Savoir sans Frontières

http://www.savoir-sans-frontieres.com

BIG BANG

Jean-Pierre Petit

The Association Knowledge without Borders, founded and chaired by Professor Jean-Pierre Petit, astrophysicist, aims at spreading scientific and technical knowledge in as many countries as possible and in as many languages as possible. To this end, all his popular scientific works, which cover a period of thirty years, and more particularly the illustrated albums he has created, are now freely accessible. Anyone is now free to duplicate the present file, either in digital form or in the form of printed copies and circulate these copies to libraries , within the context of schools or universities or associations whose aims would be the same as the association , provided that they do not derive any profit from this circulation and that they do not have any political, sectarian or confessional connotations. These pdf files may also be put on line in the computer networks of school and university libraries.

Jean-Pierre Petit intends to create numerous other works which will be accessible to a larger audience. Even illiterate people will be able to read them because the written parts will “speak” when the readers click on them. Thus it will be possible to use these works to support literacy schemes. Other albums will be "bilingual" in so far as it will be possible to switch from one language to another selected language with a mere click. Hence another tool made available to develop language skills.

Jean-Pierre Petit was born in 1937. He made his career in French research. He worked as a plasma physicist, he directed a computer science centre, he has created softwares, he has published hundreds of articles in scientific magazines, dealing with subjects ranging from fluid mechanics to theoretical cosmology. He has published about thirty books which have been translated in numerous languages.

The association can be contacted on the following internet site:

http://savoir-sans-frontieres.com

PROLOGUE

YOU KNOW, SOPHIE, I SOMETIMES WONDER WHERE EVERYTHING CAME FROM. HOW THE UNIVERSE WAS MADE...
HAS EVERYTHING ALWAYS BEEN THE SAME AS IT IS NOW? THE EARTH, THE SKY?
HAS THE SKY ALWAYS BEEN BLUE?
AND 'AVE THE STARS ALWAYS SHONE OUT OF A BLACK SKY AT NIGHT?
AT THE VERY BEGINNING, OUR UNIVERSE WAS VERY SMALL AND VERY HOT, LIKE A CONCENTRATED HELL.
AND EVERYTHING BLEW UP?
YES. BUT IT'S A VERY LONG STORY, AND TO TELL IT I'LL HAVE TO START A LONG, LONG TIME AGO.
HEY! COME AND SEE WHAT I'VE FOUND!

IT'S WEIRD. I WONDER WHAT IT IS?
NOW
100,000 YRS
35 MIN
13 SEC
1 SEC
1/10 SEC
1/100 SEC
ZERO
EXPERIMENT IN PROGRESS DO NOT TOUCH
I'D SAY IT WAS A KIND OF CHRONOTRON.
YUR... BUT DON'T THOSE MARKINGS LOOK A BIT STRANGE?
SUDDENLY...
TIRESIAS, WATCH OUT!
EEEE
A
KLONG!
ZERO

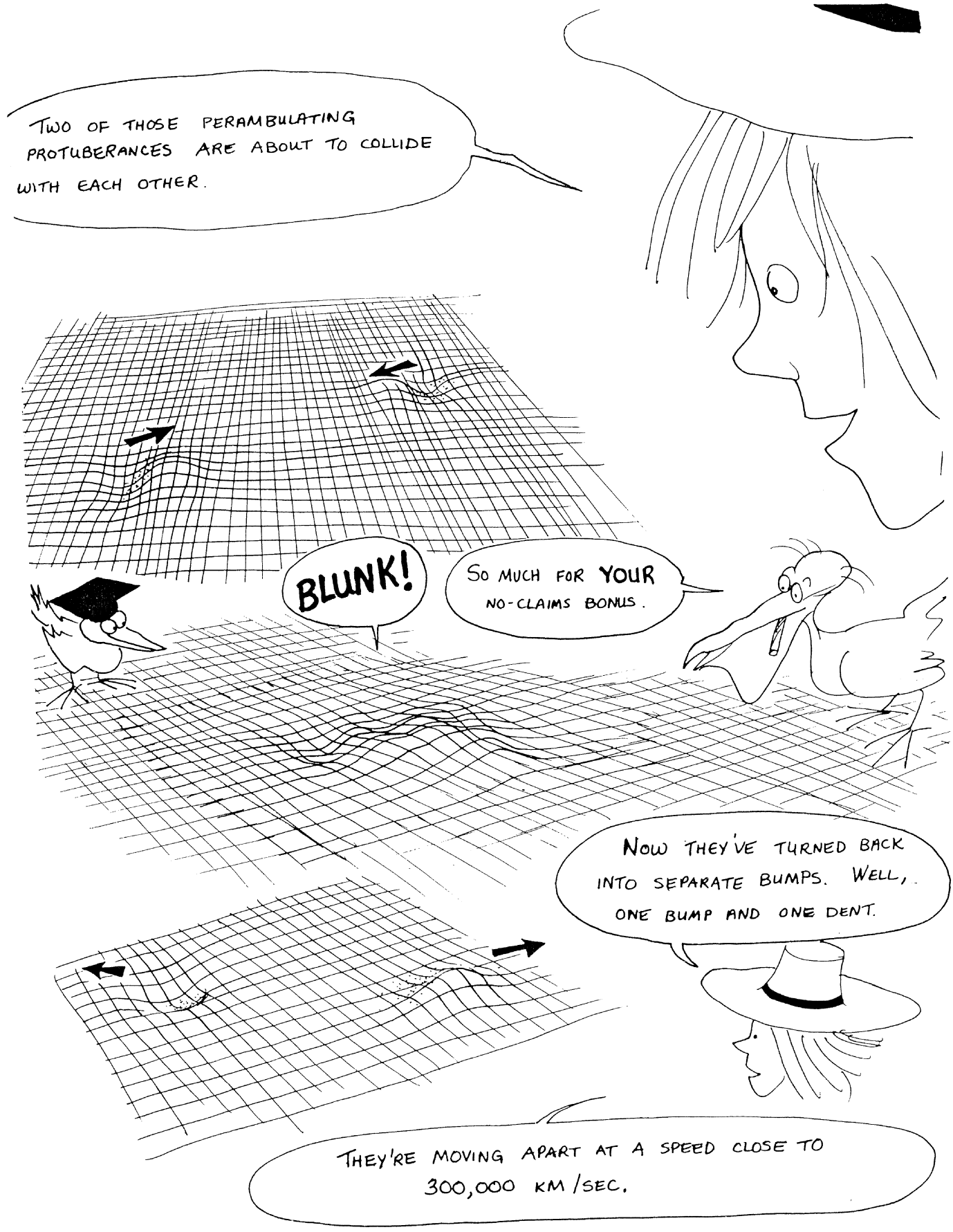
THE VERY BEGINNING

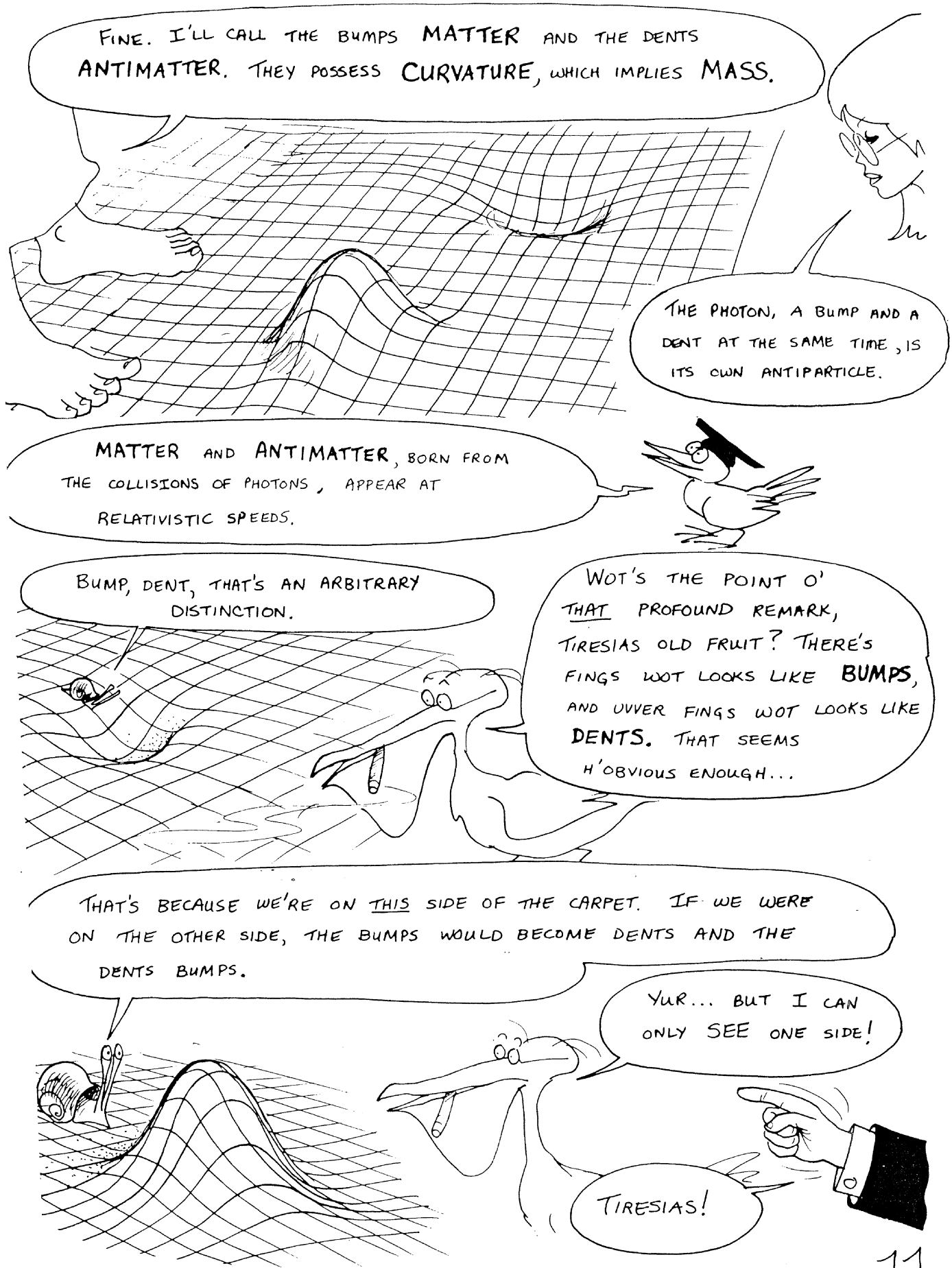
THAT'S DONE IT— ANOTHER FAILURE!
AND I'D JUST FINISHED IT...
IF YOU'RE TRYING TO LAY THE CARPET, YOU'VE MADE A REAL PIG'S BREAKFAST OF IT, THAT'S TRUE!
I THINK THE GENTLEMAN IS HAVING PROBLEMS WITH HIS CARPET, ARCHIE.
IT'S A DISASTER— BUMPS EVERYWHERE!
YOU'D EXPECT TO GET BUMPS. YOU'VE TRIED TO FIT TOO MUCH IN, AND THE CARPET'S GOT COMPRESSED...
TSSSS... WITHOUT ANY COMPRESSION THERE WOULDN'T BE ANY ENERGY. ONLY EMPTY SPACE...
I WOULDN'T MIND IF THE BUMPS WERE MORE EVENLY SPACED. BUT THERE ARE HORDES OF BUMPS, WANDERING ALL OVER THE PLACE— AT A SPEED OF 300,000 KILOMETERS PER SECOND.
IT'S QUANTIC... DIABOLICALLY QUANTIC...
IT'S WHAT?

IF THAT'S A UNIVERSE, IT HASN'T GOT MANY THINGS IN IT!
BUT IT HAS! ITS THINGS ARE THESE KINDS OF WANDERING WAVES.
THIS PARTICULAR UNIVERSE ONLY HAS TWO DIMENSIONS, SO IT'S A SURFACE. BUMPS ON THE SURFACE CORRESPOND TO PARTICLES, MASSES, AND RADIATION. IF YOU WERE LIVING IN THIS TWO-DIMENSIONAL WORLD, THIS IS WHAT YOU'D LOOK LIKE.
IT'S NOT PRETTY, NOT PRETTY AT ALL...
IN OUR ACTUAL THREE-DIMENSIONAL WORLD, PARTICLES ARE ALSO LOCAL VARIATIONS IN CURVATURE.
IT WAS BETTER BEFORE.
BEFORE WHAT?
TO HECK WITH IT... I'LL CALL THESE WANDERING WAVES PHOTONS.

OH MY GOD MY GOD MY GOD! THERE ARE MORE OF THE THINGS!
MORE?
YES - LOOK AT THAT! THEY'RE ALL OVER THE PLACE!
THAT'S NOT JUST A LUMP, EITHER; IT'S ROTATING. GOD HELP US ALL!
THEY'RE LIKE THE TWISTS YOU SOMETIMES GET IN THE BEDCLOTHES. OR EDDIES IN WATER. CRAZY EDDIES.
IT'S FUNNY — SOME TURN ONE WAY, SOME TURN THE OTHER.
AND JUST LIKE PHOTONS, THEY MOVE AT 300,000 KM/SEC.
I'LL CALL THESE EDDIES NEUTRINOS WHEN THEY TURN THIS WAY:
... AND ANTINEUTRINOS WHEN THEY TURN THE OTHER WAY:

(*) A PROPERTY KNOWN AS BLACK BODY RADIATION (GOD KNOWS WHY).


TWO OF THOSE PERAMBULATING PROTUBERANCES ARE ABOUT TO COLLIDE WITH EACH OTHER.
BLUNK!
SO MUCH FOR YOUR NO-CLAIMS BONUS.
NOW THEY'VE TURNED BACK INTO SEPARATE BUMPS. WELL, ONE BUMP AND ONE DENT.
THEY'RE MOVING APART AT A SPEED CLOSE TO 300,000 KM/SEC.

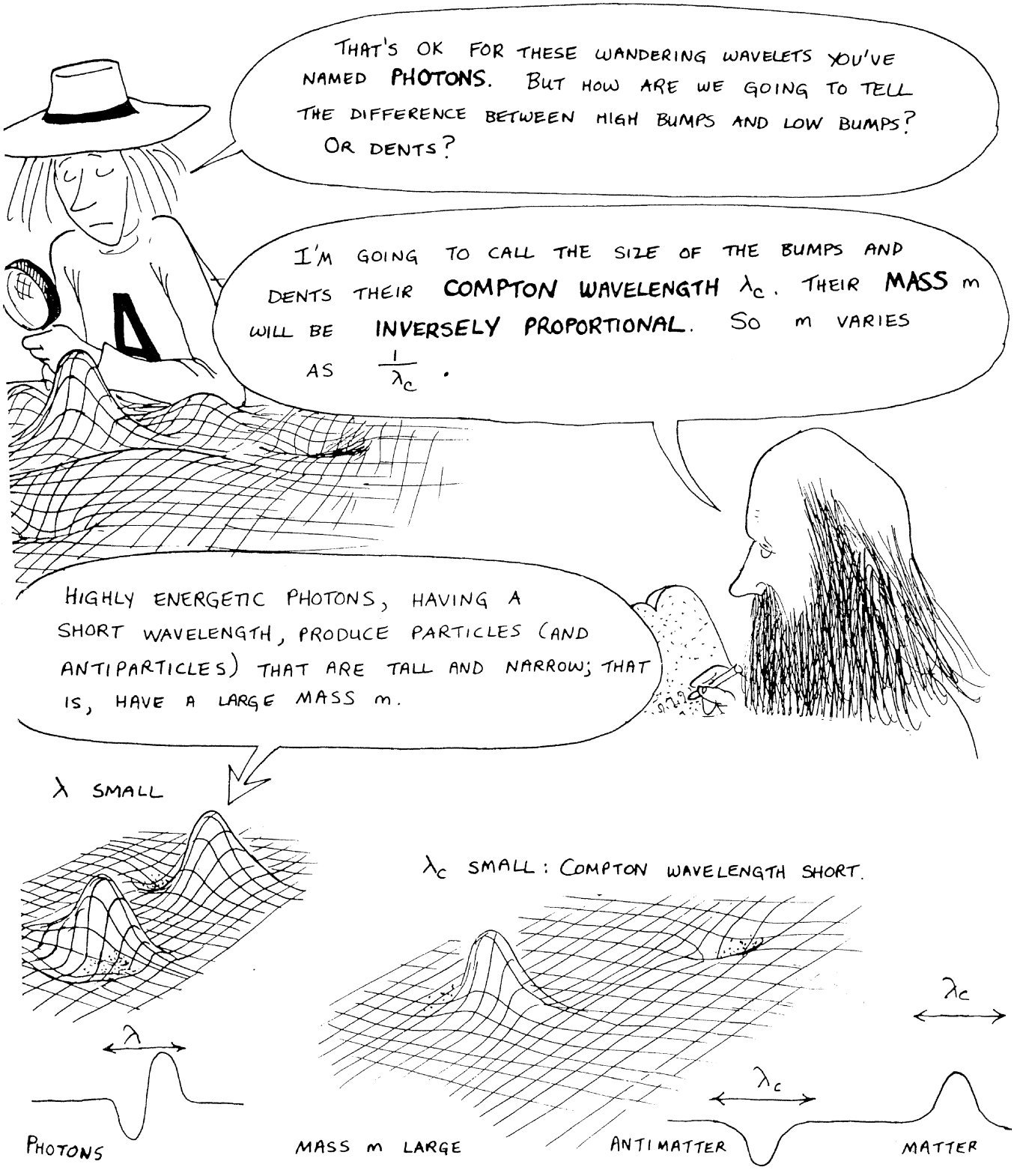

FINE. I'LL CALL THE BUMPS MATTER AND THE DENTS ANTIMATTER. THEY POSSESS CURVATURE, WHICH IMPLIES MASS.
THE PHOTON, A BUMP AND A DENT AT THE SAME TIME, IS ITS OWN ANTIPARTICLE.
MATTER AND ANTIMATTER, BORN FROM THE COLLISIONS OF PHOTONS, APPEAR AT RELATIVISTIC SPEEDS.
BUMP, DENT, THAT'S AN ARBITRARY DISTINCTION.
WOT'S THE POINT O' THAT PROFOUND REMARK, TIRESIAS OLD FRUIT? THERE'S FINGS WOT LOOKS LIKE BUMPS, AND UVVER FINGS WOT LOOKS LIKE DENTS. THAT SEEMS H'OBVIOUS ENOUGH...
THAT'S BECAUSE WE'RE ON THIS SIDE OF THE CARPET. IF WE WERE ON THE OTHER SIDE, THE BUMPS WOULD BECOME DENTS AND THE DENTS BUMPS.
YUR... BUT I CAN ONLY SEE ONE SIDE!
TIRESIAS!

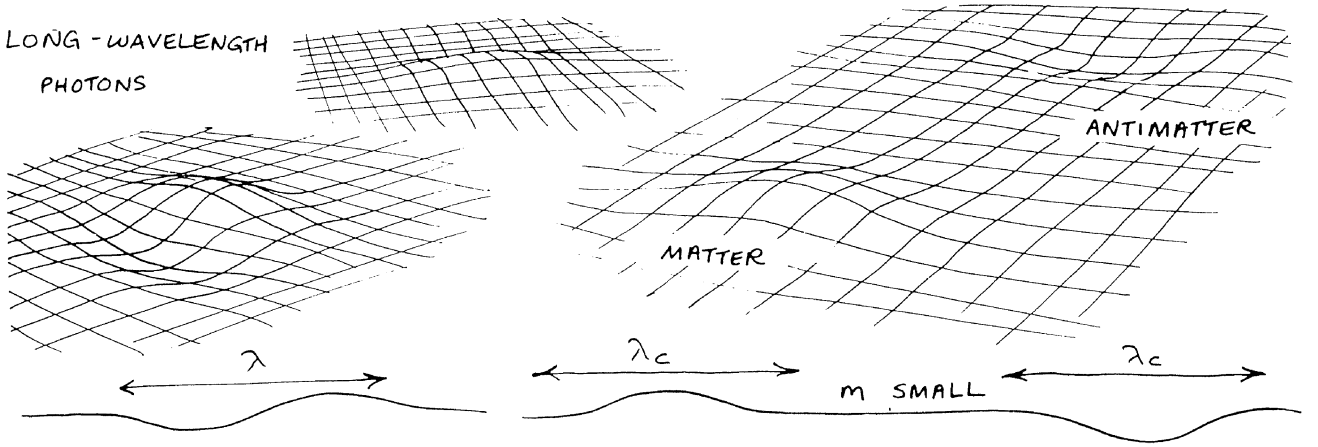
(*) FROM EPISTEMOLOGY (THEORY OF KNOWLEDGE) AND COP (COP): THOUGHT POLICE

(*) SEE THE BIBLE.

