Virginia Trimble

Cosmology: Man's Place in the Universe

In which we review the history of the Universe and explore the relationships between its properties and the presence of life

What I want to try to do in the next few pages is to review the history of the Universe from the earliest times for which we have any evidence down to the present day, with special emphasis on how conditions favorable for life seem to have arisen, and then to explore the extent to which this history is dependent upon the Universe having roughly the properties it does, and finally to inquire into the implications of varying those properties.

A Cook's tour of the universe and its early history

Let's start by taking a look (Table 1) at the scales of the things we will be discussing. Notice that the human scales in each case are close to the geometric means of the astronomical and atomic scales. Thus, we should not be surprised to find that our presence here is dependent both on the large-scale phenomena of astronomy and on the details of atomic physics.

The largest phenomenon of all is, of course, the Universe itself. It is important to be sure we agree about what we mean by "the Universe" and the various other terms we will be using. The earth and eight other planets, about 34 moons, and a variety of smaller objects are in gravitationally bound orbits around a star called the sun. We refer to this grouping as the Solar System. It has a total mass of about 2×10^{33} grams (virtually all in the sun, though most of the angular momentum is in the planets), a diameter of about 2×10^{15} cm, and an age of about 5×10^9 yr. The sun is a perfectly typical star, having a mass of 2×10^{33} g (the solar mass, abbreviated $M_\odot$, is often used as a unit for other stars), an electromagnetic radiation energy output of 4×10^{33} ergs/sec (one solar luminosity, $L_\odot$), a spectrum approximately that of a 5700 K black body, a radius of 7×10^{10} cm ($1\ R_\odot$), and a composition by weight (at least in its outer, visible layers) about 73% hydrogen, 25% helium, and 2% everything else (about half of it carbon and oxygen).

The sun, in turn, is one of about 2×10^{11} stars that are gravitationally bound in a rotating, roughly spherical system (although the most conspicuous members are concentrated in a plane considerably flatter than the proverbial pancake) called the Milky Way Galaxy (or just the Galaxy). It has a mass of at least 3×10^{44} g (but see Ostriker et al. 1974 for evidence that it may be ten times more massive than this) and a diameter of about 10^{23} cm. It is at least 10^{10} yr old. The Milky Way, in turn, is bound in a small cluster of about 30 galaxies (all but one much less massive than ours) called the Local Group. It is not certain whether higher-order structures are gravitationally bound, but there does seem to be some clustering of the clusters (Hauser and Peebles 1973). The clusters range from small ones like the Local Group up to much richer ones containing thousands of galaxies and having masses of 10^{15} $M_\odot$. Completely isolated galaxies are probably rare (Tifft and Gregory 1976). The properties of the medium between the galaxies (except within the rich clusters, where a hot intracluster gas is often a strong source of X rays; Kellogg et al. 1973) are very poorly known. The average density could be anywhere from 0 to 10^{-5} particles cm^{-3}, the intergalactic medium comprising anywhere from 0 to 90% of the total average density over large regions of space. If the density is high, the matter must also be rather hot ($\sim 10^6$ K) or exceedingly clumpy to prevent detection. A preponderance of the evidence (as summarized, e.g., by Gott et al. 1974) now seems to favor an intergalactic density at the low end of the possible range.

The clusters of galaxies (or perhaps the superclusters) appear to be distributed at random through space, with separations such that they contribute an average density of at most 10^{-31} g cm^{-3} (Ostriker et al. 1974). There is no detectable falloff of the density of clusters of galaxies out to the largest distances at which they can be seen with present telescopes. This is about 10^{28} cm or 3000 Mpc (Megaparsecs; one parsec = distance at which an object has a *par*allax of one *sec*ond of arc = 3×10^{18} cm), corresponding to a light travel time of

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several billion years. We probably observe quasi-stellar objects (quasars) at much larger distances, but their properties are so poorly understood that they add very little to our knowledge of the large-scale structure of the Universe.

The volume surveyed is sometimes called the observable universe, and it is the region for which we have direct observational evidence. Spectra of the vast majority of galaxies within this region and outside the Local Group show red shifts which are proportional to their distances from us. These are normally interpreted as Doppler shifts, implying that all the objects within the observable universe are receding from one another at speeds proportional to their separations. The proportionality constant is generally called the Hubble constant. Its value (at the present time in the history of the Universe and of astronomical research) is about 57 km/sec/Mpc (Sandage and Tammann 1975). This proportionality (Hubble's Law) is our chief evidence that the Universe is expanding.

Within the framework of some reasonable theory of gravity, like General Relativity, we can extrapolate beyond the observable region and try to learn something about the entire four-dimensional space-time volume that can, in principle, be connected to us by light signals. The word *Universe* properly refers to this entire volume and, in this sense, is not much more than 50 years old, dating back to the realization that certain bright, fuzzy patches in the sky are, in fact, galaxies like our own (Curtis 1919; Hubble 1925).

Efforts to model the Universe go back just about as far and always involve a variety of simplifying assumptions. The simplest possible set of such assumptions has proved remarkably successful. We assume (1) that General Relativity is the right theory of gravity (probably without the arbitrary additional repulsive kind of gravity, the cosmological constant, introduced by Einstein to permit a static universe), (2) that the expansion implied by Hubble's Law is isotropic and would be seen to be isotropic by any observer moving with the galaxies, (3) that the Universe is homogeneous on a sufficiently large scale, and (4) that pressure is presently unimportant and that the mass-energy of the Universe is now mostly in the form of matter rather than radiation or other zero-rest-mass particles. Under these assumptions, the Einstein field equations yield a two-parameter family of models, called the Friedmann models, and the problem of deciding what the Universe is like reduces to finding values for the two parameters. These turn out to be the present value of the Hubble constant, H_0, which we know quite well, and the present value of the local average density of mass-energy (in all forms), ρ_0, which may be uncertain by a factor of 100. Given values of these, we can answer a variety of interesting questions, like: How old is the Universe? Is it finite or infinite in volume? Will the present expansion continue forever or will gravity cause the galaxies to slow down and eventually fall back together? Roughly, a low-density ($\rho_0 < 10^{-30}$ g cm^{-3}) universe has infinite volume, is 16–20 billion years old, and will expand forever; while a high-density universe ($\rho_0 > 10^{-30}$ g cm^{-3}) has finite volume, is less than 16 billion years old, and will eventually (in a hundred billion years or so) turn around and recontract. With many ifs, buts, maybes, and other caveats, evidence now available seems to indicate that our universe is a low-density one (Gott et al. 1974). Notice that if the universe is to be a high-density one, then $\gtrsim 90\%$ of the mass-energy is neither visible nor in galaxies.

Under the same assumptions, there are some questions that we cannot answer or even ask in a meaningful fashion. One of these is Where is the center of the Universe? The assumed homogeneity and isotropy of the expansion imply that all the matter was arbitrarily close together a finite time ago in the past, so that the center of the expansion exists only in four dimensions and is something like the instant of creation; while the geometry of space-time within the framework of General Relativity is such that space is either infinite (and so can have no center) or uniformly curved, so that all points are equivalent (rather like the curved surface of the earth, only in three dimensions). It will become clear shortly that "what came before the present universe?" is another of these unanswerable questions.

