

Savoir sans Frontières

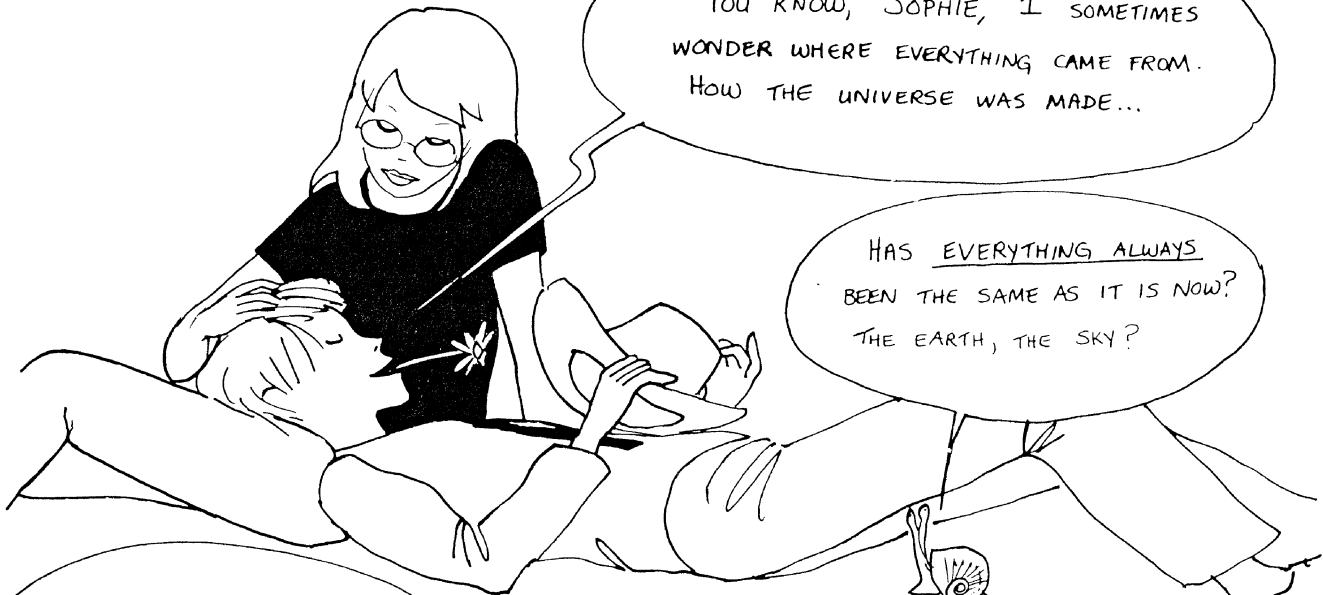
<http://www.savoir-sans-frontieres.com>

BIG BANG

Jean-Pierre Petit



PROLOGUE

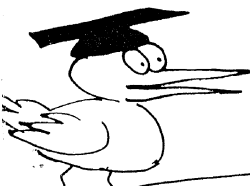


You know, Sophie, I sometimes wonder where everything came from. How the universe was made...

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?

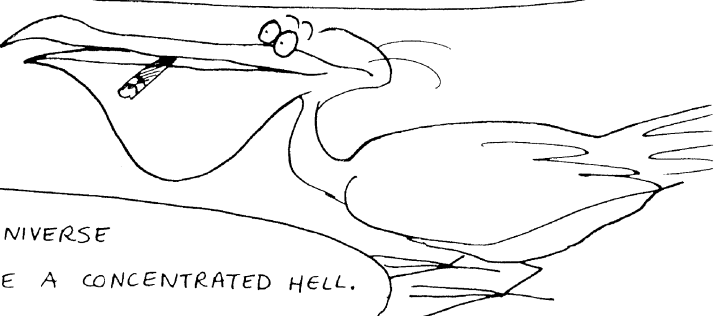


At the very beginning, our universe was very small and very hot, like a concentrated hell.


And everything blew up?

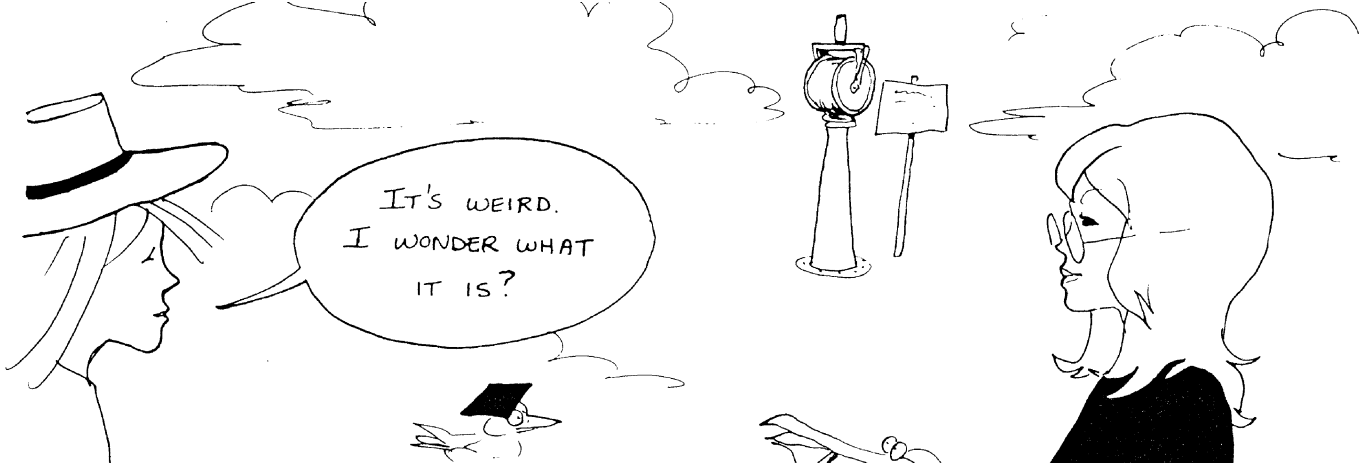


Yes. But it's a very long story, and to tell it I'll have to start a long, long time ago.

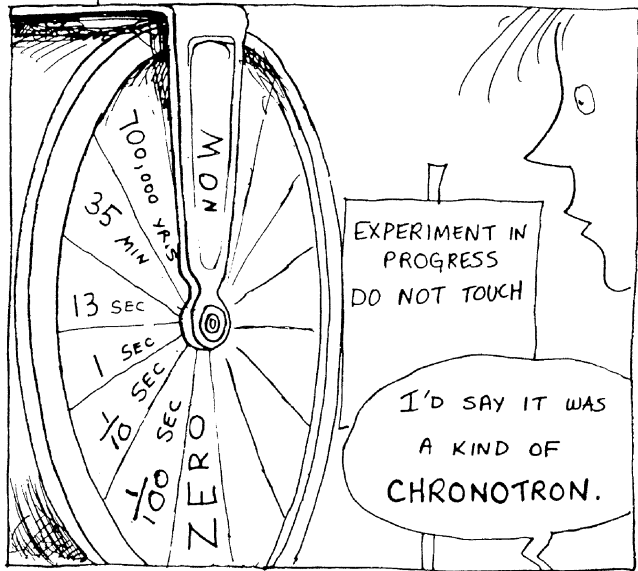


Hey! Come and see what I've found!





IT'S WEIRD.
I WONDER WHAT
IT IS?



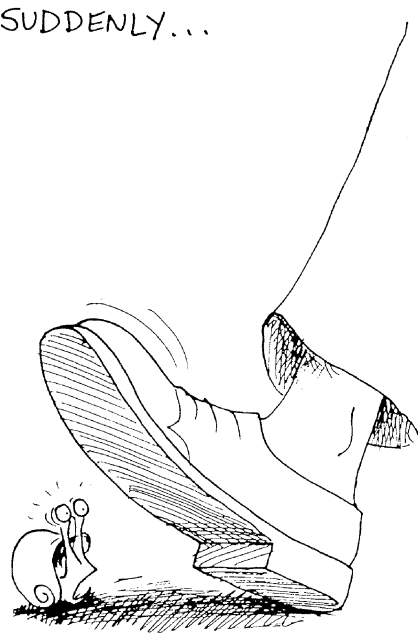
EXPERIMENT IN
PROGRESS
DO NOT TOUCH

I'D SAY IT WAS
A KIND OF
CHRONOTRON.



YUR... BUT DON'T THOSE
MARKINGS LOOK A BIT STRANGE?

SUDDENLY...



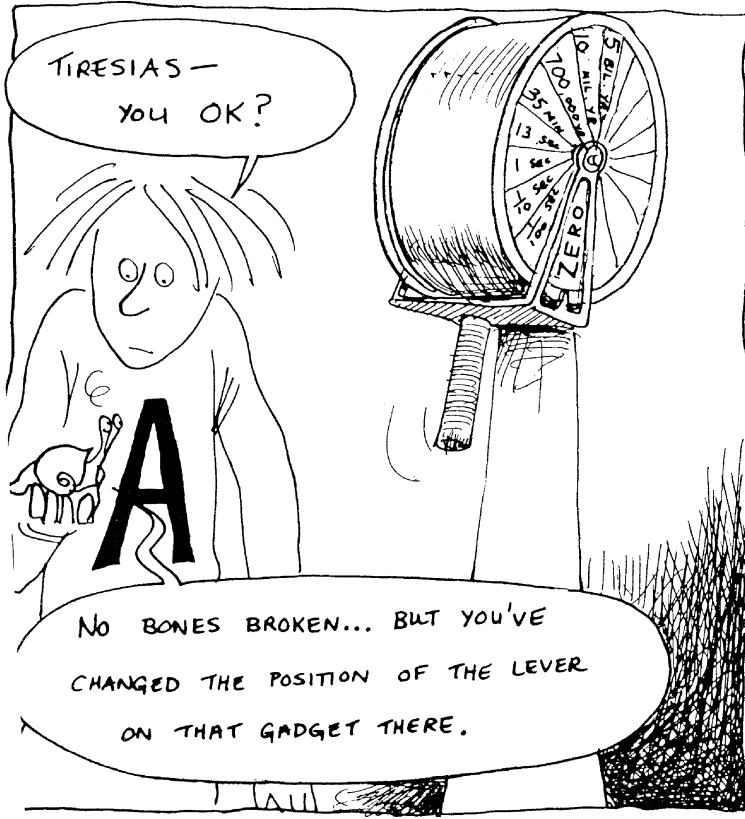
TIRESIAS,
WATCH OUT!

EEEE



KLONG!

THE VERY BEGINNING





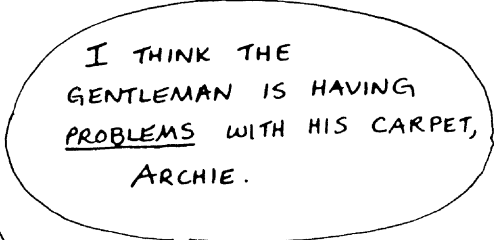
THAT'S DONE IT—
ANOTHER FAILURE!



AND I'D
JUST FINISHED
IT...



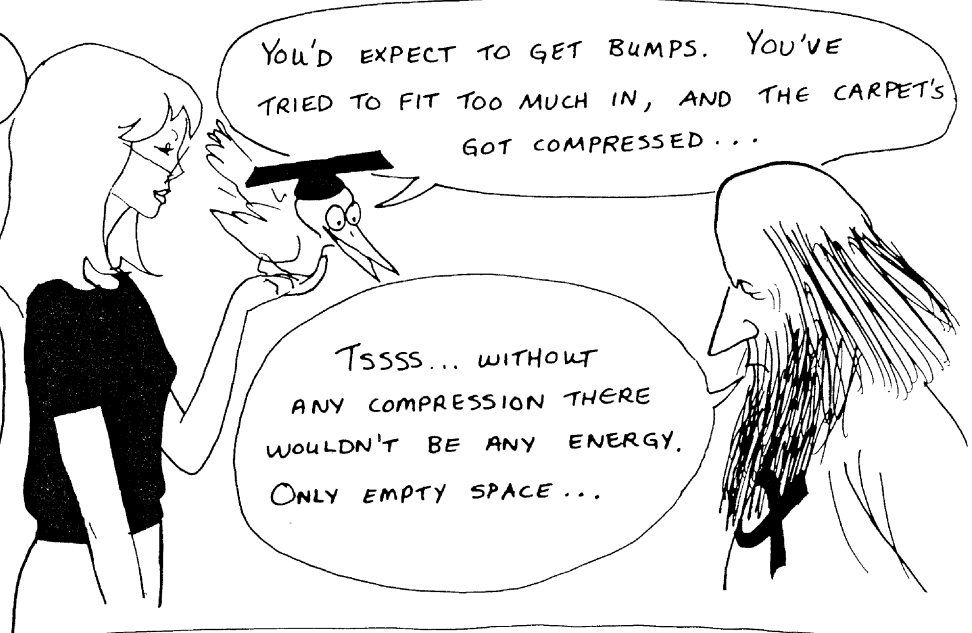
IF YOU'RE TRYING TO LAY THE CARPET,
YOU'VE MADE A REAL PIG'S BREAKFAST OF IT,
THAT'S TRUE!



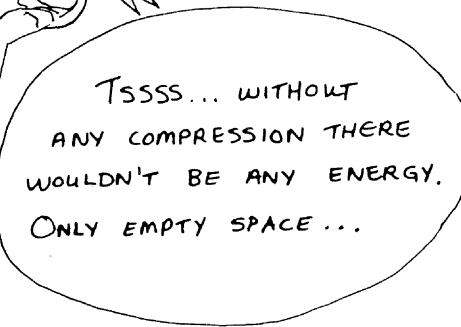
I THINK THE
GENTLEMAN IS HAVING
PROBLEMS WITH HIS CARPET,
ARCHIE.



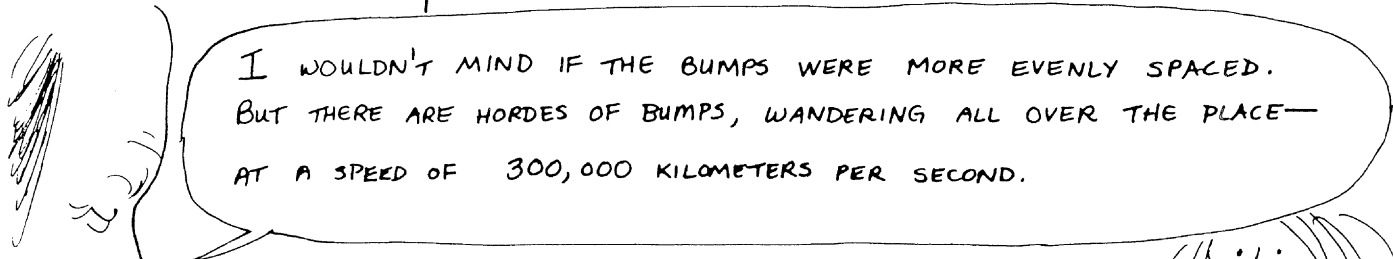
IT'S A DISASTER—
BUMPS EVERYWHERE!



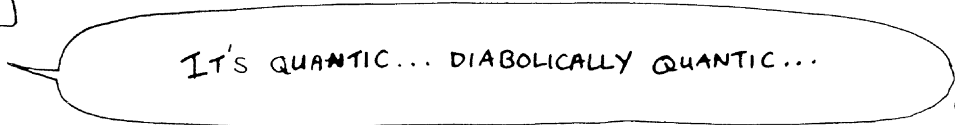
YOU'D EXPECT TO GET BUMPS. YOU'VE
TRIED TO FIT TOO MUCH IN, AND THE CARPET'S
GOT COMPRESSED...



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.

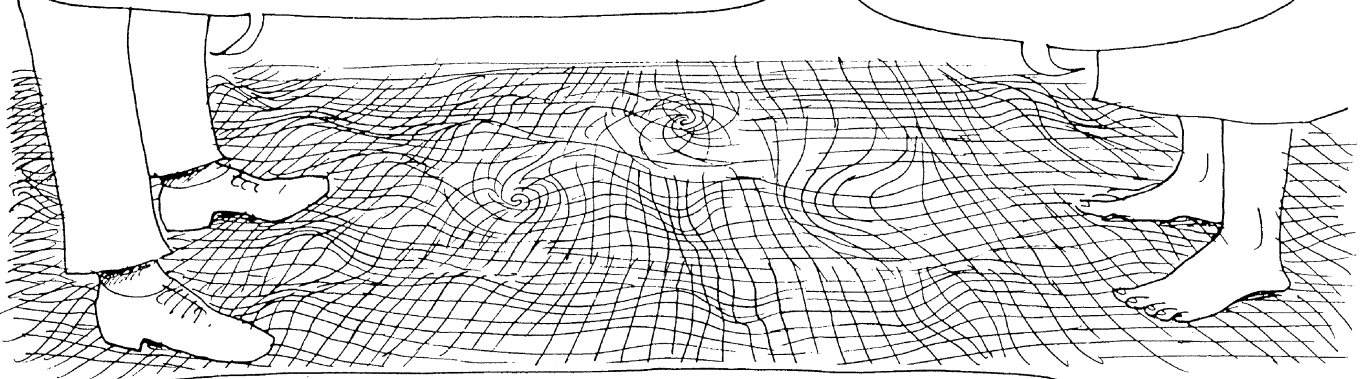
AND JUST LIKE PHOTONS, THEY MOVE AT
300,000 KM/SEC.

I'LL CALL THESE EDDIES **NEUTRINOS**
WHEN THEY TURN THIS WAY:

... AND **ANTINEUTRINOS** WHEN THEY TURN
THE OTHER WAY:

IT'S WOBBLING LIKE JELLY. THERE ISN'T A SINGLE FLAT SPOT ON THE ENTIRE CARPET. THE BUMPS ARE JAMMED RIGHT NEXT TO EACH OTHER (*).

THIS UNIVERSE IS VERY, VERY UNSTABLE. A TOTAL FAILURE!

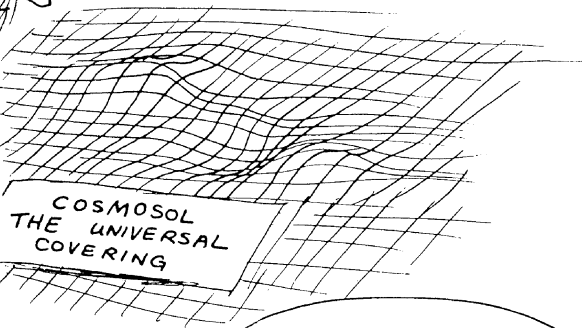


IF ONLY THERE WERE SOME ORDER IN THERE SOMEWHERE. BUT IT'S A REAL DOG'S DINNER... EVERYTHING WANDERING ABOUT AT RANDOM.

AND I HATE GAMES OF CHANCE!

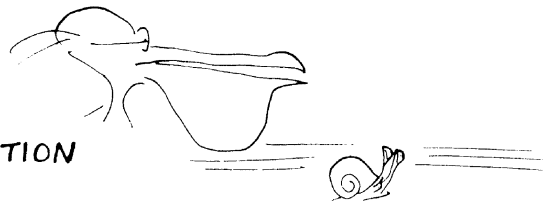
CHANCE, MY FRIEND, IS UTTERLY DIABOLICAL!

YOU SAID IT.




I DON'T EVEN LIKE PLAYING DICE...

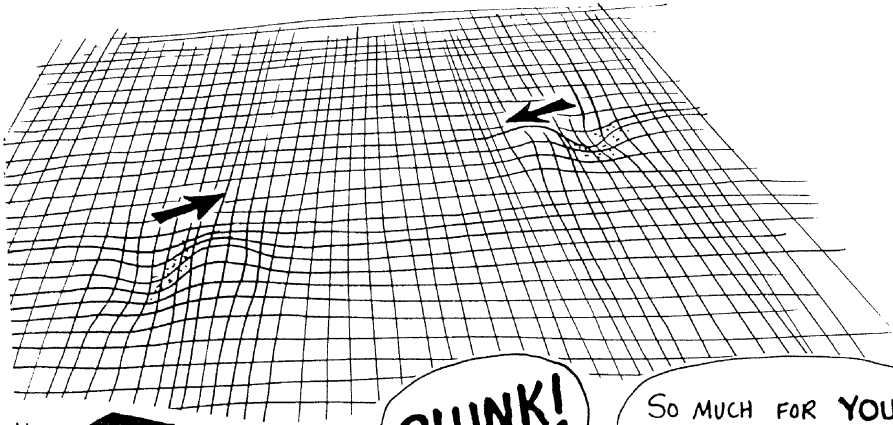
HEY, LOOK! THERE'S SOMETHING HAPPENING DOWN THERE!



