THE UNIVERSE AT LARGE

Cosmology: Where in the $&#**

by VIRGINIA TRIMBLE

Being a compilation of tabular and narrative material designed to provide a framework for the more detailed and technical articles that appear elsewhere in this issue. It can also be used as a ready reference resource for when people ask you things like: "Are there any other galaxies in our solar system?"

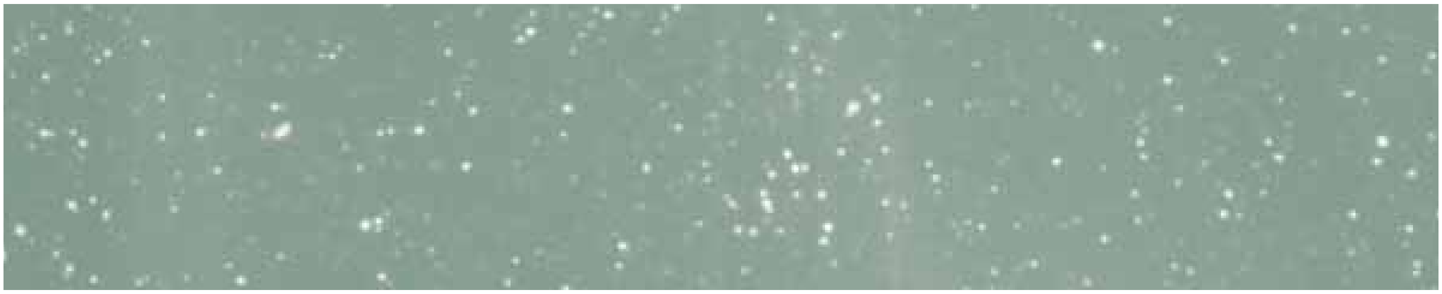
"Is it bigger than a bread box?" (Steve Allen, c. 1954, *What's My Line?*)

POWERS OF TEN

A remarkably delicate balance between the small scale phenomena of atomic and nuclear physics and the large scale phenomena of astronomy and cosmology is required for the Universe to be hospitable to chemically based life. Efforts to prove that this must be so are sometimes dignified by the name "anthropic principle." My goal here is the much more modest one of indicating where we fit into the range of objects and events. A subsidiary goal is to use common astronomical terms (solar system, galaxy, Local Group, and so forth) so many times in suitable contexts that you will never again have an excuse for forgetting which fits inside which others.

Time, length, and mass are advertised as the most fundamental physical quantities (though the $c = G = 1$ relativists and the $c = h = 1$ particle physicists manage to survive with only one, length or energy). Taking one example of each, we find:

- Geometric mean of diameter of atomic nucleus and distance to the nearest star = 14 feet, the height of a dean at a prestigious university
- Geometric mean of halflife of excited nucleus and age of the Universe = 2 minutes, upper limit to the time you will listen to telephone solicitor
- Geometric mean of mass of hydrogen atom and mass of sun = 60 kg, large dog or small dog owner.



% Universe Are You?