I'LL CALL THE SIZE OF THESE WANDERING WAVES — PHOTONS — THEIR WAVELENGTH λ (LAMBDA).
SUPPOSE I CREATE A TRAVELING WAVE BY SHAKING THIS ROPE. IF I SHAKE IT GENTLY I GIVE IT VERY LITTLE ENERGY AND THE WAVELENGTH λ IS LARGE.
NOW IF I SHAKE THE CORD MUCH HARDER, I GIVE IT A LOT OF ENERGY AND THE WAVELENGTH λ IS SHORT.
EEEEK!
SO THE MORE ENERGY A TRAVELING WAVE HAS, THE SHORTER ITS WAVELENGTH MUST BE.
I'VE DECIDED THAT THE ENERGY CARRIED BY A PHOTON, A PARTICLE OF LIGHT, WILL BE INVERSELY PROPORTIONAL TO ITS WAVELENGTH λ. THAT IS, E VARIES AS $\frac{1}{\lambda}$.
THAT'S THE WAY IT WILL BE...

THE SMALLER THINGS ARE THE HEAVIER THEY ARE





LONG-WAVELENGTH PHOTONS → PARTICLES WITH LONG COMPTON WAVELENGTH.

CONVERSELY, PHOTONS WITH RELATIVELY LOW ENERGY GIVE RISE TO A PARTICLE-ANTIPARTICLE PAIR WITH LONG COMPTON WAVELENGTH. THAT IS, LOW MASS: λ_c LARGE, m SMALL.

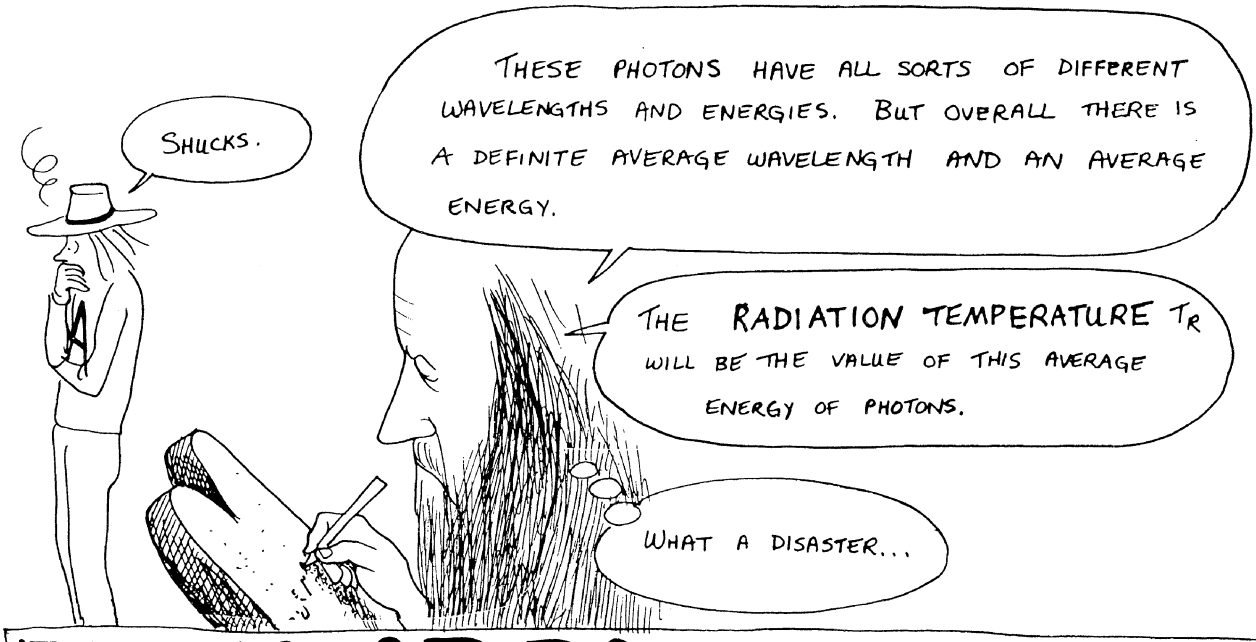
(*) REMEMBER THAT E (ENERGY) EQUALS m (MASS). SEE EVERYTHING IS RELATIVE, SAME SERIES.

HOLD IT! THERE'S SOMETHING SCREWY ABOUT ALL THIS! IT WON'T DO AT ALL...
!!!
WOOPS, SORRY.
PING
PROTONS AND NEUTRONS HAVE ALMOST THE SAME MASS. THEREFORE THEY HAVE THE SAME SIZE. BUT AN ELECTRON IS MUCH LIGHTER. LOGICALLY, THE ELECTRON MUST BE... LARGER?
THAT'S RIGHT. THE PROTON AND NEUTRON WEIGH 1.66 x 10^-27 KG. THE ELECTRON WEIGHS 9.1 x 10^-31 KG. SO IT'S 1850 TIMES LIGHTER, THAT IS, 1850 TIMES "BIGGER."...
I... ER... OH HECK...
HAVE YOU EVER SEEN A PROTON?
ER... NO.
WELL, THEN!

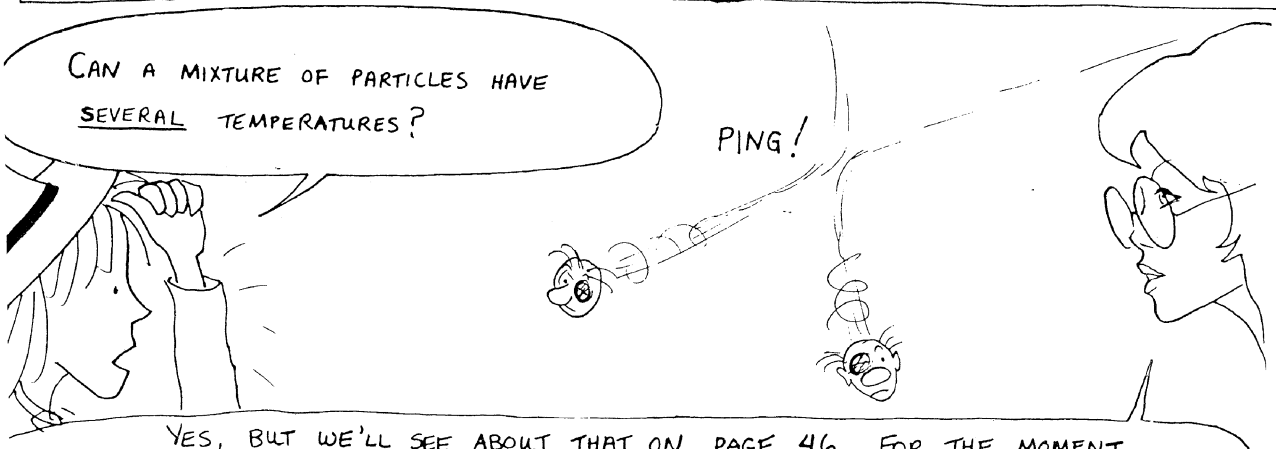
THE GENESIS OF TODAY IS UTTERLY FASCINATING.
SOPHIE, WHAT ARE YOU MAKING?
A
A HYDROGEN ATOM MORE CLOSELY RESEMBLING REALITY. WITH A BIG ELECTRON AND A TINY PROTON MAKING UP ITS NUCLEUS.
MY GOD MY GOD MY GOD! WHAT CHAOS! WELL... I THINK YOU PEOPLE CAN HELP ME PUT THIS JUMBLE INTO SOME SORT OF ORDER.

RADiATiON TEMPERATURE

T_R

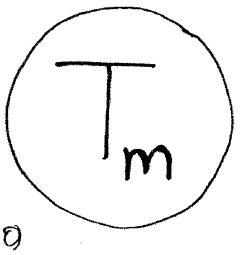


EQUiLiBRiUM STATES

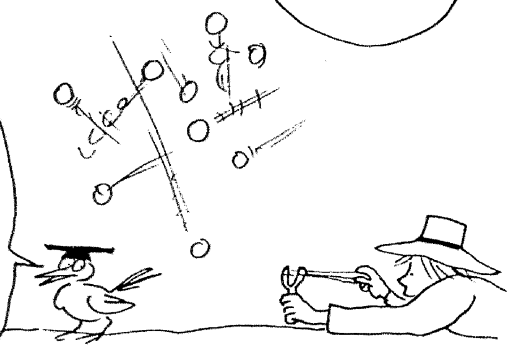


YES, BUT WE'LL SEE ABOUT THAT ON PAGE 46. FOR THE MOMENT LET'S JUST SAY THAT PARTICLES EXCHANGE ENERGY WITH EACH OTHER, OR WITH PHOTONS, THROUGH COLLISIONS. THIS MECHANISM TENDS TO REDISTRIBUTE THE TEMPERATURES, TO **EQUALIZE** THEM, SO PUTTING THE SYSTEM INTO A STATE OF **THERMODYNAMIC EQUILIBRIUM**.

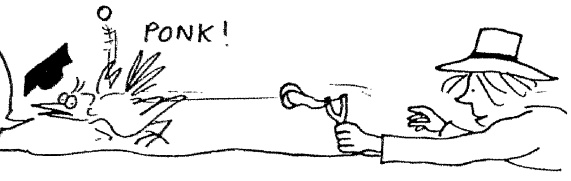
THE TEMPERATURE OF MATTER



ALL THESE **MATERIAL** PARTICLES HAVE VARIOUS MASSES m AND SPEEDS V. THE **KINETIC ENERGY** OF A PARTICLE IS $\frac{1}{2}mV^2$. BUT AGAIN, OVERALL THERE IS AN AVERAGE (**THERMAL**) ENERGY OF AGITATION.

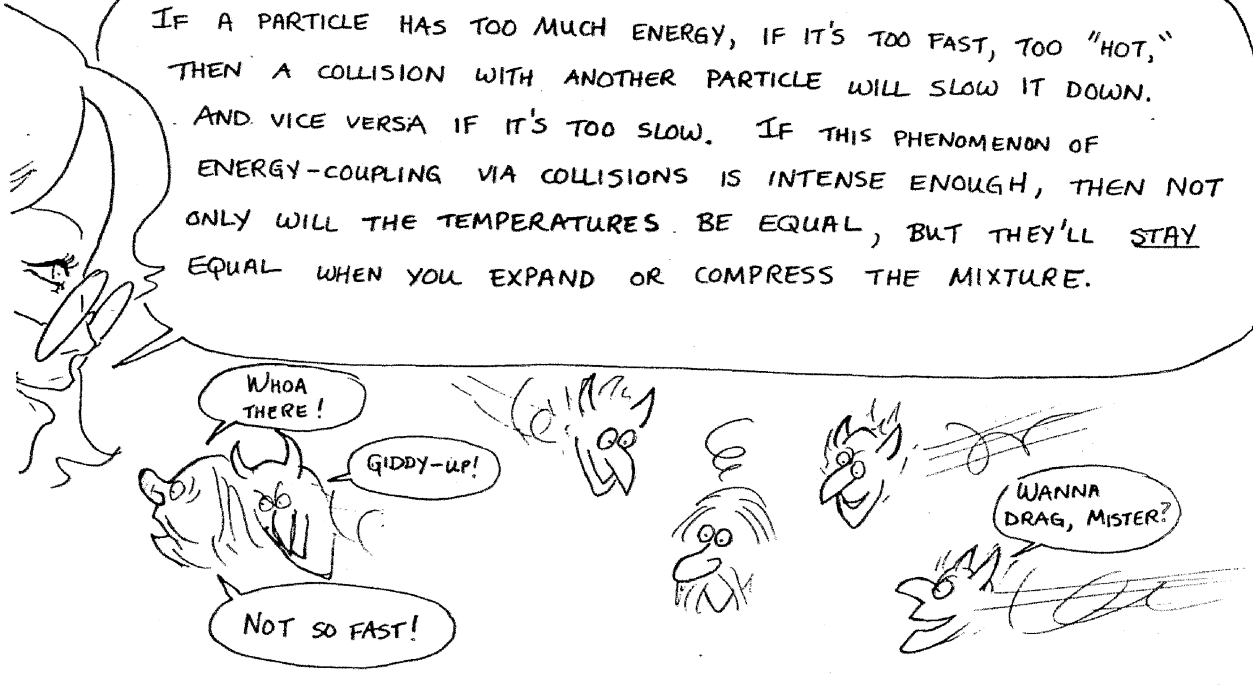


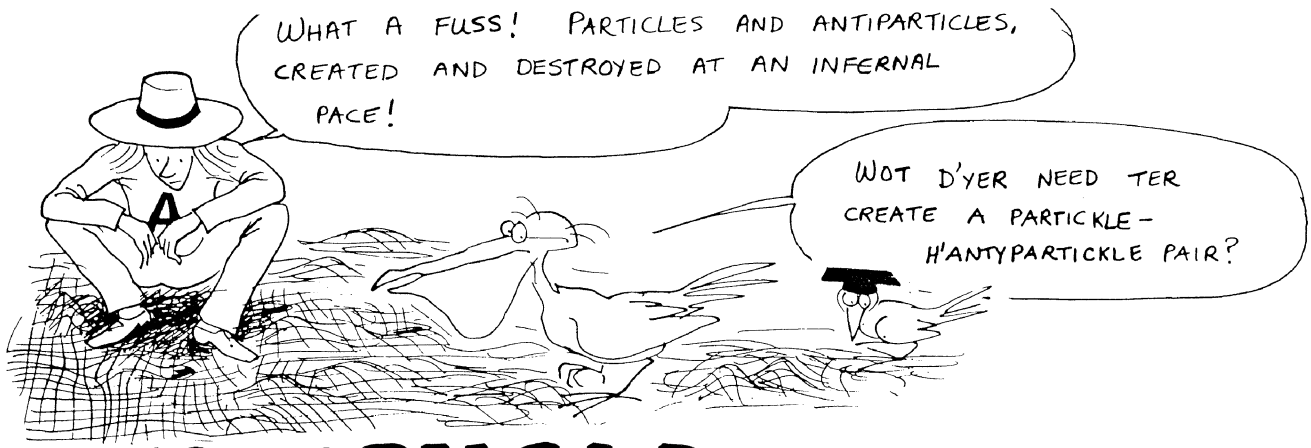
AND THE **TEMPERATURE** OF THE **MATTER**, T_m, IS THE VALUE OF THIS AVERAGE ENERGY OF **THERMAL** AGITATION.



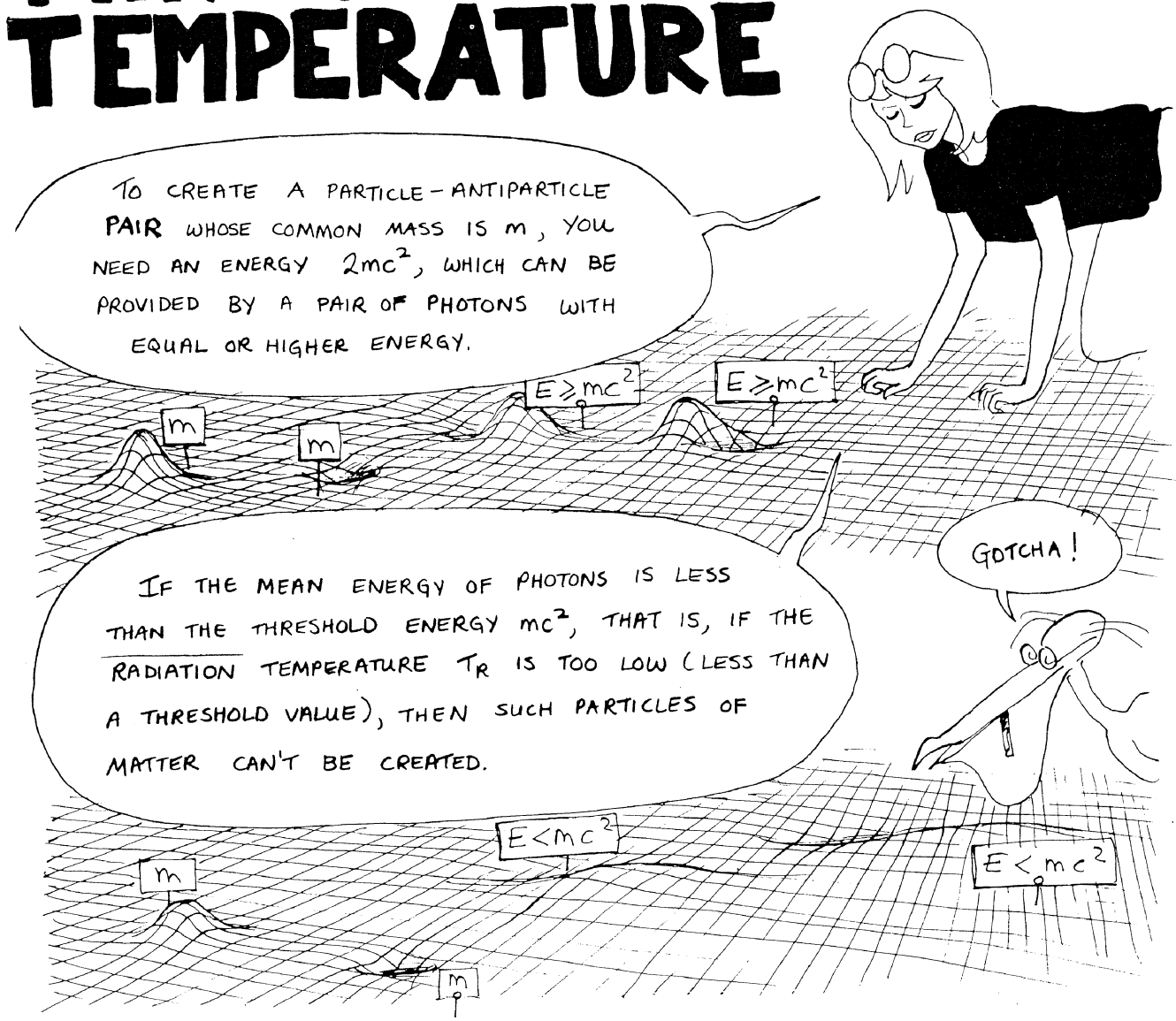
THERMODYNAMICS

IF A PARTICLE HAS TOO MUCH ENERGY, IF IT'S TOO FAST, TOO "HOT," THEN A COLLISION WITH ANOTHER PARTICLE WILL SLOW IT DOWN. AND VICE VERSA IF IT'S TOO SLOW. IF THIS PHENOMENON OF ENERGY-COUPLING VIA COLLISIONS IS INTENSE ENOUGH, THEN NOT ONLY WILL THE TEMPERATURES BE EQUAL, BUT THEY'LL <u>STAY</u> EQUAL WHEN YOU EXPAND OR COMPRESS THE MIXTURE.





