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The 2001 Paul Klopsteg Memorial Lecture: Cosmology: Man's place in the universe (a deconstruction)

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The history of the universe makes a reasonably coherent story, beginning with a hot, dense phase (the Big Bang), continuing with the formation and evolution of galaxies, stars, and planets, and reaching by now the appearance of life and intelligence (suitably defined). Some parts of the story, for instance, the evolution of stars, are well understood. Others are only fuzzy outlines (the formation of galaxies and the beginnings of life). All are heavily dependent upon the universe having key characteristics very close to the actual ones. These include the four forces of physics and about four cosmological parameters. CMPitU is a talk that tries to tell this story. The deconstruction addressed how much confidence we can place in the various chapters and variants in narrative technique. © 2002 American Association of Physics Teachers.
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I. META-INTRODUCTION

My last year before reaching tenure (1974), I was invited to join the stable of Sigma Xi National Lecturers, otherwise largely occupied by full professors, holding named, endowed chairs. I accepted with glee and a typed letter, bearing a \$0.10 stamp, and was soon en route to the chapter hosted by Dupont Chemical Corporation in Wilmington, Delaware, accompanied by my husband, Joe Weber, a box of lantern slides, and a blue memo from the department chairman, on the back of which were scrawled a few notes for a talk to be called “Cosmology: Man's place in the universe,” a title not then perceived as politically incorrect.

This talk worked well enough that I proposed the same topic a few weeks later for the chapter at Agnes Scott College, where I discovered that undergraduates fresh from a day of lectures are not as easy an audience to reach as mature chemists after a good dinner, that it helps if at least a few of the parts of the story one is trying to tell can be tied directly to the audiences' own experiences, and that a public lecturer's hour is like a psychiatrist's—50 minutes long. Thus was born my “tour talk,” which has worn out three sets of slides (now 2×2 in. rather than 3.25×4 in.), innumerable memo backs, on which have been recorded local circumstances to be folded in as appropriate, and some number in excess of 200 audiences. The version that had evolved by the end of my Sigma Xi tenure (long, because the mathematician in charge of the program had a wonderfully persuasive Viennese accent) then appeared in print.¹

Just about 27 years later, Ruth Howes phoned with the enormously flattering invitation to be AAPT's 2001 Klopsteg Memorial Lecturer. Once again, I accepted with glee and a typed letter, this time bearing a \$0.34 stamp. The talk title? CMPitU, of course, but with an additional challenge. The allotted time was 35 minutes, not 50. But, of course, AAPT members can learn things at least twice as fast as anybody else. Thus, I decided the solution was to add material, not subtract it.² The additional thoughts would be my best appraisal of the extent to which the various parts of the story were true beyond reasonable doubt, or at least supported by a preponderance of the evidence.

In the sections that follow, the main text is the language of the usual talk (with, perhaps, a few more complete, grammatical sentences) and the indented text contains commentaries on the sources, reliability of the information, and alternative ways of saying the same thing.

II. SCALES OF THINGS AND THE EARLY UNIVERSE

What I want to do over the next 45 or so minutes (10 000 words) is to describe the history of the universe, from the earliest times for which we have any evidence down to the birth of Richard Nixon, and try to explain what happened, why, and what, if anything, can be done about it. The punchline, in case it is time for your postprandial nap, is that our presence on Earth is very much the result both of the large scale phenomena of astronomy and cosmology and the small scale phenomena of atomic and molecular physics. I will return to what this might mean at the very end.

Richard Nixon is rapidly slipping from all except older memories, but is easily replaced by the name of anyone known to be slightly dishonest, tiresome, or ridiculous to a particular audience. Words like “postprandial” work in a large lecture room only with grown-ups, a good sound system, and fairly sharp diction. Oxbridge is probably best. Interwar Hollywood will do.

It will help in getting started if we have in common a bit of vocabulary indicating what “large” and “small” will mean here. Table I is a scale of distances. A typical astronomical distance is that from us to this next star, and a typical atomic one the diameter of a nucleus. Take the geometric mean of these; that is, multiply them together and take the square root. The answer is about 18 ft, which is the height of a dean at a prestigious university. Similarly for time scales, start with the approximate age of the universe and the lifetime of an unstable particle, and the geometric mean is two minutes. This, as you all know, is the attention span of a premed taking the required physics course. Finally, appropri-

Table I. Scales of things.

Length	
Astronomical: sun to nearest other star	3×10^{18} cm
Nuclear: diameter of nucleus	10^{-13} cm
Geometric mean	18 ft
Time	
Cosmological: approximate age of universe	4.5×10^{17} s
Elementary particles: lifetimes of π^0 and K^0 short	10^{-15} , 10^{-10} s
Geometric mean	2 min
Mass	
Astronomical: sun	2×10^{33} g
Atomic: hydrogen atom	1.67×10^{-24} g
Geometric Mean	100 lb

ate masses are that of a whole star and that of a single atom, and the geometric mean is about 60 kg, which is the mass of a large dog or a small Astronomer Royal.

The numbers in Table I are perfectly honest, though you can pick slightly different astronomical and nuclear processes if you prefer a slightly different geometric mean. The underlying physics is mostly the enormous ratio of the electromagnetic to the gravitational force between a proton and an electron. There is also an enormous literature on this sort of thing, starting with Dirac. (Ref. 3 lists a few of my favorites.)

Length, time, and mass are, of course, the fundamental quantities and you know perfectly well that one more is needed. Luckily, most astronomical systems are electrically neutral, because explaining how many beans there are in a Coulomb, a volt, or an amp is not to be undertaken lightly after dinner. Large scale magnetic fields, both weak and strong by terrestrial standards, are important. One Gauss = earth's approximate field and 100 G = field of refrigerator door magnet are all the calibration I have ever attempted.