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

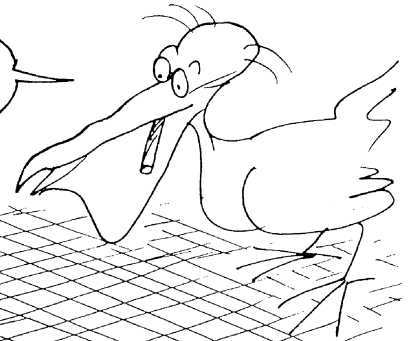
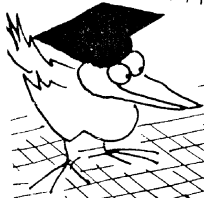


TWO OF THOSE PERAMBULATING
PROTUBERANCES ARE ABOUT TO COLLIDE
WITH EACH OTHER.

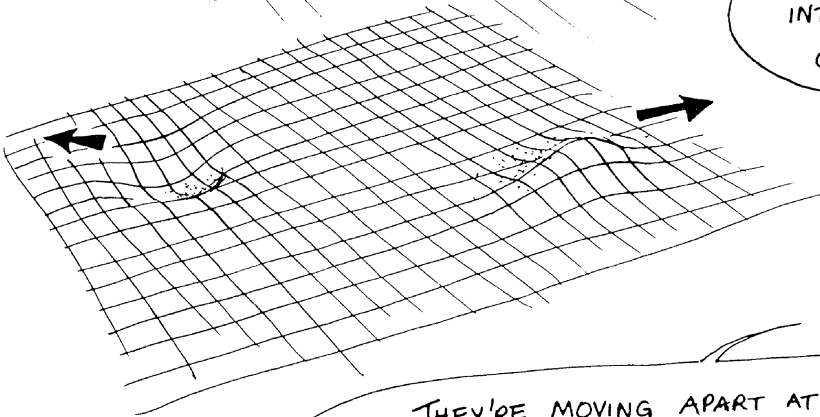


BLUNK!

SO MUCH FOR YOUR
NO-CLAIMS BONUS.

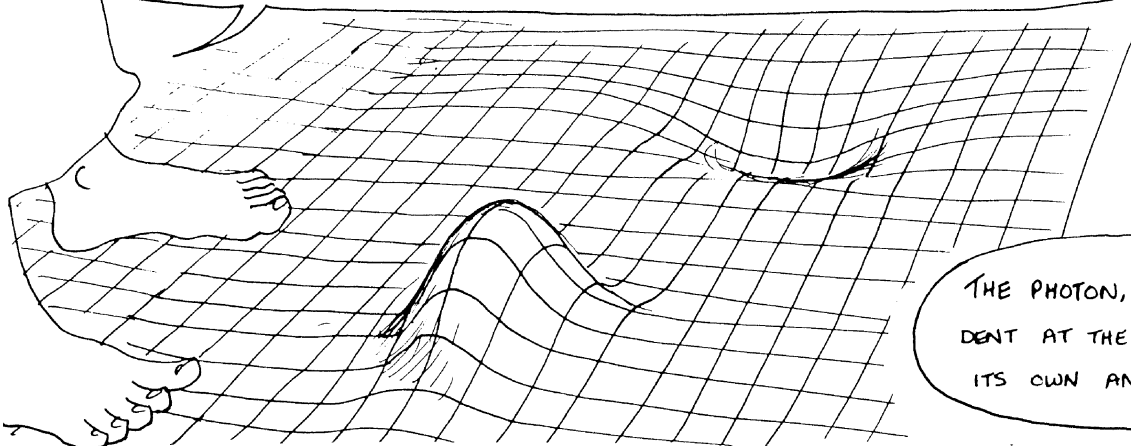


NOW THEY'VE TURNED BACK
INTO SEPARATE BUMPS. WELL,
ONE BUMP AND ONE DENT.



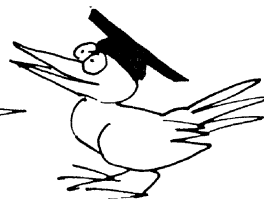
THEY'RE MOVING APART AT A SPEED CLOSE TO
300,000 KM/SEC.

FINE. I'LL CALL THE BUMPS **MATTER** AND THE DENTS **ANTIMATTER**. THEY POSSESS **CURVATURE**, WHICH IMPLIES **MASS**.

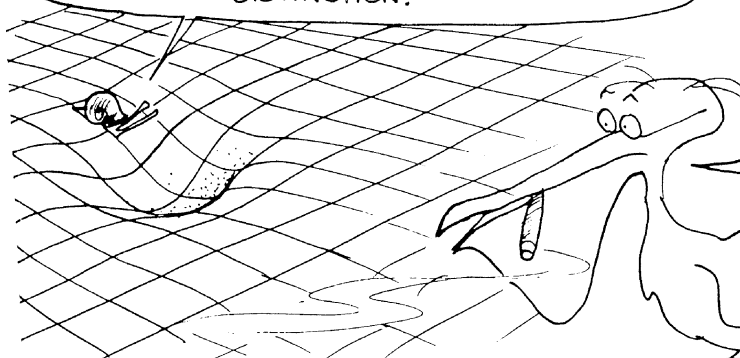


THE PHOTON, A BUMP AND A DENT AT THE SAME TIME, IS ITS OWN ANTI-PARTICLE.

MATTER AND **ANTIMATTER**, BORN FROM THE COLLISIONS OF PHOTONS, APPEAR AT RELATIVISTIC SPEEDS.

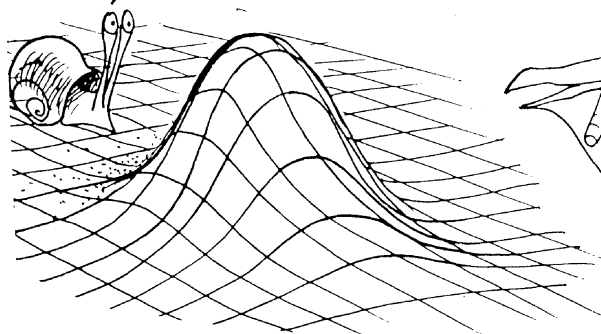


BUMP, DENT, THAT'S AN ARBITRARY DISTINCTION.



WOT'S THE POINT O' THAT PROFOUND REMARK, TIRESIAS OLD FRUIT? THERE'S FINGS WOT LOOKS LIKE **BUMPS**, AND UVER 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!

JUST MY FEEBLE LITTLE
JOKE, OFFICER...

?...

ANOTHER
EPISTOCOP! (*)

LOOK... THERE! IF A BUMP AND A DENT COLLIDE SLOWLY
ENOUGH, YOU GET BACK TWO WANDERING WAVELETS. IT'S THE
INVERSE OPERATION!

HMM... SIMPLE ANNIHILATION
OF ONE PARTICLE OF MATTER AND
ITS ANTIPARTICLE. THAT GIVES
TWO PHOTONS.

COSMIC CHAOS

HMM...

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

CREATIONS AND ANNIHILATIONS OF PARTICLES, BY MEANS OF PAIRS OF PHOTONS, FOLLOW EACH OTHER IN A FRANTIC RHYTHM. IN THIS CHAOTIC WORLD OF CEASELESS CHANGE, THERE ARE NO RECOGNIZABLE STRUCTURES. ONLY A SWARMING MASS OF PHOTONS, NEUTRINOS, ANTINEUTRINOS, AND A HOST OF OTHER PARTICLES AND ANTI PARTICLES, FLEETING AND VARIED. IT'S **CHAOS** (*).

THAT MAKES ME WONDER
ABOUT **SEXONS**.

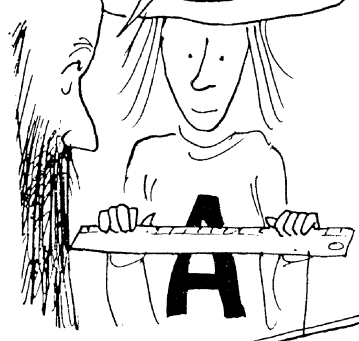
WOT THE BLAZES ARE
SEXONS?

PARTICLES THAT SPEND THEIR TIME
REPRODUCING.

AS FAR AS I CAN SEE, YOU CAN HAVE WANDERING
WAVES OF DIFFERENT SIZES, AS WELL AS TALL THIN
BUMPS OR SHORT FAT ONES.

(*) SEE THE BIBLE.

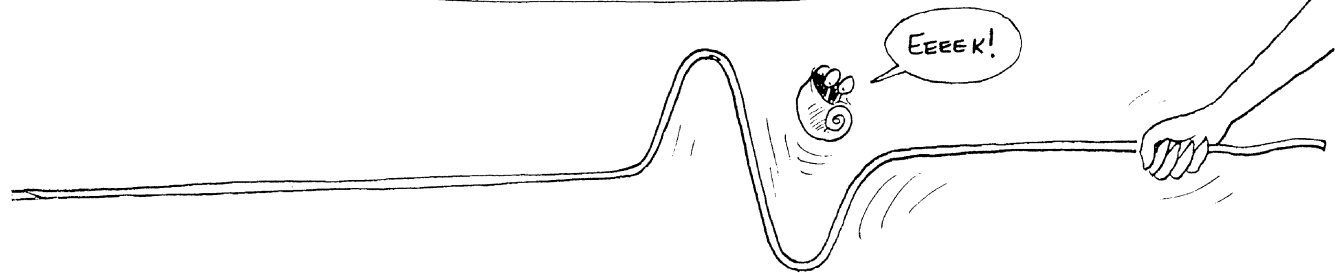
I'LL CALL THE SIZE OF THESE WANDERING WAVES - PHOTONS - THEIR WAVELENGTH λ (LAMBDA).



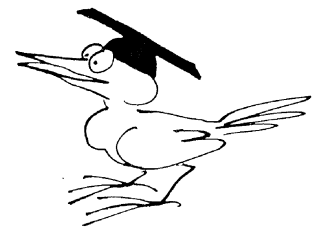
SUPPOSE I CREATE A TRAVELING WAVE BY SHAKING THIS ROPE. IF I SHAKE IT GENTLY I GIVE IT VERY LITTLE ENERGY AND THE WAVELENGTH λ IS LARGE.



NOW IF I SHAKE THE CORD MUCH HARDER, I GIVE IT A LOT OF ENERGY AND THE WAVELENGTH λ IS SHORT.



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



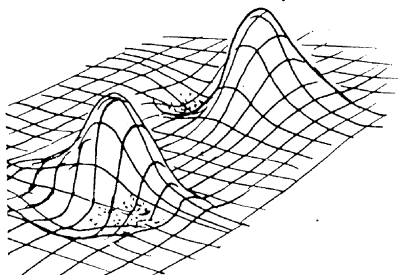
THAT'S OK FOR THESE WANDERING WAVELETS YOU'VE NAMED PHOTONS. BUT HOW ARE WE GOING TO TELL THE DIFFERENCE BETWEEN HIGH BUMPS AND LOW BUMPS? OR DENTS?

I'M GOING TO CALL THE SIZE OF THE BUMPS AND DENTS THEIR COMPTON WAVELENGTH λ_c . THEIR MASS m WILL BE INVERSELY PROPORTIONAL. SO m VARIES AS $\frac{1}{\lambda_c}$.

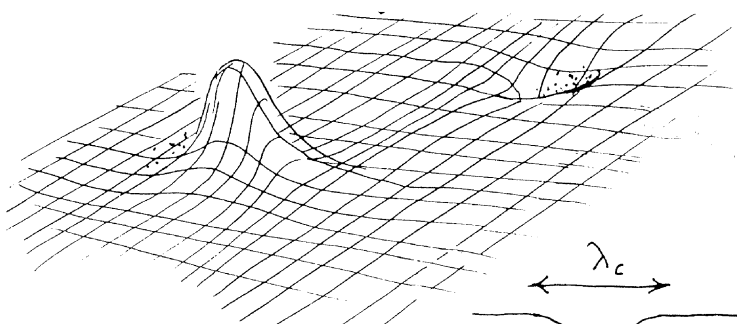


HIGHLY ENERGETIC PHOTONS, HAVING A SHORT WAVELENGTH, PRODUCE PARTICLES (AND ANTI-PARTICLES) THAT ARE TALL AND NARROW; THAT IS, HAVE A LARGE MASS m .

λ SMALL

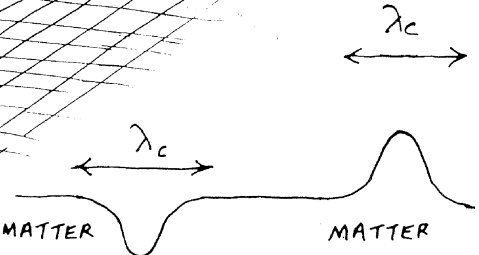


λ_c SMALL: COMPTON WAVELENGTH SHORT.



PHOTONS

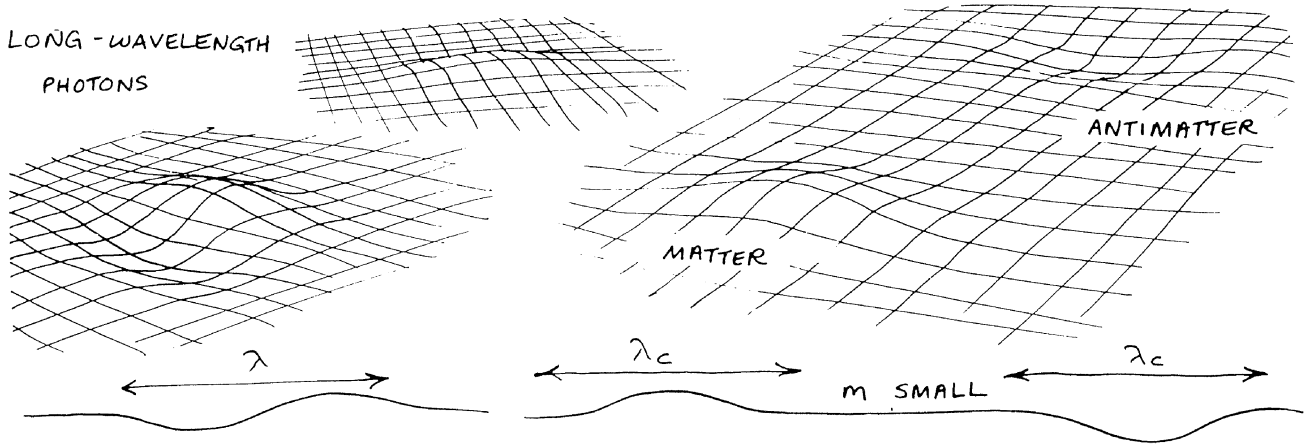
MASS m LARGE



ANTI-MATTER

MATTER

LONG-WAVELENGTH
PHOTONS



ANTIMATTER

MATTER

m SMALL

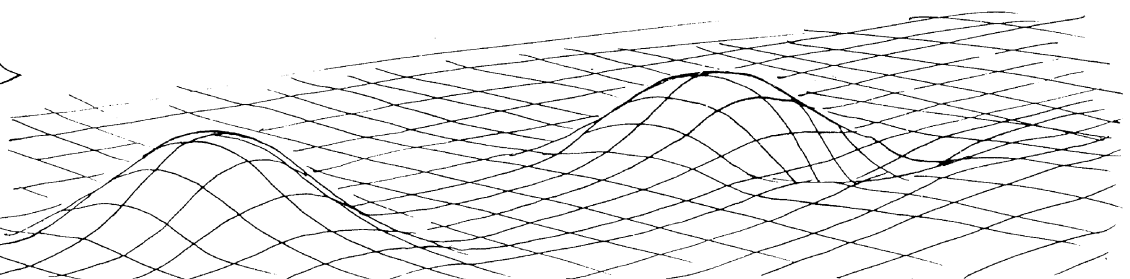
LONG-WAVELENGTH PHOTONS → PARTICLES WITH LONG COMPTON WAVELENGTH.

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.

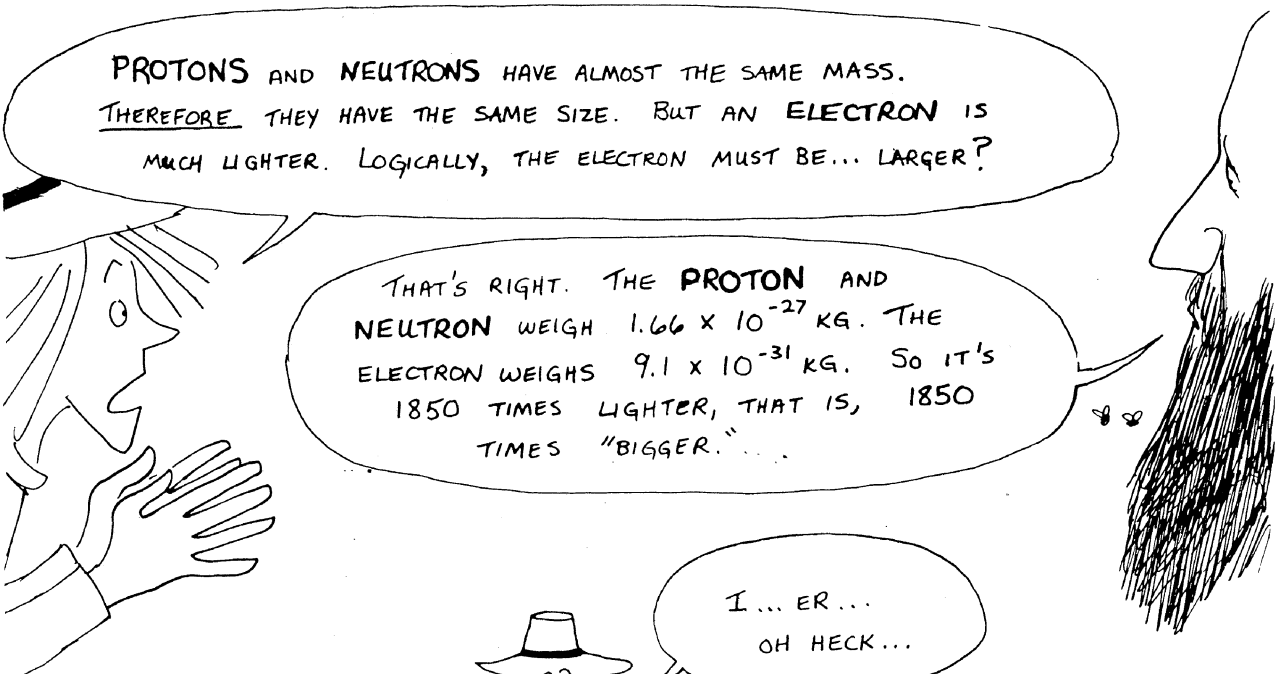
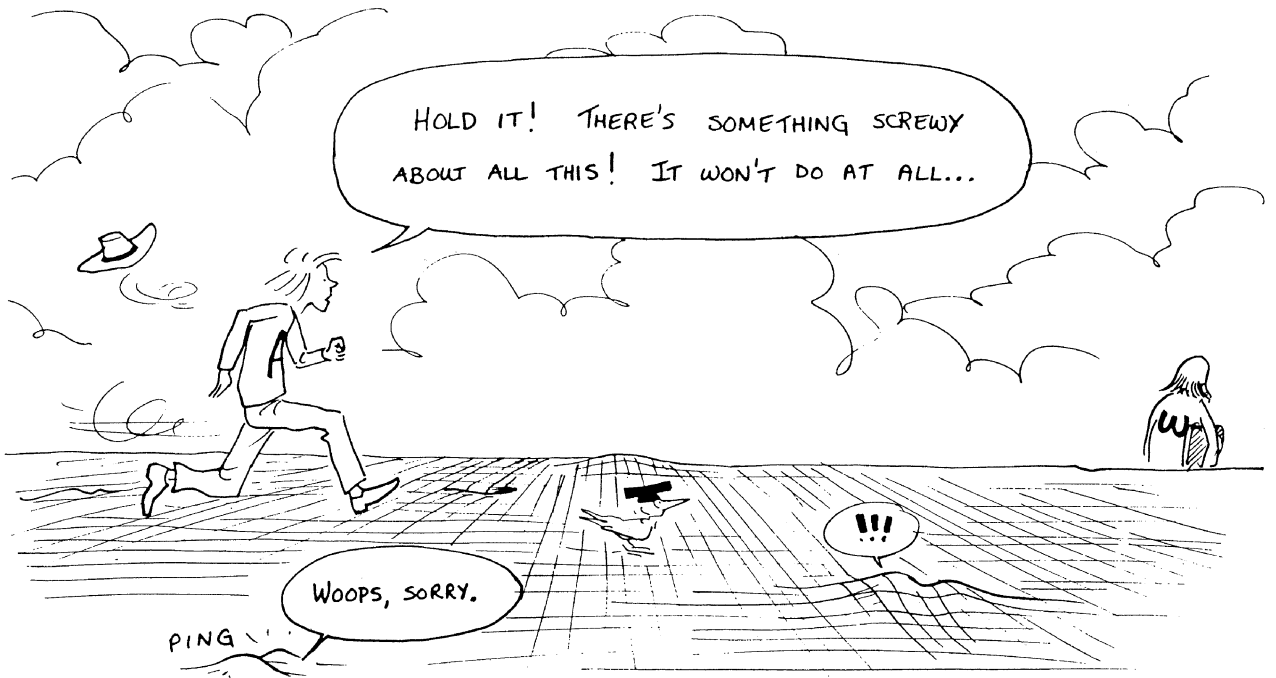
IN FACT, IT'S REALLY A LOT SIMPLER. I CAN
ASSUME THAT $\lambda = \lambda_c$, IN OTHER WORDS THAT THE
PARTICLES (AND ANTIPARTICLES) ARE THE SAME "SIZE"
AS THE PHOTONS THAT CREATED THEM.



