COMMITTEE I
The Unity of the Universe

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THE ANTHROPIC PRINCIPLE AS A UNIFYING APPROACH TO THE UNIVERSE

by

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I. INTRODUCTION: THE NEED FOR AND MEANING OF AN ANTHROPIC PRINCIPLE

A. Its Place in Science

The world is very full of things. Not just cabbages and kings, but stars and galaxies; fire and water; molecules, muons, and magnetic fields. The array quickly becomes bewildering. Thus, from the earliest times of which we have any written record, mankind has tried to make sense of it all by asking: which are the really important things, how do they relate to each other, what are their causes and purposes, and can we somehow control or at least predict them?

One approach to these questions is called religion (when it is practiced by our tribe) or magic (when practiced by the tribe in the next valley). It attributes causes and purposes to a creator or creators (somehow external to the world) and provides an organizing idea that the important things are those which are necessary for our salvation. This way of looking at the world can be made perfectly self-consistent and exceedingly resistent to disproof in the realms of organization, causes, and purposes. It does much less well in the realm of prediction and control. This nearly exhausts my knowledge of the subject, and I shall not further address it here.

Modern science is a very different approach to the same set of questions. The difference shows immediately in our use of the word Universe rather than world. The Universe is, by definition, everything there is — no external causes or forces need apply. The causes of objects, processes, and phenomena are understood, instead, as being other objects, processes, and phenomena, all equally part of the universe. And no purpose is ought or expected.

The enormous successes of science in the realm of prediction, explanation, and control require no inventorying. Reduction in tabacco use saves lives in a way that a ban on trumpet sales could not have saved the walls of Jericho.

On the other hand, science provides no firm rule for picking out important things from the rich array. In fact, we run the risk of a sort of circularity, in which we regard as important precisely those items we can explain and neglect the ones we can't.

In recent years, scientists have devoted considerable attention to a proising selection rule called the anthropic principle. It is the idea that the important things are those that, had they been very different from what they are, we would not be here to ask questions about them. Before going further, it should be emphasized that essentially no practicing scientists do this sort of thing full time. Rather, it is people with established careers in general relativity, high energy astrophysics, geology, biology, or (in my case) stellar astronomy, and so forth, who have been looking at these issues as a sort of avocation.

The principle is not quite as anthropocentric as it sounds. In this context, "we" does not really mean humanity but, rather, intelligent entities or observers capable of interacting with the universe and asking questions about it. By the same token, "intelligence" means more nearly radio astronomy (the ability to exchange information over large distances) than it does the dialogs of Plato or the quartets of Mozart.

The anthropic principle, in its broadest sense, comprises the two ideas (a) that, if the universe were very different from the way it is, we would not be here to ask questions about it, and (b) that (a) is somehow important and/or can provide independent, new information about the universe. No one who gives the matter a moment's thought can seriously doubt (a). Thus any uncertainty or interest about the principle must concern the truth of (b) and the nature of the possible importance or new information. The most extensive published discussion of these and related issues is that of Barrow and Tipler.

B. A Minimum Set of Universal Parameters

Just what are the properties that make our universe cognizable? Previous writers on the subject (Carter 1974; Carr & Rees 1979; Barrow & Tipler 1986) have chosen slightly different sets of physical and cosmological constants as vital, but all agree that G (or, equivalently, the gravitational fine structure constant, $Gm_p^2/\hbar c$, or the mass of the proton) is important and the size of the red spot on Jupiter is not. My own list has evolved slightly since I last wrote about these matters (Trimble 1977) and currently includes about a dozen items, equally divided between very small and very large scale parameters.

Laboratory Physics: The relative strengths and ranges of the four forces, gravitation, electromagnetism, the nuclear (or strong or color) force, and the weak interaction; the electron to proton mass ratio; and the existence of an exclusion principle with scale $\hbar$. One is tempted to include also c, the speed of light, but the very best relativistis assure us that it is really just a conversion factor among sets of units (electric and magnetic, or time and space)

Cosmological Physics: The age of the universe (long enough for life to develop), its density (high enough for structures to form but not so high as to turn everything into black holes), its temperature or photon-to-baryon ratio (in the range that permits structures to grow), Einstein's cosmological constant (small enough in absolute value not to dominate the dynamics), and a high degree of homogeneity and isotropy on large scales coupled with a suitable spectrum of initial perturbations on small scales.

