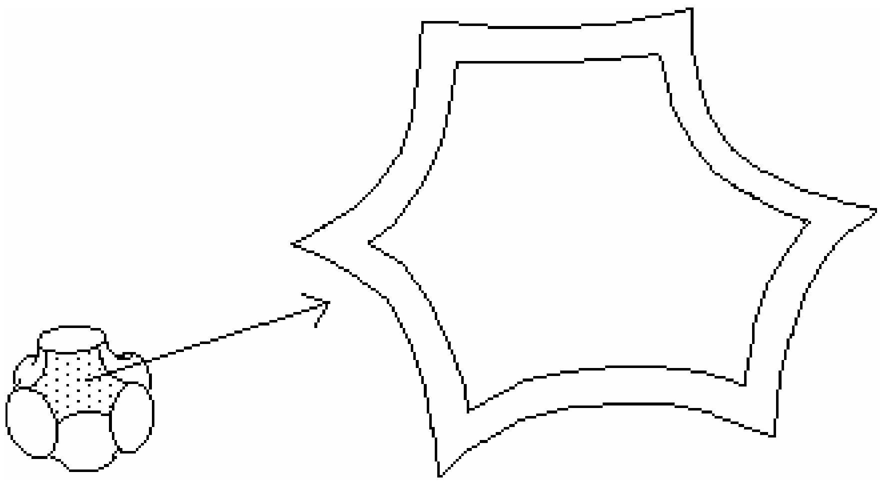
You can, if it amuses you, construct such objects and assemble this for yourself with paste-board strips.



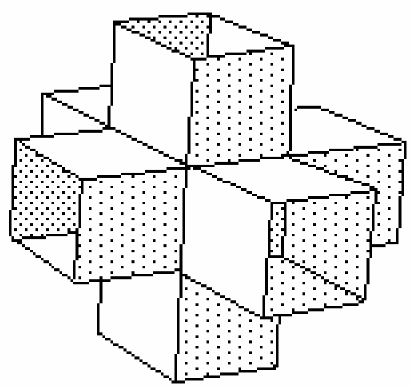
The elementary object which enables the construction of a boundary surface between a "universe" and its "shadow universe".

If you make n identical elements, you can attach them together at the circles.

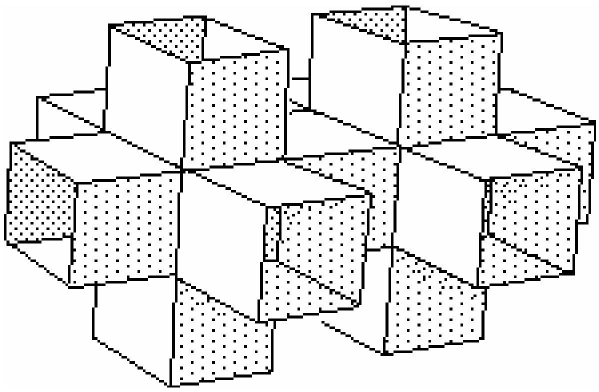
A remark in passing -- this strange, negatively curved surface is in fact produced with a single base element -- a flexible hexagon with six right angles. Here is one of them.



There is another way to make this dual partition of a tridimensional space simpler to construct. Just make this type of cruciform element:



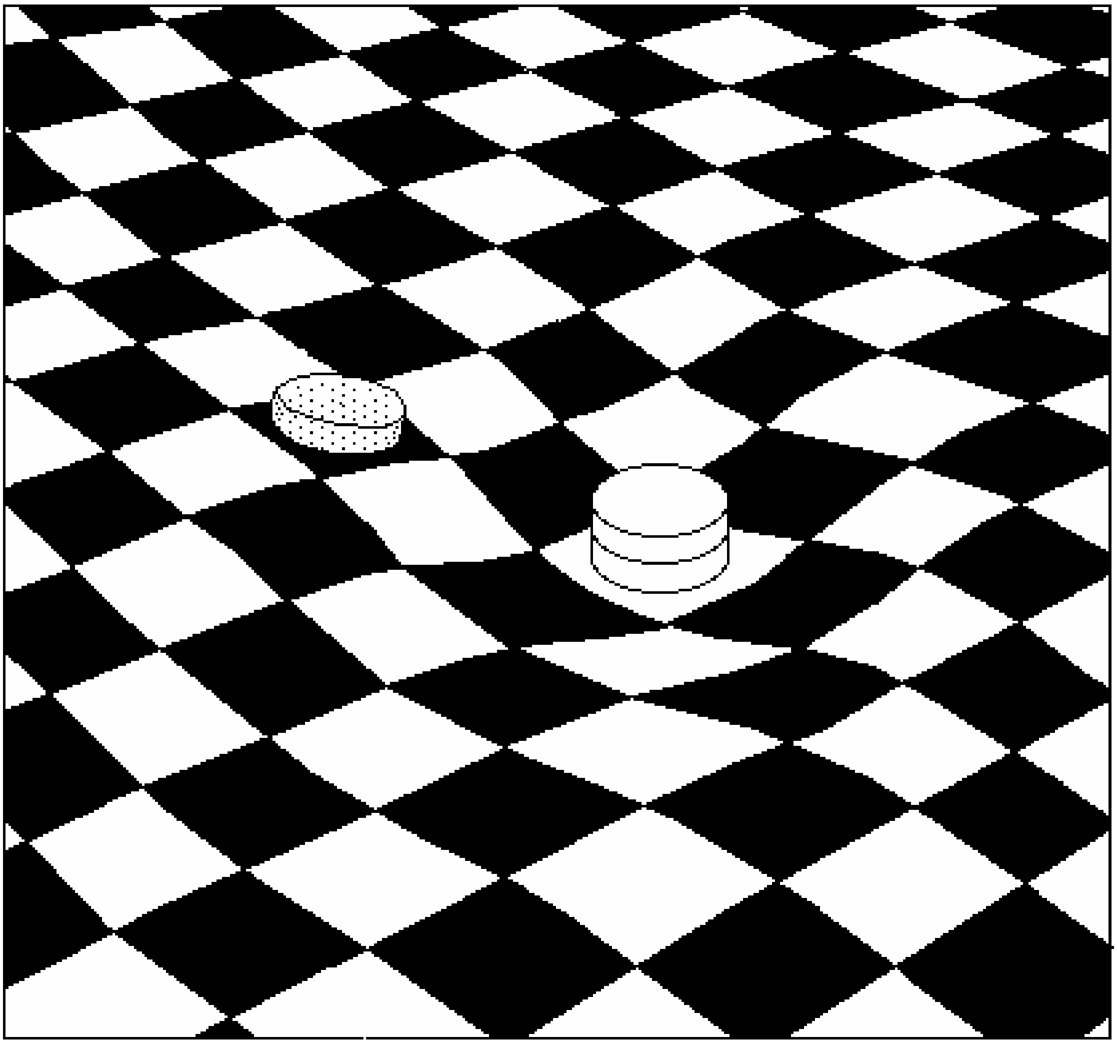
and assemble them, to infinity:



In this way We obtain a network of horizontal corridors, intersecting at right angles and prolonged by sorts of elevator cages. It is simple, but we leave to you to verify that the "complementary" space possesses the same "topology", the same form, though I agree that it takes a practiced spatial vision to find this obvious.

The simplest two-dimensional image of a didactic model in which matter and shadow-matter mix is checkers. You know that this game is played by moving pieces on the white squares. But why not use the unused black squares to play a second game, independent of the first? Just put a second set of pieces like this. The game board could then be used by two teams of players.

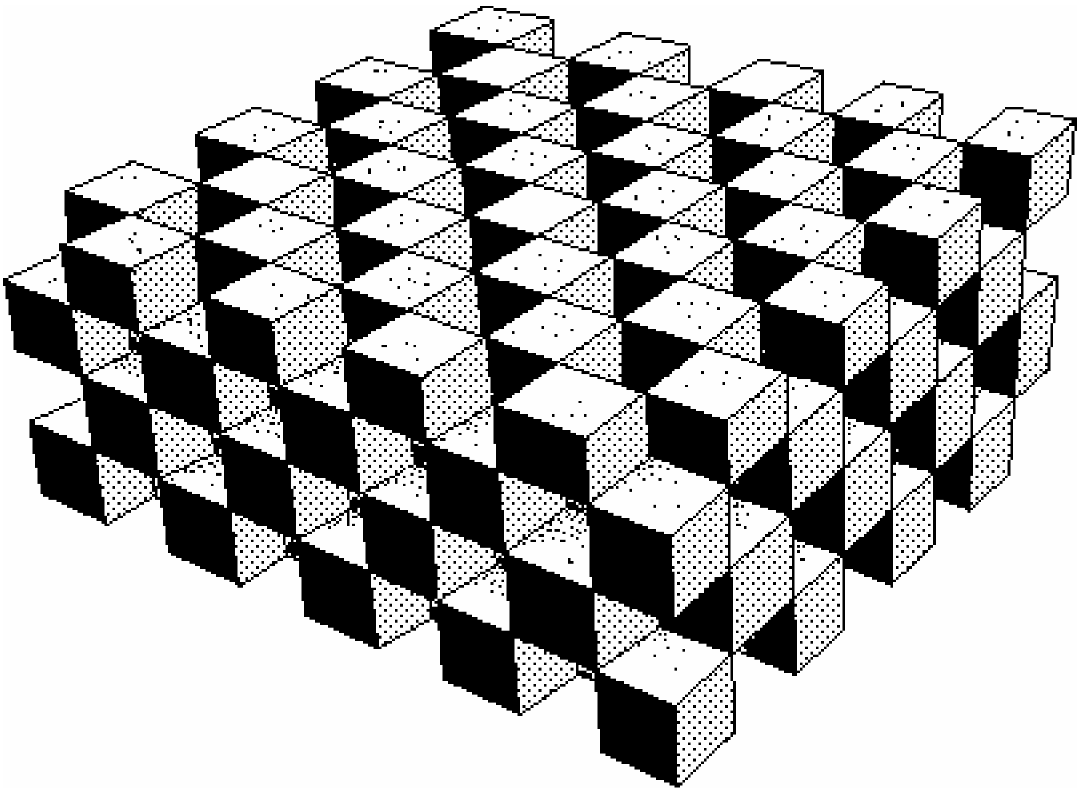
The two games would be in these circumstances totally independent. In the shadow matter model, we suppose that the first elements "communicate" with the second exclusively through the intermediary of gravitation. We could simulate this by imagining the game to be played on a "soft game board". When a piece is on a square, it would sink into the material and deform the surface. The second game's pieces would thus be "informed of its presence", without being able to interact with it, take it or be taken by it.



A double game of checkers on a soft game board. The gray piece, belonging to one of the games, is "informed" of the presence of a checker participating in the second game by the deformation of the material.

Games are often a good basis for reflection and a source of didactic models.

We note in passing that we can envisage a game of checkers in three dimensions. It suffices to take one cube out of two from a layer of cubes and pile them up on those remaining, making a translation each time. The "full" cubes become the "black squares" and the empty cubes the "white squares".



The "game of checkers in three dimensions".

Oh God, why have you forsaken me ?

Superstringers are inquiring into the fundamental object making up the universe, the key to the theory of everything. They think they have constructed the symmetry properties this unknown object should possess (according to different variants), properties founded on group theory. The group E8 x E8 is one of the variants. The groups "secrete geometry". The Galilean group, which translates all the properties of our space-time (spatial translations, rotations, plus temporal translations), in their most naive view (Euclidean, with absolute time), secretes a Euclidean space-time.

The Lorentz group secretes Minkowski space-time, that of Special Relativity.

The superstringers are researching into the geometry of a decadimensional space respecting the special symmetry properties which all elementary particles, known and unknown, obey.

Let us suppose that I have six quantities:

$$x, \; y, \; z, \; \alpha, \; \beta, \; \gamma.$$

I decide, for example, that I can add to or subtract from the first three a whole number of times a quantity a, and that I can add to or subtract from the following three $\pi/2$ a whole number of times. This constitutes a group. Its neutral elements consist of adding or subtracting a nil quantity. An object exists which satisfies these relations -- the cube. The space flowing from this group structure is a three dimensional one, paved with cubes. A sort of crystal.

Crystallography is based entirely on group theory. When we have the group, we have the way in which the crystal is built.

We might say that superstringers think they already own the good groups and are now looking now for the corresponding crystal. A ten dimensional crystal. They have the groups, but not the object. They have the keystone, but not the edifice built around it.

All this gives rise to truly surrealistic exchanges in colloquia, like one which recently took place in Aspen, Colorado. The journal Scientific American, in its January 1996 issue, ran an article entitled "Explaining everything", by Madhusree Mukerjee, staff writer. **[...]**

Seeking this magical object supposed to organize the ten-dimensional universe, some people speak about "studded spheres", hedgehogs bristling with vectors, or "hairy caterpillars", membranes with five dimensions (Duff, of London's Imperial College), capable of rolling onto themselves "like the skin of a sausage".

Schwarz, of Caltech (one of the pioneers of the theory), adds, "I should have been a truck driver!"

Others speak of "black holes with zero mass".

Jeffrey A. Harvey, of the University of Chicago, cried out:

"Does that mean that your black holes have zero mass? Do they move at the speed of light?"

"No, they have nothing, no momentum", replied Gary T. Horowitz of the University of California at Santa Barbara.

"Oh, baloney!" said Leonard Susskind of Stanford.

They have no energy, no momentum -- there's nothing there?" protested Harvey.

Strominger: "Somewhere in the universe portions of space might exist in the shape of little drops, which would turn black holes into strings if they entered them, and vice-versa. In our environment these little drops could seem to navigate in virtual universes, which would exist for an infinitesimal period of time, since they would immediately disappear, before they could be observed.

Susskind: "I personally think it's a load of crap".

In 1986 someone asked a researcher to sum up the "Theory of Everything" in seven words, and he answered:

- Oh, Lord, why have you forsaken me?

All this is interesting, and it's not over, as we can see. Never in the history of physics has a body of theory given rise to such convulsions as now, when ten articles are being published on the subject every day. And we cannot say whether the mountain will give birth to a mouse or the mouse to a mountain.

Lost, half the universe.

We said at the beginning that in its youth the universe was, in Steven Weinberg's words, "filled with diverse radiation". Matter and antimatter co-existed, in equal parts. The universe was then a thousandth of a second old with a temperature of three hundred billion degrees. The universe was an undifferentiated mix of photons (there are no anti-photons; it is its own anti-particle). All these particles had the same energy; all the components of this mixture had the same temperature (thermodynamic equilibrium).

When a particle meets an anti-particle, annihilation occurs with photon emission. This is not a problem because, during this period, photons have sufficient energy to produce the inverse reaction when they met, giving a particle-antiparticle pair.

With the passage of time, however, photons lose energy. At the end of a hundredth of a second, the temperature having fallen to (only) a hundred billion degrees, photons are no longer capable of producing pairs of hadrons (protons, anti-protons, neutrons, anti-neutrons). A frenetic depopulation occurs, a veritable hecatomb. But electron anti-electron pairs continue to be synthesized at the same rhythm. Less heavy (1850 times less than protons and neutrons), they can be synthesized from less energetic photons. As a general rule the energy of photons capable of creating particle anti-particle pairs of mass m should correspond to:

$$h\nu = mc^2.$$

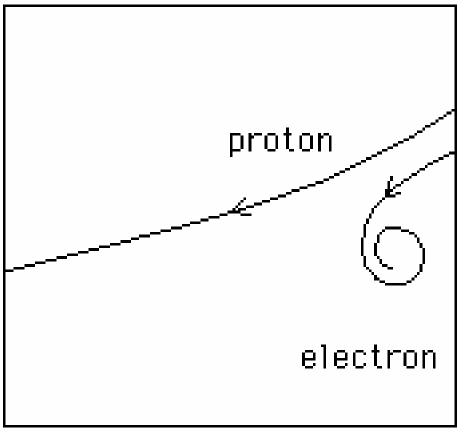
At the end of thirteen seconds the temperature falls below three billion degrees Kelvin. Photons no longer succeed in compensating losses. The hecatomb begins to strike electrons as well.

So?

Normally, everything should have eventually disappeared. Inexplicably, one out of a billion particles carrying mass subsisted. Moreover, as much antimatter should have subsisted as matter. Now, as we said above, we have not seen any of this primordial antimatter. And what is antimatter actually?

As we mentioned above, its existence was initially predicted by the Englishman Dirac. Fairly quickly afterwards the first antimatter particles were identified in cosmic rays.

Electrically charged particles crossing a magnetic field turn perpendicularly to its direction. Their direction of gyration depends on the charge. Their radius of gyration (Larmoor radius) depends on their mass. On a photographic plate the trajectories of a proton and electron are easily discernible. The electron is lighter -- its gyration radius is smaller.



One day a bizarre electron was found on a plate which turned in the same direction as protons. It had therefore a positive charge and it was considered to be a positron, the anti-electron whose existence Dirac had predicted. Later these objects were also observed in laboratory experiments. Today we synthesize anti-particles on a daily basis in particle accelerators, used as "colliders".

By the way, did you know that it takes hours of electricity input to endow charged particles with sufficient energy? They are accelerated by a variable magnetic field, just like the stomach's peristaltic movements pushing alimentary matter. For turn after turn they "surf" on magnetic waves, until they attain sufficient speed.

What is antimatter's mass? Is its mass positive or negative?

We should really say "what is its geometric representation"?

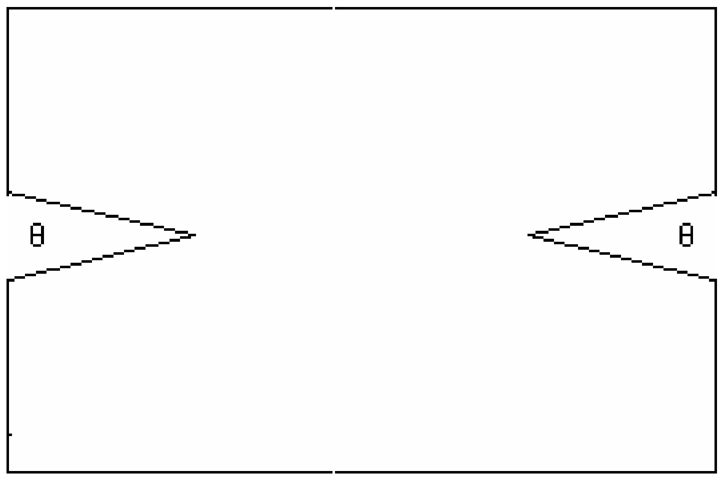
We have said that the universe is a four dimensional hypersurface. This concept makes sense only if we can plunge this 4d hypersurface into a five-dimensional universe.

We can only represent two dimensional surfaces as we have done up to now. Their dimensions will continue to be spatial. We will "abstract from time".

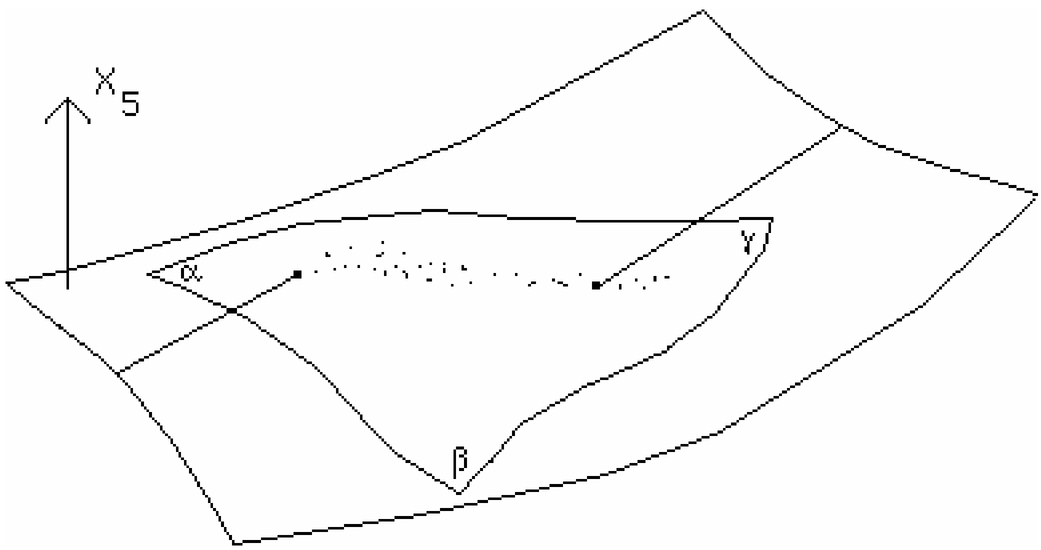
Kaluza, as we said, also introduced a fifth dimension. Let us call it x_5. We can make a drawing in which a hypersurface is completed by a supplementary dimension perpendicular to it. This fifth dimension would be reckoned as normal to the surface. Now, among the properties of the Kaluza model there is one particularly interesting one. When we change x_5

into -x5 matter becomes antimatter. This fifth dimension is in fact a "way of observing space-time". Abbé Lemaitre, a great Belgian cosmologist, one of the conceivers of the Big Bang, often said that antimatter was matter "seen upside down".

There is therefore a way to represent the mini-curvature represented by particles of matter and antimatter. They are two "mini-cones" pointing in different directions. We can give this concrete form by taking a piece of paper and making two cuts in it :



We then obtain this :



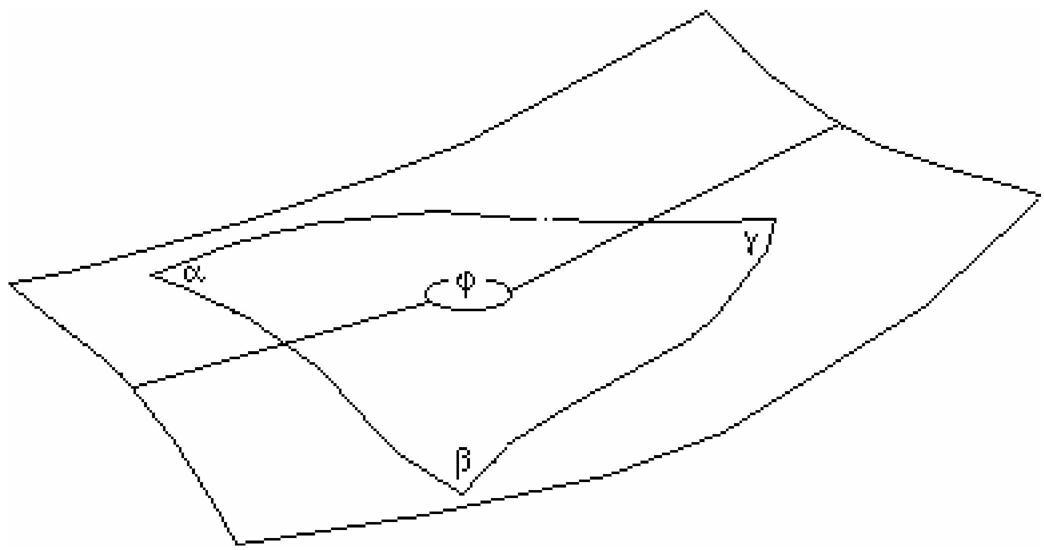
The perpendicular to this surface is the Kaluza fifth dimension. When we reverse it, we are looking at the surface "from the other side". What was on the crest goes onto the trough and vice-versa.

We draw a triangle made up of three geodesics. The sum of the angles of the triangle will be equal to :

$$\alpha + \beta + \gamma = \pi + \theta + \theta.$$

The two mini-cones give equal positive contributions. The direction in which they "point" matters little. Matter and antimatter are like this. They have positive masses, they curve space positively. Antimatter attracts antimatter, just as matter and antimatter mutually attract one another. Their "associated geometry" is simply different. Both contribute in the same way to the gravitational field. It has been shown that anti-particles fall in the Earth's gravity field. So far, apparently, no one has yet been able to show by experiment that anti-particles attract particles gravitationally.

Let us now have the two cone tips slide towards each other. We obtain this strange figure :



These two "matter and antimatter particles" annihilate one another. But the result of the operation is not a region of nil curvature. The sum of the angles of the triangle is always greater than 180^o. This "object" is a passably non-conventional way of representing a "photon" (a fundamentally four-dimensional object). It illustrates the fact that the photon is the "source of the gravitational field". It creates a positive mini-curvature.

In fact, everything that is energy creates positive curvature in space. Matter and photons are only different forms of the same entity, energy.

In the tensor energy becomes a "density of energy-matter", ρ, which is numbered in kilos per cubic meter. This term is a sum:

$$\rho = \rho_m + \rho_r .$$

The first represents energy density under the form of matter and the second energy density under the form of radiation.

Currently:

$$\rho_m >> \rho_r$$

but, previously, at t = 500,000 years it was the reverse. It is the expansion of the universe which "devalues" this form of energy as radiation, to the profit of energy in the form of matter.

How do we determine the density of matter in the form of radiation? Simple. You give the photons a "gravific mass" m_ϕ, following:

$$m_\phi c^2 = h \nu$$

and multiply by the number of photons having this frequency.

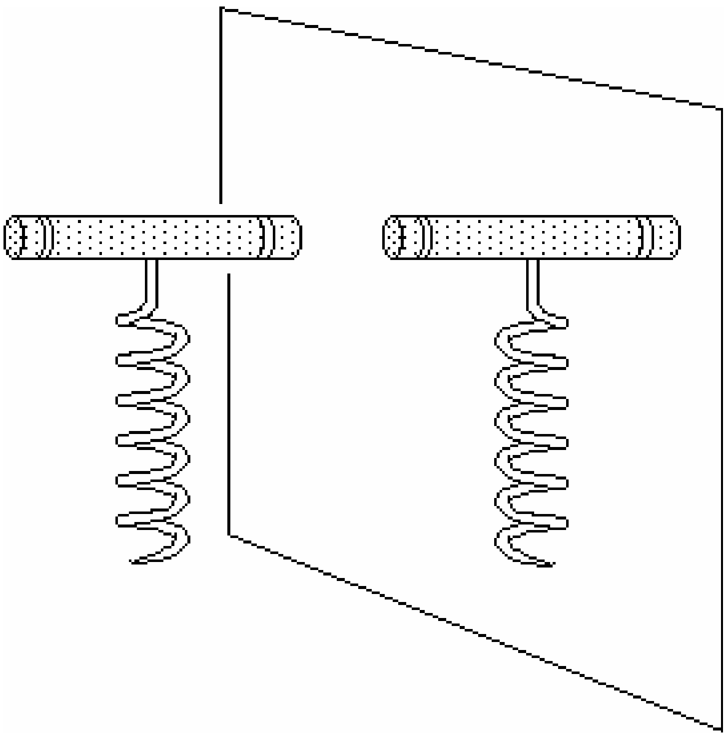
You will ask, what in the world is this mass? Isn't the photon supposed to have nil mass? Yes, but only its inertial mass is nil. Its "gravific mass" is not.