AND THAT MEANS THAT ONCE YOU KNOW
THE **MASS** OF ANY PARTICLE, YOU CAN
IMMEDIATELY DEDUCE THE WAVELENGTH OF THE
RADIATION THAT CREATED IT.



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



THE GENESIS OF TODAY IS
UTTERLY FASCINATING.

SOPHIE, WHAT ARE
YOU MAKING?

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

$$T_R$$

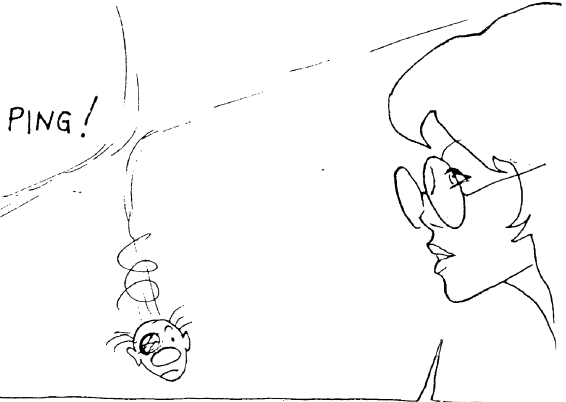
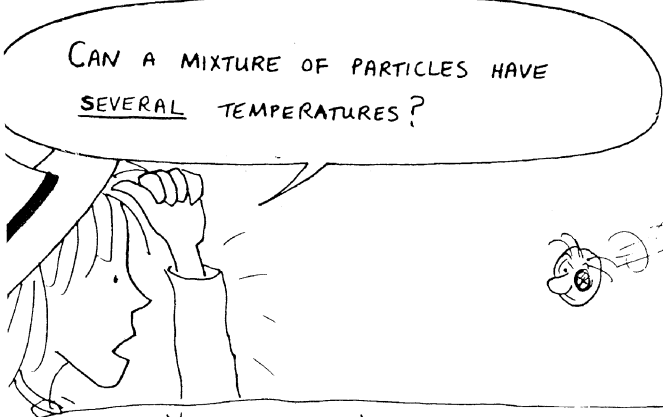


THESE PHOTONS HAVE ALL SORTS OF DIFFERENT WAVELENGTHS AND ENERGIES. BUT OVERALL THERE IS A DEFINITE AVERAGE WAVELENGTH AND AN AVERAGE ENERGY.

THE RADIATION TEMPERATURE T_R WILL BE THE VALUE OF THIS AVERAGE ENERGY OF PHOTONS.

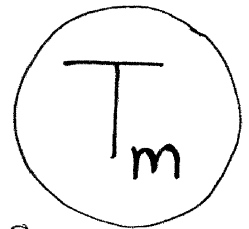
WHAT A DISASTER...

EQUILIBRIUM STATES

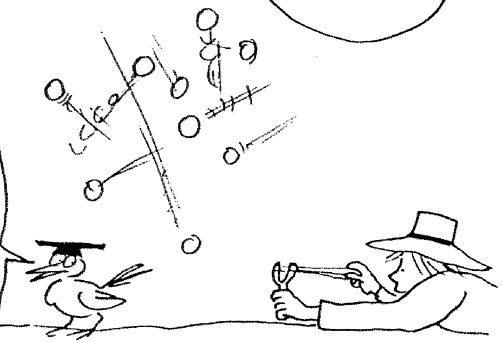


YES, BUT WE'LL SEE ABOUT THAT ON PAGE 46. FOR THE MOMENT LET'S JUST SAY THAT PARTICLES EXCHANGE ENERGY WITH EACH OTHER, OR WITH PHOTONS, THROUGH COLLISIONS. THIS MECHANISM TENDS TO REDISTRIBUTE THE TEMPERATURES, TO EQUALIZE THEM, SO PUTTING THE SYSTEM INTO A STATE OF THERMODYNAMIC EQUILIBRIUM.

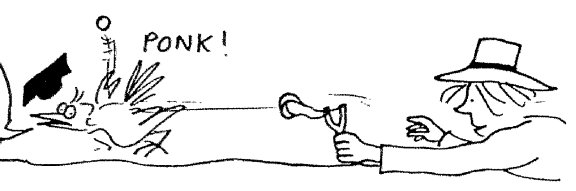
THE TEMPERATURE OF MATTER



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.

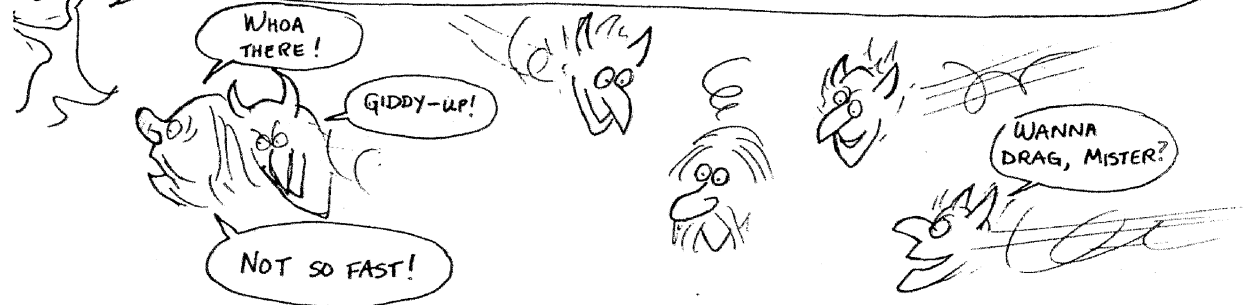


AND THE TEMPERATURE OF THE MATTER, T_m , IS THE VALUE OF THIS AVERAGE ENERGY OF THERMAL AGITATION.



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 STAY EQUAL WHEN YOU EXPAND OR COMPRESS THE MIXTURE.



WHAT A FUSS! PARTICLES AND ANTIPARTICLES,
CREATED AND DESTROYED AT AN INFERNAL
PACE!

WOT D'YER NEED TER
CREATE A PARTICLE-
H'ANTYPARTICLE PAIR?

THRESHOLD TEMPERATURE

TO CREATE A PARTICLE-ANTIPARTICLE
PAIR WHOSE COMMON MASS IS m , YOU
NEED AN ENERGY $2mc^2$, WHICH CAN BE
PROVIDED BY A PAIR OF PHOTONS WITH
EQUAL OR HIGHER ENERGY.

IF THE MEAN ENERGY OF PHOTONS IS LESS
THAN THE THRESHOLD ENERGY mc^2 , THAT IS, IF THE
RADIATION TEMPERATURE T_R IS TOO LOW (LESS THAN
A THRESHOLD VALUE), THEN SUCH PARTICLES OF
MATTER CAN'T BE CREATED.

GOTCHA!

THE EVOLUTION OF SPECIES

THE SURVIVAL OF A SPECIES OF PARTICLE IS ALWAYS PROBLEMATIC. IT CAN BE ASSURED BY A SUFFICIENTLY HIGH RATE OF PRODUCTION.

WHICH MEANS THAT THE REPRODUCTION TEMPERATURE T_R MUST BE HIGHER THAN THE FRESHOLD TEMPERATURE FOR THAT SPECIES.

IF THE TEMPERATURE T_R IS LOWER THAN THE THRESHOLD, THERE ARE SEVERAL WAYS PARTICLES CAN DISAPPEAR.

THE MOST OBVIOUS IS ANNIHILATION BY AN ANTIPARTICLE...

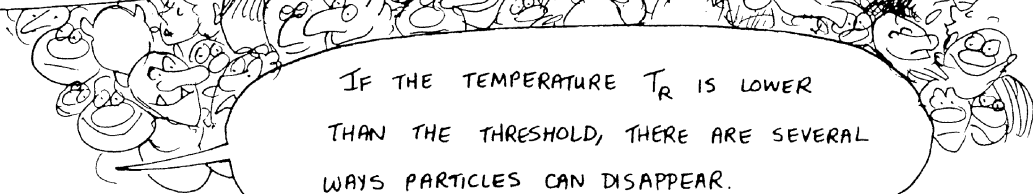
PLOP

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.

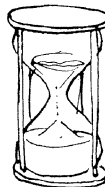


CRUIKEY!
SEXONS!



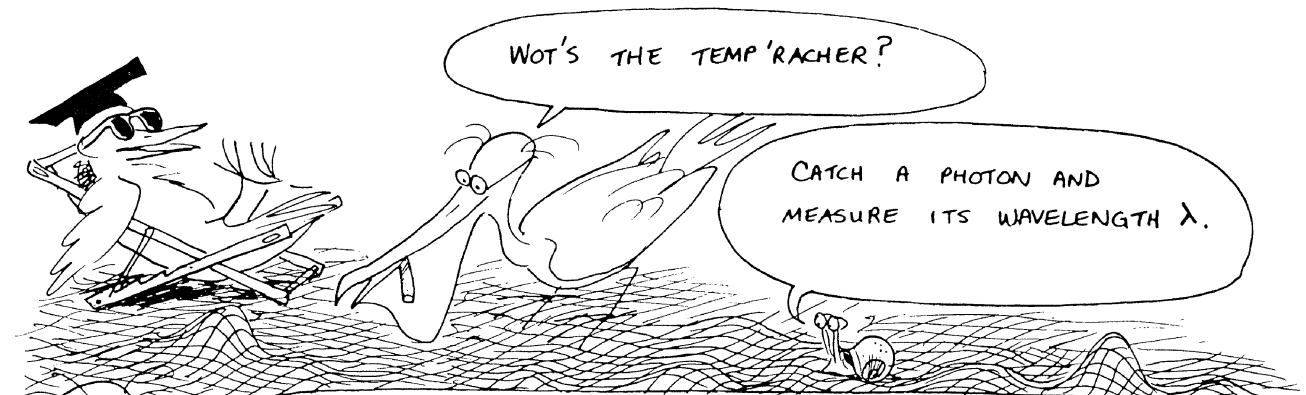
... OR A WHOLE HOST OF FATAL ENCOUNTERS WITH ANOTHER SPECIES.

THE COSMOS IS A RAT RACE!



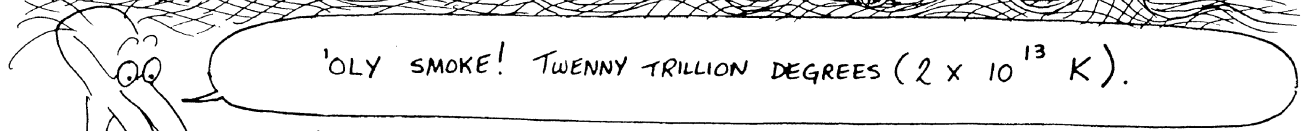
THE PROBLEM IS TO LAST OUT THE RACE...



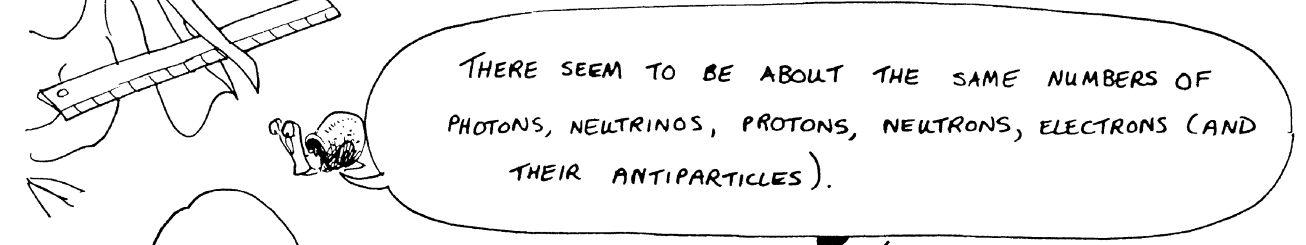


WOT'S THE TEMP'RACHER?

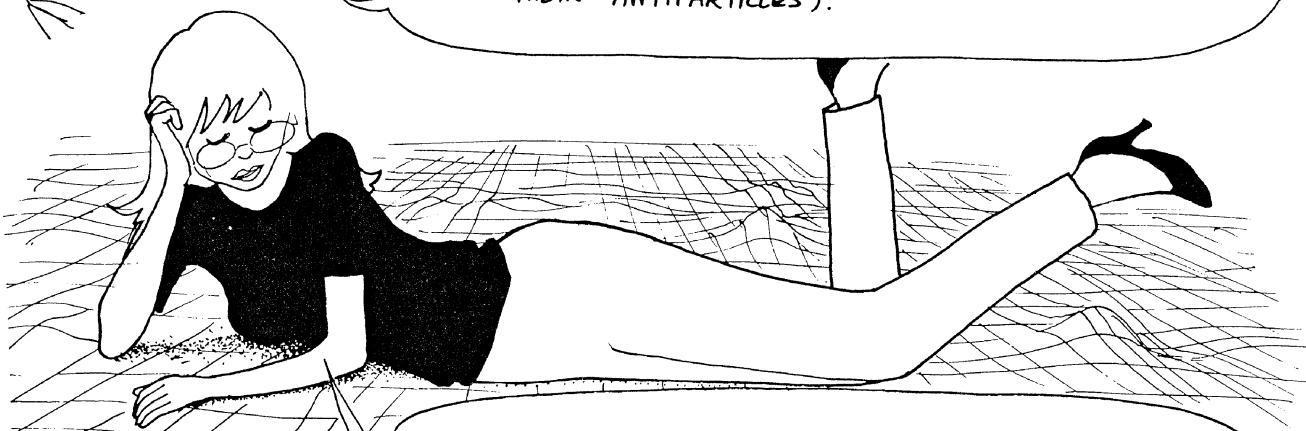
CATCH A PHOTON AND MEASURE ITS WAVELENGTH λ .



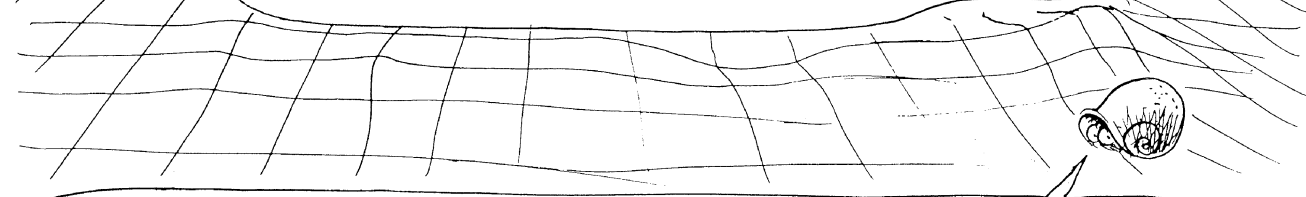
'OLY SMOKE! TWENNY TRILLION DEGREES (2×10^{13} K).



THERE SEEM TO BE ABOUT THE SAME NUMBERS OF PHOTONS, NEUTRINOS, PROTONS, NEUTRONS, ELECTRONS (AND THEIR ANTI-PARTICLES).



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.



NOW THAT'S A BIT OF A PROBLEM... IF EVERYTHING MOVES AT THE SPEED OF LIGHT, THEN **TIME (*)** CEASES TO FLOW ALTOGETHER... SO NOTHING HAPPENS.

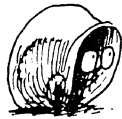
NOTHING WOULD MOVE SLOWLY ENOUGH FOR TIME TO FLOW IN A SIGNIFICANT WAY.



CRIPES!

A TOTALLY TIMELESS WORLD WOULD HAVE NO SENSE TO IT.

PERHAPS TIME IS A LUXURY THAT ONLY SOME UNIVERSES CAN AFFORD?



THAT'S DIABOLICKLE!

PAH - AFTER EVERYTHING I'VE ALREADY SEEN AND HEARD... SPACE, TIME, THE UNIVERSE... IT'S ALL HALF-BAKED MOONSHINE!

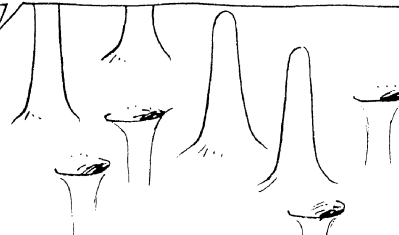
THE UNIVERSAL INGREDIENT OF EVERYTHING?



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

ELEMENTARY PARTICLES

YOU THERE — INSTEAD OF FLAPPING YOUR ARMS ABOUT, HELP ME PUT SOME ORDER INTO THESE CRAZY ELEMENTARY PARTICLES.



THOSE ONES HAVE VERY SMALL COMPTON WAVELENGTHS!

THOSE VERY MASSIVE PARTICLES ARE HYPERONS (*).

THEN COME THE HADRONS. THE PROTON AND THE NEUTRON (AND OF COURSE THE ANTIPROTON AND THE ANTINEUTRON) ARE AMONG THEM. THEY CAN COMBINE TO FORM NUCLEI. TO CREATE THESE PARTICLES, YOU NEED A RADIATION TEMPERATURE GREATER THAN 10^{13} K, THAT IS, TEN TRILLION DEGREES.

THAT MUS' BE THEIR FRESHOLD TEMP'ACHER.

THE COMPTON WAVELENGTH OF PROTONS AND NEUTRONS COMES OUT AS 1.35×10^{-12} CM. ONE TRILLIONTH OF A CENTIMETER.

PLEASE DO NOT FEED THE NEUTRONS

(*) HYPOTHETICAL PARTICLES, AT THE PRESENT STATE OF KNOWLEDGE.

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



BLIMEY - A GREEK-SPEAKIN' SNAIL!