Deeper Issues: Space is three dimensional and time unidirectional. A few (and only a few) quantities are absolutely conserved in the universe (charge, angular momentum, and total mass-energy) and are arguably all zero

(Grishchuk & Zeldovich 1978). And entropy is non-decreasing (though only in closed systems). Many of these deeper issues have anthropic aspects; for instance, it is difficult to construct complex neutral networks in fewer than three dimensions and planetary orbits are typically unstable in more (Whitrow 1955). I find it, however, impossible to imagine the consequences of being able to remember backward or of being able to create and destroy energy well enough to guess whether such properties would necessarily render the universe uninhabitable and so will not discuss them further.

<u>The Dirac Large Numbers</u>: These are so-called because they were discussed by Weyl (1919, 1934) and Eddington (1923) and, later, by Dirac (1937). They are not independent parameters, but dimensionless ratios involving both the laboratory and cosmological constants. Among the ones first noted were the ratio of electromagnetic to gravitational interaction between an electron and a proton and the ratio of the radius of the observable universe to the classical electron radius. These are both about 10^{40}. The number of particcles in the observable universe is roughly the square (or product) 10^{80}, as is the ratio of the expected proton decay lifetime to the Planck time. The cube, 10^{120}, is roughly the ratio of the total action of the universe to h and also the reciprocal of Einstein's constant Λ in dimensionless (Planckian) units.

<u>The Explicable Numbers</u>: An enormous number of things that seem to be important — the energies of chemical and nuclear reactions; the masses of planets, stars, and galaxies; the heights of people and mountains — turn out to be calculable in terms of those dozen laboratory and cosmological parameters (Carr & Rees 1979; Weisskopf 1975; Barrow & Tipler) and so do not constitute independent constraints on the properties of the universe, even if they are very important. The mass of stars (Carr & Rees 1979) is a particu-

larly nice example.

We require that gas pressure dominate over radiation pressure (which will tend to blow stars apart) and over degeneracy pressure (which will keep them from contracting until they are hot enough for nuclear reactions). In addition, pressure must balance gravity. Thus, for the upper mass limit, we can say

$$\frac{P_{rad}}{P_{gas}} \approx \frac{aT^4R^3}{NkT} \lesssim 1 \qquad \text{and} \qquad (1)$$

$$kT \approx GMm_p/R \qquad (2)$$

where M, R, and T are characteristic mass, size, and temperature for a star, N is the number of particles in it and, a is the first radiation constant, roughly $k^4/\hbar^3c^3$. Now make the substitutions $M = Nm_p$ and $R = N^{1/3}d$, where d is the average distance between particles in the star, and substitute the value of T from (2) into (1) to get

$$N \lesssim (Gm_p^2/\hbar c)^{-3/2} \approx (10^{40})^{3/2} \qquad (3)$$

Thus the fact that the number of particles in a star comes close to the 3/2 power of a Dirac number is just a consequence of stellar structure being determined by a balance between pressure and gravity. And yes, I have checked that the algebra comes out all right!

C. Possible Significances of the Anthropic Principle

The fine-tuning of man and his environment has, of course, been noticed for centuries, and one was of the pillars of rationalist arguments for the existence of a purposeful creator. A certain mismatch between the scale of the creation and that of the creature was also noticed very early and prompted the psalmist to ask "Adonoy, ma'adam...", "Lord, what is man that Thou takest knowledge of him or the son of man, that Thou makest account of him?" (Ps 144:3). Much of that fine-tuning we now attribute to the actions of darwinian evolution, and it no longer seems to require special explanation. The vital aspects of the Universe are now thought of as those that make heirarchical structures, chemistry, planets, life, and evolution themselves possible. A simple example is the ratio of the strengths of the electromagnetic and nuclear forces, which, if varied up or down by an order of magnitude, would no longer permit stable atoms to interact and bind in molecules; even a factor of three change would eliminate liquid water at all temperatures. We will attempt later to assemble a more complete list of these vital aspects.

Although of view of just what needs to be explained has changed, the psalmist's explanation is, of course, still a possible one: the necessary properties were built in as initial conditions and integration constants by a purposeful creator. Many (by no means all) modern theologians apparently subscribe to something like this view. It does not seem to be testable in a Popperian sense.

