CHAPTER 9
COSMOLOGY

Our discussion of forces and unified theories allows us a glimpse of conditions at the origin of the Universe. Understanding the very smallest constituents of matter enables us to build a model of the very largest -- the Universe itself.

Cosmology is the study of the origin, evolution, and fate of the Universe. In this chapter we explore what has come to be called the "standard model" of cosmology: a big bang plus inflation.

First we will consider observational evidence -- cosmic expansion, the relative abundances of primordial elements, and the three degree cosmic background radiation -- that the Universe originated in a hot big bang. Then we will discuss the evidence for a period of inflation in the early Universe. With the big bang and inflation in hand, we will trace the evolution of the Universe to its (projected) ultimate demise. Finally, we will speculate about what preceeded the big bang.

Throughout the chapter, we elaborate on two major themes: that the Universe is evolving, and that the origin and fate of the largest of structures, the Universe, depends on its smallest consituents, the elementary particles and the forces through which they interact.

LARGE-SCALE STRUCTURE

Any cosmology must account for features astronomers actually observe in the present Universe. These observations -- including the large-scale structure of the Universe (superclusters and voids); universal expansion; the three-degree background radiation; the "horizon"; cosmic "flatness"; and the predominance of matter over anti-matter -- place rigorous constraints on any theory. We shall discuss each of these in turn.

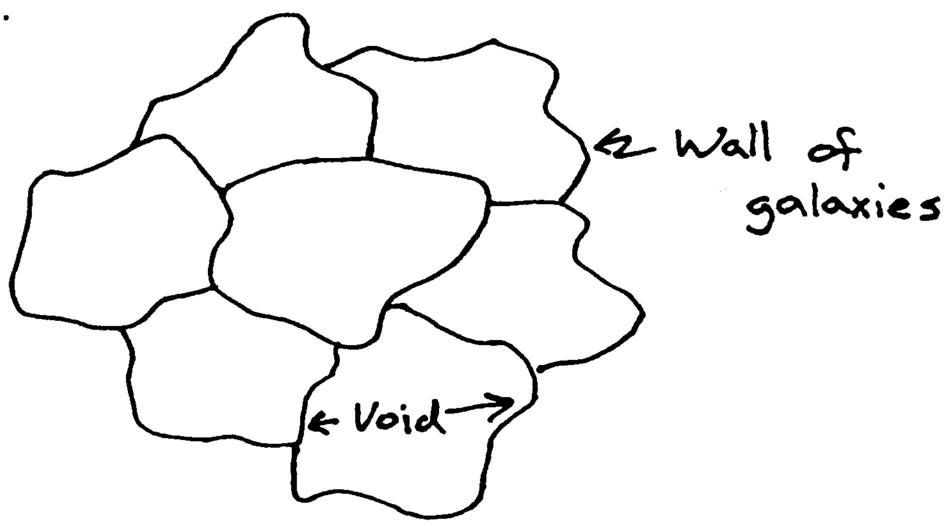
We live in a small corner of a vast Universe. Planet Earth is one of nine known planets orbiting our local star, the Sun. Also included in this solar system are many moons (orbiting various planets), asteroids (planetesimals -- rocks of a few kilometers to hundreds of kilometers in diameter -- most of them confined in orbit between Mars and Jupiter), vagrant comets ("dirty snowballs" of ice and rock originating from orbits beyond Pluto and occasionally tugged into the inner solar system by the planets or, perhaps, by passing stars), dust particles, and gases boiled off the sun (the solar wind). The solar system is about 8 light hours in diameter.

Our sun is a typical star. Astronomers estimate about ten percent of all the stars in the Galaxy have masses similar to the sun -- and hence have similar temperatures, radiant output, and lifetimes.

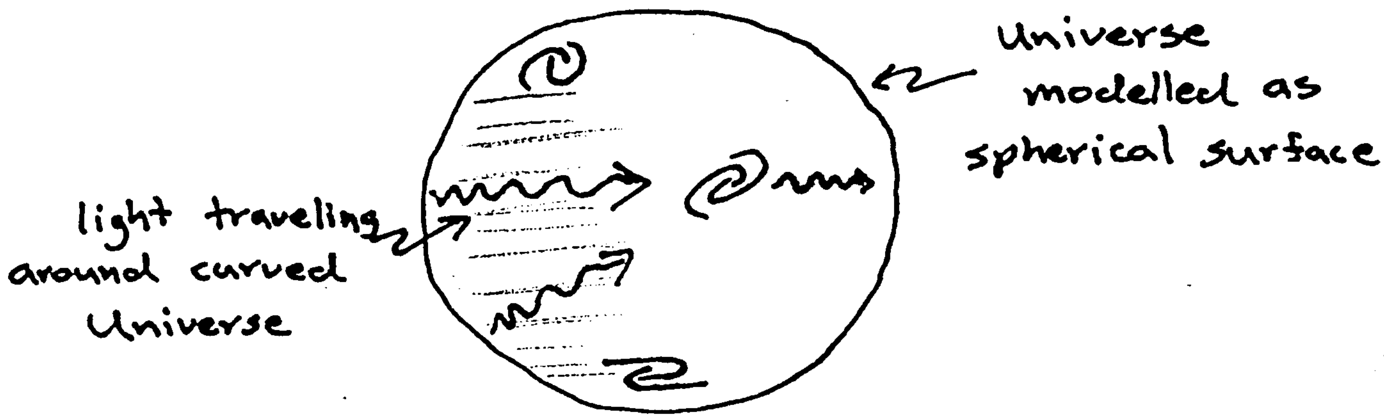
Our Galaxy, the Milky Way, harbors hundreds of billions of stars, with a total mass, including interstellar gas and dust, of perhaps a trillion solar masses. It is a spiral galaxy, a structure common among the galaxies -- like a giant pinwheel with a bulge at its core. It revolves once every 250 million years, and it has a diameter about 100,000 light years -- a typical galaxy in a Universe of galaxies.

Astronomers estimate there are about 100 billion galaxies in the observable Universe -- about as many galaxies in the Universe as there are stars in a typical galaxy. Our nearest neighbor among the major galaxies -- the Andromeda galaxy -- lies two million light years away. The galaxies group themselves in clusters and superclusters -- systems of thousands of galaxies, gravitationally bound, orbiting a common center of mass. Galaxies, like stars, interact. They collide. Larger galaxies swallow smaller ones, or if two galaxies graze each other in passing, tidal forces distort the structures of both. The galaxies dance ponderous do-se-dos across the sky.

Astronomers are still mapping the large scale structure of the Universe, and it is not yet certain how the clusters are distributed. However, preliminary maps indicate clusters and superclusters distribute themselves in a giant foam -- the galaxies along the walls of immense bubbles, with voids in between the walls. The average void spans 300 million light years.



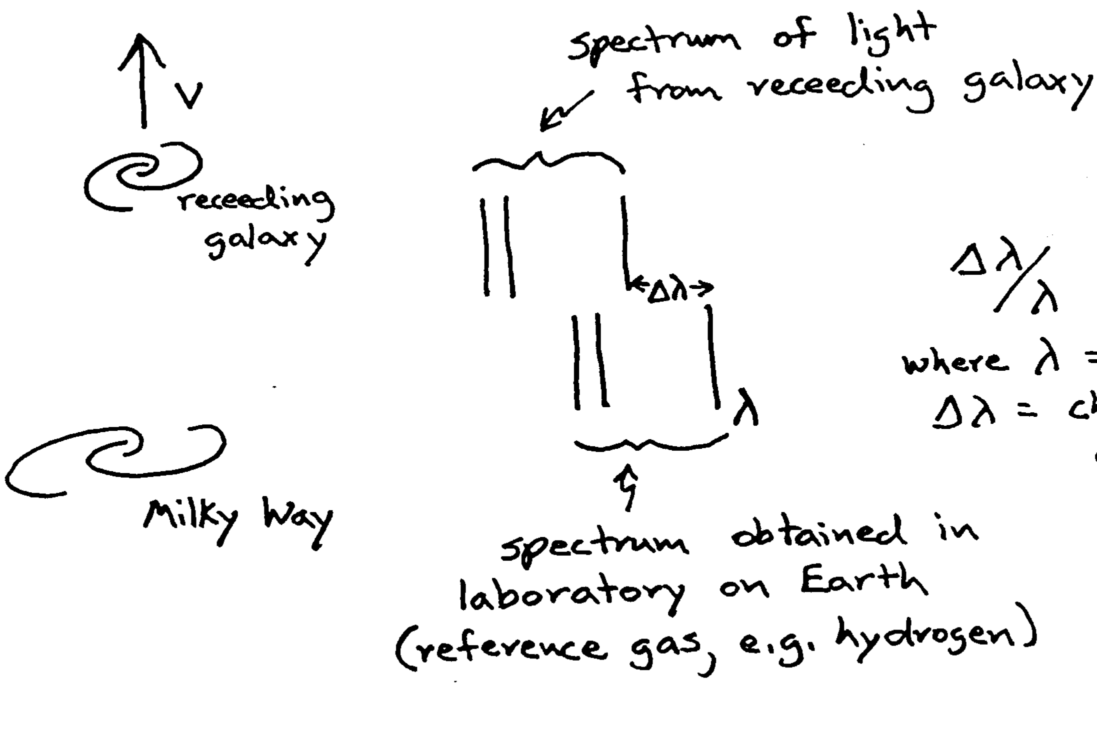
Astronomers have detected light from galaxies as far as 13 billion light years away. We do not know how much farther the Universe extends. Presumably, it has no edge, and we might eventually see around the curvature of the Universe -- light perhaps from our own Milky Way in its infancy.



COSMIC EXPANSION

Besides explaining the large scale structure, cosmology must explain cosmic expansion: the distant galaxies are flying away from us, and the farther galaxies fly from us faster than the nearer ones. Cosmic expansion is the first strong piece of evidence for a big bang -- a gargantuan explosion -- at the origin of the Universe.

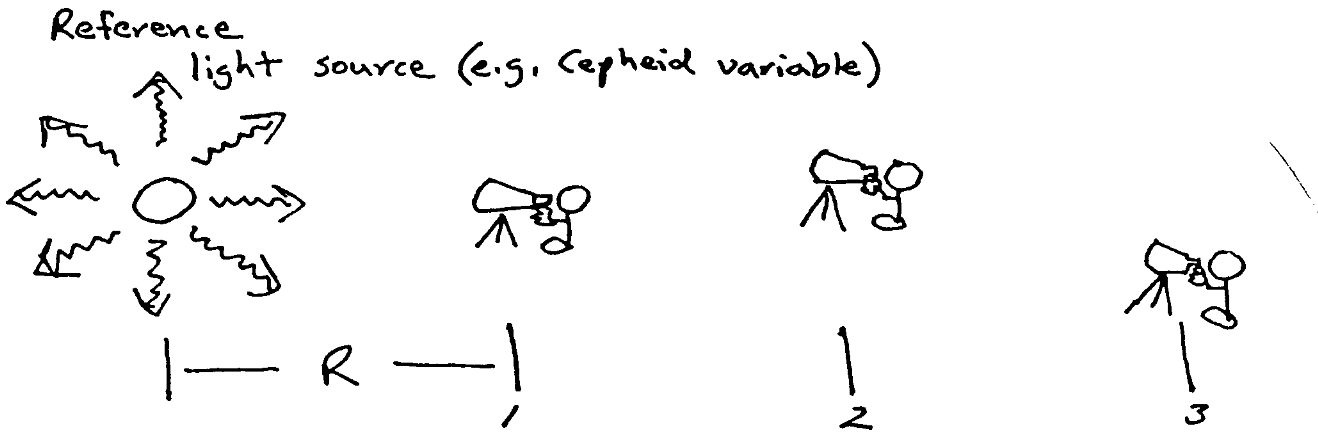
Astronomers measure a galaxy's recessional velocity by comparing its spectrum to a laboratory spectrum. If a galaxy is receeding, its spectral lines are red-shifted in proportion to its velocity.



$$\Delta\lambda/\lambda = V/c$$

where λ = reference wavelength
$\Delta\lambda$ = change in wavelength due to red shift

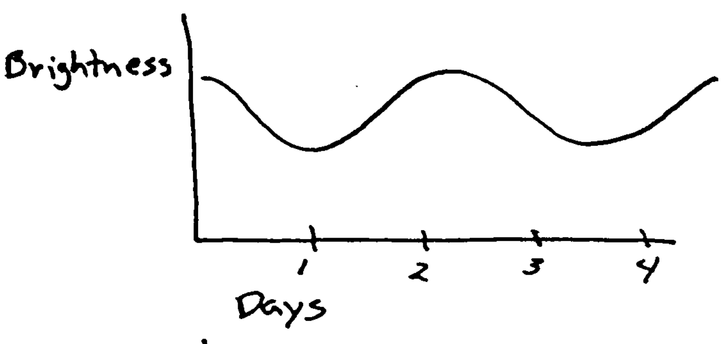
Measuring the distance to a galaxy is much more tentative than measuring its velocity. To relatively nearby galaxies (within 100 million light years or so), astronomers try to find "standard candles" (light sources of known intrinsic luminosity) embedded in the galaxy. Comparing the known luminosity of such objects (how much light they actually emit) with their apparent brightness, as seen from Earth, gives the distance to the object.