THRESHOLD TEMPERATURE



THE EVOLUTION OF SPECIES

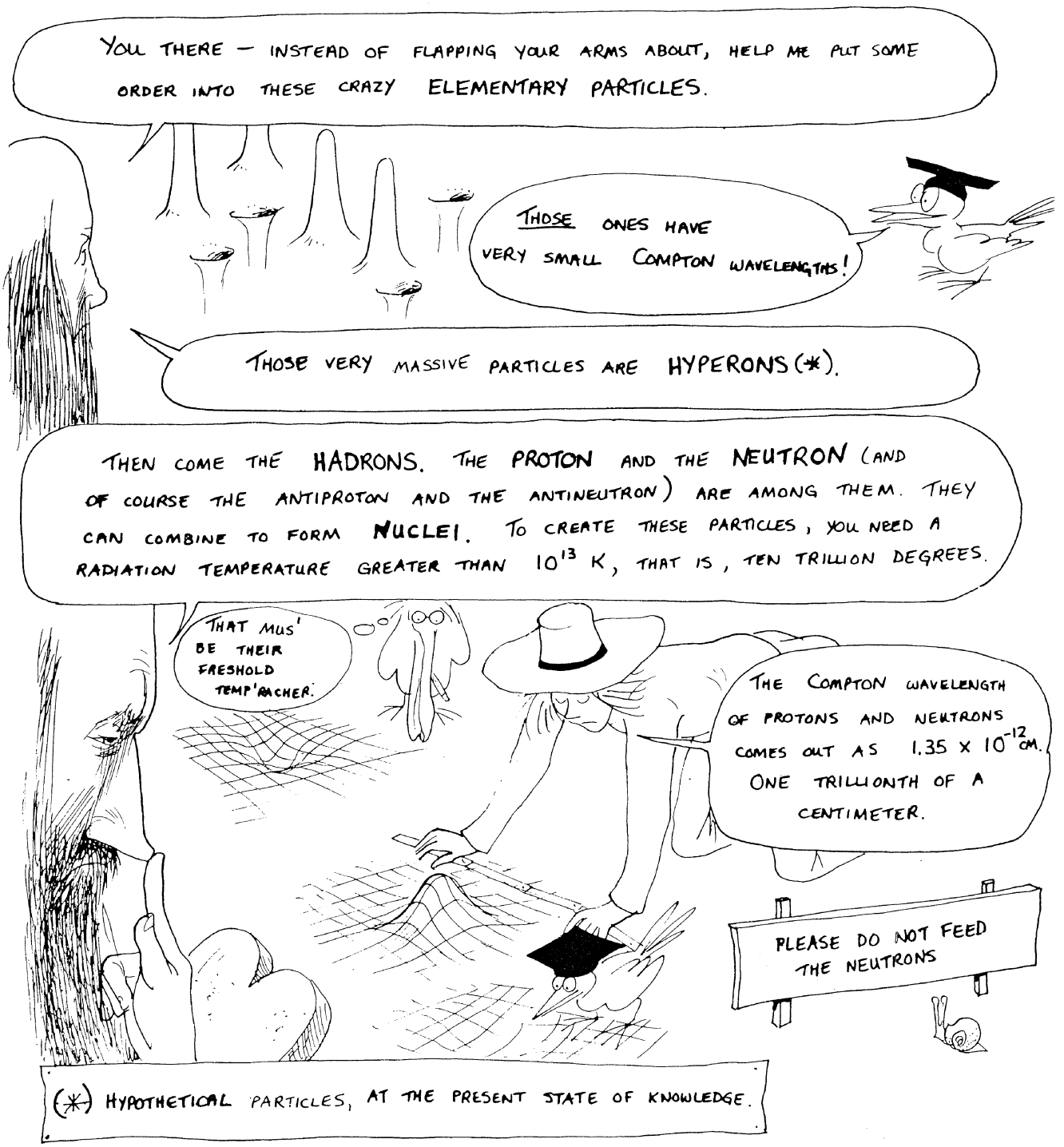
IN ADDITION, PARTICLES HAVE THEIR OWN **LIFETIMES**. AFTER THESE HAVE PASSED (*), THE PARTICLES DECOMPOSE SPONTANEOUSLY INTO OTHER PARTICLES, AND RADIATION.

(*) ... THEIR RESERVE OF CHRONOL RUNS OUT: SEE EVERYTHING IS RELATIVE.

WOT'S THE TEMP 'RACHER?
CATCH A PHOTON AND MEASURE ITS WAVELENGTH λ.
'OLY SMOKE! TWENNY TRILLION DEGREES (2 x 10^13 K).
THERE SEEM TO BE ABOUT THE SAME NUMBERS OF PHOTONS, NEUTRINOS, PROTONS, NEUTRONS, ELECTRONS (AND THEIR ANTIPARTICLES).
AT A HIGH ENOUGH TEMPERATURE, EVERYTHING IS RELATIVISTIC. EVEN PARTICLES OF MATTER TRAVEL AT VELOCITIES NEAR THE SPEED OF LIGHT c.
IN EVERYTHING IS RELATIVE WE SAW THAT AS A PARTICLE'S SPEED TENDS TO THE SPEED OF LIGHT, ITS PROPER TIME FLOWS LIKE SYRUP.

A COSMIC TIME THAT MIGHT BE THE AVERAGE OF INDIVIDUAL PROPER TIMES.

ELEMENTARY PARTICLES

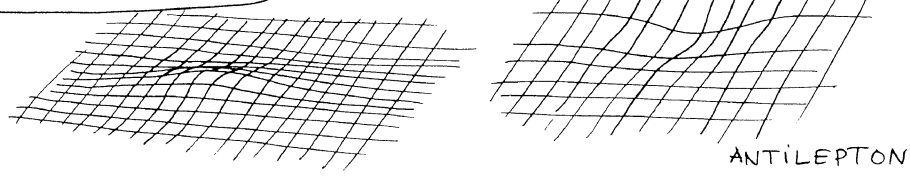


HADRON COMES FROM HADROS, WHICH MEANS "HEFTY" IN GREEK.

BLIMEY – A GREEK-SPEAKIN' SNAIL!

OBVIOUSLY THERE ARE AS MANY ANTIHADRONS AS HADRONS.

NOW, HERE COME THE LEPTONS(*).



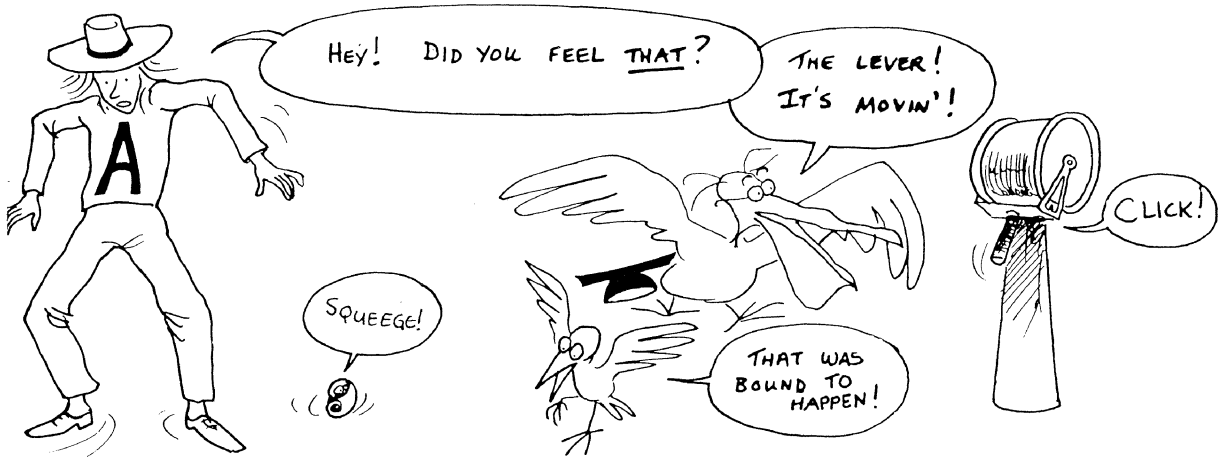
TO CREATE THEM, YOU NEED A RADIATION TEMPERATURE OF 6 BILLION DEGREES – THEIR THRESHOLD TEMPERATURE.

THE BEST KNOWN LEPTON IS THE ELECTRON, AND ITS COUNTERPART THE ANTIELECTRON, OR POSITRON. NOTE THAT THE THRESHOLD TEMPERATURE FOR CREATING ELECTRONS IS 1850 TIMES LOWER THAN THAT FOR PROTONS AND NEUTRONS.

THAT MAKES SENSE, BECAUSE YOU NEED 1850 TIMES LESS ENERGY TO CREATE AN ELECTRON THAN YOU DO A PROTON.

(*) FROM THE GREEK LEPTOS, THIN.

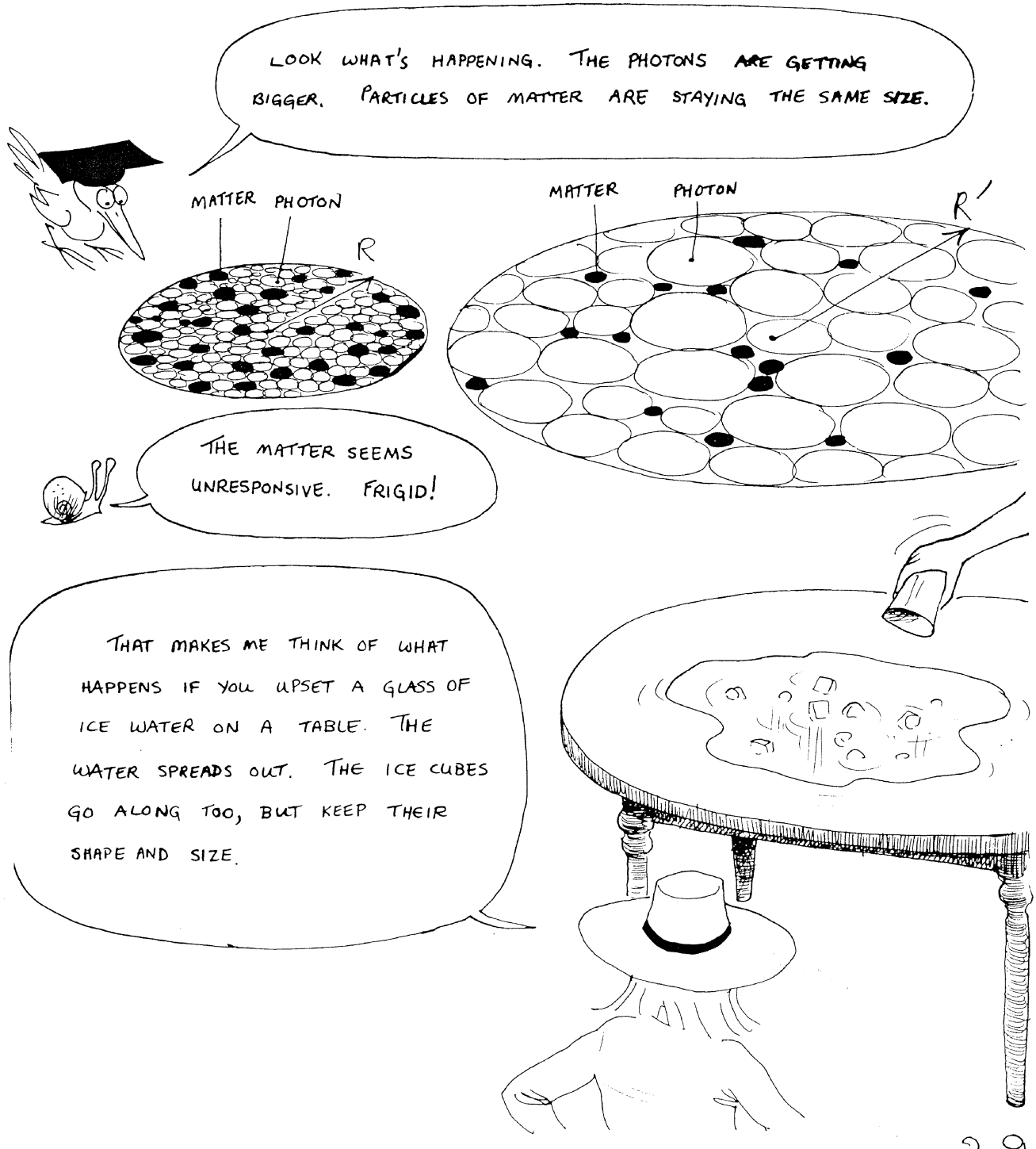
EVERYTHiNG FALLS APART



THE SITUATION WAS TERRIBLY CHRONOGENIC – TIME COULD HARDLY WAIT TO APPEAR. THE CHRONOTRON STARTED UP, THEREBY PRODUCING THE FIRST EVENT, THE FIRST INSTANT.

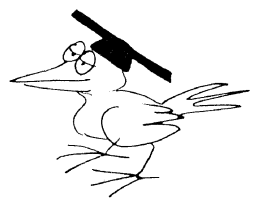
WHERE ARE YOU GOING? WHAT'S HAPPENING?
IT'S THE EXPANSION... THE STRAIN'S GOT TOO MUCH, IT'S ALL BREAKING UP. EXCUSE ME...
I'M JUST TAKING A LITTLE TRIP.
I CAN'T ABIDE CHANGE!
EH?
YOU'LL SEE. IT'LL CALM DOWN A BIT EVENTUALLY.
WELL I NEVER! HE'S LEFT US TO FEND FOR OURSELVES.
GOODBYE. HAVE A NICE EXPLOSION.
RUINED, UTTERLY RUINED!
WHERE'D 'E GO?
IT LOOKS LIKE A MANHOLE COVER. INTO THE CATACOMBS OF THE UNIVERSE?

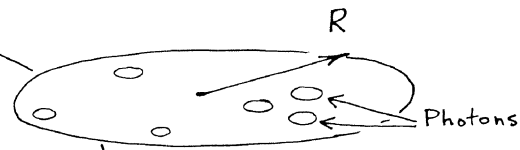
THE CONSERVATION OF MASS



BECAUSE THE SIZE OF PARTICLES OF MATTER IS RELATED TO THEIR MASS, I DEDUCE THAT **MASS IS CONSERVED.**

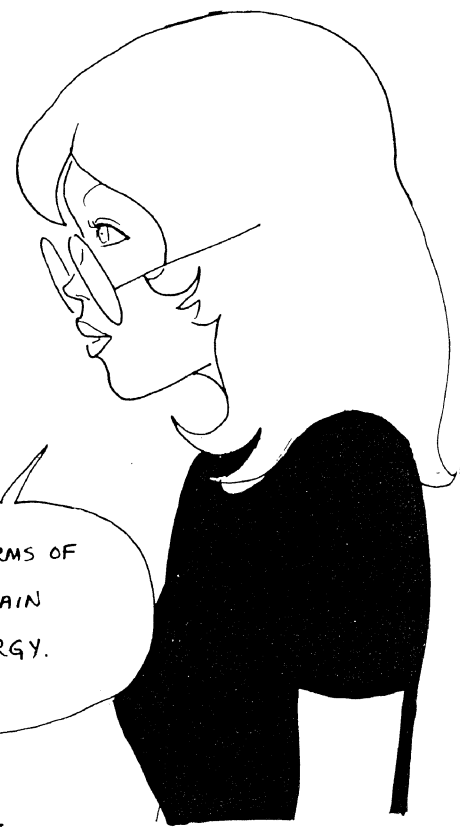
ON THE OTHER HAND, THE PHOTONS SPREAD OUT, SO ARE LOSING **ENERGY.**





IF R IS THE RADIUS OF THE UNIVERSE, THEN, SINCE THE WAVELENGTH λ OF PHOTONS UNDERGOES THE SAME EXPANSION (λ VARIES LIKE R), I ALSO DEDUCE THAT THE RADIATION TEMPERATURE, WHICH VARIES AS $\frac{1}{\lambda}$, DECREASES AS $\frac{1}{R}$.

IT'S HAPPENING JUST AS IF THE UNIVERSE CREATES ITS OWN SPACE, ITS **COSMOTOPE** (*), BY SECRETING... EMPTINESS...



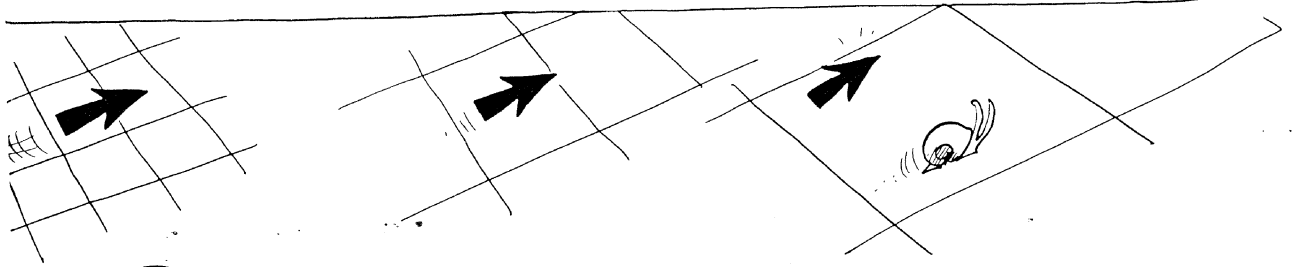
MATTER AND LIGHT ARE JUST TWO DIFFERENT FORMS OF THE SAME ENTITY: **ENERGY / MATTER.** THE PHOTONS RETAIN THEIR SPEED OF 300,000 KM/SEC BUT LOSE ENERGY.

(*) FROM COSMOS (COSMOS) AND TOPOS (PLACE). THE PLACE THAT THE UNIVERSE INHABITS.

HERE'S A GOOD WAY TO VISUALIZE THE WAY THE PHOTON SPREADS OUT AND THE ACCOMPANYING ENERGY LOSS.

BUT HOW DOES MATTER BEHAVE DURING THIS EXPANSION?

THE UNIVERSE SECRETES SPACE LIKE A CREATURE GROWING A SHELL. THE MORE TIME PASSES, THE MORE SPACE PARTICLES HAVE TO MOVE AROUND IN. WHEN THE SIZE OF THE UNIVERSE DOUBLES, THE SPEED OF AGITATION OF PARTICLES HALVES. SO THEIR KINETIC ENERGY IS DIVIDED BY 4. THE SPEED OF AGITATION VARIES AS THE INVERSE OF THE RADIUS R OF THE UNIVERSE, WHEREAS THE TEMPERATURE OF MATTER VARIES AS $\frac{1}{R^2}$



BUT... WE SAW JUST NOW THAT THE RADIATION TEMPERATURE T_R VARIES AS $\frac{1}{R}$. SO MATTER TENDS TO COOL DOWN QUICKER THAN RADIATION?

EFFECTIVELY. BUT PHOTON-MATTER COLLISIONS REHEAT IT. THEY HAPPEN FREQUENTLY ENOUGH TO MAINTAIN A STATE OF THERMODYNAMIC EQUILIBRIUM ($T_R = T_m$) FOR A CERTAIN PERIOD OF TIME.

THE TEMPERATURE ($T_R = T_m$) HAS DROPPED TO A HUNDRED BILLION DEGREES, WELL BELOW THEIR THRESHOLD TEMPERATURE OF TEN TRILLION DEGREES. THEY'VE ANNIHILATED EACH OTHER IN PAIRS AT A TREMENDOUS RATE AND ONLY **ONE IN A BILLION** SURVIVES.

SOPHIE - MOST OF THE PROTONS, NEUTRONS, ANTIPROTONS, AND ANTINEUTRONS HAVE VANISHED. BUT WHY ARE THERE STILL JUST AS MANY ELECTRONS AND POSITRONS (ANTIELECTRONS) AS BEFORE?
THE THRESHOLD TEMPERATURE OF ELECTRONS IS ONLY SIX BILLION DEGREES.
ONLY SIX BILLYON BLINKIN' DEGREES... DID YER 'EAR THAT?
WELL, YOU MUST ADMIT IT'S A LOT COOLER...
NOW THAT'S REALLY BIZARRE... THE TEMPERATURE IS 100 BILLION DEGREES... PROTONS, NEUTRONS, AND THEIR ANTIPARTICLES MOVE AT ONE TENTH OF THE SPEED OF LIGHT. BUT ELECTRONS ARE STILL RELATIVISTIC.
YUR. WOT? WOJJA MEAN?

THE SYSTEM IS STILL IN A STATE OF **THERMODYNAMIC EQUILIBRIUM**: THE COUPLING BETWEEN ALL PARTICLE SPECIES, AND RADIATION, IS STILL INTENSE. THE KINETIC ENERGIES OF PARTICLES OF MATTER ARE, ON AVERAGE, EQUAL: $\frac{1}{2} m_{PROTON} (v_{PROTON})^2 = \frac{1}{2} m_{ELECTRON} (v_{ELECTRON})^2$.

LET ME SEE... SINCE THE MASS OF THE ELECTRON IS 1850 TIMES SMALLER THAN THAT OF THE PROTON, THEN IN ORDER TO COMPENSATE (AT A GIVEN TEMPERATURE), THE SPEED OF AGITATION OF THE ELECTRON MUST BE MUCH HIGHER.

IN FACT, SINCE THE THRESHOLD ENERGY FOR THE CREATION OF A PARTICLE OF MASS m IS JUST mc^2, THEN AS SOON AS THE SYSTEM COOLS TO THE POINT AT WHICH ITS SPEED OF AGITATION V IS NOTICEABLY SMALLER THAN c, THE CREATION OF THESE PARTICLES CEASES AND THEIR POPULATION DROPS DRAMATICALLY.

IN UWER WORDS: IF A POPYERLATION OF PARTICKLES OF MATTER STOPS BEIN' RELATIVISTICK, IT GETS DECIMATED!