Barrow and Tipler (1986) stake out some neighboring ground, putting the anthropic principle in context as a recent version of teleogical approaches to the world (crudely, the idea that goals, purposes, and ends can function as causes in the natural world as well as in human affairs). They note past examples of success, like least action principles in quantum mechanics and Fermat's (correct) calculation of the laws of refraction from the assumption that light rays minimize their travel time. They adopt a strong version of the anthropic principle (that observers not only do exist in our universe but must exist in any possible one) and use this to make a definite prediction that the universe must be closed, probably in such a way that all world lines remain continuously in causal contact. This is, at any rate, testable. I suspect it is also wrong.

The weak anthropic principle — that observers do exist and would not with other combinations of forces and cosmological parameters — is, in a sense, merely an extreme version of selection effect. As such, it admits of several possible interpretations fairly close to the mainstream of modern physics. These include multiple universes, incomplete physics, and the primacy of complexity.

One can imagine multiple universes arising in three ways. First, our own four-dimensional space time may be positively curved and closed so as eventually to recontract. Then successive cycles of expansion followed by contraction might be marked by different values of G, e, and all the rest, only a few of which permit the appearance of natural philosophers. These successive cycles are not really permitted by general relativity (crudely, once you reach a singularity from non-singular conditions, you can't get out again (Hawking & Ellis 1973)), but never mind, we are going to need some new physics anyway.

Second, multiple universes may coexist in time, either ab initio, imbedded in some higher-dimensional space (Wheeler 1971) or splitting off whenever a quantum-mechanical measurement is made, as in Everett's (1957) multi-world interpretation of quantum mechanics. Again, only a few universes would have (ab initio, or after the early splits) sets of properties permitting observers. Third, within an inflationary model for the universe (Kazanas 1980) one might imagine that nucleation occurred many times at many places, leading to exponentially expanding bubbles with many different energies of symmetry-breaking (hence many different force ratios etc.), one of which happens to be cognizable and ours. Linde's (1983) chaotic inflation might lead to this. Only in the third case, where bubbles eventually meet, can one universe ever communicate with another. Thus about the only test one can imagine is the attempt to determine whether the set of parameters permitting life is a reasonable fraction of the total. It is, at any rate, not quite a set of measure zero. Our universe is, for instance, apparently more isotropic than anthropy requires (Raine & Thomas 1986).

The next of these relatively conventional interpretations is that we simply have not yet understood all the physics, and, when we do, it will be obvious why the assorted constants have the values they do. Undoubtedly there is some truth in this. The electroweak unification has turned some aspects of the weak interaction into calculable quantities. Its coupling constant, for instance, is the electromagnetic one times the square of the ratio of the W boson mass to that of the electron. Since the W mass also tells us the range of the weak interaction, two parameters have been collapsed into one. The Grand Unified Theories (GUTs) similarly render the photon-to-baryon ratio calculable. Unfortunately, the versions that get this right predict a lifetime for proton decay shorter than the observed lower limit of 10^{32} yr. I suspect this can be got round. Then, when we finally have a quantum theory of gravity and a superunification of it with the other forces, the combinations of constants in the Dirac numbers suggest that both Gm_p^2/e^2 and the age of the universe ought to be calculable quantities. Within this framework, the anthropic principle should be thought of as providing signposts indicating where we ought to look for the new physics. I subscribe to essentially this point of view most of the time. Those who similarly incline should keep in mind John Wheeler's description of the equivalence principle and Mach's principle as signposts on an old, disused road, now replaced by the highway of general relativity. We should expect something similar to happen to the anthropic principle!

Finally comes the interpretation I have described as the primacy of complexity. I have not seen it explored at length anywhere in print, but heard of it as a throw-away remark by Richard Feynman over the lunch table. He asked us to consider water molecules, whose structure and energy levels can be calculated with great precision. But nothing in those calculations would ever lead us to expect ocean waves and waterfalls, which come from a very large number of molecules interacting. The implication is that a universe with a sufficiently large number of particles of different kinds and at least several different forces by which they can interact will inevitably develop structures with the kind of complexity and unpredictability that we call intelligence in ourselves and orneriness in our teen-aged children. I can see no way of testing this hypothesis! By greatly opening up the range of cognizable universes, it seems also to make the anthropic principle superfluous.

II . AN OUTLINE OF HISTORY

A. The History of the Subject

Teleology and arguments from design go back at least to the Greeks. Barrow and Tipler (1986) have provided a thorough and insightful review of these precursors of the anthropic principle. The 20th century version logically begins with the large number investigations of Weyl (1919, 1934), Eddington (1923, 1946),and Dirac (1937) and Dicke's (1957, 1961) realization that chemically based observers could exist in our universe only when its age was comparable to the lifetimes of stars. Among the other astronomical culture heroes who addressed large numbers, was Zwicky (1939), who created one of his own, e^{6X10^7}, the Boltzman factor for electrons in competition with radiation at a an average universal temperature of 100K!