For energy in the form of matter these two masses are identical, which constitutes the *principle of equivalence.*

The transformation of a particle into an anti-particle corresponds to a certain symmetry C, which is called "charge conjugation". Geometrically we can say that, in Kaluza's description, this changes x_5 into $-x_5$.

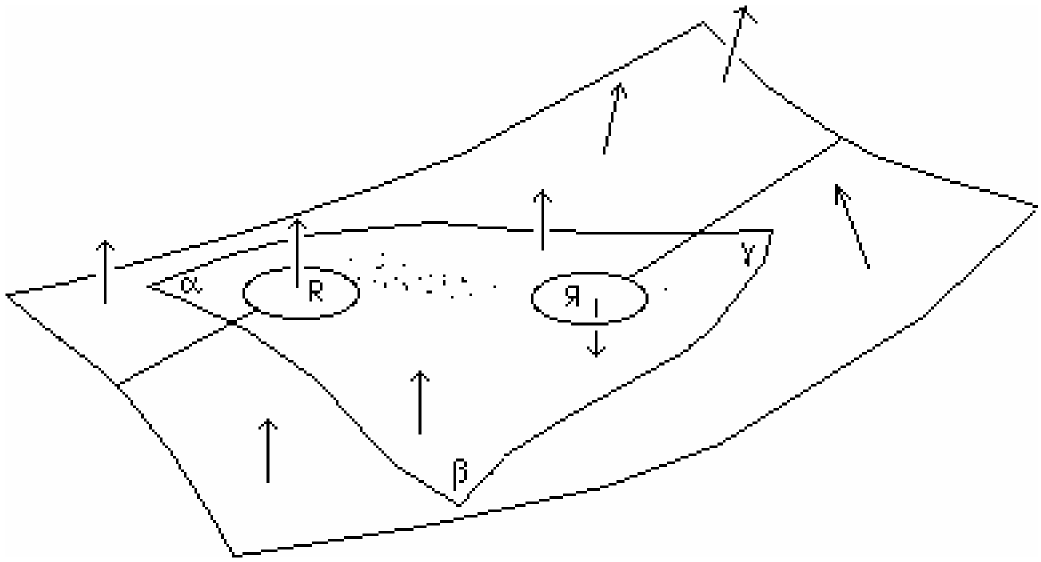
Richard Feynman later produced a different description of antimatter. According to him, an anti-electron could be considered as an ordinary electron but navigating in reverse time and possessing an opposite spin. That is to say it was "in a mirror" with respect to the ordinary electron whose image it became.

This mirror symmetry is called enantiomorphism. Your right and left hands are enantiomorphs. The image of a corkscrew in a mirror is enantiomorphic with respect to a corkscrew-object :

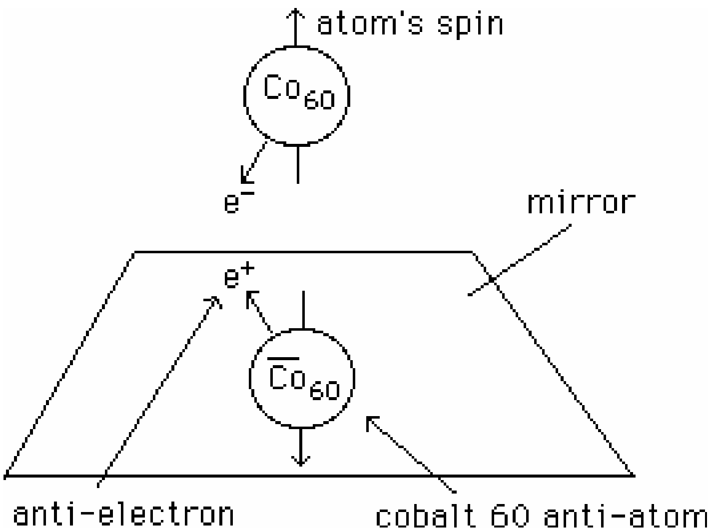


We also call this symmetry P-symmetry. P stands for "parity".

If we follow Feynman's idea, we can imagine that antimatter is a piece of space-time where objects are placed in a mirror and the arrow of time is opposite. We have represented this arrow of time in the following drawing. A "normal" particle represented by the letter R and the enantiomorphic particle by the Russian letter Я (ia), its mirror image :



We know that our universe is not totally symmetrical, called the "violation of the parity principle". The idea was originally launched in the fifties by two Chinese, Tsung Dao Lee and Chen Ning Yang. Later another Chinese researcher, living in the United States, Chien-Sung Wu, performed the first experiment demonstrating this phenomenon while studying the radioactive disintegration of Cobalt 60. Wu showed that electrons "preferred" to emerge from the atom in a direction opposite to its spin :



The first anti-atoms have recently been created, an extremely important event. It is therefore not inconceivable that we will one day create an anti-atom of Cobalt 60. Instead of emitting an electron, it would then emit an anti-electron, a positron and we would observe a phenomenon of inverse parity violation.

In 1967, this asymmetry of the universe induced Andrei Sakharov to imagine that there might not be just one, single universe, but two, born at the same time and living separate lives, with opposite arrows of time. They would also be enantiomorphs. What is right in one would be left in the other.

For the moment this theory is the only one justifying the noted absence of cosmological antimatter. According to Sakharov it would simply have absconded to a twin universe of our own. More precisely, in one of the panels the synthesis of antimatter from quarks would have been more rapid than that of antimatter, due to the dissymmetry noted above. In the other panel, where antimatter is composed of anti-quarks, it would be the reverse situation.

At the moment of frenetic annihilation in the two panels, this dissymmetry would create a slight excess of matter in one panel and an equivalent excess of antimatter in the other.

Sakharov had even envisaged in his writings that matter could pass from one of these "panels" to the other.

At the millennium's end, decidedly, ideas are bubbling away merrily.

A bit about my recent personal work.

I am writing these lines in June 1998. They are based on the text of a book that I wrote three years ago which my friend Sidney Keith translated into English. At the time we hoped to find an American publisher. Sidney did look around and follow leads but in the end we found no-one (it's true that Sidney is a Buddhist). The manuscript found its way onto a shelf and remained there for years.

It was while creating this site that I had the idea, with Sidney's agreement, of publishing it on Internet. However I first had to rework the text, which I tried to do in France. The text, therefore, might lack a little homogeneity

We wish this manuscript to be freely available in any language. Any readers interested by the book and who are capable of translating it into their own language (Swedish, Hungarian, Yiddish...) for the benefit of their non English speaking compatriots is free to do so and free to publish it on their own website. It would also be possible to add a link to this site to signal the existence of the translation on theirs.

As the writer I will address a legally valid letter of authorization to do so to any person who undertakes such a translation. However it may not be used to obtain any financial profit, that is to say through publication or sale. They may only give free access to it on their site, as we do.

This idea seemed an interesting one to me because a free product, available to all, is a product that :

- Beats all competition
- Can be a rival to products from even the most powerful multinationals
- Doesn't bring any salary costs or stock and stock control problems. No management or fiscal problems either and with extremely low operating costs.
- Can be circulated throughout the planet without any advertising budget.
- Is available 24 hours a day, 7 days a week.

- Can be modified,brought up to date and adapted to client demand at any time.

In short, a product with every quality. Its only disadvantage is that it doe not make any money. But in life, nothing's perfect.

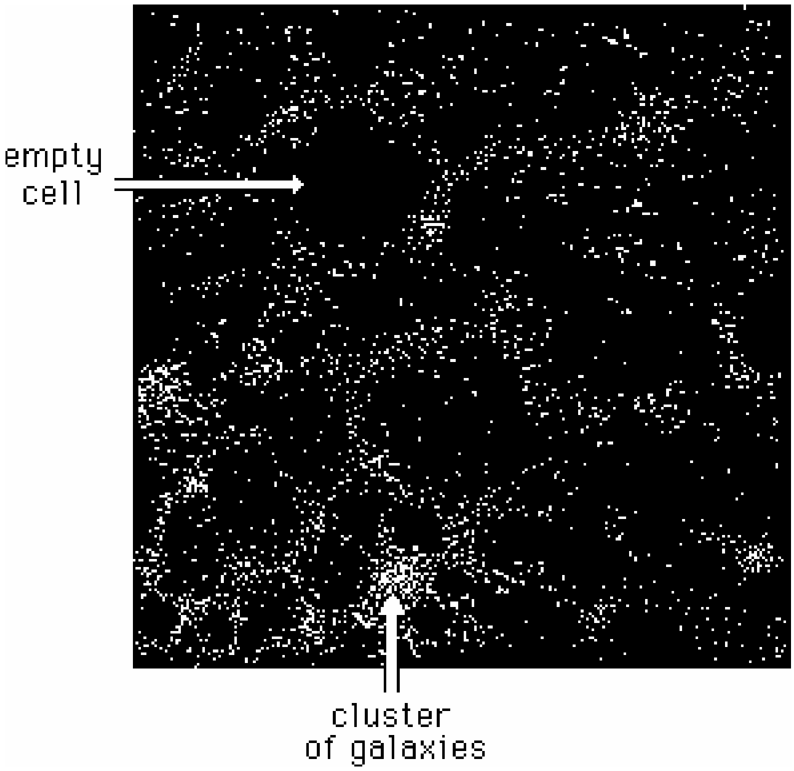
In reworking the text I had to first take my own research and discoveries into account (which the reader can find in the Geometrical Physics A and Geometrical Physics B sub-sections). If I had wanted to do so completely I would have had to completely dismantle Sidney's translation or write another book and ask him to translate it afterwards. I therefore did what I could to re-use the work already done and translated to which I've added original material. I could also have gone into greater detail on the work that Pierre Midy, Frederic Landsheat and I have done on astrophysics and cosmology but that would require many more pages and here I have to pay a translator to ensure that those added to Sidney's book are of sufficient quality. If I translated them myself it wouldn't be good enough and as a whole, it would lack homogeneity. The reader is therefore invited to refer to the introduction to Geometrical Physics A for everything concerning our own work in astrophysics and cosmology.

A few words about the model. Instead of a single field equation (Einstein equation) let us consider a set of two coupled equations (which implies two interacting twin universes). Everything can be justified on mathematical grounds. Matter attracts matter through Newton's law. We call the second matter, which belongs to the second universe : "ghost matter".

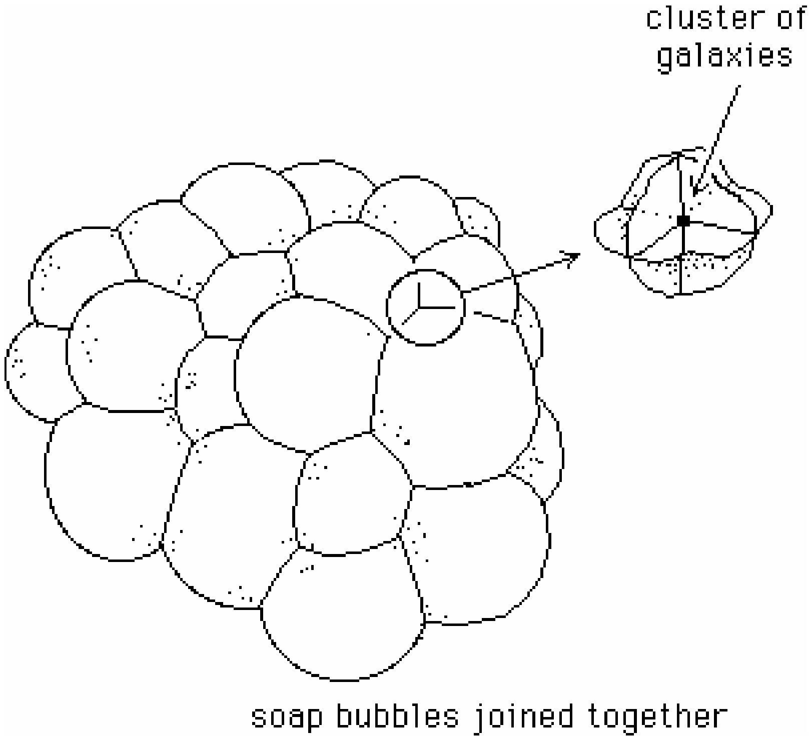
Two "ghost particles" attract each other, through Newton's law. But a "normal" particle and a ghost matter particle repel each other through an "anti-Newton's law" (the force is proportional to the inverse of the square of the distance between the two). All that comes from the mathematical structure of the system, but it can only be understood by a specialist in differential geometry.

But we get many interesting results.

For a long time now astronomers have been puzzled by the appearance of the VLS, the "Very Large Structure" of the universe. We knew that galaxies tend to assemble in clusters of hundreds or thousands of individuals, such as the Virgo and Coma clusters. It was thought that these clusters would belong to wider structures which they called "superclusters". But after patient observation the results turned out to be fairly different. Matter (galaxies) was found to be organized around large empty bubbles (100 light years wide on average).

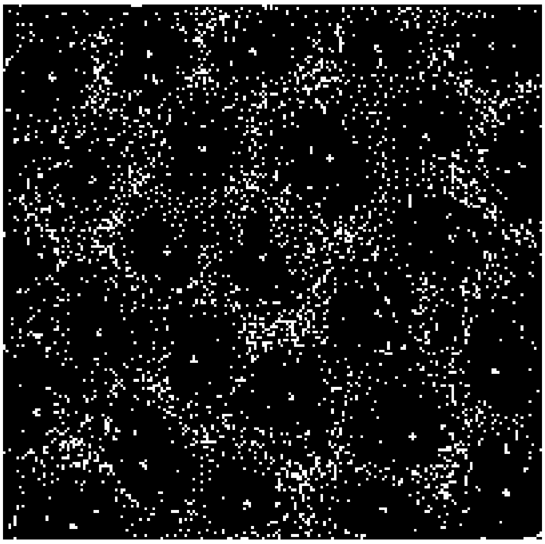


It looks like soap bubbles joined together :

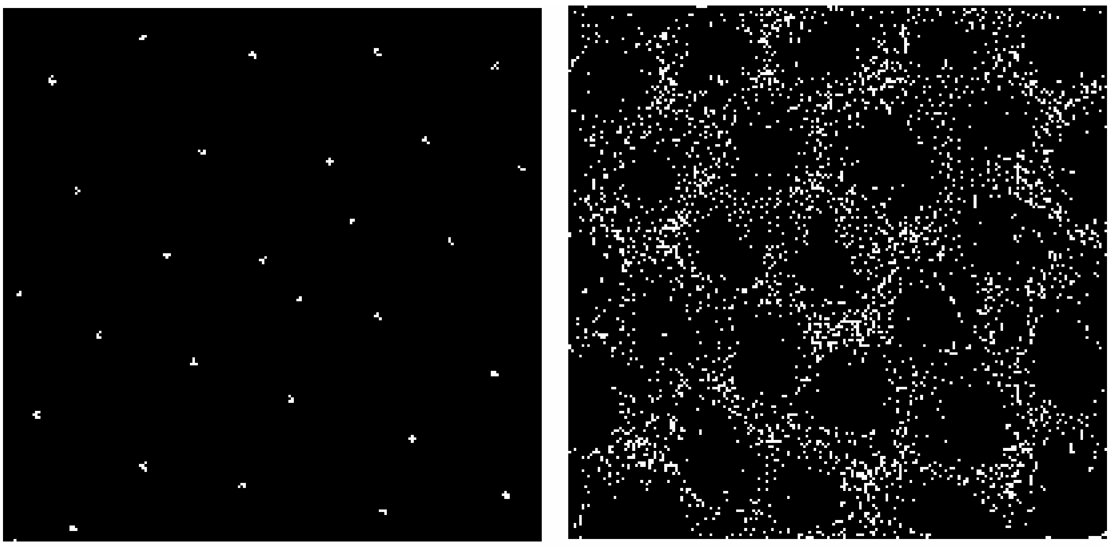


According to this new large size design, clusters of galaxies were the "knots" of such a distribution, the points at which several bubbles joined.

In 1994, using our model, Frédéric Landsheat undertook a numerical 2d simulation on a big system and showed that, in the early universes, the two populations tend to separate. The ghost matter forms big clumps and repels the ordinary matter, ours, into the remaining space :



On this figure the reader can see clumps of ghost matter, situated at the center of each "cell". On the next figure: left, the ghost matter's clumps, right, the galaxies' distribution over space. We rediscover the cells, shown up by observation.



ghost matter clumps — "galaxies", in the remnant place

Many attempts were made previously using numerical simulations with a single population. But the resulting systems were not stable in time.

However Landsheat obtained remarkably stable structures in time. The explanation : the clumps stabilize the cells and the cells confine the clumps at their geometric center. Between the two : some "no-matter's land".

We considered that to be an interesting result.

A complete description of these recent results would require a whole book. It concerns a new description of the universe, as was evoked in preceding sections.

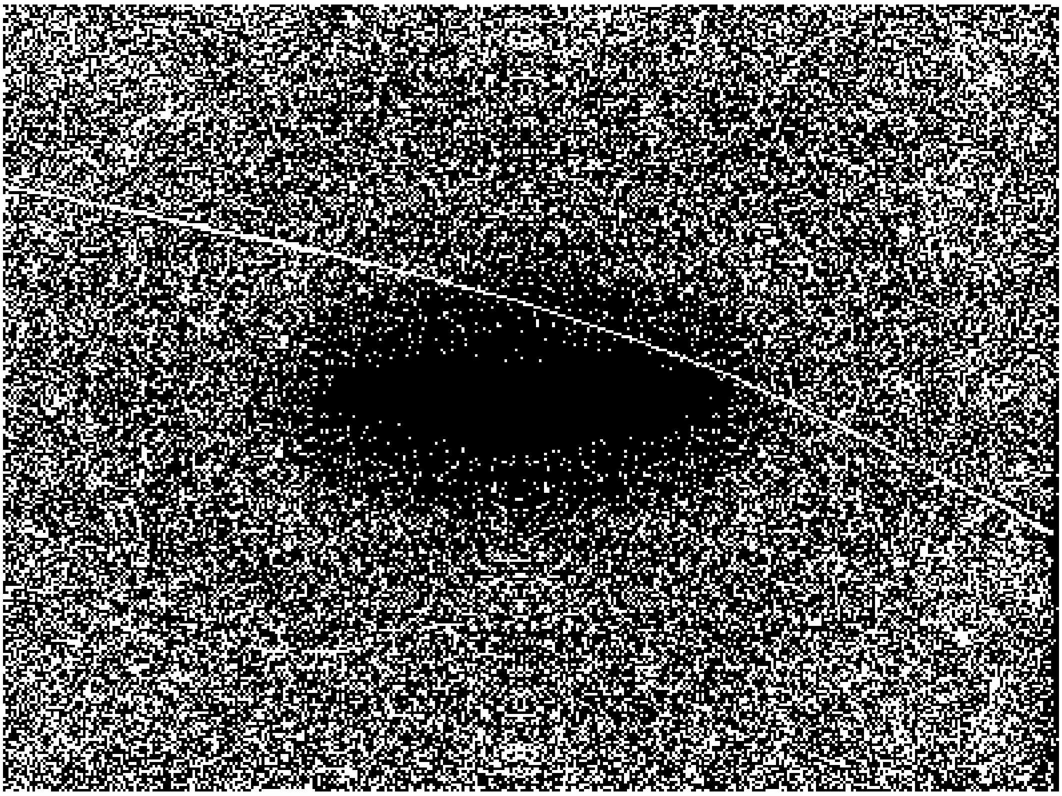
The birth of the early galaxies is another interesting aspect of research. We know that galaxies are very ancient objects but we don't know how they formed. Our numerical simulations give a relatively fast formation rate for ghost matter clumps. These then repel ordinary matter which then tends to form this "soap bubble joined together" system. Matter is compressed into a flat structure during the process, thus allowing fast radiant cooling. We believe that this could be the phenomenon triggering the formation of galaxies. They first take the form of flat structures and knots. Matter immediately invades the interstitial space between them and tends to confine the young galaxies because of repulsive forces. This view of galaxies nested in a distribution of ghost matter distribution was presented in a preceding section, as was the spiral structure created by the friction of the galaxy on its invisible environment.

We think that this phenomenon, confinement due to the surrounding repulsive ghost matter, explains the "missing mass effect".

Ghost matter may be considered as a sort of dark matter, except that instead of being located within galaxies, it lies outside.

We have shown (see the papers on the web site) that the surrounding ghost matter produces a "negative gravitational lensing effect". Traditionally, strong gravitational lensing effects are considered as a proof of the existence of dark matter in galaxies and clusters of galaxies. Some people even say that one can establish the distribution of dark matter from these lensing measurements.

The matter-ghost matter model brings an alternative interpretation of the phenomenon. In effect, if ghost matter repels ordinary matter, it "repels" photons too. So that a hole, in a uniform ghost matter distribution, would focus light rays as follows :



Then the deviation of light rays is a combination of two effects :

- One due to the mass of the galaxy (10 %)
- One due to the environment of ghost matter (90%)

The following text is based on these papers :

Jean-Pierre Petit et Pierre Midy : Geometrization of matter and anti-matter through coadjoint action of a group on its momentum space. 1 : Charges as additional scalar components of the momentum of a group acting on a 10d-space. Geometrical definition of anti-matter. Geometrical Physics B : 1, April 1998.

Jean-Pierre Petit and Pierre Midy : Geometrization of matter and anti-matter through coadjoint action of a group on its momentum space. 2 : Geometrical description of Dirac's anti-matter. Geometrical Physics B : 2, April 1998.

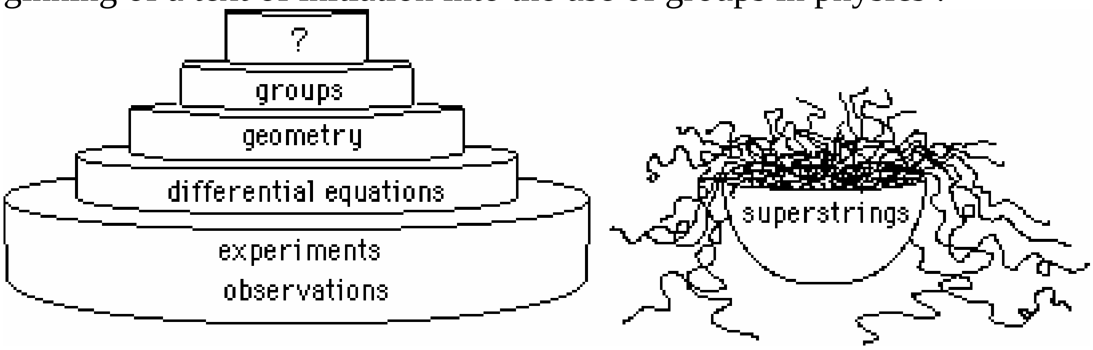
Jean-Pierre Petit and Pierre Midy : Geometrization of matter and anti-matter through coadjoint action of a group on its momentum space. 3 : Geometrical description of Dirac's anti-matter. A first geometrical interpretation of anti-matter after Feynmann and so-called CPT-theorem. Geometrical Physics B : 3, April 1998.

Jean-Pierre Petit and Pierre Midy : Geometrization of matter and anti-matter through coadjoint action of a group on its momentum space. 4 : The Twin group. Geometrical description of Dirac's anti-matter. Geometrical interpretations of anti-matter after Feynmann and so-called CPT-theorem. Geometrical Physics B : 4, April 1998.

These papers are all based on group theory and have been presented in several important mathematical seminars, in France. They are highly appreciated by French mathematicians. But not by astrophysicists. We will see why.

A mathematical barrier.

All our work in astrophysics and cosmology is based on the theory of groups. Here is a reproduction of a drawing which can be found at the beginning of a text of initiation into the use of groups in physics :



A group is considered as the most abstract tool of the mathematical world but, paradoxically, it is not technically difficult. The beginning of Geometrical Physics B is a 150 page introduction to the use of "dynamic groups" in physics. To be able to read it you just have to know what a matrix is. For people who do not know, there are lots of definitions in this section of the website. If you have a minimum of knowledge in algebra, you can read these pages. You could go to a desert island with them and wouldn't need anything more (except, perhaps, some aspirin).

From a purely technical point of view this part of mathematics is much simpler that some others, such as that on differential geometry in Geometrical Physics A, which refers to General Relativity.

However I would not say :

- Take the first part, Geometrical Physics A, and go to a desert island to study it.

It wouldn't work. Too hard, too complex. Too much additional material is required. But world of the group is technically simple, I swear it.

I would be happy if a few young students read the introduction to Geometrical Physics B and got some intellectual benefit from it. I really hope they do. I wrote this part specially for them. Remember ;

- A little abstraction distances physics.
- A lot of abstraction brings it back.

The basis of this entire approach is an invention of the French mathematician Jean-Marie Souriau, now retired but well known throughout the world among specialists in group theory. A published work of his is still available in English, though it is difficult to read, entitled

Structure of Dynamic Systems

Published by the American editor Birkhauser. But my good friend Jean-Marie likes mathematical concision and very precise language so that while his work is crafted like a jewel, I wouldn't encourage my worst enemy to read it. Souriau invented lots of things such as :

The coadjoint action of a group on its momentum space.

I honestly believe that this is probably the greatest discovery in physical theory for the last fifty years. I also think that Souriau is the Lagrange of the 21st century. His ideas have brought me both enthusiasm and inspiration.

Try this. Go to a neighbor's house, knock on the door and say :

- Do you know what the coadjoint action of a group on its momentum space is ?

People will probably answer "no". Try again with a physics professor at university. Probably the same negative reply. Try again with a specialist in theoretical physics. Once more, it is highly likely that the reply will still be "no". I'm not even sure that if you took an average physician from the Department of the Theory of Physics at the Institute of Advanced Studies of Princeton, you wouldn't still have as little success.

Conclusion : very few people know of this mathematical tool, except high level mathematicians, mainly specialists of group theory. But, generally, these guys ignore the fact that it is tool that can be efficiently used in physics. They have the key, not the lock . You'd think it was a Woody Allen story.