In order to see how this all came about, we need to look back to the earliest times for which we have any evidence—to a time when the universe was very hot and very dense, 10 or 20 billion years ago. This is called the Big Bang, and whatever you may have read elsewhere, Big Bang means no more than this hot, dense phase, out of which the universe is presently expanding. “Very hot” and “very dense” mean that the conditions in the entire universe were at least as extreme as those at the center of a star now, so that some of the same nuclear reactions occurred as the ones in stars. The time scale comes from three separate lines of evidence, relying on different kinds of physics: the ages of the oldest stars, the number of years that various unstable elements like uranium and thorium have been decaying, and the expansion of the universe itself. Luckily they all agree.

Out of this early, hot, dense universe came hydrogen and helium and a very small amount of lithium, some light or photons, and a bunch of neutrinos that will not concern us further here. And the matter was lumpy. This is a good thing, because the average density of the universe is something like one atom per cubic meter, and, without the lumpiness, you would be a poor, lone hydrogen atom, and in all your life you would never meet even one other hydrogen atom. You may

also have heard that 90% or more of the stuff in the universe is not atoms at all, but some sort of rather mysterious dark matter. This is perfectly true, and the dark matter is essential to the process of galaxy formation, but plays little role in the rest of our story.

The evidence for the hot, dense stage is two-fold: the cosmic microwave background radiation (including its extreme isotropy and very precise black-body spectrum) and the abundances of deuterium, helium, and Li^7 in gas that has not been processed through stars, especially the ubiquity of a little less than 25% helium. These are all mutually consistent in a universe with a Big Bang in its past, and somewhere between extraordinarily difficult and impossible to account for otherwise.

There are people who know that the age of the universe is, say, 14.7 Gyr, 13.5, or 15.4. But 10–20 Gyr is the narrowest range on which I would bet money. The three time scale indicators are physically independent and actually agree to rather better than a factor 2. The best radiochronometer is the ratio of thorium to europium (they are coproduced) in very old stars. The stellar evolution indicator is the smallest star mass that has so far used up its hydrogen fuel and become a red giant. And the cosmic clock is the reciprocal of the Hubble constant, with small corrections for acceleration or deceleration of the expansion.

The lumps, otherwise known as the spectrum of primordial fluctuations, were surely there, and a combination of data from the 3 K background radiation and from the large-scale distribution of galaxies and clusters in space tells us that the spectrum is one where there was equal power amplitude on each length scale as it came into causal contact — 3×10^{10} cm at an age of one second, 10^{18} cm at one year, and so forth. Explaining both this shape (a Harrison–Zeldovich spectrum) and the amplitude ($\Delta\rho/\rho \approx 10^{-5}$ when the radiation temperature was 3000 K) is among the problems that inflation is supposed to solve, but not in a public talk.

The lumpiness of the early universe was quite subtle, but gravitation gradually pulled the matter together in the denser regions, emptying out the more tenuous ones, and thus the galaxies formed. Probably halos of dark matter assembled first, and the familiar hydrogen and helium (baryonic matter) flowed into them somewhat later. Just how the galaxies formed, so that the matter is now very lumpy while the radiation is still very smooth, is arguably the single most important unsolved problem in modern astrophysics. Many very clever theorists are working on it right now, which is not the same as saying that we can expect an answer by bedtime. Part of the problem is that, although galaxies continue to develop and change their shapes now, the most important part of the growth process ended long ago, and did not necessarily emit much radiation. Thus, we can study it only at great distances and with large telescopes. (Remember that light travels at a large, but not infinite, speed, so that we look back into the past by looking far away.)

Modern simulations of structure formation begin with a set of cosmological parameters—the expansion rate, baryon density, density in cold and/or hot

dark matter, and the value of the cosmological constant Λ and represent the material as particles with various properties and masses as large as 10^8 solar masses (or it will not all fit one even a large, modern computer). The Λ term actually improves the agreement between modeled and observed amounts of clustering at the present age of the universe. Some forms of dark matter work better than others, but the modelers are still experimenting with combinations of hot+cold, self-interacting, decaying, and other classes of dark matter.

Luckily the nuclear processes in the early universe are only the beginning of that story, because the chemistry of hydrogen and helium by themselves is not very interesting. Indeed the chemistry of helium is more or less nonexistent. The rest of the nuclear reactions happen inside stars, especially massive ones.

III. FROM GALAXIES TO STARS

The most conspicuous thing that galaxies do is turn gas into stars. At the same time, they develop the various internal structures we see today, spiral arms, spheroidal haloes, nuclei, and so forth. Most of the nuclei (including ours) have massive black holes at their centers, and in a few cases, accretion onto these black holes emits the visible light, x rays, radio waves and all that we call quasars. Collisions and mergers of protogalaxies are also part of the picture, and the later stages can be watched in images of distant objects taken with the Hubble Space Telescope, the Kecks, and so forth. These images have done a good deal to clarify the fact that small entities, galaxy parts as it were, are the sites of much early star formation, and that more is triggered during collisions and mergers.

Star formation, unlike galaxy formation, which largely ended long ago, is an ongoing process, and galaxies can be classified by how much of their gas has, so far, been turned into stars. For some, it is half or less. For others, including large spirals like our own Milky Way, only 10% or 20% of the gas remains (although more may still be flowing in from the outer halo). And the elliptical galaxies used up nearly all their gas long ago, and indeed may well no longer have any stars like our sun that would be capable of hosting planets with carbon-based life.

This part of the story has become a good deal more complex in recent years. Galaxies were once thought to acquire their identity early on and to evolve as isolated entities thereafter, turning gas into stars and being enriched in heavy elements made by those stars down to the present. Observations of protogalaxies now extend back to redshifts in excess of 5, and it is clear that the correct picture is one that mergers of dark matter halos, inflow of gas, and star formation all occur together over a long period. This is one of the areas in which I am currently struggling not to tell people either less or more than I really know about the subject.