With this background, we can now say that the earliest event for which we have any evidence is a time about 15–20 billion years ago when the Universe was much hotter and denser than it is at present. The evidence for the time scale comes from (1) running the Hubble expansion backwards in time and asking how long ago would all of the galaxies have been arbitrarily close together (H_0 = 50 km/

Table 1. Scales of phenomena being considered

Atomic scale	**Human scale**	**Astronomical scale**
	TIME	
Nuclear decays *10^{-14} seconds*	Attention span of physics undergraduates *1 minute = 60 seconds*	Age of the Universe *6×10^{17} seconds*
	MASS	
Hydrogen atom *2×10^{-24} grams*	Typical Sigma Xi member *140 lb = 6.5×10^{4} grams*	Solar mass *2×10^{33} grams*
	LENGTH	
Diameter of atomic nucleus *10^{-13} centimeters*	Height of dean at prestigious university *18 feet = 546 cm*	Distance from sun to next star *1 parsec = 3×10^{18} cm*
RATE OF	ENERGY	OUTPUT
Atomic decay *10^{-3} erg/second*	Output of large electricity generating plant *200 megawatts = 2×10^{15} ergs/second*	Luminosity of the sun *4×10^{33} ergs/second*

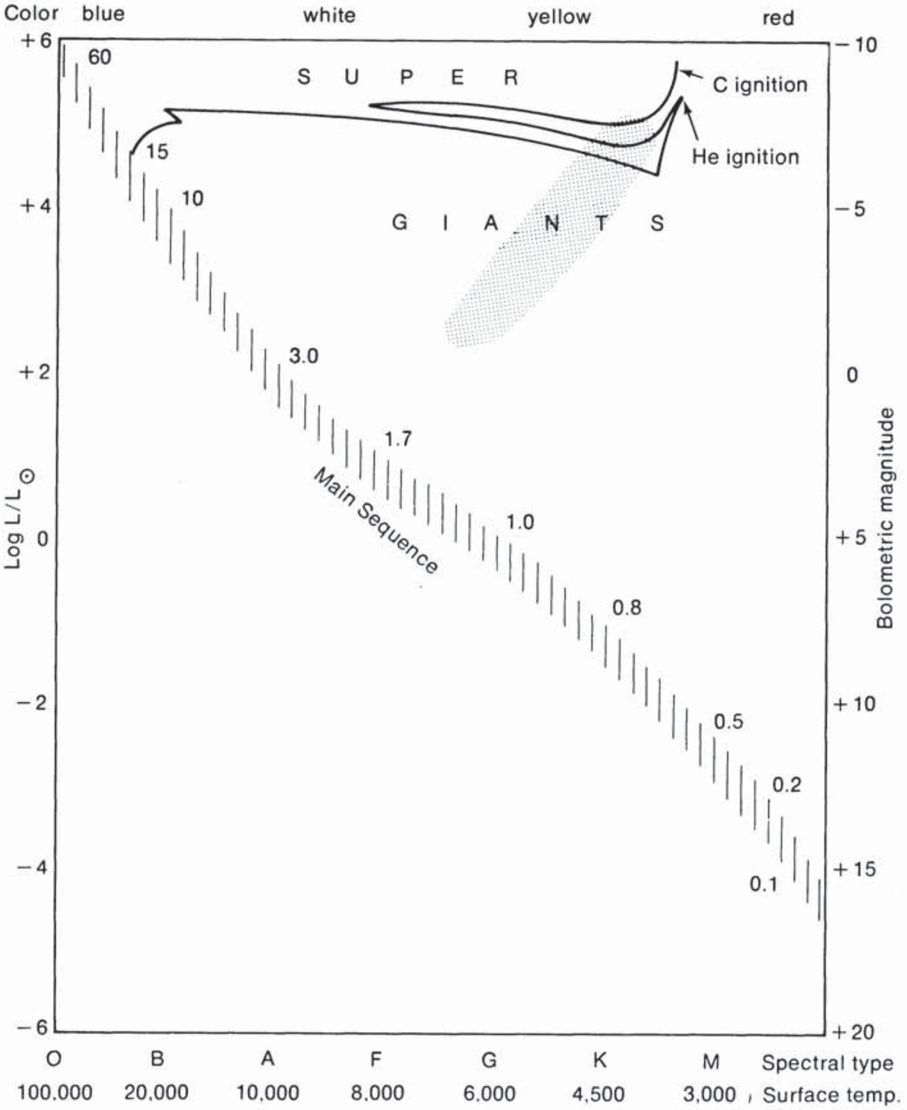

Figure 1. Hertzsprung-Russell (HR; color-magnitude) diagram for a representative group of stars young enough that the entire Main Sequence is still populated. Notice the curious scales always used by astronomers. The vertical scale is the logarithm of total luminosity in solar units, or magnitudes which are logarithms (base $100^{1/5}$) of the reciprocal of the luminosity in fairly arbitrary units. The horizontal scale is surface temperature (though neither exactly linear or logarithmic) or color or spectral class (an ancient and honorable way of dividing up the stars which somewhat predates the realization that temperature is the most important determinant of spectral line intensities) and runs backwards. Masses in solar masses are given at representative points along the main sequence. The evolution of a typical massive star through the supergiant region is shown, along with the points at which helium and carbon burning start. Most of the time is spent close to the main sequence and in the red supergiant region. The stars in the stippled region of the diagram are generally or always variable in luminosity with regular periods of 3–30 days. They are called Cepheid variables, after the prototype, Delta Cephei, and are important distance indicators for nearby galaxies, because their periods are correlated with their total luminosities.

sec/Mpc = 1.67×10^{-17} sec^{-1}, or $1/H_0 = 2 \times 10^{10}$ yr), (2) the ages of the oldest stars in our Galaxy, probably 12–18 billion years, and (3) the ages of the radioactive elements in the Solar System, which tell us that the earth and meteorites solidified about 4.65 billion years ago, and that synthesis of these elements had been going on for 7 to 13 billion years before that (Gott et al. 1974). The evidence for the high temperature and density comes (1) again from running the Hubble expansion backwards, conserving mass-energy and the numbers of various kinds of particles, including photons, and (2) from the existence of two relics of the hot, dense phase. These relics are an isotropic background of microwaves having a blackbody spectrum corresponding to a present temperature of 2.7 K (Peebles 1971) and the seemingly universal presence of helium, with an abundance of 20–30% by weight (Trimble 1975). Thus, if we run a picture of the Universe backwards about 20 billion years, we see it at a temperature $T \gtrsim 10^{10}$ K and a density $\rho \gtrsim 1$ g cm^{-3}. Under these circumstances, many kinds of matter and radiation come into equilibrium, and the relative numbers of various kinds of particles (protons, neutrons, electrons, positrons, neutrinos, photons, and perhaps others) depend only on T. As the Universe expands and cools, unstable particles decay or annihilate; and others undergo nuclear reactions, resulting in about 25% He^4 and traces of H^2 (deuterium), He^3, and Li^7, as well as about 75% ordinary hydrogen (Wagoner et al. 1967) in the standard cosmological models.

Unfortunately, this hot, dense phase (sometimes called the Big Bang) also wiped out any evidence of what (if anything) went before. Hence the question What happened before the Big Bang? belongs to the realm of pure speculation (philosophy?) rather than that of physics. It is rather like putting a car into a steel blast furnace and asking the trickle of molten metal that comes out whether it was a Pinto or a VW before. You just can't tell, because the evidence has been destroyed.