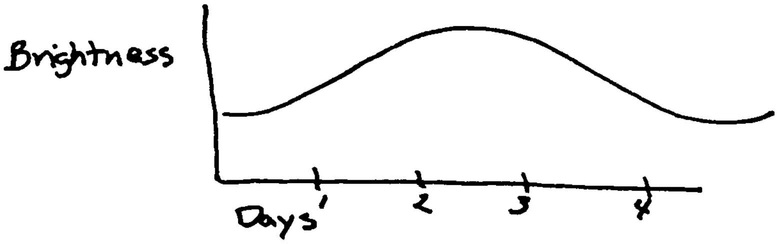
Observer at 2R receives 1/4 as many photons as observer at 1R. Observer at 3R receives 1/9 as many photons as observer at 1R.

number of photons $\approx 1/R^2$ Therefore $R \approx \sqrt{1/\text{number of photons}}$

Common standard candles include Cepheid variable stars and blue giants. Cepheids vary cyclically in lumonisity, and the period of the cycle is proportional to the star's intrinsic luminosity. So measuring the period of a distant Cepheid reveals its intrinsic luminosity.



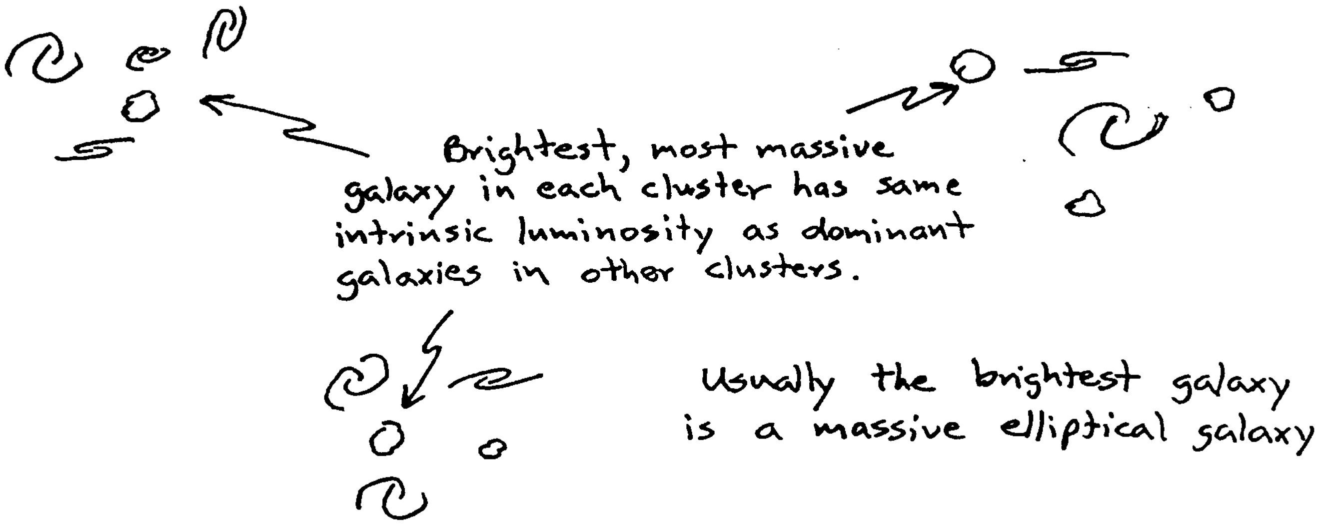
Cepheid variable with low intrinsic luminosity has shorter period light curve...



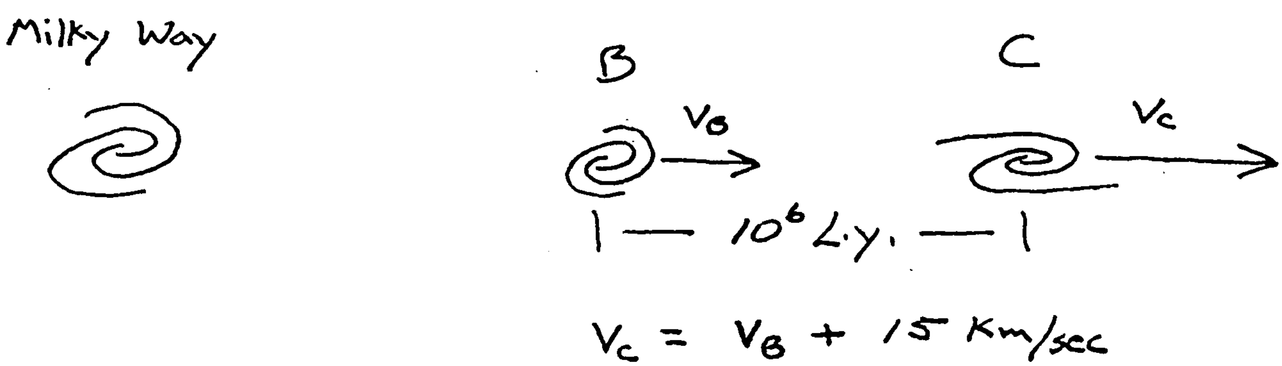
... than Cepheid variable with longer period.

We can measure the intrinsic luminosity of blue giant stars in our own galaxy. Assuming the blue giants in distant galaxies have the same intrinsic luminosities as those in the Milky Way, we can calculate their distances.

Astronomers can't use Cepheids and blue giants to measure distance to the farthest galaxies, however: they are so far away we can't resolve any internal structure. So astronomers use galaxies themselves as the standard candles. Galaxies come in clusters. Assuming the most massive galaxies in each cluster have about the same intrinsic brightness, we can use them as the standard candles.



Astronomers Edwin Hubble and Milton Humason documented the Universal expansion with a long series of observations in the 1940's. Their initial measurements have been refined, and astronomers now estimate the rate of recession is about 15 km/sec per million light years. That is, if galaxy C lies 1 million light years farther from us than galaxy B, then C is moving, on the average, 15 kilometers per second faster than B, away from us. The exact rate of recession with distance is uncertain. Estimates range between 15 and 30 km/sec per million light years. The uncertainty stems from our inability to measure distances precisely: astronomers aren't sure exactly how far away the distant galaxies are.

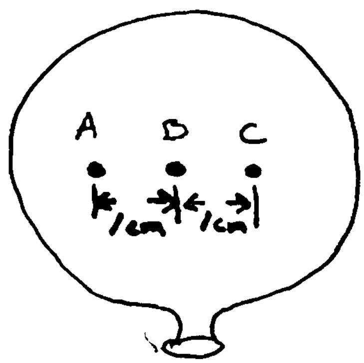


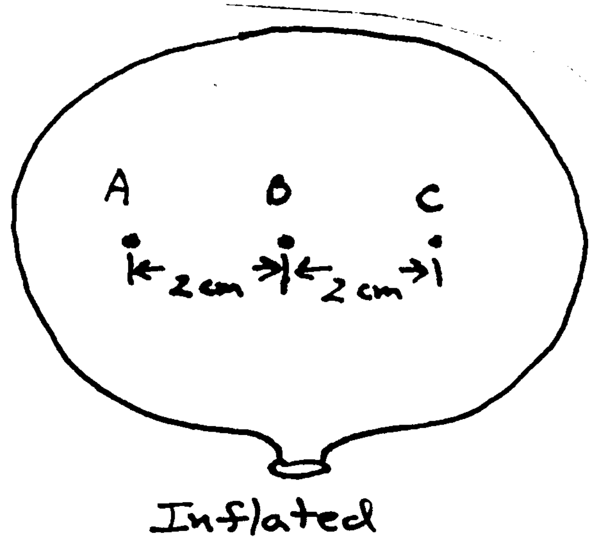
Actually, some galaxies in our local cluster move toward us, down the gravitational potential of the Milky Way, but on the larger scale, the galaxies are receeding.

A MODEL OF EXPANSION

We can model this Universal expansion nicely. Take a marking pen, and draw dots (representing galaxies) on the surface of a spherical balloon (the Universe). Blow up the balloon. Every dot (every galaxy) moves away from every other.

Next find three dots equally spaced in line. Label them A, B, and C.





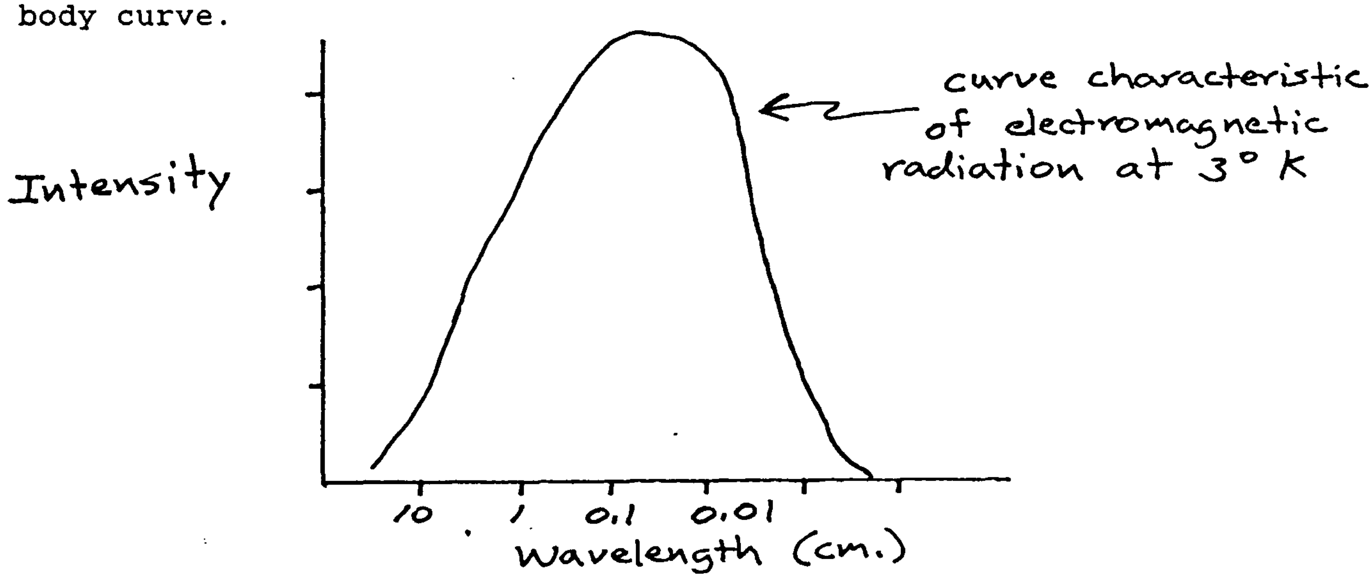
Inflate the balloon so that the distance from A to B doubles, and measure the distance from A to C. C moves <u>two</u> units from A while B moves one unit from A. Similarly the speed of recession of the galaxies is proportional to the distance of their separation. In our balloon model, galaxy C, twice as far away as B, moves twice as fast from A in the Universal expansion.