Modern star formation cannot be quite like the primordial sort, because the gas has now been polluted with about 1% (by mass) of dust made of heavy elements synthesized in early generation of stars. This affects how that gas cools, condenses, and fragments into stars. It also affects the observability of the process, because even small amounts of

dust are remarkably opaque to visible and ultraviolet light,⁴ making the study of star formation regions largely the realm of infrared and millimeter astronomers. Actually, these last are the same size as normal astronomers, but their tools are radio telescopes with surfaces smooth enough to focus wavelengths of a millimeter or less.

A visible light photograph of a star formation region shows three sorts of things—hot, bright, young blue stars, hot gas illuminated by them, and dark, absorbed compact blobs of gas and dust, where the formation may still be going on. IR and mm images probe into the dark regions, and show that cores of relatively dense gas are growing in mass, contracting in size, rotating, and sometimes breaking apart to make binary stars.

All or most stars initially form in clusters of a few dozen to a few hundred thousands members, from clouds of cold, molecular gas. The youngest clusters still have clouds of gas and dust around. Older ones may have wisps. And the oldest are just stars, again so old that there are probably none left with life-bearing planets.

Did our sun form as part of a cluster? Almost certainly yes. Indeed the other members of it have perhaps left their traces on the orbits of our outer asteroids and in the details of the composition of the gas from which we formed. These suggest a cluster of a few hundred stars, a bit larger than the average. But only the most massive, compact clusters can survive for as long as the 5 Gyr lifetime of our sun and solar system. Thus, the other stars of our natal system have long since moved away on independent orbits through much of the disk of the Galaxy. It would, somehow, be neat to be able to point to a particular star in the sky and say that it formed with our sun. Unfortunately, this is impossible.

The formation of stars is the least-well-understood part of their lives, partly because it happens under the blankets of interstellar dust and partly because star formation has the same sort of complexity as weather forecasting. That is, many things are going on at the same time over an extended region, all of which matter to what will happen next, and even modern computing power falls quite a bit short of being able to track them all. In the stellar case, gravitational forces, emission and absorption of light, convection and turbulence, rotation of the cloud and of the galaxy, and magnetic fields all matter, and all vary in complex ways over a star-forming cloud. Impacts on a given cloud by expanding supernova remnants, spiral arm waves, and collisions with other clouds are also important, and one must simultaneously track length scales from cloud sizes (many parsecs) to star sizes, a dynamic range of 10^8 . Thus, if you describe all the properties of a cloud to even the best theorist in the world, she still will not be able to tell you how many stars it will form, what their masses will be, how many will be in close binary pairs, and so on.

We know quite a lot about these matters from observation, however. Star formation is inefficient—only a few percent of the gas does it at each opportunity. Small stars like the sun are much commoner than massive, bright stars, and half or more of them all are in binaries.

The state of the art numerical computations of star formation now extends to being able to follow a very small cloud (say 50 times the mass of the sun) down to where protostellar cores have acquired their identities, but not down to the scale of the stars themselves or of the disks around them where planets form.

About now, somebody is likely to ask whether the colors in the pretty pictures bear any resemblance to reality. The answer is “yes, but.” First, no color emulsion or set of filters and photodetectors has the same response curve as the human eye. Second, any blackbody source at a temperature near that of the sun (about 5600 K, a very common sort of temperature for stars) is bound to look white. This is not a coincidence, but a product of evolution; our eyes are most sensitive at the peak of the solar spectrum. Third, we lose color vision in low illumination anyhow (somewhere around a tenth of a foot candle). Fourth, particular elements in particular excitation and ionization states radiate monochromatic colors—the red of H- α , the green of forbidden ionized oxygen transitions, and so forth—but these tend to be mixed together in real gas clouds, again yielding something like white. Hubble Space Telescope images for the public are generally honest in a relative sense, but color enhanced. Images from bands other than visible light are, of course, color coded.

And also about now, some deep but slow thinker is likely to ask, as long as you are stopped, why the universe started expanding from an equilibrium state. This is assuming a fact not in evidence; ask him to talk to you afterward.

IV. NUCLEOSYNTHESIS AND THE DEATHS OF STARS

A newly formed star derives its energy and brightness from the fusion of hydrogen to helium in chains of nuclear reactions that we can duplicate in the laboratory. Our sun has been doing this for about 5 billion years, and will continue to do it for another five or so. Young stars are also likely to have very active surfaces with lots of star spots, flares, prominences, and so forth, which die away as the star ages to the condition of the sun. This is lucky, because such activity is responsible for a variety of inconvenient terrestrial events like failure of over the horizon radar and collapse of power grids.

A star keeps its brightness about constant until it runs out of hydrogen fuel at its center (though the sun is now about 30% brighter than it was when it formed, and Earth has somehow coped). The exhausted helium core then contracts and the outer layers expand and cool. Cool gas emits red light, and, with the enormous creativity of nomenclature for which astronomers are world renowned, we call these big, red stars red giants. The sun will become a red giant in roughly 5 billion years, and the oceans will boil away if we have not done something worse to them in the meantime.

The core of the star continues to contract and so gets hotter, until another set of nuclear reactions starts, in which helium is fused to carbon and oxygen. This begins to sound interesting, since we are made largely of carbon and oxygen. Eventually that fuel is also exhausted, the star becomes an even bigger, redder giant, and begins shedding its outer layers in a sort of wind. This is as far as stars of small mass like the sun go up the periodic table. Their cores never get hot enough for additional reactions. We can, however, often observe the departing envelope, because it uncovers a core so hot that ultraviolet light from it ionizes that gas. Thus, we see a fuzzy, sometimes colorful and morphologically complex

gas cloud, with a very hot, compact star at its core. The cloud gradually dissipates and the core star fades to become what is called a white dwarf.