Time Scales of Human and Astronomical Phenomena

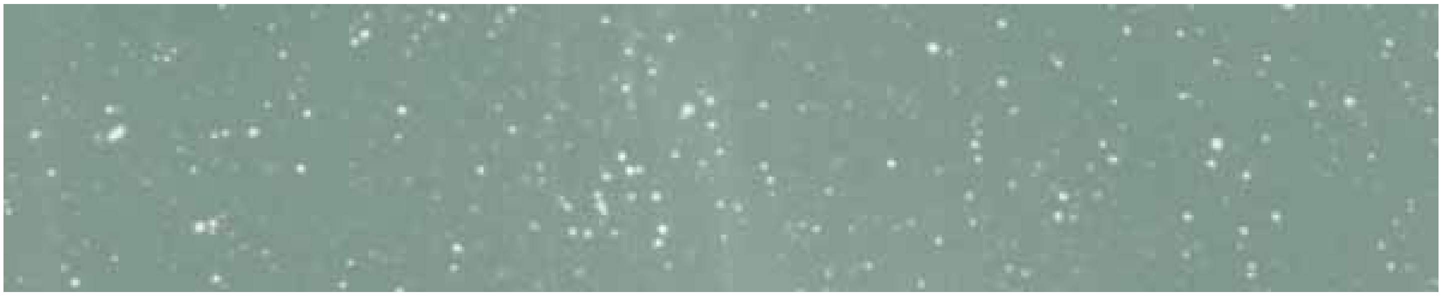
Log *t* (years)	**Event**
-50	Planck time
-9	shortest human reaction time; rotation of Crab Nebula pulsar
-8	heart beat after running; QPOs in X-ray binaries
-7	breath after running; core collapse in type II supernova, rotation periods of old pulsars
-6	time you expect to wait when told “just a minute”; most rapid rotation of white dwarfs
-5	attention span of freshman physics class; solar oscillations
-4	the 50-minute hour; orbit periods of cataclysmic binaries
-3	work day; most rapid variability in active galaxies, quasars, etc.
-2	long weekend; pulsation and orbit periods of moderately compact stars and binaries
-1	number of days I need in a month; pulsation periods of Cepheid variables; orbit periods of “hot Jupiters”
0	length of small NSF contract; orbit period of earth, detectable changes in luminosity of most active galaxies and in pulsation and orbit periods of stars and binaries
+I	lifetime of breadbox; age of SN 1987A, evolution of stars undergoing last helium flash
+2	age of professor; life of nova shell
+3	significant changes in spoken languages; age of Crab Nebula as now seen
+4	neolithic culture (agriculture, cities, pottery, baskets, writing); lifetimes of planetary nebulae
+5	paleolithic culture, anatomically modern man; ages of youngest detectable protostars and star bursts
+6	assorted hominids, earliest tools; lifetime of very massive star
+7	giant mammals; lifetime of progenitor of SN 1987A, lifetimes of pulsars
+8	dinosaurs; lifetime of moderate-mass stars, crossing times in dense cores of clusters of stars and galaxies
+9	single-celled life; relaxation times in dense cluster cores
+9.66	age of solar system
+10	lifetime of solar mass star, dynamical time scale of less dense clusters
+10.2	age of Universe

The first three tables provide additional examples of logarithmic steps in length, time and mass that take us from atomic to astronomical scales. The units are centimeters, years, and grams. Some powers of 10 are missing because I couldn’t think of anything interesting that exists or happens on that scale. Suggestions from readers of items to fill the gaps would be much appreciated.

In these days of energy-consciousness, one ought perhaps to have one more table, of energies or a related quantity. The one shown on page 55 is called power if you are a householder and paying for it, or luminosity if you are an astronomer and not paying for it. Students in introductory astronomy courses are always a little surprised by the enormity of the answer they find to the question: What would it cost you to keep the sun shining for a year if you had to pay Southern California Edison Company 12¢ per kilowatt hour to do it?

A COOK’S TOUR OF THE UNIVERSE

The Earth is a planet, and there are times when one feels that the most important issue is whether the



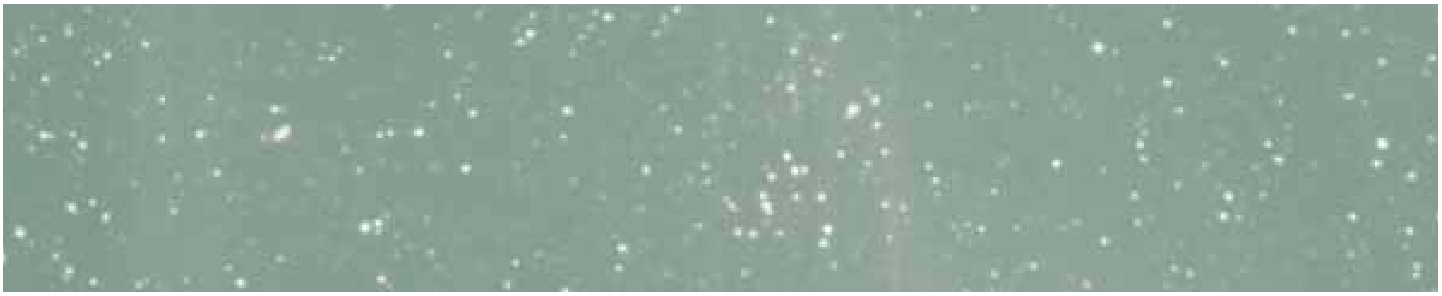
capital E and the “the” are forbidden, compulsory, both, or neither. Planets are undoubtedly the most familiar of astronomical objects, since most of us have lived on one most of our lives (if there is anyone out there for whom this is not true, I don’t want to know about it). The nine planets of our Solar System can be categorized as terrestrial or earthlike (meaning made of rocks and metals with at most thin layers of other stuff) and Jovian or Jupiterlike (meaning made mostly of gases, especially hydrogen and helium). The former are Mercury, Venus, Earth, and Mars; the latter Jupiter, Saturn, Uranus, and Neptune. Pluto is a misfit, possibly related to the moons of the outer Jovian planets or to the mostly-icy denizens of the Kuiper belt slightly further from the sun. Kuiper belt objects are the source of comets with relatively small orbits. The (still unseen) objects that feed into the supply of nearly-parabolic comets come from the Oort Cloud.