THE THREE-DEGREE BACKGROUND RADIATION

The three degree cosmic microwave background (CMB) provides the second piece of evidence for a hot big bang.

In 1964 Arno Penzias and Robert Wilson of Bell Laboratories, tuning the radio antenna at Holmdel, NJ, heard a radio hiss in the heavens. Everywhere they pointed the antenna they recorded background static corresponding to microwave radiation of temperature about three degrees Kelvin (three degrees above absolute zero). Other radio astronomers had recorded the static but ignored it.

At first Penzias and Wilson thought the static resulted from a fault in the system electronics or pigeon droppings in the antenna, but they shooed the pigeons and refined the antenna -- and the background hiss refused to go away. Only after discussing the problem with a group of theoretical physicists at Princeton who were studying the early Universe did they realize they were observing relic radiation from the origin of the Universe -- radiation predicted as much as thirty years previously by George Gamow. Other observations confirmed its existence and filled in points on its black body curve.



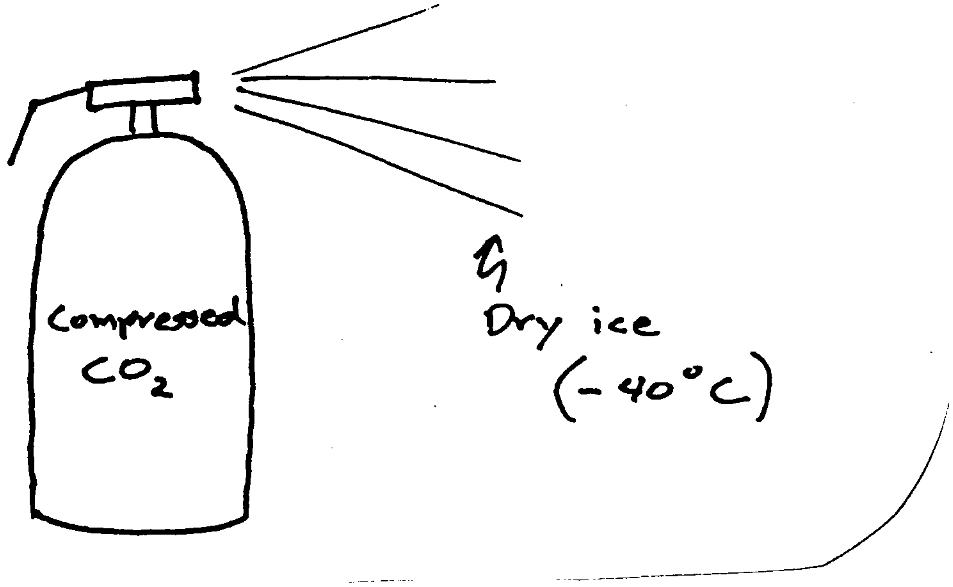
Cosmologists believe the three degree background radiation represents remnant energy of the big bang, a fireball at the origin of the Universe. At the big bang, the Universe was unimaginably hot and dense. As it expanded, it cooled just as gas in a cylinder cools when the piston is withdrawn. What we detect today is energy released at the creation, cooled over billions of years of cosmic expansion. We live in a giant microwave oven, the dials (fortunately) set at only three degrees above absolute zero.

COOLING BY EXPANSION

Several examples illustrate the phenomenon of cooling with expansion:

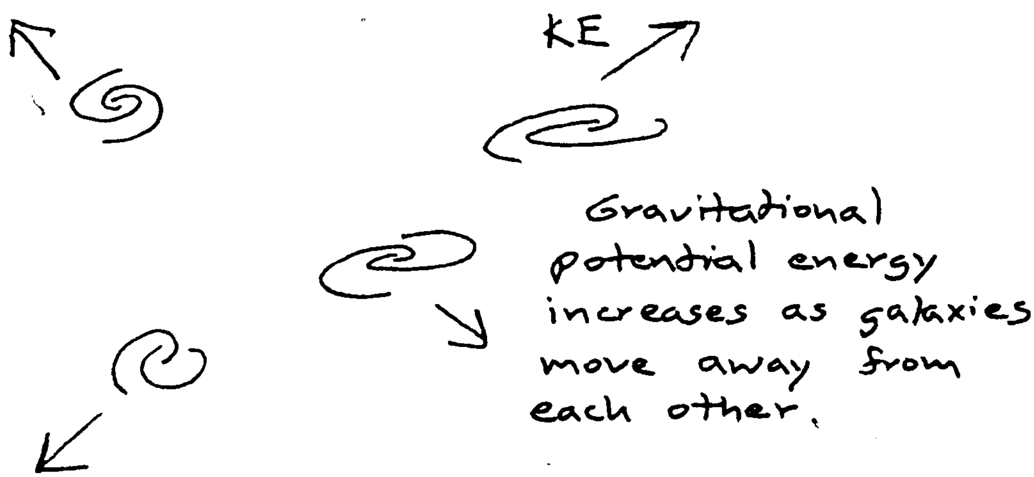
If you force air through pursed lips, it feels much colder than air gently exhaled through a wide-open mouth. (That's how you cool a hot drink.)

Compressed gas cools when released from its storage cylinder. In fact, compressed carbon dioxide, as in some fire-extinguishere, cools below -40 degrees -- cold enough to produce dry ice.

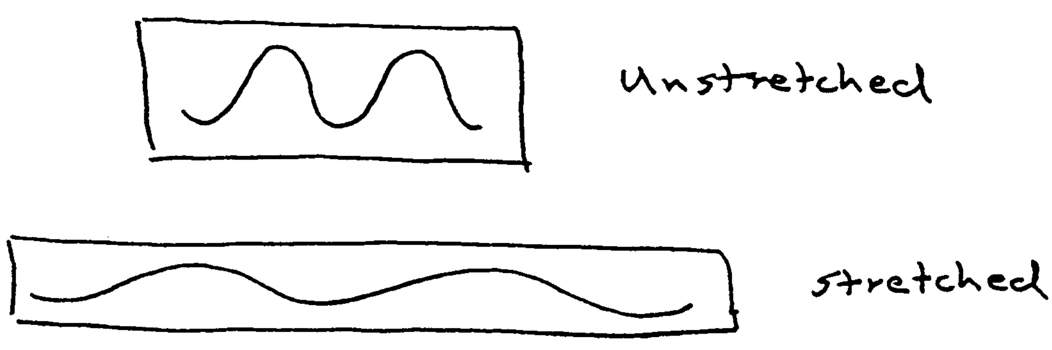


As we discussed in Ch.4, stars cool when they expand. The kinetic energy of hot gas in the core decreases as it lifts overlying layers away from the center of mass. Since temperature is a measure of kinetic energy, the core temperature drops.

On a grander scale, the entire Universe cools as it expands. As in a star, kinetic energy is converted into gravitational potential energy as the Universe "lifts" all the galaxies away from each other.



Even radiation cools as the Universe expands. An analogy illustrates the process: Take a stretchy sheet, such as a balloon or nylon stocking. Draw a wave train on it.



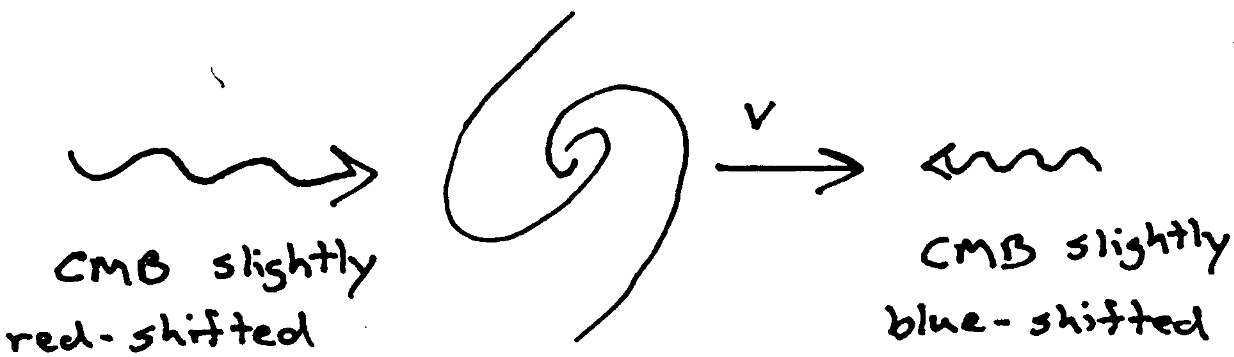
stretch the sheet along the direction of the wave train: the wavelength increases.

In the expanding Universe, spacetime stretches, and, if the speed of light is constant, frequency decreases (since c = f). As its frequency decreases, so does a photon's energy, by E = hf. Since temperature is a measure of kinetic energy, temperature must decrease.

AN ABSOLUTE FRAME OF REFERENCE?

Parenthetically, note another interesting point: the background radiation, in effect, provides an absolute frame of reference to detect motion in the Universe. Our galaxy, and therefore the sun and us on Earth, are traveling through the background radiation in the direction of the constellation Leo. We detect a slight blueshift of the background radiation in the direction of Leo, a slight red shift in the opposite direction.

In a way, we've come full circle, back to Newton's absolute space.



ABUNDANCE OF THE PRIMORDIAL ELEMENTS

The third clue implying a big bang is the proportion of light elements. By mass, the Universe is about 75% hydrogen, 25% helium, with only a trace of all the heavier elements. These ratios, and the ratios of key elements like deuterium, are exactly what theorists predict as residue from a big bang.

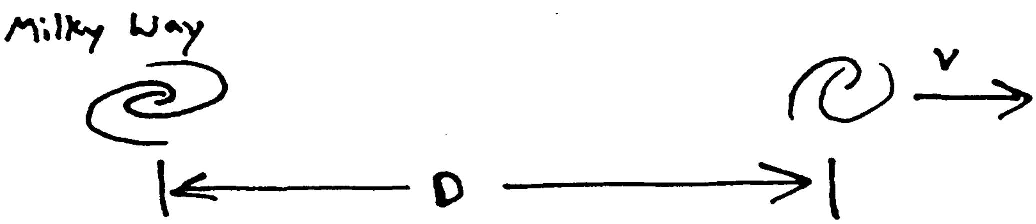
Hydrogen is the simplest atom, with but a single proton in the nucleus and a single electron bound to it by the electromagnetic force. Heavier nuclei are amalgamations of hydrogen nuclei produced by fusion. There are no stable atoms with atomic weight 5, and there was not enough time after the big bang during which conditions allowed nucleosynthesis of many heavier nuclei. So helium (atomic weight 4) is the heaviest stable residue from the creation. Only stars can forge the heavier elements, and if the Universe is in some kind of "steady state," with stars present for an infinity of time, we would expect a much higher proportion of the heavier elements than is actually observed.

It turns out deuterium (hydrogen with an extra neutron in the nucleus and symbolized by the letter "D") is a sensitive indicator of conditions in the big bang. Stars degrade deuterium, or fuse it to helium, so all the deuterium in the Universe was formed in the big bang. The ratio of D to H indicates the proportion of neutrons in the early Universe as well as the overall density, temperature, and numbers of hadrons. The deuterium ratio agrees nicely with the relative abundances of H and He. Furthermore, the ratio of deuterium indicates the total amount of hadronic matter in the Universe is only about 10% that required to close the Universe, i.e. stop its expansion and cause it to collapse.

AGE OF THE UNIVERSE

The final testimony in favor of a big bang comes from measuring the age of the Universe. Four independent methods date the beginning of the Universe between 10 and 25 billion years ago, and consensus places the beginning about 15 billion years ago.