Bondi's (1952) book apparently formed something of a bridge from these ideas to the anthropic principle as formulated by Carter (1974). Subsequent relevant papers number in the hundreds, those of Carr and Rees (1979) and Weisskopf (1975) being particularly useful in identifying those ratios that are not separate coincidences but necessary consequences of the strengths of the several forces. Barrow and Tipler (1986) provide as nearly complete a set of references as one could hope for.

The remainder of this section addresses the history of the universe, from the earliest times to the birth of Richard Nixon, and attempts to identify the events and processes without which we could not be here in Atlanta. These, in turn, set the standard anthropic constraints on the values of the parameters listed in Sect. I.B. I undoubtedly owe the idea that the formation of the solar system, the death of the dinosaurs, and the French revolution belong in the same paper to a childhood reading of H.G. Wells' *Outline of History*.

B. The Early Universe

We can look back with reasonable clarity in time some 10 or 20 billion years to an epoch when the universe was very much hotter and denser than at present. The time scale comes independently from the ages of the oldest stars (in globular clusters), the decay rates and residual amounts of radioactive isotopes (especially $U^{235,238}$, Th^{232}), and the rate at which clusters of galaxies are moving apart from each other (Hubble's constant, H_o). The factor of two uncertainty is likely to remain with us yet a while. The evidence for the high temperature and density comes from the presence today of nuclides (H^2, $He^{3,4}$, Li^7) that can only be fused under rather restricted conditions and from the all-pervasive 3K microwave background radiation.

If we take as our fundamental variable z, the observed redshift of radiation coming from the past, and signify values now with subscript 0's, then the relationships among quantities are quite simple:

$$T = T_o(1+z) \qquad \rho(\text{matter}) = \rho_0(1+z)^3$$
$$R = R_o(1+z)^{-1} \qquad \rho(\text{radiation}) = \rho_0(1+z)^4 \qquad (4abcd)$$

where R is the distance between any two objects moving with the universal expansion or the characteristic size of the universe. Unfortunately, we do not know the precise functional form of R(t), since it depends on average density or geometry. The possible range is probably between $R \propto t^{\frac{1}{2}}$ (a universe just closed by radiation) and $R \propto t$ (empty universe), with $R \propto t^{2/3}$ (a universe just closed by matter) being a popular choice.

Out of this hot, dense early state come hydrogen and helium, in a ratio roughly 3:1, photons and neutrinos (in thermal distributions), and, perhaps, whatever exotic substance makes up the dark matter today. The expansion, in the large, is very nearly homogeneous and isotropic. How much of this is vital?

Residual hydrogen is very important, not just for water, but to act as the primary stellar energy source so that time scales will be long enough for life to develop. Because the helium is made by fusion of protons and neutrons in a ratio determined, first, by thermal equilibrium, and, later,by the neutron half-life, the amount made is exceedingly sensitive to the strength of the weak interaction (constituting an anthropic argument for its actual value). The initial rate of expansion, average density, temperature, strong force coupling constant, and degree of homogeneity and isotropy also enter into the calculation. For instance, a universe closed by baryons, unless lumpy in just the right way, will make more helium than we see (though not necessarily more than would be tolerable for life). None of these quantities is currently calculable (or "predictable" in the quaint modern sense of the word), except possibly the temperature from Grand Unified Theories (Sect. I.C). Most of the input parameters must fall within about a factor of 10 of their actual values to give us some, but not all, helium.

If wider variations are considered, much worse things than pure helium eventuate. For instance, a cool, dense, slowly expanding universe with larger coupling constants could well turn everything to black holes or neutron star material. We can imagine its inhabitants sitting around, conversing in very low voices, and thinking that our universe is no where near dense enough to be habitable!

An excessively hot universe would be equally unsatisfactory. Until the matter and radiation decouple and the matter density dominates, structures cannot form through gravitational processes. In addition, the background temperature must drop low enough for chemical processes to be able to reject heat. The tolerances on temperature are, at very most, a factor of 100 (or 100^3 in photon-to-baryon ratio). Curiously, the dark matter is so unconspicuous and non-vital in many ways that we cannot be sure of its nature or even presence.