THIRTEEN SECONDS.
THE TEMPERATURE HAS FALLEN TO THREE BILLION DEGREES.
10 BILLION YR
5 BILLION YR
100 MILLION YR
700,000 YR
34 MIN
3 MIN
13 SEC
1 SEC
1/100 SEC
ZERO
A
'EY, LOOK AT THE H'ELECTRONS AN' THE H'ANTIELECTRONS! IT'S 'OLESALE SLAUGHTER!
NATURALLY — IT'S BELOW THEIR THRESHOLD TEMPERATURE.
IT'S LIKE A COSMOLOGICAL SUPERBOWL!
AGAIN, ONLY ONE IN A BILLION SURVIVES.
WOT A MESS...

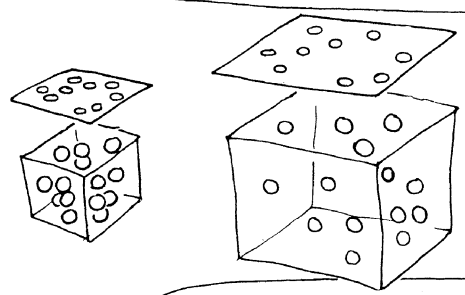
FOR A WHILE, NOTHING MIGHT REMAIN EXCEPT PHOTONS... THERE'S A POSSIBILITY...
... MAYBE SOME PLACE ELSE THERE ARE UNIVERSES THAT MISFIRED.
ONE OF THE MAJOR MYSTERIES OF COSMOLOGY IS HAVING NO EXPLANATION OF WHY MATTER AND ANTIMATTER DIDN'T JUST ANNIHILATE EACH OTHER COMPLETELY.
AT THIS POINT IN THE TALE, IT'S ALWAYS THE SAME... THERE COMES A MOMENT WHEN THE PROBLEM OF ANTIMATTER IS JUST SWEPT UNDER THE CARPET... PFFFFT! ANTIMATTER ALL GONE!
TIRESIAS, LET ME REMIND YOU OF OUR RULES. ONLY FACTS! NO WILD SPECULATIONS.
I'M GETTING FED UP WITH EPISTOCOPS.
PSSSSST!

THE RADIATION ERA

HMMM... TOO SOON FOR GOIN' FISSION...

THERE'S NOT A LOT IN THE UNIVERSE AT THE MOMENT, APART FROM LIGHT.

THE ENERGY/MATTER, WHICH WAS EQUALLY DIVIDED INTO MATTER, ANTIMATTER, PHOTONS, AND NEUTRINOS, IS NOW ALMOST EXCLUSIVELY IN THE FORM OF PHOTONS AND NEUTRINOS — **RADIATION.** EVERY TIME THE RADIUS R OF THE UNIVERSE DOUBLES, THE DENSITY OF MATTER DECREASES. IT'S A SIMPLE MATTER OF DILUTION...



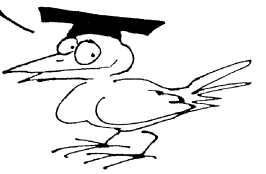
ON THE TWO-DIMENSIONAL CARPET UNIVERSE, WHEN R DOUBLES, THE DENSITY IS DIVIDED BY $2 \times 2 = 4$. IN OUR THREE-DIMENSIONAL UNIVERSE, IT IS ACTUALLY DIVIDED BY $2 \times 2 \times 2 = 8$.

THE DENSITY OF MATTER VARIES AS THE INVERSE CUBE OF THE "SIZE," THE "RADIUS" R, OF THE UNIVERSE.

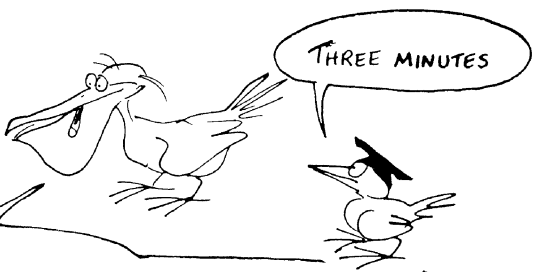
BUT FOR US PHOTONS IT'S MUCH MORE DRAMATIC, THE EXPANSION USES UP ALMOST ALL OF OUR ENERGY, BIT BY BIT. THE AMOUNT OF ENERGY/MATTER THAT WE CARRY DECREASES AS THE INVERSE OF THE RADIUS R OF THE UNIVERSE.

WHICH MEANS THAT THE DENSITY OF ENERGY/MATTER OCCURRING IN THE FORM OF PHOTONS VARIES AS THE INVERSE <u>FOURTH POWER</u> OF R.

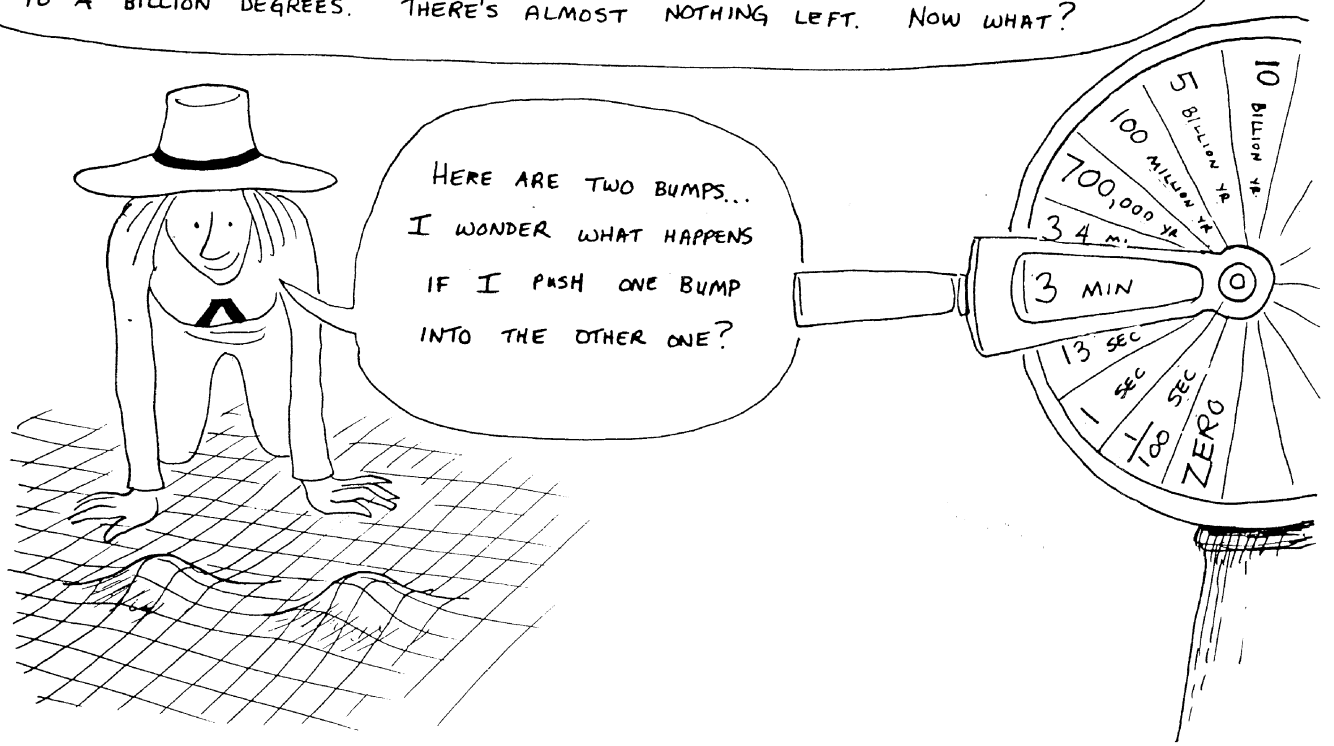
ALL THE WHILE MATTER REMAINS COUPLED TO PHOTONS, IT IS CONTINUALLY REHEATED. THIS HAPPENS UNTIL THE COMMON TEMPERATURE ($T_R = T_m$) FALLS TO 3000 DEGREES — WHICH TAKES ABOUT 700,000 YEARS.



NUCLEOSYNTHESIS



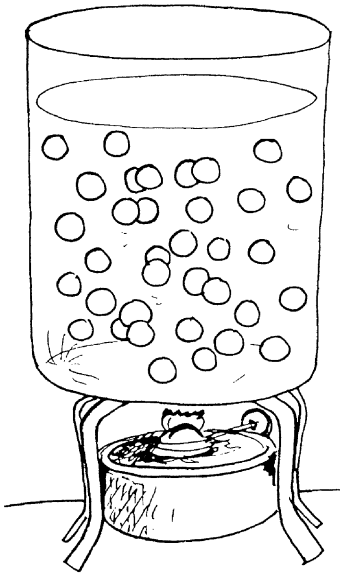
WOW... COMPARED TO WHERE WE WERE ON PAGE 31, THE FIRST HUNDREDTH OF A SECOND, THE SIZE R OF THE UNIVERSE HAS MULTIPLIED A HUNDREDFOLD, AND THE TEMPERATURE ($T_R = T_m$) HAS FALLEN TO A BILLION DEGREES. THERE'S ALMOST NOTHING LEFT. NOW WHAT?



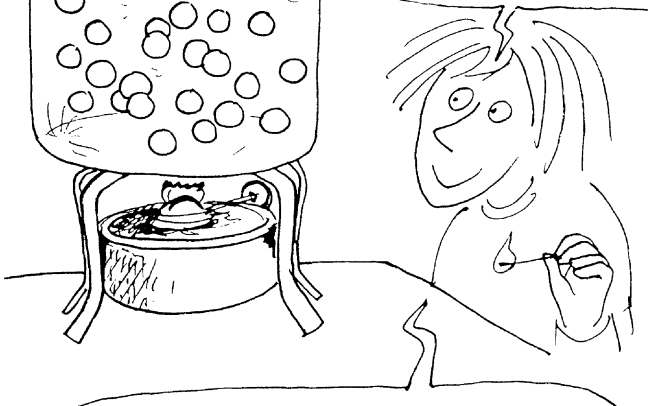
THEY START BY REPELLING EACH OTHER.
PLOK
THEN THEY ATTRACT EACH OTHER TO FORM A SINGLE OBJECT.
WHEN TWO BUMPS COLLIDE, THREE THINGS CAN HAPPEN... IF THEY ARE MOVING SLOWLY, THEY BOUNCE OFF EACH OTHER...
WOOPS, PARDON ME.
WHEN THE BUMPS ARE MOVING VERY QUICKLY, THEY CROSS EACH OTHER'S PATHS SO FAST THAT THEY DON'T HAVE TIME TO INTERACT.
?...
THEY CAN ONLY JOIN TOGETHER IN A DEFINITE RANGE OF VELOCITY OF AGITATION (TEMPERATURE).
AND A VIOLENT COLLISION WITH A THIRD PARTICLE BREAKS UP THE STRUCTURE FORMED IN THIS WAY.

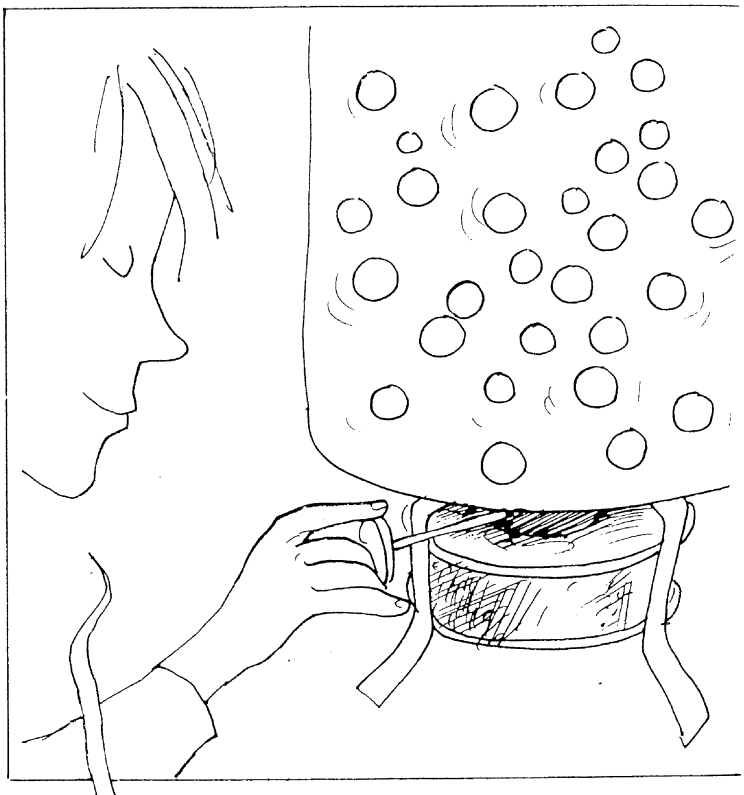
THESE FUSION REACTIONS PRODUCE THE FIRST ATOMIC NUCLEI. THE PROCESS OF MORPHOGENESIS LEADS TO THE FIRST FORMS, THE FIRST STRUCTURES, IN THE UNIVERSE.
A
IT'S AN AMUSING LITTLE TRICK, THAT. THERE'S AN ATTRACTIVE FORCE AND A REPULSIVE FORCE. AT LARGE DISTANCES, THE REPULSIVE FORCE WINS; AT SMALL DISTANCES, THE OPPOSITE HAPPENS.
I'M GOING TO TAKE SOME MAGNETS, AND COAT THEM IN RUBBER.
THE RUBBER COMPRESSES EASILY, SO IF I PRESS TWO SPHERES AGAINST EACH OTHER THEY'LL STAY STUCK TOGETHER BY THE MAGNETIC FORCE.
S
N
S
N
NOW I'LL TIP THEM INTO A LARGE TUB OF WATER...
... SO THEY CAN MOVE AROUND.

TWO FORCES COME INTO PLAY. AN ATTRACTIVE FORCE: MAGNETISM. A REPULSIVE FORCE: THE ELASTICITY OF THE RUBBER COATING. WHEN THE BALLS TOUCH, THE ELASTIC FORCES COME INTO PLAY. THE STRENGTH OF THE MAGNETISM IS ARRANGED SO THAT WHEN THE RUBBER IS COMPRESSED FAR ENOUGH, IT TAKES OVER. THERE IS AN INTERMEDIATE POSITION AT WHICH THE FORCES BALANCE OUT.



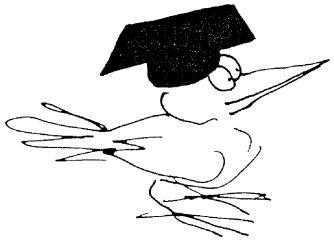
THE RUBBER IS LIGHT ENOUGH FOR THE DENSITY OF THE SPHERES TO BE ESSENTIALLY EQUAL TO THAT OF WATER. NOW I'LL HEAT UP THE ACTION A LITTLE...





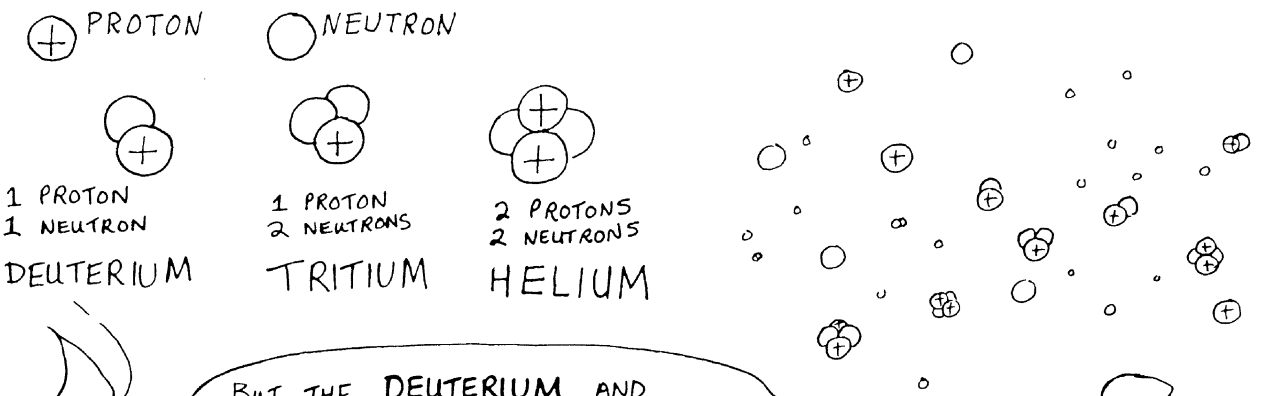
WHEN THE TEMPERATURE IS LOW, THE BALLS BOUNCE GENTLY OFF EACH OTHER, AND NOTHING HAPPENS. WHEN THEY BUMP INTO EACH OTHER, THEY DON'T HAVE ENOUGH ENERGY TO COMPRESS THE RUBBER FAR ENOUGH FOR THE MAGNETIC FORCE TO COME INTO PLAY. THE MAGNETISM CAN ONLY ACT AT SHORT RANGE.

OK, I'LL TURN UP THE HEAT.

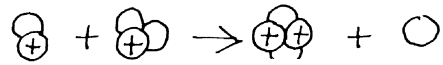


GREAT, IT WORKS! IT'S THE RIGHT TEMPERATURE (LARGER THAN THE THRESHOLD TEMPERATURE). THE AMOUNT OF AGITATION IS JUST RIGHT.
BLIMEY! THEM BALLS IS STICKIN' TERGEVVER IN PAIRS!
IF I APPLY TOO MUCH HEAT, THESE STRUCTURES ARE BROKEN UP BY THERMAL AGITATION.
WHAT HAPPENS IF YOU COOL IT?
ARCHIE ALLOWS THE WATER TO COOL. THE TURBULENCE DECREASES. AT A CERTAIN MOMENT, SOME OF THE BALLS COUPLE TOGETHER. BUT, SINCE THE TEMPERATURE CONTINUES TO DROP, THIS NUCLEOSYNTHESIS STOPS.
THAT'S IT, I'M AFRAID. IT'S TOO COLD. THE BALLS AREN'T AGITATED ENOUGH TO JOIN TOGETHER ANY MORE.
WE'RE BELOW THRESHOLD.

THE SAME THING HAPPENS WHEN THE TEMPERATURE OF THE UNIVERSE DROPS BELOW A FEW **BILLION DEGREES**. THAT IS, AFTER A FEW **MINUTES** THEN STRUCTURES WITH TWO, THREE, OR FOUR "BALLS" CAN FORM.