Knowing current expansion rates, it's possible to extrapolate backward to the time at which all the matter in the Universe was confined to a geometric point.



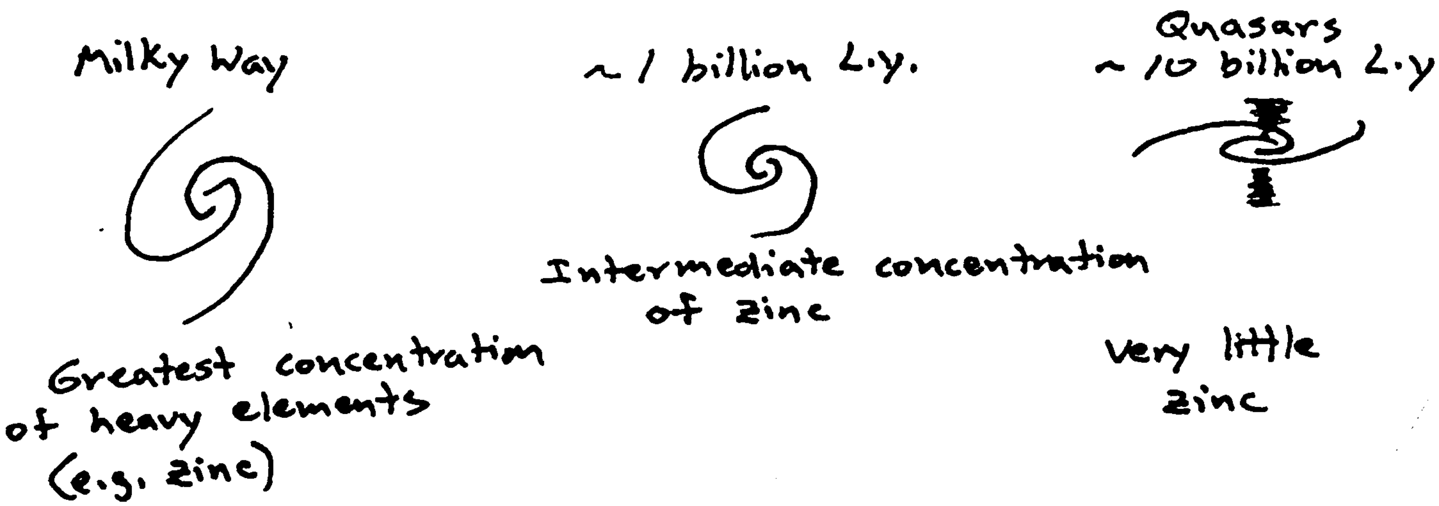
$$D = vt$$

$$t = v/D$$

where t is time since big bang, D is distance to a reference galaxy, and v is the galaxy's recession velocity.

The ages of globular clusters provide another estimate for the age of the Universe: The oldest known stars in globular clusters are between 10 and 15 billion years old. Astronomers can calculate a cluster's age if they can determine which stars in the cluster have just started to fuse helium. For instance, if all the stars heavier than 1 solar mass have ignited helium fusion (or fusion of heavier nuclei), but stars less than 1 solar mass are still fusing hydrogen, they know the cluster is about 10 billion years old. (It takes 10 billion years for a star of 1 solar mass to fuse all the hydrogen in its core.)

Astronomers can date the galaxies, too. The farthest known galaxies lie about 13 billion light years away, and the farthest galaxies appear to be the youngest: they have the lowest concentrations of heavy elements, indicating their stars haven't had time to create many nuclei heavier than helium. More distant yet are some quasars, which may be galaxies at birth. In general, the farther out astronomers peer, the younger the galaxies: apparently, the first galaxies formed about 14 billion years ago.



Finally, radioactive decay helps date the Universe, just as it helps to date rocks and fossil specimens here on Earth. By measuring the average galactic concentration of uranium 238 and its daughters, for example, we know what proportion of the uranium has decayed. Knowing the half life of uranium, we can calculate how long the uranium has been decaying -- a lower limit on the age of the galaxies and their stars, the supernovas, that forged uranium.

THE BIG BANG

All the evidence cited above indicates the Universe began about 15 billion years ago with a hot, dense big bang. In that event, all mass and energy -- and time itself -- flashed into existence.

The big bang flung mass and energy like shrapnel from a bomb, and the shards -- the material that became the galaxies -- still hurtles away. The CMB, astronomers surmise, is relic energy of the big bang, cooled over countless eons of time.

In considering the big bang, we tend to think as if we could step back and observe the process from "outside" -- an impossibility, since the Universe includes us. The big bang occurred at once everywhere in the Universe. It was an explosion into being of the Universe itself. There is no outside the Universe, no center, and no edge.

Before the big bang there was "nothing" (a condition called the "vacuum"). There was no mass, no energy, no time. The big bang created the fermions and the forces. It created the very structure of the Universe -- spacetime -- as well as the rules governing interactions in that structure.

An analogy might be awakening in the morning: in deep sleep, where is the mind? There is "nothing." When we awake, suddenly there is everything -- the entire Universe. Similarly, we might regard the big bang as the Universe itself "awakening."

PREDICTIONS OF BIG BANG THEORY

Big bang theory explains the observational evidence cited above, but it is unsettling in that it predicts a singularity at the origin of the Universe: matter and energy confined at infinite density in a geometric point. Known physical laws cannot describe a singularity, and physicists cannot re-create the singularity experimentally.

Physicists, however, can calculate conditions after about 10^{-32} seconds post big bang, and experiments in particle accelerators re-create conditions that existed after about 10^{-12} seconds. The theory predicts temperatures and densities so extreme that the four forces of nature were unified as one Force.

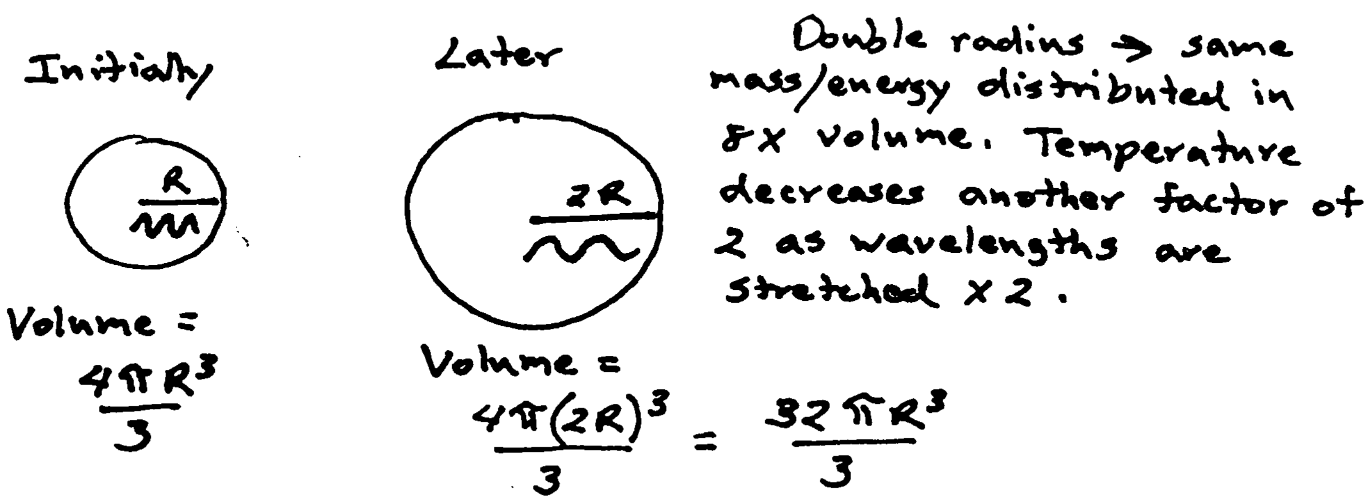
PROCESSES AT WORK DURING COSMIC EVOLUTION

Given an initial singularity and explosive expansion, physicists can calculate the subsequent evolution of the Universe. That evolution was characterized by a series of transitions as the Universe cooled -- transitions in which the various particles and forces "froze out," like snowflakes precipitating from water vapor in a cloud. Most of the transitions occurred during the first second after the big bang.

As we discussed previously, the Universe cools as it expands. Mass/energy density decreases and radiation energy decreases (wavelengths increase) as spacetime stretches.

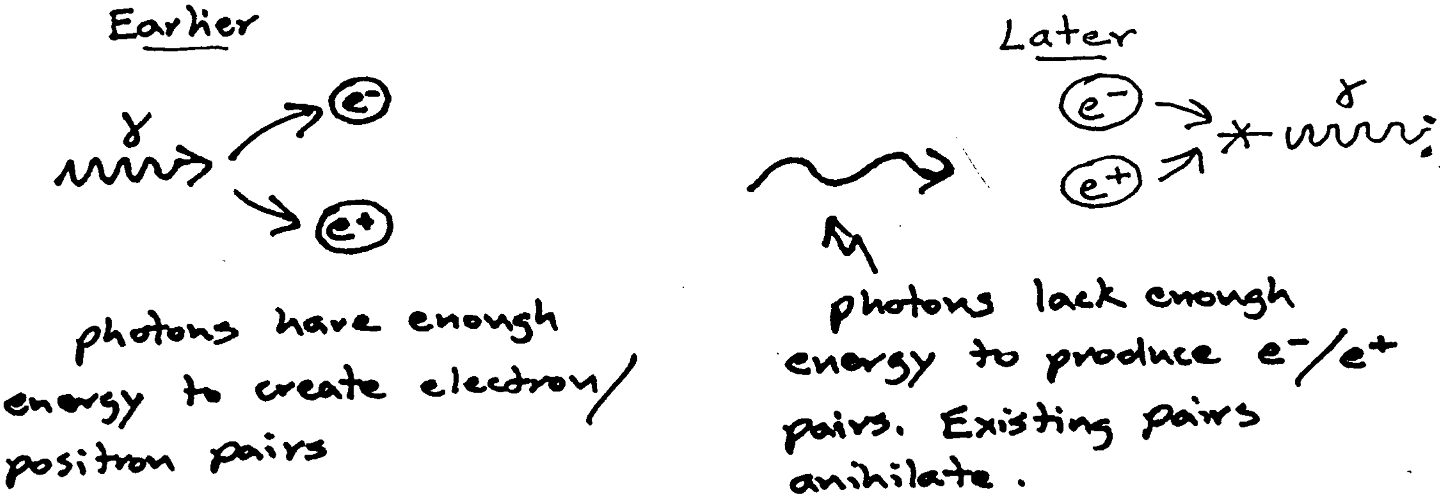
All mass/energy were created at the big bang (and perhaps augmented during inflation -- see below). No more has erupted into the Universe, and none has evaporated from it. In the very early Universe, all that mass/energy was confined to a small volume. As the Universe expanded, the mass/energy diffused into the larger volume -- the same furnace trying to heat a larger house -- and the Universe cooled.

The temperature of the Universe is proportional to the mass/energy density (mass/energy per unit volume), and it decreases as the inverse fourth power of the Universe's radius (1/R^4). That is, doubling the radius of the Universe drops the temperature to one-sixteenth the initial temperature.



Every subatomic particle has a characteristic mass energy. If the necessary energy is available -- in the very early Universe or in a particle accelerator -- particle/anti-particle pairs are produced. The system reaches an equilibrium at any given temperature: as many particles are produced as annihilated.

As the energy density of the system decreases (e.g. as the accelerator powers down or as the Universe expands) the equilibrium shifts: more particle pairs annihilate than are produced, and the number of particle/anti-particle pairs in the system decreases.