We now know of a dozen or more planets orbiting other stars (*Beam Line*, Vol. 27, No. 2, p. 31–35), the largest class of which have masses like the Jovian planets but orbits like the terrestrial ones, and so are called hot Jupiters by their friends. We expect, but do not know, that observations will eventually reveal large numbers of other planetary systems, both like and unlike ours, and that moons, comets, asteroids, meteors, and so forth will be common features. No comet with an orbit suggesting it originally belonged to another star has ever been seen. Planets and subplanetary detritus are not a major contributor to the mass or luminosity anywhere, but they are, of course, the only life-bearing entity we know of.

The Sun is a star, with a mass (2×10^{33} g), radius (7×10^{10} cm), luminosity (4×10^{33} erg/sec), age (4.55 Gyr), heavy element abundance (1.7 percent everything that is not hydrogen or helium), and all the other properties you can think of, very much in the middle of the range for stars in general. The extremes of the ranges (for example all stellar masses are between 0.085 and 120 $M_\odot$) are understood in terms of the physics of gravitation, electromagnetism, and nuclear reactions, though the distributions through the ranges are not. We also

Sizes of Terrestrial and Celestial Objects and Systems

Log l (cm)	**Object (etc.)**
-33	Planck length
-13	atomic nucleus (1 fm)
-8	Bohr orbit; divide between X-ray and gamma-ray wavelengths (1 Angstrom)
-4	near infrared wavelengths (1 μm), largest bound interstellar atoms
-3	magnetic domains
0	distance between atoms in interstellar space; rules of thumb
+l	small bread box
+2	distance between atoms in intergalactic space; people, radio waves
+3	biggest animals
+4 to 5	biggest buildings and trees
+6	tallest mountains, comets, small asteroids, and moons; neutron stars, Schwarzschild radii of stellar mass black holes (approximate division between dominance of solid body and gravitational forces)
+7 to +8	moderate to big moons and asteroids
+9	earth, white dwarfs
+10	Jupiter, brown dwarfs
+11	sun and other main sequence stars
+12	distance of “hot Jupiters” from parent stars
+13	sun-earth distance (1 astronomical unit)
+15	diameter of Pluto’s orbit, heliosphere
+17	Oort cloud of comet progenitors (limit of solar system)
+18	widest bound star pairs; core of dense star cluster
+19	diameter of globular star cluster (3 parsecs)
+20	giant molecular cloud
+21	width of spiral arm in Milky Way
+22	thickness of disk of old stars in Milky Way
+23	diameter of visible part of Milky Way and other biggish galaxies
+24	diameter of massive halo of Milky Way and other biggish galaxies, distance between galaxies in rich cluster
+25	core of rich cluster of galaxies
+26	diameter of rich cluster of galaxies; our distance from Virgo
+27	largest scales on which we see structure and streaming in the Universe
+28	distance light travels in 10^{10} years (radius of “observable” Universe)



Masses of Terrestrial and Celestial Objects and Systems

Log M (grams)	Object (etc.)
-27	electron
-24	proton
-19	big molecule
-16	small virus
-5	Planck mass
-3	large cell (not ostrich egg!)
0	grain of salt you should take all this with
+2	typical bread box
+5	large people
+16	mass of fresh water needed each year for optimum health of current world population
+18	comet, small asteroid or moon (dividing line between dominance of solid body forces and gravitation)
+27	terrestrial planets
+30	Jovian planets
+32 to 35	stars
+36	typical young star clusters (unbound)
+39	large old star clusters giant molecular clouds
+39 to 43	small galaxies
+45	big galaxies
+48	rich cluster of galaxies
+56	Universe to $r = c \times$ age