Two men are traveling in a train. One suddenly says to the other :

Do you know what the coadjoint action of a group on its momentum space is ?

and the other replies :

- Hey, you want my hand in your face?

Why is such a concept so little known and used twenty five years after its discovery?

For several reasons.

- The first is that my friend Souriau neither speaks, writes nor reads English, which, nowadays, is a serious handicap. Alas, at his age he must consider it incurable.

- The second is that he has practically invented his own mathematical language, spoken only by an infinitely tiny number of people today, the language of **symplectic geometry**.

Let us try another experiment. Go up to a mathematician when he's doing his shopping in the morning, or as he leaves church or the synagogue, and ask him what symplectic geometry is. You'll see him run off as fast as he can.

I learnt Souriau's language but the last time I used it during a lecture in a mathematics institute I had to have a local translator.

- The third reason is that when a phrase in a text was not strictly indispensable, Souriau removed it. One of Souriau's works, from the point of view of density, is like a lump of neutron star, you can pass three months on two pages.

- The fourth is that Souriau does not criss-cross the world from congress to congress. he prefers to stay in his apartment with his cat Pioum, discuss with friends and refuses to give fancy names to his theories, such as black hole, catastrophe or chaos theory, which the general public likes. How do you set about marketing a concept such as the **symplectic cohomologic class**.

I always said to him :

- Jean-Marie, you need an agent!

Geometrization of elementary particles.

Why is this very abstract concept of coadjoint action so important? Because it give us the possibility of geometrizing physics. It transforms mass, energy, impulsion and spin into pure geometric objects. Believe me, it's really beautiful.

All you need is a simple family of square matrixes, obeying a certain set of rules, which transforms it into a group. As suggested in the above drawing, a group generates its own space, its own geometrical world. The groups of physics produce particles, considered as pure geometrical objects.

In Euclid's world, we find families of objects : straight lines, planes, spheres, points. These geometrical objects form Euclid's zoo. Particles are similar. They form the zoo of a different geometrical world, that's all.

The figure also suggests that groups lead to rather useful differential equations, as the mathematician Jean-Marie Souriau showed in 1972 by the "KKS" method, or Kostant Kirilov Souriau method.

From the Bargmann group, Souriau derived a non-relativistic Schrödinger equation.

From the central extension of the Poincaré group he derived the Klein-Gordon equation. Other variants led him to the Pauli and Dirac equations

Some years ago, I became fascinated by the world of this old alchemist Souriau and the tools he invented. I asked him to teach me and he did. After a certain time I tried to invent new groups. Or more precisely, I extended some existing ones to a higher number of dimensions.

In a preceding section I briefly mentioned the young Pole, Kaluza, who added a fifth dimension to the universe in 1920. People once called this additional dimension ζ (spell dzeta. It's a Greek letter).

All Souriau's works are based on a five dimensional representation of the universe :

$$(x , y , z , t , \zeta)$$

What is this additional dimension? For Souriau it is a pure mathematical tool making the development of the quantum circus possible.

Physicist are puzzled. Some think "this is a very small dimension, so small that we cannot measure it". I'm not quite sure they are right.

When physicists try to define a characteristic length associated with this additional dimension, they find the Planck length :

$$10^{-33} \text{ cm}$$

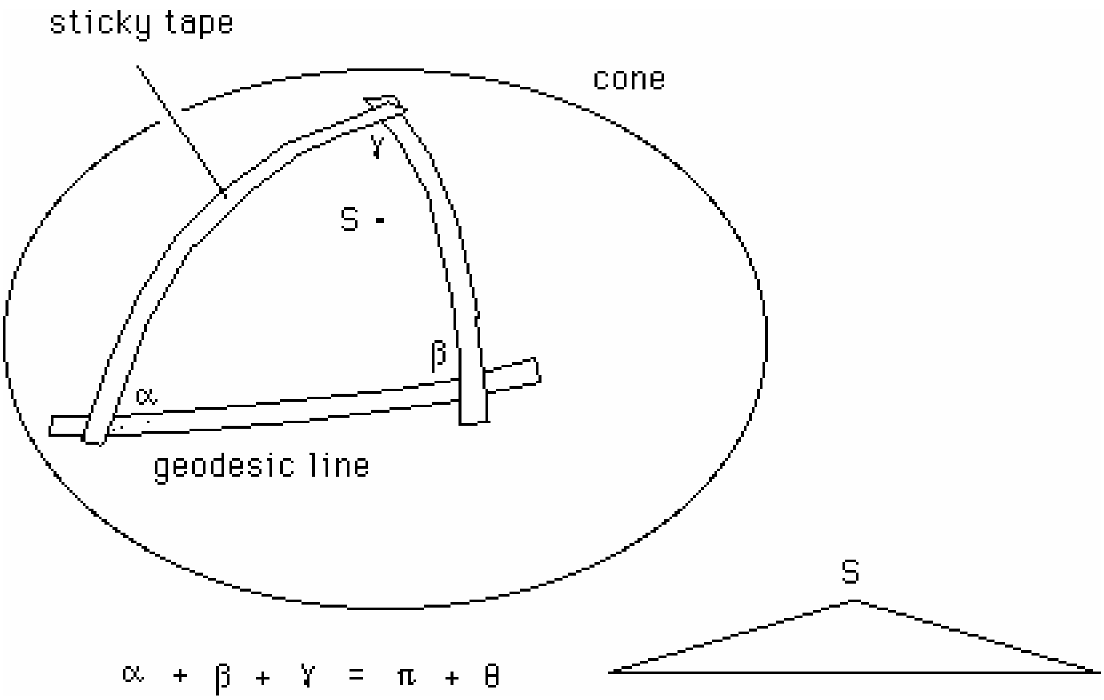
Very, very small....

Personally I tend to think that the very smallness of the length is some sort of a message from Nature. The fifth dimension belongs to the quantum world. It looks like if the message could mean :

- Give up. I am a simple number, an angle.

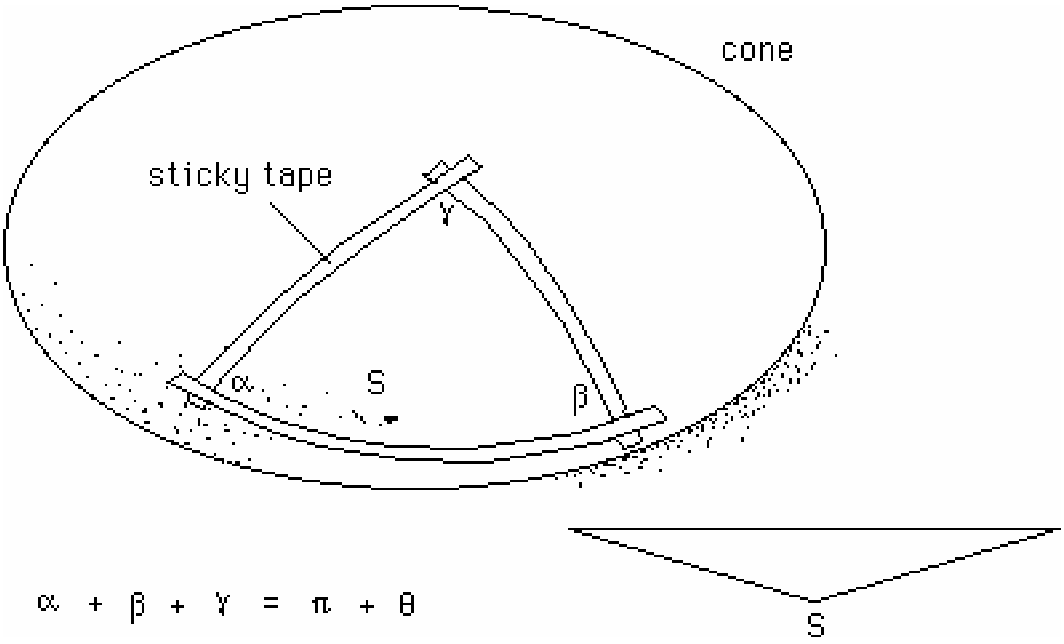
We have suggested above that the mass could be identified with the curvature of space. According to this idea, the summit of a cone is a point-like mass.

A cone is a portion of space which contains a certain amount of curvature, this latter being concentrated into a point. If we trace a triangle around the summit made of geodesic lines, the excess of the Euclidean sum allows us to measure the "quantity of angular curvature" contained within this part of the surface.



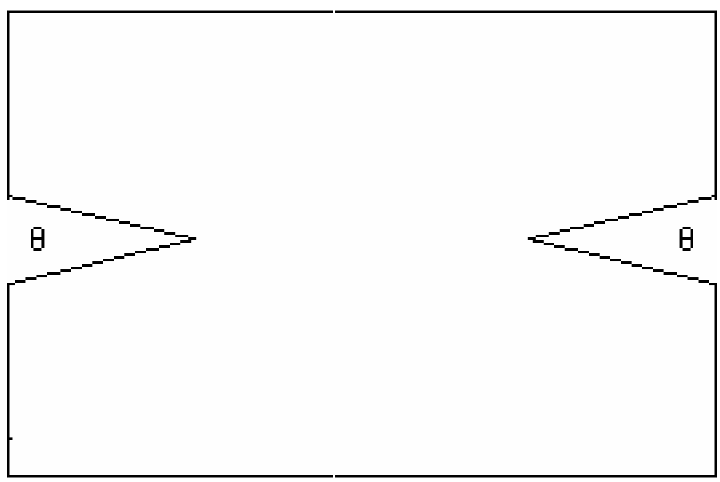
The sum of the angles is not dependent on the layout of the geodesics, which we obtain by sticking adhesive tape on the surface of the cone, providing that the triangle contains the summit S. To find out more see the beginning of Geometric Physics A.

This cone, this two dimensional geography, exists independently of the space in which we have chosen to represent it (here a three dimensional space). If we turn our cone inside out and decide to trace our geodesics "on the other side", it won't make any difference to the result.

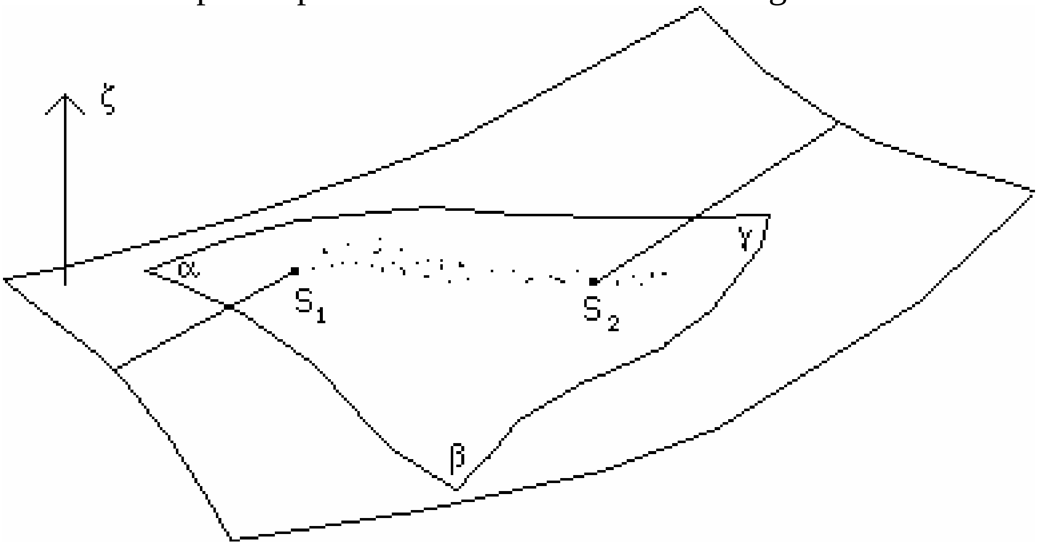


The only difference is that in the two figures the point of the cone "points" in a different direction.

We know that we can create a cone from a plane simply by making a cut. In the same way we can create two conical points on the surface :



There are also two ways to close the lines of the cutouts. If we choose to have our conical points point in different directions we get :



We have already covered this above where we called this fifth dimension the Kaluza dimension. We have also said that this figure was a good image of the matter/anti-matter duality.

I have extended this to a greater number of dimensions. Instead of adding a unique fifth dimension :

$$(x , y , z , t , \zeta)$$

I have added six :

$$(x , y , z , t , \zeta_1 , \zeta_2 , \zeta_3 , \zeta_4 , \zeta_5 , \zeta_6)$$

The reader will instantly cry :

- Stop. I already had problems going from three dimensions to four. With five I can no longer follow and six is touching on madness?

For a long time I worked with a blind mathematician. he turned spheres in his head (the eversion of the sphere).

The eversion of the sphere is a star subject in mathematics, its first version proposed by the American mathematician Anthony Phillips in 1967 (published in the Scientific American that year). Morin found a second. I personally found a curious way of everting a torus. We will come to all this later on the website.

I remember extremely difficult sessions with the blind mathematician. I had terrible headaches but he would say to me with a smile :

- Close your eyes and you'll see things more easily.

Modern physics requires an extension of the geometric context, by an increase in the number of dimensions in space.

What is quantum mechanics?
Nothing other than geometry in five dimensions instead of four.

But how does one adventure into such strange, unthinkable worlds?

Learn to think differently. Group theory is the light that illuminates obscure worlds. The group not only allows us to manipulate space, it is space itself, it holds it within.

Souriau showed in another book (Géométrie et Relativity, Editions Hermann, 1964) that the passage from matter to antimatter is obtained by inverting the fifth dimension, by changing ζ τo - ζ .

Remember Plato. The Greek philosopher believed that men took for real what was, in fact, just shadows projected on walls of a cave. Objects which will forever escape our direct perception.

For the physicist of today, space and time represent the wall of the cave. The structures appearing there are just shadows. And we are just shadows observing other shadows. At best, we can only try to imagine the mechanism of the magic lantern outside our perceptive universe of four dimensions, three of space and one of time. The lantern is localized in a ten dimensional space. Today, many people are in agreement with this figure.

The additional dimensions are like invisible cogwheels. By inverting the fifth dimension, Souriau changes the place of a cogwheel and the particle-shadow changes its behavior. It begins to behave like ... antimatter.

I too tried to dream of this magic lantern that the hand cannot reach and the eye cannot see. I gave it six supplementary cogwheels and I generalized Souriau's idea by supposing that by inverting the six cogwheels simultaneously I would obtain a purely geometric definition of antimatter.

I considered that the inversion of the six
additional dimensions was the
geometric definition of the concept of antimatter.

We say that we should judge a tree by the fruit that it bears. It so happens that by giving space six additional dimensions I was able to make an equal number of quantic sizes which could be identified as :

the electric charge

the baryonic charge

the leptonic charge

the muonic charge

the tauonic charge

the gyromagnetic coefficient.

First, the geometrization of the elementary particles and a description in which the quantum numbers appear as pure geometric quantities.

The specialist will immediately object :

- What about quarks? You don't deal with them !

I agree. But I hold something that will give , as we will later show, a clear geometrical status to anti-matter.

Souriau was the first to give its geometric signification to spin in 1972, which became a little more sophisticated than people had previously believed. Since Souriau, particles have ten geometrical attributes. When grouped, they form what he calls the particle's momentum, i.e. the set :

(Energy, impulsion, spin)

Geometrical expansion (with six supplementary dimensions) gives these particles six additional attributes :

$$(q , c_B , c_L , c_\mu , c_\tau , \varpi , \text{Energy, Impulsion, Spin})$$

A peculiar particle is a peculiar choice for this set of quantities. But not all can be used. The charges can have three different values :

Electric charge $q = \{ +1 , 0 , -1 \}$
Baryonic charge $c_B = \{ +1 , 0 , -1 \}$
Leptonic charge $c_L = \{ +1 , 0 , -1 \}$
Muonic charge $c_\mu = \{ +1 , 0 , -1 \}$
Tauonic charge $c_\tau = \{ +1 , 0 , -1 \}$

If we limit the description to photons, protons, neutrons, electrons, neutrinos, and their anti-particles, the can take twelve values :

Gyromagnetic factor

$$\varpi = \{ \pm \varpi_p , \pm \varpi_n , \pm \varpi_e , \pm \varpi_{\nu e} , \pm \varpi_{\nu \mu} , \pm \varpi_{\nu \tau} \}$$

p : refers to a proton
n : refers to a neutron
e : refers to an electron
ν_e : refers to an electronic neutrino

ν_μ : refers to a muonic neutrino
ν_τ : refers to a tauonic neutrino

Specialists knows that three different types of neutrino exist.
All the charges of the photon are nil. The same is true for its gyromagnetic factor. Then, a photon is the set :

$$(0, 0 , 0 , 0 , 0, 0 , \text{Energy, Impulsion, spin} = 1)$$

A proton corresponds to :

$$(+1 , 1 , 0 , 0 , 0 , \varpi_p , \text{Energy, Impulsion, Spin} : 1/2)$$

An electron corresponds to :

$$(-1 , 0 , 1 , 0 , 0 , \varpi_e , \text{Energy, Impulsion, spin} : 1/2)$$

The classification of the usual particles becomes very simple :

	proton	electron	neutron	photon	neutrinos		
					ν_e	ν_μ	ν_τ
electric charge	1	-1	0	0	0	0	0
baryonic charge	1	0	1	0	0	0	0
leptonic charge	0	1	0	0	1	0	0
muonic charge	0	0	0	0	0	1	0
tauonic charge	0	0	0	0	0	0	1
magnetic gyrofactor	ϖ_p	ϖ_e	ϖ_n	0	?	?	?
mass	$m_p > 0$	$m_e > 0$	$m_n > 0$	0	0	0	0
energy	>0	>0	>0	>0	>0		
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	$\frac{1}{2}$		

particles

As we can see, there are three different neutrinos, called :

νe : electronic neutrino
$\nu\ \mu$: muonic neutrino
$\nu\ \tau$: tauonic neutrino.

The electronic neutrino corresponds to the set :

$$(0 , 0 , 1 , 1 , 0 , \varpi_{\nu e} , \text{Energy, Impulsion, spin} : 1/2)$$

Notice it has no electric charge but, just as for the electron, it does have a leptonic charge

$$c_L = 1$$

(in Greek, leptos means light, baryos means heavy).

The superstring men are searching for the basic entity, the ten dimensional object from which everything comes.

Personally, I think that if such an object were discovered one day, it would be linked to what Souriau calls the *momentum*. Then, a good name could be :

momentum relied pioneer

in short :

morpion

Superstring men hunt the morpion.

This unitary idea means imagining that the magic lantern is a sort of crystal which can take an infinity of positions and produce an infinity of colors. According to the different shades there will be families of colors. We could thus compare the particles mentioned above to the totality of colors :

red, orange, yellow, green, blue, indigo

(I hasten to add that this has nothing whatsoever to do with what is called the quantic chromodynamic)

There are an infinity of shades of orange or blue which suggest, in this didactic image, the different state of particles which could be endowed with a whole range of energies or impetuses. the "spin vector" is quantified. Its module is constant but it can adopt an infinity of different directions.

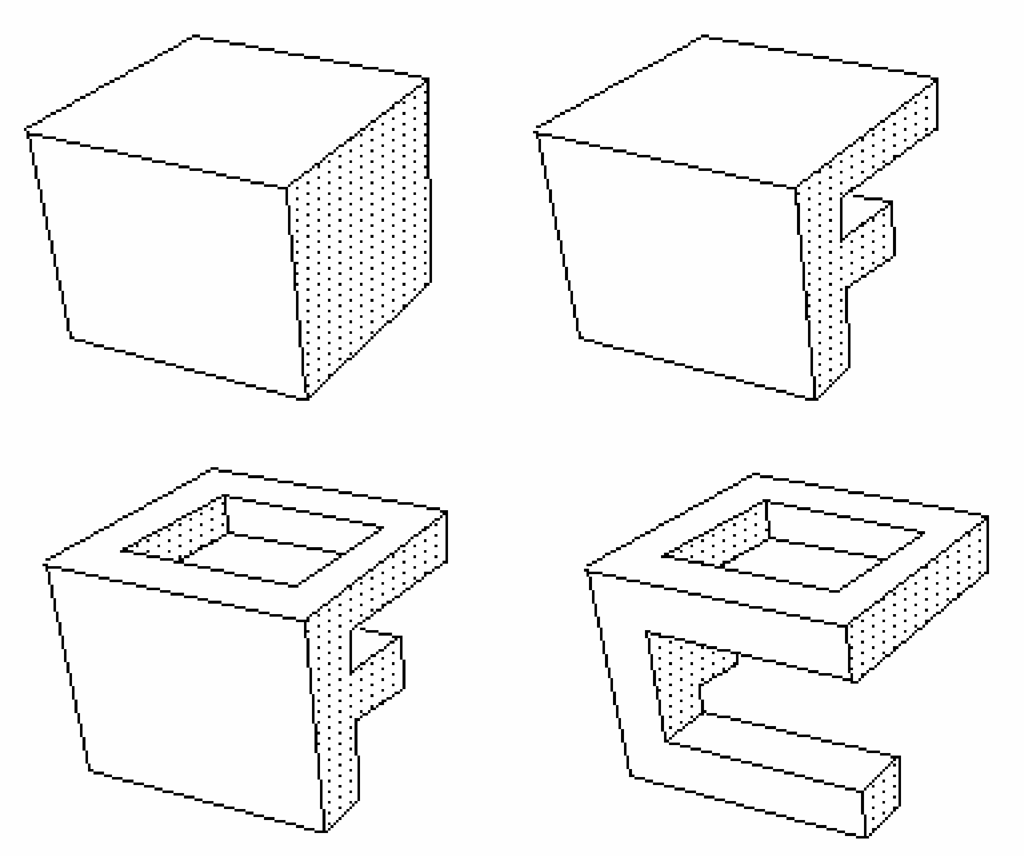
A particle could be seen as the reflection of
a crystal projected on the "cave wall".

The spectra can be prolonged? Other radiation exists beyond visible light, ultraviolet, X-rays , gamma rays.

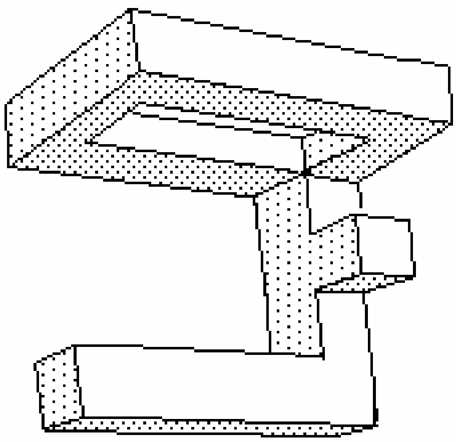
Ideally we would like to find not only the elementary geometric entity but also the tool, the group, allowing us to act on it and give it every possible appearance.

Currently we are not able to do such things. We content ourselves with knowing a few rules concerning particles of the type, "red plus yellow equals orange", or "blue plus yellow equals green".