This will happen to the sun in about 5 billion years, and if the Earth's oceans had not already boiled away when the sun was a red giant, they would freeze when it became a dim, dark white dwarf. Thus, the answer to Robert Frost's question is fire first, and ice afterward. And if you do not know what Robert Frost's question was, your homework for the weekend is to locate a book of his poems and find out.

I have left out completely the class of stars less massive than 0.4 M, which fuse only hydrogen, are completely convective (mixed), live a really long time, and end their lives as helium white dwarfs. At the present age of the universe, this has happened only in binary systems, where stars get stripped down to cores.

A typical white dwarf, though it contains the mass of a whole star, is only about the size of the earth. Thus, it is enormously dense, and if you had a matchbox full of material from one, you could not pick it up, because it would weigh several tons. Many white dwarfs also have very strong magnetic fields, though they do not have spots, flares, coronas, or other evidence of activity like the sun.

Notice that our low-mass star has kept most of the carbon and oxygen it made down inside the white dwarf. Thus, if we want to find the source of the heavy elements in the sun, in the earth, and in ourselves, we will have to look at the lives of more massive stars. A star which begins with 10 or 20 or 50 times the mass of our sun will be enormously bright, and so use up all its fuel in millions of years rather than billions, sort of like a Cadillac with an enormous fuel tank but lousy mileage, in comparison with a Honda. Such stars have such short lives that life is unlikely to have time to evolve on its planets, even if it has some.

Massive stars can also get much hotter at their centers than little ones, so that, in due course, carbon begins to fuse to oxygen and neon, then neon burns, then oxygen, to make magnesium, silicon, and sulfur. The star develops an onion-like structure, with alternating shells of the various fusion processes and the products in between. It also expands its surface and can be either a red or a blue supergiant. At a temperature approaching 10 billion Kelvin (compared to 10 million in the Sun) silicon begins fusing to iron and other nearby elements in the periodic table, especially the unstable isotope Ni⁵⁶, and the star develops an iron core.

Our star is about to get into serious trouble. Iron is the most tightly bound of all atomic nuclei, and no more energy can be extracted from it. It is like trying to get money out of the government. Thus, the core gradually grows until it reaches a critical mass of about 1.4 times the mass of the sun, called the Chandrasekhar limit, curiously enough because it was discovered by Chandrasekhar. You cannot count on these things. Hubble's law was discovered by Lundmark.

The Chandrasekhar limiting mass is the largest that can be supported by degenerate electron pressure. This is not a statement about the stars' moral principles, but about the distribution of electron velocities. What happens is that it becomes energetically favorable for the electrons to combine with the protons in the nuclei and make neutrons. Now a neutron is much smaller than a proton plus an electron, and so the core of the star collapses suddenly and catastrophically. Suddenly means in less than a second, compared to the

millions of years of previous stellar life; and catastrophically means that it releases about 10^{53} ergs of gravitational potential energy. Now an erg is a very small amount of energy, about a fly doing one pushup. But 10^{53} is a very large number, and this is more than the star has radiated over its entire previous life.

All this energy, in the form of neutrinos, gravitational radiation, and light comes flooding out in an enormous hurry, pushing the outer layers of the star before it. We see a sudden flare-up of the star, called a supernova, and the carbon, oxygen, magnesium and silicon, iron and calcium, and all that the star has made over its lifetime is tossed out into the general interstellar medium, where it gets mixed into the dominant hydrogen and helium and becomes raw material for future generations of stars. The collapsed core is now only a few miles in diameter, but contains about 1.5 solar masses, and so is enormously dense, even compared to a white dwarf. Because it is made mostly of neutrons, we call it a neutron star. Neutron stars generally form with very strong magnetic fields (10^{12} Gauss, compared to 10^{6-8} G for white dwarfs, and about 10 G for our sun). They are also rapid rotators, and the combination of strong field and rapid rotation is responsible for a sort of search-light pattern of radio radiation that we call a pulsar. The remnant of a supernova recorded by the Chinese in the year 1054 now has at its center a pulsar with a rotation period only 1/30th of a second, so there is a whole star rotating around faster than your eye can resolve. This is perhaps a good thing. An astronomer who had gone up to a mountaintop observatory and returned to report that he had seen a star winking at him many times per second would perhaps have been suspected of having something besides milk with his midnight lunch.

Occasionally, a stellar core collapses to an even higher density, so that its escape velocity is larger than the speed of light. Such things are called black holes, and because nothing not even light, can get out, pictures of them are very expensive and very hard to come by. The normal end point of massive stars is, however, the supernova plus neutron star scenario, returning several solar masses of heavy elements to the interstellar medium.

This section needs fewer apologies than most. Stellar structure and evolution really is a solved problem: the stars we compute and the stars we see are the same sorts of beasts. A few caveats: (a) the core is really built as Ni^{56} rather than Fe^{56} , because there is time for nuclear/strong force reactions to come into equilibrium but not weak interactions; (b) the supernova SN 1987A really did confirm most of what we were expecting—the mass of the progenitor, the production of 10^{53} ergs or so in neutrinos, 18 of which were captured on Earth, the gamma ray signature of Ni^{56} decaying via Co^{56} to stable Fe^{56} , and so forth; (c) elements beyond $Z=30$ are made by neutron captures, many in SN explosions themselves, others in the phases where hydrogen and helium are both fusing in thin shells in intermediate mass stars; (d) Lundmark had a quadratic rather than linear velocity–distance relation and so did not exactly discover Hubble’s law; but Mayer and Waterston really did come up with most of the ideas about stellar energy coming from contraction that are credited as a rule to Kelvin and Helmholtz, including the Kelvin–Helmholtz time scale; and (e) I

have a fun story about the Chandrasekhar limit really being discovered by Chandra and not, as a Soviet colleague had claimed, by a Russian named Yakov Frenkel, but we are running out of time. Chandra, incidentally, was my “Doktor Grossvater,” but I was still VERY much in awe of him.