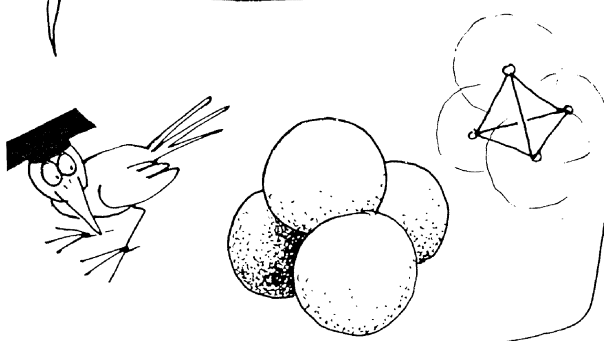
BUT THE **DEUTERIUM** AND **TRITIUM** SO CREATED CAN COMBINE BY A **NUCLEAR REACTION**:



DEUTERIUM + TRITIUM GIVES HELIUM + NEUTRON

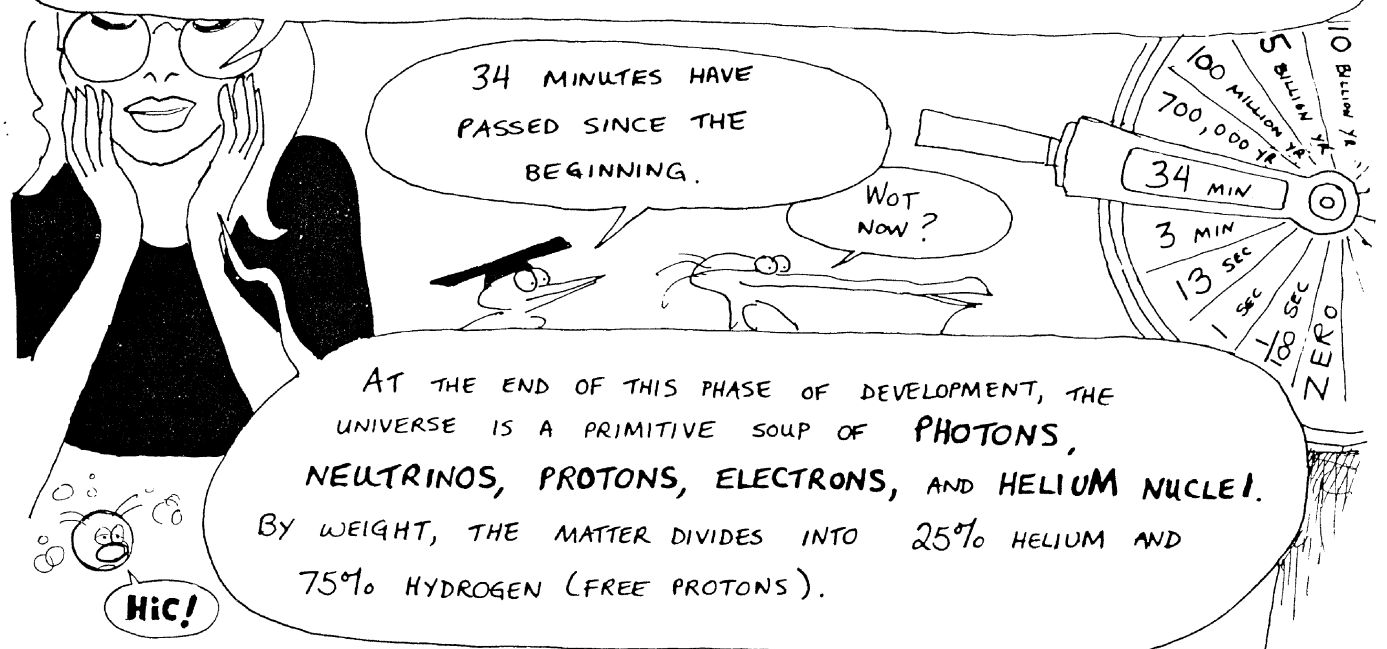
AT THIS POINT, THE UNIVERSE IS A **HYDROGEN BOMB.**

SO, EVERYTHING TURNS INTO HELIUM?



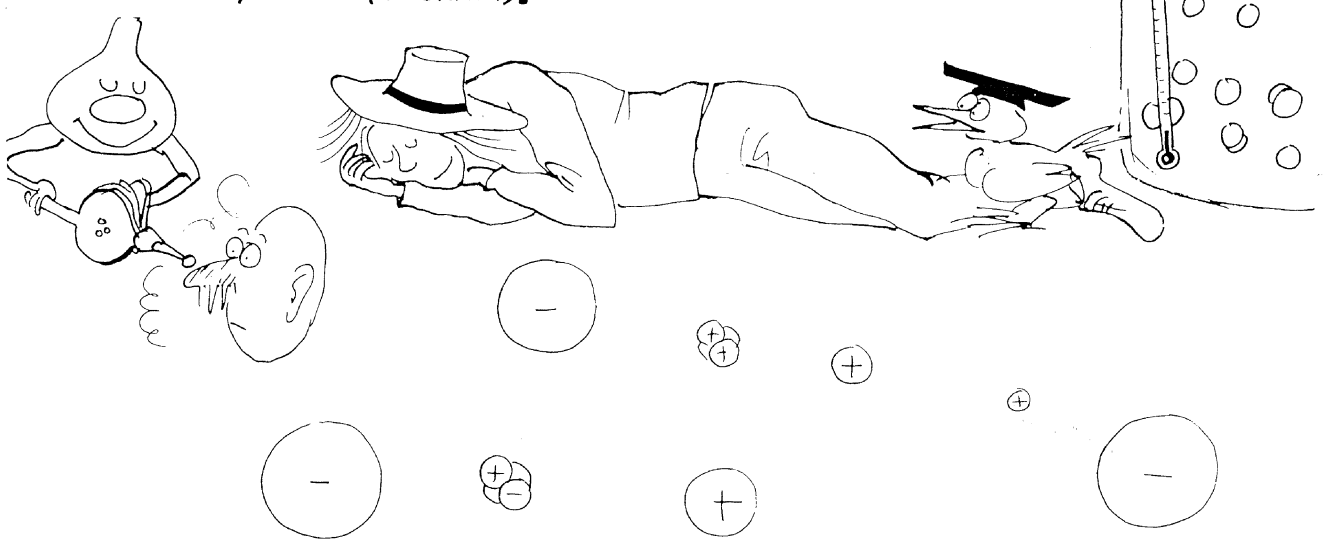
THE HELIUM NUCLEUS IS VERY SYMMETRIC, COMPACT, AND ROBUST. IF THE TEMPERATURE WERE TO STAY CONSTANT, THEN ALL MATTER WOULD TURN INTO HELIUM. BUT AFTER 34 MINUTES, THE TEMPERATURE FALLS TO 300 MILLION DEGREES AND THE NUCLEOSYNTHESIS STOPS. THE NUCLEONS (PROTONS AND NEUTRONS) NO LONGER HAVE ENOUGH VELOCITY TO OVERCOME ELECTROSTATIC REPULSION. THE GAME IS PLAYED OUT.

THE REMAINING FREE NEUTRONS DISINTEGRATE. THEY ARE NATURALLY UNSTABLE, AND TRANSFORM — IN 109 SECONDS — INTO A **PROTON-ELECTRON** PAIR.



AT THE END OF THIS PHASE OF DEVELOPMENT, THE UNIVERSE IS A PRIMITIVE SOUP OF **PHOTONS, NEUTRINOS, PROTONS, ELECTRONS,** AND **HELIUM NUCLEI.** BY WEIGHT, THE MATTER DIVIDES INTO 25% HELIUM AND 75% HYDROGEN (FREE PROTONS).

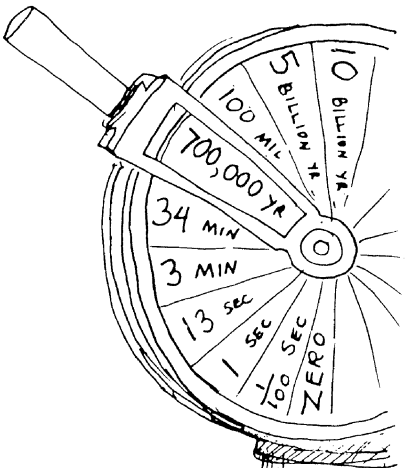
FOR [700,000] YEARS... NOTHING HAPPENS. THE UNIVERSE CONTINUES TO EXPAND, AND THE PHOTONS EXPAND WITH IT. THE PHOTON GAS CONTINUES TO HEAT THE MATTER, AND THE TEMPERATURES T_R AND T_m STAY EQUAL (THERMODYNAMIC EQUILIBRIUM).

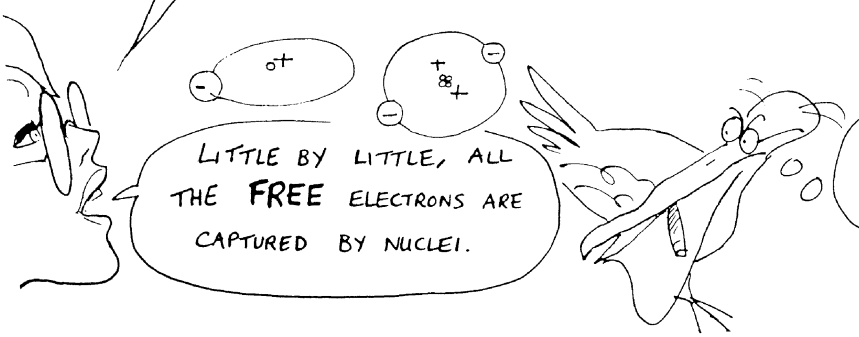


AND THE TEMPERATURE DROPS TO [3000 DEGREES KELVIN]

THE TRANSPARENT UNIVERSE

ANOTHER MORPHOGENETIC MECHANISM COMES INTO PLAY. ELECTRICAL FORCES TEND TO ATTRACT ELECTRONS TO NUCLEI TO FORM ATOMS. THERMAL AGITATION IS SUFFICIENTLY LOW NOT TO BREAK THESE STRUCTURES UP AS SOON AS THEY ARE FORMED, IN COLLISIONS WITH OTHER ATOMS OR WITH OTHER INGREDIENTS OF THE SOUP.





LITTLE BY LITTLE, ALL THE **FREE** ELECTRONS ARE CAPTURED BY NUCLEI.

THESE CRAZY BLOOMIN' ATOMS... WIV 'NORMOUS GREAT EE-LECKTRONS... GIVES ME THE CREEPS, IT DOES!

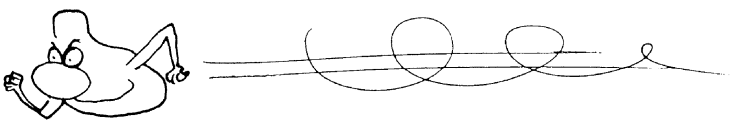
AND THE UNIVERSE BECOMES **TRANSPARENT.**

WHAT DO YOU MEAN, BECOMES TRANSPARENT? DO YOU MEAN IT WAS OPAQUE BEFORE?

BEFORE, PHOTONS WERE CONSTANTLY INTERACTING WITH MATTER. NO PHOTON COULD TRAVEL VERY FAR WITHOUT BUMPING INTO SOMETHING IN THE SOUP.

DECOUPLiNG

ONCE IT WAS OVER, PHOTONS COULD TRAVERSE THE LENGTH OF THE UNIVERSE WITHOUT NOTICING THAT MATTER EXISTED. PHOTONS AND MATTER WERE **DECOUPLED**. FOR TWO REASONS. FIRST, THERE WAS A LOT OF ROOM. SECOND, PHOTONS INTERACT LESS WITH NEUTRAL MATTER (ATOMS).

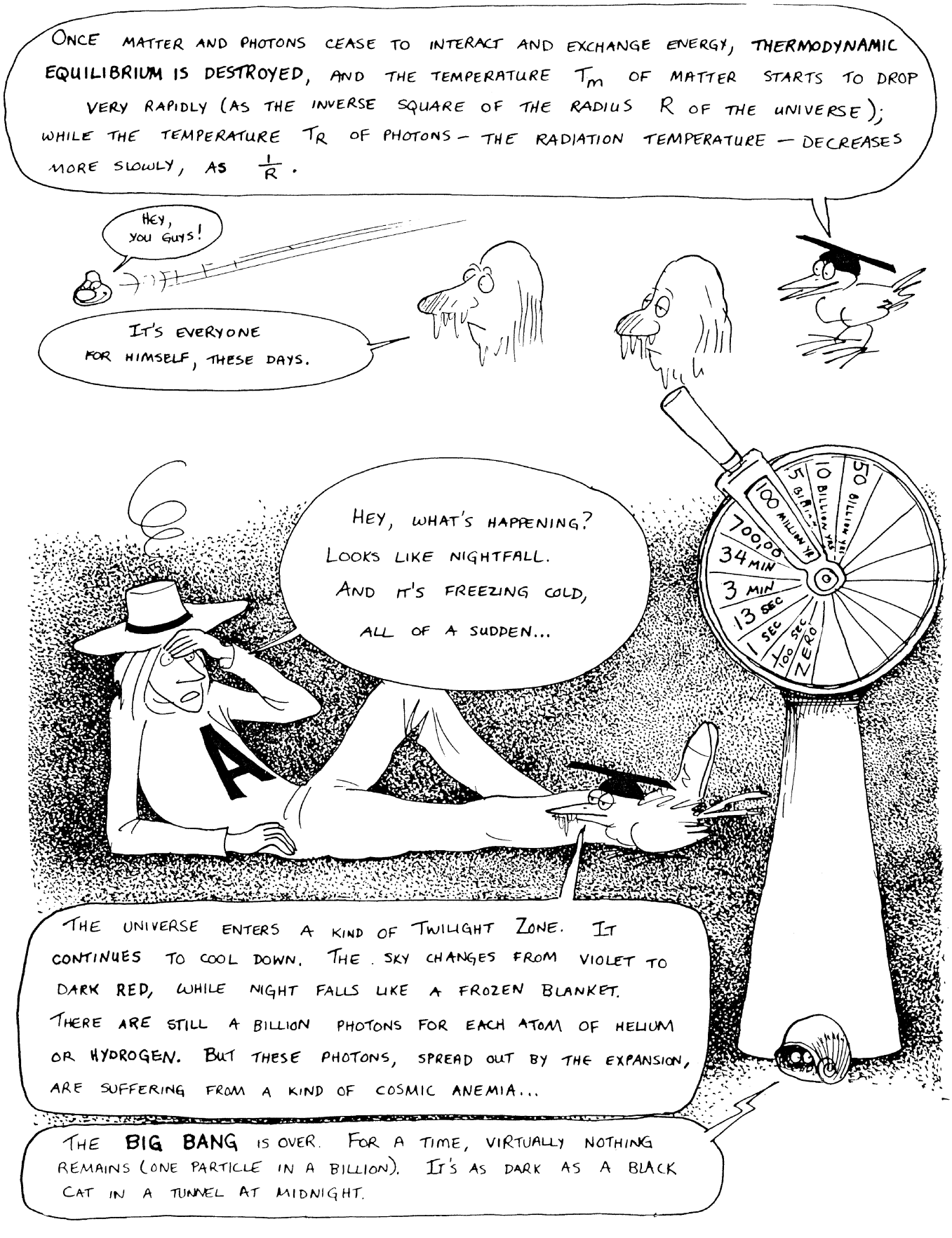


'ERE, 'ANG ON... WHEN YER LOOKS FROUGH A TELLYSCOPE, YER LOOKS "STRAIGHT INTO THE PAST," DONTCHA?

YES, BUT EVEN WITH A FANTASTICALLY POWERFUL TELESCOPE, YOU WOULDN'T BE ABLE TO OBSERVE A PHENOMENON THAT OCCURRED WHEN THE UNIVERSE WAS ONLY 700,000 YEARS OLD.

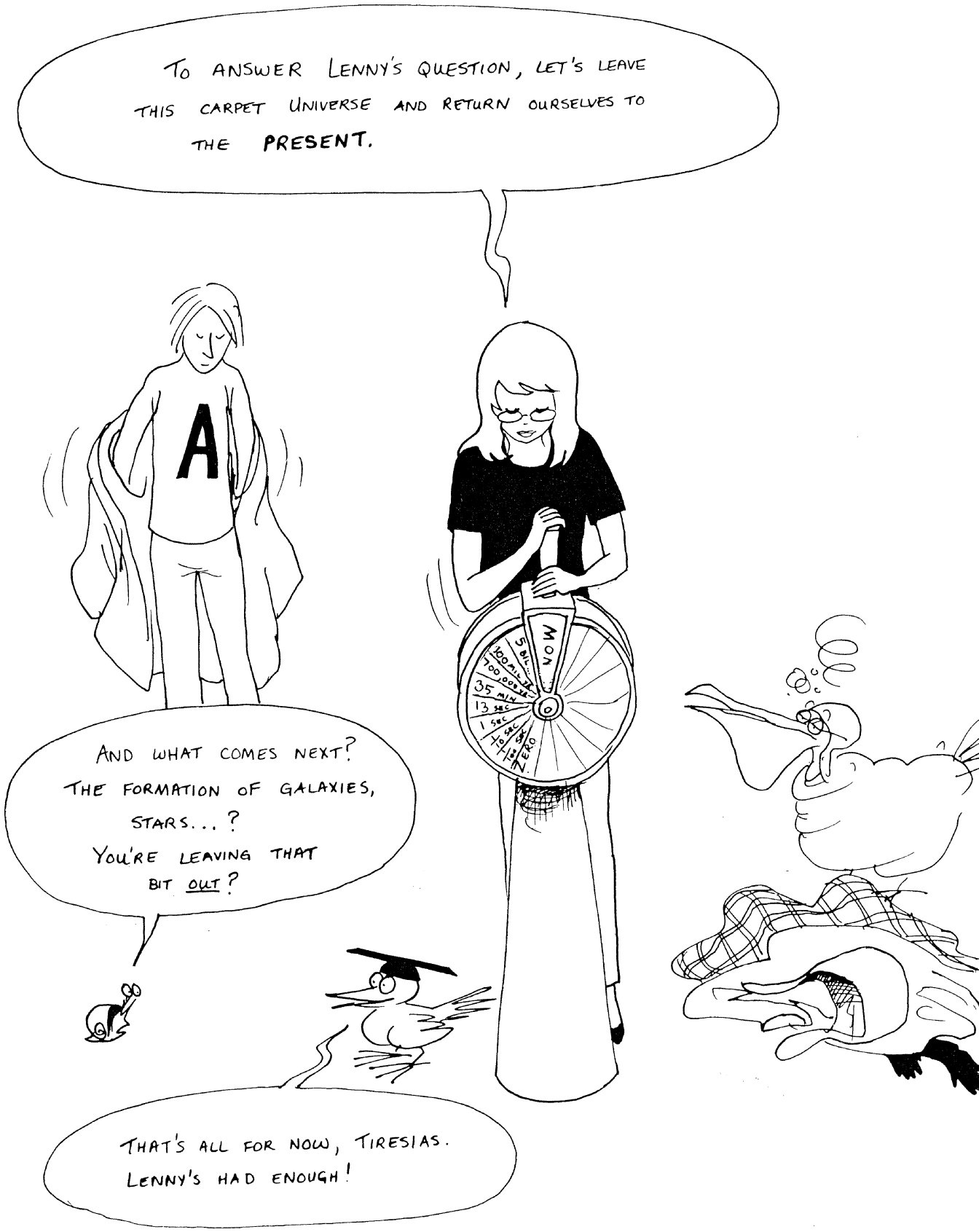
SO, THE PAST... THE VERY ANCIENT PAST OF THE UNIVERSE MUST ALWAYS STAY VAGUE AN' 'AZY, RIGHT?

YES - IT'S IMPOSSIBLE TO PSYCHOANALYZE THE UNIVERSE.