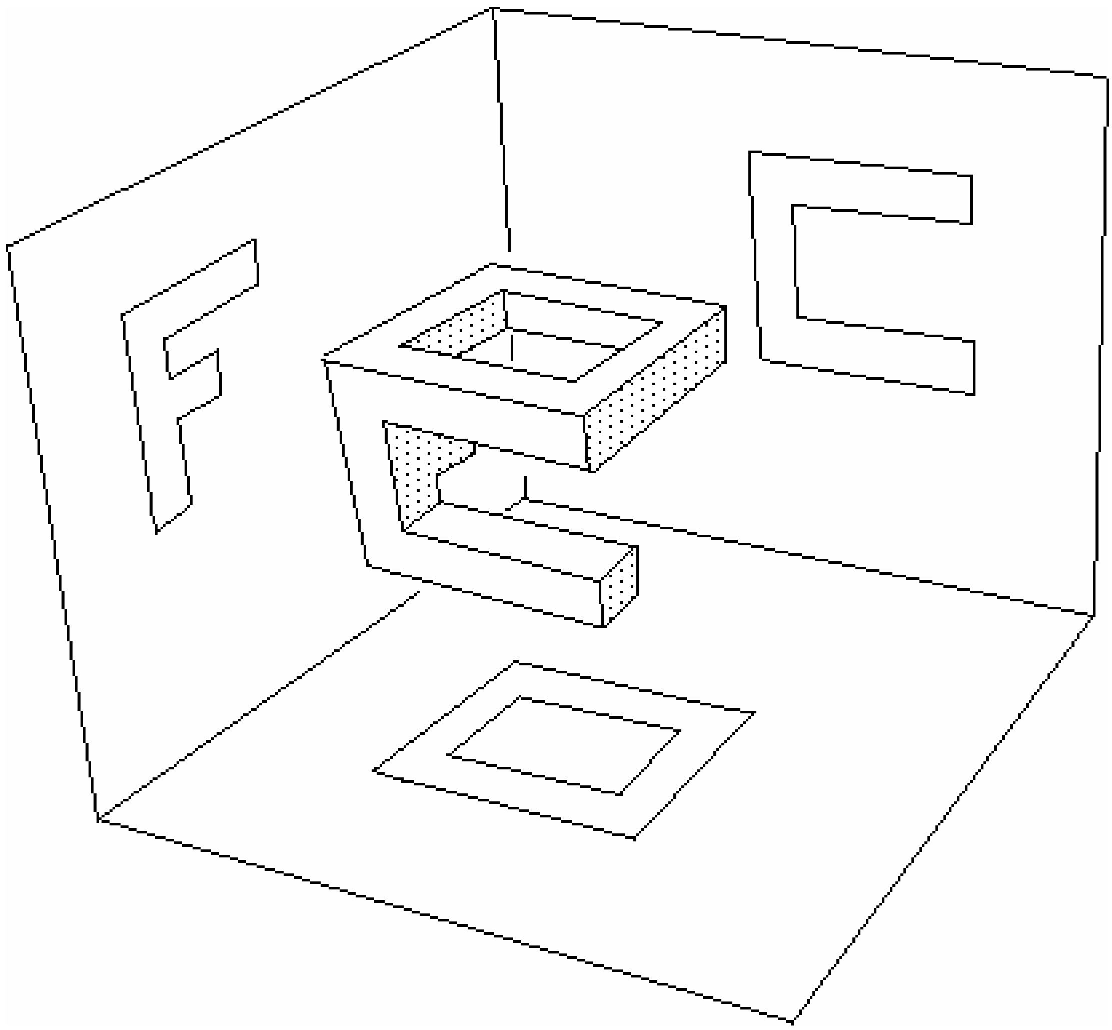
We can also explore the *symmetries* of particles. here we shall employ a different image. Let us take a wooden cube and machine it in three perpendicular directions as in the following diagram :



The same object seen from a different angle :



When lit laterally or vertically, the object projects different shadows :

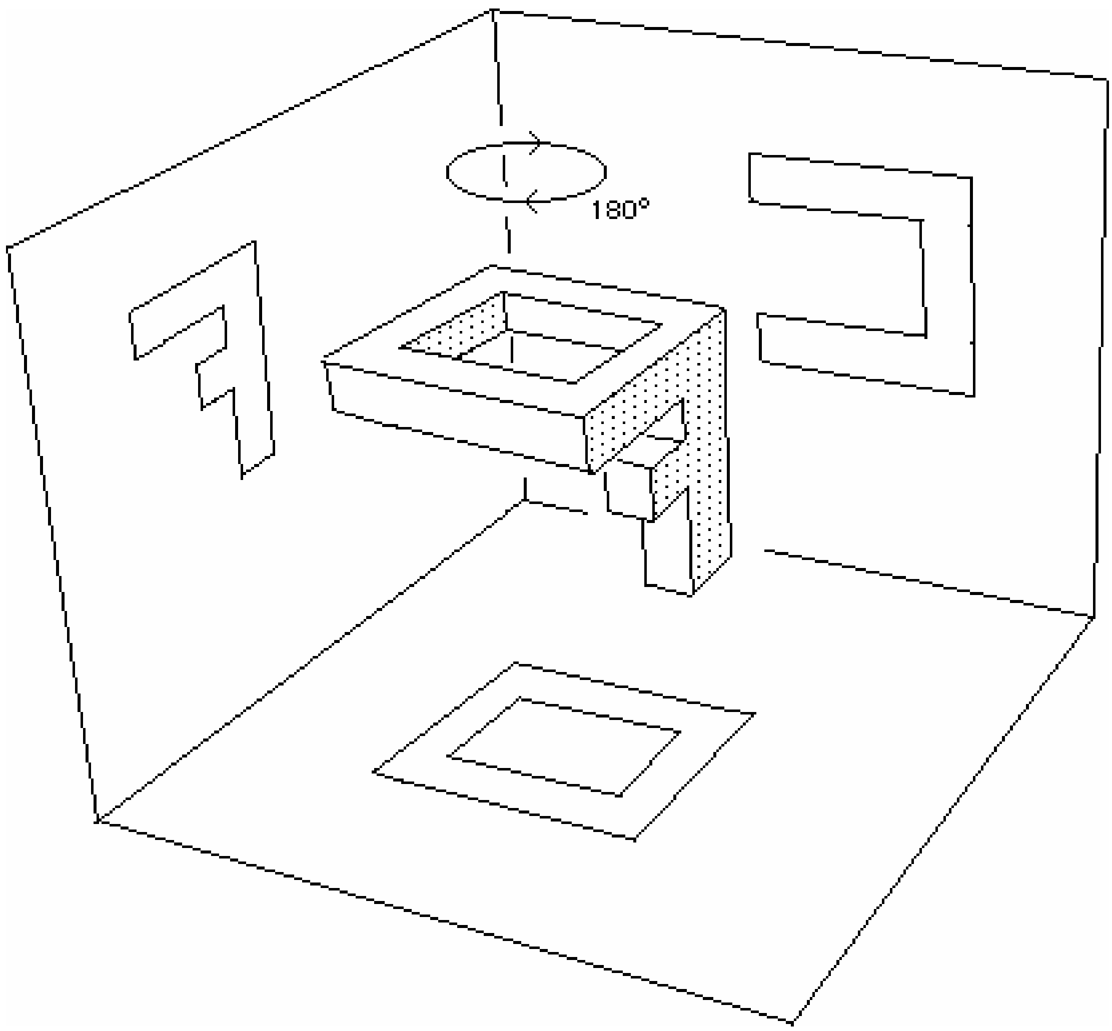


We made sure here that the projections looked like letters of the alphabet:

F C O

We have made light arrive from three different directions but we could just have well had one screen and turned the object. Its not the crystal that everyone is looking for but at least it gives us an idea. If we limit ourselves to rotations of 90° we can see that different shadows can already be produced with just one object. Now let us look at 180° rotations.

It becomes obvious that some shadows are modified by a rotation of 180 degrees while others are not. The following rotation has transformed the letter F to its mirror image whereas the letter O remains unchanged :



Imagine that elementary particles are sorts of shadows coming from a decadimensional machine that we don't yet know how to design or conceptualize. Nevertheless we have access to certain of its properties of symmetry and the duality matter-antimatter is one of them.

There are several classic and well known symmetries. One is the "right-left" symmetry (the image of an object in a mirror"). The physicist calls it a P-symmetry (P for "parity"). The mathematician says that the object and its image in a mirror are *enantiomorphic.*

A second symmetry is the T-symmetry. Same story, but with a reversed time.

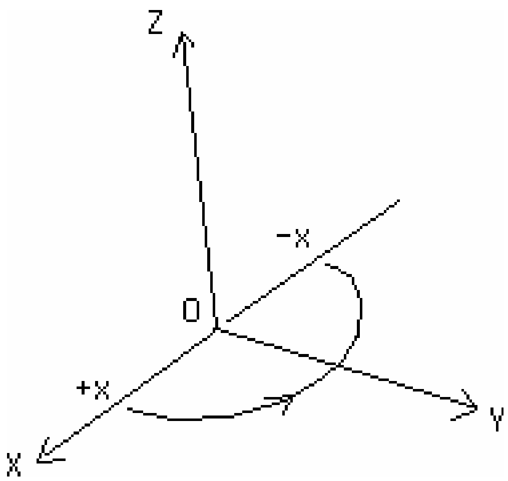
A third is called C-symmetry, or charge conjugation. It corresponds to:

$$(q , c_B , c_L , c_\mu , c_\nu , c_\tau , \varpi) \longrightarrow (-q , -c_B , -c_L , -c_\mu , -c_\nu , -c_\tau , -\varpi)$$

We have introduced a new symmetry, the ζ-symmetry, corresponding to:

$$(\zeta^1, \zeta^2, \zeta^3, \zeta^4, \zeta^5, \zeta^6) \longrightarrow (-\zeta^1, -\zeta^2, -\zeta^3, -\zeta^4, -\zeta^5, -\zeta^6)$$

A change of the signs of a coordinate is equivalent to a 180° rotation.



After Dirac, the transformation of matter into anti-matter corresponds to a C-symmetry. The signs of the charges are reversed, but energy and mass are unchanged.

What about the photon ? Its charges are zero :

(0, 0 , 0 , 0 , 0, 0 , Energy, Impulsion, spin = 1)

Because - 0 = + 0 the photon is identical to its antiparticle. Think about the analogy : the shadow of objects turning in front of a projector. Everything is shadow, as Plato said. The group is the projection system and during the rotation operation the shadow, called photon, remains invariable. The didactic image of the photon is the letter O that we met before, the shadow of our sculpted wood cube which remains unchanged when we turn it through 180°.

We get the second zoo :

antiparticles after Dirac

	anti-proton	anti-electron	anti-neutron	anti-photon	anti-neutrinos		
					$\overline{\nu}_e$	$\overline{\nu}_\mu$	$\overline{\nu}_\tau$
electric charge	- 1	1	0	0	0	0	0
baryonic charge	-1	0	1	0	0	0	0
leptonic charge	0	- 1	0	0	-1	0	0
muonic charge	0	0	0	0	0	-1	0
tauonic charge	0	0	0	0	0	0	-1
magnetic gyrofactor	$-\varpi_p$	$-\varpi_e$	$-\varpi_n$	0	-?	-?	- ?
mass	$m_p > 0$	$m_e > 0$	$m_n > 0$	0	0	0	0
energy	>0	>0	>0	>0	>0		
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	$\frac{1}{2}$		

There are three different neutrinos. As they have charges (leptonic, muonic, tauonic) the are not identical to their antiparticle (we don't know if they own a non-zero gyromagnetic factor).

Inhale deeply. The breath of quantum mechanics begins to fill you.

Not one antimatter but two.

During the fifties Richard Feynmann, a Nobel prizewinner, put forward the following idea. According to him, if we take the image of a particle and we make it evolve backwards in time, it will become indistinguishable from an antiparticle.

The symmetry right-left is the P-symmetry (P means "parity").

The inversion of time is called T-symmetry.

Then Feynmann said :

A PT-symmetrical particle is identical to a C-symmetrical particle.

After Dirac, a C-symmetrical particle (all charges inverted) is its anti-particle. Feynmann suggested that a PT-symmetrical particle was also an antiparticle.
Consider an electron, its electric charge is q = - 1. It also own a leptonic charge

$$c_L = 1$$

Its spin is 1/2. It also own a non-zero gyromagnetic factor ϖ_e . To sum up, an electron corresponds to the set :

$$(-1 , 0 , 1 , 0 , 0 , \varpi_e , \text{Energy, Impulsion, spin} : 1/2)$$

After Dirac, an anti-electron corresponds to the set :

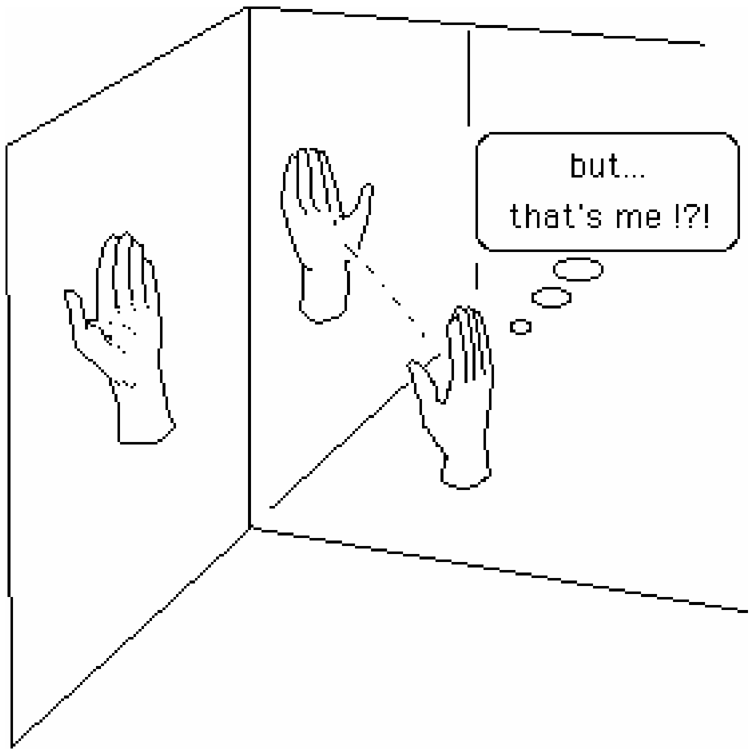
$$(+1 , 0 , -1 , 0 , 0 , - \varpi_e , \text{Energy, Impulsion, spin} : 1/2)$$

The energy is still positive. The spin is unchanged.

Feynmann suggested another description of anti-matter. The anti-matter of Feynmann has the same electric charge as the corresponding particle of matter. But it travels backwards in time. It is also P-symmetrical.

The following figures show that the combination of two successive P-symmetries is identity.

PP = identity.



The " CPT theorem"

Feynmann thought that the symmetries C and PT were equivalent :

C = PT

As a consequence, as :

$$CC = \text{identity}$$

it gives :

$$CPT = \text{identity}$$

This the famous so-called "CPT-theorem", which asserts that if all the charges of a particle are reversed (C-symmetry), that is we take its image in a mirror (P-symmetry) and it travels backwards in time (T-symmetry), it behaves exactly like an ordinary particle.

But this "theorem" is not a real theorem. You will not find its demonstration anywhere.

Negative energy particles ?

For almost half a century theoretically physicians considered such inverted particles or antiparticles going backwards in time as mental artifices. No one would have risked saying they did existed or didn't.

"Invert space", that seemed possible. Mirrors do it easily.

Invert charge : we do it every day in particle colliders by making antimatter (Dirac's antimatter).

Invert time, now there is something really disconcerting. It then becomes a question of mathematics. We said above that groups act like "particle transformers". It is possible to build groups which reverse the pointers of objects' time by inverting their movement and making them go backwards in time, just as if we were winding a cinema film backwards.

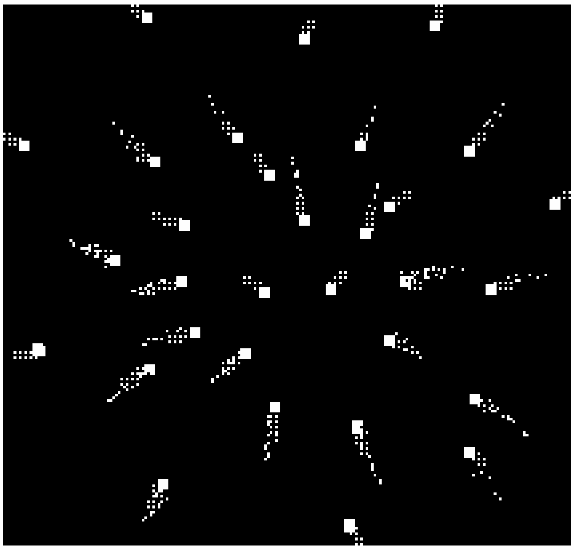
This the coadjoint action of a group on its momentum space allows us to understand what sort of dimensions are associated with particles, particularly their energy and their impetus.

According to Einstein's ratio of equivalence :

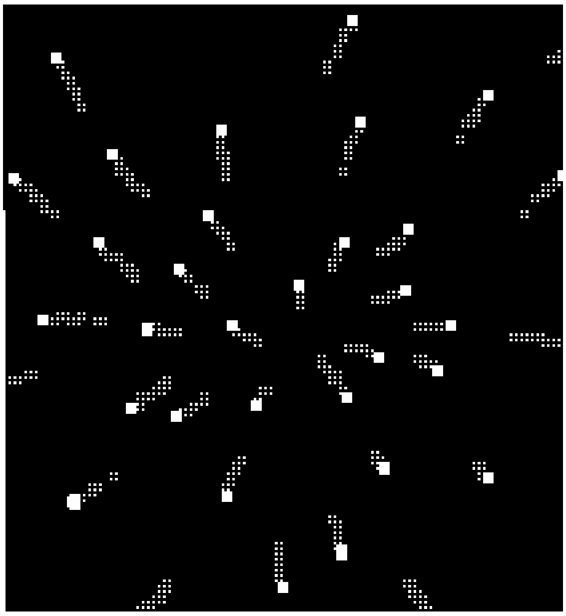
$$E = mc^2$$

Energy is synonymous with mass. I'll give you a fairly good image to help you understand. You know that there are clouds of interstellar matter in galaxies. Sometimes these clouds are affected by gravitational instability (see the model of the mattress and buckshot above. Left to their own devices, the atoms of a gas cloud attract each other and fall on top of each other to form a more condensed object : a proto-star.

So let us sit next to such a contracting cloud and film it. We see that atoms fall towards the center of gravity of the system increasingly rapidly.



If we run the film backwards what do we see? We see the opposite process. The masses will distance themselves more and more from each other.



This (crude) image suggests that when the time is reversed, mass is reversed. Only the coadjoint action of a group on its momentum space allow us to demonstrate that. Everything becomes clearer if one thinks in terms of groups. But which groups are able to reverse time ?

Well, all the dynamic groups on which our physics is based, for example the Lorentz group, pillar of Special Relativity. Every physicist knows that all the equations of physics are "time-reversible".

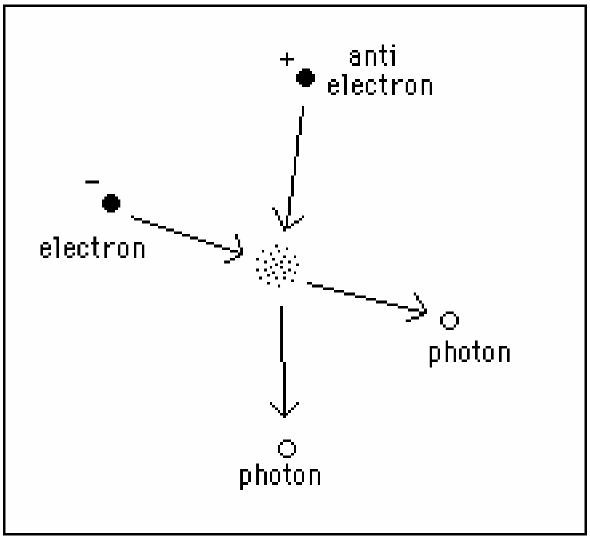
As a consequence, Feynmann anti-matter does not identify Dirac anti-matter, for their mass and energies have opposite signs.

Feynmann anti-matter has negative mass and energy.

Similarly the CPT-symmetrical of a particle travels backwards in time. The CPT-theorem must then be rephrased as follows :

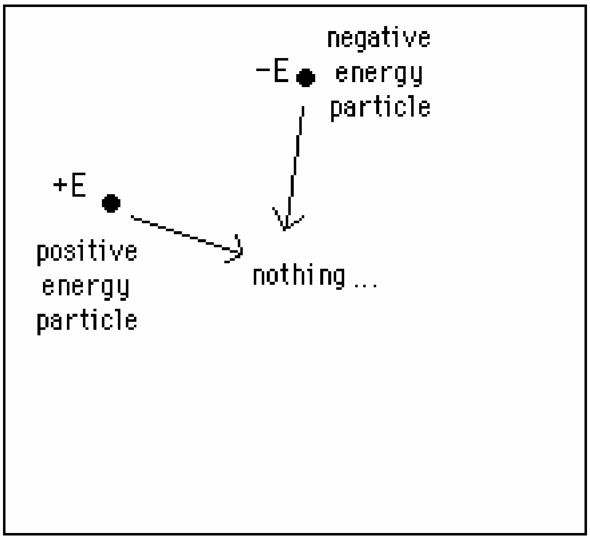
The CPT-symmetrical of a particle is identical to this particle
except that it has negative mass and energy.

Negative mass particles are a nuisance for physicians. If two particles, one of matter and one of anti-matte meet, we say that they annihilate each other. In fact they don't because they become photons. There is conservation of energy-matter.



But when a positive energy particle meets a negative energy particle the result is ... nothing.

$$(E = + mc^2) + (E' = - mc^2) = \text{zero}$$



It is already hard enough to explain why the universe, which should have started off being made half of matter and half of anti-matter, hasn't been entirely converted into photons, light (in fact we can't explain it at all). If, as well, this universe contained as much negative mass as positive, it should simply have disappeared. There wouldn't be any universe left at all.

For the last fifty years, theoretical physicians have managed to resolve the problem by saying that God, in his infinite wisdom, didn't create any particles with negative energy and as well as that, the sanctuary where they keep the components of the Lorentz-Poincaré group, which reverse time and therefore energy, is permanently guarded by winged cherubs.

Solution : two universes instead a single one.

To overcome this problem and avoid having to call on God at each moment, he probably has far more important things to do, I have introduced a new group, which goes with twin space, made up of two folds. The second fold contains negative energy particles, with negative masses. The second fold and ours are linked through a CPT-symmetry, so that this second fold is somewhat puzzling.

- Its arrow of time is reversed, with respect to ours.
- The second fold, the second universe, is enantiomorphic with respect to ours. What is right in our world is left in this twin world, and vice-versa.
- It contains protons, neutrons, electrons and neutrinos, but all the associated charges are reversed (electric, baryonic, leptonic and so on...)

In the section Geometrical Physics A we have called this second universe a ghost universe, for no light can come from it. The interaction is based solely on gravitational forces. As the masses of the second universe behave as if they are negative, they attract each other, but a particle of our universe and a particle of this ghost universe repel each other. The group structure justifies the chosen dynamics, which were the starting point of our cosmological model.

In the work in the section Geometrical Physics A of the site, we have suggested arguments in which the second universe could be hotter than ours. Composed of immense masses of gas at 1000 to 2000° and emitting infra-red ghost photons, organized life would not be possible there. If it were, the ghost world's eventual antichronous inhabitants would live with time that ran in the opposite direction to ours.

If it were possible and if our technology one day allowed us to communicate with the antichronous people, we would find ourselves in very interesting situations, even if only on an economic level. The antichronous people, in relation to ourselves, would be eager for our waste and would be trying by every means possible to get rid of their raw materials.

Imagine that such a meeting was be possible. A planet, with antichronous inhabitants is going to pass close to Earth. We have mandated the UN General-Secretary with the important task of making contact with these beings. He's nervous.

- Be careful, says the first scientist. When you meet them you should first say "good-bye" because in their time system they are leaving.

- Don't forget, says a second, when you're talking to them that they know everything you are going to say before you say it. Take it into account.

- Conversely, says a third, they don't know your previous phrase. Always remember that.

When the planet is sufficiently close, the Secretary-General's message goes out in the form of electromagnetic waves.

- There's a problem, says another scientist.
- Which one ?

- The retrochronian receiver works like an emitter in their world so under their time it's they that are sending us the message...

While terrestrial scientists continue to discuss the problem the antichronous planet disappears into the depths of the cosmos

.

The UN president is disappointed.

- Really, to have missed such an important appointment is disheartening. Can you imagine what it means for the economy...

- Sir, the meeting couldn't happen.

- Why?

- Think about it. If it had happened it would have left traces in our past.

A challenger to the black hole ?

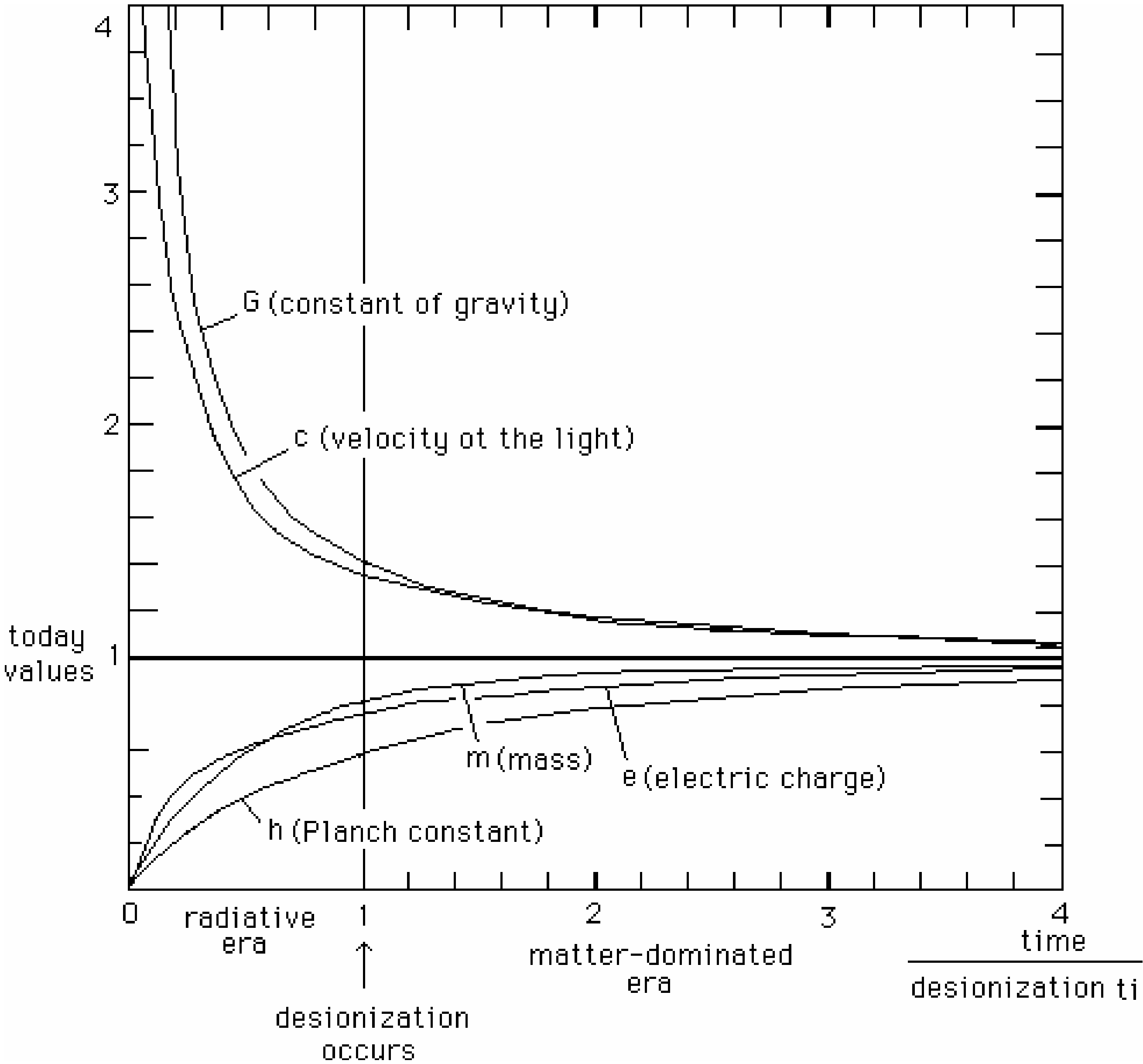
We have said the most horrible things about the black hole in this book. That's not very nice for people who live off the idea so perhaps we should propose an alternative.

In my opinion the twin model should eventually allow us to come up with another scenario. Work in this area hasn't yet advanced sufficiently to be included in Geometrical Physics A, but we can already say a few words about it here.

Those who have read the Geometrical Physics A articles in detail will have noticed no doubt that the radiative phase, which refers to the very early universe, uses variable constants. When we go back in the past, towards the hypothetical time t=0, the speed of light, which had been constant until then, begins to race and tends towards infinity. Every constant in physics also begins to drift. The gravitational constant also tends towards infinity but mass, electrical charge and Planck's constant tend towards zero. The following is drawn from the article :

J.P. Petit and Pierre Midy : Matter ghost-matter astrophysics.3 : The radiative era :

The problem of the "origin" of the universe. The problem of the homogeneity of the early universe. Geometrical Physics A : 6, April 1998.