A Few Powers and Luminosities

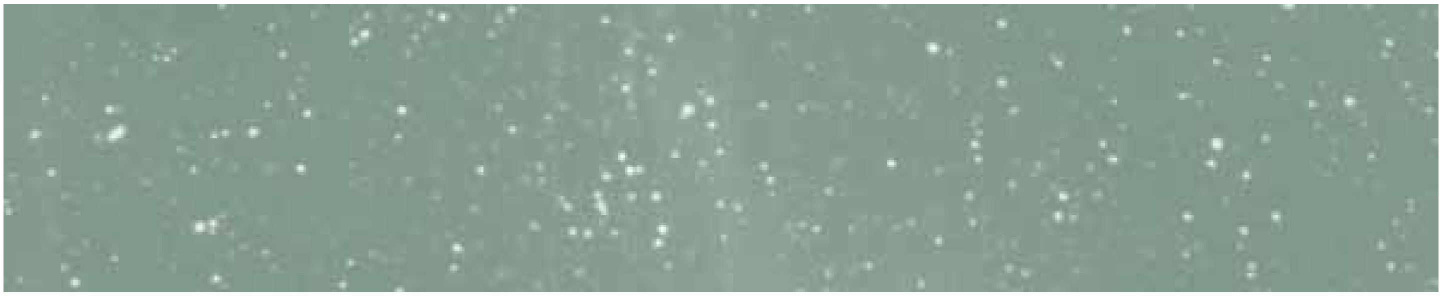
Log L (erg/sec)	Object (etc.)
-3	hardworking hydrogen atom
+7	hardworking bread box (thermal radiation at room temperature)
+9	human metabolism
+10	hardworking horse
+22	world energy consumption (*very* crude)
+24	solar flux hitting earth
+30 to 39	stars (sun = 33.6)
+44	Milky Way galaxy
+54	"observable" Universe

have a reasonable grasp of what stars do for a living as a function of mass and time. The sun is about half way through using up its available hydrogen via the proton-proton chain of fusion reactions to form helium; Betelgeuse has used all its hydrogen and is not long for this galaxy; and FG Sge has probably just had the last gasping flash of nuclear reactions (turning helium to carbon and oxygen) that it will ever be allowed. Stellar lifetimes are proportional to M^{-x}, where x = 1–4, because large mass means high central temperature (so that pressure can balance gravity) and so rapid reactions and very large luminosity.

Most of the dots of light you see in the sky are actually gravitationally bound pairs or binary stars. It is not entirely true that having a stellar companion and having habitable planets are mutually exclusive, but almost. That we orbit a single star is not, therefore, improbable.

Star clusters are the main or only sites of star formation (at least here and now, and probably also there and then). The process of a large cloud of cold gas collapsing and fragmenting into stellar mass cores is a collective one, some times triggered by encounters with other clouds, expanding supernova remnants, or other shocks. The majority of clusters so formed dissipate (because only 1 percent or so of the gas actually ends up in stars). Thus we see a good many young clusters (like the Pleiades, the Hyades, the Jewel Box, and other favorite objects for small telescopes) of various masses, but only big, compact old clusters (called globular clusters) are still around. It would be fun to be able to point to other stars in the sky and say that they formed in the same cluster with our sun. But the sibship has orbited the galactic center dozens of times since birth, and the members have strayed beyond recovery.

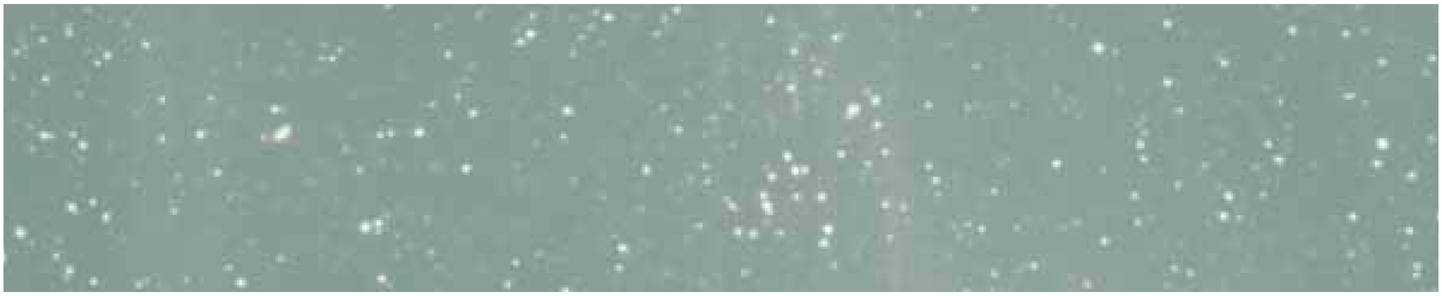
The Milky Way is a galaxy, consisting of something like 10^{11} stars, the majority in a fairly thin disk, rotating every 200,000,000 years or so, and the rest in a more spheroidal non-rotating halo. We cannot draw very good pictures of it because of living inside, where the view is partly blocked by dust, and because some methods of measuring distances are not single-valued. Available evidence is, however, consistent with its being a fairly typical spiral galaxy (meaning not quite as pretty as the