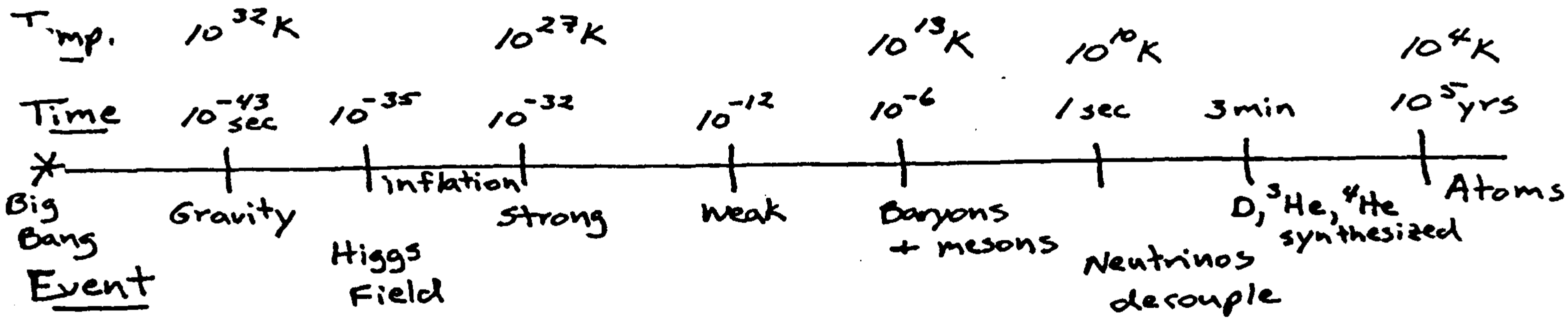


Boiling water offers an analogy. Heat from the stove burner (at high energy density) creates bubbles of steam ("particles"), and they roil the water. Lift the pan off the stove, and the bubbles disappear (no more "particles" are produced). Each of the fundamental particles has its characteristic "boiling point," the energy density required to produce that particle.

This scenario of particle production and annihilation applies to bosons as well as fermions. For example, while the temperature of the Universe exceeded 180 GeV (roughly the rest energy of a vector boson/anti-vector boson pair) vector bosons (along with other particles) filled the Universe, and the weak force was a common interaction. (Physicists describe this condition as "electro-weak unification:" the weak force was indistinguishable from the electromagnetic force.) When the Universe cooled below that critical temperature, vector bosons disappeared through mutual annihilation, and electromagnetism separated from the weak force.

The example of the electroweak transition described above illustrates spontaneous symmetry-breaking in the early Universe. Below about 180 Gev, the electromagnetic force "froze out" from the weak force. Similarly, the strong force had separated from the electroweak force earlier, when the Universe cooled below 10^19 Gev (about 10^27 degrees) -- the energy required to produce X particles (the theoretical bosons which mediate the inter-conversion of quarks and leptons.) Temperature (available energy) determines which bosons are present, and which bosons are present -- X's or W's or photons, etc. --determines how fermions interact.

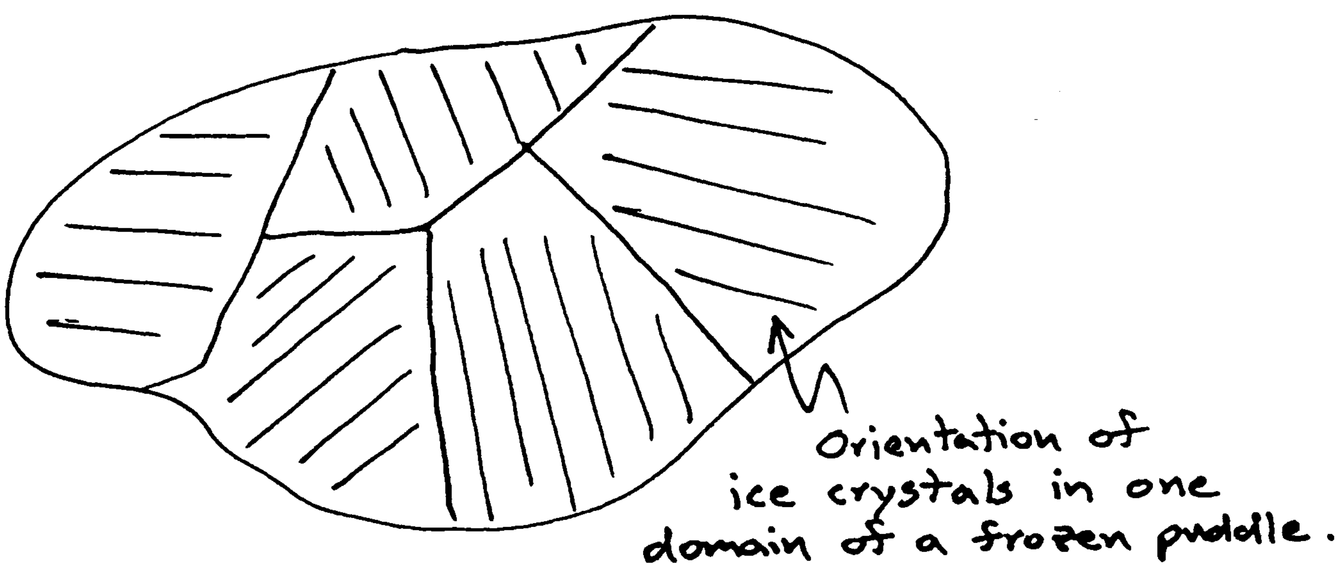
Big bang theory postulates multiple "freezings" during the evolution of the Universe: each of the four forces and each of the fermions froze out as the Universe cooled.



Cloud formation and precipitation provide an analogy: in cool air, water vapor condenses and forms a cloud. Cooler still, larger droplets aggregate, and it rains. Colder still, the droplets crystallize into snowflakes. Colder still, snowflakes clump together.

These "freezings" may not have occurred uniformly throughout the early Universe. Cosmologists believe that, during the first 10^-35 seconds after the big bang, expansion (and therefore cooling) outpaced the speed with which Higgs fields could form. In this "supercooled" Universe (which was actually still very hot -- about 10^27 degrees -- but colder than the Higgs transition temperature) Higgs fields formed in different domains. One of these Higgs domains (a "bubble") then inflated and became our Universe. (See below.)

We observe an analogous process when a shallow puddle freezes. The ice crystals on different areas of the surface orient in different directions, since the freezing begins at several different points simultaneously.



Perhaps domain formation explains the large-scale structure of the Universe (walls and voids). At one of the transitions --the Higgs transition, or perhaps the electro-weak transition -- freezing pushed hadronic matter to the walls of domains and formed the vast, foamy structure we map today. (On the other hand, supernova explosions in the early, more violent Universe may have "bulldozed" mass/energy into its observed piles. We don't have enough data to know for sure.)

OTHER CONSTRAINTS ON COSMOLOGY

Big bang theory successfully accounts for the Universal expansion, cosmic background radiation, and ratios of the primordial elements, but by itself, a big bang cannot accomodate the following observations:

1. **The cosmic "horizon".** That the background radiation appears uniform in all directions poses a dilemma: On the one hand, the most distant objects appear too far apart ever to have been in communication. Quasars, the most distant objects yet observed, lie up to 14 billion light years away, and we are just now seeing light that they emitted when the Universe was less than one-fifth its present age. If it has taken light most of the age of the Universe to reach us from a quasar in the east, that light cannot yet have reached an equal distance --the "horizon" -- in the west.

On the other hand, the cosmic microwave background is uniform in all directions, to about one part in 10,000 (the current limits of measurement), and it is older than light from the quasars. (It has been traveling toward us since radiation decoupled from matter about 100,000 years after the big bang, before galaxies began to form.) The only way energy can equilibrate in a system is if all parts of the system are, at some time, in contact: Equal temperature implies a thorough thermal mixing of the contents. So it would seem the distant reaches of the Universe <u>must</u> have been in contact at some time.

CMB arriving at Earth from West cannot have reached the horizon on the East

2. **Homogeneous and isotropic Universe.** On the largest scales, the Universe appears homogeneous (equal mixtures of the same components) and isotropic (there is no preferred direction). Astronomers find equal numbers of galaxies all directions, and the most sensitive indicator of energy distribution in the Universe, the cosmic microwave background, is uniform in all directions to the limits of current measurement.

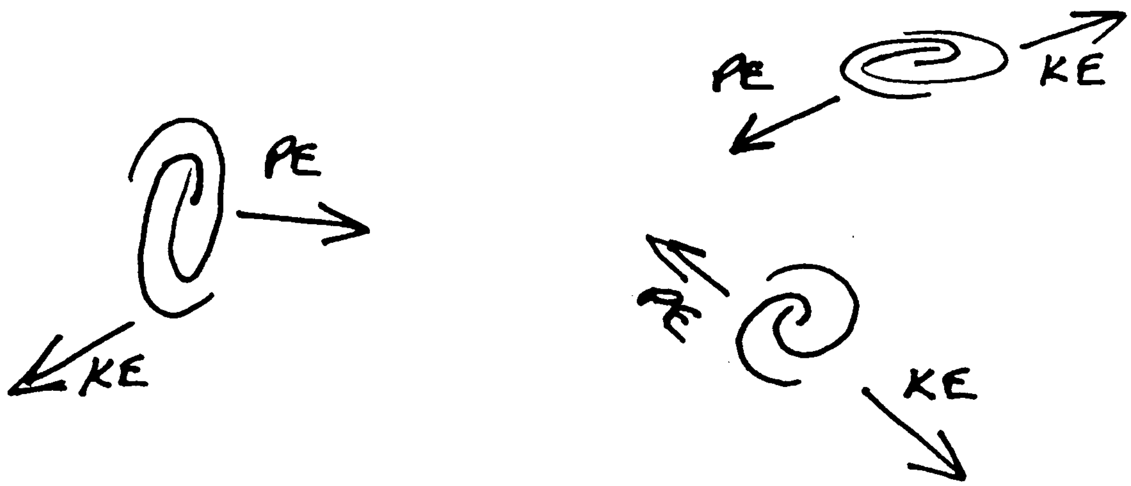
Furthermore, astronomers find the same spectral lines in the far corners of the Universe that they find in our own neighborhood: stars in the distant galaxies produce the same chemical elements as in our own.

Astronomers believe an observer in any other galaxy would see the same overall structure we do -- the same general distribution of galaxies, the same cosmic microwave background, the same physical processes in all directions.

3. **Clumpiness.** On the other hand, superimposed on the uniform background is an obvious clumpiness: energy and matter aggregate in galaxies and galaxy clusters. (At least the visible matter and energy clump in galaxies. Astronomers have not yet mapped the large-scale distribution of dark matter.) The galaxy clusters, in turn, aggregate along walls of the large scale structure, and the walls are separated by tremendous voids. Furthermore, whole clusters appear to be moving in relation to the cosmic background radiation. What produced this large scale structure and these dynamics?

4. **"Flatness".** There are two great processes at work on the scale of the Universe -- a push and a pull. On the one hand, the galaxies fly away from one another, launched by the big bang. On the other hand, gravity slows that universal expansion.

By the evidence, the gravitational potential energy of the Universe is very close to balancing the kinetic energy of the galaxies. The Universe would appear very different if one were much larger than the other: a Universe in collapse (or already collapsed!) if gravity (i.e. the total mass of the Universe) grossly overmatched its kinetic energy; vaster voids and fewer clumps if kinetic energy (the energy of motion imparted at the origin) grossly exceeded gravity. How is it the gravitational energy of the Universe so closely balances the kinetic energy?



Astronomers describe this balance in terms of the geometry of spacetime: If there is enough mass/energy in the Universe to stop expansion and, eventually, collapse the Universe, the Universe has a net positive curvature. If the Universe lacks adequate mass/energy, it has a net negative curvature. If the mass/energy is just adequate to balance the kinetic energy of the galaxies, the Universe is geometrically "flat."