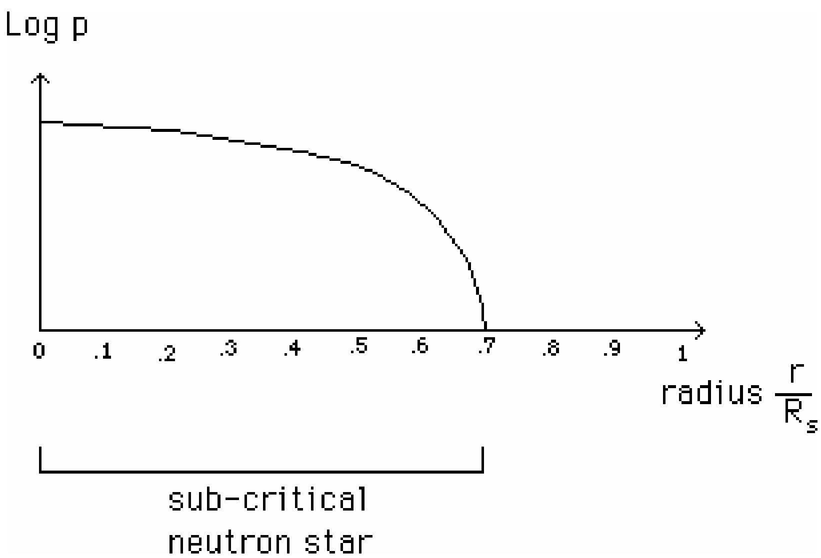
In a word, physics changes, begins to race suddenly.

Globally this translates as an alteration of the constants of physics when radiative pressure, which is an energy density, reaches a certain threshold.

We have begun to open doors leading to a representation of the universe with two entities in interaction, twin universes. We have studied a certain number of phenomena which could arise from gravitational interaction between these two entities. But we do not master the "twin quantum world". As we have seen above, Souriau, using the "Kostant-Kirilov-Souriau" method, the KKS method, derived quantum mechanics equations from groups. Would it be possible to apply this method, or a similar method, to the "twin group"? I believe it would. It should give a new insight on the quantum world, possibly through a system of coupled quantum mechanics equations.

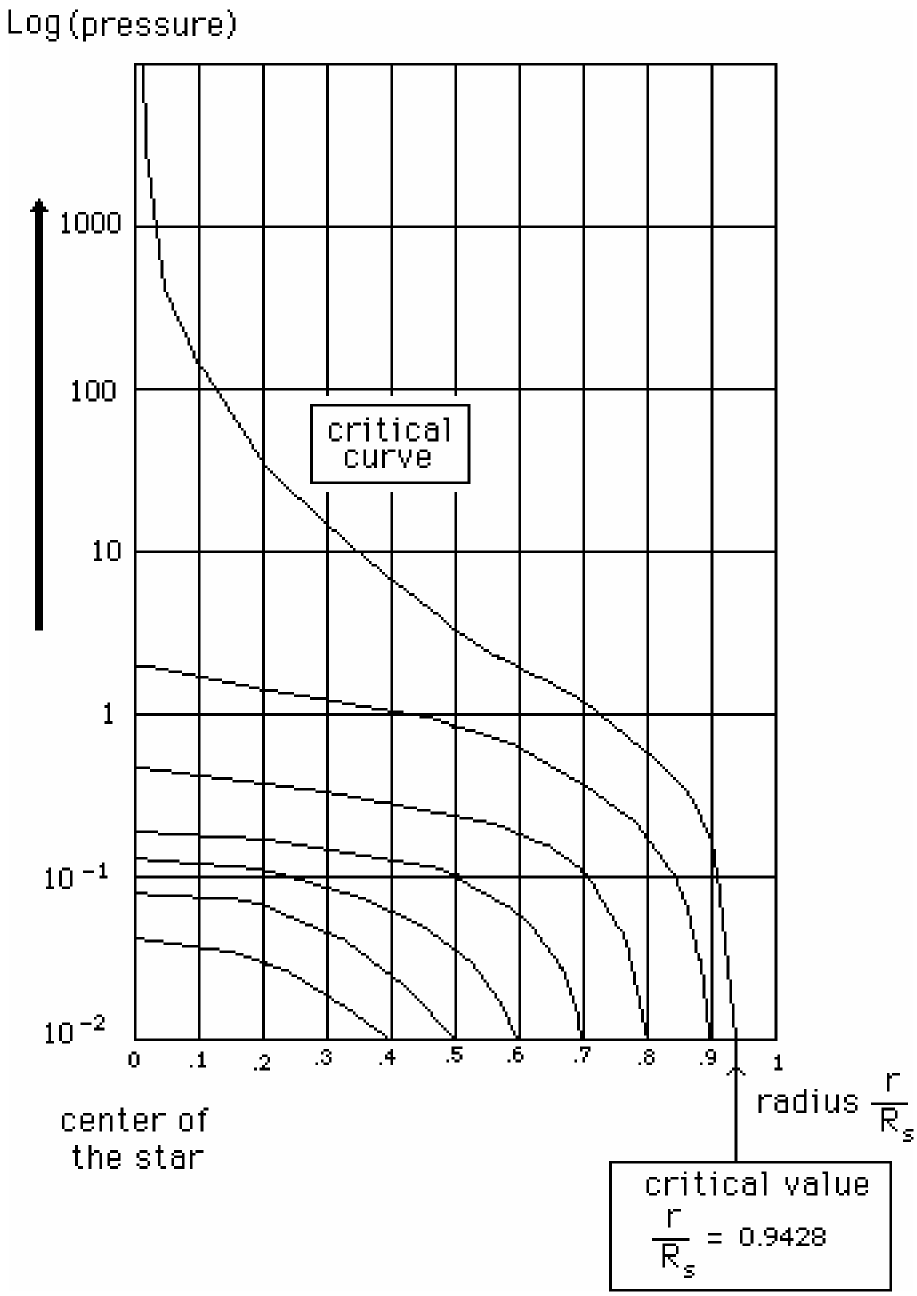
I believe that a "twin quantum model" might explain puzzling phenomena such as the solar neutrino deficit. I also believe that such a model could raise a new kind of criticity, with hyperspace bridge creation, where the local electromagnetic energy density would overcome a certain threshold value.

In the classic model of the neutron star the Tolmann-Oppenheimer-Volkov equation gives the value of the pressure inside it, the star being assimilated to some sort of large, dense crystal with a constant mass density : 10^{15} g/cm^3. The following figure shows the typical evolution of the pressure inside the star against the distance to its center :



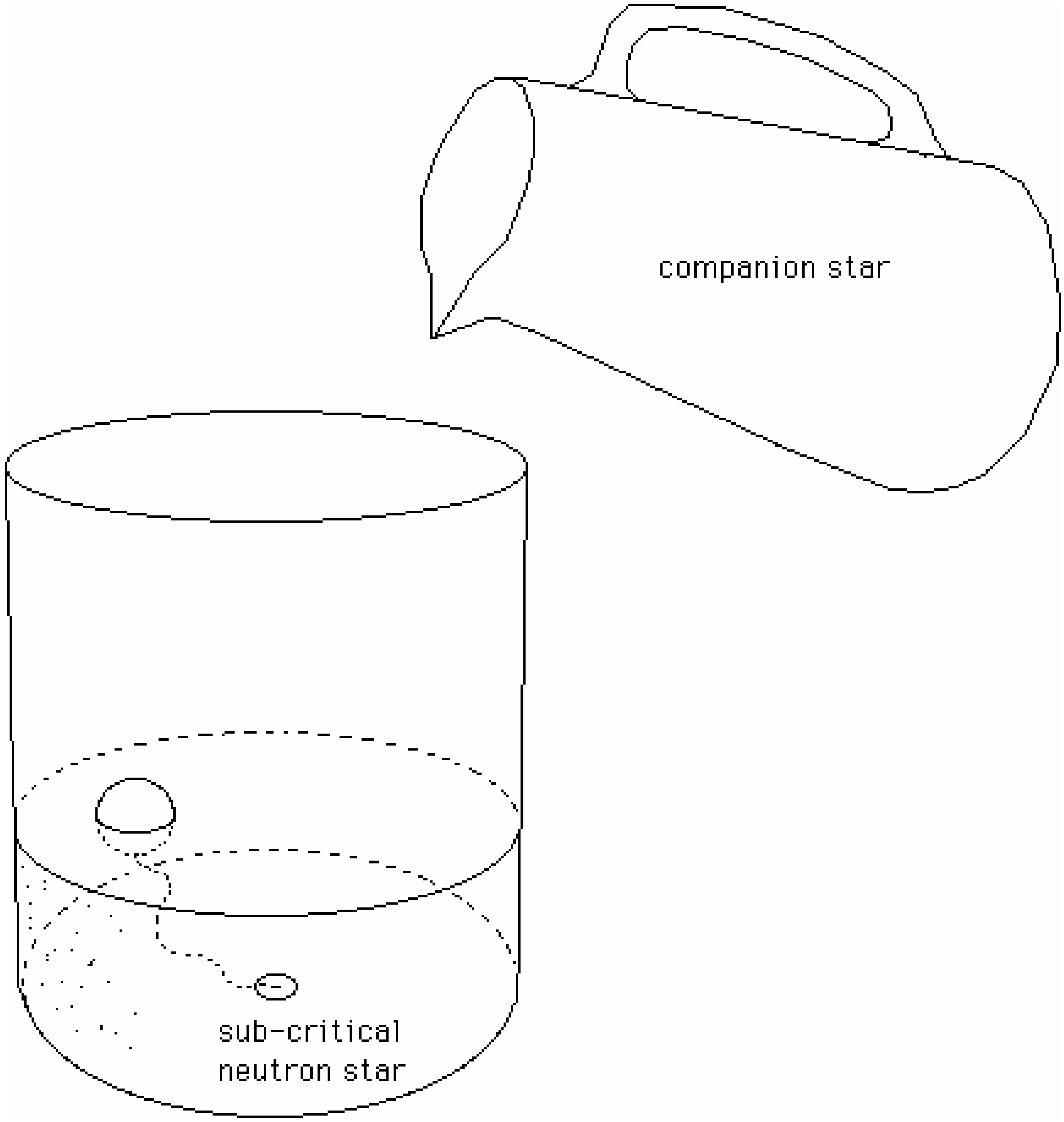
The point where the pressure tends to zero corresponds to the surface of the star.

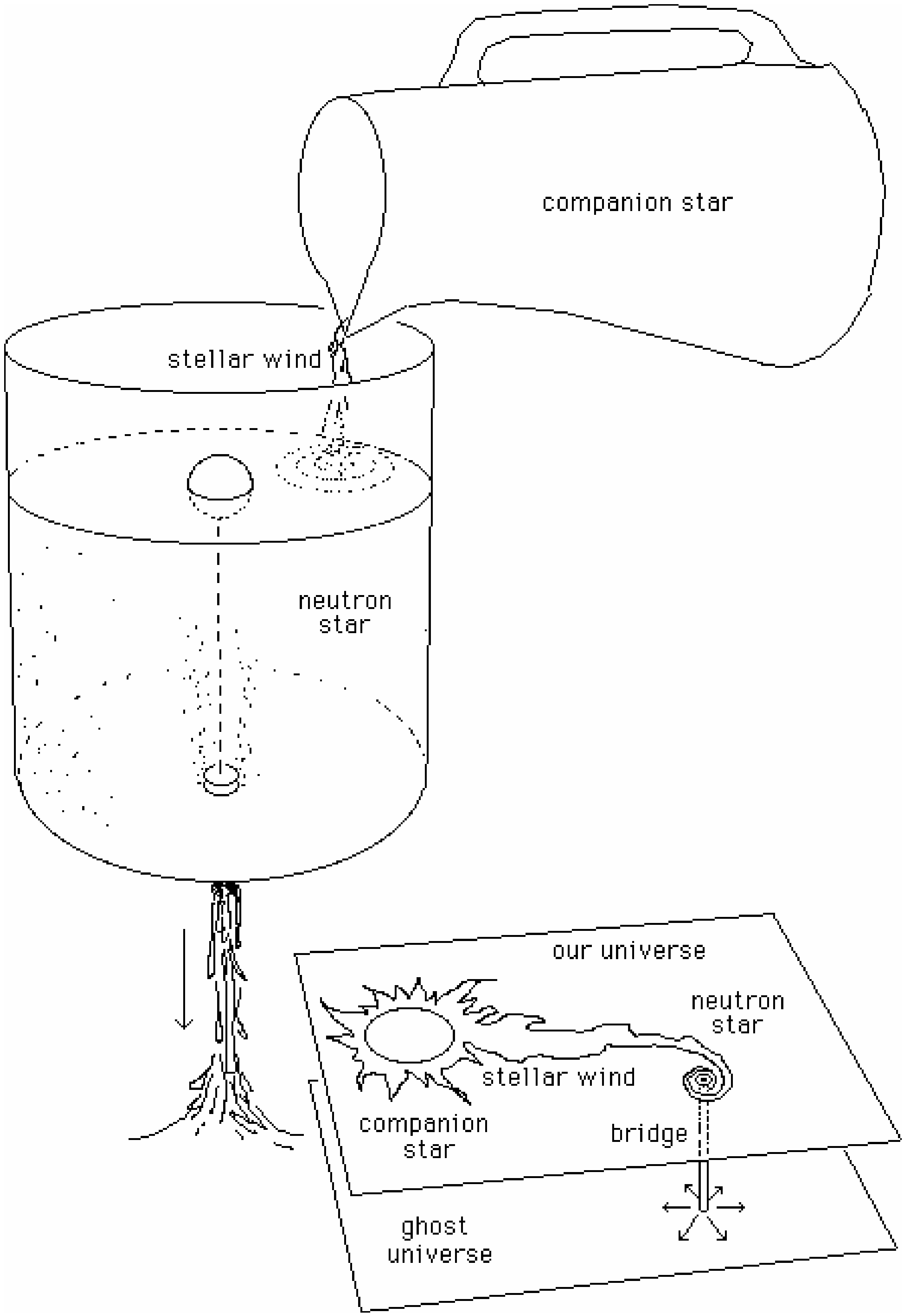
When the mass of the neutron star increases, its Schwarzschild radius (see appendix 3) tends to be equal to the radius of the star. The classic answer is then "the neutron star becomes a black hole". But if one looks closer, another kind of criticity occurs before the Schwarzschild radius tend to the star's radius. All good specialists know that when the mass of the star increases, the pressure at the center suddenly tends towards infinity as in the following figure :



The pressure tends to infinity when the radius of the star is 0.9428 the Schwarzschild radius.

I believe that this vertiginous increase in pressure at the heart of the star should cause local modifications of the values of physical constants and create a passageway between the two universes, what we call, in mathematics, a hypertoric bridge. Matter could therefore escape as if it were overfilled.

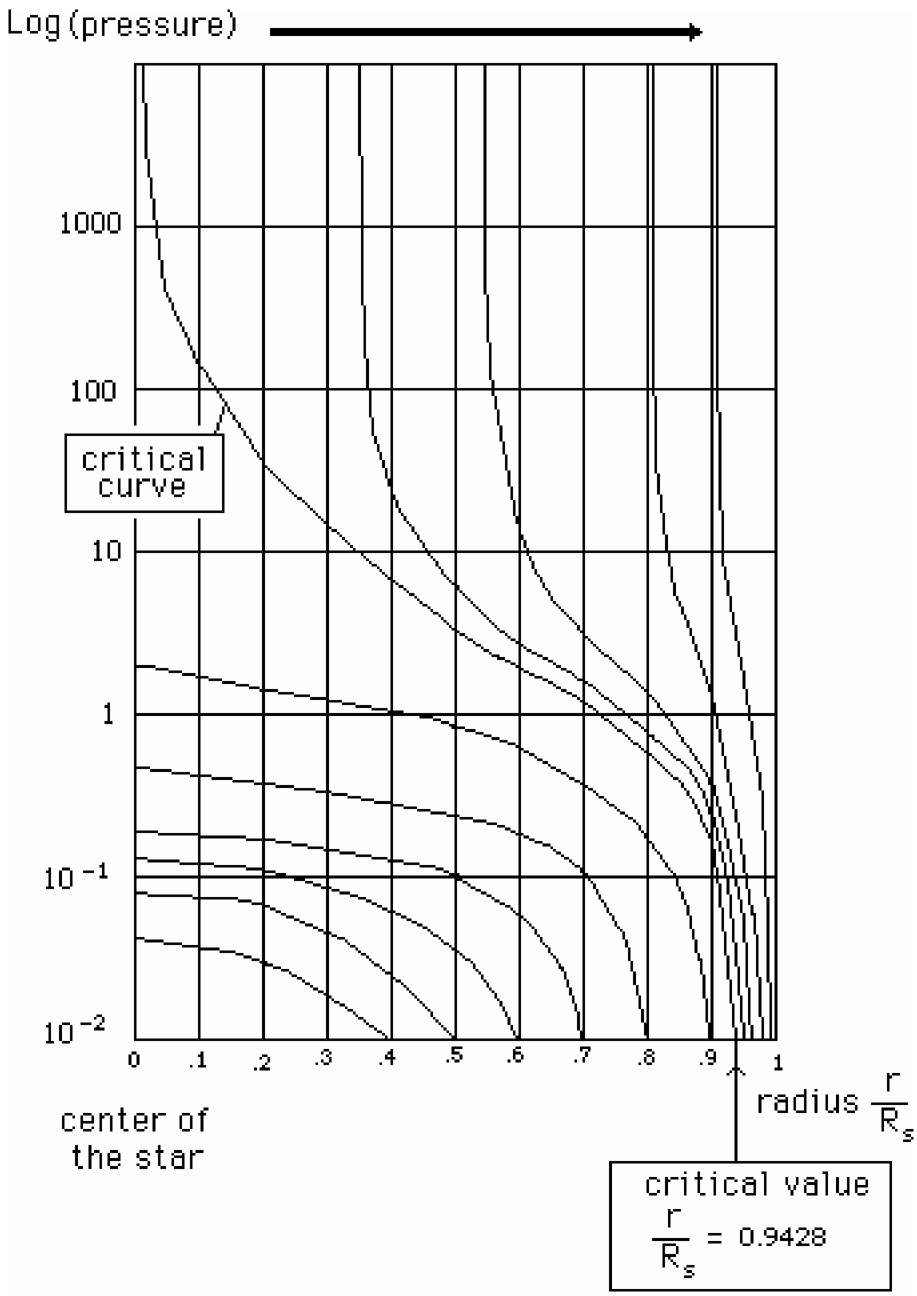



companion star
stellar wind
neutron
star
our universe
neutron
star
stellar wind
companion
star
bridge
ghost
universe

According to this idea, which, we must say, is the result of as yet uncompleted work, a hyperspace bridge would occur at the center of the star through which matter could flow at relativistic velocity and expand in the second universe.

This configuration would allow the neutron star to get rid of all the matter supplied by a companion, corresponding to its stellar wind.

But if we consider the merging of two neutron stars, the phenomenon would be much more violent. If we use the TOV model, we can calculate the pressure and see that the central, hypertoric singularity would extend very rapidly to the periphery :



Under such conditions, a large fraction of the matter could be transferred towards the second universe accompanied by the emission of gravitational waves and gamma-rays.

We know that phenomenal emissions of energy have recently been detected (December 1997), far greater than those associated with supernovae. These "objects" were named "hypernovae". But simply giving an object a name and stopping there (as is the case for quasars, which remain a complete mystery) has never advanced things one jot. Such powerful emissions, as well as gamma flashes, could be linked to such a as yet unmodeled phenomenon.

Conclusion (June 1998)

A provisional conclusion : As this text is being put on Internet, it is likely to be improved and modified in the future with the addition of new chapters.

In this document we have touched on a certain number of astrophysical and cosmological subjects. We have seen that men have often been a lot less wise than they liked to pretend. We have also thrown in a few personal ideas whose value only the future can tell.

Whatever, I feel that we are in a deep scientific crisis and maybe at the threshold of important paradigmatic changes.

Nevertheless, one might say, great technological progress has been made. The Internet network is itself is a good example, and a spectacular one, having transformed the planet into a village in the space of a few years. What about fundamental research? Well according to Souriau it has been stagnating since the last notable discovery, in 1950, that of quantic electrodynamics by Feynmann, that is to say almost half a century ago.

Let us make a comparison.

Science underwent spectacular changes at the turn of the century, let us say between 1895 (the discovery of radioactivity by the Frenchman Becquerel) and 1932 (discovery of the neutron by the Englishman Chadwick). During those thirty-seven years there was a flowering of fundamental discoveries that we don't need to list here.

But in the following thirty-seven, which brings us to the beginning of the 60's, can anyone mention a fundamental discovery made during this period? Which modern scientist can pretend to inscribe his name in the history of science?

Are we suddenly lacking in imagination at a time when there are apparently more researchers now than there have ever been.

It is obvious that fundamental research is going through a profound crisis. Theoretical physics has not advanced one jot since the 50's despite the periodic and noisy announcements of the superstring men :

- We have never been so close to the goal (Michael Duff, Scientific American, 1998)

But what goal ?

Reminder :

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Jean-Pierre Petit

Appendix 1

Why can't we go faster than light ? Why does time freeze when V tends towards c ? Why is the measurement of the speed of light invariant ? Newtonian cosmological models. The free fall time concept.

In the course of the book we have constantly treated the universe, space-time, as a "four-dimensional surface" and juggled with didactic images in two dimensions. That being the case, we have always carefully avoided speaking of aspects linked with Special Relativity. Despite that we have been able to cover cosmology, sometimes in a fairly sophisticated manner, with the help of geometrical images. Why then is it so complicated with real facts and calculations? Why does it seem so difficult to produce a simple geometric image illustrating the key concepts of Special Relativity, with, as its principal feature, the impossibility of moving at a speed greater than that of light?

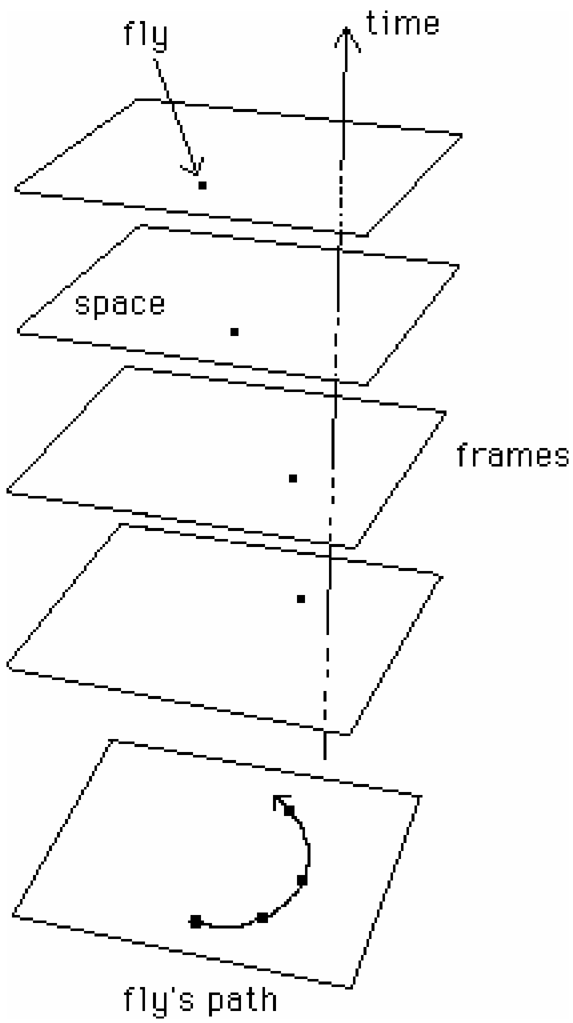
There are other aspects, just as troubling. When a particle sees its speed tend towards c, its mass tends towards infinity. To accelerate still more would give it infinite energy. You will be told that this is the reason why the fateful speed c cannot be attained.

The reader might imagine this as a truck carrying a strange load whose mass grows according to its speed.

I was like that myself for a long time. I did not understand even though I am capable of manipulating complex mathematical formalisms. Mathematicians are certainly lucky. One could say they don't need to understand. Manipulating signs seems enough for them. But I am a physicist, I need images and intuition.

Let us begin by picturing what classical, non-relativistic space time might be....

If we remove a dimension from space it becomes a plane. We can move on a plane, like a fly strolling across a table. We can photograph the fly at successive moments and then superpose the exposures, like this:

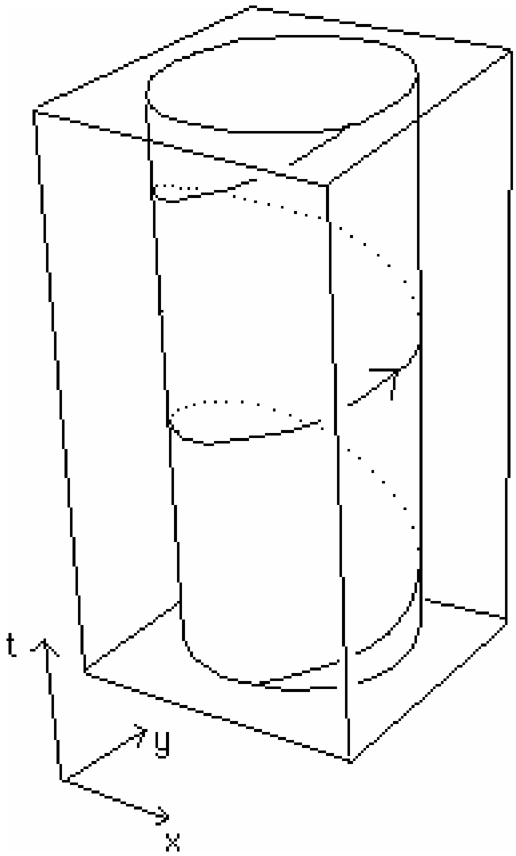


Above, exposures done at successive moments. The point represents the fly's position. By projection we obtain what is called a trajectory. If we suppose that space and time are continuous, the space in which the fly moves can be likened to a chessboard with infinitely small "squares". Similarly an infinity of possible exposures exists, separated by time intervals "as short as we wish".

In fact, this image is mathematical fiction since we consider that it not conceivable to analyze a portion of the trajectory whose length would be smaller than the "Planck length", 10^{-33} cm., just as it is not possible to analyze two states separated by a time interval shorter than the "Planck time", 10^{-43} seconds. But don't let us not mix everything up. We will come back to this later.

This corresponds to the hypothesis of the "space-time continuum" (still a hypothesis, but to discuss it would require another book...).

Based on the continuity hypothesis our 3d space-time (two dimensions of space and one of time) is a prismatic object.