Cosmic Inventory

What	Where		What Else
PLANETS (ours is called Earth)			
9 planets	live in (our) Solar System	with	The Sun, moons, comets, etc.
other planets	live in (other) solar systems or planetary systems	with	one star per system + stuff
STARS (ours is called the Sun)			
all stars	formed in clusters*	with	10–10^6 other stars
few stars	still live in clusters*	with	10–10^6 other stars
90% of all stars	live in binary (etc.) systems	with	1–5 other stars
most/all stars	formed in and still live in galaxies	with	10^6–10^{12} other stars
GALAXIES (ours is called the Milky Way or The Galaxy)			
most galaxies	live in small groups	with	a few to a few dozen other galaxies + intracluster gas
a few galaxies	live in rich clusters*	with	1000 or more other galaxies + very hot gas
GROUPS OF GALAXIES (ours is called the Local Group)			
most small groups	are part of more extended structures	with	other groups and clusters
RICH CLUSTERS* OF GALAXIES (the nearest is called the Virgo Cluster)			
rich clusters	are easy to see and so used as tracers		
LARGER SCALE STRUCTURES (ours is called the Virgo Supercluster)			
small groups and rich clusters	define more or less the same density inhomogeneities, often in sheets or filaments	with	other groups and clusters up to 100 Mpc away
UNIVERSES (ours is called the Universe)			
4-d universes	may live in higher dimension spaces	with	other universes

It is entirely possible (but undesirable) to confuse clusters of stars with clusters of galaxies (verbally, not if you are looking at one). The phrase “star cluster” is OK (and there are two types, called globular clusters and galactic or open clusters). The phrase “galaxy cluster” will almost always cause confusion. “Cluster of galaxies” is safe.



ones most often shown in elementary text books). Its spiral arms are clearly present but do not extend continuously all the way around. Virtually all known spiral galaxies have masses within a factor 10 of that of the Milky Way. In all cases 90 percent or so of the mass is not normal stars or gas. We call it dark matter and discuss it constantly at conferences and in books and papers. Atlases of galaxies are dominated by spirals partly because they are pretty and partly because they are both brighter than the commonest kind and found preferentially in our (relatively low density) part of space.

Giant elliptical galaxies, especially the ones at the centers of rich clusters, can include as many as 10^{13} stars plus dark matter. Dwarf ellipticals and dwarf spheroidals have only a million or a billion stars. They are the commonest sort, but, being so small, contribute rather little to the mass and luminosity of the Universe as a whole. Irregular galaxies include low-mass ones with lots of gas and current star formation (like the Large and Small Magellanic Clouds), but also everything else that doesn't look like a spiral or an elliptical, for whatever reason. In general, we find ellipticals near the centers of rich clusters, while spirals prefer the outskirts or homes in small groups. The correlations of mass, morphology, location, chemical composition, and other properties of galaxies are understood by a number of astronomers. Unfortunately they understand somewhat different things.