V. PLANETS, LIFE, AND INTELLIGENCE

As a result of generations of massive stars, the nuclear reactions in them, and their explosions as supernovas, by the time the solar system formed, it did so out of material that was about 2% heavy elements, and, as a result, planets like the Earth had become possible. Within our own solar system, the Earth is unique in both its interior characteristics and its hydrosphere and atmosphere. The Earth is just massive enough to have experienced lots of chemical differentiation, so that it has an iron core and a rocky mantle. Its 24 hour rotation plus the fluid iron core are responsible for its magnetic field. This field provides some protection from cosmic rays as well as permitting the operation of compasses, so that Boy Scouts can find Girl Scouts. Mars, with the same rotation period but smaller mass, has no field, and neither does Venus, with the same mass as Earth, but very slow rotation. Mars, at least, is covered with rust partly because iron is still abundant in its crust.

Convection currents in the rocky mantle result in what is called plate tectonics and continental drift. This smashing together and separating of the Earth’s crustal plates results in the formation of mountains and valleys, earthquakes and volcanoes, and also the production of ores, without which it is difficult to imagine modern technology being possible. Neither Mars nor Venus has plate tectonics in operation at present.

Our atmosphere and hydrosphere are also unique, and have come from some combination of two processes. First, the gradual outgassing of water, carbon dioxide, nitrogen, and so forth trapped between rock grains as the earth formed, and second, numerous impacts of comets and asteroids, rich in these lighter substances because they formed far out in the solar system, where it was cold. The topology of the Earth’s surface is the product of competition between plate tectonics pushing up bits and erosion by water wearing them down. Our climate and weather are again a product of complex interactions between sunlight, the details of the Earth’s orbit and rotation (which are not quite constant, hence ice ages and such), and the properties of the water and air.⁵

Where the water and air came from continues to be a topic of debate. The first time I taught geophysics, it was all outgassing. Then impacts became popular, partly in connection with the interpretation of the Cretaceous–Tertiary boundary at 65 million years ago. Several large comets have recently been shown to have deuterium to hydrogen ratios much larger than the terrestrial one, so impacts of things like these cannot have been the source of most of the water. Another ongoing debate is whether the convection in the mantle (yes, this really is flow of solid rock, but the time scale is 10^8 yr) occurs in a single layer of cells between core and crust or two layers with only partial mixing between them. It is a little difficult to imagine advanced lifeforms on a planet uniformly covered by a 3 km sea, as we would be without the continuous rebuilding of con-

tinents, but just how tight the constraints are on habitable planets in terms of amounts of U, Th, K⁴⁰, etc. to keep the core hot and drive the convection is obviously very uncertain. I cannot see that the one versus two layers of cells would matter to anybody except geophysicists.

A decade ago, we knew of no planets outside the nine of our own solar system and three orbiting a pulsar (but they are products of the supernova explosion, not residual earths, though their masses are like ours). Starting in the fall of 1995, three groups of astronomers have been reporting more and more planets orbiting other stars. The methods used can identify only planets with the mass of Saturn or larger, and they are best at finding ones with orbit periods of a year or less. Most of the planets found so far are "hot Jupiters," that is, large masses, but as close to their stars as Mercury is to the sun, or even closer. A few have periods of several years. At least one star is known to have three massive planets, and several have two. About 5% of stars like the sun (meaning the same mass, and fairly large abundances of the heavy elements) have such planets, and it is not at all obvious whether these make the existence of other planetary systems more like ours more or less likely.

The solar system began its life with about 2% of its mass in heavy elements capable of complex chemistry. It also began with a rich assortment of moderately complex molecules. Radio, millimeter, and infrared astronomers have identified more than 100 different sorts of molecules in the dense gas clouds now forming stars. These include interstellar water vapor, carbon dioxide, methane, ammonia, formaldehyde (which is a preservative), methyl alcohol (another preservative), ethyl alcohol (you all know what that is good for—indeed there is enough ethyl alcohol in the molecular cloud at the center of our galaxy to make 70 million bottles of high proof scotch; the only problem is to get it here). There is also interstellar formic acid, from which we deduce the existence of interstellar ants. Of course, if we had not seen it, you could deduce the existence of interstellar anteaters. That is a UC Irvine joke. Our campus animal is the anteater. The reason is that we are a very new campus, and all the good animals were taken. UC Santa Cruz has the banana slug.

This range of interstellar molecules (which also includes some things like HC₉N that are never found on earth) includes the raw materials for what is called a Urey atmosphere experiment (because it was first carried out by Stanley Miller, but it was Urey's idea). In such an experiment, you take water and dissolve in it some mix of carbon, nitrogen, and oxygen-bearing molecules to make a clear solution. Add energy in the form of an electric current (like lightning) or ultraviolet light (which reached the Earth's surface before ozone formed in the air), and wait a while. When you come back on Monday, you will find brown sludge at the bottom of your flask, consisting of a mix of insoluble and poorly soluble complex organic molecules. In this way you can make amino acids, phosphates, bases, sugars, and such. That is the molecules whose polymers are, in turn, proteins, amino acids, and the other molecules of importance to terrestrial life.

We know that nature has also carried out this experiment to this stage more than once, because carbon-rich meteorites arriving on earth from the asteroid belt sometimes have a mix of amino acids, bases, hydrocarbons, and so forth.