Our prismatic space-time. The fly's trajectory is inscribed as a spiral drawn on a cylinder, projected in space from a circle. The circle is the purely spatial representation of the trajectory, outside time, and the spiral is the trajectory in space-time, and called a world-line.

Time becomes then an infinitely sharp knife with which we can make horizontal "cuts" at a constant t, each cut being a "moment". A cinematographic film is a three-dimensional space-time. Each frame is a two-dimensional space. By separating all the frames with a pair of scissors and then piling them up, you will obtain a third dimension -- time, the chronology of events.

It is the same with three dimensions of space and that of time. We would then have "a four-dimensional prism", of which each section would be a 3d volume. Of course, this can no longer be represented, it is mentally inconceivable. In the preceding sections we have constantly urged the reader to imagine extension to a greater number of dimensions so we hope that he has now got used to such strange gymnastics.

The key ideas of General Relativity and Special Relativity can be summed up in a single sentence:

Everything is geometry.

In taking up General Relativity, we have replaced mass with curvature and trajectories with geodesics and this has worked quite well. However, in the matter of time in this prism, we haven't come across any speed limit. A priori, all trajectories are imaginable. The representation even allows us to find out the speed of the fly's wanderings. Its spiral trajectory resembles a winding staircase.

The climb can be more or less steep. You might think that the more elongated the spiral, the faster the fly is going. In fact it's the opposite that's true. If you compress the spiral, like a spiral spring, the speed becomes greater, for the fly completes a loop in a shorter lapse of time.

This being so, nothing stops us, geometrically, from compressing this "spring" to a point at which the fly moves faster than light. It is impossible to define a limitation in this type of geometrical representation. Note also that nothing prevents us drawing a spatio-temporal trajectory that moves in reverse time on certain segments.

What should we do? Put notices up in this space-time saying:

- *It is strictly forbidden to exceed the speed of light.*

and:

- *It is forbidden to follow reverse-time paths in this space-time.*

How do we escape from the deadlock in order to geometrize Special Relativity?

Simply by changing the variable. As we have seen in the course of this book, time constantly plays tricks on us, eluding us like a mirage. We have always wanted to treat it as a free variable in which we can move as we please.

Time is not a free variable, if it were, what would be to stop us reversing its course to move in our prism in "reverse-time"?

Time is the result of an operation of measurement. The correct statement is not therefore :

-Tell me the distance you have covered and the time you have taken to do it and I will tell you your speed.

But:

Tell me your point of departure, your point of arrival and the speed at which you traveled and I will tell you how much time the trajectory has taken you and ... the distance you have traveled.

Now we are going to completely overturn our representation of space. Instead of imagining a space-time whole, we will imagine an angular reference-point and speed, this latter enumerated with reference to c.

Just now the fly was walking in a circle, a unidimensional space (having a single coordinate) with curvilinear abscissa, measured in centimeters between a point of departure and a point of arrival. The notion of distance covered was non-ambiguous.

But we know that in Special Relativity space and time become strangely elastic.

You are familiar perhaps with Plato's myth of the cave. The Greek philosopher claimed that people were living in a cave and what they called reality was only shadows projected onto the grotto's wall, coming from objects we do not see at all. Special Relativity is a platonic vision of the world. Everything becomes relative.

Years ago, in a street in the town where I live, I was looking at a street-lamp. Its glass was frosted and spherical. The light was at the center and flies, imprisoned in its interior, projected shadows onto the spherical screen.

I thought of Plato, of his cave.

I knew quite well that the flies were moving only on the lamp's glass and that I was only seeing their shadows, but that was my reality. If I had changed the screen or placed a larger or smaller one on the lamp, the length of the trajectory-arcs taken by my flies would have been modified.

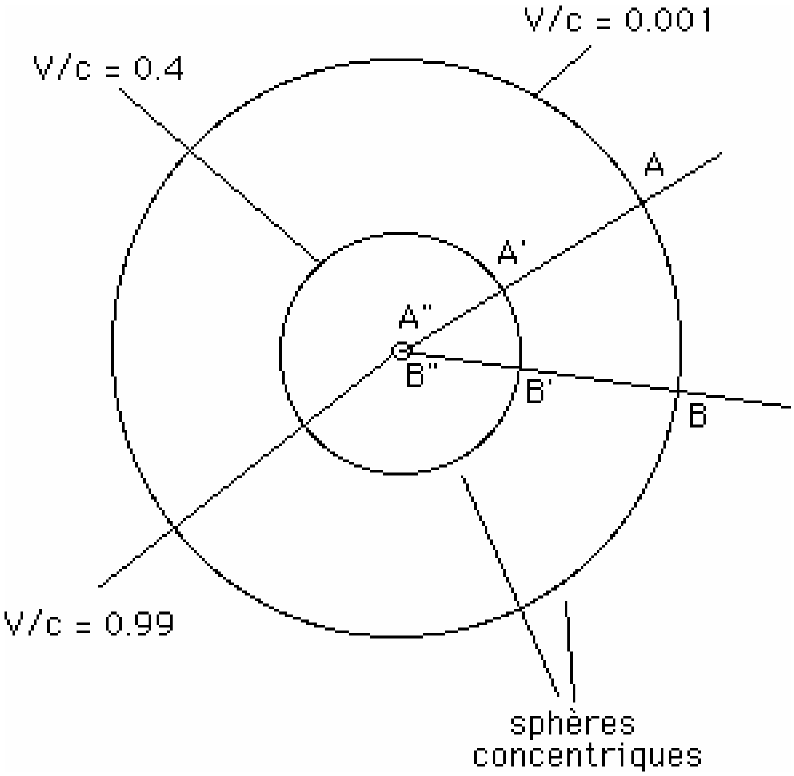
What is conserved after the operation? The angular position of the flies with respect to the light filament, which remains the same. Finally it wasn't really the flies that were important to me as objects, but the rays of light that projected their images onto my spherical screen.

Here, summed up in two sentences, is the foundation of Special Relativity:

There are no objects.
There are only images.

To us a moving "thing" could be considered as a sort of lighthouse beacon coming from a point. The image of the point is projected onto a spherical screen whose radius depends on the V/c relationship, the relation between the object's speed and the speed of light. This speed will be the "first course" of the problem. I could say simply, as an example :

My "thing" moves at V/c = 0.4.



Two angular positions of the "lighthouse beacon" are shown on the image, and three different materializations of the trajectory according to the V/c relationship. The faster we go, the longer the path. Or rather, the path's image will be shorter since everything is image. When V tends towards c, the radius of my projection screen tends towards zero.

We have illustrated here what is called Lorentz contraction. Now it remains for us to materialize time.

I see mistrust in your eyes, your eyebrows arched.

- What is this?

Everything will be cleared up very quickly; your mental system of representation will change that's all. Your intuition will mutate. To accomplish this we will finish by introducing a model.

Let us imagine submarines which can navigate in this "medium", as if on a planet made up entirely of water. They are equipped with propellers that cause them to cruise deeper the faster they go.

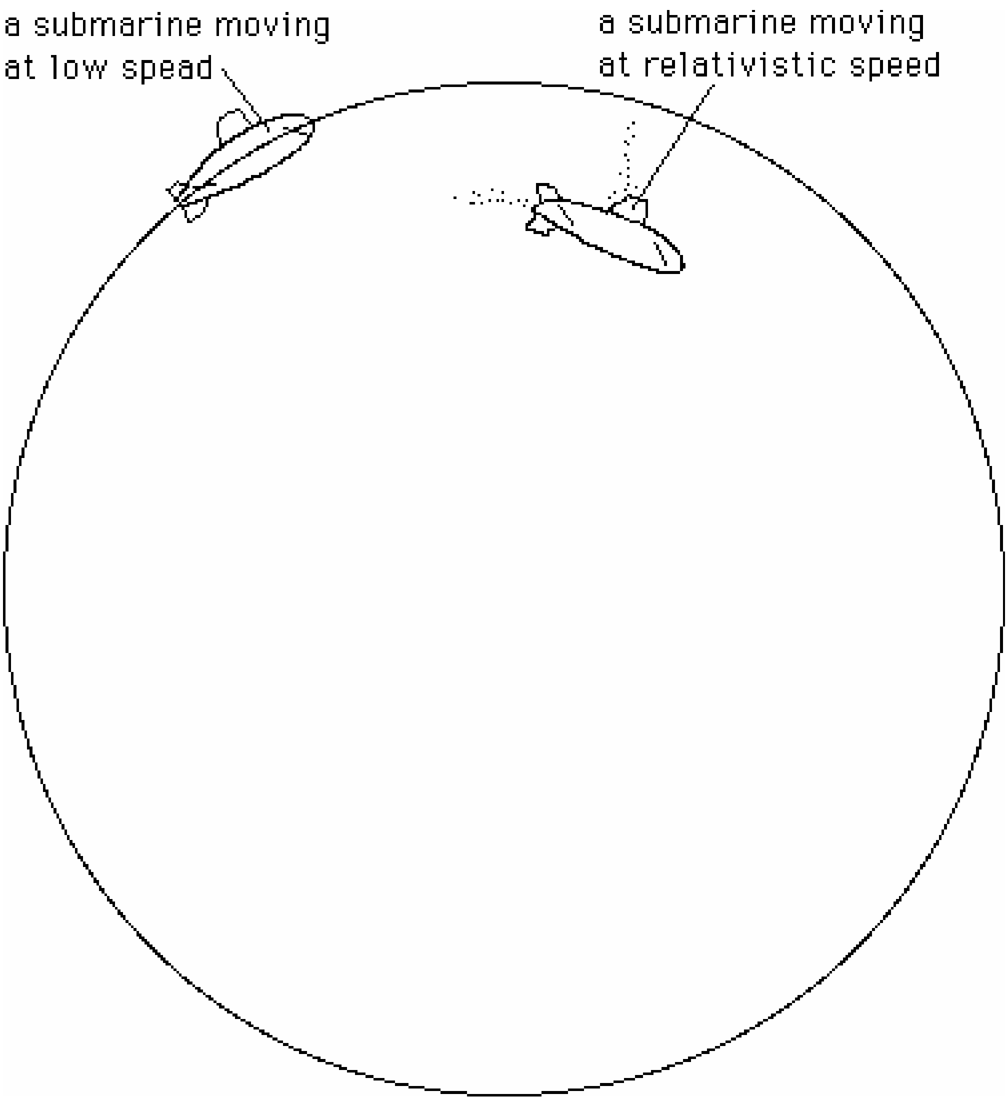
On a planet, a position is established through angles, longitude and latitude. To make a trip from point A to point B is to go from

(Longitude θ_A, latitude φ_A)

to

(Longitude θ_B, latitude φ_B)

On a normal, solid planet, the distance AB is quickly measured. It suffices to join two points with a geodesic arc. But our planet is not a normal planet. It is the planet of Special Relativity. If we make the trip at low speed, the distance covered will be at a maximum. At relativistic speed the submarine will navigate closer to the planet's center, on a sphere of smaller radius therefore, and distance covered will be reduced (Lorentz contraction).



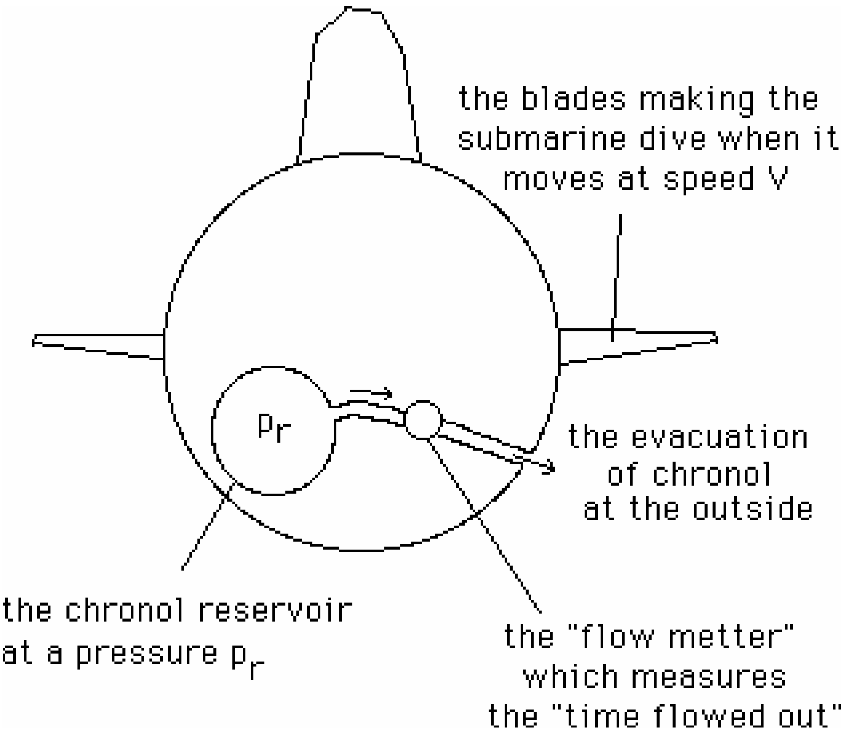
This makes up the first part of the answer:

- *Tell me from what point you leave, at what point you arrive, at what fraction of the speed of light you go on this path and I will tell you the distance you have covered.*

The problem of time remains. Our submarines will be equipped with fluid clocks. Let us call this fluid chronol. The submarines themselves navigate in chronol. Everything bathes in this chronol.

In the submarine, we measure the flow of time with a flow-meter. Inside is a reservoir of chronol, under a reservoir pressure p_r. We expel this fluid outside the submarine where a depth dependent pressure p prevails. The flow of time is proportional to the pressure difference

$$(p_r - p)$$



Thus, the closer we approach V = c, the slower time flows.

A new aspect of the "Lorentz contraction" and answer to the question:

- *Tell me from where you left, what was your point of destination and at what fraction of the speed of light you traveled and I will tell you how much time your trip took.*

We see that the journey's time depends on traveling speed. This has been experimentally confirmed by comparing elapsed times between a control clock on Earth and an identical atomic clock on board a satellite. A comparison of the two "time flows" reveals a difference between them in accordance with the laws of Special Relativity.

Let us return to our model -- how can we ensure that the flow of time cannot be reversed? Simple, just make sure that the outside, ambient pressure is always less than the on board pressure p_r. Under these conditions the flow meter will always function in the same direction.

We said that "the faster the submarine goes, the greater its depth". However a maximum depth exists in this drop of liquid, corresponding to V = c, which we situate ... at the center of the sphere. We therefore understand the essentially geometric nature of this V< c.

This amounts to saying:

- We cannot descend deeper than to the center of a sphere.

What happens when we move at a speed very close to c? We move on a sphere with a very small radius. The distances we cover are minute.

And time?

Simple -- at the center of the drop of liquid, the pressure is equal to the pressure pr of the submarine's reservoir. At speed c, we literally move on the spot and time no longer flows, it "freezes". You can understand now why we have trouble defining a measurement of time in the vicinity of the Big Bang. What do we make the watch with if all the components of the universe move at speeds tending towards c?

The flow of time is therefore contingent. At the end of the day it is not the distance we have covered which counts, but the time spent in our space vessel.

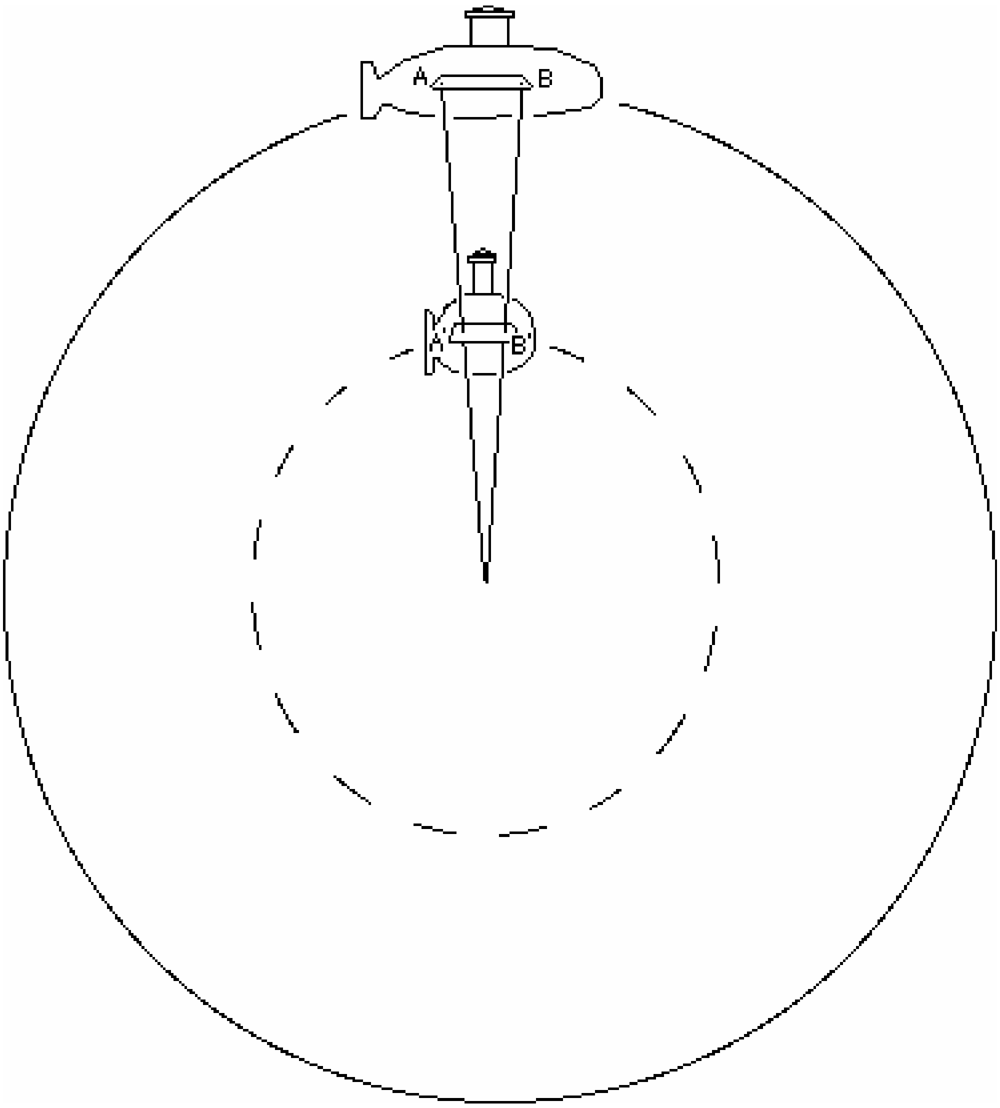
If we take two submarines, one of which proceeds at a non-negligible speed compared with c while the other is practically immobile, the clocks on board will record different lapses of time.

We say that to part is to die a little. In fact it seems to be the reverse.

The invariance of c:

Pushing this model a little further, we can reveal the paradox of the invariance of the measurement of c, at whatever speed the observer proceeds. Photons in some sense "live" at the center of this drop of liquid (and since their "proper" time does not flow, we can say that their death is, so to speak, stuck to the other side of their birth). We could compare them to lighthouse beacons.

Let us imagine another two submarines. The first is on the surface of our liquid and immobile. The second is moving at a speed V and navigates therefore at a depth, as shown by the broken line. It is "shorter" (Lorentz contraction).



The two radii vectors represent not two successive positions of the second submarine, but the passage of a photon able to be observed by both of them. Let us imagine that a passenger in the first, stationary submarine's can "read" the photon's trajectory on a special screen in the submarine; he sees it cross the segment AB = L.

A passenger in the second, moving submarine also sees the movement of this same photon on his screen and measures the displacement as A'B' = L'.

Time is measured in the two submarines with chronol clocks, and does not flow in the same way. For the passenger in the stationary submarine the path AB = L of the photon takes a time t and for the passenger in the moving submarine the path A'B' = L' takes a time t'. But because of pressure differences, as the photon-beacon sweeps the angle Q the measured lapse of time t' is less than t. The invariance of the measure of c will correspond to

$$c = L/t = L'/t'$$

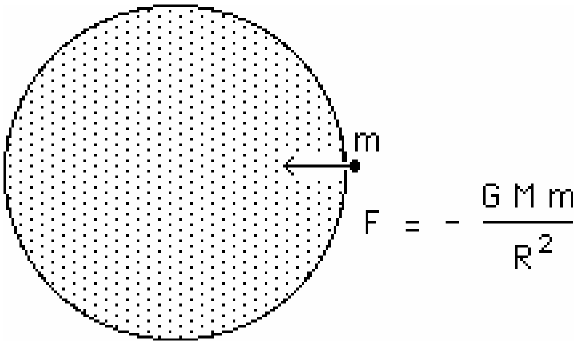
The two submariners will measure the same speed for the photons. A relativistic version of Plato's myth of the cave.

Models of the universe with Newtonian tools. First, "free fall time".

It was a great surprise in 1934 when Milne and MacCrea rediscovered the main lines of the Friedman models, products of a tensor, relativistic field equations and horribly complicated calculations using theoretical baggage dating from the nineteenth century. We will explain why later.

Milne and MacCrea started from a spherical ball of dust. That is to say a group of masses m, without speed of agitation, in other words without pressure. This is also the approximation used by Friedman and, as a general rule, in General Relativity when it is question of constructing a cosmological model. The idea is fairly realistic, to the extent that we consider the "molecules" of the cosmos as its galaxies, whose speeds of agitation of from 500 to 1000 km/s are small compared with c. In relativistic equations we can make this term correspond to the effect of pressure and show that it is around V/c, therefore negligible compared with others.

We can easily demonstrate (though we will not do so here) that the force of gravity created by a homogeneous sphere of radius R, at a distance r > R to this one, is equal to that which would be created by a mass-point located at r = 0 and equivalent to the entire mass M of the sphere. Let us suppose that this force acts on a control mass which is precisely at the surface of this sphere of dust, that is to say at r = R. We have:



This force will communicate to an acceleration the particle:

$$\Gamma = \frac{d^2R}{d\,t^2} = R''$$

In applying Newton's law, $F = m\,\Gamma$, it becomes:

$$R'' = -\frac{G\,M}{R^2}$$

That is to say the differential equation:

$$R''R^2 + GM = 0$$

This is exactly the equation Friedman had arrived at. It has three types of solutions. I'll leave you the trouble of finding the "elliptical" and "hyperbolic" solutions. The simplest corresponds to the so-called "Einstein-de Sitter" model. It suffices to suppose that it has the form:

$$R = a\,t^{\,n}$$

We calculate the first and second derivatives of this second function of t.

$$R' = a\, n\, t^{\,n-1}$$

$$R'' = a\, n\, (n - 1)\; t^{\,n-2}$$

The equation gives:

$$a^3\, n\, (n - 1)\; t^{\,3n-2} + GM = 0$$

There is a sum of two terms. The first can depend on time or not. The second does not depend on it at all. For this to work we need the exponent of t to be nil, which gives

$$n = 2/3.$$

Then:

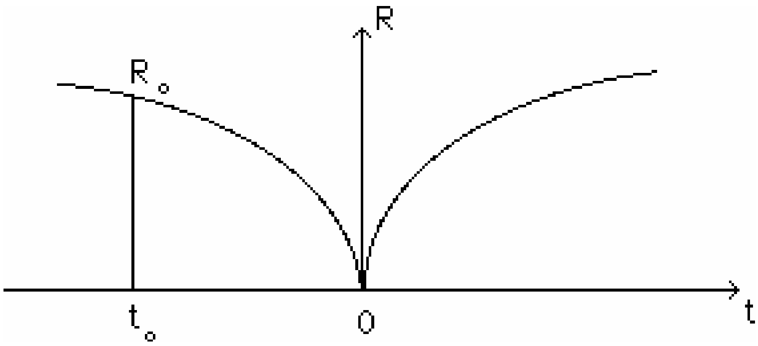
$$a = \sqrt[3]{\frac{9}{2}\, G\, M}$$

and the solution is written:

$$\boxed{R(t) = \sqrt[3]{\frac{9}{2}\, G\, M}\;\; t^{\frac{2}{3}}}$$

We note in passing that this solution is "time-reversible". If we prefer the idea of an expansion, we obtain a parabolic curve.

Mathematically the solution exists equally for t positive and for t negative. The complete curve is then:



We can consider the left-hand part as describing the implosion of a dust ball under the influence of its own forces of gravity, from a radius R_o, at a time t_o. These two quantities will be then linked by the relation :

$$R_o = \sqrt[3]{\frac{9}{2} G M} \; t_o^{\frac{2}{3}}$$

or, in reversing :

$$t_o = \frac{R_o^{\frac{3}{2}}}{\sqrt{\frac{9}{2} G M}}$$

Let ρ be the mass by volume in this sphere of homogeneous density. We have :

$$M = \frac{4}{3} \pi \rho R_o^{3}$$

Which gives us the free fall time t_o :

$$t_o = \frac{1}{\sqrt{6 \pi G \rho}}$$

Curiously, the initial radius of the dust sphere is eliminated. The free fall time depends only on the density of matter r. We rediscover the result initially obtained by Jeans, which is referred to in the chapter entitled "Gravitational Instability".

We see therefore that with two cents worth of mathematics we can accomplish quite a few things in the end.

Now, why do we succeed in finding the same differential equation as Friedman when he had to extricate it from very complicated calculations (which quite surprised people at the time)? Simply because Newtonian physics is something quite profound and close to the world of General Relativity. Both of these equations are local. If we assimilate curved space locally to flat Euclidean space, and have c tend towards infinity, we come across the Newtonian model.

Appendix 2

Absolute temperature and the speed of thermal agitation.
Escape velocities of different objects.
Speed of circular orbit.