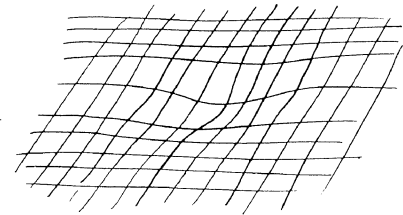
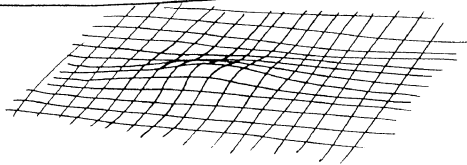


OBVIOUSLY THERE ARE AS MANY ANTIHADRONS AS HADRONS.



NOW, HERE COME THE LEPTONS(*)

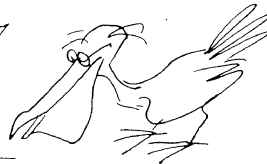
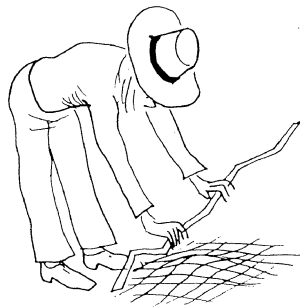
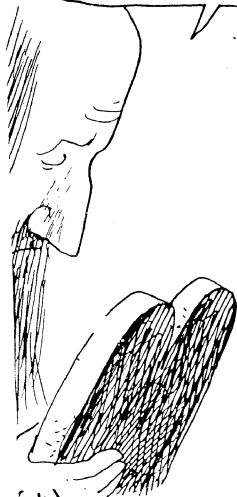
LEPTON



ANTI LEPTON

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 ANTI-ELECTRON, 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.

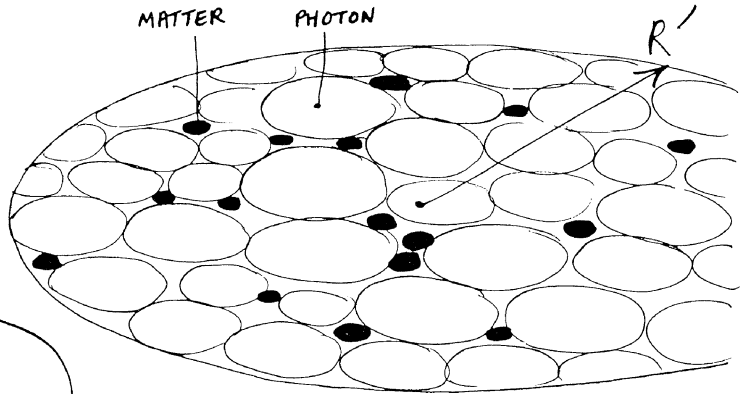
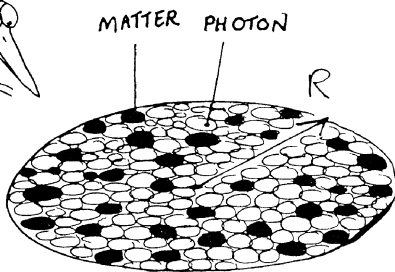
RUINED,
UTTERLY RUINED!

WHERE'D 'E GO?

IT LOOKS LIKE A MANHOLE COVER. INTO THE
CATACOMBS OF THE UNIVERSE?

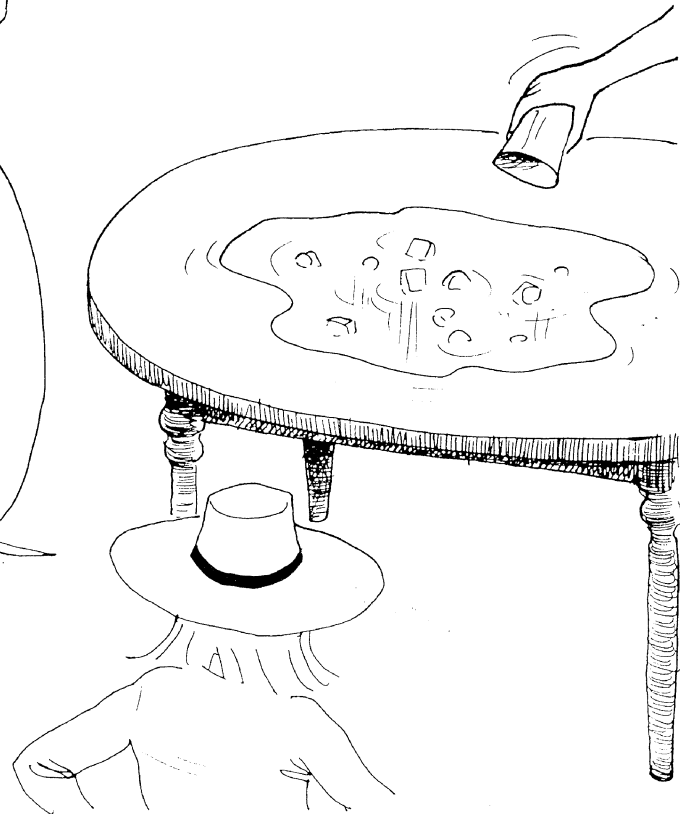
THE CONSERVATION OF MASS

LOOK WHAT'S HAPPENING. THE PHOTONS ARE GETTING BIGGER. PARTICLES OF MATTER ARE STAYING THE SAME SIZE.



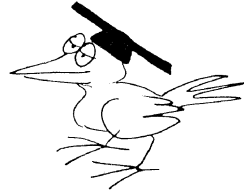
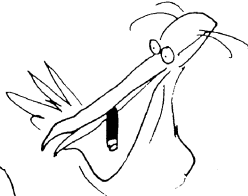
THE MATTER SEEMS UNRESPONSIVE. FRIGID!

THAT MAKES ME THINK OF WHAT HAPPENS IF YOU UPSET A GLASS OF ICE WATER ON A TABLE. THE WATER SPREADS OUT. THE ICE CUBES GO ALONG TOO, BUT KEEP THEIR SHAPE AND SIZE.

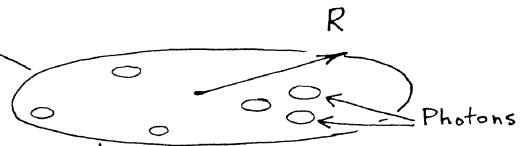


BECAUSE THE SIZE OF PARTICLES OF MATTER IS RELATED TO THEIR MASS,
I DEDUCE THAT MASS IS CONSERVED.

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.

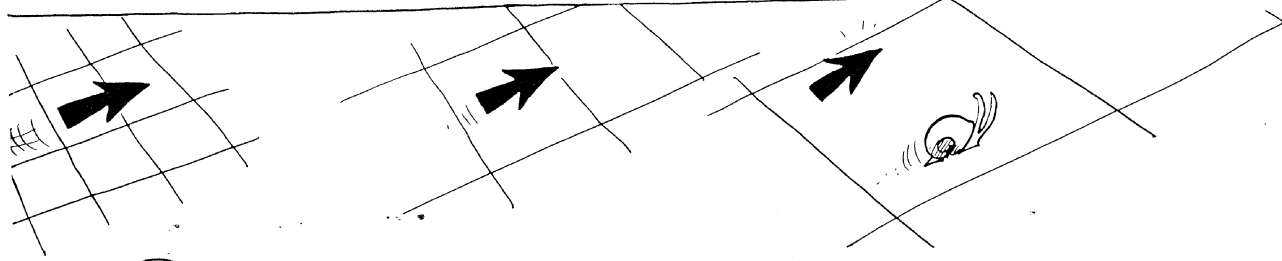
(*) FROM COSMOS (COSMOS) AND TOPOS (PLACE). THE
PLACE THAT THE UNIVERSE INHABITS.

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 $\frac{1}{R^2}$



BRRRR!!

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.



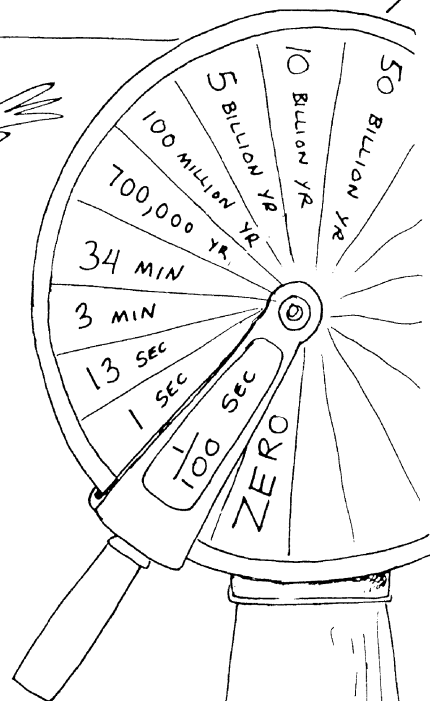
THANKS, FOLKS!

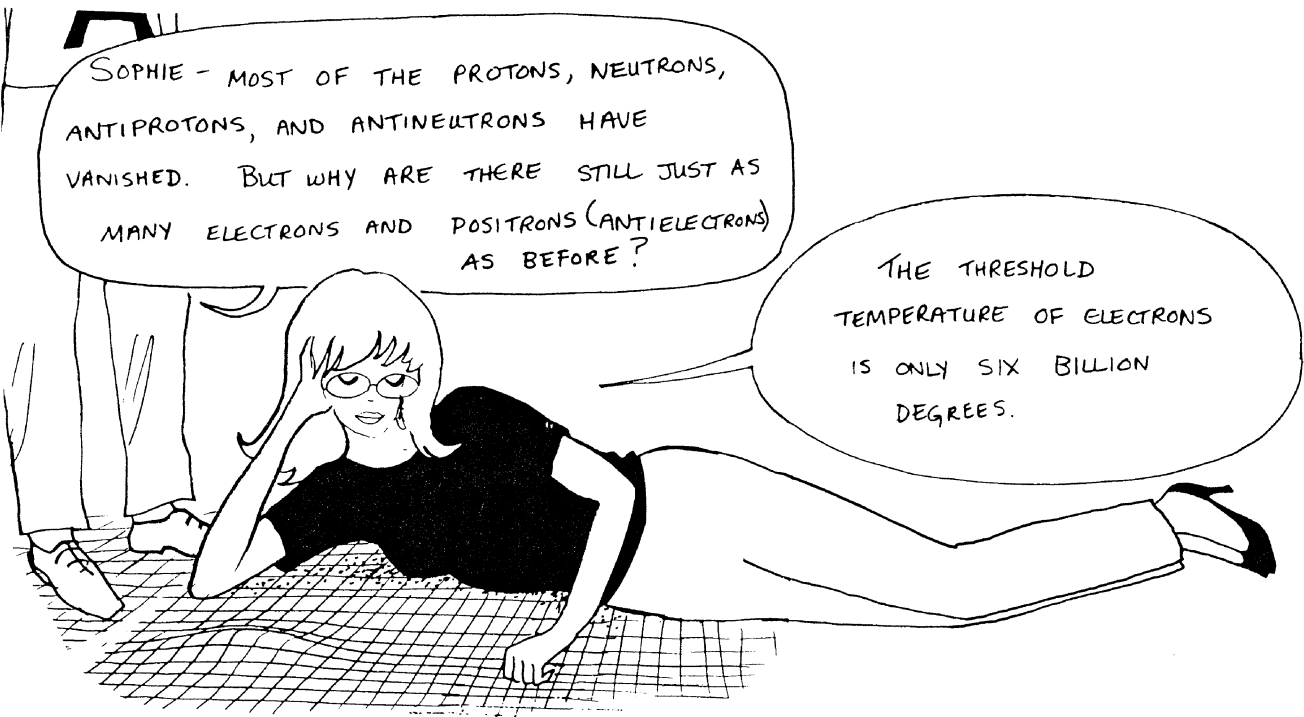
A HUNDREDTH OF A SECOND

PROTONS, NEUTRONS, ANTIPROTONS, AND ANTINEUTRONS ONLY GO AT ONE TENTH THE SPEED OF LIGHT c .



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:

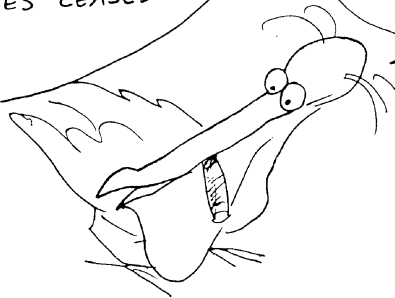
$$\frac{1}{2} m_{\text{PROTON}} (v_{\text{PROTON}})^2 = \frac{1}{2} m_{\text{ELECTRON}} (v_{\text{ELECTRON}})^2.$$



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.

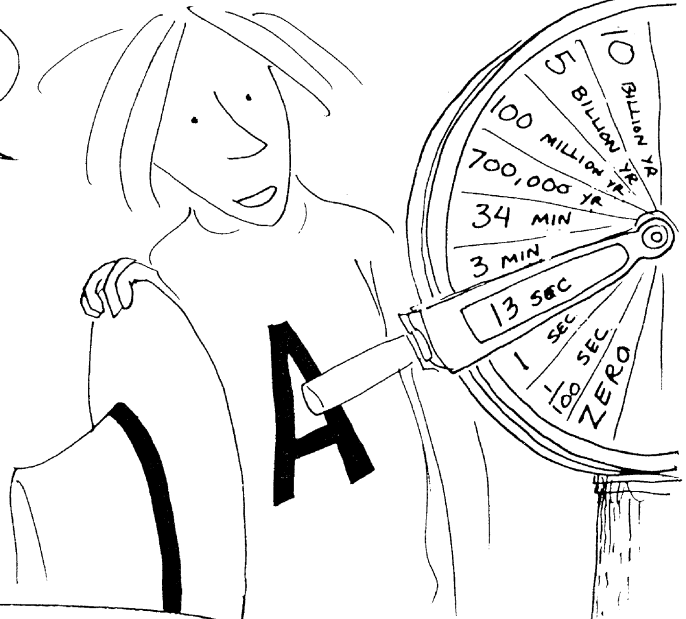
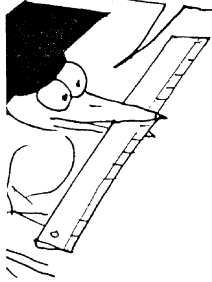
IN FACT, SINCE THE THRESHOLD ENERGY FOR THE CREATION OF A PARTICLE OF MASS m IS JUST mc^2 , THEN AS SOON AS THE SYSTEM COOLS TO THE POINT AT WHICH ITS SPEED OF AGITATION v IS NOTICEABLY SMALLER THAN c , THE CREATION OF THESE PARTICLES CEASES AND THEIR POPULATION DROPS DRAMATICALLY.

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.



'EY, LOOK AT THE H'ELECTRONS AN'
THE H'ANTIELECTRONS! IT'S 'OLESALE
SLAUGHTER!



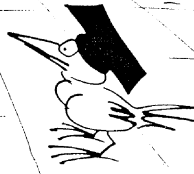
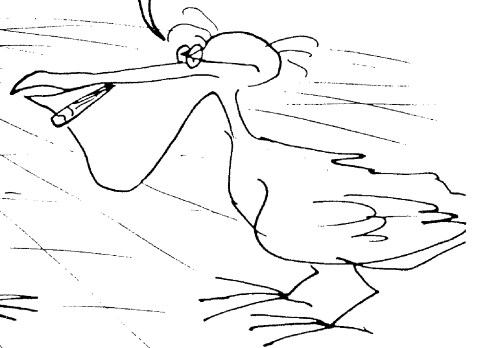
NATURALLY - IT'S BELOW THEIR
THRESHOLD TEMPERATURE.

IT'S LIKE A COSMOLOGICAL SUPERBOWL!



AGAIN, ONLY
ONE IN A BILLION
SURVIVES.

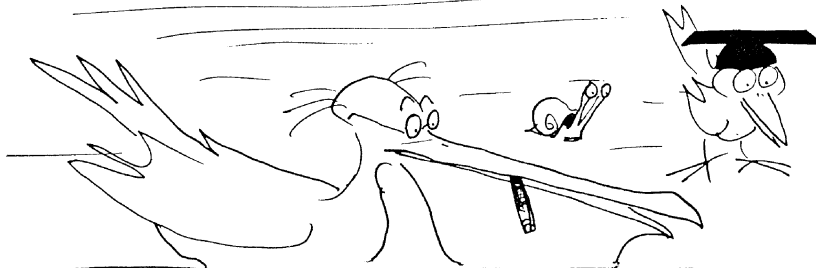
WOT A MESS....



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 SWEEPED 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 GAN' 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...

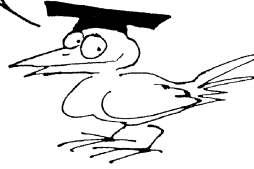
ON THE TWO-DIMENSIONAL CARPET UNIVERSE, WHEN R DOUBLES, THE DENSITY IS DIVIDED BY $2 \times 2 = 4$. IN OUR THREE-DIMENSIONAL UNIVERSE, IT IS ACTUALLY DIVIDED BY $2 \times 2 \times 2 = 8$.

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.

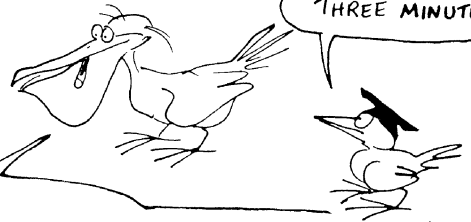
WHICH MEANS THAT THE DENSITY OF ENERGY/MATTER OCCURRING IN THE FORM OF PHOTONS VARIES AS THE INVERSE FOURTH POWER OF R .

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.



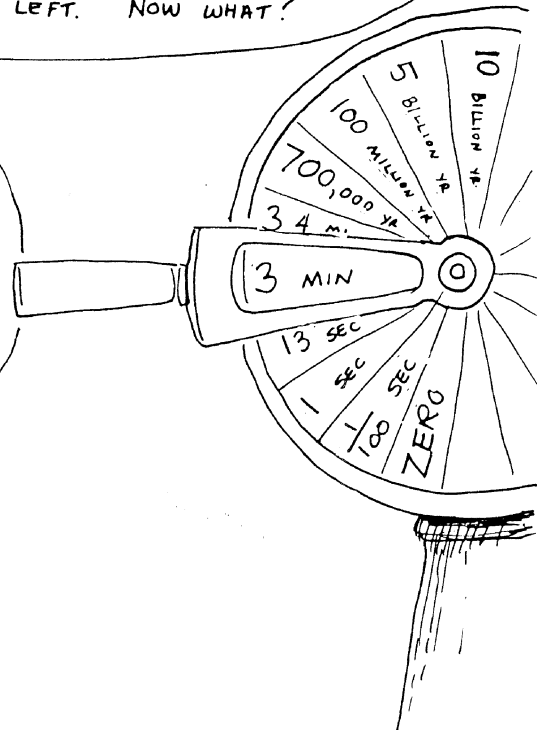
NUCLEOSYNTHESIS

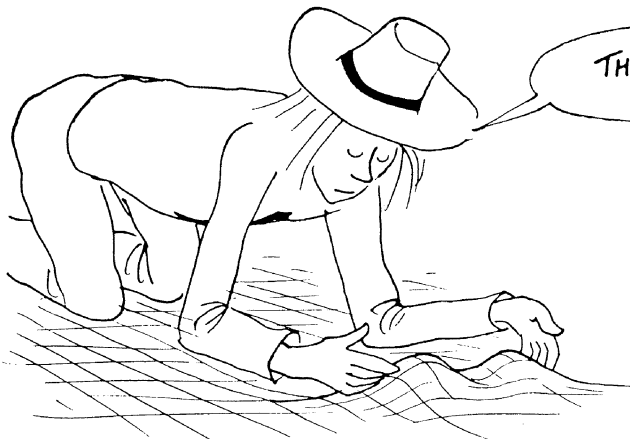
THREE MINUTES



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?

HERE ARE TWO BUMPS...
I WONDER WHAT HAPPENS
IF I PUSH ONE BUMP
INTO THE OTHER ONE?



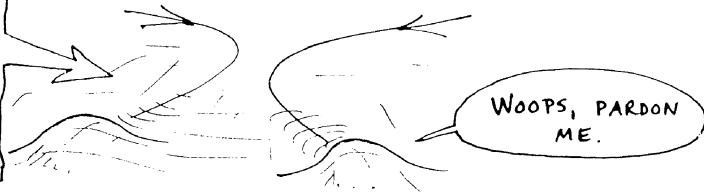


THEY START BY REPELLING EACH OTHER.