At some point, some of these molecules became complex

enough to be capable of self-reproduction, after which the mechanisms of Darwinian natural selection take over, and the evolution from a slime mold to a politician is practically inevitable. Intelligence can be defined in many ways, but if one of your goals is communication across interstellar distances, the most important item is not the quartets of Mozart, the plays of Sophocles, or Euclidean geometry, but radio astronomy.

True, I guess, as far as what it says (but it does not say much), except perhaps the inevitability of evolution toward complexity. Respectable biologists entertain a very wide range of opinions on this point. Ernst Myer of Harvard, at one end, expects slime molds to be very common, and politicians to be very rare. At the other extreme come those who have focused on convergent evolution (the appearance of rather similar structures of great complexity—like wings and eyes—that have evolved on earth more than once from different underlying structures and yet function rather similarly). Simon Conway Morris of Cambridge University, for instance, has a particularly fine slide that shows a degree-granting ceremony in which the caps, gowns, and hoods are worn by an assemblage of what are clearly progressive reptiles, evolved from dinosaurs in the 65 Myr without a K-T impact.

VI. THE COURSE OF EVENTS AND POTENTIAL FOR EXTRATERRESTRIAL LIFE

So far, we have watched the early universe set the stage for galaxy formation. Galaxies then formed stars, where nuclear reactions made the heavy elements needed for terrestrial planets and chemically based life. Planets (though not our sort) are common, and we then inevitably want to ask how many inhabited ones will there be, by what, and for how long.

Of course there are people who think they know the answer to this. Silver spaceships land in their yards and take them for rides. These people generally also have other problems, and if any of you are among them, I do not want to know about it.

Let us go at it the other way, as a sort of elimination process, in stages. (1) our Milky Way contains about 200 billion stars (in other words, if you could collect a dollar from each, it would just about take care of this year's federal budget deficit); of these (2) about half are in binary systems, where planet orbits would be unstable (as three-body systems always are, in Newtonian mechanics as well as in human psychology), leaving (3) about 10¹¹ single stars, of which about 90% are either massive, short lived ones, or the small, faint ones that radiate no ultraviolet for the Urey atmosphere process to get complicated chemistry started, leaving (4) about 10 billion stars more or less like the sun in mass, composition, and life expectancy, of which (4) at least 5% have planets of the hot Jupiter sort, suggesting perhaps (5) another 5% or half a billion with families of planets more or less like the solar system.

Now you must fold in your best estimate of (6) the probability of life arising on another earth (perhaps fairly high), (7) the probability of intelligence or radar astronomy evolving (perhaps fairly low), and (8) the life expectancy of a civilization once it develops. This is completely unknown,

since we know only a lower limit of about 100 years (in the sense of our ability to communicate at a distance.) And, of course, we hope to know only a (growing) lower limit for a very long time. The possibilities are (a) the life of the star, billions of years, (b) the duration of the species, millions of years, at least for the higher mammals on earth, or (c) something set by technology, in the worst case the predilection of species to destroy their planets as soon as they acquire the ability to modify them significantly.

Even if the development of life and intelligence are fairly common, a very short life expectancy will mean that we are, in effect, alone in the Galaxy, for any message we might send or receive would arrive long after the sender had ceased to be interested in interstellar communication.

This bit is, of course, more sermon than science, and you may well disagree. The remark about species not enduring forever has, however, always been true in the fossil record, and is not contradicted by turtles, coelocanth, or other so-called living fossils, which are, in fact, of very different species from the Mesozoic ones. It is just that we have more words for different types of artiodactyls than for different types of testudinas, and this goes double for bugs and fungi.

VII. THE UNDERLYING PHYSICS

In any case, life has appeared and evolved to the complexity of a typical AAPT member in at least one case, here on earth. And somehow, we find ourselves on a planet, in a galaxy, orbiting a star, in a universe that seems remarkably hospitable to chemically based life. Experts in physics and cosmology have arrived at slightly different integers (from 6 to about 16) for the number of quantities you need to know to specify the underlying physics of this universe.⁶ I fastened long ago on eight as the critical number, because there truly are exactly four forces of physics that describe how one small amount of matter can interact with another and four quantities that correspondingly describe the large scale properties of the cosmos.

Let us look first at the forces. Most familiar is gravity. You experience it as you sit there in your chair rather than flying up to the ceiling, when you trip at the top of the stars, and fall down, and so forth. Gravity is responsible for the structures of things that are more or less spherical (the larger moons, planets, stars, galaxies, and their clusters, their orbits around each other, and the expansion of the universe). It is the weakest of the four forces. But it always wins for large objects because it is always attractive and you cannot shield things from it.

Next comes electromagnetism, which you experience when you leave your watch in a drawer with a magnet and the watch stops working or when you stick a finger in a light socket and are surprised. One of the first things I learned on going to England is that 220 V is more of a surprise than 110. I was trying to change a light bulb. You might think, at my advanced age, I should know how to change a light bulb. All I can tell you is that they screw in differently in England.

You also experience the electromagnetic interaction as you sit there quietly digesting your dinner, because all of chemistry, including biochemistry, is essentially electromagnetic in nature. When Richard Feynman said that yesterday's mashed potatoes are today's brains (this is more obvious in some people than in others), he was talking about an electro-

magnetic process. Finally, the emission and absorption of light, radio waves, x rays, and all the rest are EM processes, which is why the collective name is electromagnetic radiation.

Less familiar is the nuclear force or interaction, sometimes also called the strong, color, or gluon force. It holds together the nuclei of atoms (which would otherwise fall apart because of the electromagnetic repulsion of the protons) and is responsible for nuclear reactions in which the total numbers of neutrons and of protons are separately conserved. The nuclear force is attractive between all combinations of p's and n's, but has a very short range, so that it is not able to stabilize nuclei with more than about 200 particles in them.