Even by its definition, the absolute temperature T of a gas is the measure of the average kinetic energy of its constituents, plus a coefficient (where Boltzmann's constant k intervenes).

$$T = \text{constant} \times \frac{1}{2} m V_T^2$$

If it is a question of molecules, m represents the mass of one of them, and V, its mean thermal velocity. These are concepts borrowed from kinetic gas theory. In inverting this formula, we obtain :

$$V_T = \sqrt{\frac{8 k T}{\pi m}}$$

where the Boltzman constant has the value, in the MKSA unit system:

$$k = 1.38\ 10^{-23}$$

If the element is the hydrogen atom (mass)

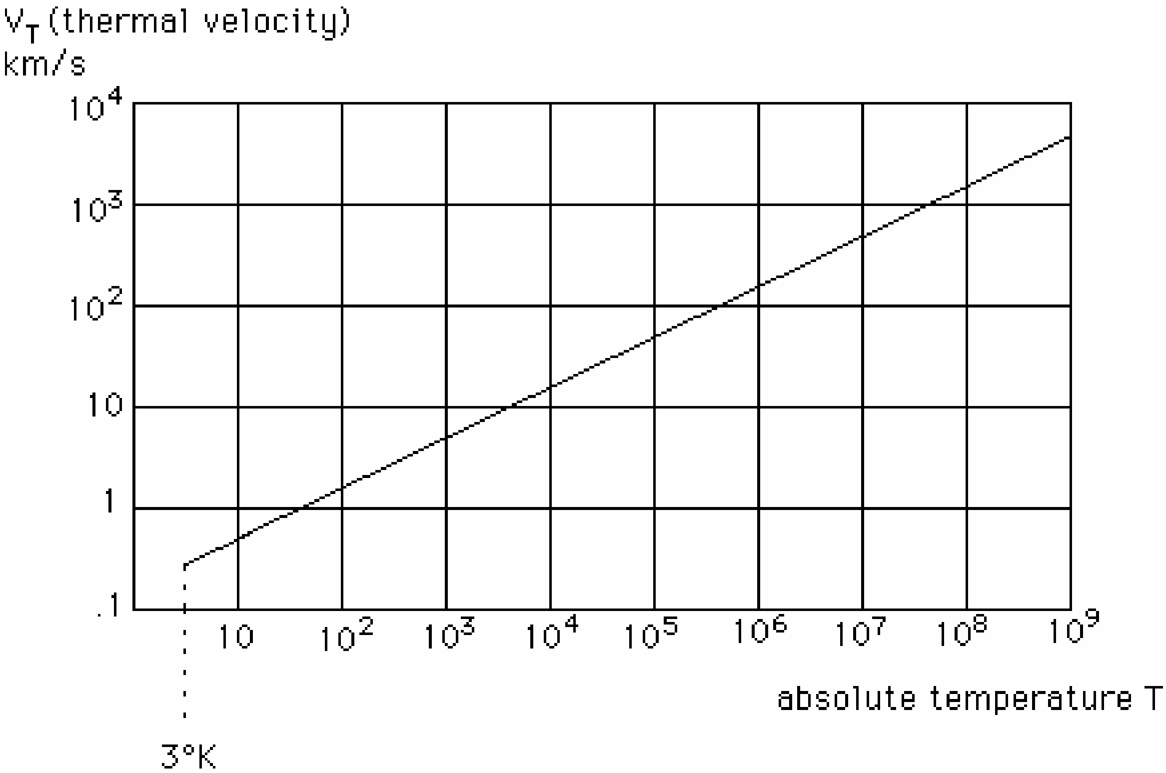
$$V_T = 145 \sqrt{T}$$

where T is in degrees absolute and V_T in meters per second.

In the universe there exists gaseous masses at all possible temperatures. You could stroll without discomfort in some, while others have a temperature numbered in thousands of degrees, providing they are sufficiently rarefied.

When an astronaut makes an excursion into space, hundreds of miles high, he enters into an environment of ultra-rarefied air whose temperature is measured in thousands of degrees Kelvin. However this air does not burn simply because the heat flux he receives from contact with this "burning air" is insignificant. This simply means that the molecules of air around him move at thousands of meters per second instead of 400 meters per second, as they would in dense air, and that this air is heated by the sun's energy.

If we return to the link between absolute temperature and the speed of agitation in a mass of hydrogen, we will see more clearly by studying the following diagram :



The curve (represented here in logarithmic coordinates) stops on the left, at the value 2.7°K, which is the temperature of the cosmic "oven", the most absolute void, in the current state of the universe's evolution. We will be surprised to note therefore that this "ultra-cold" hydrogen atom nevertheless moves at 250 meters per second.

In interstellar space vast masses of gas exist at all temperatures. In a cloud with a temperature of ten degrees absolute, the hydrogen atoms' speed of agitation (taken as reference, these clouds containing more than just hydrogen) is equal to 458 meters per second.

In a cloud at 100° Kelvin, this speed surpasses four and a half kilometers per second.

In the solar corona, at 6000°, the hydrogen atoms move at a dozen kilometers per second.

Beyond, the values of these speeds are interesting if we compare them to the escape velocities associated with certain objects.

Escape velocities:

Let there be a mass M, which we will consider as pointlike and also a mass m which is trying to escape from its attraction. The force which binds them is :

$$F = \frac{G M m}{r^2}$$

To succeed in escaping beyond a certain distance R from the attractive mass M, the mass m must furnish certain work, which is expressed by an integral, and escape will become impossible when the work required equals the kinetic energy of the mass m. Which is written :

$$E = - \int_R^{\infty} \frac{G M m}{r^2} dr = \frac{G M m}{R} = \frac{1}{2} m V^2$$

Whence the value of the escape velocity, which this mass m must possess at least in order be able to leave the attractive object.

$$V_L = \sqrt{\frac{2\,G\,M}{R}}$$

G is the gravitational constant which, as always in MKSA units, has the value :

$$G = 6.67\ 10^{-11}$$

Let us take an object located at a distance from the galaxy in the order of its diameter ≈ a hundred thousand light-years. The speed of light is $c = 3\ 10^8$ m/s. There are $3.15\ 10^7$ seconds in a year. Therefore a light-year has the value 10^{16} m and this distance is $10^{16} \times 10^5 = 10^{21}$m.

The sun's mass is $2\ 10^{30}$ k. Our galaxy numbers two hundred billion stars in which, to schematize, the sun can be considered as a "typical" star. This gives a total mass of $4\ 10^{41}$ k. The order of magnitude of the escape velocity is therefore :

$$V_L = \sqrt{\frac{2 \times 6.67\ 10^{-11} \times 4\ 1O^{42}}{10^{21}}}\ \text{m/s} = 231{,}000\ \text{m/s}$$

We know that the mass recorded in the galaxy is considerably less than that required to prevent stars from escaping, but this result is obtained through different reasoning (where the galaxy is no longer treated as a point mass) and we will therefore not go into it here. Because of this, astronomers think that there might be an immense halo of gas around the galaxy, for example. Let us suppose there is and that it's composed of hydrogen. To ensure that it does not fall back into the galaxy its atoms must have a speed of agitation greater than its escape velocity. Take a look at the preceding chart. The gas will have to be very hot : at least three million degrees. It could be a part of the primitive nebula from which the galaxy was formed, being heated during the first moments of star birth.

The escape velocity of clusters.

A cluster of galaxies, that is a thousand galaxies, a million light years distant on average. Cluster diameter: 10 million light-years (a tenth of the diameter of the "bubbles"). Or 10^{23}.

These numbers are just indicative. There exist clusters of varying size and density.

Galaxy (spiral, observations, etc.) mass : 10^{41} kilos. So smallest cluster mass: 10^{44} k.

$$V_L = \sqrt{\frac{2 \times 6.67\ 10^{-11} \times 4\ 1O^{44}}{10^{23}}}\ \text{m/s} = 365{,}000\ \text{m/s}$$

which is greater than the galaxies' (measured) speed of agitation in the clusters (from 500 to a thousand km/s). Therefore these clusters should evaporate. Even more so as clusters exist which are ten times less rich and whose escape velocities would therefore be lower. Let us imagine a hundred galaxies, located in a cluster of shorter radius: 3 million light-years. So a factor :

$$\frac{\sqrt{3}}{\sqrt{10}} - O.5$$

would lower the escape velocity to: 183 km/s.

To assure the cohesion of such clusters we would need a mass ten times greater than for large clusters. A factor of 30 for the large clusters, making for an escape velocity of 2000 meters per second. A factor of a hundred for the smaller clusters.

Escape velocity with respect to large clouds of interstellar matter.

Typical mass: 100,000 solar masses, or $2\ 10^{35}$ k.

Characteristic size: 40 light-years.
Escape velocity: 5 km/s, that of these young stars.

Appendix 3

How to calculate the Schwarzchild characteristic radius (the radius of the horizon sphere of an hypothetical black hole)

Let us return to the calculation above, that of escape velocity. The energy which the mass m disposed of to escape was therefore its kinetic energy

$$\frac{1}{2}\ m\ V^2$$

But how can we ignore the possibility that this object could propel itself by transforming its mass into energy? This energy could not exceed mc^2. We are only concerned here with orders of magnitude.
We have said that the energy corresponding to work against the force of attraction exercised by a heavenly body of mass M was :

$$\frac{G\,M\,m}{R}$$

Then we were dealing with an attractive object supposed to be pointlike. But as is shown elsewhere (Appendix 1), uniformly distributed matter contained in a sphere exercises on an object outside it the same attractive force as it would if it were concentrated at its geometrical center. The energy above will therefore be the same as if it were leaving the surface of a heavenly body of radius R.

Let us now suppose that the energy which could be liberated by mass m in order to escape is of the order of mc^2. This will lead us to :

$$\frac{G\,M\,m}{R} < m\ c^2$$

A mass m, putting such energy into play, could still escape from the attraction of the heavenly body of mass M and radius R. But it then becomes clear that if this mass is contained in a sphere of radius :

$$R_c = \frac{G\,M}{c^2}$$

escape will become impossible. Once again, with a different coefficient, we find the celebrated Schwartzschild radius

$$R_S = \frac{2\,G\,M}{c^2}$$

of the "sphere horizon" of the black hole, if it really does exist.

Again we notice the close relationship between the Newtonian and relativistic worlds, which enabled us to rediscover the equation leading to the Friedman models with a few lines of calculation(Appendix 1).

Appendix 4

The method of evaluating distances by parallax and the Hubble constant.

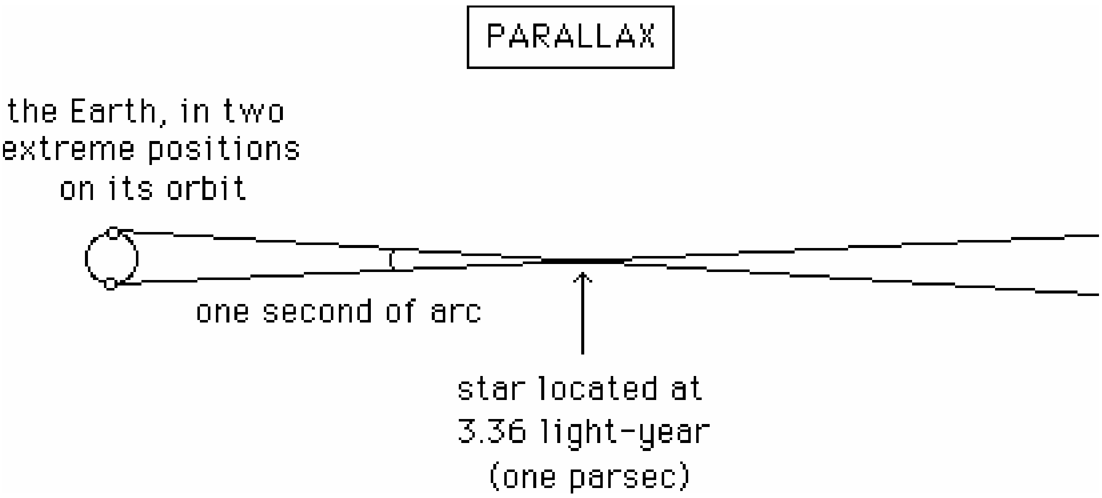
According to the standard model the constant H_o is the coefficient of proportionality between the distance of objects and their speed of recession. It is therefore a speed divided by a length. In the MKSA system we evaluate it in meters per second. But the meter is a ridiculous length for astronomers, just like kilometers.

We can count in light years. How many meters in a light-year?

Speed of light:

A year is 365 days of 24 hours, each counting 3600 seconds.
A year =
In one year light travels therefore:
which we round off to 10^{16} m.
One with sixteen zeros. Here is something quite beyond our mental scale, which is already saturated at a billion.
Astronomers prefer to utilize the parsec (abbreviation of "per second"). This is the distance under which the solar system is seen as an apparent diameter of one second of an arc. A tour of the horizon is 360^o. The moon is seen as an apparent diameter of about one second, 60 minutes of an arc, 3600 seconds.
A parsec has the value of 3.26 light-years, or 3.26 10^{16} m.

This signifies that a star at 3.26 light-years distance would move against the background of distant stars one second of arc between two extreme positions of the Earth:



Alpha Centauri, the closest star, is at 4.2 light-years.

One second of arc is not measurable to the naked eye, but it is with an optical instrument equipped with a photographic plate. We understand why Tycho Brahe, incapable of discerning this phenomenon of parallax, had inferred in 1586 that the Earth did not move (see Appendix 5). He had simply underestimated the distance of the stars by a factor of ten thousand, believing that they were at the same distance as the planets of the solar system. Thinking that the brilliant stars were closer than the dim ones (it is often the reverse -- the most brilliant stars in the sky, like Sirius, are not closer, just more emissive), he determined their distances badly.

We can also see why Bessel was able to effect the first measurement of stellar distance in 1886 when using the resources of photography for the first time

To measure the distance to stars located one parsec away by the parallax method requires a "power of angular resolution" greater than one second of arc and an equivalent stability of aim. A second of arc is a 5 cm object seen from one kilometer away. Even the smallest telescope has a precision ten times greater than this. We can deduce from this that it is therefore quite easy to measure the distance of objects located at a few dozen of light-years from the Earth by the parallax method. However beyond this distance we are very dependent on the telescope's optical and mechanical characteristics.

In cosmology, the unit of distance is the megaparsec, a million parsecs. This is in the order of magnitude of the diameter of the great empty bubbles around which galaxies are arranged. It is also that of the distance of galaxy clusters.

A megaparsec is $3.26\ 10^{22}$ meters.

The former value of the Hubble constant was:

H_o = 45 kilometers per second per megaparsec.
or :

$$H_o = \frac{4.5\ 10^4 \text{ m/s}}{3\ 10^{22} \text{ m}} = 1.5\ 10^{-18} \text{ m/s par m}$$

The age of the universe which is deduced from it is :

$$A = \frac{2}{3}\frac{1}{H_o} = \frac{2}{3 \times 1.5\ 10^{-18}} = 4.44\ 10^{17}\text{sec} = \frac{4.44\ 10^{17}}{3.15\ 10^{7}} = 1.4\ 10^{10}\text{yrs}$$

Fourteen billion years.

Recent measurements made by the Hubble telescope have revised this constant to the value of 70 km/s per megaparsec. Or in MKSA, a value of :

$$H_o = \frac{7\ 10^4 \text{ m/s}}{3\ 10^{22} \text{ m}} = 2.3\ 10^{-18} \text{ m/s per meter}$$

The age of the universe then becomes 9 billion years.

The galaxies in which Hubble was able to detect Cepheids are at distances d of the order of 50 million light-years, or:

$$d = 5\ 10^{7} \times 10^{16} = 5\ 10^{23} \text{ m}$$

Multiplying by the Hubble constant we find their speed :

$$V = 2.3\ 10^{-18} \times 5\ 10^{23} = 1.15\ 10^{6}\ \text{m/s} = 3.83\ 10^{-3}\ c$$

This is the red shift :

$$z = 0.00383$$

In fact what we measure is z just as d, thanks to the Cepheids. Then we can deduce the value of H_o.

Appendix 5

The slow displacement of galaxies in clusters

A remark intended to reassure the reader. We had said above that the Andromeda galaxy was in the process of falling down on us. This does not mean that it is coming towards us. The speed we measure is only the projection of its speed vector on the "line of sight", deduced from its red shift (Doppler effect).

If Andromeda were really coming at us, how long from now would the collision occur?

I do not know at what speed Andromeda is moving, but its distance, 2.2 million light-years, is a good measure of the average distance separating galaxies with clusters. Let us take a speed of 500 km/s. That gives a time of :

$$\frac{2.2\ 10^6 \times 10^{16}\ \text{m}}{5\ 10^5\ \text{m/s}} = 4.4\ 10^{16}\text{sec} = \frac{4.4\ 10^{16}}{3.15\ 10^7} = 1.4\ 10^9\ \text{yrs}$$

A billion and a half years, so you can sleep peacefully.

This is why we wrote that galaxies were moving "lazily" at a speed of 500 to a thousand kilometers per second within the cluster.

A galaxy (our own, Andromeda) has a diameter in the order of a hundred thousand light-years. We have been saying that stars are minute objects, separated by immense voids. For galaxies, this is no longer the case. The average distance which separates them is numbered in millions of light-years. They are distributed within the clusters like little peas separated by distances of the order of a meter. The probability of encounter grows proportionally. But as they move very slowly we consider that only one encounter occurs within a cluster over a time lapse of the order of ten billion years (the age of the universe). For this reason we never observe "galaxies in interaction" here or there.

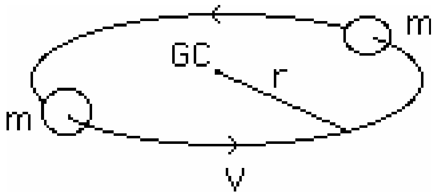
On the basis of calculations of probability, astronomers have deduced from this that galaxies made of matter and antimatter cannot both exist in the same cluster. Their encounter would not go unobserved.

Appendix 6

Weighing Stars

Spectroscopy allows us to obtain information on the composition and temperature of stars, but how can we weigh them?

Let us consider two stars of the same type and at the same evolutionary stage which orbit around their common center of gravity on a circular trajectory of radius r.



The equilibrium of these two masses m expresses the fact that centrifugal force is balanced by the force of gravity:

$$\frac{G\ m^2}{(2\ r\ )^2} = \frac{m\ V^2}{r}$$

An astronomer knowing the speed V and the distance 2r can deduce the value of the mass m.

$$m = \frac{4\ r\ V^2}{G}$$

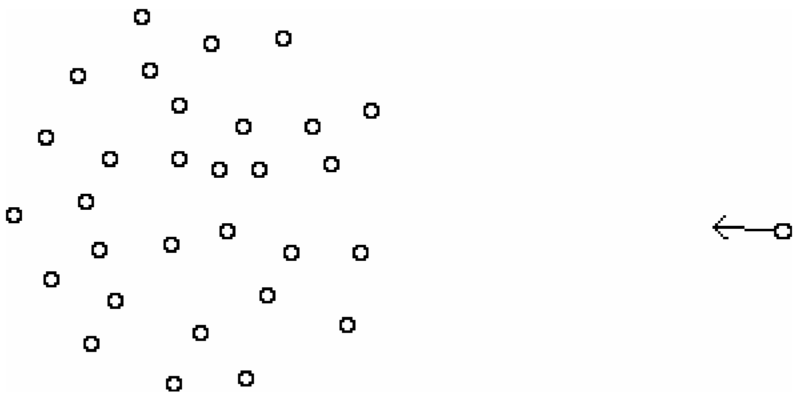
Thus astronomers have been able to determine the mass of stars of a given type. When these stars are coupled with other, different stars, it is possible to determine their masses also.

Appendix 7

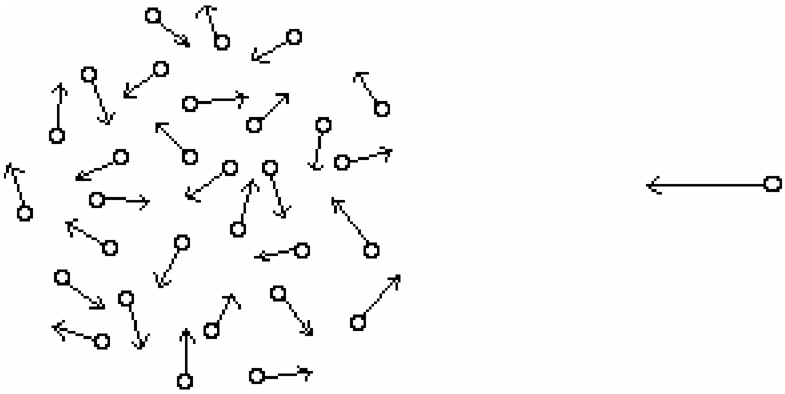
Planck length and Planck time

We will now once more take up the problem of the mass m which leaves a heavenly body of mass M. But this time we will imagine the escape of a photon of energy hν. Bizarre, the reader might think, doesn't the photon have zero mass? Yes and no. Its "inertial mass" is nil, but not that which can be considered its "gravific mass".

In fact, as a general rule, it is not mass that creates a gravitational field, but energy. For example, if we consider a group of mass m, at rest (each member with respect to the others) it creates an attractive gravitational field. Let us now imagine that the groups members are agitated, with turbulent relativistic movements, the field then becomes more intense.



The gravitational force exercised on a control particle by a group of immobile masses.



This same force, when these masses are animated by a movement of relativistic thermal agitation.

To calculate the field produced it is not necessary to sum the masses at rest m_o, but the masses :

$$m = \frac{m_o}{\sqrt{1 - \frac{V^2}{c^2}}}$$

where V represents the speed of thermal agitation in this medium.

Mass *is* energy. Put a brick in an oven. Heat it, it will weigh...more. Of course this is not measurable, but it is very real. According to the principle of action and reaction, the Earth attracts the brick, and the brick attracts the Earth. Therefore the gravitational field created by a hot brick is greater than that created by a cold brick.

It would be simpler to say that what creates a gravitational field is a concentration of energies :

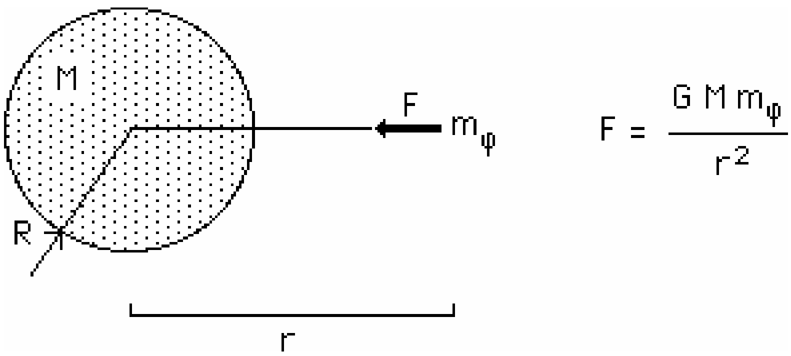
$$E = \frac{m_o c^2}{\sqrt{1 - \frac{V^2}{c^2}}}$$

Photons are also regions of condensation of energy. They contribute to the gravitational field. Two photons which encounter each other "attract each other gravitationally" Although this might make a theoretical physicist scream, it is not idiotic to attribute to the photon a fictive gravific mass, according to the relation:

$$h\,\nu = m_\varphi\, c^2$$

and to calculate the work done by this photon to leave the star. On a theoretical level this is crude, but at least it gives the order of magnitude of the problem.

Going back to preceding scheme : The attractive mass is a filled sphere of constant density. Therefore the field which it creates, according to a known theorem already referred to, is the same as that created by the same mass situated at its center.



We rediscover the order of magnitude of the energy dispensed for this effort of escape (from r = R to r = infinity).

$$E = \frac{G\,M\,m_\varphi}{R}$$

The photon will lose this energy. Far from the heavenly body it will have a weaker energy hν. We call this phenomenon the gravitational red shift.

$$m_\varphi\, c^2 = h\ \nu \qquad \text{ou :} \quad m_\varphi = \frac{h\ \nu}{c^2}$$

We can then determine the order of magnitude of the radius of a heavenly body of mass M such that it loses all its energy to a photon. Again we come across the Schwarzschild radius:

$$R_s = \frac{G\,M}{c^2}$$

That is to say the radius of a black hole's sphere-horizon. Thus, if they do exist, nothing can escape a black hole, neither mass nor light. Whence its name.

Now we can amuse ourselves by performing the following exercise Let us suppose that the mass (energy) opposing the escape of the photon is ...its own energy. Let us suppose that it creates a local curvature in space sufficiently strong to affect its own trajectory, to the point of making it turn round and round like a dog chasing its own tail:

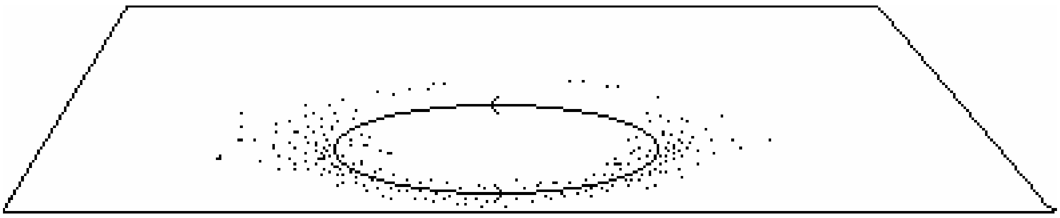


Image of a particle trapped by its own gravity field.

It is enough to replace this photon's mass M with this fictive, equivalent mass m_φ and to identify R_S with its wavelength λ.

$$R_s = \lambda = \frac{G\,m_\varphi}{c^2} \qquad\qquad m_\varphi\, c^2 = h\,\nu = \frac{h\,c}{\lambda}$$

whence :

$$\lambda = L_p = \sqrt{\frac{G\,h}{c^3}}$$

We arrive at a length which we call the Planck length :

$$L_p = 1.615\ 10^{-33}\ \text{cm}$$

We arrive at the same result with a particle of any mass m whatsoever, identifying its Schwarzschild radius with its Compton wavelength.

$$\lambda_c = \frac{h}{m\,c} \quad \text{ou} \quad m = \frac{h}{\lambda_c\, c}$$

$$R_s\ (\text{Schwarzschild}) = \lambda_c = \frac{G\,m}{c^2} = \frac{G\,h}{\lambda_c\, c^3}$$

whence:

$$\lambda_c = L_p = \sqrt{\frac{G\,h}{c^3}}$$

Let us come back to this photon, trapped by its own self. The orbital period of this strange object, which "orbits around itself at the speed of light c", is then the Planck time :

$$t_p = \frac{c}{L_p} = \sqrt{\frac{2\,\pi\quad c^5}{G\,h}} = 0.539\ 1\ 0^{-43}\ \text{second}$$

Thus we understand why it is conceptually impossible to move particles possessing such an energy hν (photons or particles carrying a "true mass"). This is a universe where "nothing can happen any more", since even the photons turn round and round, chasing their tails like mad dogs, and can no longer propagate.

Thanks to this little bit of reasoning we have put our finger on the absolute limit of our current physics, determined by the thicknesses of its knife and of the "present moment". This the "distinguishing power" of our theoretical machinery, which cannot analyze phenomena involving times and distances less than Planck quantities, or events occurring in a time less than Planck time.