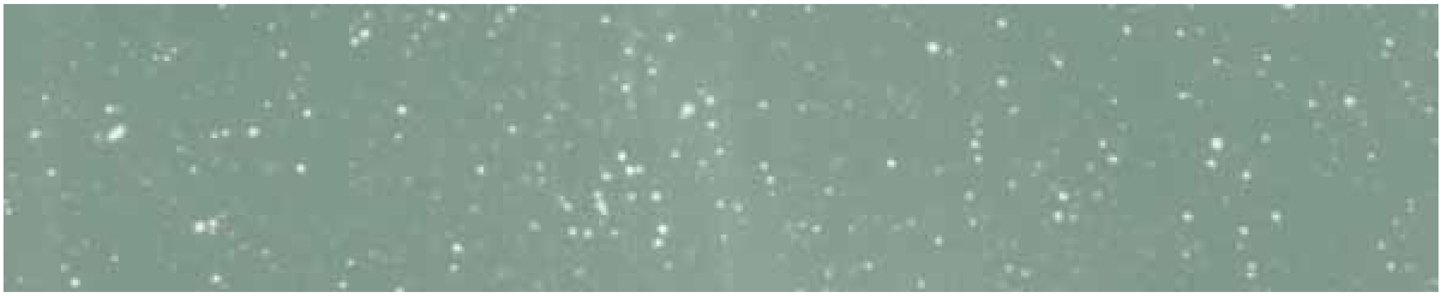
Truly isolated galaxies may never exist. Certainly as a rule we find them to be clustered on a wide range of scales, from pairs and small groups up to rich clusters and superclusters. Understanding how the galaxies formed and got into their present heirarchical structures is probably the most important unsolved problem of modern astrophysics.

The Local Group is a small group of galaxies. It includes two large spirals, us and the Andromeda Nebula (and would look like a binary galaxy from far enough away). The other members are a moderate-sized spiral (M33) and more than two dozen irregulars and dwarf spheroidal galaxies. We are currently finding new, small, obscure members of the Local Group at a rate of about one per year.

The Virgo Cluster is the nearest of the relatively rich clusters of galaxies. Its name indicates merely that you look past the stars of the constellation Virgo to see it, and the distance is anything from 10 to 25 million parsecs, depending on who you ask. A still richer cluster, further away, is called Coma (for the same reason). We live on the outskirts of the region of space where the motions of galaxies are seriously perturbed by the mass of the Virgo cluster and so can claim to be members of the Virgo supercluster. One implication is that our velocity of recession from the Virgo cluster (or conversely its from us) is smaller by 100–250 km/sec than would be the case if the cluster weren't there.

The evidence for deviations from homogeneity and smooth expansion in the Universe becomes less persuasive when we look at still larger scales but does not vanish. The largest-scale structures seem to be sheets and filaments of galaxies and clusters outlining voids with density well below the cosmic average. Voids of 30–50 Mpc are common, and one can probably trace coherent structures of 100–200 million parsecs. Streaming velocities of at least a few hundred km/sec around smooth Hubble expansion are found over comparable size regions, and we are in the process of trying to associate particular velocity perturbations seen among the galaxies with the masses that cause them and with the velocity-induced dipole we find for the 3K microwave background radiation. This last is some 600 km/sec (after allowance for the earth's orbit speed, rotation of the Milky Way, our orbit around the Andromeda galaxy, and a few other things) and also requires explanation in terms of a scenario for the formation and clustering of galaxies.

The Universe is a universe whether capitalized or not. A convenient definition is "all of the four-dimensional space-time that we can ever communicate with and the contents thereof." It is convenient because it will equally offend the beginning student (who does not understand the words, at least in that order) and the advanced theoretical physicist (who does not agree with the words, at least in that order). It is older than a breadbox (by 10–20 Gyr), bigger than a breadbox (probably infinitely so), and not a good source of ground truth.



Key Events from the Big Bang to the Birth of Richard Nixon

early, hot, dense phase (comprising baryogenesis, big bang nucleosynthesis and probably other things)
*formation of galaxies and large scale structure
*first generation of stars (pure hydrogen + helium) initial nucleosynthesis and distribution by supernovae
second and later generations of stars
additional nucleosynthesis, including secondary products, distribution by supernovae, novae, planetary nebulae, etc.
formation of planetary systems with terrestrial planets
chemical evolution
origin of life (self-replicating systems with information storage capacity)
biological evolution
tool-making, radioastronomy, etc.

It is possible that these two stages were more or less simultaneous or even inverted.

AN OUTLINE OF HISTORY

First came the *Big Bang*, meaning that the entire Universe (in the sense just undefined) passed through a state of nearly homogeneous thermodynamic equilibrium at a temperature in excess of 10^{10} K, out of which it has been expanding ever since. (Evidence that there was such a state is discussed in the *Beam Line* Vol. 25, No. 1, p. 25.)* Early in the expansion, the baryonic material gradually transformed itself from a soup of interacting protons, neutrons and electrons to hydrogen and helium nuclei in a ratio of about 10:1, with much smaller numbers of deuterium and lithium-7 nuclei also forming. We suppose that there is a sea of cosmic neutrinos sent freely on their way at this time, though it has yet to be seen.