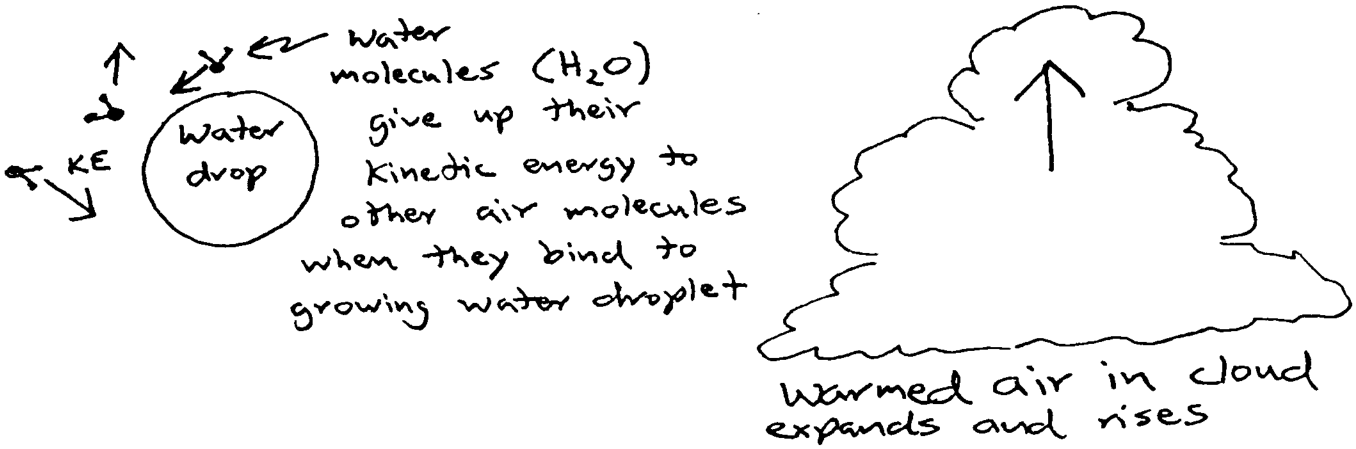
4. **The monopole problem.** One of the predictions of big bang theory is the production of magnetic monopoles. Physicists calculate that, at the extreme densities of the big bang, magnetic monopoles (isolated north or south poles) should have been produced in numbers rivalling the numbers of protons and neutrons. Yet we can't find them. In fact, no magnetic monopole has been detected. Where are they, or do they even exist?

INFLATION

Alan Guth, now at MIT, was working on the monopole problem when he arrived at the idea of inflation. Inflation refers to an era of exponential expansion beginning about 10^{-35} seconds after the big bang. From that time until 10^{-32} seconds, the Universe ballooned exponentially, doubling its radius about 1000 times. Spacetime stretched faster than light. After inflation, it was about the size of a grapefruit, 10^{50} times its pre-inflation diameter.

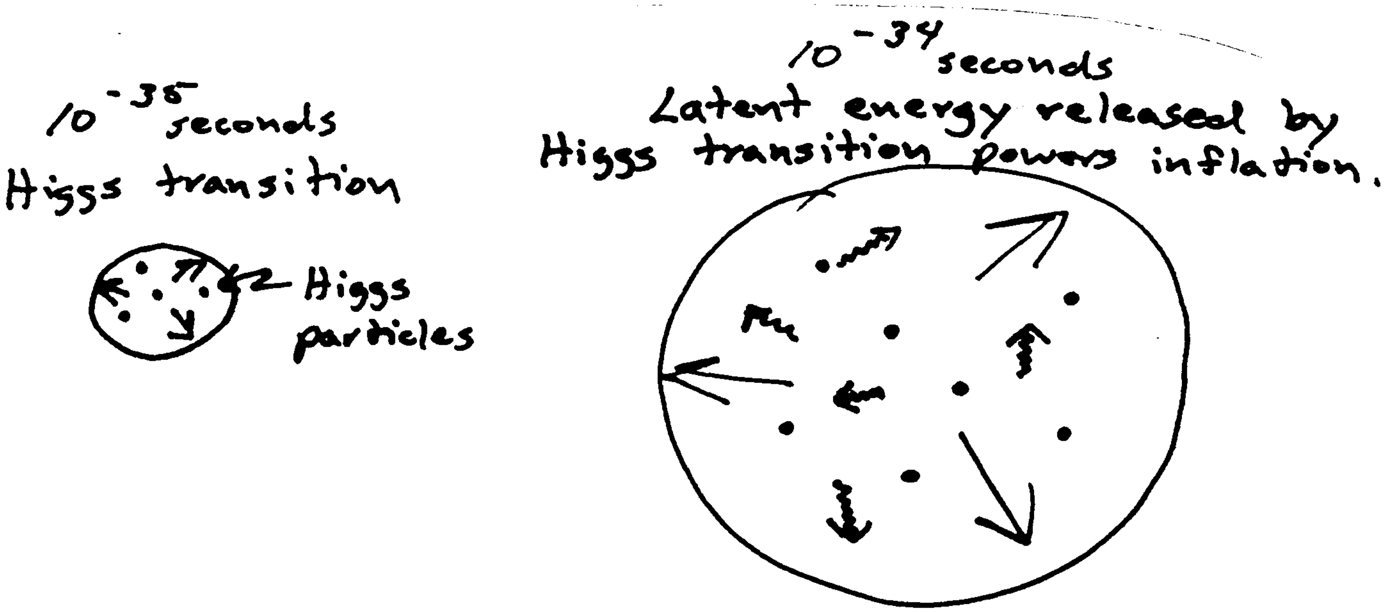
Cosmologists postulate inflation was driven by energy released during transition to a Higgs field. At the big bang, the Universe was pure energy. At some time in its expansion, it dropped below the temperature at which a Higgs field could form. First, a word on the latent heat released in phase transitions, then a word on the Higgs field.

Symmetry breaking, or any other phase transition, may release "latent energy." When rain drops condense out of the water vapor in a cloud, for instance, the condensation releases latent heat and warms the surrounding air: hydrogen bonds between water molecules in the rain drop provide a lower energy state, and newly bonded molecules transfer their kinetic energy and bonding energy to other free molecules in the air. The warmed air, then, expands and rises.



Similarly with the Higgs field. At a critical temperature after the big bang, the Higgs field "froze out" from the cloud of energy. As it froze out, it released latent energy. (Equivalently, since fields are quantized, we may discuss this process in terms of Higgs particles -- the quanta of the field: As the Higgs particles froze out, they released latent energy.)

This produced a curious effect: Even though the Universe expanded, latent energy filled that new volume. It was as if, during the ignition cycle in a car's engine, the gases maintained the same temperature (same kinetic energy) throughout their expension, pushing the piston with exactly the same force throughout the power stroke.



The latent energy released during the Higgs transition pushed the Universe with the same force throughout inflation.

What we have just described is characteristic of Higgs fields in general: A Higgs field maintains a constant, positive energy density -- called a "false vacuum" -- even in the absence of particles and radiation.

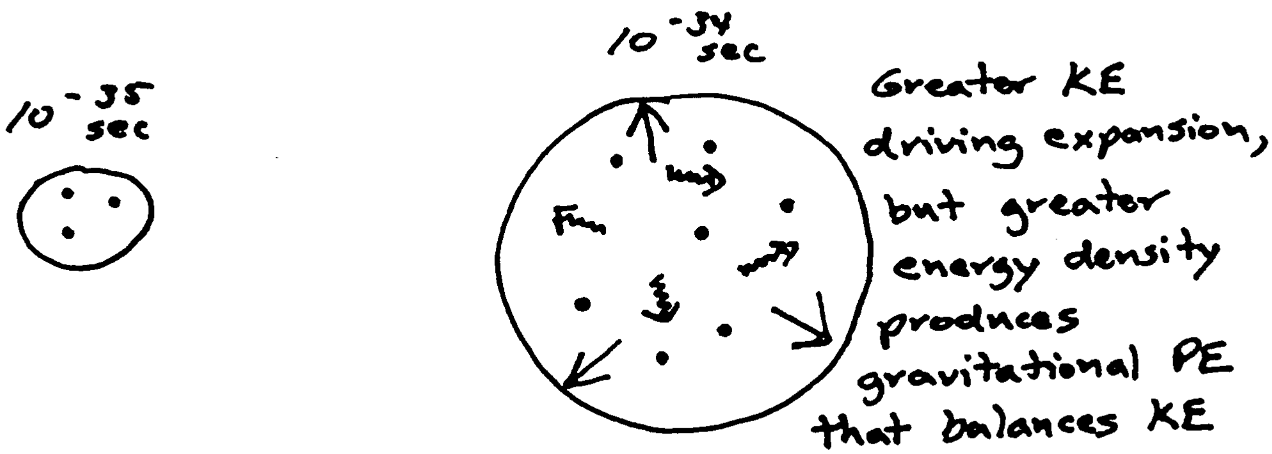
Inflation ended at another transition: energy stored in the Higgs field "froze out" into leptons and quarks. The end of inflation marks the end of the GUT era, when the strong force separated from the electro-weak force.

PROBLEMS SOLVED

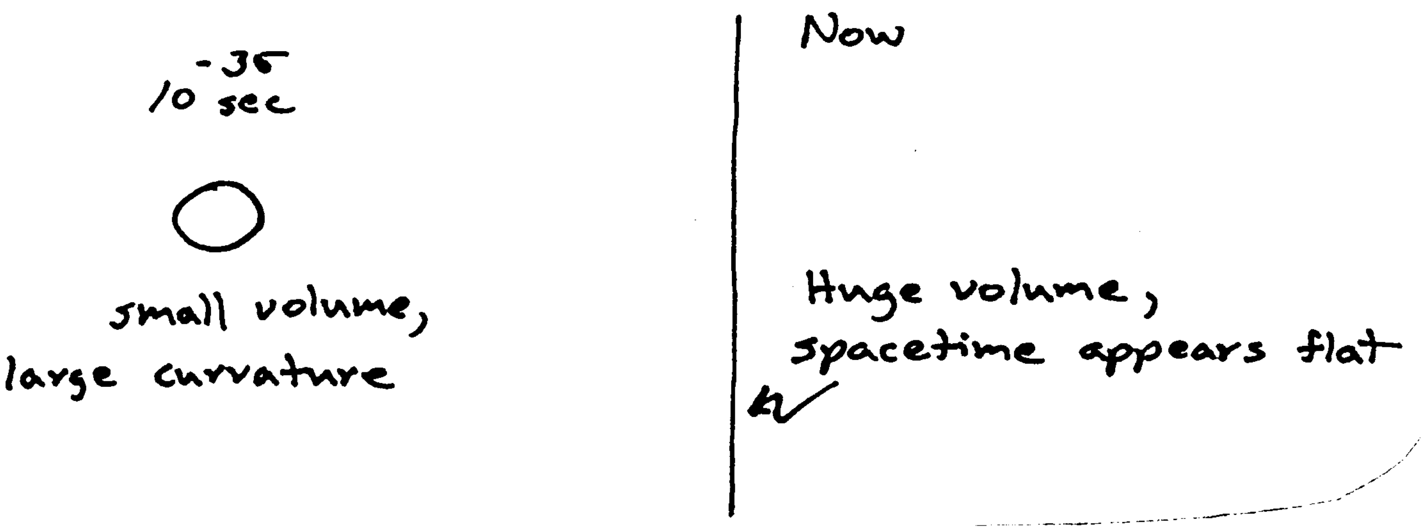
Inflation neatly resolves the problems baffling big bang theory:

-- There is a uniform (3 degree) horizon because all parts of the Universe were causally connected (i.e. able to communicate, hence equilibrate temperature) before inflation.