Galaxies and stars

Coming out of the hot, dense early universe we therefore see some radiation (which continues to cool, down to 3 K by the present time) and some matter, in the form of hydrogen and helium. Luckily this is not all that happened, because the chemistry of H and He is not very interesting! The matter at this stage was not perfectly smooth but was concentrated in lumps. This is also fortunate for us, because, as we have already seen, the average density of matter in the Universe is exceedingly low. Thus, in the absence of local concentrations of matter, the average hydrogen atom would not have encountered another hydrogen atom for the last 10 billion years or so, and would be very lonely. The cause of the lumps is not well understood, though they are not unexpected, since, when the Universe was very young, there had not yet been time for interactions and smoothing to have occurred across large distances. But they must have been there, because we see galaxies and clusters now. There has been some success in calculating how the lumps must have grown and developed into proto-galaxies (Jones 1976).

The evolution of a galaxy is largely a matter of the exchange of material between stars and an interstellar gaseous medium and the nuclear processes that occur in stars. Many different types of galaxies are observed (of which the most clearly defined are Ellipticals, with their brightest stars distributed throughout a spheroidal volume, and Spirals, with their brightest stars concentrated in spiral-shaped arms in a plane; see any elementary astronomy textbook for pretty pictures). They come with different total masses, luminosities, kinds of stars, colors, amounts of gas, shapes, abundances of heavy elements, and spatial distributions of these and other properties. Serious efforts to understand the evolution of galaxies go back only about 20 years, and the field is changing so rapidly now that it is hard to say more than that it looks as if we may be able to account for the observed ranges of properties and their correlations in terms of a rather small number of initial conditions in the lump, e.g. total mass, size, angular momentum, and degree of turbulence (Trimble 1975; Audouze and Tinsley 1976).

A protogalaxy becomes a galaxy when some appreciable fraction of its gas has been converted into stars. The most distant galaxies, seen as they were 3–5 billion years ago, do not look very different from the nearby ones, but the quasars may represent some early stage of the galaxy formation process, which appears to have been largely completed within a few billion years after the initial hot, dense phase of the Universe. We do not, in other words, see any obviously young galaxies nearby.

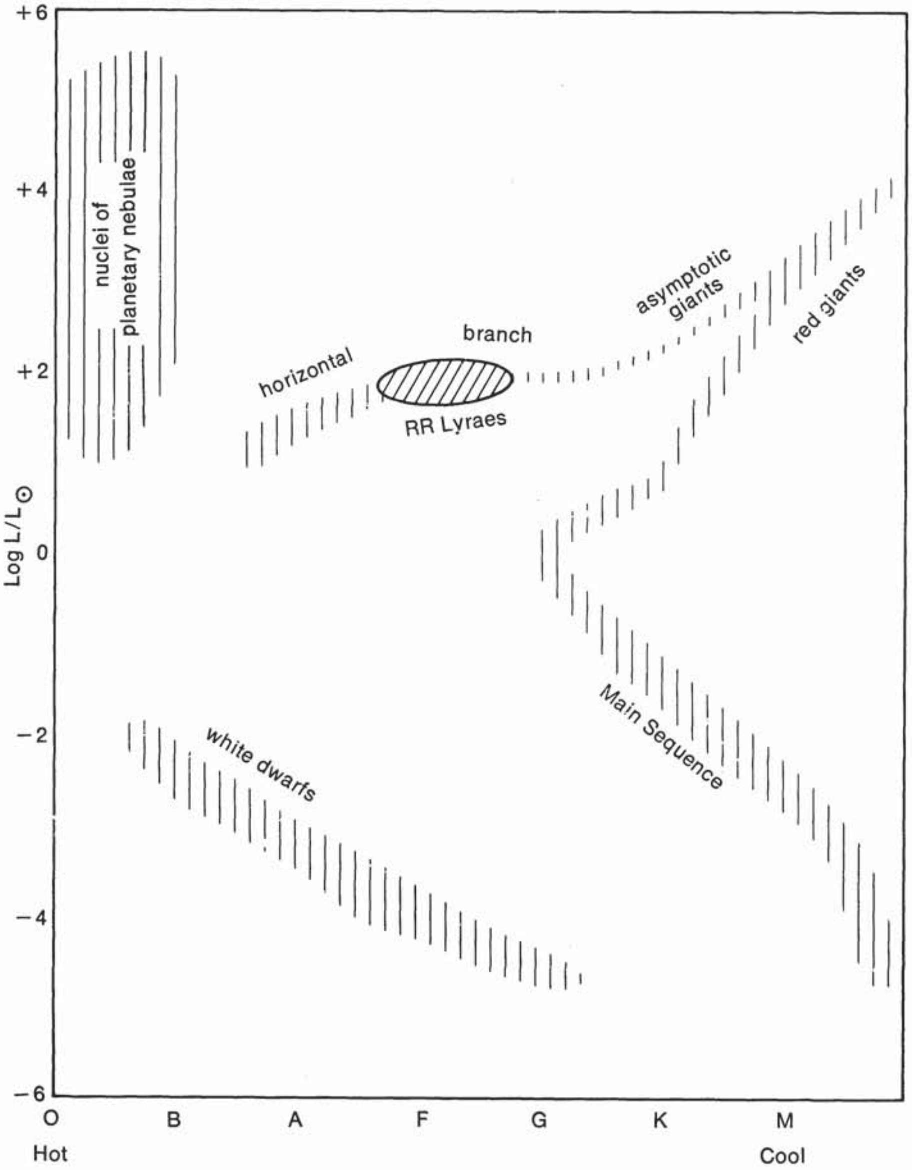

Figure 2. Hertzsprung-Russell diagram for a cluster of stars old enough ($\sim 10^{10}$ yr) that stars like the sun (~ 1 M$_\odot$) are leaving the Main Sequence. The evolutionary track of a single star would go from the main sequence up into the red giant region along the heavily populated track, down to the horizontal branch (when He is ignited), back up to the red giant region along the asymptotic branch, then horizontally (and very rapidly) across from right to left as a planetary nebula is shed, and finally down into the white dwarf region. The stars in the region labled RR Lyraes are variables (also named for their prototype RR Lyrae) with periods less than about a day.

The process of star formation from interstellar gas, on the other hand, has continued to the present time in our own and most other galaxies (though at widely varying rates). We can almost see it happen before our eyes, at least in the sense that we see some bright, naked-eye stars (for instance the brightest ones in Orion) that did not yet exist as separate bodies at the time of our remote Zinjanthropan ancestors. We do not have an adequate theory of star formation (lots of people would say we have none at all), but we can learn quite a lot about it by looking.