It must, however, enter somehow into the growth of structure, and there is now an enormous literature on the subject of galaxy formation in universes dominated by hot, cold, warm, decaying, and other forms of dark matter (Trimble 1987).

C. The Formation and Evolution of Galaxies

The present average density of matter in the universe is roughly one atom per cubic meter; thus, in the absence of structure, you would be a poor, lone, lorn hydrogen atom and, in all your life, you would never meet even one other hydrogen atom. There are two main difficulties connected with understanding the large structures we see (galaxies and clusters thereof). First, one needs an initial spectrum of perturbations (against the background of large scale homogeneity and isotropy seen and needed for nucleosynthesis etc.). It is at least possible that the inflation scenario may account for this, though the perturbations as most straightforwardly calculated come out with excessively large amplitudes (Guth 1984; Gelmini et al. 1983). Second, the perturbations on galactic and cluster scales (0.1-10 Mpc) must be able to grow to their present non-linear amplitudes without introducing fluctuations into the microwave background larger than the ones we see.

This last is not an anthropic constraint! I see no reason why we could not live quite happily in a universe with patches of $\Delta T/T \sim 1$ all over the sky, though a large body of theorists would suddenly be unemployed. The need for galaxies, hence the initial perturbations, *is*, however, anthropic. The particular sizes of the lumps we see now (Carr & Rees 1979) are probably determined by the balance of known forces (for instance cooling time $\approx$ free fall time) and so provide merely another limit on the possible range of Gm_p^2/e^2 so that galaxies will be large compared to stars but small compared to the universe. The amplitudes of the initial perturbations needed may constitute a separate anthropic limit on the properties of the potential responsible for inflation (Gelmini et al. 1983).

Growth of the perturbations at low amplitude will produce roughly spherical configurations only if the expansion of the universe is roughly isotropic. Apparently the actual expansion is even more isotropic than actually needed (Draine and Thomas). In addition, the gradual growth must not be disrupted by the onset of rapid exponential expansion or by recollapse. This (and several other time scale requirements) mean that the equations of expansion of the universe must not be dominated now by a cosmological constant, Λ, though the inflationary epoch certainly was. Looking at the basic equation,

$$H_o^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G(\rho + p/c^2)}{3c^2} + \frac{\Lambda}{3} - \frac{k}{R^2(t)} \qquad (5)$$

we conclude this limits Λ to a range within $\pm H_o^2$ or so of zero. Expressed in Planckian units, this is the remarkably small value 10^{-120} (cube of the traditional Dirac number). In units of H_o^2 it is about one. I am, therefore, not persuaded that the smallness of Λ that we see and require is a separate fact from the large age of the universe compared to the Planck time (which, we have already seen, is necessary for stars and life).

Once galaxies have acquired their identities, with density contrasts of order unity, the vital process is the fragmentation and condensation of gas into stars. Owing to a great deal of hard work over the last twenty years, beginning with the PhD dissertation of Beatrice M. Tinsley, we now have a reasonably complete picture of these processes and the correponding chemical, luminosity, and color evolution of galaxies (Tinsley 1981). These processes clearly constrain the strengths of gravity and electromagnetism and the sizes of galaxies, so that cooling and fragmentation can occur in the age of the universe and the galaxies be able to retain metal-rich gas expelled from evolved stars. The limits seem to be the same factor-of-ten ones that come from Big Bang nucleosynthesis, nuclear reactions in stars, and chemistry.

D. Stars

Stars perform two absolutely vital functions from the point of view of chemically-based life. First, the relatively low-mass ones fuse hydrogen to helium over billions of years and, by so doing, provide long-term stable environments and sources of high-grade energy for their planets. Second, the ones significantly more massive than our sun burn additional fuels beyond hydrogen and helium, thereby synthesizing virtually all the rest of the elements, in roughly the proportions we see (Burbidge et al. 1957; Trimble 1975).

What demands do these functions place upon the fundamental constants? First, bound nuclei must be possible and their formation exoergic, a rather delicate limit on the ratio of the strong interaction to the electromagnetic. If you would like carbon and oxygen in roughly equal proportions, as seen, the tolerances become only a few percent, a point first appreciated by Hoyle (Hoyle et al. 1953). Second, contraction of gas clouds must heat protostars sufficiently to reach nuclear ignition temperatures but not so much that reaction rates speed up and shorten the lives of stars to less than biological time scales. Since gravity is balanced by thermal pressure in stable stars, this limits the ratio Gm_p^2/e^2. The limit is not quite so severe as you might think, since the same ratio sets the numbers of particles in stable stars, and, if it were different, nuclear reactions with time scales of 10^9 yr would still occur, but in larger or smaller stars.