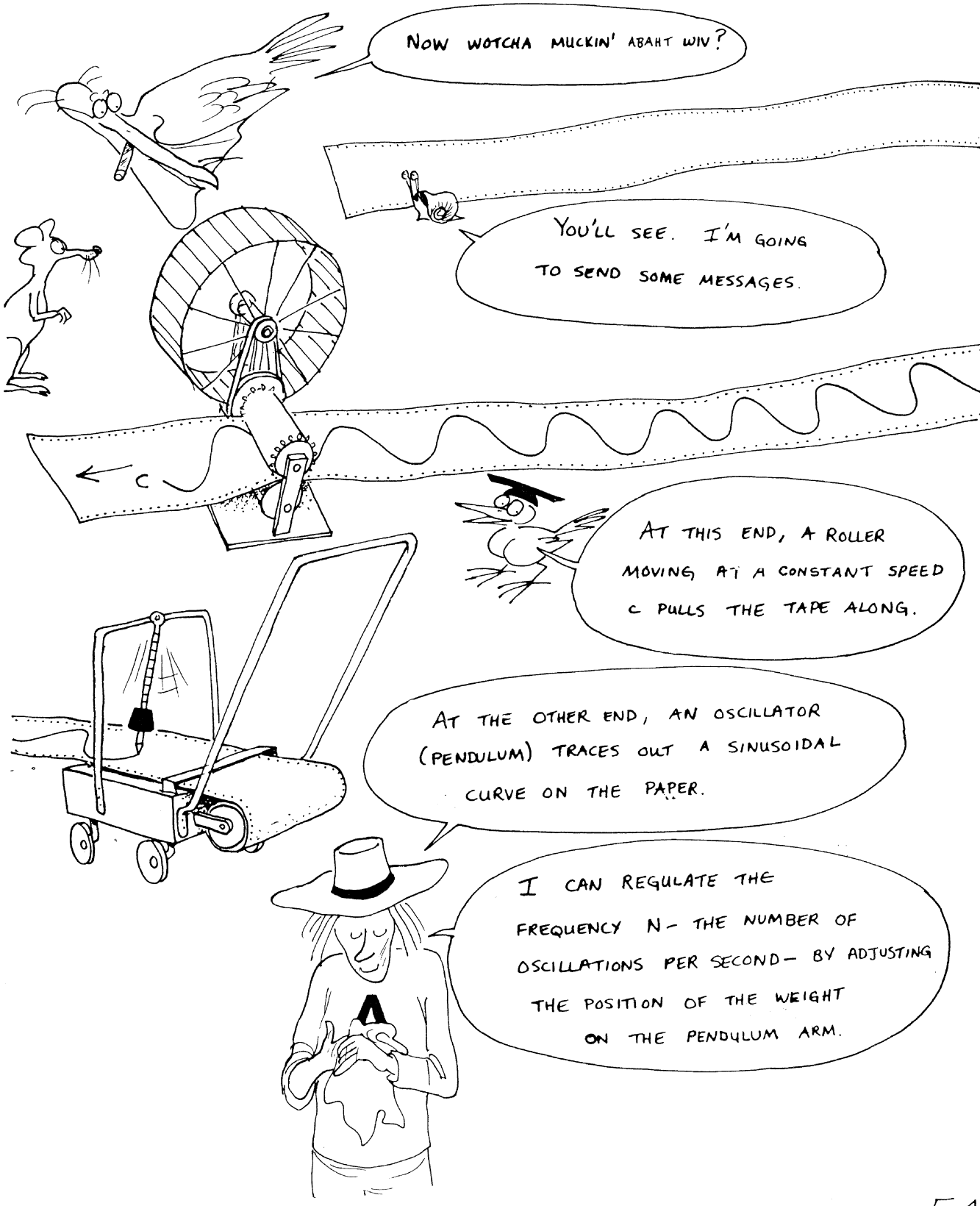

ONCE MATTER AND PHOTONS CEASE TO INTERACT AND EXCHANGE ENERGY, THERMODYNAMIC EQUILIBRIUM IS DESTROYED, AND THE TEMPERATURE T_m OF MATTER STARTS TO DROP VERY RAPIDLY (AS THE INVERSE SQUARE OF THE RADIUS R OF THE UNIVERSE); WHILE THE TEMPERATURE T_R OF PHOTONS – THE RADIATION TEMPERATURE – DECREASES MORE SLOWLY, AS $\frac{1}{R}$.
HEY, YOU GUYS!
IT'S EVERYONE FOR HIMSELF, THESE DAYS.
HEY, WHAT'S HAPPENING? LOOKS LIKE NIGHTFALL. AND IT'S FREEZING COLD, ALL OF A SUDDEN...
50 BILLION YRS
10 BILLION YRS
5 BILLION YRS
100 MILLION YRS
700,00
34 MIN
3 MIN
13 SEC
1 SEC
1/100 SEC
ZERO
THE UNIVERSE ENTERS A KIND OF TWILIGHT ZONE. IT CONTINUES TO COOL DOWN. THE SKY CHANGES FROM VIOLET TO DARK RED, WHILE NIGHT FALLS LIKE A FROZEN BLANKET. THERE ARE STILL A BILLION PHOTONS FOR EACH ATOM OF HELIUM OR HYDROGEN. BUT THESE PHOTONS, SPREAD OUT BY THE EXPANSION, ARE SUFFERING FROM A KIND OF COSMIC ANEMIA...
THE BIG BANG IS OVER. FOR A TIME, VIRTUALLY NOTHING REMAINS (ONE PARTICLE IN A BILLION). IT'S AS DARK AS A BLACK CAT IN A TUNNEL AT MIDNIGHT.

BRRR... BLASTED BLUE NORTHERS!
THE WAVELENGTH OF PHOTONS IS 0.15 MM, WHICH CORRESPONDS TO A RADIATION TEMPERATURE $T_R = -173°C$.
ATOMS NOW TRAVEL AT 150 METERS/SECOND, SO THE TEMPERATURE OF MATTER $T_m = -267°C$.
GREAT... I GUESS I'VE GOT SOME SORT OF IDEA HOW THE UNIVERSE WORKS, NOW.
BUT AN IMPORTANT QUESTION REMAINS: WHAT'S IT ALL FOR?
YOU KNOW, ARCHIE'S RIGHT. WHAT'S THE PURPOSE?
YUR... WOTSIT GOOD FOR?

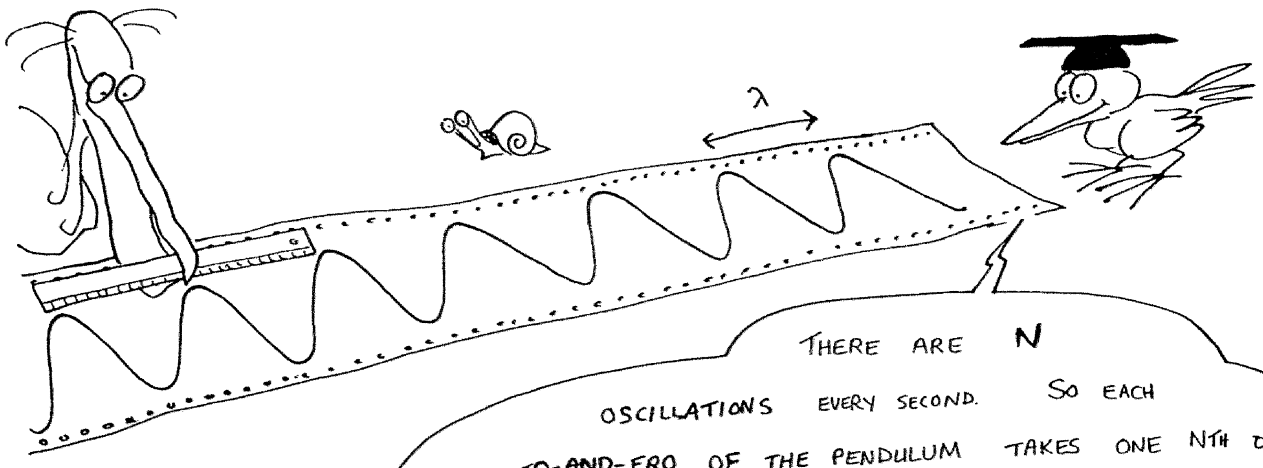
WELL... TO BEGIN WITH, THERE WAS A LOT OF ANYTHING IN A STATE OF TOTAL CONFUSION.
CHAOS
AND THEN THE UNIVERSE SET ABOUT MAKING STRUCTURES, WHICH BECAME MORE AND MORE COMPLEX...
NUCLEI, ATOMS...
I'VE DISCOVERED THE BASIC COSMOLOGICAL PRINCIPLE.
AH... AND WHAT IS IT?
WHY MAKE THINGS SIMPLE WHEN YOU CAN MAKE THEM COMPLICATED?
HMMPH... NOT BAD, YER LITTLE SHAGGY GOD STORY... BUT IT'S JUST BLINKIN' SPECKYERLATION. THEO-RETTICKLE FANTASIES. WOT MAKES YER FINK REALITY IS REALLY LIKE THAT?


TO ANSWER LENNY'S QUESTION, LET'S LEAVE THIS CARPET UNIVERSE AND RETURN OURSELVES TO THE PRESENT.
A
MON
5 BIL
100 MIL YR
700,000 YR
35 MIN
13 SEC
1 SEC
10 SEC
100 SEC
ZERO
AND WHAT COMES NEXT? THE FORMATION OF GALAXIES, STARS...? YOU'RE LEAVING THAT BIT OUT?
THAT'S ALL FOR NOW, TIRESIAS. LENNY'S HAD ENOUGH!

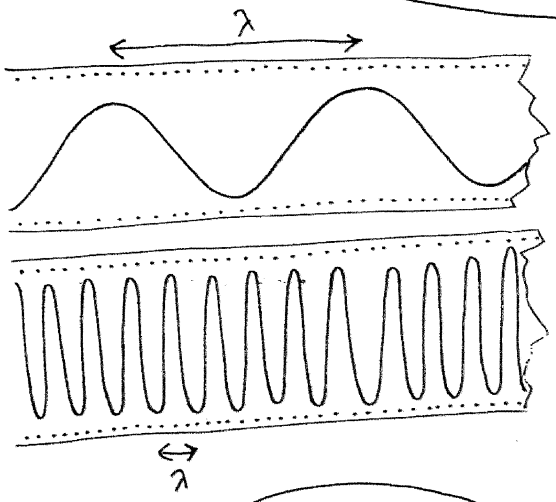
THE DOPPLER EFFECT



RIGHTEY-HO! AN' I CAN MEASURE THE WAVELENGT OF THE SIGNAL RECEIVED.



THERE ARE N OSCILLATIONS EVERY SECOND. SO EACH TO-AND-FRO OF THE PENDULUM TAKES ONE NTH OF A SECOND: THAT'S THE PERIOD OF THE WAVE. DURING THAT TIME, THE TAPE MOVES A DISTANCE $\lambda = \frac{c}{N}$ (THE WAVELENGTH).



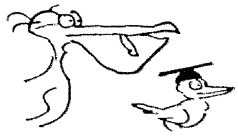
LOW FREQUENCY, LONG PERIOD, LARGE WAVELENGTH. HIGH FREQUENCY, SHORT PERIOD, SMALL WAVELENGTH.

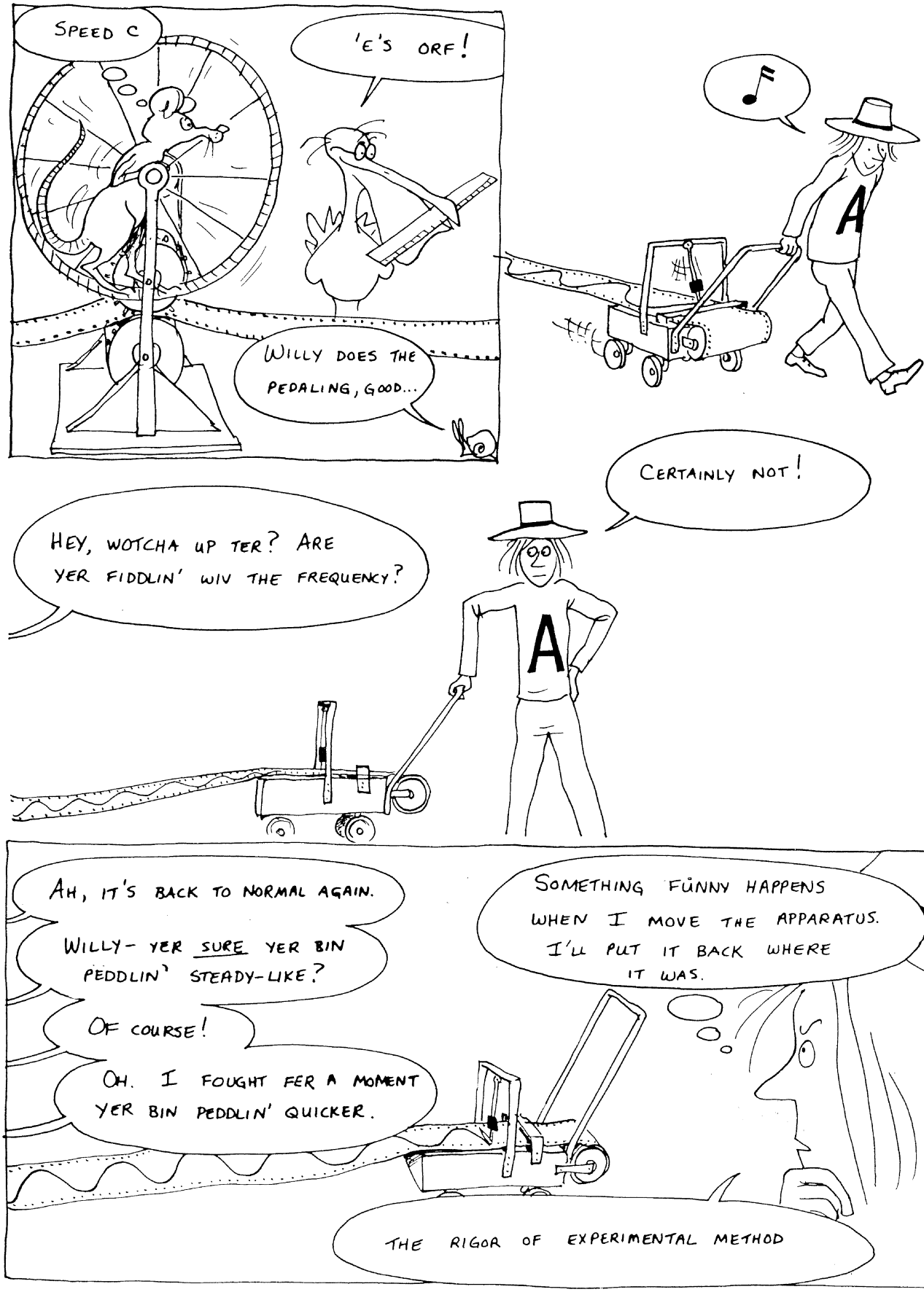
I CAN USE THAT TO COMMUNICATE.

IT'S IMPORTANT, COMMUNICATION IS.

READY?

GOOD. I'LL TRY AN EXPERIMENTAL LONG-DISTANCE TRANSMISSION.

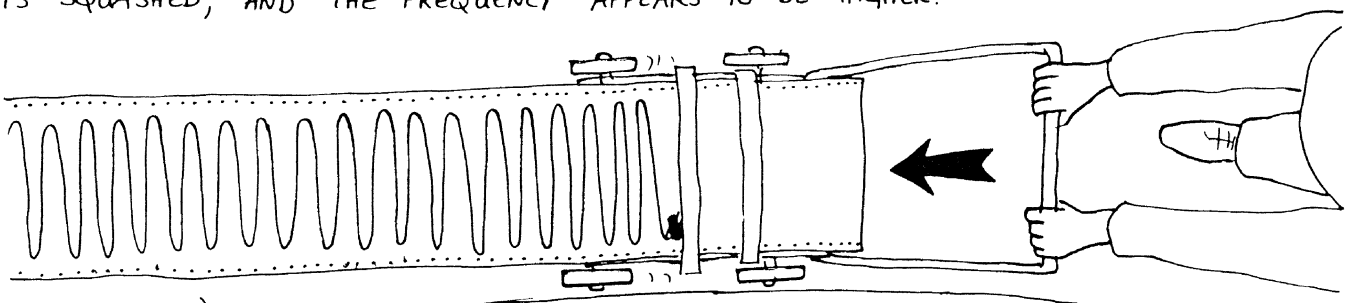



SPEED C
'E'S ORF!
WILLY DOES THE PEDALING, GOOD...
A
CERTAINLY NOT!
HEY, WOTCHA UP TER? ARE YER FIDDLIN' WIV THE FREQUENCY?
A
AH, IT'S BACK TO NORMAL AGAIN.
WILLY- YER SURE YER BIN PEDDLIN' STEADY-LIKE?
OF COURSE!
OH. I FOUGHT FER A MOMENT YER BIN PEDDLIN' QUICKER.
SOMETHING FUNNY HAPPENS WHEN I MOVE THE APPARATUS. I'LL PUT IT BACK WHERE IT WAS.
THE RIGOR OF EXPERIMENTAL METHOD

!!!
WILLY, GET PEDDLIN', DAMMIT!
I AM PEDALING YOU TWERP!
IF YOU DON'T LIKE IT, YOU CAN DO THE JOB INSTEAD OF ME!
HOLD IT, HOLD IT! WHAT'S THE PROBLEM?
A
?..
(A)
(B)
(C)
IT'S BACK TO NORMAL AGAIN NOW. BUT A WHILE AGO THE WAVELENGTH SUDDENLY INCREASED (A). THAT IS, THE APPARENT FREQUENCY OF THE RECEIVED SIGNAL DROPPED. THEN, AFTER AN INTERVAL OF NORMAL RECEPTION (B), THE FREQUENCY INCREASED (C) ... THAT IS, THE WAVELENGTH λ GOT SHORTER AGAIN.

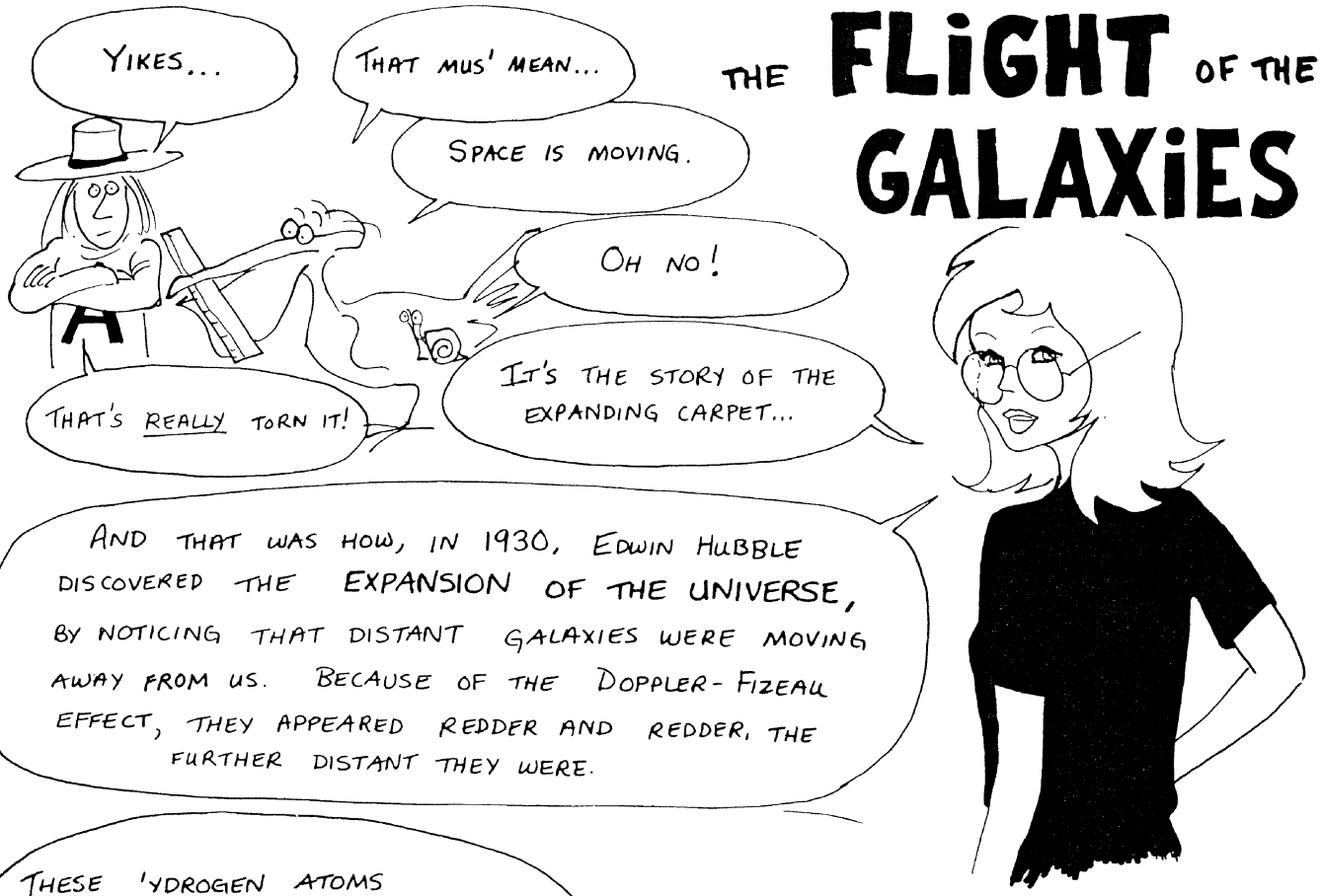
HEY, YOU GUYS: CAN I STOP NOW?
YES, WILLY. HOLD YOUR HORSES.
WILLY SAYS HE KEPT PEDALING STEADILY ALL THE TIME.
PERHAPS THE PAPER STRETCHED OR SHRUNK?
NO, ARCHIE. IT'S THE DOPPLER-FIZEAU EFFECT.
THE POPPLE-FIZZY WHAT?
WHEN YOU MOVED THE CART, YOU CHANGED THE APPARENT FREQUENCY.
WHEN THE CART MOVES AWAY, THE SINUSOID IS STRETCHED, AND THE FREQUENCY APPEARS LOWER

WHEN THE CART RETURNS, ADVANCING ALONG THE TAPE, THE SINUSOID IS SQUASHED, AND THE FREQUENCY APPEARS TO BE HIGHER.



FAIR ENOUGH — LET'S TRY THE EXPERIMENT AGAIN.
MAN YOUR POST, WILLY.
'E'S CHANGED THE FREQUENCY?
OR ELSE HE'S MOVING AWAY.
IT'S HAPPENING AGAIN, JUST LIKE LAST TIME.
YUR THAT'S IT! 'E'S STILL MOVIN' ORF!
AND THE OSCILLATOR'S STILL OVER THERE.
NO, YOU BUNCH OF DUMMIES, I AM NOT MOVING OFF! I'M HERE!