In our region of the Galaxy (often called the solar neighborhood), young stars are (almost?) invariably found in groups and in the presence of denser-than-average clouds of gas and dust, in the spiral arms of the Galaxy. The very youngest stars are typically still hidden behind the remnants of the clouds from which they formed and are seen only as infrared sources. We are led, then, to a picture in which a typical dense (10^{3-5} cm^{-3}), massive ($\sim 10^5$ M$_\odot$) interstellar cloud (these are observed as sources of radio line emission) is shocked by a collision with another cloud, with the expanding shell from one of the supernovae (which we will meet later) or with the density wave which is believed to be responsible for the characteristic spiral shape of our own and many other galaxies. The shock starts the cloud collapsing under its own weight. As it contracts, excess angular momentum forces it to fragment into star-sized pieces. This means masses from about 0.05 to 100 M$_\odot$, the lower limit being set by the requirement

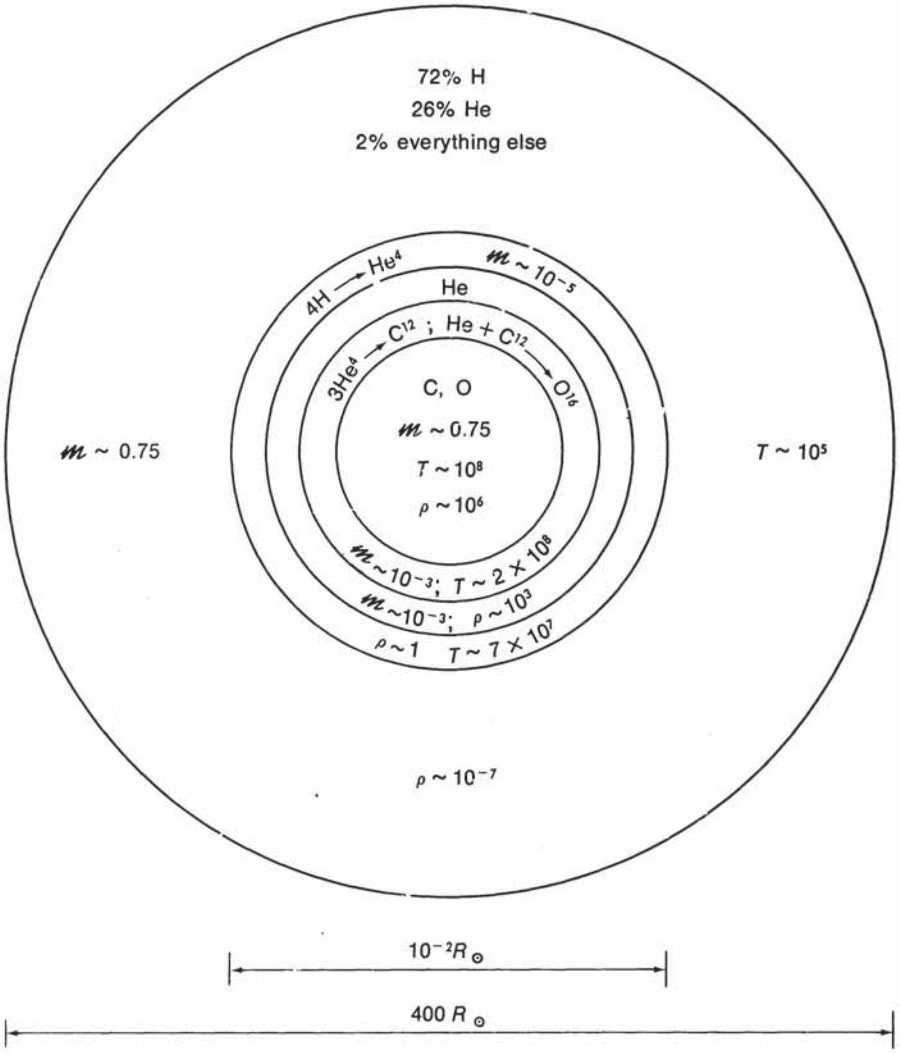

Figure 3. Interior structure of a 1.5 $M_\odot$ (solar type) star shortly before it sheds its planetary nebula and becomes a white dwarf. Masses of the various zones are given in solar masses, temperatures in Kelvins, and densities of the zones in g cm^{-3}. Only the primary constituents and nuclear reactions are indicated. Notice the great disparity in scale between the inner and outer regions.

that the center of the piece eventually become hot enough for nuclear reactions to occur and the upper limit by the tendency for radiation pressure to blow material off a star that is too massive and bright. We cannot predict how many stars of each mass will form from a particular cloud (this is one of the senses in which we have no theory of star formation), but observation shows that, over the history of our own and most other galaxies, more than half the mass has gone into stars less massive than the sun. Thus small fragments are favored over large ones, and the smallest stars are the most common.

The fragments are called proto-stars and continue to contract under their own self-gravity (on a time scale that depends on their mass, amounting to about 0.1% of the time they will spend undergoing nuclear reactions) until their centers reach a temperature of about 10^7 K. Because the very first generation of stars must have been nearly pure hydrogen and helium, a variety of processes that now occur during the contraction phase (including, probably, those that lead to the formation of planets) will not have happened. At a central temperature near 10^7 K, hydrogen begins to fuse to form helium (either directly, or using carbon, nitrogen, and oxygen as catalysts, when they are available and at slightly higher temperature) with the liberation of about 7×10^{18} ergs/gram.

Stars have clearly solved the problem of controlled nuclear fusion, which we are now attacking in the laboratory. The differences are (1) the stars can start with pure H and convert two protons to neutrons (via the weak interaction) to make He, while we must start with substances (deuterium, tritium, lithium) in which this has already been done; (2) the star does it at much higher temperature and density than is contemplated in the lab; and (3) the star will take 10^{6-12} years to get all the energy out, while we hope for rather faster operation.

The energy liberated by hydrogen-burning keeps the pressure inside the star constant and stops its contraction. The star will remain in hydrostatic equilibrium until its hydrogen fuel is exhausted. The hydrogen-burning phase of stellar life is called the Main Sequence stage, from the star's position on a diagram of brightness vs. surface temperature (Figs. 1 and 2). Such plots are called Hertzsprung-Russell (HR) diagrams and are of considerable assistance in understanding stellar evolution. Notice the one-to-one relationship between stellar mass and position on the Main Sequence. This, in turn, implies a relation between mass and lifespan, since the fuel supply depends on mass and the rate of fuel consumption depends on luminosity (which scales as about M^3 on the Main Sequence, as was first understood by Eddington 1926). A star's structure remains stable until hydrogen has been exhausted in about the inner 10% of its mass. This implies a main sequence lifetime of nearly 10^{10} yr for a star like the sun (70% hydrogen in the inner 2×10^{32} grams, yielding 7×10^{18} ergs/gram, and being used to supply 4×10^{33} ergs/sec). But a 20–100 $M_\odot$ star at the upper end of the main sequence can last only 10^{6-7} yr, while stars of less than about 0.75 $M_\odot$ have not had time to leave the main sequence in the age of the Universe. Almost 90% of the stars we see are on the Main Sequence, accounting for the name and implying that it is the longest-lived phase.

Most astronomers and physicists feel that we have a good quantitative understanding of the main sequence phase (despite the continuing nonappearance of the expected solar neutrinos; Bahcall and Davis 1976), but the ratio of speculation to "hard" theoretical (and observational) facts will gradually increase as we move away from the main sequence. The evolution of normal stars as a function of mass has been studied by numerous groups. Three recent series of papers by W. D. Arnett, I. Iben, and B. Paczyński (referenced in Trimble 1975) cover all the phases we will be discussing here.