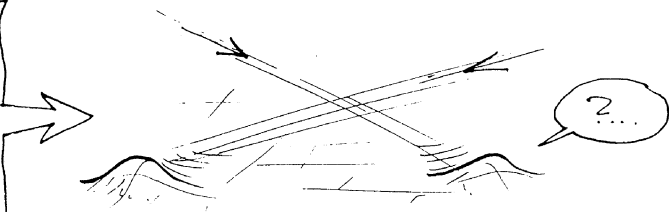


THEN THEY ATTRACT EACH OTHER TO FORM A SINGLE OBJECT.

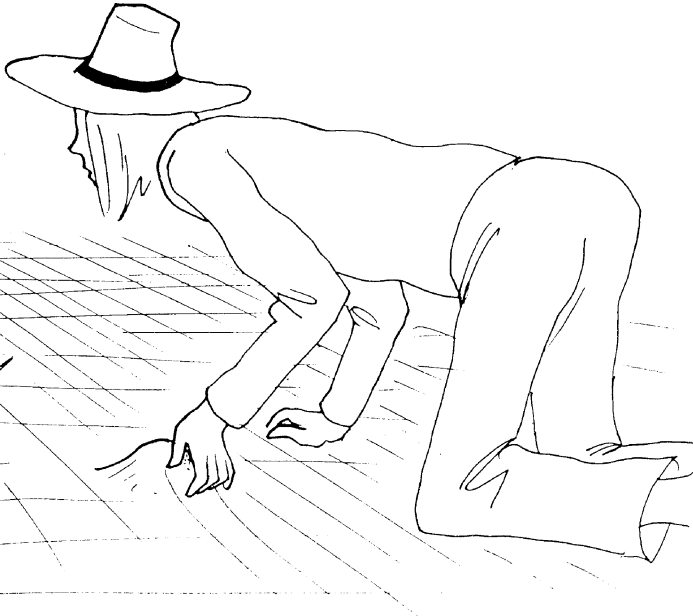
WHEN TWO BUMPS COLLIDE, THREE THINGS CAN HAPPEN... IF THEY ARE MOVING SLOWLY, THEY BOUNCE OFF EACH OTHER...



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).



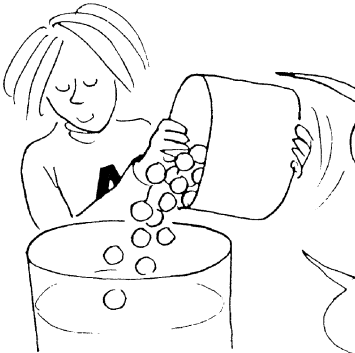
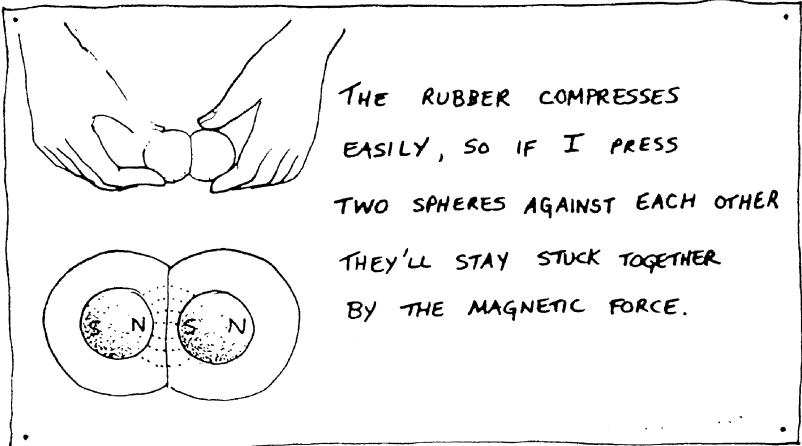
AND A VIOLENT COLLISION WITH A THIRD PARTICLE BREAKS UP THE STRUCTURE FORMED IN THIS WAY.



THESE FUSION REACTIONS PRODUCE THE FIRST ATOMIC NUCLEI. THE PROCESS OF MORPHOGENESIS LEADS TO THE FIRST FORMS, THE FIRST STRUCTURES, IN THE UNIVERSE.

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.



NOW I'LL TIP THEM INTO A LARGE TUB OF WATER...

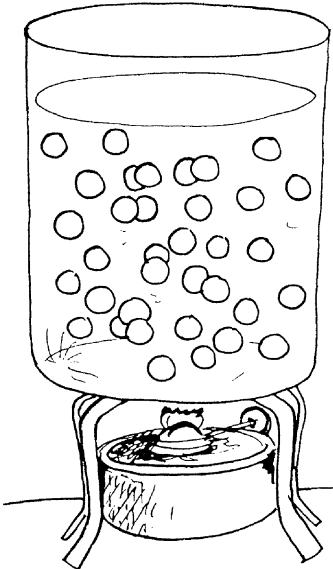
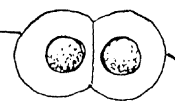
... SO THEY CAN MOVE AROUND.

TWO FORCES COME INTO PLAY. AN ATTRACTIVE FORCE: MAGNETISM.
A REPULSIVE FORCE: THE ELASTICITY OF THE RUBBER COATING.

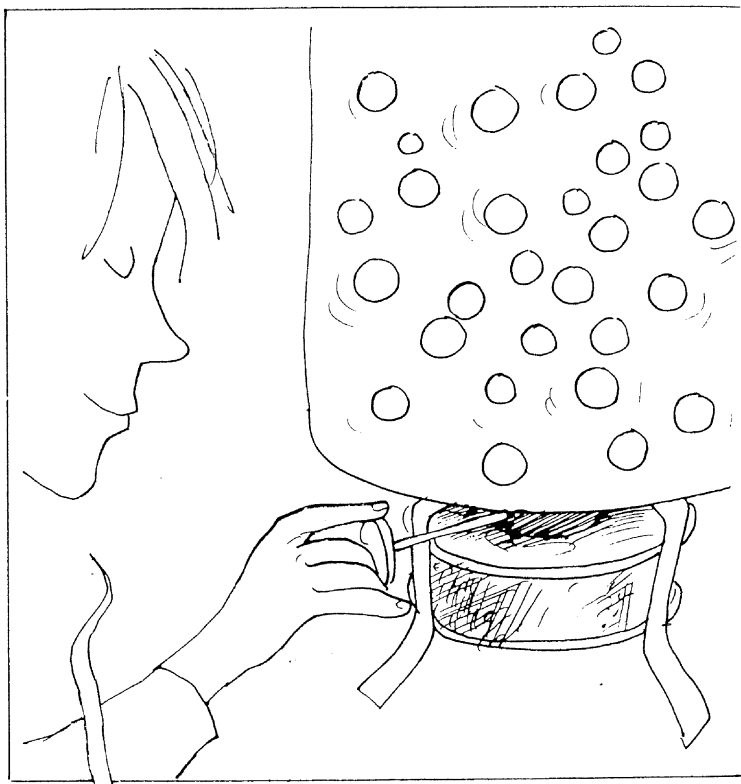
WHEN THE BALLS TOUCH, THE ELASTIC FORCES COME INTO PLAY. THE STRENGTH OF THE MAGNETISM IS ARRANGED SO THAT WHEN THE RUBBER IS COMPRESSED FAR ENOUGH, IT TAKES OVER. THERE IS AN INTERMEDIATE POSITION AT WHICH THE FORCES BALANCE OUT.



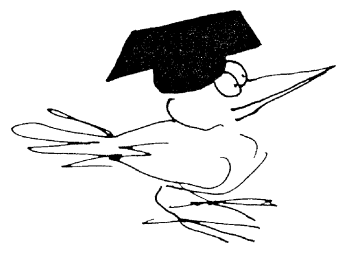
THE RUBBER IS LIGHT ENOUGH FOR THE DENSITY OF THE SPHERES TO BE ESSENTIALLY EQUAL TO THAT OF WATER. NOW I'LL HEAT UP THE ACTION A LITTLE...

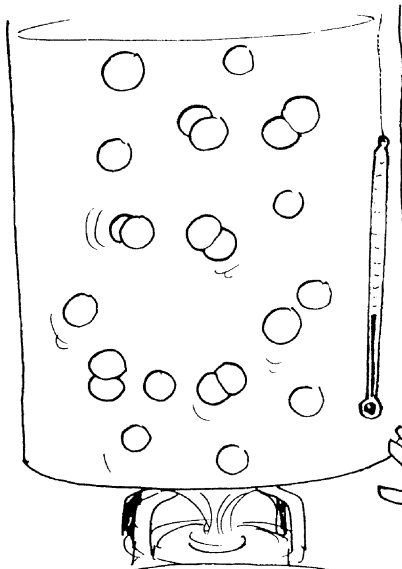


WHEN THE TEMPERATURE IS LOW, THE BALLS BOUNCE GENTLY OFF EACH OTHER, AND NOTHING HAPPENS. WHEN THEY BUMP INTO EACH OTHER, THEY DON'T HAVE ENOUGH ENERGY TO COMPRESS THE RUBBER FAR ENOUGH FOR THE MAGNETIC FORCE TO COME INTO PLAY. THE MAGNETISM CAN ONLY ACT AT SHORT RANGE.



OK, I'LL TURN UP THE HEAT.



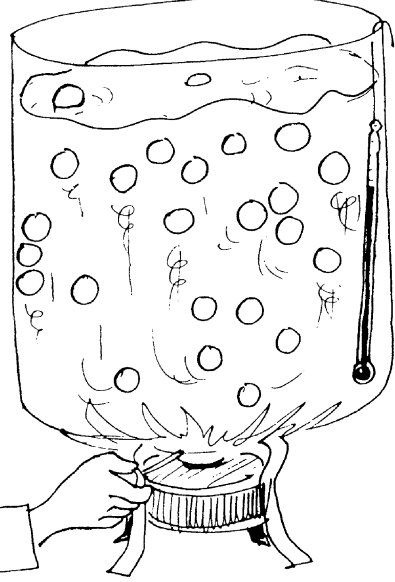


GREAT, IT WORKS! IT'S THE RIGHT TEMPERATURE (LARGER THAN THE THRESHOLD TEMPERATURE). THE AMOUNT OF AGITATION IS JUST RIGHT.

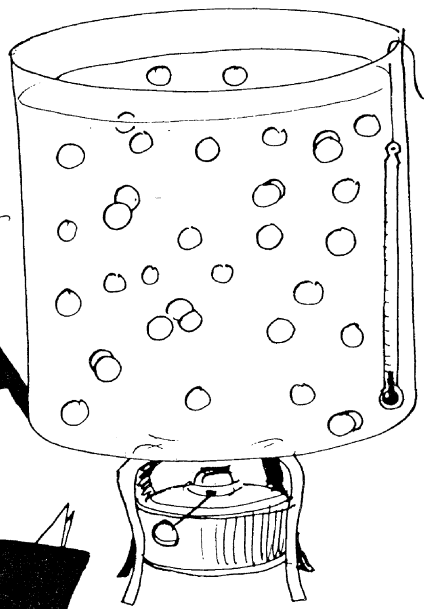
BLIMEY! THEM BALLS IS STICKIN' TERGEVVER IN PAIRS!

IF I APPLY TOO MUCH HEAT, THESE STRUCTURES ARE BROKEN UP BY THERMAL AGITATION.

WHAT HAPPENS IF YOU COOL IT?

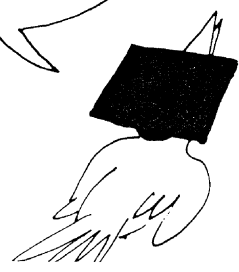


ARCHIE ALLOWS THE WATER TO COOL. THE TURBULENCE DECREASES. AT A CERTAIN MOMENT, SOME OF THE BALLS COUPLE TOGETHER. BUT, SINCE THE TEMPERATURE CONTINUES TO DROP, THIS NUCLEOSYNTHESIS STOPS.



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.

⊕ PROTON

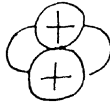
○ NEUTRON



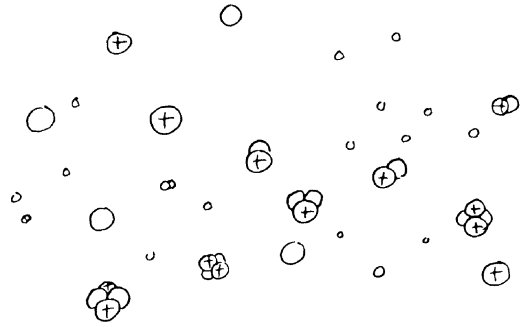
1 PROTON
1 NEUTRON
DEUTERIUM



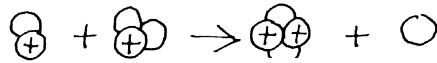
1 PROTON
2 NEUTRONS
TRITIUM



2 PROTONS
2 NEUTRONS
HELIUM



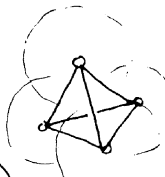
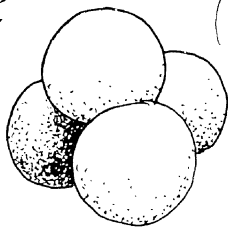
BUT THE DEUTERIUM AND TRITIUM SO CREATED CAN COMBINE BY A NUCLEAR REACTION :



DEUTERIUM + TRITIUM GIVES HELIUM + NEUTRON
AT THIS POINT, THE UNIVERSE IS A HYDROGEN BOMB.



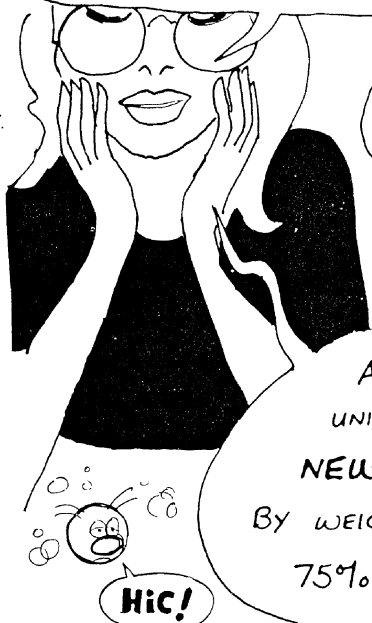
SO, EVERYTHING TURNS INTO HELIUM?



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.

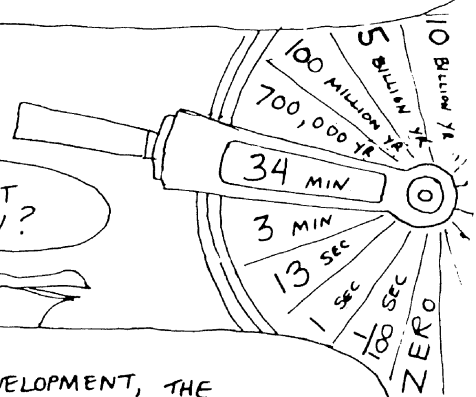


THE REMAINING FREE NEUTRONS DISINTEGRATE. THEY ARE NATURALLY UNSTABLE, AND TRANSFORM - IN 109 SECONDS - INTO A PROTON-ELECTRON PAIR.



34 MINUTES HAVE PASSED SINCE THE BEGINNING.

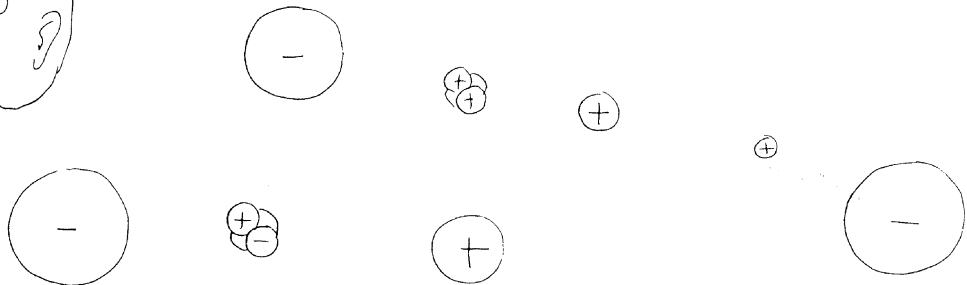
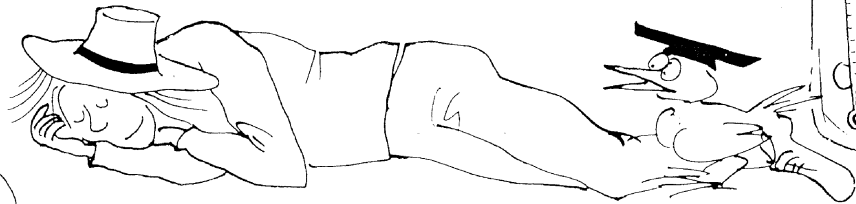
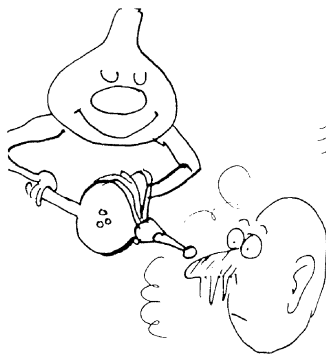
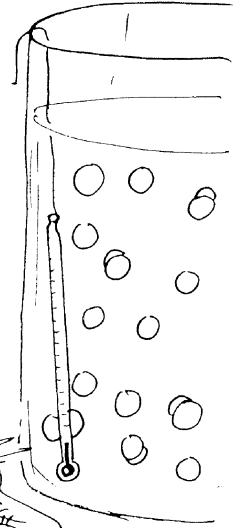
WOT NOW?



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).

Hic!

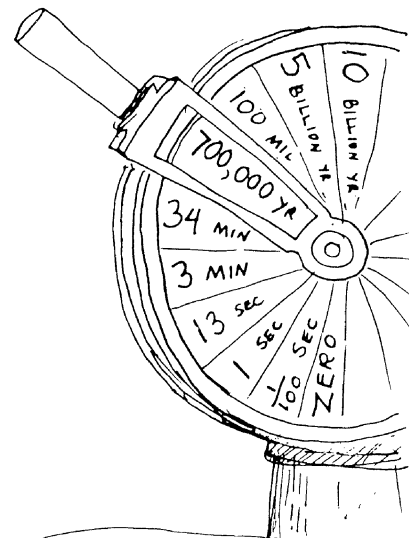
FOR **700,000** YEARS... NOTHING HAPPENS. THE UNIVERSE CONTINUES TO EXPAND, AND THE PHOTONS EXPAND WITH IT. THE PHOTON GAS CONTINUES TO HEAT THE MATTER, AND THE TEMPERATURES T_R AND T_m STAY EQUAL (THERMODYNAMIC EQUILIBRIUM).



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.

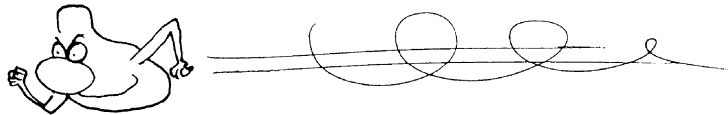
WHAT DO YOU MEAN, BECOMES TRANSPARENT? DO YOU MEAN IT WAS OPAQUE BEFORE?

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

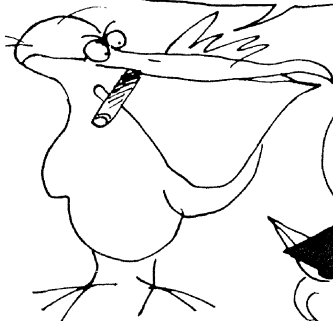
HMMMMPH!

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...

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
 $T_R = -173^\circ\text{C}$.