That limit is not infinitely elastic, either, though. Stars must be small compared to galaxies (in order to permit successive generations and chemical evolution). On the other hand, they must be massive enough to hold their planets in stable orbits (against perturbations by other stars, the tidal force of the whole galaxy, and whatever else there be, like supermassive black holes) at distances where lots of high-grade photons per square centimeter will arrive and where the equilibrium temperature will permit chemical reactions at reasonable rates (the most severe version of this is: temperatures where water is a liquid).

In addition to the heavy elements being synthesized, it is necessary that they be blown out into interstellar space in order to serve as raw materials for further generations of planet-supporting stars. This happens in events called supernovae. In the so-called Type I SNe, the energy source is nuclear reactions — rapid burning up to the iron peak of degenerate carbon and oxygen. This automatically disrupts the star. For the Type II's, however, most of the energy comes from the collapse of the core of a massive star to a degenerate neutron configuration. Transfer of energy from this collapse to the heavy element envelope is accomplished at least partly by neutrino scattering. The ejection process therefore sets a lower limit to the weak interaction coupling constant which is not so very much smaller than the upper limit set by the Big Bang not turning everything to helium (Carr & Rees 1979; this paper, incidentally is so densely packed with facts, numbers, and relationships that another colleague was able to turn its six pages into an entire popular book).

Both degenerate carbon ignition and core collapse happen only when an electron-degenerate configuration approaches the Chandrasekhar (1935) limiting mass. Both kinds of supernovae therefore require that this mass be less than the maximum stable mass of hydrogen-burning stars (the Eddington limit, set by radiation pressure). The two masses are of the same order of magnitude (as is the lower mass limit for normal stars and the upper mass limit for neutron stars) near $(10^{40})^{3/2}$, and can be expressed as several different possible combinations of G, m_p, m_e, $e^2/\hbar c$ and so forth. Thus there are several possible ways of expressing the constraint that white dwarfs be less massive than the heftiest stars. One of them is to say that the equation of state must not be too stiff; that is, $\hbar$ must not be too large. This is our first explicit limit on quantum mechanical phenomena, although the precise balance between electromagnetism and nuclear forces that makes possible equal amounts of carbon and oxygen is also dependent upon shell structure in the nucleus and so on $\hbar$.

E. Planets and Chemistry

Here, for the first time, we come to atoms and molecules, solids and liquids, in addition to the ionized plasmas of the early universe, galaxies and stars. The first requirement, clearly, is that these bound configurations be able to exist in a universe whose age is comparable with the lifetimes of stars. If the binding energies of atoms were smaller by a factor 1000, they would still all be ionized in the 3K radiation background. This permits $e^2/\hbar c$ to be smaller than its actual value by, at most, a factor 10 (requiring water to be a liquid at some temperature cuts this freedom to a factor of only two or three).

Going the other direction, the electron orbits must not be nestled down inside the nuclei if they are to interact and make molecules. This means that the ratio of the electromagnetic to the strong coupling constant must not be much more than a factor 100 larger than it is. Looking at the atom quantum mechanically, nucleons can crowd closer together than electrons because they are more massive. Undoubtedly this is really the same constraint: nucleons are the more massive particles because they are controlled by the stronger force. A grand unified theory that brings quarks and leptons into the same multiplet will presumably permit calculation of the force and mass ratios, though not perhaps immediately.

Finally, the existence of crystalline structures (including DNA) requires that atoms be localizable to higher precision than their sizes. This again limits m_e/m_p and, like all the other atomic and molecular phenomena, clearly requires the existence of an exclusion principle with $\hbar$ at least in the range that atoms are bigger than single nucleons (or string lengths?!) and smaller than the things you want to make out of them.

The details of planetary system formation and chemistry are both, of course, enormously complex. In both cases, however, their reduction to fundamental physics is coming along nicely. Quantum chemistry does explain the periodic table; and a particular simulation of the formation of our solar system (Aarseth 1980) made 10 planets, which is certainly nine to the order of accuracy considered here. I do not know enough about either topic to be sure whether they can be used to put tighter limits on $e^2/\hbar c$ etc. than we have already found.