The photons slip out of thermal equilibrium with the baryons at the epoch called *recombination or decoupling*, at a temperature near 3000 K (corresponding to a redshift of about 1000), after which atoms are mostly neutral for a while and photons can stream freely through space. At about the same time, the energy density in radiation falls below that in matter.

Next comes *structure formation or galaxy formation.* The idea is that the low-amplitude density fluctuations that have been present since (before) the Big Bang grow more or less linearly with redshift (as fast as they can in an expanding substrate) until they approach non-linearity, and can start doing things that are too difficult to calculate analytically. It is almost impossible to make this happen in a pure-baryon universe without ruffling up the background photons by a factor 10 or so more than is observed ($\Delta T/T$ = something $\times 10^{-4}$ vs something $\times 10^{-5}$). Non-baryonic dark matter is an enormous help, because its fluctuations can start amplifying toward superclusters

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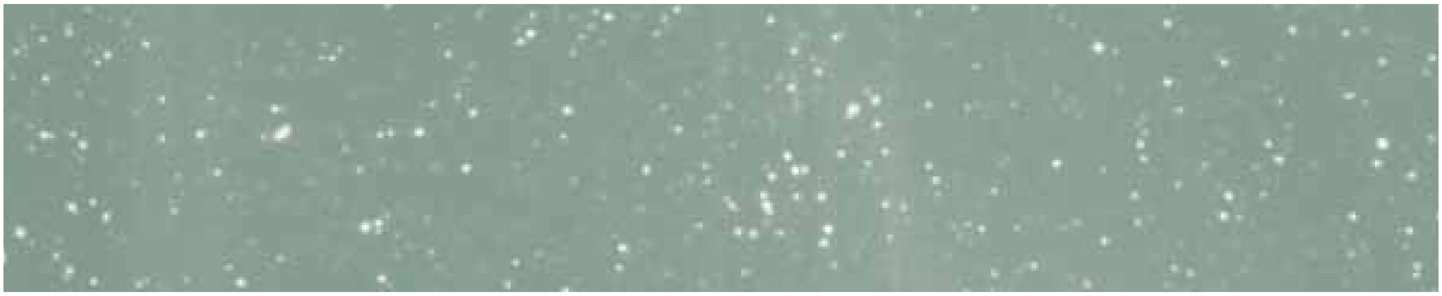
**As for what came before the Big Bang, the short (polite) answer is that the state of thermodynamic equilibrium washed out nearly all the evidence. Probable exceptions include (a) a spectrum of low-amplitude density fluctuations required if we are eventually to get galaxies; (b) the amount of excess of baryons over anti-baryons relative to the number of photons; and perhaps (c) the dark matter, whatever it is.*



and voids before $T = 3000$ K without distorting the photons except gravitationally. Then, after decoupling, baryonic gas flows into existing potential wells to start becoming galaxies (etc.). Structure formation is an essential early step, because the average baryonic density of the Universe is about one atom per cubic meter, and, in the absence of density fluctuations, no committee could ever have more than one member (possibly not such a bad state of affairs).

Astronomers have been asking for more than 30 years whether structure arose in a "bottom-up" (little things form first and heirarchically cluster) or "topdown" (big things form first and fragment) fashion. The answer appears to be "no." That is, neither sort of scenario in its pure form does a good job of matching the patterns of clusters and voids that we see in both real and redshift space. Neither, truthfully, do the more complex scenarios, however much you multiply entities in the form of hot + cold dark matter, topological and nontopological defects, non-zero cosmological constant, tilted spectrum of the initial-perturbations, or whatever.