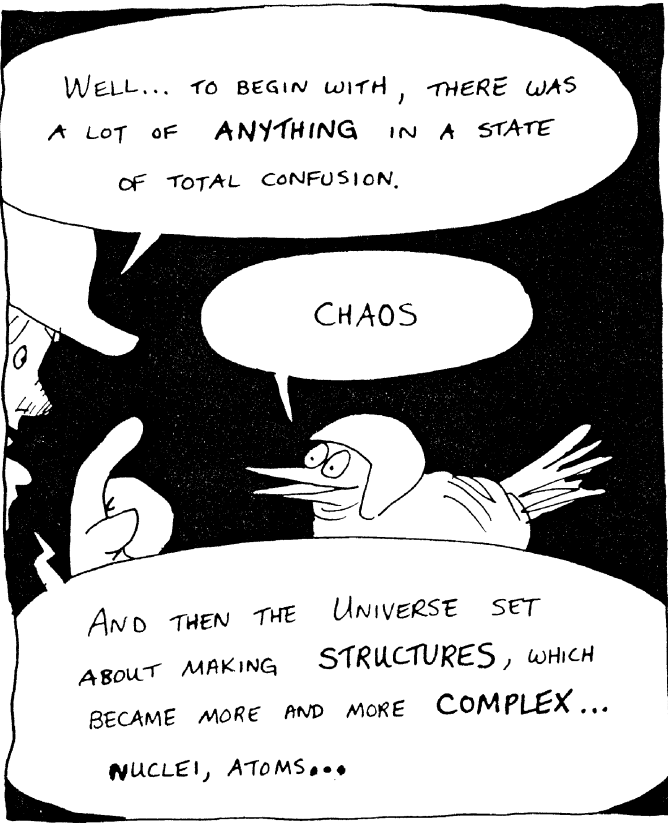
ATOMS NOW TRAVEL
AT 150 METERS/SECOND,
SO THE TEMPERATURE OF
MATTER $T_m = -267^\circ\text{C}$.

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.

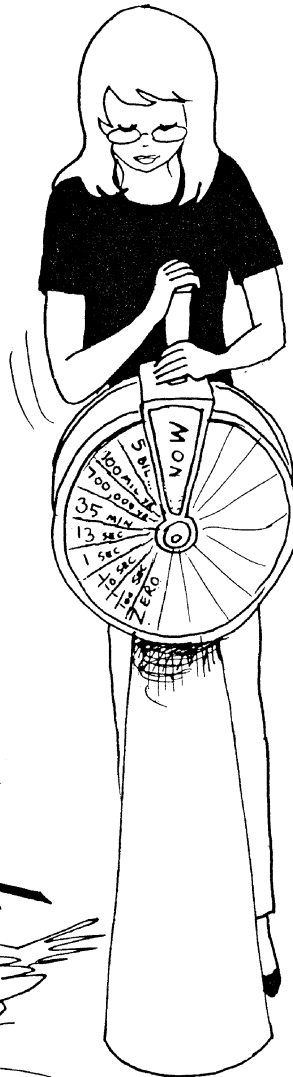
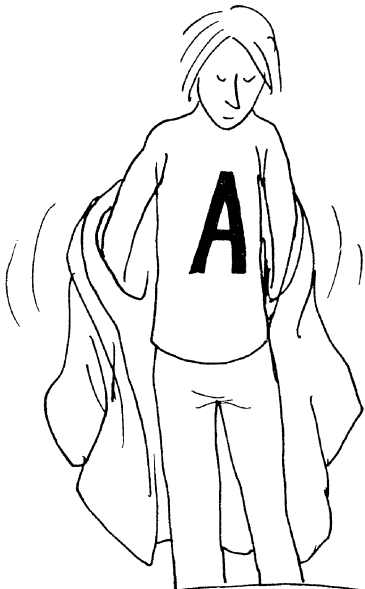
AH... AND
WHAT IS IT?

WHY MAKE THINGS SIMPLE
WHEN YOU CAN MAKE THEM
COMPLICATED?



HUMPH... NOT BAD,
YER LITTLE SHAGGY GOD
STORY... BUT IT'S JUST
BLINKIN' SPECKYERLATION.
THEO-RETTICKLE FANTASIES.
WOT MAKES YER FINK REALTY
IS REALLY LIKE THAT?

TO ANSWER LENNY'S QUESTION, LET'S LEAVE
THIS CARPET UNIVERSE AND RETURN OURSELVES TO
THE PRESENT.

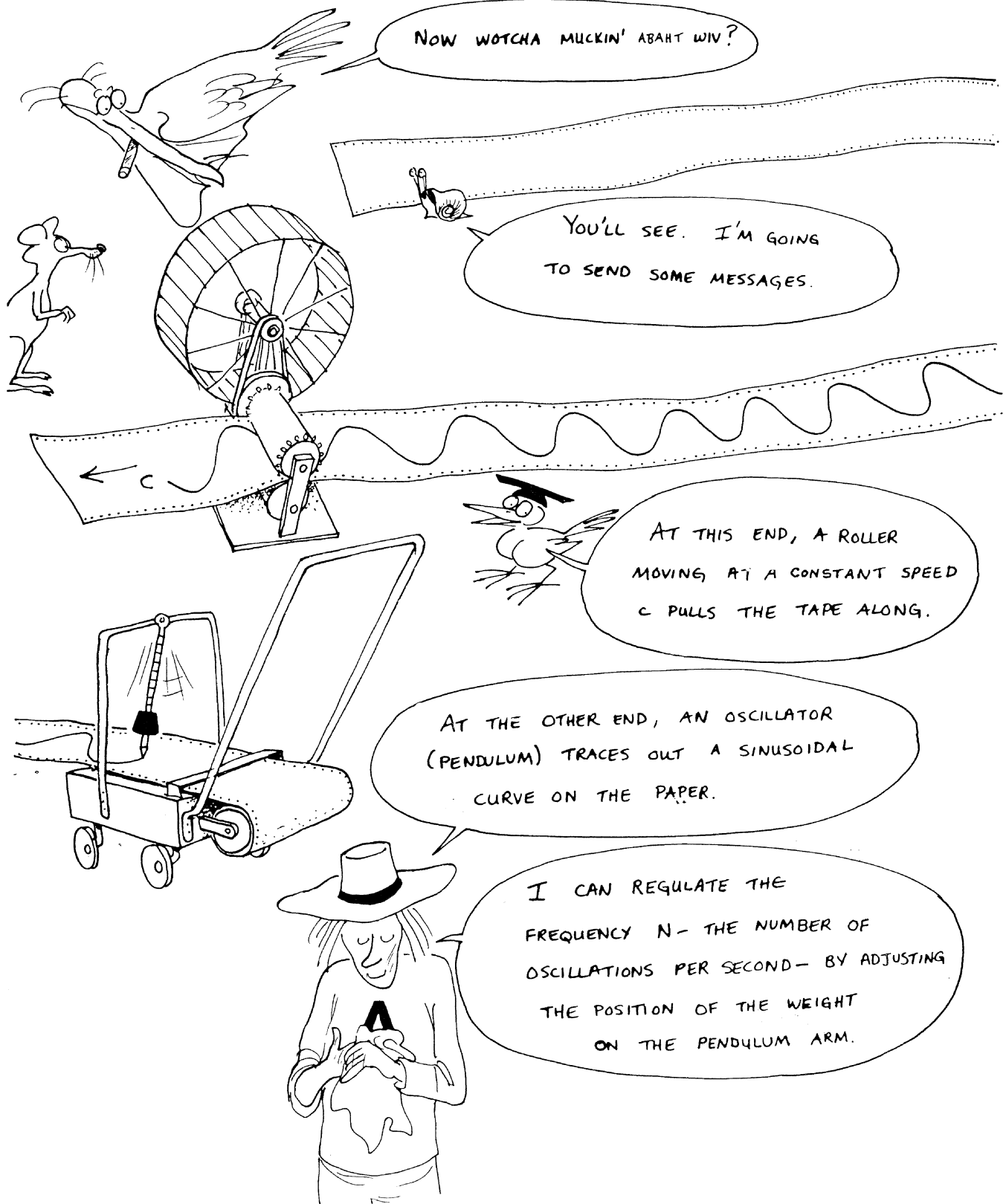


AND WHAT COMES NEXT?
THE FORMATION OF GALAXIES,
STARS... ?
YOU'RE LEAVING THAT
BIT OUT?

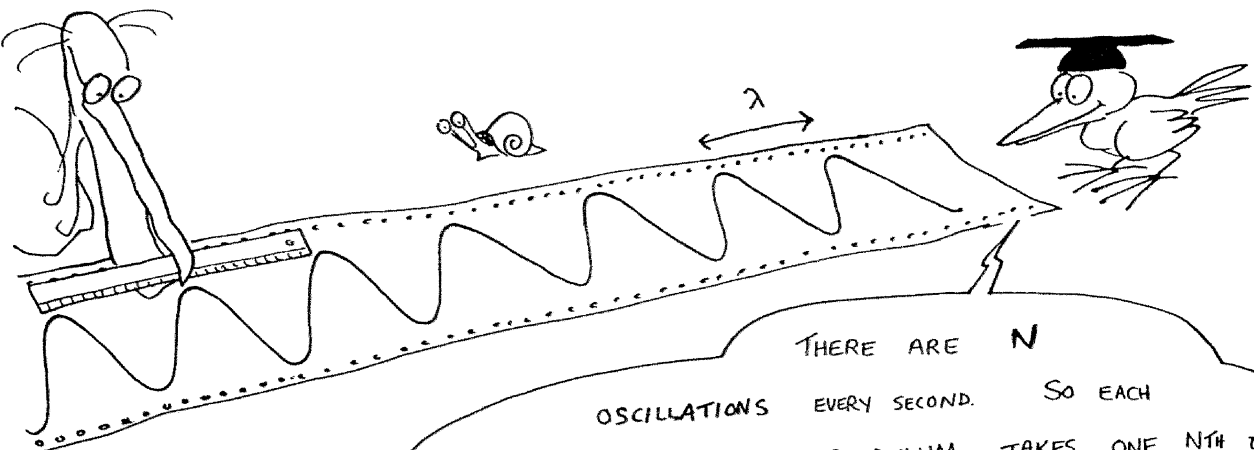


THAT'S ALL FOR NOW, TIRESIAS.
LENNY'S HAD ENOUGH!

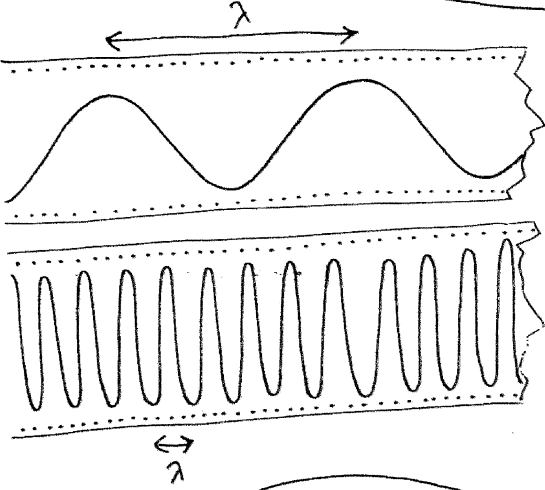
THE DOPPLER EFFECT



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



THERE ARE N OSCILLATIONS EVERY SECOND. SO EACH TO-AND-FRO OF THE PENDULUM TAKES ONE N TH 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.

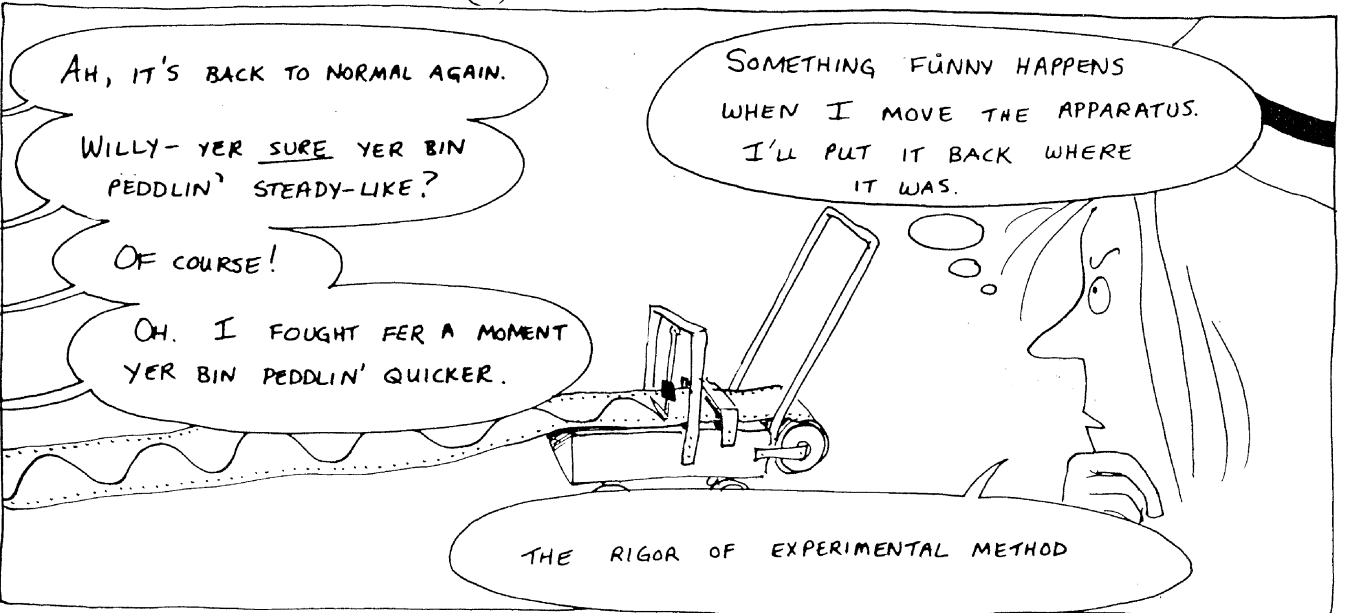
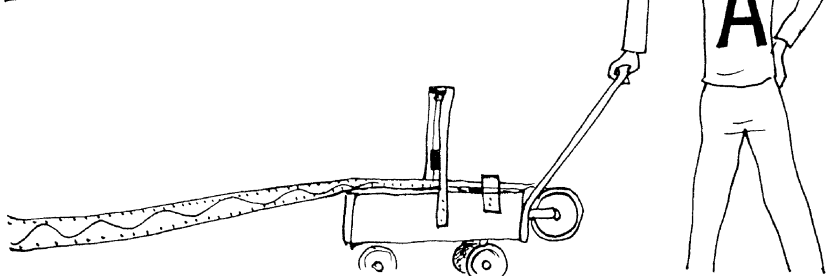
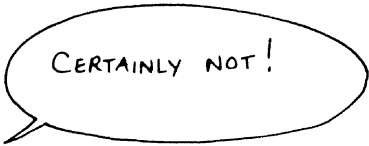
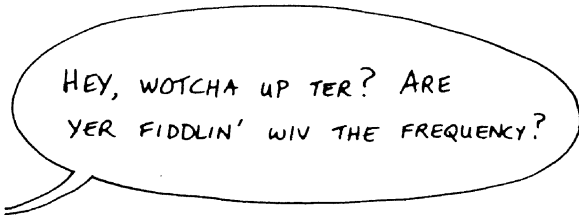
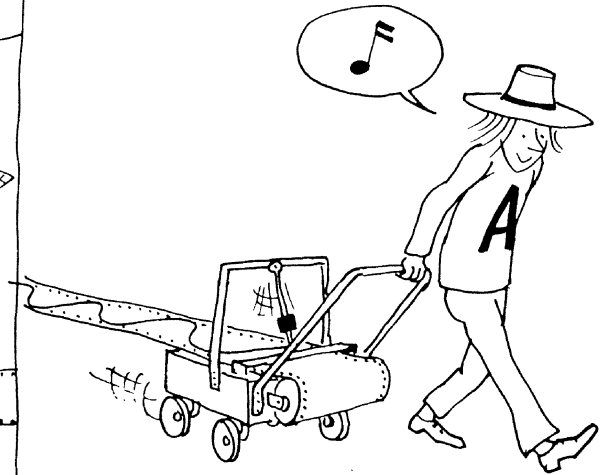
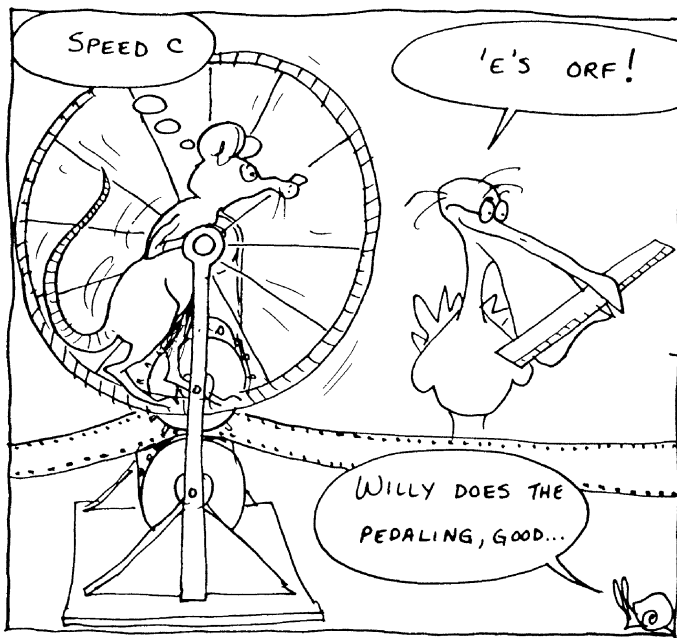
IT'S IMPORTANT, COMMUNICATION IS.



READY?

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





!!!

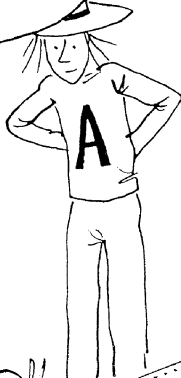
WILLY, GET PEDDLIN', DAMMIT!

I AM PEDALING YOU TWERP!

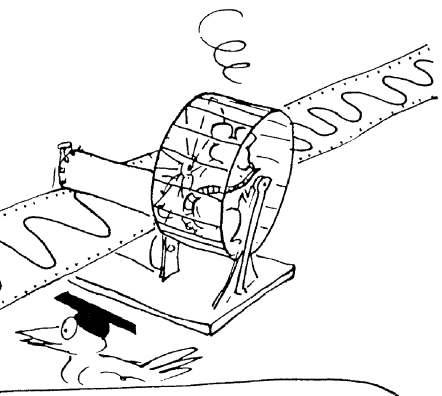
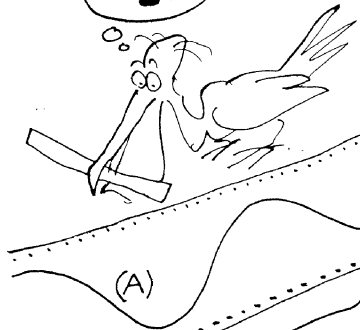
IF YOU DON'T LIKE IT, YOU CAN DO THE JOB INSTEAD OF ME!



HOLD IT, HOLD IT! WHAT'S THE PROBLEM?

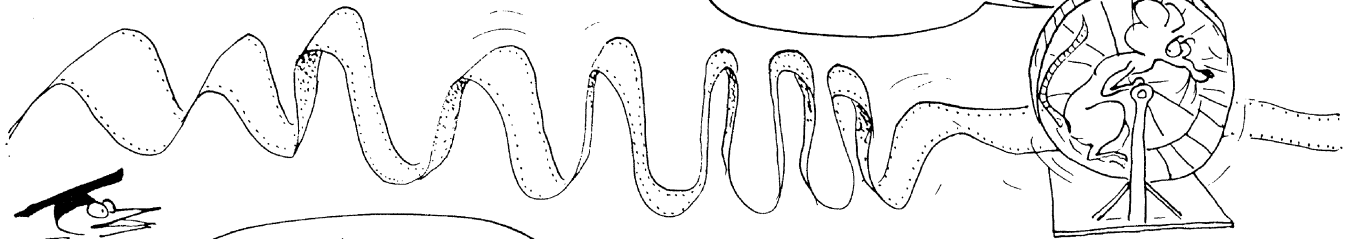


?