F. Life, Evolution, and Human History

The chain of chemical reactions that led to the first self-replicating molecule is not (yet) known, although many of the precursors can be synthesized in the laboratory under a wide range of conditions. Whether or not the origin and evolution of life are likely events is endlessly debated, mostly in connection with discussions of extraterrestrial life and searches for it (SETI: the Search for ExtraTerrestrial Intelligence). Equally thoughtful people have arrived at 1 and 10^9 as the number of planets within the galaxy upon which life has started up. (This is not the most uncertain number in the anthropic game; Martin Rees has pointed out that we know the masses of the particles making up the dark matter only to within a factor 10^{77} — from 10^{-5} eV axions to 10^6 M_o black holes!). In Hoyle's extreme version of panspermia, the number is actually less than one per galaxy.

The current tide of fashion is definitely running against widespread, indepently-evolved, extraterrestrial life (Barrow & Tipler 1986, Ch. 8 & 9). In a sense this need not concern us here, since the weak-anthropic-principle-as-selection-effect guarantees that there must be at least one set of observers in our universe and the conditions necessary for that one set to appear must obtain. One of the better-defined parts of the argument centers around the numbers of habitable planets and the length of time they can remain habitable (with neither runaway glaciation or runaway greenhouse effect). The problem is essentially meteorological, and the reader is invited to insert his own favorite joke about the reliability of cloud-cover forecasts.

My own prejudice is that life and intelligence are tougher than you think they are (the phrase is Hoyle's; he was thinking about possibilities for survival of nuclear wars). Two favorite examples, one old and one new: first, Dale Russell's (1981) Stenonychosaurus, a late Cretaceous, bipedal dinosaur, with opposable first finger and forward-looking (stereoscopic?) eyes. Its cerebral hemispheres exceed those of any living reptile in relative size and equal those of some living mammals. It could arguably have been taught to fetch and carry and answer to its name (Ycho for short, I should think). Second, as we have all been told second hand, advanced organisms die when given only heavy water, which differs from H_2O in viscosity, freezing point, and the effective value of m(nucleus)/m(electron), this last by a factor two. But apparently simple prokaryotic cells can adapt to the difference and, after a period of retarded replication, carry on as usual (S. Brenner, private communication to Barrow & Tipler). Since the cells had surely never been challenged this way before, I find the result remarkable, and suggestive that most of the discussion about the necessity for very particular sorts of mitochondria, enzymes and so forth may be heavily overconstraining the problem of life.

In summary, the details of biochemistry (including poetry) are of course very sensitive to details of the input physics, but I think it has not been demonstrated that those details are vital for the appearance of observers. The ranges of constants that permit chemistry may well also always permit biochemistry.

Finally we come to cultural (rather than biological) evolution, the realm of human history. We are several scientific revolutions away from being able to reduce any part of this to fundamental physics, even if we should want to. It has, nevertheless, anthropic aspects. We are not so very far away from blowing ourselves to smithereens and/or drowning in our own garbage. If this is a typical development for intelligent(?) observer species, then the presence of question-askers in the universe must be transient or sporadic. I find this slightly more disturbing than the thought that there might never have been any observers.

This view is evidently not a common one. Several years ago, I asked a large undergraduate class in a course called "Cosmology: Man's Place in the Universe" to express their views on the future of human and extraterrestrial life. They thought it did not matter very much whether humanity survived or not (this I suspect is normal adolescent world-weariness). But, in addition, they still thought it didn't matter even if we were the only living creatures in the galaxy or in the universe. The strong anthropic principle is evidently not widely held in the younger generation.

The writing of history, like astronomy, has its fashions. One that comes and goes is the general idea that the important aspects are those without which "now" would be very different. A debated aspect is whether Napoleon (or any other single Great Man) can be important in this sense, or whether only collective, economic, political, etc. institutions and movements matter. This is roughly analogous to questions about the exact degree of sensitivity of life (broadly defined) to particular values of the coupling constants. In the historical realm as well as the astronomical and biological, I belong to the "it will probably all come out in the wash" school, and suspect that one could pluck quite a few well-known individuals and events out of the stream and still find the modern river more or less where it is. Thus the introduction of the printing press into England was probably a much more important event than the Wars of the Roses; this does not keep me from being more interested in the fate of the Princes in the Tower than in Caxton's antecedents.