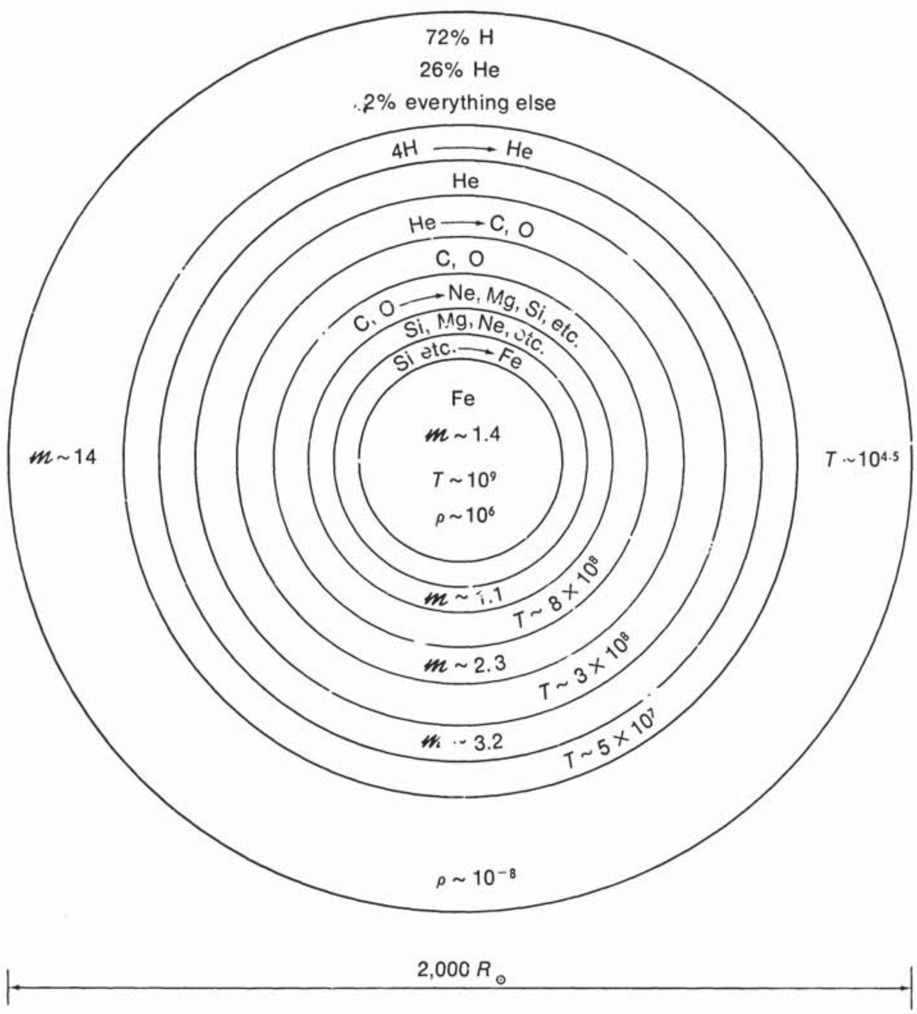

Figure 4. Interior structure of a massive (22 $M_\odot$) star shortly before it becomes a supernova. Only the primary constituents are shown, and those rather schematically. Masses of the various zones are in solar masses, temperatures in Kelvins, and densities in g cm^{-3}. Notice again that more than half the mass and virtually all of the volume is still occupied by the hydrogen-rich envelope, whose composition has been relatively unaffected by nuclear processing in the star.

Exhaustion of hydrogen in the stellar core introduces a discontinuity in composition and mean molecular weight. As a result, the equilibrium structure becomes a very extended one (Hoyle and Lyttleton 1942, 1949). The outer layers of the star rapidly expand and cool, while the core once again contracts under its own weight, liberating gravitational potential energy to keep the star shining. The resulting star is called a red giant (or red supergiant, in the case of the most massive stars which become even bigger and brighter) for obvious reasons.

Our sun will become a red giant in about another five billion years. When it does, it may become so large that its outer layers engulf the earth. In any case, its greatly increased luminosity is expected to raise the temperature of the earth to the point where the oceans boil away.

The increasing temperature of the contracting stellar core soon raises the temperature of the surrounding hydrogen enough that it begins to fuse to helium, again liberating nuclear energy. About as much hydrogen is burned in the red giant phase as was burned on the main sequence, but the star is about 10 times as bright, so the phase lasts only about 10% as long. Red giants (Betelguese and Antares are examples) are thus rarer in the sky than main sequence stars.

For all but very tiny stars ($\lesssim .3\ M_\odot$, which have not yet had time to leave the main sequence anyway), the core eventually becomes hot enough for nuclear reactions involving helium to occur. The onset of helium burning occurs explosively in stars like the sun (because the cores are so dense the matter is partly degenerate, thus pressure does not immediately increase when the reactions drive the temperature up) causing a readjustment of the stellar structure. The star lands in the horizontal branch region of the HR diagram (Figs. 1 and 2), while more massive stars merely remain in the red giant region during helium burning. Both phenomena are seen—the lower-mass helium burners as a collection of stars strung out horizontally across the HR diagrams of old star clusters, in which stars $\sim 1\ M_\odot$ are leaving the main sequence, and the high-mass helium burners as a clump on the red giant branch of the HR diagrams of young clusters, in which ~ 2–$10\ M_\odot$ stars are now leaving the main sequence. The helium-burning phase is still shorter than the red giant phase, because the star remains quite bright and helium-burning produces fewer ergs per gram than hydrogen burning.

The products of helium burning are carbon and oxygen, in roughly equal amounts. This is clearly of some importance, since we and other terrestrial living creatures are in large measure made of them. The approximately equal production of carbon and oxygen is the result of a delicate balance between the electromagnetic repulsion of the interacting helium atoms and the detailed nuclear structure of the products (Fowler et al. 1975) and, in the absence of some deeper understanding of the forces involved, must be regarded as an extremely fortunate coincidence from our point of view.

The exhaustion of helium at the center of the star, like that of hydrogen earlier, results in the core contracting to liberate gravitational potential energy and the outer layers again expanding. Helium soon begins to burn in a thin shell around the inert carbon-oxygen core (Figs. 3 and 4). During this double-shell-burning phase, low-mass stars again ascend to the red giant region of the HR diagram (where, in old clusters, we see them as a scattering of stars to the blue side of the normal red giant branch, the so-called asymptotic giant branch), more massive ones remaining as red supergiants. During this phase, convection can bring the products of nuclear reactions in the stars themselves up to their surfaces. Many asymptotic giant stars show excess carbon (and s-process products) in their atmospheres. In addition, in second and later generation stars, which had some heavy elements to begin with, several reactions involving He, C, N, and Ne liberate some neutrons. These are captured, primarily by iron and heavier nuclei, building up many (but not all) of the elements and isotopes between iron and lead (atomic numbers 27–82); by the so-called s process (the *s*low addition of neutrons, interspersed with beta decays).

From here on, the evolution of a star depends importantly on its mass and takes one course for stars $\lesssim 6\ M_\odot$ and another for stars $\gtrsim 6\ M_\odot$ with a possible narrow intermediate range in which carbon burning starts so explosively (again because the core is degenerate) that the star is completely disrupted. The mass at which this transition occurs has been discussed often and from many viewpoints (e.g. Woolf 1974).