Least familiar is the weak interaction. It describes the decay of neutrons (which last only about 11 minutes unless they are safe inside nuclei or neutron stars; you cannot go to the drugstore and buy a box of neutrons), as well as any process that involves neutrinos, and nuclear reactions in which p's are changed to n's, or, conversely, including the critical set that provides energy for the sun and most other stars for most of their lives. The weak interaction has an even shorter range than the strong or nuclear one, and it can be either attractive or repulsive (like electromagnetism) because it has the equivalent of two kinds of charge.

All of these other forces lose out to gravity on large scales, the nuclear and weak because they are short range, and the electromagnetic because the electric charges of objects can be shielded by an equal amount of the opposite charge. The universe is very close to electric neutrality (probably the sum of the charges is exactly zero, but we cannot measure it this precisely), and so are large astronomical objects.

Next come the large scale properties of the universe. I have listed them in a sort of code. First is the Hubble constant, H . Elementary textbooks describe H as the expansion rate of the universe, but it is really a measure of its age, 10 or 20 billion years I mentioned at the beginning. Next comes the average density in all forms, including familiar matter (baryons), less familiar sorts of dark matter (nonbaryonic), and even dark energy (or the cosmological constant, or quintessence). Knowing the sum of all these (which can be easier to measure than each individually) is equivalent to knowing the geometry of the universe. It turns out to be flat, that is, as near to the equivalent of four-dimensional Euclidean space-time as you can get in an expanding space.

Third is the temperature, or entropy, or ratio of photons to baryons. The present temperature is about 2.7 K, and we know exactly how its ratio to the density of matter scales with time as we look back to the early universe. The temperature or photon-to-baryon ratio is one of the inputs into the calculation of how much hydrogen, helium, deuterium, and so forth ought to have been produced in the hot, dense, Big Bang phase. The calculation agrees with what we see. The fourth large scale property of the observable universe is its overall homogeneity and isotropy at the present time and at the epoch when the matter and radiation ceased close communication (near $T=3000$ K), upon which was superimposed by that time a very subtle ensemble of ripples, fluctuations, or primordial perturbations.

Now, if any one of these eight quantities had been very different from what it is, we would not be here to talk about it. There are countless examples, of which these are only a few of my favorites. For instance, if the electromagnetic force were somewhat stronger, all the electrons would be pulled inside the atomic nuclei—no Bohr orbits, no chemis-

try, no us. Make it weaker, and the electrons all float away at the temperature of the universe. Indeed if the electromagnetic coupling constant changes by even a factor of 3 (remember it is a factor of 10^{40} stronger than gravity), water is not a liquid at any temperature. Similarly, a weaker or stronger weak interaction would either prevent hydrogen from fusing to helium in stars or have turned the entire baryon supply into helium in the Big Bang. In either case, there would be no source of energy for the stars. If gravity were too strong, the primordial fluctuations would all have grown to black holes, and if it were too weak, galaxies could not have formed from those fluctuations.

Similar considerations hold for any of the large scale properties. If the temperature were too high, pressure would have prevented galaxy formation. Too low, and the baryons would have become neutral very early and fallen into the centers of galaxies, making star bursts of massive stars, and leaving too little left over for the later formation of metal rich stars. Other combinations would yield a universe in which Big Bang nucleosynthesis turned everything to iron (the most tightly bound nucleus, remember), and we would be giant lumps of stainless steel, sitting around rusting, and conversing in very low voices. Finally, if you were to try to change two or more of the quantities to balance each other and get back to a habitable universe, you would come up against the fact that each dominates a different set of phenomena and objects, so that if you fix one item (for instance, by making gravity weaker but the density larger so that galaxies can still form), you would discover that something else has gone wrong (stars never get hot enough for fusion, or the most massive objects that have time to cool, contract and form stars in the age of the universe are smaller than stars).

VIII. POSSIBLE MEANINGS

The apparent fitness of the world for humans, or chemically based life, or something in between was noticed centuries ago, and various implications discussed by serious philosophers (if this is not an oxymoron), many of whom ended up with some sort of “watchmaker” argument for a creator of wondrous powers. The other three interpretations are somewhat younger, but none is in any sense original with me.

First comes the traditional one, “G.d has been very careful.” This is a possible answer. It may even be the right one. But it is not a scientific answer in the sense that it does not lead you to carry out any further experiments, calculations, or observations.

The second possibility is additional underlying physics that we have not yet understood but that, when we do, will make it obvious why the various quantities in Tables II and III have the relationships they do. This answer has been popular with theoretical physicists over the years in connection with efforts to unify the four forces. Unification has already succeeded for the electroweak force, the idea for which won Weinberg, Glashow, and Salam a Nobel Prize, and the confirmation of which, by the discovery of new, predicted particles won another physics Nobel for Rubbia and van der Meer. The next stage, including the nuclear force, is Grand Unified Theories (GUTs, as in “cosmology takes GUTs,” according to a conference T-shirt some years ago). An early one of these correctly calculated the photon to baryon ratio, but got some other things wrong, including the lifetime of the proton. GUTs and the next, presumably final

Table II. The forces of nature.

Name	Strength	Typical phenomena
Gravity	$Gm_{ep}^m/\hbar c = 3 \times 10^{-42}$	Structure of spherical objects, orbits, expansion of the universe
Electromagnetism	$e^2/\hbar = 1/137$	Structure of atoms and molecules, chemistry, EM radiation, magnetic fields
Nuclear	$G_s \approx 15$ (but exponential fall-off with distance)	Structure of atomic nuclei; reactions that conserve n’s and p’s separately
Weak	$G_w \approx 10^{-13}$ (but exponential fall-off with distance)	Neutron decay; anything with neutrinos; reactions where n’s are transformed to p’s or conversely

stage (called SuperUnification or SuperSymmetry, which brings in gravity) predict an assortment of new particles, none of which has yet been seen in laboratory experiments, but several of which might contribute to dark matter.