Much the same probably applies to individual human affairs. If I had not written this paper, someone else would have (in fact, to first order, lots of people already have!); and if you were not reading it, someone else would be, and so forth. In human affairs, as in particle physics, I suspect that the only absolutely essential aspect is that there be lots of particles of different kinds and lots of ways they can interact (Sect. I.C).

III. IMPLICATIONS AND APPLICATIONS OF THE ANTHROPIC PRINCIPLE

If we accept that the fact of our being here has some information content, then we can go on to try to use that information in one of several possible ways. The strong anthropic principle (that observers must exist) seems to have the potential of actually telling us the answer to ancient and honorable questions of physics and cosmology. Barrow and Tipler (1986), for instance, come very close to concluding that a strong anthropic principle requires quantum gravity to behave in a particular way and the universe to be closed. I am not persuaded that observational evidence really supports this point of view (Trimble 1987).

Second, one might suppose that anthropic considerations would at least lead us to the right physics necessary to calculate the vital parameters and dimensionless ratios of section I.B. This was the point of view taken by Dirac (1937) when he concluded that the constant of gravity must be decreasing with time fast enough to keep Gm_p^2/e^2 constant. The change required is rather larger than data on the stability of stellar structure and planetary dynamics permit. It is also unnecessary. As Dicke (1957, 1961) showed, that particular large number is roughly equivalent to the requirement that the universe be old enough for stars to have produced heavy elements and life to have evolved. Thus even for very different particular values of G and e^2, observers would always find that the age of their universe was roughly equal to stellar lifetimes.

Eddington (1923, 1946) took this approach much further, attempting to calculate the electron/proton mass ratio, the number of protons in the universe (2.136×2^{256}), and the fine structure constant among others. Curiously his calculations have something of the same mix of quantum mechanics and general relativity to which Eddington violently objected when Chandrasekhar (1935) applied it to calculations of the structure of degenerate stars. Eddington's calculations strike most physicists today as odd, "not even wrong." In addition, there are actual algebraic and numerical mistakes, according to Feynman.

The third, and least ambitious,application of the anthropic principle is as a guide to important areas of reasearch. Sciama (1971) expressed this point of view when he said that he couldn't understand why any scientist works on anything except cosmology or particle physics. These are clearly the "important" disciplines, in the sense of being most likely to tell us why the universe is the way it is. They are not, in practice, the most popular. Within the American Physical Society, members of the division of particles and fields are outnumbered by the fluid dynamicists and plasma physicists and absolutely swamped by the condensed matter division members. Similarly, a sample of 375 members of the American Astronomical Society (Trimble 1985) included only 19 more-or-less full-time cosmologists (though for what it is worth, their papers are cited about twice as often as those of the average astronomer).

Clearly, then,most of us do not take an anthropic viewpoint when choosing our subdisciplines! On the other hand, the traditional class structure that ranks "fundamental" or "basic" research above "applied" research, has an anthropic (in this sense) flavor to it. So also do some of the "bandwagon" phenomena of modern research. The recent flocking toward work on dark matter, numerical simulations of galaxy formation, and the intersection of particle physics and cosmology (these turn out to be closely related topics and are persued by many of the same people; Turner 1986, Trimble 1987) I think reflects a realization that these are fundamental problems,as well as ones that have rather suddenly been rendered ripe for exploitation by simultaneous advances in observational techniques, computing power, and mathematical physics. How seriously I take anthropic considerations shows in my own research which has recently concentrated on statistics of binary stars — the distributions of their mass ratios, angular momenta, and so forth. This is not quite as unfundamental as it sounds, in the sense that the processes which determine the relative numbers of high and low mass stars formed under various circumstances are (a) not well understood, (b) important for the rate of heavy element production in galaxies and for estimates of the numbers of habitable planets, and (c) somewhat constrained by these statistics, but it is not cosmology either!

Looking toward the future of scientific research, it is perhaps significant that a very large proportion of entering graduate students in astronomy and physics departments say that they want to work on cosmology and high energy particle physics. Admittedly, that's what we said at the corresponding points in our own careers, and here we are doing condensed matter physics and binary star statistics. But these expressed wishes do suggest that an anthropic definition of "what is important" appeals to protoscientists and that there will continue to be an adequate supply of gifted people to work on fundamental problems. Whether the experimental and observational and computational facilities they will need to do this work will also continue to be available is another issue,to be discussed, perhaps, by a committee on "the unity of funding" rather than the unity of science!

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