All stars shed some material throughout their lives. We see a continuous solar wind of particles leaving our sun, and the rate of mass loss is observed to be much larger in some bright, red stars. Thus a star may reach the end of helium shell burning with only ½–¾ of its original mass (or even less, if it is in a binary system). But it is the original mass that counts, the center of the star continuing to evolve almost unaware of the surface losses. The lower mass stars, like our sun, never get hot enough for any further nuclear reactions to occur after helium burning. Rather, various instabilities in the shells gradually lift off the outer layers of the star, leaving behind the very hot, very dense core. The lost layers are heated and ionized by light from the remaining core and become responsible for one of the more frequently photographed phenomena of astronomy, the planetary nebulae (again see any elementary text for pictures). The name reflects their appearance in a small telescope, not any imagined connection with planets. The remaining core has a density of about 10^6 g cm^{-3} and a radius of only about 10^4 km (the size of the earth). It is initially very hot even at the surface (10^{5-6} K) since it has just finished nuclear reactions, sometimes resulting in a detectable source of soft X rays (Hearn et al. 1976), but cools off in a matter of millions of years to some tens of thousands of degrees. The nebulae dissipate within 10^4 years (judging from their measured expansion rates), leaving behind faint (because they are tiny) stars, moving in the HR diagram from the region marked "nuclei of planetary nebulae" down toward the white dwarf region. The matter in these stellar cores is degenerate, thus they can neither radiate away the kinetic energy of the electrons nor contract any further. Degenerate matter is subject to the uncertainty principle; thus to compress it you must localize the particles further, raising the uncertainties in their momenta and, therefore, their kinetic energies. You must add energy to degenerate matter in order to compress it. Only the thermal energy of the nuclei is available and is gradually radiated away over billions of years, leaving the star as a gradually cooler and fainter white (and eventually yellow, red, and black) dwarf. This will be the final state of our sun. As seen from earth (which will, of course, be thoroughly frozen), it will not look much brighter than the full moon does now. The answer to Robert Frost's question therefore appears to be fire first and ice later.

Notice that the white dwarfs retain most or all of the carbon and oxygen produced in low-mass stars. Thus, we are going to have to follow the evolution of more massive stars to see the origins of the heavy elements found in the sun, the earth, and ourselves. In stars above about 6 $M_\odot$, the carbon-oxygen core gets hot enough for further nuclear reactions to occur. The burning of carbon and oxygen produces relatively abundant elements like neon, magnesium, silicon, and sulfur. As one source of fuel is exhausted, further contraction of the core causes further heating until another fuel can be tapped. Finally, the burning of elements near silicon produces a stellar core which is mostly iron and nickel, the star as a whole rather resembling an onion (see Fig. 4). Energy is liberated in each of the nuclear reactions, though not as much as in hydrogen or helium burning, but most of it is carried away by neutrinos (rather than photons), which do not contribute to keeping the star shining. These phases are, therefore, very short lived ($<10^4$ yr), and the HR diagram is no longer a particularly useful tool for following the evolution.

Once the star develops an iron core of about 1 $M_\odot$, it is in serious trouble. The nucleus of iron is the most tightly bound of all atomic nuclei; hence no reaction involving it can liberate any energy. The core of the star just continues to contract and get hotter and denser until several processes begin to occur (more or less simultaneously) which drain energy away from the core, causing it to collapse suddenly and catastrophically. The two main processes are (1) the breaking up of Fe back into He nuclei by high energy gamma rays and (2) the reaction of protons with electrons to form neutrons and neutrinos. Both of these soak up energy, and the latter especially also reduces the effective sizes of the particles in the stellar core. The core therefore collapses until a new source of pressure (the neutrons becoming degenerate) stops it at a radius of about 10 km. The product is called a neutron star, and the process liberates some 10^{53} ergs of gravitational potential energy (comparable with the total radiation output of the star over its entire previous life).

This liberation of energy and its distribution through the star result in a variety of violent phenomena, including (probably), (1) a burst of neutrinos, (2) a burst of gravitons, (3) the *r*apid addition (r process) of neutrons to iron from the core to build heavy elements up to at least plutonium and maybe further, (4) some very high-temperature nuclear reactions in the intermediate layers which yield a variety of rare, intermediate-weight isotopes, (5) a rapid brightening of the outer layers of the star until it may outshine its entire galaxy for some weeks (we call this a supernova when we see it, which happens at a rate of once every few hundred years in the solar neighborhood, or about every 30 years in a large galaxy), (6) the acceleration of some material from the surface of the star to relativistic speeds, after which we call the particles cosmic rays, (7) the expulsion of one-to-many solar masses of material from the star at speeds of 10^{3-4} km/sec (we see such expanding clouds around old supernovae in the solar neighborhood), and (8) the storing of energy in rapid rotation of the neutron star, which then gradually feeds it out again over the next 10^{6-7} yr in forms which cause us to see it as a pulsar. The association of neutron star formation with supernovae was first suggested by Baade and Zwicky (1934) and confirmed by the detection of a pulsar in the Crab Nebula (Staelin and Reifenstein 1968), which is the gaseous remnant around the site where the Chinese reported seeing a supernova explosion in 1054 C.E. From our point of view, the most interesting thing a supernova does is to distribute the heavy elements made by nuclear reactions in the massive star back into the interstellar medium.

I have said nothing so far about the evolution of pairs of stars—binary systems—which constitute at least half the stars in the solar neighborhood. The presence of a close companion influences a star's life profoundly (see, e.g., Paczyński 1971 for a review of some of the effects) particularly in the later stages. It may even lead to an occasional massive star collapsing past the neutron star stage down inside its own Schwarzschild horizon to form a black hole. (Possibilities for black hole formation and their properties have been reviewed many times, e.g. Thorne 1974.) No one has yet followed a massive star in a close binary system all the way from the main sequence to supernova explosion, and the effects on nucleosynthesis are unknown but thought to be small. The core of the star should continue on its merry way even after the outer layers are stripped off and given to the companion star.

In the case of normal supernovae, we observe the shedding of the outer layers, and careful spectroscopic studies have found extra amounts of various heavy elements in them (Kirshner and Oke 1975; Peimbert and van den Bergh 1971; Peimbert 1971), representing the products of nuclear reactions in the stars. These then enrich the general interstellar medium, so that second and subsequent generations of stars that form will contain a component of elements besides hydrogen and helium (about 2% in our sun and 3–4% in stars now forming), in proportions which are reasonably well understood theoretically (Trimble 1975). The presence of heavy elements in turn implies the possibility of planets like the earth.

Planets and life

If we are interested in life in the universe, one of the first things we will ask a star is whether or not it has planets, preferably with solid surfaces and preferably located at such a distance from the parent star that water is a liquid at least some times and in some places. Unfortunately, direct observation cannot answer this question for any star but the Sun. In the past, theories of the formation of the solar system often involved events, like the close passage of two stars, which would be so rare that we could easily be the only planetary system in the Galaxy. Recent theoretical studies (see, e.g., *Scientific American,* Sept. 1975) have, however, come around to a view in which leaving behind some material in planets is a natural part of condensing a star out of the interstellar medium. On this basis, planets should be quite common. There is some indirect supporting evidence (van de Kamp 1975). Careful study of the motions of several nearby stars across the plane of the sky has revealed evidence of a roughly sinusoidal wiggle, typically with a period of years and an amplitude of a small fraction of a second of arc, such as would be produced by the star and a planet with a mass 1–10 times that of Jupiter orbiting around their mutual center of mass. And if the presence of Jupiters can be taken to imply the presence of Earths, then many or most stars (at least those of roughly solar type) may well have planets with solid surfaces.

The nature of the atmospheres of these planets will also be important for the possibility of life. The earth's orginal atmosphere was not its present oxidizing one, but rather a reducing one (made up of things like CO, CO_2, NH_3, CH_4, H_2, and H_2O at various stages) according to several lines of evidence. These include the kinds of gases found on other planets and released by volcanoes, the reduced nature of the minerals deposited until about a billion years ago, and the necessary conditions for the origin of life itself.