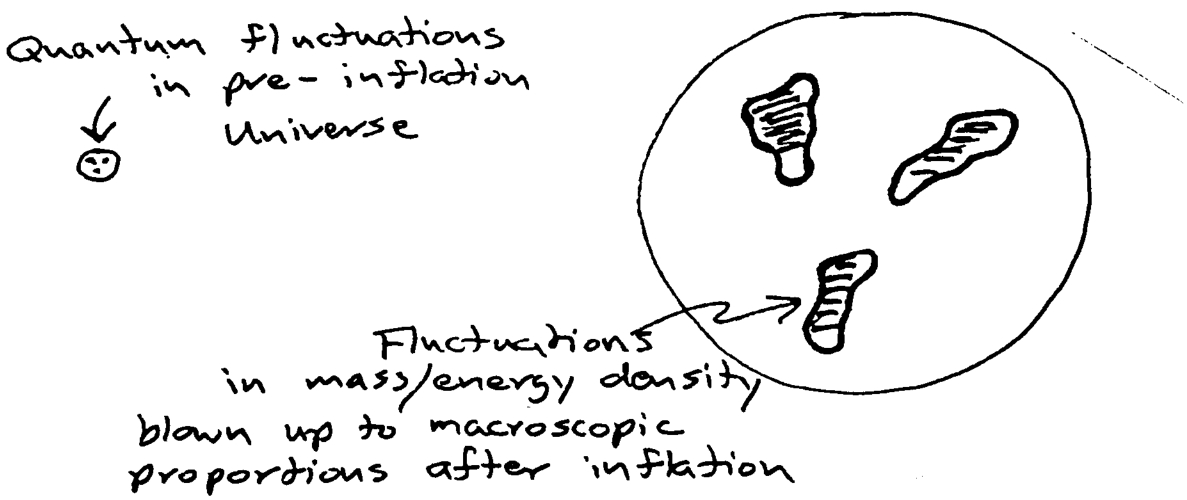
-- The Universe is flat because energy density remained constant during inflation. Since inflation itself is driven by energy density, but gravitational attraction is also proportional to energy density, kinetic energy of expansion must exactly balance gravitational potential energy.



Another way to visualize flatness is to think of the Universe as the surface of a balloon. Before inflation, the balloon had a very short radius, hence large curvature. Inflation blew up the balloon to such a large radius that it now appears flat to an observer on the surface, just as the Earth's horizon appears flat as seen from a Kansas wheat field.



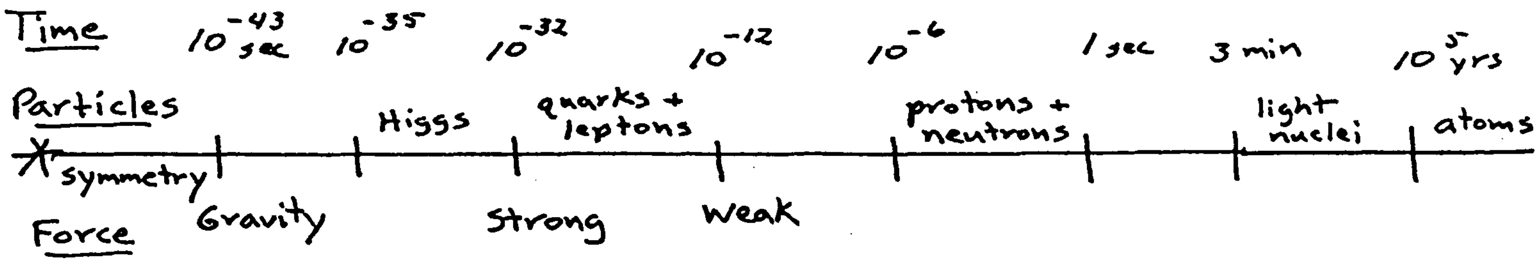
-- Clumpiness results from quantum fluctuations in the pre-inflation Universe blown up to macroscopic scales during inflation. As with any subatomic system, the pre-inflation Universe experienced random fluctuations in mass/energy -- a few more virtual pairs here than there. These quantum fluctuations, blown up by inflation, became the kernels of mass/energy that accumulated galaxies in our Universe.



-- Monopoles, produced before inflation, were scattered hither and yon as spacetime inflated. Cosmologists estimate that there may be only one monopole in the observable Universe.

THE STANDARD MODEL

Now we're ready to trace the evolution of the Universe, from the big bang to the present (see also time line on p. 178).



At the creation, in a fireball of unimaginable temperature and density, was supersymmetry: pure energy, with no distinguishable particles or forces.

The fireball expanded rapidly and, as it expanded, it cooled. At 10^-43 seconds after the big bang, gravity froze out from the supersymmetry, separating from the strong-electroweak force (GUT). X-particles converted leptons to quarks, and vice versa.

At 10^-35 seconds after the big bang, when the temperature fell below 10^27 degrees (10^15 GeV), bubbles of Higgs fields began to form. One of those bubbles, which became our Universe, inflated very rapidly, doubling in radius every 10^-34 second. Spacetime ballooned to about 10^50 times its original diameter.

At the end of inflation, still at about 10^27 degrees, the Universe experienced another phase transition. There was no longer sufficient energy density to replenish X particles, so the strong force froze out from the electroweak force. Energy contained in the Higgs field froze out as leptons and quarks, stealing the energy that drove inflation.

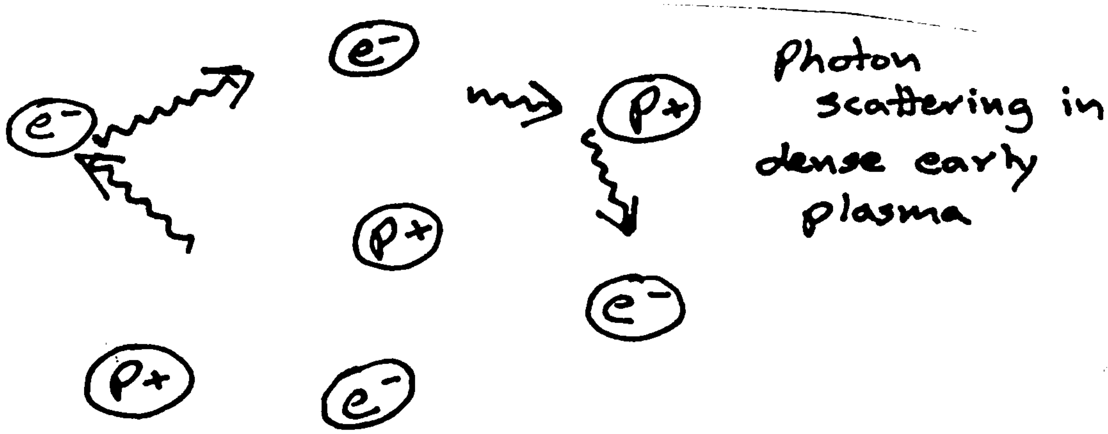
Expansion continued after inflation -- it continues today -- but much more sedately.

During the era immediately after inflation, from about 10^-35 second to 10^-6 second, the Universe consisted of leptons, vector bosons, quarks, and gluons in a sea of radiation. Below 10^12 degrees K (at about 10^-6 second), quarks could combine to form hadrons.

10^-12 second after the big bang, below 180 GeV, vector bosons annihilated faster than they could be produced, and the electromagnetic force separated from the weak force. Neutrinos uncoupled from leptons and quarks at this phase transition (there were no longer enough vector bosons to catalyze their interaction), and they could fly essentially unimpeded through the Universe. Domain formation at this transition may have contributed to the large scale structure of the Universe.

At about three minutes, at 10^9 degrees, fusion reactions produced the primordial atomic nuclei -- -- which, with hydrogen (a single proton), account for essentially all the mass in the Universe.

For the next 100,000 years the Universe remained so hot that electrons were stripped immediately from any nucleus, and atoms could not form . During this "plasma era" the Universe was opaque to electromagnetic radiation: among all the charged particles of the plasma -- electrons and protons and light nuclei -- a photon could travel only a short distance before being scattered.



Only after the Universe cooled enough to form atoms could photons travel freely through spacetime.

Nuclei captured electrons, forming atoms, at about 3000 degrees K, roughly 100,000 years after the big bang. Later still, in a cooler Universe, atoms could combine to form molecules, some of them, such as DNA, comprising millions of atoms. Today, in a cooler, friendlier stage of evolution, we find all around us the marvelous, fragile molecules of life.

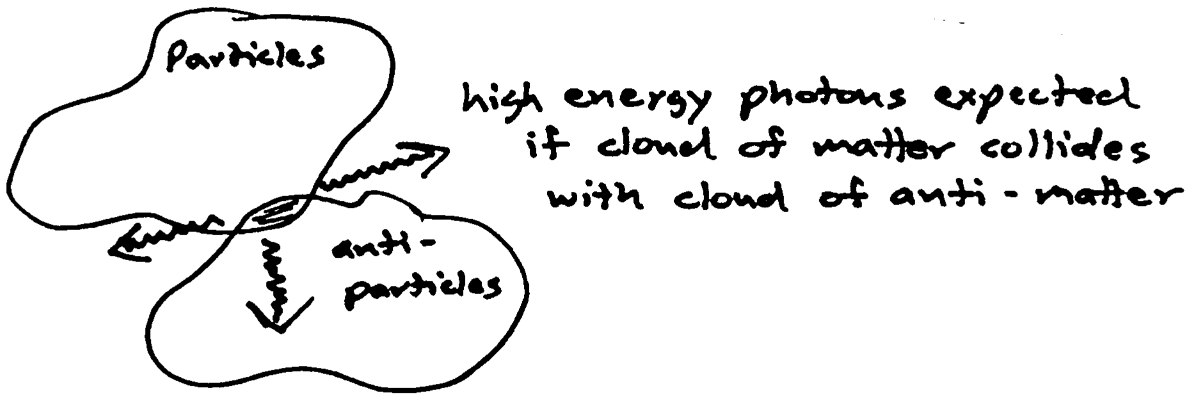
UNANSWERED QUESTIONS

All in all, we have a remarkably detailed understanding of the creation. Particle accelerators now probe conditions at the electroweak transition, and experiment confirms theory. However, a number of questions remain:

-- What produced the large-scale structure? Did it result from domain formation? Or from quantum fluctuations? Or was there some other mechanism at work?

-- Did inflation actually occur? If so, what was its mechanism? Particularly, is there really such a thing as a Higgs field? (No Higgs particles have been found, to date.)

-- Why is there a predominance of matter over anti-matter? Analysis of cosmic ray debris shows a ratio of about 1 antiproton for every proton -- about the number of anti-protons expected from cosmic ray collisions with atoms in the Earth's atmosphere: there is no evidence that cosmic ray anti-particles originate in vast clouds of anti-matter elsewhere. Nor do astronomers detect any evidence of the tremendous outpourings of energy expected if pockets of anti-matter were colliding with matter.



-- What is the fate of the Universe? Specifically, what is the value of Ω, the ratio of actual mass/energy to the mass/energy required for closure? (An open Universe lacks enough mass/energy to halt its expansion. A closed Universe contains enough mass/energy to stop the expansion and re-collapse).

-- What is the nature of the dark matter in the Universe? Astronomers know there is much more mass associated with galaxies than can be accounted for by observations in the visible spectrum. Hadronic matter (i.e. protons and neutrons) only accounts for about 10% of the mass required to close the Universe, but theory indicates Ω must be close to 1.

-- What preceeded the big bang?

In the following sections, we will explore answers to these questions and describe experiments, planned or in progress, that will test our hypotheses.

TESTING THE STANDARD MODEL

A number of experiments and observational programs underway to test the standard model:

New observatories are collecting information about large-scale structure. Dedicated telescopes map the distribution of galaxies, and the Cosmic Background Explorer satellite, just launched (11/89) will study the cosmic microwave background in unprecedented detail, seeking evidence of anisotropies at the creation that may elucidate the large-scale structure.

Larger ground-based telescopes, made possible by new mirror technology, look farther out into the heavens and back to the time when when galaxies first formed. A space-based telescope, the Hubble telescope, due for launch in early 1990, will lift our eyes above the "dirty window" of the atmosphere and give us a much clearer view of the distant, and earlier, Universe.

THE PREDOMINENCE OF MATTER OVER ANTI-MATTER

Asymmetry in the decay of X particles -- the particles responsible for unifying the strong force with the electro-weak -- may explain the predominance of matter over anti-matter. When X particles decay they may produce a slight excess of particles over anti-particles.