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?



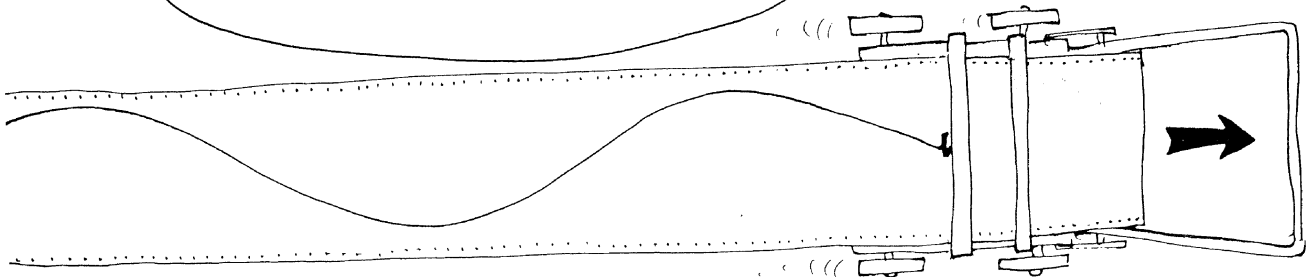
NO, ARCHIE. IT'S THE
DOPPLER-FIZEAU EFFECT.

THE POPPLE-
FIZZY WHAT?

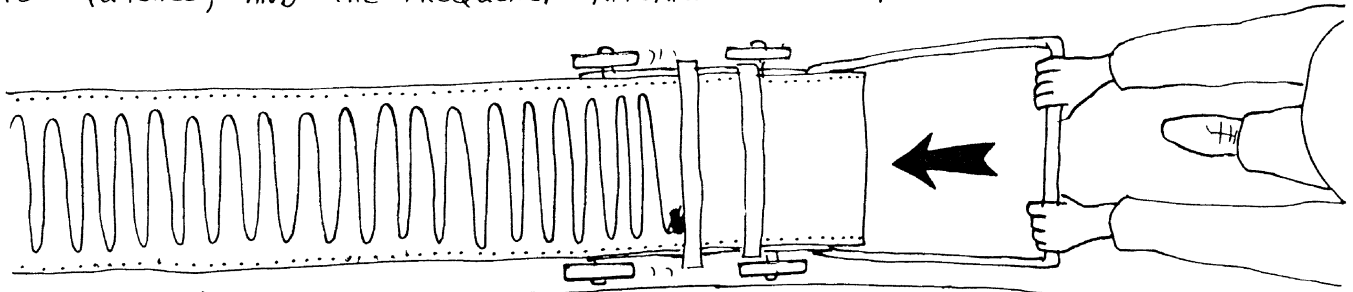
WHEN YOU MOVED THE CART,
YOU CHANGED
THE APPARENT FREQUENCY.



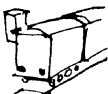
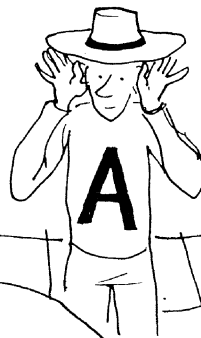
WHEN THE CART MOVES AWAY,
THE SINUSOID IS STRETCHED,
AND
THE FREQUENCY APPEARS LOWER



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



THAT'S EXACTLY WHAT HAPPENS WHEN YOU LISTEN TO THE WHISTLE OF A TRAIN PASSING AT HIGH SPEED. WHEN IT'S APPROACHING, THE SOUND SEEMS HIGHER; WHEN IT PASSES THE SOUND CHANGES TO A LOWER NOTE.



HEY, THAT'S INTERESTING...

WITH A SYSTEM LIKE THAT, IF I KNOW AHEAD OF TIME THE WAVELENGTH OF THE SIGNAL BEING EMITTED BY A MOTIONLESS SOURCE, I CAN CALCULATE THE SPEED OF APPROACH OR RECESSION OF THE SOURCE.



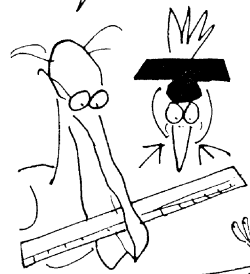
AND WHAT HOLDS FOR SOUND IS ALSO TRUE OF LIGHT. OBJECTS THAT ARE MOVING AWAY LOOK MORE RED, AND THOSE THAT ARE APPROACHING LOOK MORE BLUE.

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!

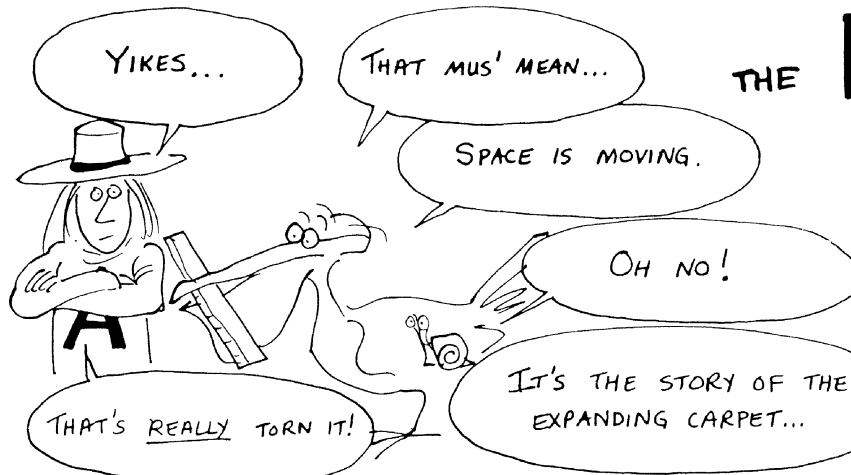


AND THE OSCILLATOR'S
STILL THERE.

No, you BUNCH OF DUMMIES,
I AM NOT MOVING OFF!
I'M HERE!



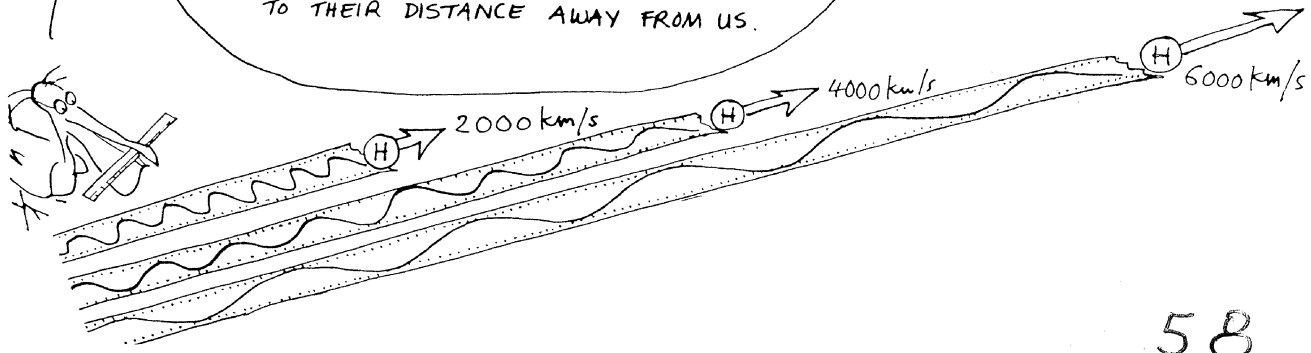
THE FLIGHT OF THE GALAXIES



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 'HYDROGEN ATOMS 'EMIT LIGHT AT A WAVELENGTH OF 1 CM, IN FEORY. THE DOPPLER 'EFFECT 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.



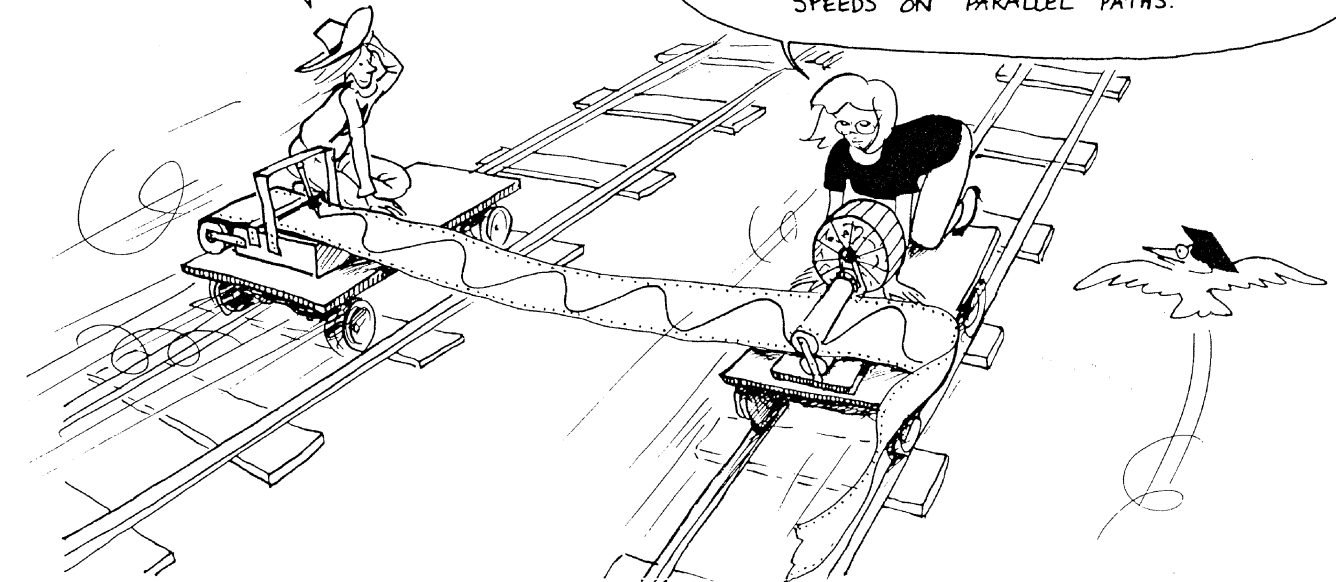
UMPF. SO WOZZAT MEAN? FINGS
H'ACCELLYRATE WHEN THEY GET FURTHER
AWAY FROM US?

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.

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.



SO OUR ENTIRE UNIVERSE
IS UNDERGOING AN
EXPANSION?

LISTEN, I'VE GOT ANOTHER
EXPLANATION. SUPPOSE THAT TIME...
IS SPEEDING UP.

BUT THAT... THAT
DON' MEAN ANYFINK!

YOU CAN THINK OF THE OSCILLATIONS OF ATOMS - HYDROGEN, SAY - AS THE
"PULSE" OF THE UNIVERSE. IMAGINE A UNIVERSE WHOSE PULSE ACCELERATES.
THE OLDER YOU GET, THE FASTER THE PULSE BEATS. IMAGES OF THE PAST LOOK
LIKE A SLOW-MOTION FILM. AND THE DOPPLER EFFECT IS JUST AN
ILLUSION.

THAT'S CERTAINLY AN IDEA, TIRESIAS - IN THE
IMAGINATION ANYTHING IS POSSIBLE. WHAT YOU'RE REALLY SAYING
IS THAT THE LAWS OF PHYSICS MIGHT EVOLVE IN TIME, WHICH
IS AN IDEA SUGGESTED BY FRED HOYLE.

HEAVEN'S FUNDAMENTAL IS COLD

BUT THERE'S ANOTHER ARGUMENT IN
FAVOR OF THE EXPANSION, AND ITS
COROLLARY, THE BIG BANG.

EEEEEP!

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.

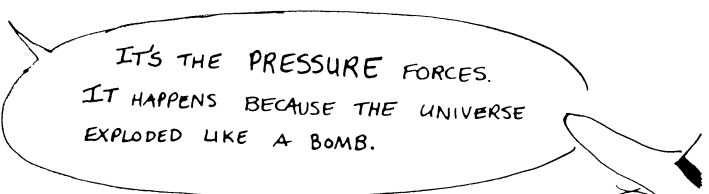
EEEEEP!

OH CRIKEY...

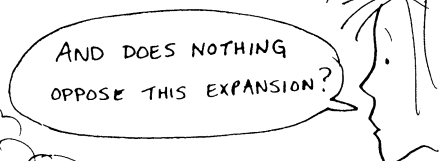
FRIEDMANN MODELS




SOPHIE - WHAT CAUSES THE H'EXPANSION OF THE UNIVERSE?



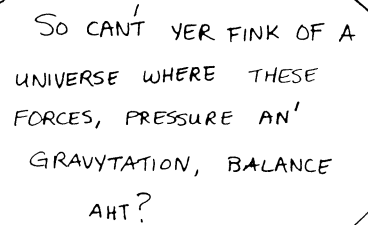
IT'S THE PRESSURE FORCES. IT HAPPENS BECAUSE THE UNIVERSE EXPLODED LIKE A BOMB.




AND DOES NOTHING OPPOSE THIS EXPANSION?




THE FORCE OF GRAVITY TENDS TO MAKE THE UNIVERSE COME TOGETHER AGAIN-TO IMplode.




SO CAN'T YER FINK OF A UNIVERSE WHERE THESE FORCES, PRESSURE AN' GRAVYTATION, BALANCE AHT?



IT CAN BE SHOWN THAT SUCH A BALANCE IS IMPOSSIBLE. THE SLIGHTEST DISTURBANCE AWAY FROM BALANCE, AND THIS "STATIC" UNIVERSE WOULD EITHER IMplode OR EXPLODE.



EXPLOSION



IMplosion

THE COSMOLOGICAL HORIZON

SOPHIE - ACCORDING TO HUBBLE'S LAW, THE SPEED OF RECESSION OF OBJECTS INCREASES WITH THEIR DISTANCE...

SO, LOGICALLY, THERE SHOULD EXIST OBJECTS THAT REcede FROM US AT SPEEDS EQUAL TO, OR GREATER THAN, THE SPEED OF LIGHT!?

BUT... WE COULDN'T RECEIVE LIGHT FROM THOSE!

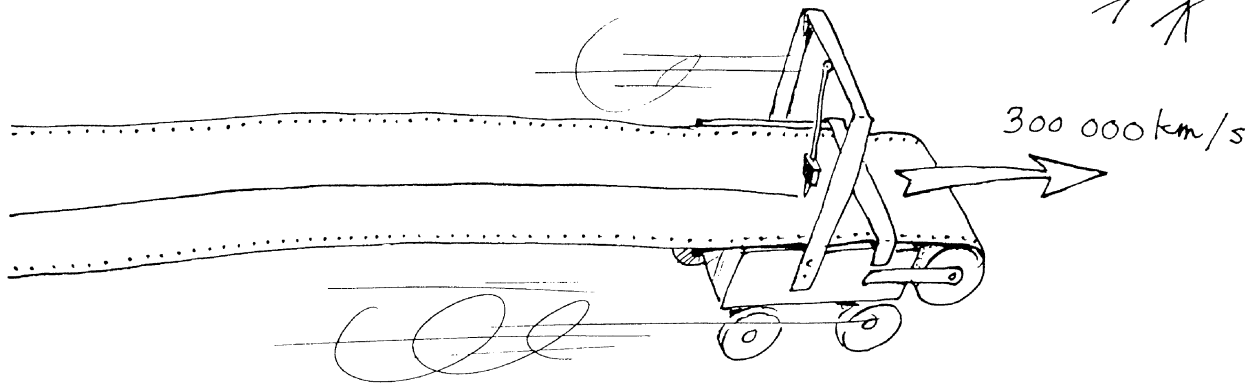
WHY NOT? IF A PLANE FLIES PAST ME AT SUPERSONIC SPEED, I CAN STILL HEAR THE SONIC BOOM.

MY DEARS, YOU HAVE TO LOOK AT THINGS IN A DIFFERENT LIGHT.

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 RECEPTION 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

SO WHAT, NOW, IS THE MEANING OF THE RADIUS R OF THE UNIVERSE?



OUR STORY BEGAN WHEN THE UNIVERSE WAS AGED ONE HUNDREDTH OF A SECOND. IMAGINE THAT AT THAT MOMENT WE HAD DRAWN A CIRCLE, OR BETTER A SPHERE, OF RADIUS R . THEN FOLLOW THE EXPANSION OF THAT SPHERE OF REFERENCE AS TIME FLOWS. THAT'S ALL.

BY DOING THAT, WE DON'T PREJUDGE WHETHER SPACE IS FINITE OR INFINITE (*).

SHE'S GOT LOVELY EYES...

'ERE, YOU TWO!

THIS CARTOON BOOK ISN'T FINISHED YET!

HI-HI-HI

YOU'RE STILL NEEDED.

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

TELL ME, THEN: INSTEAD OF H'EXPLODIN' COULD OUR UNIVERSE IMPLODE?

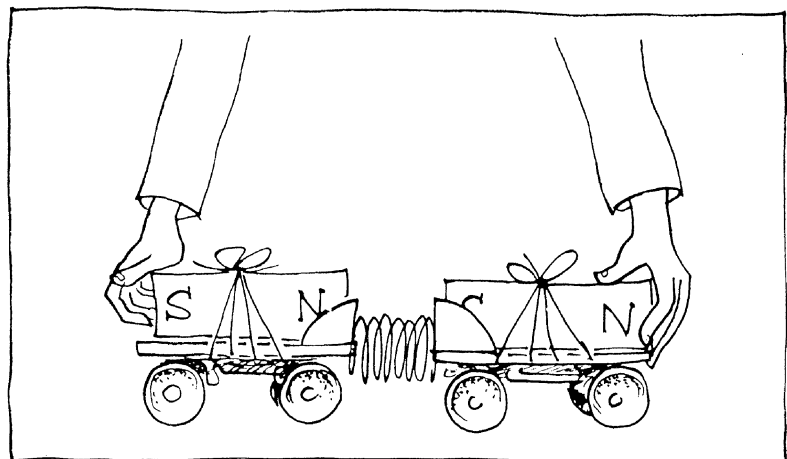
IN A SENSE THERE'S THAT POSSIBILITY.

IN FACT, IT'S POSSIBLE THAT TIME MIGHT DECIDE TO RUN BACKWARDS...

Tsss!...

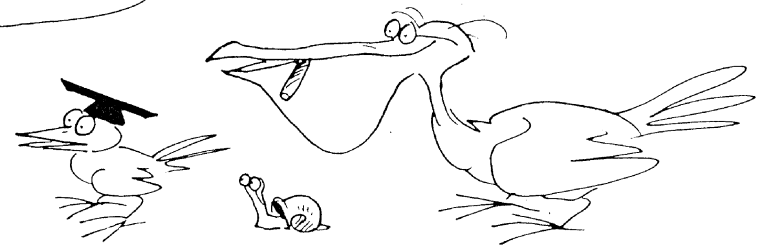
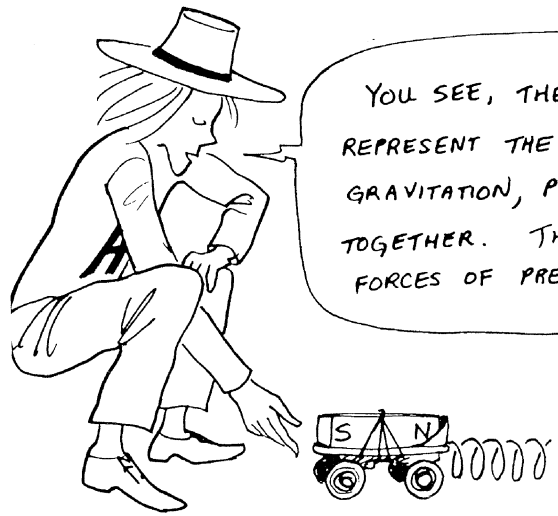


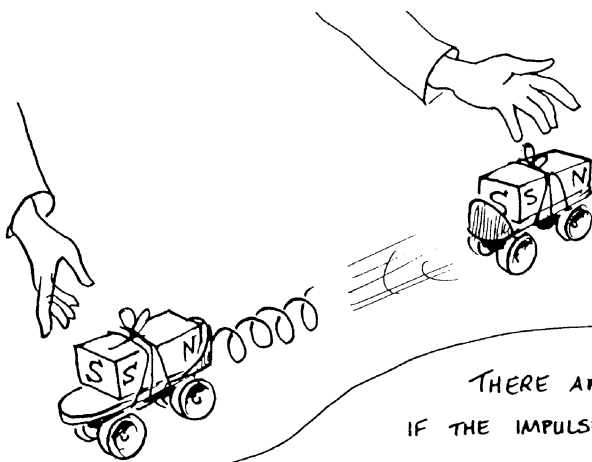
ANOTHER GADGET, ARCHIE?