An assortment of numerical relationships or coincidences among our eight quantities have been claimed as supporting evidence for the “new physics” interpretation of the habitability of the universe. For instance, the ratio of electromagnetic and gravitational forces is also the ratio of the size of the observable universe to the diameter of atomic nuclei (or the range of the strong force) to within a factor of 10 or so. And that number squared (about 10^{78} or 10^{80}) is the number of particles in the observable universe (which brings in H, c, and the density). The number of particles in a typical star is that number to the 3/2 power, and the photon to baryon ratio is the one-quarter power. The former is understood. I am not sure about the latter.

Third comes the concept of multiple universes, in which only a few (including, of course, ours) happen to have a combination of forces and large scale properties that make them habitable. Multiple universes could mean a large number of independent four-dimensional space-times, imbedded in five- or higher-dimensional space, or a single space time that alternately expands and contracts. Such oscillation is possible within the framework of general relativity only if there is matter with negative density around somewhere. I do not mean antimatter (which has positive density, though some charges opposite from the familiar ones) or even quintessence (which has negative pressure, but the density is still positive). Indeed it is difficult to imagine at all. Many space times, perhaps budding off from one another in many episodes of inflation, are currently rather in fashion, though the

Table III. Characteristics of the Universe.

Symbol	Meaning	Numerical value
H_0	Hubble’s constant; time scale of cosmic expansion	$(3 - 6 \times 10^{17} \text{ s})^{-1}$
Ω, Λ	Densities in matter (all forms) Cosmological constant (dark energy) geometry	$\Omega + \Lambda \approx 1$ Space flat or nearly so
T, η	Temperature photon to baryon ratio; entropy	$T = 2.7 \text{ K}$ $\eta \approx 10^{10}$
$\Delta\rho/\rho$	Deviations from pure homogeneity	$\Delta\rho/\rho \approx 10^{-5}$
$Q, n,$	and isotropy: normalization and slope of spectrum	$n \approx 1$

fashion has swung between these multiverses and new physics several times since I started talking about this subject in public.

Fourth is the nature of shear complexity. Perhaps all it takes is a very large number of particles of several sorts and a bunch of different kinds of forces to produce the kind of unpredictability that we call intelligence in ourselves and orneriness in our teenage children (or parents, as appropriate). This was Feynman's favorite, at least some of the time. He drew an analogy with water. Quantum electrodynamics (the quantum version of the electromagnetic force) allows you to calculate many things about one water molecule—the angle between the two hydrogen ears (about the same as Mickey Mouse), the frequencies of radiation that it can emit and absorb, even the approximate temperature at which it will cling to other water molecules and solidify. Nothing in those calculations would ever lead you to predict the existence of ocean waves or waterfalls, which arise from the interaction of enormous numbers of water molecules (and two forces—EM and gravity), in a way that we cannot calculate, even in principle. Perhaps that is all the universe needs to produce life and intelligence.

Clearly I do not know which of these four ideas is correct (or I would have told you only the correct one), though they do more or less exhaust the list currently under consideration.⁷

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¹V. Trimble, *Am. Sci.* **65**, 76 (1977). In case you wondered, in the interim, I have also published about 400 papers, book chapters, reviews, and such and given about 500 talks on other subjects, or at least with other titles, if the Universe may be supposed to include everything.

²There is a precedent for this in the form of an old European, Rabbinic story, of which the intermediate advice is to take the goat into the house.

³M. J. Rees, "The cosmological significance of e^2/Gm^2 and related numbers," *Comments Astrophys. Space Phys.* **4**, 179 (1972); B. J. Carr and M. J. Rees, "Anthropic principle and the physical world," *Nature* (London) **278**, 605 (1979), and portions (but only portions) of J. D. Barrow and Frank J. Tipler, *The Anthropic Cosmological Principle* (Oxford University Press, New York, 1986).

⁴Within living memory, one could show the obscuring power of small amounts of particulate matter graphically by blowing cigarette smoke into the beam of the projector. Not a smoker myself, I always bummed a cigarette to do this. The last few times I tried, no one was prepared to admit they owned cigarettes. And the law now forbids such doings. Chalk dust from clapping erasers is not an adequate substitute.

⁵That box of slides mentioned in the Introduction is now wood rather than metal and contains about 75 images, many of which are my own perfectly awful drawings of the insides of stars, but also astronomical images, landforms (including the orange grove in San Bernardino, where plate motion has put a kink in all the rows of trees; the site is now fields of waving condos), numbers, and text. I have simply left out here some lines from the talk that are incomprehensible without the images.

⁶M. J. Rees, *Just Six Numbers* (Basic Books, City, 2001), is at one end of this set of integers. The listings in the Particle Data Book are at the other.

⁷The "more physics" point of view is described by S. W. Weinberg in *Dreams of a Final Theory* (Pantheon, City, 1993). The "multiverse" concept appears in M. J. Rees, *Before the Beginning* (Addison Wesley, New York, 1997). The Feynman thought is from a lunchtime conversation (at the Caltech cafeteria, properly called Chandler Hall—nobody knows who Chandler was—improperly called the Greasy, of which it is much less these days than it used to be) at which the author was present, some time in the 1970s. A. H. Guth, *The Inflationary Universe* (Jonathan Cape, City, 1996) gives some indication of how inflation feeds into multiple universes, as does A. Linde, "The future of the universe," in *The Origin and Evolution of the Universe*, edited by B. Zuckerman and M. A. Malkan (Jones and Bartlett, City, 1996), p. 127. Finally, and returning whence we came, to convergent evolution and the potential for finding ourselves on other planets; see S. Conway-Morris, *The Crucible of Creation: The Burgess Shale and the Rise of Animals* (Cambridge University Press, Cambridge, 1998).