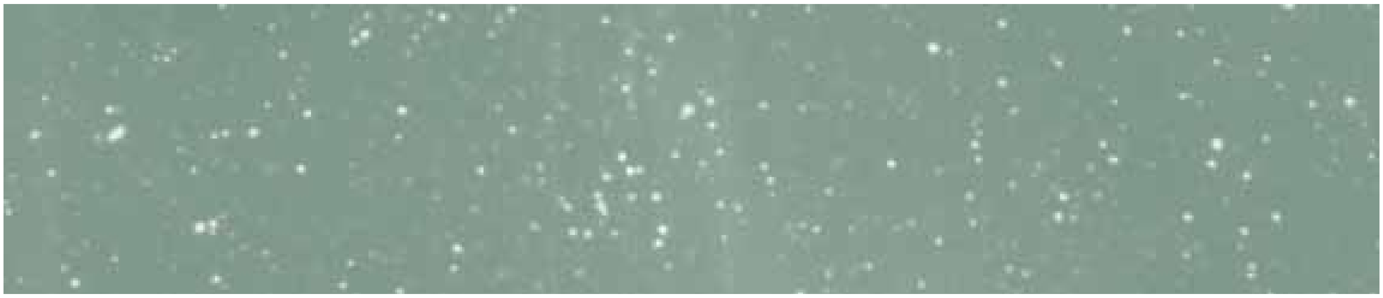
Next come *stars*. In fact, the earliest ones may well precede most of the large scale structure we now see. They must have been pure hydrogen and helium, and none are left. Either they were all massive and died long ago, or they have painted themselves with a concealing thin coat of heavy elements by passing through interstellar gas over the years.

Nucleosynthesis is the process of building up heavy elements from lighter ones and occurs in all stars. Massive stars live only millions of years and ones like the sun billions of years). Thus we expect chemical enrichment to begin with elements (like oxygen) that can be made from scratch in the most massive stars and liberated in core-collapse supernovae, to be followed by things like iron (made in other kinds of supernovae) and carbon (made and liberated mostly by intermediate mass stars). Still later appear the elements which can be made only in second-generation stars with some initial heavy elements present at their birth. These included nitrogen (much of which comes from proton captures on previously-existing carbon and oxygen) and the products of slow neutron capture on iron-group seeds (the *s*-process), including barium and yttrium. The detailed abundance patterns both of old stars in our galaxy and of gas in galaxies where star formation has been slow are a reasonable match to what you would expect from these theoretical considerations.

Planets co-form with stars. But the advent of terrestrial planets must await the increase of heavy elements to some critical value. This value is not known (and is of some importance if you want to estimate the number of habitable planets in the Milky Way). We currently have no information on the composition of any other stars with terrestrial mass planets, nor have the theorists done much exploring of how the evolution of proto-planetary disks depends on composition. Thus we do not know whether it is interesting that the sun is one of the most metal-rich stars in its neighborhood.

Chemical evolution, in this context, is the build-up from simple molecules like water, carbon dioxide, and ammonia to complex ones like amino acids, phosphates, and bases. It has gone some ways already in interstellar gas, where we see many dozens of compounds, including methyl and ethyl alcohol, HC_7N (no, you can't buy that one at the drug store), and formic acid.* Carbon-rich meteorites harbor a wide range of amino acids (including ones we don't use) and other macromolecules. One would very much like to answer the question: Where did chemical evolution go from there? Life on earth has long ago eaten the traces of its own birth. Places we might look for hints of the later history include comets that have not yet been much exposed to sunlight and sub-surface layers on Mars. It is perhaps a little difficult to make this latter sound like an exciting reason for multiple Martian expeditions. Luckily the search strategy is essentially similar to that for actual life, present or past.

**The UCI campus animal is the anteater (basically because we are a relatively young university and all the good animals were taken), and it is left as an exercise for the reader to supply some appropriate pun or other witticism. For extra credit, have a go at the UC Santa Cruz animal, the banana slug.*



Life can be defined however you wish. If you allow me to describe it as the appearance of molecules that can both store information and reproduce themselves accurately (using much less than their rest mass energy), then it becomes obvious that evolution from slime molds to politicians is practically inevitable. In a truly infinite Universe, this must have happened an infinite number of times. It has happened at least once even in our own parochial little Local Group. But, since astronomy handed over to chemistry and biology a paragraph or two back, it is time for me to tiptoe away and leave you to study for the quiz. It will be open book, and the main questions will require you to order astronomical objects by their sizes and ages.

Suggestions for Further Reading

The Origin and Evolution of the Universe (ed. B. Zuckerman and M. A. Malkan, 1996, Jones and Bartlett) has chapters devoted to each of the major events in cosmic history.

The Anthropic Cosmological Principle (by J. D. Barrow and F. J. Tipler, 1985, Oxford University Press) is the standard discussion emphasizing why the Universe might be so hospitable to complex, intelligent life.