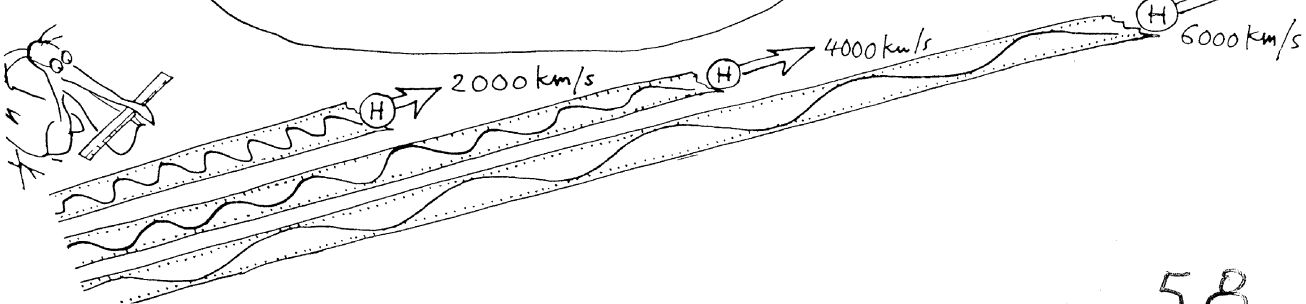
THE FLIGHT OF THE GALAXIES



AND THAT WAS HOW, IN 1930, EDWIN HUBBLE DISCOVERED THE EXPANSION OF THE UNIVERSE, BY NOTICING THAT DISTANT GALAXIES WERE MOVING AWAY FROM US. BECAUSE OF THE DOPPLER-FIZEAU EFFECT, THEY APPEARED REDDER AND REDDER, THE FURTHER DISTANT THEY WERE.

THESE 'YDROGEN ATOMS 'EMIT LIGHT AT A WAVELENGF OF .1 CM, IN FEORY. THE DOPPLER 'EFFECK SHOWS A SPEED OF RECESSION OF 2000, 4000, AND 6000 KM/SEC.

HUBBLE COULD ESTIMATE THE DISTANCE SEPARATING US FROM THESE GALAXIES, BY CONSIDERING THEIR APPARENT LUMINOSITY. HE DEDUCED THAT THE VELOCITY OF RECESSION WAS PROPORTIONAL TO THEIR DISTANCE AWAY FROM US.



UMPF. SO WOZZAT MEAN? FINGS H'ACCELLYRATE WHEN THEY GET FURTHER AWAY FROM US?
NOT EXACTLY. THE CARPET EXPANDS IN ALL DIRECTIONS. IMAGINE A POINT A WHICH, AT TIME t=0, IS ONE METER AWAY. AFTER ONE SECOND, IT IS AT 1.2 METERS. SO ITS SPEED OF RECESSION IS 20 CM/SEC.
A
A'
B
B'
IN THE SAME PERIOD OF TIME, A POINT B, SITUATED INITIALLY 2 METERS AWAY, ENDS UP AT A DISTANCE OF 2.4 METERS (AT B'). AND ITS SPEED OF RECESSION RELATIVE TO YOU IS 40 CM/SEC.
THE DOPPLER EFFECT TELLS YOU RELATIVE VELOCITIES.
THERE'S NO VARIATION OF THE WAVELENGTH IF BOTH TRANSMITTER AND RECEIVER MOVE AT THE SAME SPEEDS ON PARALLEL PATHS.

HEAVEN'S FUNDAMENT iS COLD

A WHILE BACK, WE SAW THAT ONLY ONE PHOTON IN A BILLION WAS TRANSFORMED INTO MATTER.

AND ANTIMATTER!

SO THERE SHOULD STILL BE A LARGE NUMBER OF THESE PRIMITIVE PHOTONS, ABOUT 500 PER CUBIC CENTIMETER. (AND AS MANY NEUTRINOS, BUT THEY'RE HARDER TO DETECT.)

THEIR WAVELENGTH SHOULD BE ABOUT 5 MM, WHICH CORRESPONDS TO A RADIATION TEMPERATURE T_R OF 3 DEGREES ABSOLUTE (-270° C).

THESE PHOTONS, OF VERY LOW ENERGY, WERE DETECTED BY PENZIAS AND WILSON IN 1964. THEY ARE THE CINDERS OF THE **BIG BANG**; TANGIBLE PROOF OF THE GREAT COSMIC DANCE.

EEEEP!

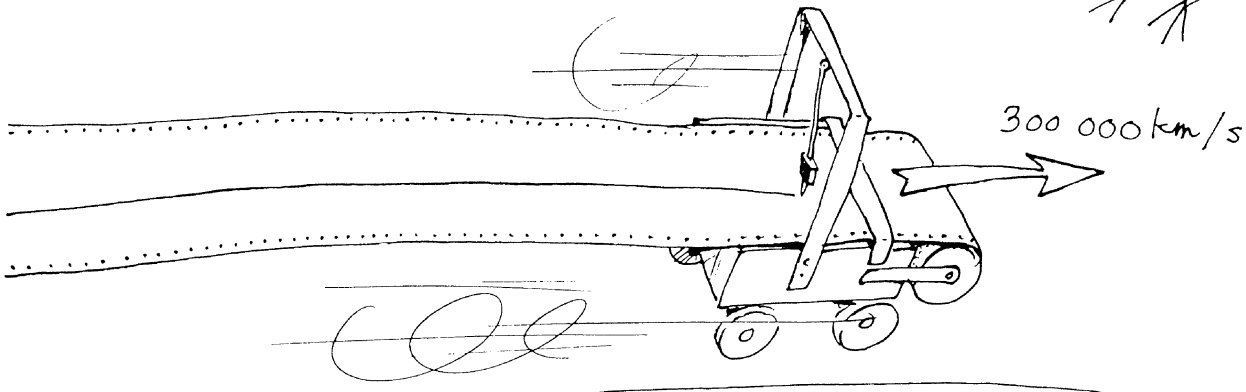
OH CRIKEY...

FRIEDMANN MODELS

THE COSMOLOGICAL HORIZON

DER PHENOMENON OF **MOTION** HAS EIN EFFECT ON DER **TIME** (*). EIN OBJECT VOT MOOFS AT A SPEED APPROACHING DAT OF LIGHT, 300,000 KM/SEC, SEEMS — RELATIVE TO US, DE OPSERVERS — TO BE IN A DIFFERENT "TIME BUBBLE." VE OPSERVE ITS MESSAGE AS A KIND OF SLOW-MOTION FILM.

AND IF THIS OBJECT MOVES AWAY FROM US AT THE SPEED OF LIGHT ITSELF, THE TIME DISCONNECTION BECOMES TOTAL. ITS TIME SEEMS TO FLOW LIKE TREACLE.



BECAUSE OF THIS SLIPPAGE, THIS SKIDDING OF TIMES RELATIVE TO EACH OTHER, THE FREQUENCY OF WAVES AT THE RECEIVER IS LOWERED. AND THIS PHENOMENON, A RELATIVISTIC EFFECT, ACTS IN ADDITION TO THE **DOPPLER** EFFECT. WHEN THE VELOCITY OF RECESSION OF THE TRANSMITTER, RELATIVE TO US, REACHES c, THEN THE FREQUENCY OF THE RECEIVED WAVES FALLS TO ZERO. THE SAME GOES FOR THE ENERGY, THE WAVES AND THE MESSAGE!

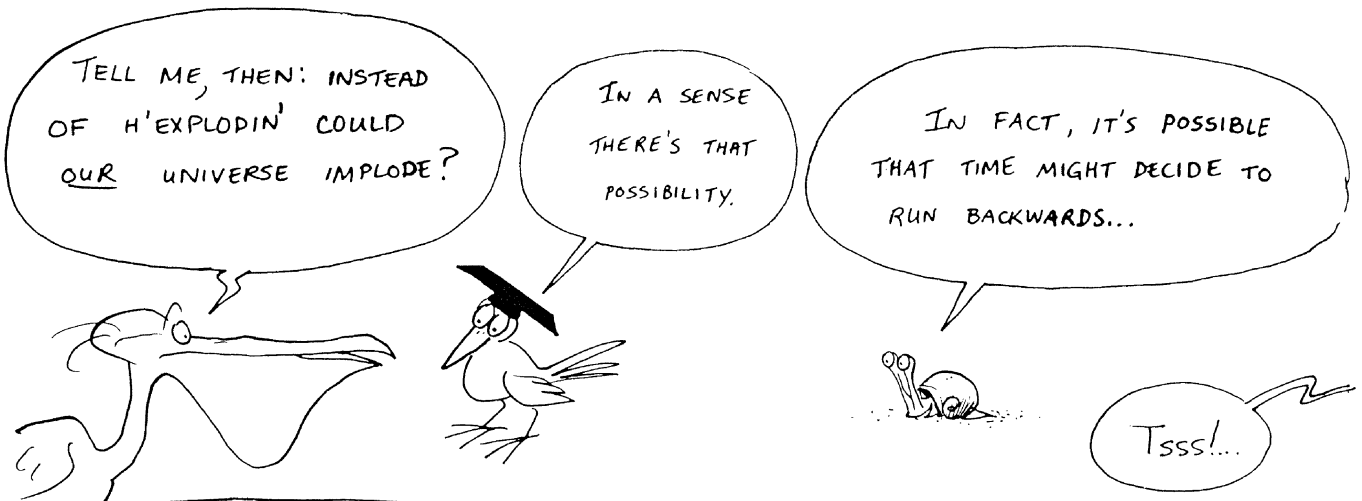
WAVES OF ZERO FREQUENCY ARE WAVES GOODBYE!

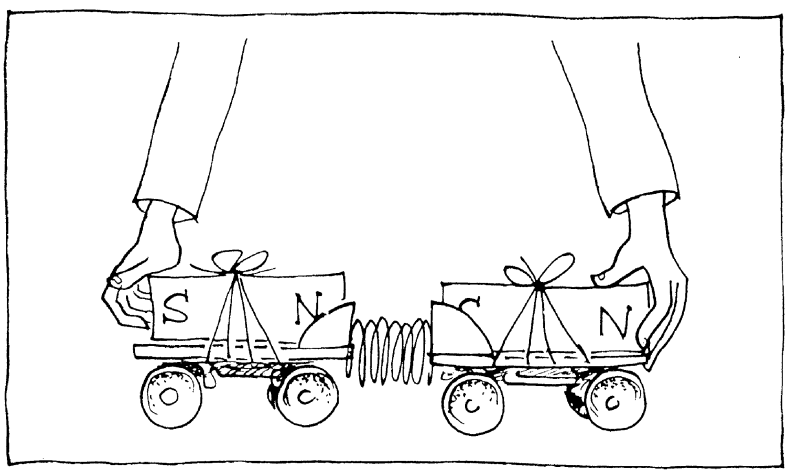
(*) SEE **EVERYTHING IS RELATIVE**, SAME SERIES.

FOR THE OBJECTS THAT SURROUND US, A RELATIVE VELOCITY EQUAL TO 300,000 KM/SEC IS ATTAINED ON A SPHERE CALLED THE **HORIZON**. IT IS NOT THE FRONTIER OF THE **THINGS THAT EXIST**; BUT THE FRONTIER OF THE **THINGS WE CAN KNOW ABOUT**. THE ACCESSIBLE UNIVERSE IS JUST A TINY PART OF THE VASTER UNIVERSE. THIS HORIZON IS AT A DISTANCE OF SOME TENS OF BILLIONS OF LIGHT-YEARS. THE RANGE OF THE MOST POWERFUL TELESCOPE ON THE EARTH TODAY, THE **PALOMAR** TELESCOPE, IS ABOUT 1 BILLION LIGHT-YEARS.

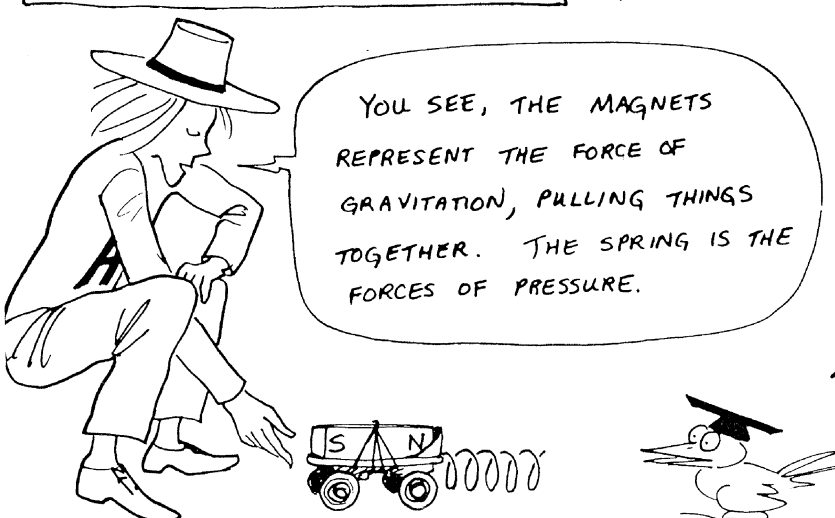
The Boss

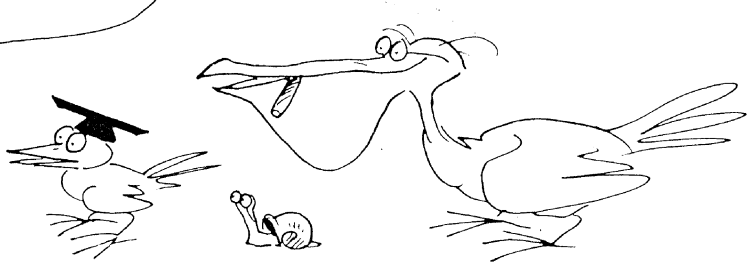
(*) SEE HERE'S LOOKING AT EUCLID, SAME SERIES.

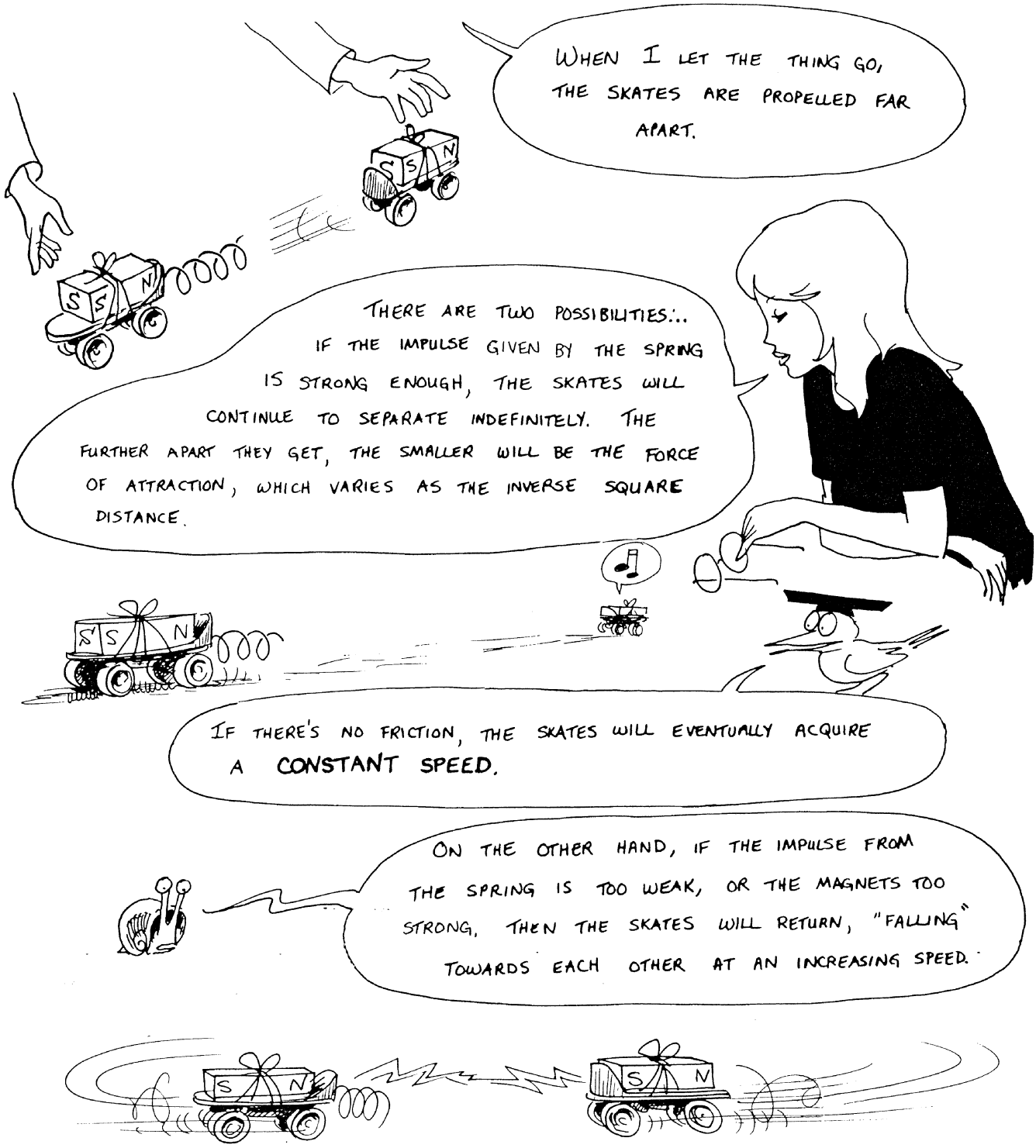




ARCHIE HAS ATTACHED TWO MAGNETS TO ROLLER SKATES, MAKING THEM ATTRACTED TO EACH OTHER. BUT A COMPRESSED STRING TRIES TO PUSH THE SKATES APART AGAIN.

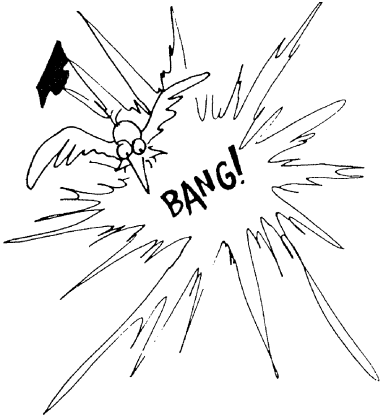




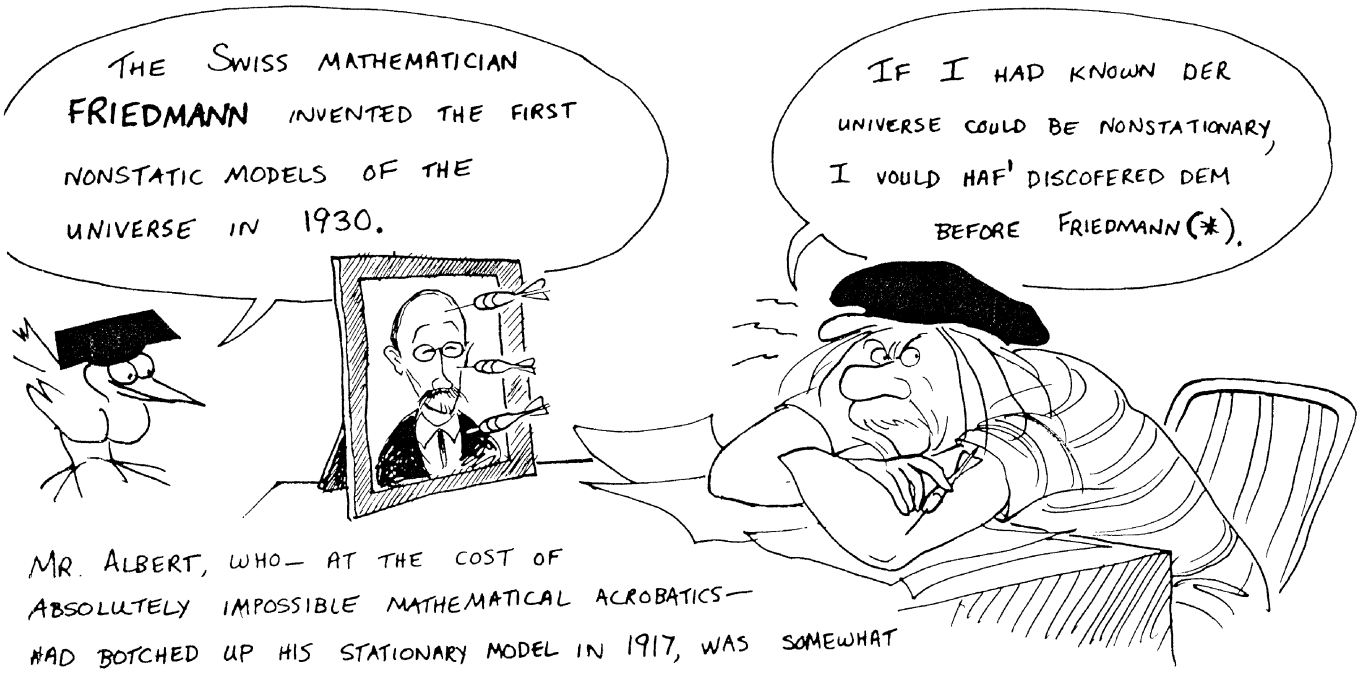


THIS SUGGESTS TWO POSSIBLE TYPES OF UNIVERSE:

FIRST SCENARIO: THE EXPANSION CONTINUES INDEFINITELY. WHEN THE LAST STARS BECOME EXTINCT, THERE WILL BE ETERNAL NIGHT, ABSOLUTE COLD, THERMAL DEATH.