This is the "grain of the film", or the time between two successive images of a movie.

At what distance from time t = 0, in the Big Bang model, would such extreme conditions pertain? The answer is simple. When

$$t = 0.539\ 10^{-43} \text{ second}$$

When the age of the universe equals the Planck time we conceive that theoreticians have serious difficulties in describing it.

Appendix 8

The quantum melody

An electron which is supposed to "orbit" around the proton, the whole constituting a hydrogen atom, is in fact a stationary wave, with the De Broglie wavelength :

$$\lambda = \frac{h}{m_e V_e}$$

Let us note the force of electrostatic attraction with the centrifugal force :

$$\frac{e^2}{4 \pi \varepsilon_0 R^2} = m_e \frac{V_e^2}{R}$$

e is the electron's charge (and the proton's).
m_e is the electron's mass, R that of its orbit, V_e its "speed of circular orbit" in this mechanical description. The electrostatic attraction force is $1/R^2$.

$1/ 4\pi\varepsilon_o$ is the constant linked to the electrostatic force.

On the right, the centrifugal force.

$m_e = 0.9\ 10^{-30}$ kilo

$e = 1.6\ 10^{-19}$ coulomb.

$$\frac{1}{4 \pi \varepsilon_0} = 9\ 1\ 0^9$$

Very well, but how do we choose the orbit's radius R ?

By assimilating the electron's movement to a resonance phenomenon. We will say that the only possible orbits in which this "resonance" can appear and last, are those whose perimeter $2\pi R$ is equal to a whole number of times the associated wavelength. This is to say that then :

$$2 \pi R = n \lambda = \frac{n h}{m_e V_e}$$

Or :

$$V_e = \frac{n h}{2 \pi R m_e}$$

By replacing the relation (electrostatic force equals centrifugal force) linking R and V, we obtain:

$$R = n^2 \frac{h^2 4 \pi \varepsilon_o}{(2 \pi)^2 m_e e^2}$$

with :

$$\hbar = \frac{h}{2 \pi}$$

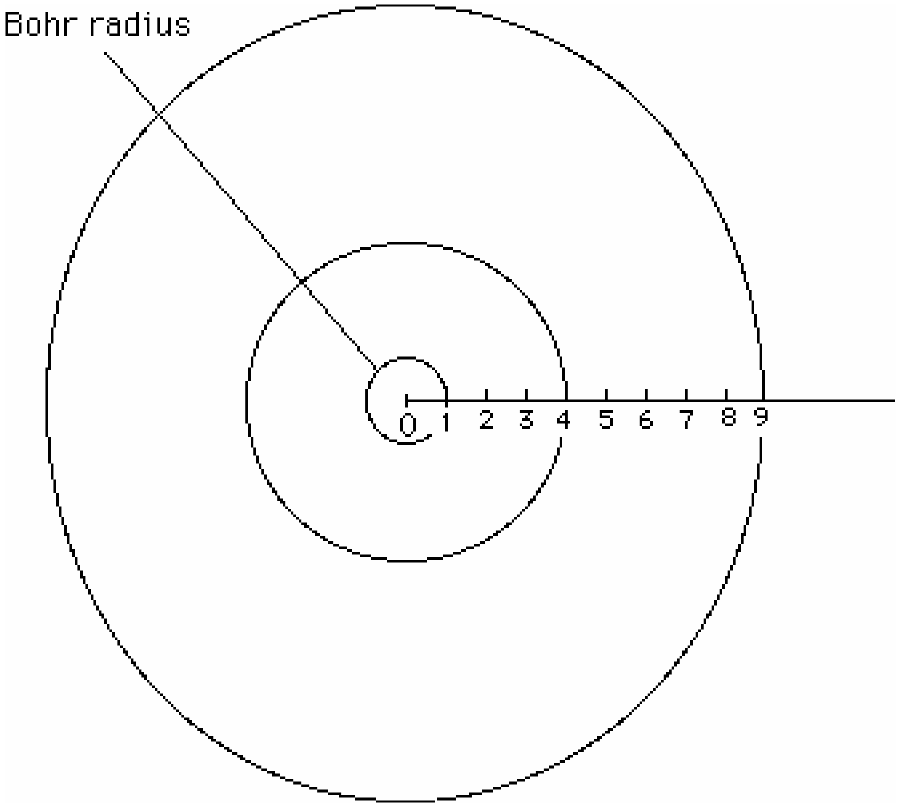
$$R = n^2 \frac{4 \pi \varepsilon_o \hbar^2}{m_e e^2} = n^2 R_b$$

This is to say n^2 times what we call the Bohr radius R_b, the diameter of the hydrogen atom, which has the value $0.58\ 10^{-8}$ cm. In this description, the electron can occupy only the orbits:

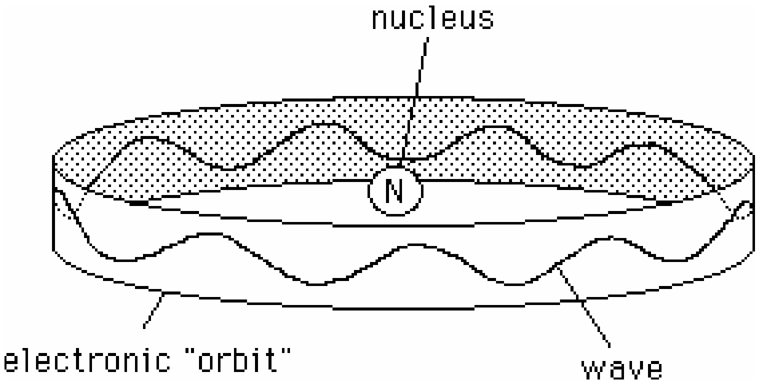
n = 1 (fundamental level): $R = R_b$

n = 2 : $R = 4 R_b$

$n = 3 : R = 9\ R_b$ etc....



In fact it is much more complicated, as you can well imagine, and we must take into account many other things. But at least it gives to the non-initiate the beginning of a view of something rather different from one ball turning around another, and a glimpse into the "quantification of orbits". Here is one of these possible orbits, showing how the wave function bends on itself. This suggests a resonance phenomenon.



Let us take again the relation:

$$2\,\pi\,R = n\,\lambda = \frac{n\,h}{m_e\,V_e}$$

which we can write :

$$m_e\,R\,V_e = n\,\frac{h}{2\,\pi}$$

The first component represents what is called the kinetic moment. It can take only the whole values of the quantity :

$$\frac{h}{2\,\pi}$$

Planck's constant has therefore the dimension of a kinetic moment, that is to say of the product of a mass by a length by a speed. It is expressed in

kilos x meter^2 / sec

But we also have:

$$\text{Energy} = \frac{h}{\tau\ (\text{ period = time })}$$

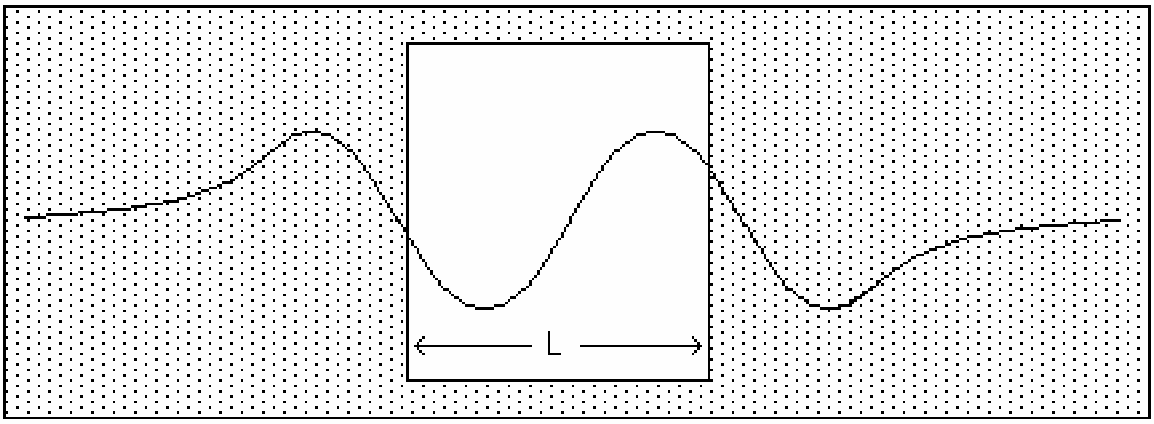
Therefore this is also an energy multiplied by a time :

$$h = 6.63\ 10^{-34} \text{ joules per second.}$$

Let us suppose that we wanted to measure the speed of a particle passing before us in the form of this "wave packet". Let us come back to our model of a disturbance propagating along a rope, supposing that the measurement of the disturbance's speed can be based on that of the wavelength, that is say that the two are linked by the De Broglie relation :

$$\lambda = h/\ m\ V.$$

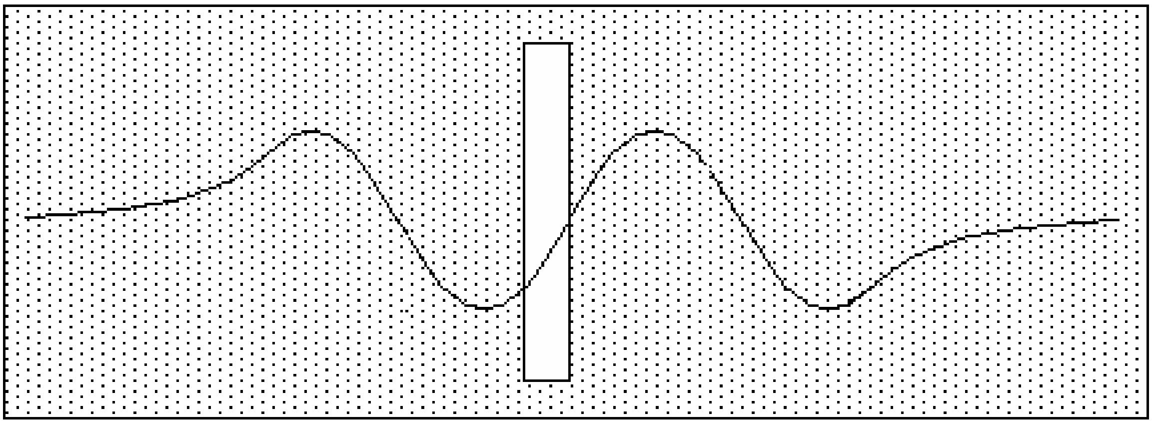
We base our measurement on an instantaneous exposure of what we see through the window. We see that we cannot know this speed (or the impulsion mV) with unlimited precision. If our window is too narrow, we will only see a sinusoidal arc, too short to be able to determine the oscillation's wavelength with precision. If we content ourselves with this exposure, our measurement of the speed will become imprecise.



A wide window (uncertainty about position) enables a good determination of the wavelength.

A wide window gives good precision to the measurement of speed but imprecision (L) as to position. This is only a rather crude image of the

Heisenberg principle of uncertainty which postulates that the product of the uncertainty in the measurement of position by that of the uncertainty in the measurement of a particle's speed is a constant, equal to the Planck constant.



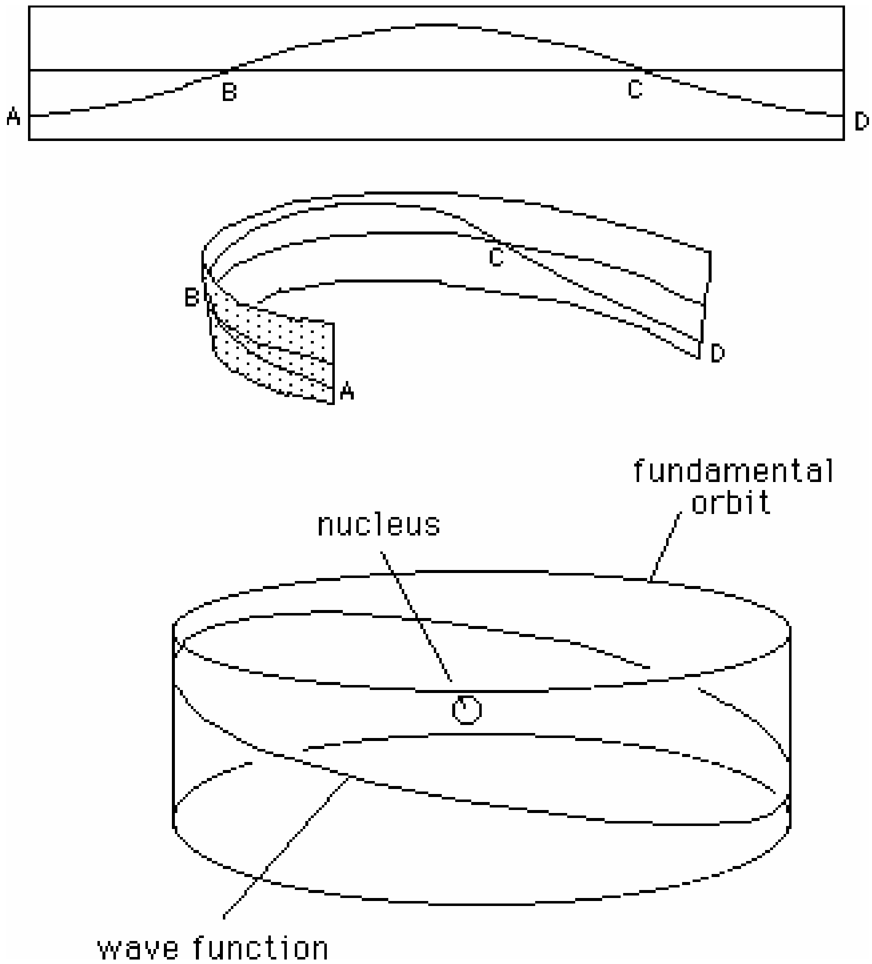
The narrower the window the less precise the measurement of speed.

Our point of observation is a window of a certain width. Through which we imagine we take an instantaneous photograph of the rope.

But let us return to the idea of the wave function bending onto itself and which resulted in the quantification of orbits, whose radius grows as n^2. The value n = 1 corresponds to what is called the fundamental state of the electron in the hydrogen atom. This corresponds to :

$$2 \pi R = \lambda$$

If we draw the sinusoidal arc corresponding to the electron's wave function in its fundamental state, around the nucleus, it is reduced to its simplest expression, with at each moment a single maximum and a single minimum. This is a unique sinusoidal arc, bent onto itself. We obtain this:



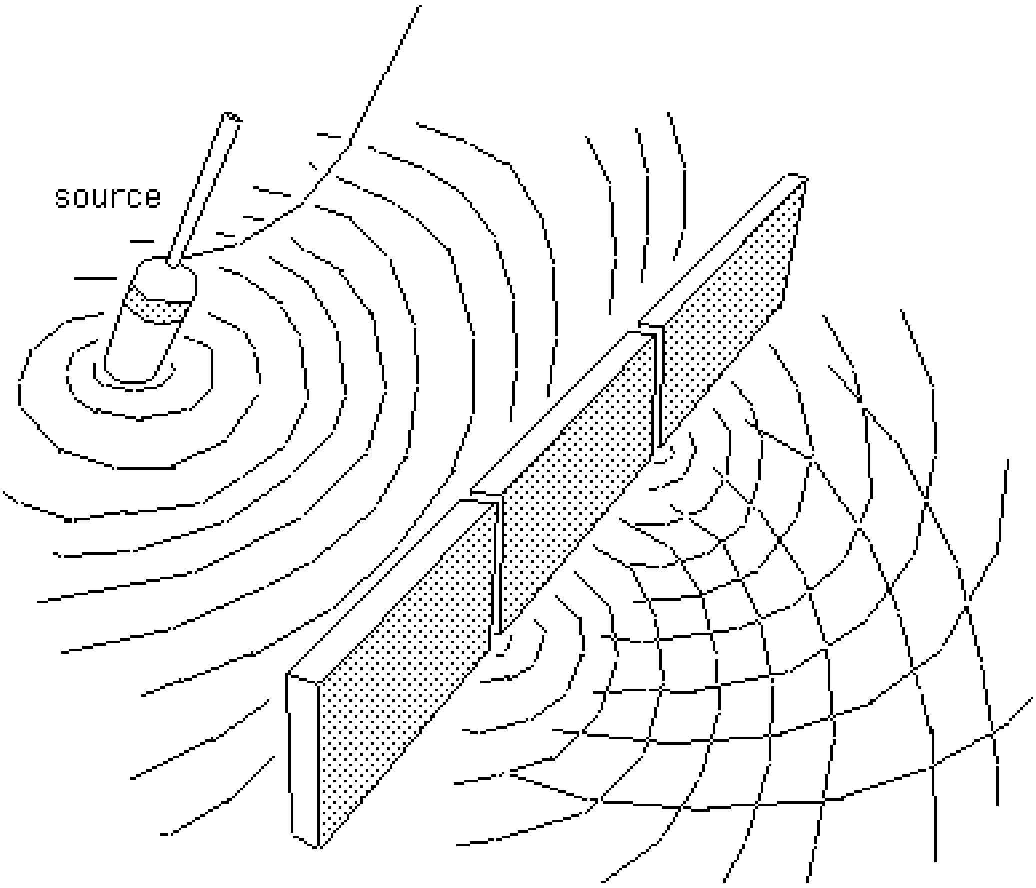
We can see that we would have difficulty in determining the electron's position in its orbit at a given moment. It is in fact completely indeterminate. In the course of the book we have represented the electron as a ball attached to a string and imagined that we could simulate this indeterminacy of position by having the ball turn around very fast, until our eye can no longer localize it. We can imagine another appropriate model to illustrate this property. Let us imagine a sort of circular canal, filled with water, with a single wave circulating around with a sort of swashing. The fundamental state would be the "swash of order one", with a single maximum of the water's height and a single minimum at each moment. On the "following orbit", another "canal" located at a greater distance, a "swash of order two", with two maxima and two minima. Etc....

An electron "ambling" around a nucleus is the "space which swashes". We are a long way from the representation of a little rolling marble.

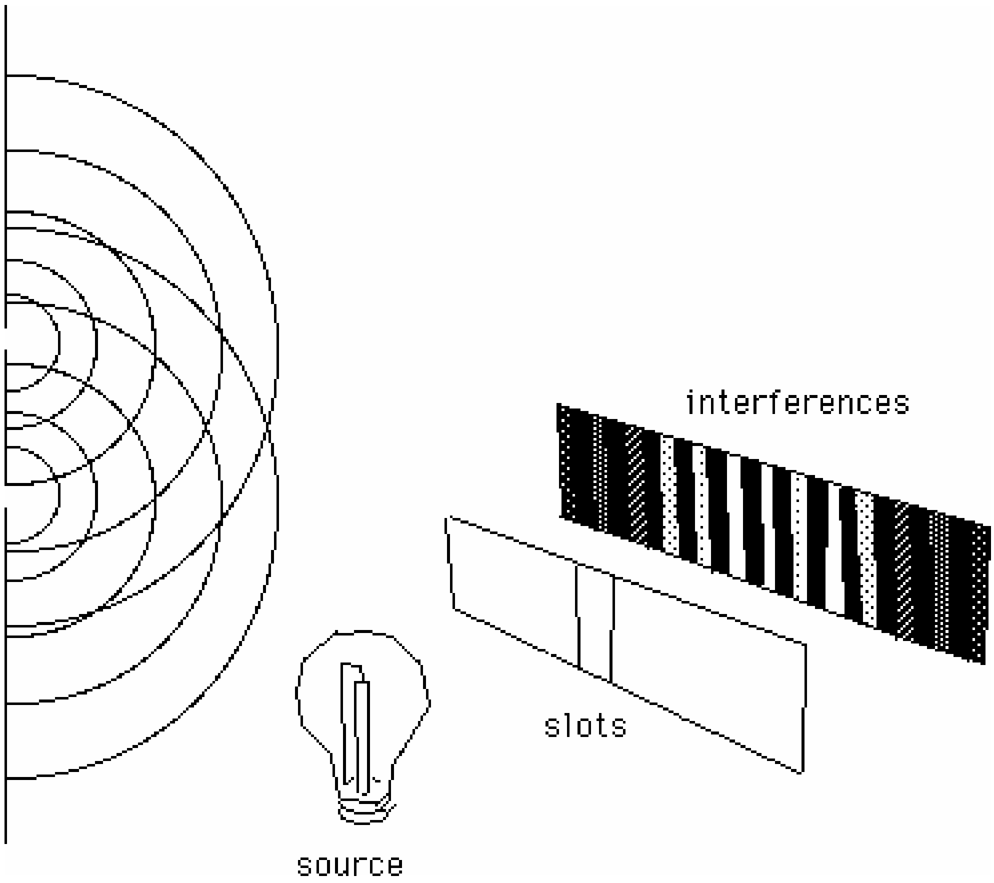
In quantum mechanics the quantities familiar to us in physics -- position, energy, etc. -- are not perfectly determined. In fact an "object" in quantum mechanics is a "superposition of possible states", each being affected by a probability, a difficult concept to grasp. Einstein did not like this idea, and said that he did not believe that God played dice.

We briefly referred in the course of the book to this strange "tunnel effect" enabling a proton to cross the "potential barrier" repelling it, constituted by a positively charged nucleus.

A classic experiment exists called the Young slits. We pass light coming from a single source through two slits. If light is a wave, we will have interference. It is easy to illustrate them using the model of oscillations propagating on the surface of a liquid. The waves then pass through two narrow passages in a wall :



Downstream from the slits there is a system of nodes where the oscillations are in phase and reinforce each other. Between them, on the contrary, the two solicitations cancel each other out on the liquid's surface. If we put some fluorescence in the water and wrote laterally with a light brush we would see places where the water rose and descended and others where it stayed put.



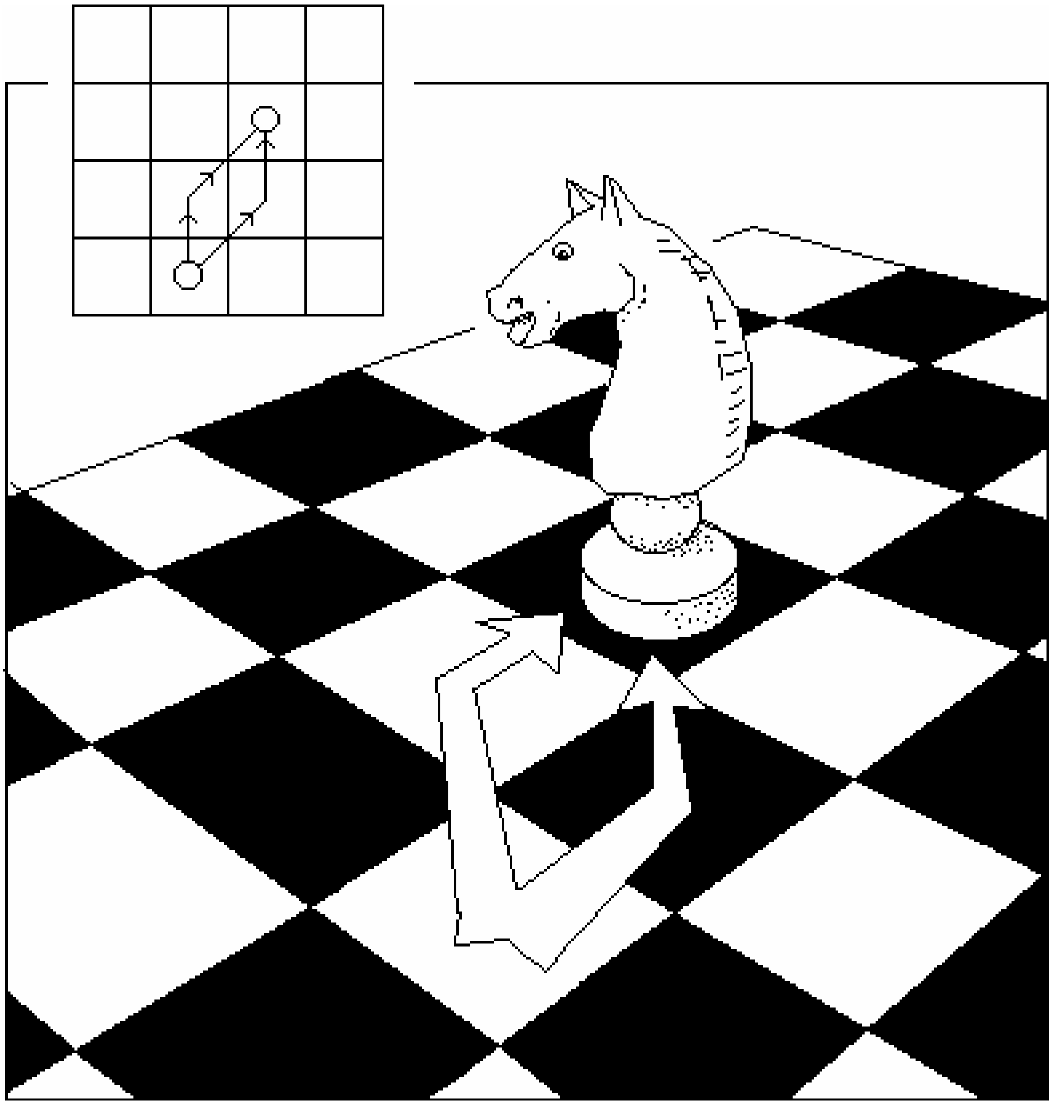
With light the effect is similar and by using systems of slits we can create bands on a screen which alternate between luminous (where the luminous waves are in phase) and dark (where they are in opposition and cancel each other).

But the paradox of quantum mechanics is that we can create interferences by sending these photons one by one. A photon can therefore interfere with itself. But then, which slit did it pass through?

Only quantum mechanics can give a precise and coherent answer to that question. As long as the photon is not absorbed, it does not have a well defined position. It only has a probability of being somewhere, in particular of passing through the right or left slit.

There exists a game in which a certain piece symbolizes uncertainty regarding the path followed. It is only an image of course, a simple gambit merely intended to stimulate the reader's imagination, but I end this Appendix by giving it to you, since it is amusing.

It is the chess knight. When it moves, it can use two different paths to land in the same square. This is in the rules of the game. And you cannot decide which path it has effectively followed:



The quantum uncertainty of the path followed by a chess knight.

So the next time you play chess, you might find yourself wondering, "Hmm! Which way did my knight go?"