In Ch.7 we discussed asymmetries involving the weak force: beta decay preferentially emits electrons in one direction, and a neutral kaon is more likely to decay into positrons and pions than into electrons and pions.

One clue to X decay asymmetry is the ratio of photons to nucleons. There are about 10 billion photons for every proton in the Universe. Presumably, when X particles decayed they produced an excess of one particle in ten-billion. That is, the decay produced ten billion and one particles for every ten billion anti-particles. That one-in-ten-billion became the matter in our Universe, and the photons produced in particle/anti-particle anihilations became the background radiation.

$$\text{many X particles} \rightarrow \frac{10^9 + 1 \text{ particles}}{10^9 \text{ anti-particles}} \rightarrow 1 \text{ particle} + 2\times10^9 \text{ photons}$$

No conceivable particle accelerator can reproduce energies (10^19 GeV) required to create X particles and study their decay. However, experiments seeking evidence of proton decay may give indirect information: If X particles exist, they should catalyze the decay of protons. Physicists seek proton decay in huge underground pools of water or carbon tetrachloride (underground to limit "background noise" from cosmic rays). So far, none have been found, but more sensitive detectors are under construction.

In fact, proton decay -- <u>if</u> protons decay -- may offer another explanation for the apparent predominance of matter: antimatter may "hide" inside matter. One possible mechanism of proton decay is

$$p \longrightarrow e^{+} + \pi^{0}$$

proton — positron — neutral pion

The neutral pion has the composition $d\bar{d}$, a down/anti-down pair. It decays to gamma rays when the pair anihilates. The positron is the anti-particle to the electron, and it anihilates the electron that was paired to the original proton. In this (purely speculative) scenario, what we call "matter" is really a mixture of matter and antimatter.

<u>THE FATE OF THE UNIVERSE</u>

The fate of the Universe depends on the mass/energy density. If there is enough mass/energy to stop the expansion and collapse the Universe back on itself, a "big crunch" will end it all. An observer would witness cosmic evolution run backward: increasingly higher temperatures and densities will meld forces and fermions until the Universe disappears into a singularity.

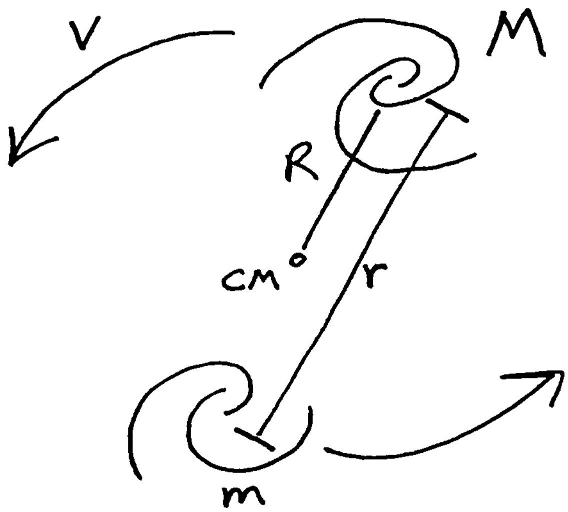
If the Universe is open (not enough mass/energy to stop the cosmic expansion) or flat (exactly enough mass/energy to balance the expansion) we look forward to a dull, cold dissipation. Neutron stars, white dwarfs, and brown dwarfs ultimately will radiate away gravitational energy and become cinders in the sky. If protons decay, matter will evaporate, and the resulting photons will cool toward zero energy in expanding spacetime.

Those other remnants of mass/energy, black holes, radiate themselves away by the Hawking mechanism. Hawking particles annihilate anti-particles, and the resulting photons drift through the expanding Universe, cooling.

The Universe stretches itself to sleep.

DARK MATTER

Astronomers can count stars and galaxies to estimate the total luminous mass in the Universe. They can estimate the amount of non-luminous mass by other means. For instance, measuring orbital separation and velocities of interacting galaxies indicates their total mass.



Galaxies in orbit around common center of mass

$$Mv^2/R = -GMm/r^2$$

centrifugal force — Gravitational attraction

Comparing these independent assessments, astronomers find less than one-tenth of the mass in a typical galaxy radiates at wavelengths we can detect. The predominance of mass in the Universe is dark.

Whether the Universe is open or closed depends on the amount of dark matter. Dark matter candidates include "ordinary" invisible matter, like planets, brown dwarfs, and cold gas clouds, and "extraordinary" matter like black holes and exotic particles.

Evidence related to the amount of primordial deuterium indicates there is too little ordinary matter to close the Universe. The amount of primordial deuterium was determined by proton and neutron densities at three minutes after the big bang. Astronomers can measure the amount of primordial deuterium, and those measurements indicate there cannot be enough protons and neutrons -- the most massive components of ordinary matter -- to close the Universe. In fact, deuterium studies indicate there is only about 10% the ordinary, hadronic matter required for closure.

New generations of telescopes will help map the distribution of dark matter in the Universe. With better information how galaxies orbit each other, astronomers will be able to calculate the total mass in galaxies and galaxy clusters.

The same underground observatories seeking proton decay recently helped establish new limits on the mass of the electron neutrino. Neutrinos produced in Supernova 1987 were detected, and the spread in their arrival times indicates their mass must be less than about 20 eV. Neutrinos are a prime candidate for the dark matter, and they require a mass of about 20 eV to close the Universe. New generation neutrino detectors, both those dedicated to studying astronomical sources and those associated with particle accelerators, will measure neutrino masses more accurately.

Proton decay itself (or absence thereof) would clarify the nature of dark matter: the mode of decay depends on whether sypersymmetric particles exist. Supersymmetric particles are likely candidates for dark matter.

Without supersymmetric particles:

$$p \rightarrow e^+ + \pi^0$$

With supersymmetric particles:

$$p \rightarrow \mu^+ + K^0$$

muon kaon

New cosmic ray telescopes, such as the Fly's Eye in the Utah desert, seek exotic particles among cosmic rays. X-ray and gamma-ray telescopes, scheduled for orbit in the 1990's, will map the high-energy sky and provide further clues to the distribution of black holes.

Particle accelerators are probing higher energies and, thereby, reproducing conditions that existed within a pico- (10^-12) second of the big bang. In October, 1989, physicists at the Stanford Linear Collider and CERN (the European accelerator laboratory) announced evidence, based on the decay of the Z particle, that there are at most three families of particles. This places constraints on the nature of the dark matter in the Universe and confirms the three-family model predicted by cosmologists on the basis of other evidence (ratios of the primordial elements.)

New generations of particle accelerators will look for exotic particles. No one knows the energy spectrum of candidates such as the supersymmetric particles, but they may be within reach of the superconducting supercollider. A major goal of the supercollider is to find the Higgs boson and explore realms where there may be other exotic particles associated with the dark matter.

Probably the most important discoveries will be those we can't even guess. Particle physicists cite the "Columbus phenomenon." Exploring higher energies with new accelerators is like Columbus' voyage: even though he didn't find a route to India, he found other strange, new lands.

WHAT PRECEEDED THE BIG BANG?

Conditions at the origin, within 10^-43 seconds after the big bang, are indescribable, given our current knowledge and mathematical sophistication. But that doesn't stop some intrepid physicists from speculating about what preceeded the big bang. Theoreticians such as Stephen Hawking, at Cambridge University, feel they have at least the basic tools to explore that realm.

Modelling conditions before the big bang, cosmologists assume an initial "vacuum," and quantum gravity, and they assume basic laws of quantum mechanics still apply.

First, consider the argument of Edward Tryon, of Hunter College of New York, that the net energy of the Universe is zero. If $\Omega = 1$, as many theorists believe it must, the gravitational potential energy of the Universe exactly balances the kinetic energies of the receeding galaxies. Also, the mass/energy of the universe exactly balances the (negative) gravitational energy it generates. (See diagrams on p.182 and p.183 .)

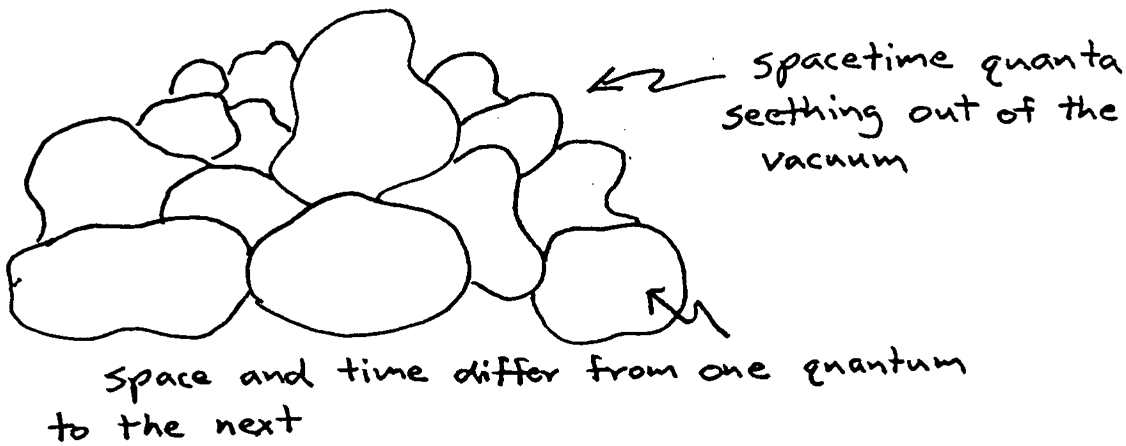
Similarly, other quantities balance: net momentum is zero, since there are as many galaxies flying north as flying south, as many flying east as west. Net electric charge is zero, too, since there are as many protons as electrons.

Now apply the uncertainty principle. If $\Delta E \Delta t \geq h$, and ΔE, the net energy of the Universe is 0, the Universe might exist for an indeterminate amount of time. Like virtual particles, the entire Universe might have begun as a quantum fluctuation -- an eruption out of the "vacuum."

By definition, the vacuum is the absence of mass and energy, but, as noted by John Wheeler, now at the U. of Texas at Austin, the vacuum "is the scene of the most violent physics." It seethes with virtual particles.

Moreover, it seethes with fluctuations in spacetime itself. Enter quantum gravity: at the smallest scales -- less than 10^-33 cm and before 10^-43 seconds -- gravity (i.e. spacetime) is quantized. It is disjointed. It comes in discrete bits and pieces. Living at that level, as described by David Schramm and Leon Lederman,* would be like taking a step from your living room toward the kitchen and finding yourself in the bathroom two weeks in the future.

* From _Quarks to the Cosmos_



Cosmologists imagine "bubbles" of spacetime, at the quantum level, ballooning then disappearing like virtual particles. Now suppose, just suppose, conditions in one of those bubbles were such that, instead of collapsing back into the quantum sea, it inflated.

Presto. A Universe.

This is speculation, and currently untestable. But theorists are beginning to model such scenarios with some mathematical rigor. The crux of the problem, currently, is understanding quantum gravity.

SUMMARY

In this chapter we discuss the origin, evolution, and fate of the Universe.

There is evidence (the three degree background radiation, proportions of primordial elements, and the cosmic expansion) that the Universe originated in a big bang. However, big bang theory by itself fails to explain certain observed features of the Universe: flatness, large-scale structure, and the horizon. These can be accomodated by inflation, a period of rapid expansion at the origin.

We model the evolution of the Universe by processes related to cooling (resulting from expansion): spontaneous symmetry breaking ("freezings") and shifts in particle/anti-particle equilibrium at different termperatures produce the particles and forces. The large-scale structure of the Universe may result from domains, with mass/energy concentrated along domain boundaries.

We don't yet know the fate of the Universe, but it is calculable. If there is enough mass to close the Universe, it will collapse back on itself. If the Universe is open or flat (not enough mass for closure) spacetime will expand indefinitely. By our current reckoning, the net mass/energy of the Universe (gravitational "pull" balancing the "stretch" of kinetic energy) is close to zero.

With better understanding of the particles and forces, and understanding quantum gravity, physicists may ultimately understand what preceeded the big bang.