SECOND SCENARIO: THE FORCES OF GRAVITY FINALLY WIN OUT. AFTER REACHING ITS MAXIMAL EXTENSION, THE UNIVERSE "FALLS BACK ON ITSELF. ALL STRUCTURES— GALAXIES, STARS— ARE SQUASHED FLAT. THE VERY ATOMS ARE BROKEN. AND THE **BIG BANG** UNBANGS ITSELF AGAIN... READY FOR A NEW REBOUND OF THE UNIVERSE, AND A NEW PHASE OF EXPANSION.



MR. ALBERT, WHO— AT THE COST OF ABSOLUTELY IMPOSSIBLE MATHEMATICAL ACROBATICS— HAD BOTCHED UP HIS STATIONARY MODEL IN 1917, WAS SOMEWHAT PEEVED. FRIEDMANN HAD STOLEN HIS VICTORY. HE SULKED ABOUT GENERAL RELATIVITY FOR MANY LONG YEARS.

ACCORDING TO THE FRIEDMANN MODELS, THE UNIVERSE UNDERGOES INDEFINITE EXPANSION IF THE (PRESENT) DENSITY OF MATTER IS LESS THAN 5×10^{-30} GRAMS PER CUBIC CENTIMETER. THE UNIVERSE WOULD THEN HAVE AN INFINITE VOLUME, AN INFINITE SPATIAL EXTENT.

(*) AUTHENTIC REMARK OF **EINSTEIN.**

THE GEOMETRY ~~Y~~IES OF THE UNIVERSE

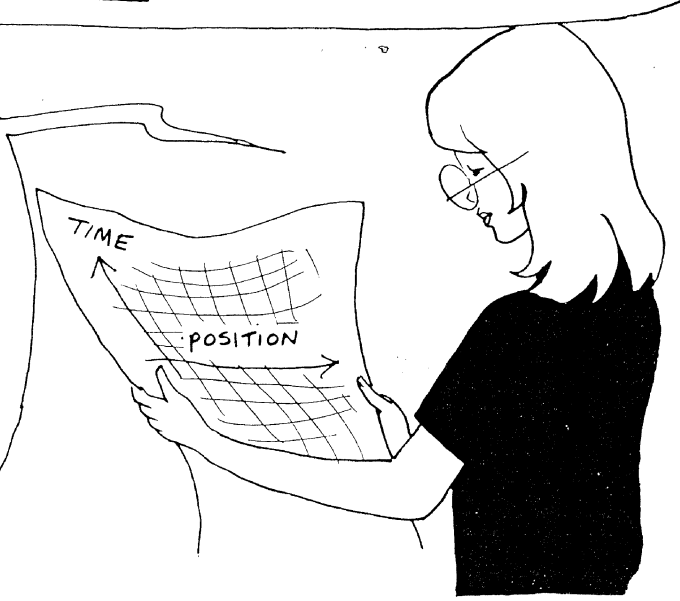
WHAT SHAPE IS THE UNIVERSE?

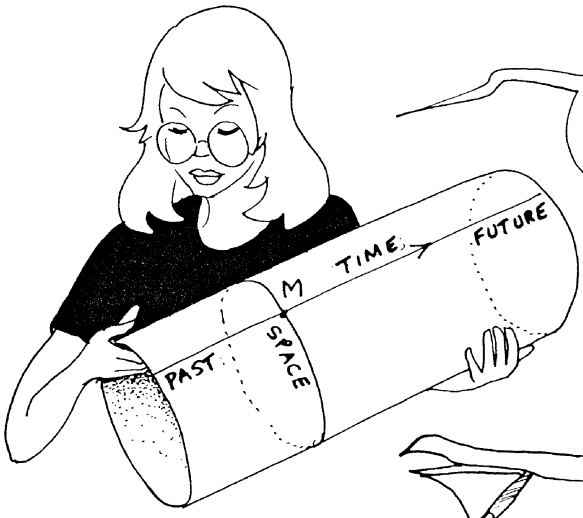
THE UNIVERSE IS, TO US, A FOUR-DIMENSIONAL HYPERSURFACE, IN WHICH SPACE AND TIME ARE INTERMINGLED. THE IDEAS DISCUSSED ABOVE CORRESPOND TO DIFFERENT PRESENTATIONS OF THIS **UNIVERSAL ENTITY** THAT IS **SPACE-TIME.**

RECALL THAT THE NUMBER OF DIMENSIONS OF A SPACE IS THE NUMBER OF QUANTITIES NEEDED TO DEFINE THE POSITION OF A POINT WITHIN IT.

MEET ME ① TUESDAY AT 11 O'CLOCK AT THE CORNER OF ② SIXTH AVENUE AND ③ FIFTH STREET ON THE ④ THIRD FLOOR : FOUR QUANTITIES.

IN DRAWINGS, WE CAN ONLY REPRESENT SPACES OF TWO DIMENSIONS, **SURFACES.** SO WE CAN STUDY A SPACE-TIME WITH TWO DIMENSIONS, ONE OF SPACE AND ONE OF TIME.





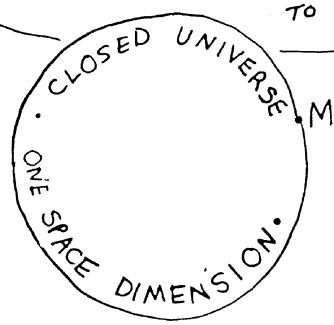
IN THIS WAY THE FIRST MODEL OF A CLOSED UNIVERSE, THE STATIC MODEL OF EINSTEIN, IS REPRESENTED AS A CYLINDER.

LESSEE NAR... IF I UNNERSTAN', WE'RE INSIDE THE CYLINDER?

NO, ON IT!

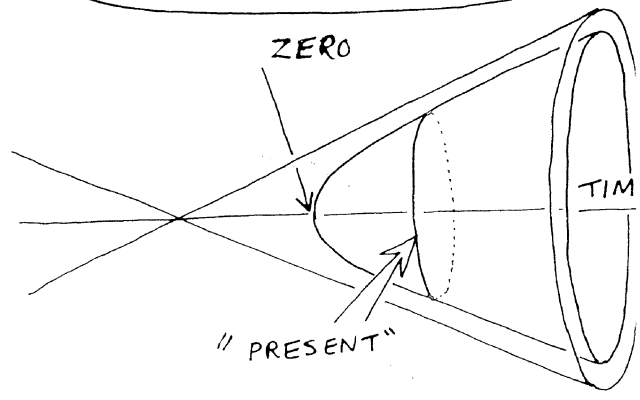
AT A GIVEN INSTANT, AN OBJECT IS REPRESENTED BY A POINT M ON THE SURFACE; AND THE UNIVERSE AT THAT INSTANT REDUCES TO A CIRCLE.

IF THE OBJECT IS MOTIONLESS IT DESCRIBES A GENERATOR OF THE CYLINDER (A LINE ALONG ITS LENGTH) AS TIME FLOWS.



IT IS EASY TO REPRESENT THE EXPANSION OF THIS CLOSED UNIVERSE AS A FUNCTION OF TIME, GIVING A NONSTATIONARY MODEL OF THE UNIVERSE.

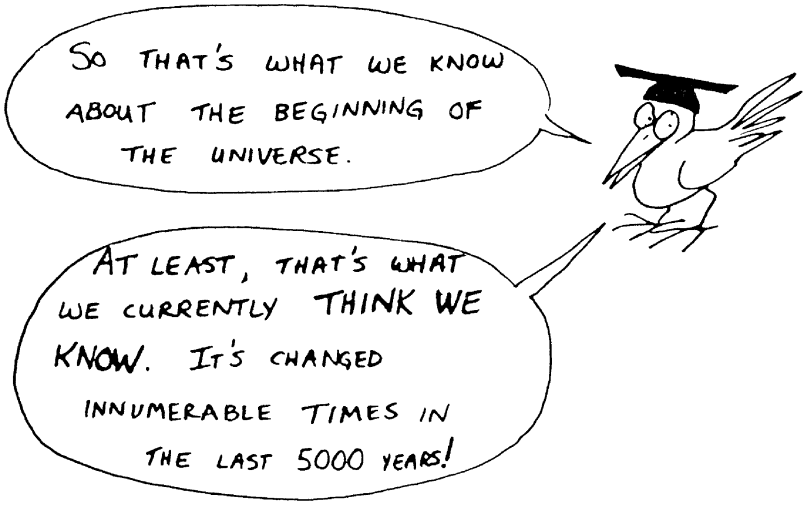
FOR EXAMPLE, HERE'S A TWO-DIMENSIONAL PICTURE OF AN INDEFINITELY EXPANDING SPACE-TIME.

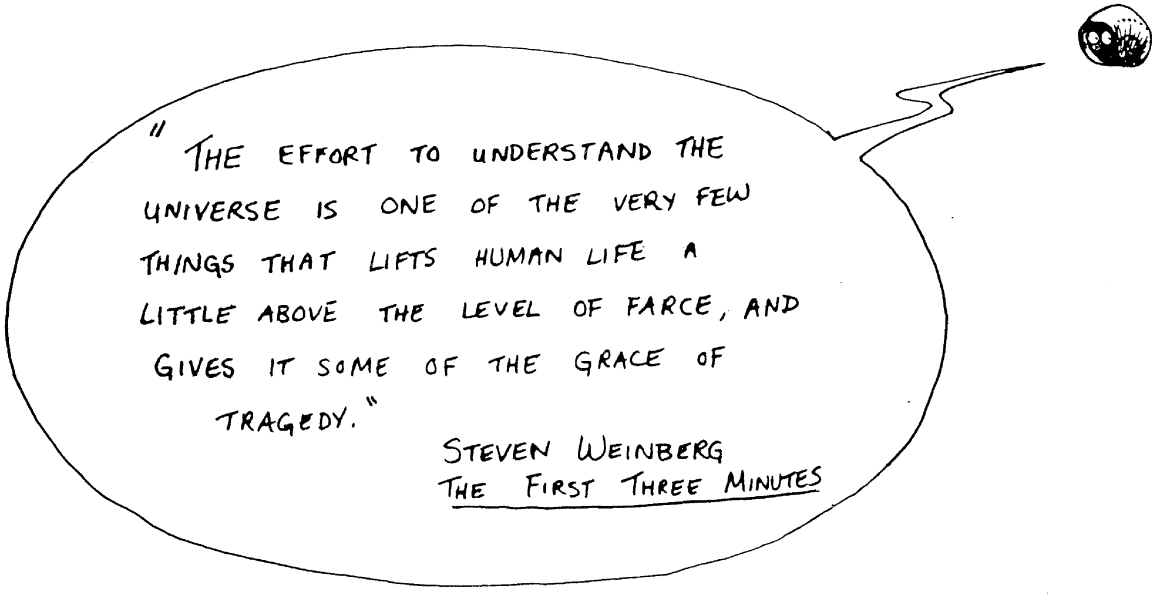


TIME
FUTURE
M
PAST
THE CYCLIC UNIVERSE LOOKS LIKE A LOT OF LINK SAUSAGES.
M
TIME
SPACE
BOUNDARY OF THE UNIVERSE
TIME
BUT COME TO THAT, WHY SHOULD TIME HAVE TO BE "OPEN," THAT IS, OF INFINITE EXTENT BOTH INTO THE FUTURE AND THE PAST?
WE'RE HERE.
YER MEAN YER COULD 'AVE TIME WOT... CLOSES UP ON ITSELF?

HERE WE ARE AGAIN!
TIME
NO PROBLEM... IF YOU CLOSE THE EINSTEIN MODEL UP ON ITSELF, YOU GET... A TORUS.
IN THIS TOTALLY CLOSED SPACE-TIME, THE SAME EVENTS REPEAT THEMSELVES OVER AND OVER AGAIN, AFTER A TIME T WHICH IS THE PERIOD OF THIS WEIRD UNIVERSE.
BIG BANG SINGULARITY
TIME
PRESENT
YOU CAN ALSO MAKE A CYCLIC UNIVERSE COLLAPSE ON ITSELF.
STATE OF MAXIMAL EXPANSION
IT'S A STRING OF SAUSAGES, CLOSED UP ON ITSELF, WITH JUST ONE SAUSAGE!
OH, LOOK AT LENNY!!!
HE'S CRACKED UP COMPLETELY. YOU COULD SEE IT COMING...

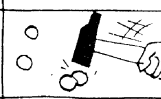
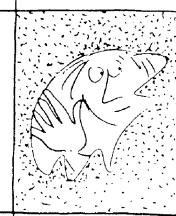
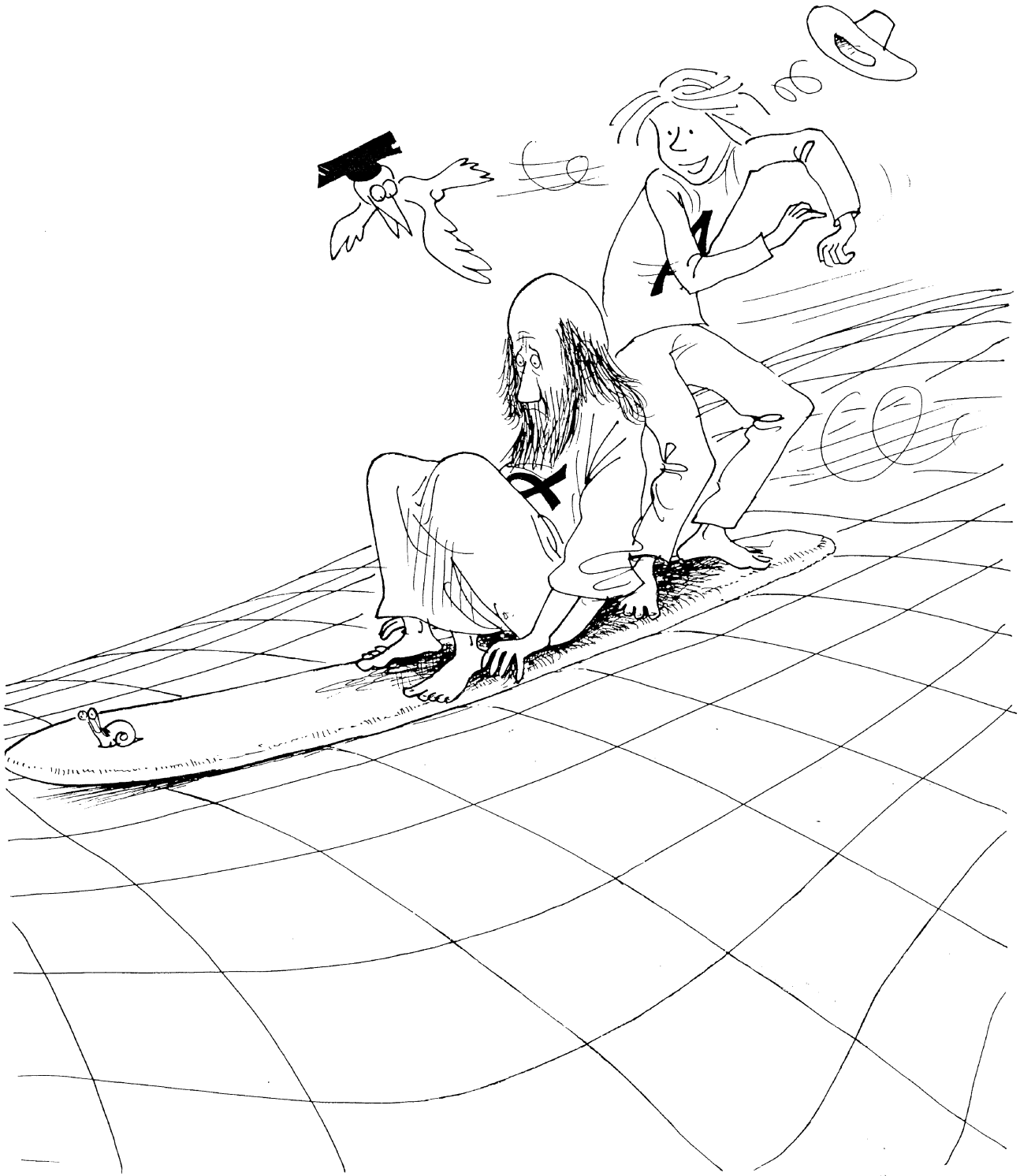
EPILOGUE





THE END

THE COSMODRAMA

TIME	TEMPERATURE	DENSITY	PHENOMENA
BEFORE...	$T \geq 10^{12}$ DEG		?..
$\frac{1}{1000}$ SEC	300 BILLION DEG.		UNDIFFERENTIATED SOUP OF PHOTONS, NEUTRINOS, ANTINEUTRINOS (THE PHOTON IS ITS OWN ANTIPARTICLE), PROTONS, ANTIPROTONS, NEUTRONS, ANTINEUTRONS, ELECTRONS, AND ANTIELECTRONS (POSITRONS).
$\frac{1}{100}$ SEC	100 BILLION DEG.	4 BILLION GM/CM^3	SLAUGHTER OF THE HADRONS (PROTONS, ANTIPROTONS, NEUTRONS, ANTINEUTRONS). ONE IN A BILLION REMAINS. THE REST HAVE BEEN ANNIHILATED BY THEIR ANTIPARTICLES, PRODUCING PHOTONS.
$\frac{1}{10}$ SEC	30 BILLION DEG.		NOT A LOT. TOO HOT FOR ATOMIC NUCLEI TO FORM.
1 SEC	10 BILLION DEG.	380,000 GM/CM^3	NEUTRINOS "LIVE THEIR OWN LIVES" AND CEASE TO INTERACT WITH MATTER.
13 SEC	3 BILLION DEG.		BATTLE BETWEEN THE ELECTRONS AND THE ANTIELECTRONS. AGAIN ONLY ONE IN A BILLION SURVIVES.
3 MIN	1 BILLION DEG.		NUCLEOSYNTHESIS: FORMATION OF HELIUM NUCLEI. DISAPPEARANCE OF FREE NEUTRONS (LIFETIME: 109 sec).
35 MIN	300 MILLION DEG.	1 GM/CM^3	NUCLEOSYNTHESIS FULLY ACHIEVED: 25% HELIUM, 75% HYDROGEN.
700,000 YR	3000 DEG.		AFTER THE ANNIHILATION OF ALMOST ALL MATTER AND ANTIMATTER, THE UNIVERSE ENTERS THE "RADIATIVE ERA" WHERE MATTER/ENERGY OCCURS CHIEFLY AS RADIATION. WHEN THE TEMPERATURE DROPS TO 3000°, NEUTRAL ATOMS FORM AND PHOTONS CEASE TO INTERACT WITH MATTER: THE "TRANSPARENT" UNIVERSE.
100 MILLION YR	$T_R = -173°C$ $T_m = -267°C$		NO LONGER REHEATED BY PHOTONS, NEUTRAL ATOMS OF HELIUM AND HYDROGEN UNDERGO A RAPID DROP IN TEMPERATURE. FORMATION OF GALAXIES AND THE FIRST STARS.
5 BILLION YR			FORMATION OF THE EARTH.
10 BILLION YR	$T_R = -270°C$	10^{-30} GM/CM^3	EMERGENCE OF LIFE.
TODAY			INVENTION OF THE ATOMIC BOMB...