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.

YOU SEE, THE MAGNETS REPRESENT THE FORCE OF GRAVITATION, PULLING THINGS TOGETHER. THE SPRING IS THE FORCES OF PRESSURE.





WHEN I LET THE THING GO,
THE SKATES ARE PROPELLED FAR
APART.

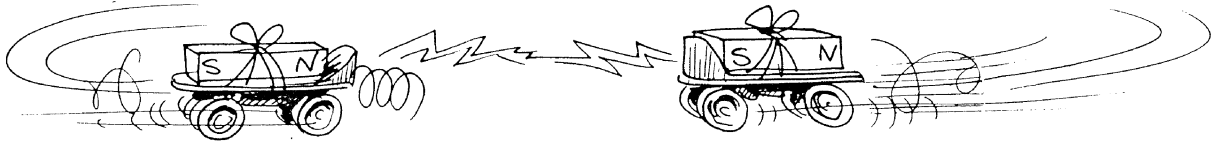
THERE ARE TWO POSSIBILITIES...
IF THE IMPULSE GIVEN BY THE SPRING
IS STRONG ENOUGH, THE SKATES WILL
CONTINUE TO SEPARATE INDEFINITELY. THE
FURTHER APART THEY GET, THE SMALLER WILL BE THE FORCE
OF ATTRACTION, WHICH VARIES AS THE INVERSE SQUARE
DISTANCE.



IF THERE'S NO FRICTION, THE SKATES WILL EVENTUALLY ACQUIRE
A CONSTANT SPEED.

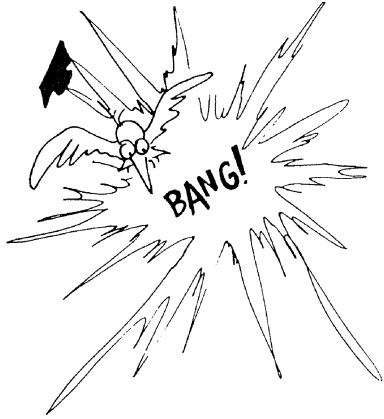


ON THE OTHER HAND, IF THE IMPULSE FROM
THE SPRING IS TOO WEAK, OR THE MAGNETS TOO
STRONG, THEN THE SKATES WILL RETURN, "FALLING"
TOWARDS EACH OTHER AT AN INCREASING SPEED.



THIS SUGGESTS TWO POSSIBLE TYPES OF UNIVERSE:

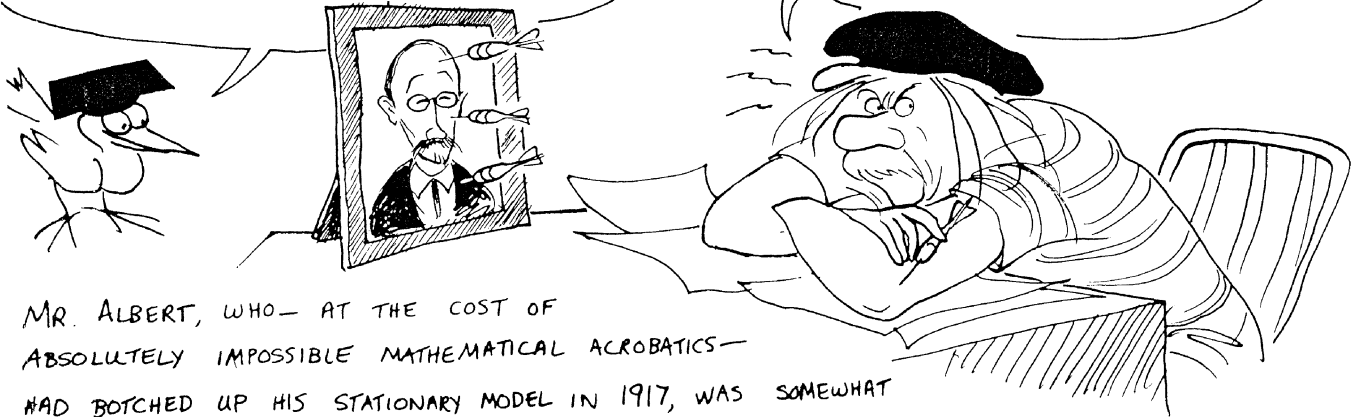
FIRST SCENARIO: THE EXPANSION CONTINUES INDEFINITELY. WHEN THE LAST STARS
BECOME EXTINCT, THERE WILL BE ETERNAL NIGHT, ABSOLUTE COLD, THERMAL DEATH.



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.

THE SWISS MATHEMATICIAN **FRIEDMANN** INVENTED THE FIRST NONSTATIC MODELS OF THE UNIVERSE IN 1930.

IF I HAD KNOWN DER UNIVERSE COULD BE NONSTATIONARY, I WOULD HAF' DISCOVERED DEM BEFORE FRIEDMANN (*).



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 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.



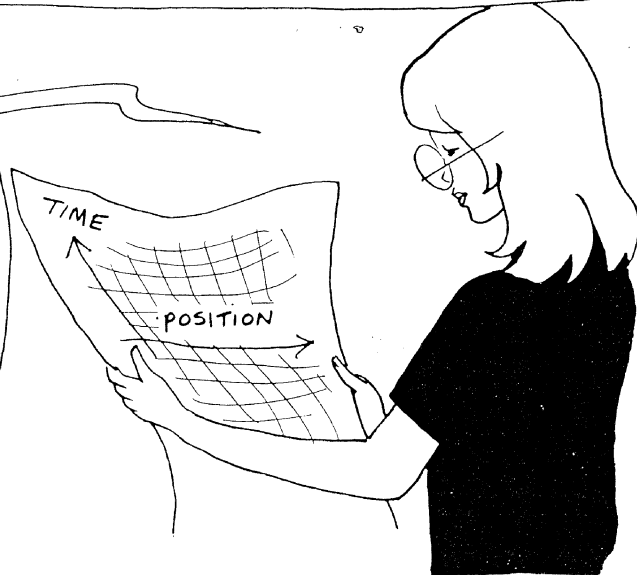
RECALL THAT THE NUMBER OF DIMENSIONS OF A SPACE IS THE NUMBER OF QUANTITIES NEEDED TO DEFINE THE POSITION OF A POINT WITHIN IT.

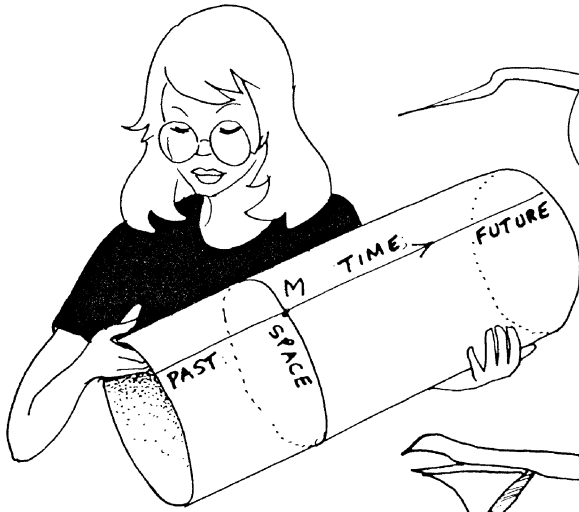


MEET ME ① TUESDAY AT 11 O'CLOCK AT THE CORNER OF ② SIXTH AVENUE AND ③ FIFTH STREET ON THE ④ THIRD FLOOR : FOUR QUANTITIES.



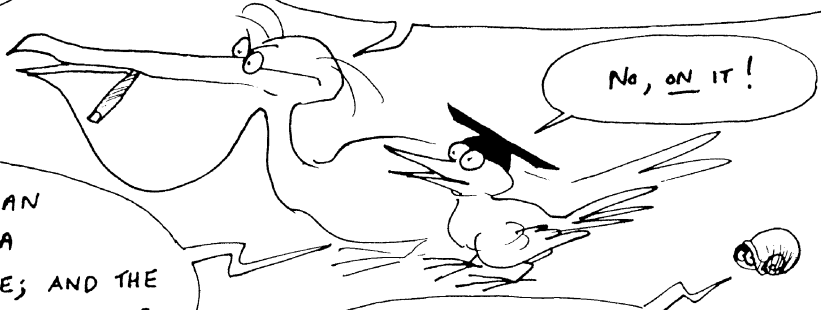
IN DRAWINGS, WE CAN ONLY REPRESENT SPACES OF TWO DIMENSIONS, SURFACES. SO WE CAN STUDY A SPACE-TIME WITH TWO DIMENSIONS, ONE OF SPACE AND ONE OF TIME.



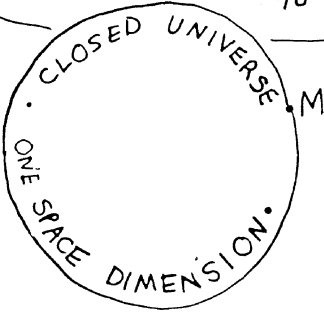


IN THIS WAY THE FIRST MODEL OF A CLOSED UNIVERSE, THE STATIC MODEL OF EINSTEIN, IS REPRESENTED AS A CYLINDER.

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



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.

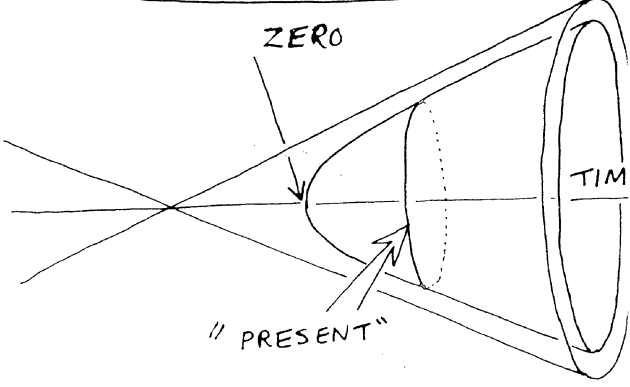


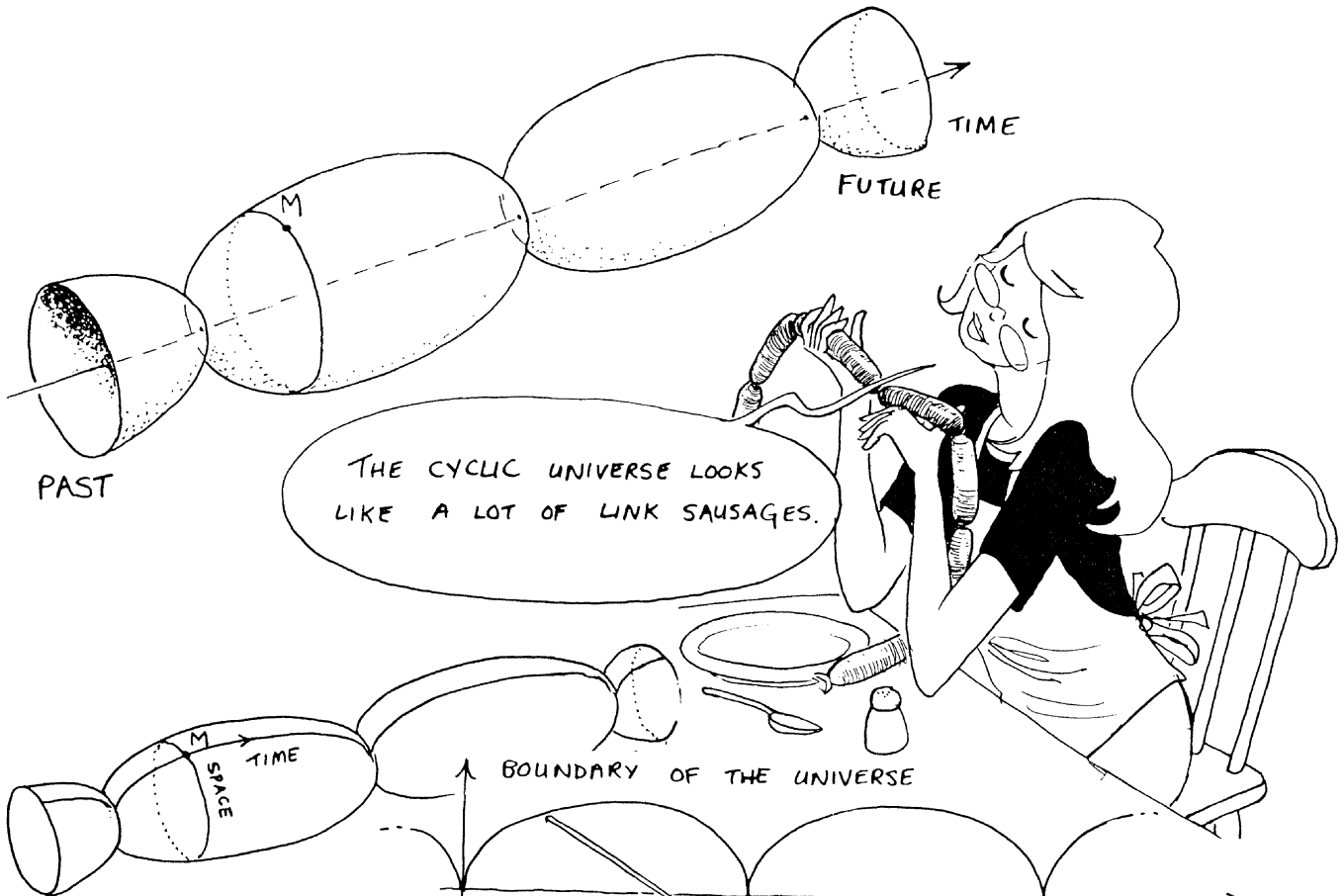
IF THE OBJECT IS MOTIONLESS IT DESCRIBES A GENERATOR OF THE CYLINDER (A LINE ALONG ITS LENGTH) AS TIME FLOWS.



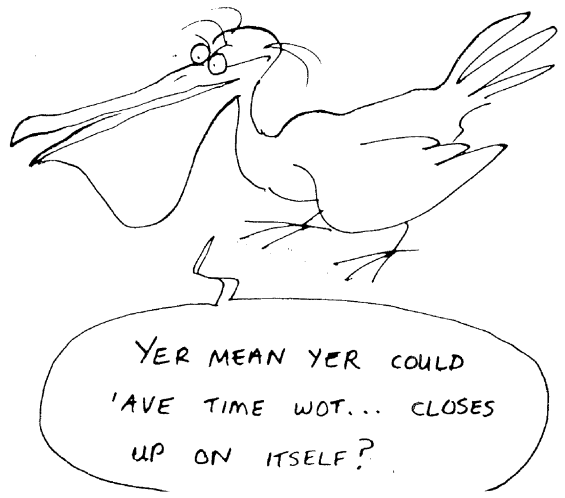
IT IS EASY TO REPRESENT THE EXPANSION OF THIS CLOSED UNIVERSE AS A FUNCTION OF TIME, GIVING A NONSTATIONARY MODEL OF THE UNIVERSE.

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



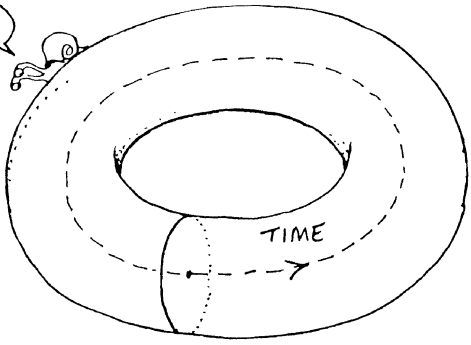


BUT COME TO THAT, WHY SHOULD TIME HAVE TO BE "OPEN," THAT IS, OF INFINITE EXTENT BOTH INTO THE FUTURE AND THE PAST?



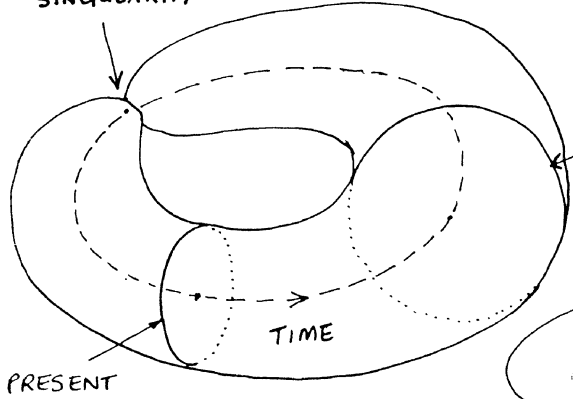
NO PROBLEM... IF YOU CLOSE THE EINSTEIN MODEL UP ON ITSELF, YOU GET... A TORUS.

HERE WE ARE AGAIN!



IN THIS TOTALLY CLOSED SPACE-TIME, THE SAME EVENTS REPEAT THEMSELVES OVER AND OVER AGAIN, AFTER A TIME τ WHICH IS THE PERIOD OF THIS WEIRD UNIVERSE.

BIG BANG SINGULARITY

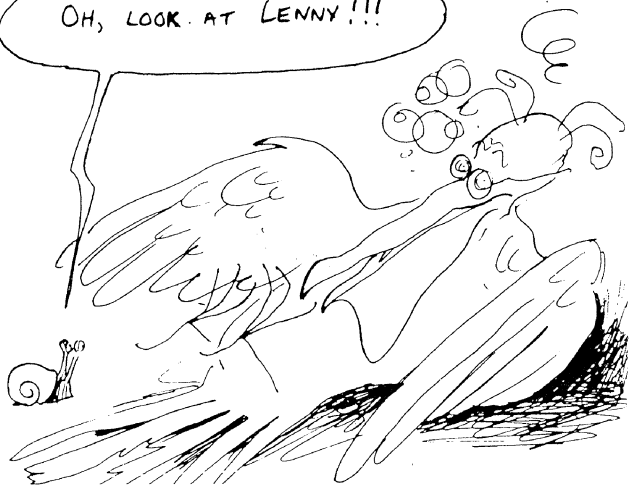


YOU CAN ALSO MAKE A CYCLIC UNIVERSE COLLAPSE ON ITSELF.



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

SO THAT'S WHAT WE KNOW
ABOUT THE BEGINNING OF
THE UNIVERSE.



AT LEAST, THAT'S WHAT
WE CURRENTLY THINK WE
KNOW. IT'S CHANGED
INNUMERABLE TIMES IN
THE LAST 5000 YEARS!

" THE EFFORT TO UNDERSTAND THE
UNIVERSE IS ONE OF THE VERY FEW
THINGS THAT LIFTS HUMAN LIFE A
LITTLE ABOVE THE LEVEL OF FARCE, AND
GIVES IT SOME OF THE GRACE OF
TRAGEDY. "


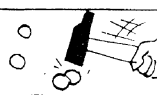


STEVEN WEINBERG
THE FIRST THREE MINUTES



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, ANTI PROTONS, NEUTRONS, ANTINEUTRONS, ELECTRONS, AND ANTI ELECTRONS (POSITRONS).
$\frac{1}{100}$ SEC	100 BILLION DEG.	4 BILLION GM/CM^3	SLAUGHTER OF THE HADRONS (PROTONS, ANTI PROTONS, 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 ANTI ELECTRONS. 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	$T_R = -173^\circ\text{C}$ $T_m = -267^\circ\text{C}$		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	$T_R = -270^\circ\text{C}$	10^{-30} GM/CM^3	EMERGENCE OF LIFE.
TODAY			INVENTION OF THE ATOMIC BOMB...