The constituents of this primitive atmosphere are interesting from several points of view. First, they are made of the commonest chemically reacting elements (H, O, C, and N in order of abundance). Second, they contain the elements that occur most abundantly in terrestrial living creatures. Third, they are more or less the things you need in order to do the kind of experiment suggested by Urey and carried out by Miller (1953; and many others since) in which substances like methane, ammonia, formaldehyde, and carbon dioxide are dissolved in water and energy added (in the form of ultraviolet radiation, electric currents, mechanical shocks, etc.). Under these circumstances, many chemical reactions occur, whose products (if the right inorganic reactants are made available) include a wide variety of simple organic molecules—amino acids, sugars, bases, phosphates—and some of their polymers (Stephen-Sherwood and Ord 1973). And fourth, these and a wide variety of other simple organic and inorganic molecules are now known to be widely distributed through the interstellar medium (Herbst and Klemperer 1976). Molecules detected include interstellar CO, CN, NH_3, H_2S, H_2O, formaldehyde and hydrocyanic acid, formic acid, methyl and ethyl alcohol, and HC_5N, which has the same molecular weight as glycine, the simplest amino acid, and about 30 others. These molecules and the presence of amino acids (in a racemic mixture of left- and right-handed forms, which leads us to believe they are nonbiological) in several meteorites (Jungclaus et al. 1976, and references therein) seem to indicate that both the raw materials and prebiological organic molecules will be widely distributed in suitable environments, like the surfaces of planets.

No laboratory experiment has yet taken the complete step from the raw materials to a self-reproducing molecule. Perhaps this is just as well; the first biochemist who makes a self-reproducing molecule may find out that it eats biochemists. Ways to approach self-reproduction have been discussed by Calvin (1975) in these pages. In any case we (or at least the infidels among us) do know that the step has been taken at least once, for here we are; and by the time you read this, laboratory experiments or the Viking Mars lander may have shown that it can be taken more than once. In the meantime, we can only say that there does not seem to be any reason to suppose that the earth is special or that chemical life is not likely to have appeared many times over the history of the galaxy. The evolution of terrestrial life and its effects on the atmosphere and other components of the environment have been reviewed in this journal by Cloud (1974). Suffice it to say that, once you have self-reproduction, then the entire mechanism of Darwinian selection and mutations takes over, and the evolution from a primeval slime mold to a local politician seems practically inevitable. We therefore expect that life will eventually become intelligent life in many cases.

But this, in turn, raises another question; if there is this sort of inevitability in the progress from the hot, dense early universe to the formation of galaxies, stars, planets, and life, then there should be lots of other civilizations floating around space. Where are they? Of course, there are people who think they know the answer to this question—large silver ships drop out of the sky, land in their gardens, and take them for rides. These people generally have other problems as well. Others have tackled the question in a slightly different way. They start with the total number of stars in the galaxy, eliminate those that are too short-lived, too cool, or too close to another star to provide comfortable environments, guesstimate factors for the probabilities of planets, the origin of life, and the development of civilization, by which they mean not the quartets of Mozart or the dialogues of Plato, but rather radio astronomy—that is, the ability to communicate across interstellar distances. Many such efforts (Shklovskii and Sagan 1966; Ponnamperuma and Cameron 1974; Sagan 1973; and references therein) end up with an estimate that a civilization may have appeared every $10^{2\,{}^{+2}_{-1}}$ years over the history of the Galaxy. A carbon-based biochemistry is assumed, but there is no presumption (and little likelihood!) that the products would look like us. Other kinds of biochemistry may possibly increase the numbers of civilizations above these estimates.

The question of whether we have millions of neighbors, thousands, or none then reduces to the question of how long a civilization lasts. Possible answers range from 10^2 years (the time over which we seem capable of advancing(?) from the first radio broadcasts to self-destruction) to 10^7 years (the time scale for biological evolution from one species to another among the higher mammals) on up to 10^{10} years (the main sequence lifetime of the host star). These answers correspond to our having no company at all, other civilizations within a thousand parsecs or so, or near neighbors within 100 or even 10 parsecs, corresponding to round-trip light travel times comparable with human lifetimes.

Some effort has been made to test this last, most optimistic, hypothesis by pointing large radio telescopes in the directions of nearby, solar-type stars and listening for a while (see Sagan and Drake 1975 for some of the details). No positive results have been reported. This is not particularly discouraging, because the sensitivity was such that nothing could have been seen unless a comparably powerful telescope, operating in a radar, broadcasting, mode, was pointed directly at us. The range of such experiments will be considerably extended when the Very Large Array, presently under construction in New Mexico, comes into operation in the 1980s. We could do still better with present technology, to the point of being able to detect even a relatively weak radio planet like the earth out to a distance of several hundred parsecs (though the cost would be comparable with the cost of the Apollo program or a very small war). This is, therefore, perhaps a good time to start thinking about the consequences for society (including zealous companionship in scientific research!) of the possible discovery that ours is merely one of many civilizations, and (given the time scales involved, inevitably) rather a backward one at that. The sociological implications may be worth worrying about.

Universal constants and their importance

Whether we are alone or one of thousands or millions of civilizations in the Galaxy, we seem to be a fairly natural product of the total history of the Universe. It is, therefore, of some interest to ask whether any universe would have done, or is ours special? This is quite different from asking whether the earth and sun are special, because there are lots of stars and one can do some kind of statistics. The Universe, on the other hand, is by definition unique in our experience. One can, however, characterize the Universe in terms of a fairly small number of properties, which lead to the history we have discussed, and ask what would have happened if one or more of these properties had been different from what we see it to be. We will require eight parameters—four small-scale ones and four large-scale ones (Table 2). The four small-scale properties are the four forces of nature, the four ways in which one bit of matter or radiation can interact with another. Understanding the internal structure of the so-called elementary particles (protons, neutrons, mesons, etc.) may require a fifth force, or even an entirely different way of looking at the problem (Heisenberg 1976), but we cannot say anything very concrete about its size or possible variations at the moment. These four forces are the gravitational, electromagnetic, nuclear (or strong), and weak interactions, in order of decreasing familiarity. Table 2 lists them in order from strongest to weakest.

Most of the dire consequences of changing the forces mentioned in Table 2 require changes of an order of magnitude or more and thus do not rule out a factor of two decrease in G over the past 10 billion years (Van Flandern 1976), though this can probably be ruled out in other ways (Roxburgh 1976). But changing the electromagnetic force (the charge on the electron) by even a factor of three would mean that water could not be a liquid at any temperature, while very small changes in the ratio of the electromagnetic to nuclear force would cause helium burning to produce either all carbon or all oxygen rather than a mix of the two.

Similarly, looking at the Universe on the largest scale, we find four important parameters. Two of these are the numbers that told us which of the Friedmann models we live in. They are H_0 and ρ_0 and measure the age and average density of the Universe. A third is the entropy of the Universe, which can also be expressed as the ratio of the number density of photons to the number density of heavy particles (protons and neutrons). This defines the present temperature (which we measure with some precision) and, therefore, the temperature and density at which helium was formed in the Big Bang. Finally, we have the homogeneity and isotropy, which we originally put in as one of our cosmological assumptions, but which are also observed to be approximately true and seem to be necessary for galaxy formation (Collins and Hawking 1973). The changes in these properties required to produce the dire consequences are often several orders of magnitude, but the constraints are still nontrivial, given the very wide range of numbers involved. Efforts to avoid one problem by changing several of the constants at once generally produce some other problem. Thus we apparently live in a rather delicately balanced universe, from the point of view of hospitality to chemical life.

Implications

It seems, in other words, that the Universe must be more or less the way it is just because we are here. This anthropic principle ("cogito ergo mundus talis est") has been further explored by Carter (1974). It is of some interest to try to understand what it might mean that our Universe should fall within a rather narrow range, favorable to life, for each of several parameters. It may just mean that God (or the Initial Conditions, depending on your point of view) has been very careful. This is a possible answer—it may even be the right one—but it is not a scientific answer, at least in the narrow sense that it does not lead one to make any further observations, do any further experiments, or carry out any further calculations.

There are, of course, other possibilities. It could be, for instance, that ours is merely one of many universes, and that it is only those very few with particularly favorable properties that ever develop living creatures who ask these strange questions. There are two senses in which this could be so. If our Universe is, in fact (contrary to the preponderance of the evidence, but by no means impossibly) of the sort that will eventually turn around and recontract, one might imagine a (finite or infinite) series of cycles of expansion and contraction, each constituting a separate universe and each having its own values of the fundamental constants. This violates our initial assumption that general relativity is the right theory of gravity, because, within its framework, when you once achieve singular conditions (like infinite density) out of nonsingular ones (i.e. after the first recontraction), you can never get out again (Hawking and Ellis 1973). Perhaps this should not worry us too much, though, because general relativity is a classical (non-quantum) theory, and at sufficiently high densities, quantum mechanical effects will become important (Zeldovich 1971) and must profoundly change the nature of gravitation (Misner et al. 1973).

The alternative, if our Universe is an infinite, ever-expanding one, is that a number of four-dimensional space-times (universes) might be imbedded in five (or higher) dimensional space, existing simultaneously, from the point of view of a five (or higher) dimensional observer. There is no easy way to picture five (or higher) dimensional space with a three (or lower) dimensional mind, and it is probably hopeless to try.

A third possibility is that, at some time in the distant future, when we have understood "all" the physics of the universe, it will be obvious that the various quantities must have the relationships they do. There is some hint that this might be so in the "large numbers." These are several simple combinations of the constants in dimensionless form that, depending on just how you write them, are all of order unity, 10^{40} or 10^{80}. For instance, the radius of the observable universe ($c/H_0 \sim 10^{28}$ cm) divided by the classical electron radius ($e^2/m_ec^2 \sim 10^{-12}\,cm$) is about 10^{40}. And the ratio of the electromagnetic to gravitational forces between an electron and a proton (e^2/Gm_em_p) is 2×10^{39}, and the number of particles in the observable universe, N_0, is about 10^{80}, i.e. $(10^{40})^2$. Alternatively, these can be written as $8\pi G\rho_0/3H_0^2 \sim 1$ (this is

Table 2. Universal forces and properties and consequences of varying their values

Force	*Phenomena controlled*	*Consequences of lowering*	*Consequences of raising*
Nuclear or strong	Structure and reactions of atomic nuclei	Early universe converts all matter to heavy elements; no source of energy for stars.	No nuclear reactions at all or none past helium; no heavy elements made, so no chemistry.
Electromagnetic	Structure and interactions of atoms and molecules	Electrons not bound to atoms; no chemical reactions possible.	Electrons inside nuclei; no chemical reactions possible.
Weak	$\nu_e + n \leftrightarrow p + e^-$ and other beta decays	No hydrogen burning possible; no source of heat or heavy elements.	Early universe converts all matter to helium. No energy sources for stars.
Gravitational	Structure and dynamics of planets, stars, and galaxies	Stars don't get hot enough for nuclear reactions to occur.	Nuclear reactions so rapid that star lifetimes very short.

Property of Universe	*Value*	*Consequences of lowering*	*Consequences of raising*
Rate of expansion	$H_0 \sim 55$ km/sec/Mpc	Matter all comes out of early universe in dense configurations.	Galaxies can't form; matter ends up spread out uniformly.
Average density now	$\rho_0 = 10^{-32} - 10^{-30}$ g cm^{-3}	Galaxies can't form; atoms very lonely.	Early universe turns all matter into heavy elements; no energy sources.
Entropy or temperature	$\eta = \eta_\gamma/\eta_{\text{baryon}} \sim 10^{-9}$ or $T = 2.7$ K	Early universe turns all matter into heavy elements; no stellar energy source.	Galaxies can't form due to radiation pressure.
Isotropy and homogeneity	$\Delta T/T \sim 10^{-3}$	Galaxies can't form in anisotropic expansion.	

equivalent to saying that the universe is not far from the boundary between ever-expanding and recontracting models) and $(c/H_0)/(e^2/m_e c^2) \sim N_0{}^{1/2} \sim 10^{40}$. The largest number of constants appears in $j(j+1)\hbar c/e^2 = \ln(j(j+1)\hbar c/Gm^2)$ (J. W. Follin, Jr., pers. comm. 1976), where, in all of these expressions, H_0 is the present value of Hubble's constant, m_e, e, and j are the rest mass, charge, and spin of the electron ($j = \frac{1}{2}$), G is the constant of gravity, c is the speed of light, ρ_0 is the present average density of the universe, $\hbar = h/2\pi$ and h is Planck's constant, and $m = m_e m_\mu/(m_e + m_\mu)$ and m_μ is the rest mass of the muon.

There are other numbers (involving stars and such) that come out $\sim N_0{}^{1/4}$ and $N_0{}^{3/4}$. A variety of interpretations of these large numbers have appeared from the time of Dirac (1938) and Eddington (1946) to the present (Rees 1972; Wheeler 1974). Some of the numbers may only express conditions for the formation of stable stars with reasonable lifetimes. Others, especially $G\rho_0/\mathrm{H}_2^0 \sim 1$ (which implies that G must change if it is to be true for all time) and its variants, have been made the cornerstone of whole new, nonrelativistic cosmologies (typically not in very good accord with observations). Perhaps when we have learned enough physics, we will understand that these relationships must hold and why.

Finally, it may be that the complexity and nonpredictability which we call intelligence (in ourselves, and orneriness in our adolescent children) is an inevitable result of just having enough particles interacting. By way of analogy (R. P. Feynman, pers. comm. 1975), consider a water molecule, whose structure, energy levels, and so forth can be calculated with some precision by the methods of quantum mechanics. But nothing in that calculation would ever lead us to predict waterfalls. The waterfall is a result of very many particles interacting in ways we cannot, in practice, predict or calculate. Similarly, perhaps whenever there are enough particles interacting, no matter what laws or forces govern their behavior, a sort of complexity results which we would acknowledge as a fellow intelligence. One might, therefore, imagine a universe in which the early, hot state had turned everything into neutron star material, and the exceedingly compact creatures living there would contemplate a universe like ours and claim (in very low voices, presumably) that it couldn't possibly have any intelligent life in it because the density was too low.

When this paper is delivered as a talk to Sigma Xi chapters, I generally stop at this point and ask if there are any questions, comments, rude remarks, or other feedback. I have tried to work some of the commonest of these into the text, but the reader who would like to know more about "the Universe" will find a variety of other interesting questions—and a few answers—in the references cited.

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