Abstract

We argue that if string theory as an approach to the fundamental laws of nature is correct, then there is almost no room for anthropic arguments in cosmology. The quark and lepton masses and interaction strengths are determined.
1 A brief outline of the anthropic principle

It is probably fair to say that the existence of humans is an indisputable fact, (pace Sartre). Yet curiously an explanation of this fact was, for most of history, held to be unnecessary. Until the time of Copernicus, it was widely believed that humanity was the center of the Universe, and the Universe was made for it, ideas exemplified by many creation myths in a wide variety of cultures. At least in western civilization, such an established view was overturned when Copernicus demonstrated that the Earth was in orbit around the Sun, and thus put on an equal footing with the other visible planets. Although there was no fundamental explanation for his observations, it removed humanity from a central place in the universe. The Earth became simply one of the six then known planets. The reason behind Copernicus’ observations was found by Newton. The laws of universal gravitation and mechanics allowed for an explanation of the gross structure of the Solar system and also permitted one of the first anthropic questions to be asked. Why is it that the Earth is in an orbit with a mean distance from the Sun, \( r_\oplus \sim 1.50 \times 10^{13} \) cm, and a low eccentricity, \( e \sim 0.016 \)? The advantages for life on Earth are easy to see: these orbital parameters provide a stable temperate environment in which human life, as we know it, can exist comfortably. A relatively small change in \( r_\oplus \) would lead to an Earth that is either too cold or too hot, and a change in \( e \) to a situation in which there were violent swings in temperature between the seasons.

As more has been understood, it has been noticed that, apparently, a number of features of the universe have to be more or less “just so”, or humans would not exist. Specific examples have been offered for over a century (as reviewed in Barrow and Tipler, [1]), and include noting that the Sun has to be very stable, the Earth cannot be too small (else it could not hold an atmosphere) or too large (as gravity would effectively crush organisms made of molecules), the universe has to be large and dark and old for life to exist because at least two and probably three generations of stars are needed to make the heavy elements life depends on, etc.

The essential point made in anthropic arguments is that we should not be surprised that the Earth is where it is, because if it were in a different orbit, then we would not be here to ask the question. The question is, by virtue of its self-referential nature, nugatory. That does not mean the question is not worth asking. It may well be that in the future, our understanding of how the Solar system was formed would enable us to argue successfully that terrestrial planets are inevitable in stellar systems of our type. Equally well, they may be unusual phenomena.

Carter [2], appears to be the first to formalize what is meant by the anthropic principle. He described three types of scientific reasoning. One is “traditional.” Arguments based on our existence are regarded as extra-scientific. The laws of nature are used to make predictions in a deductive way. There is some degree of arbitrariness involved because it is not exactly clear what the laws of nature are, what the constants of nature are, and what choices of boundary conditions or quantum states are to be made. In contrast, reasoning based on
the “weak” anthropic principle allows us to place restrictions on what we are
going to consider to be realistic. Our existence as observers is privileged in both
space and time by virtue of our own existence. The weak anthropic principle is
interesting and unobjectionable. It adds to our insights, but does not preclude a
fully scientific explanation of any feature of the universe, including the origin of
the universe and the understanding of why the laws of physics are what they are,
with such explanations not depending in any way on knowing whether humans
exist. What this is saying really is that our existence in a recognizable form is
intimately related to the conditions prevailing now in our part of the galaxy.
“We are here because we are here,” would be the sound-bite associated with this
attitude. It has not much predictive power except that since the Solar system
does not seem to be particularly unusual in any way then it would be reasonable
to suppose that life, and indeed quite possibly some form of civilization, should
also be common at the present epoch. (A most un-anthropic conclusion).

The historical starting point, within the context of modern physics, for an-
thropic reasoning is to explain the so-called large number coincidence, first for-
malized by Dirac, [3]. Three large dimensionless quantities, all taking values
\( \sim 10^{40} \), can be found in cosmology. The first is the dimensionless gravitation-
al coupling referred to the proton mass \( m_p \),

\[
\frac{\hbar c}{Gm_p^2} \sim 2 \times 10^{38} \tag{1}
\]

The second is the Hubble time, \( T \), referred to the same scale,

\[
\frac{T m_p c^2}{\hbar} \sim 6 \times 10^{41} \tag{2}
\]

The final quantity is a measure of the mass \( M \) of the visible universe also referred
to the same scale

\[
\sqrt{\frac{M}{m_p}} \sim 5 \times 10^{39} \tag{3}
\]

At first sight, the similarity of these numbers can either be regarded as a
incredible coincidence or a deep fact. But in reality we should not be surprised.
As was first explained by Dicke [4], in a big-bang cosmology these relations are
perfectly natural. The age of the Universe must be in a certain range: not too
young as described earlier, but also not so old that stars have largely exhausted
their hydrogen fuel. Dicke showed that the above bounds on the age of the
universe were equivalent to the coincidence of the numerical values (1) and (2).
The equivalence of (2) and (3) can be interpreted as saying that we must live in
a universe with a density close to the critical density. The natural explanation
of the second equivalence is then the existence of an inflationary epoch.

However, anthropic reasoning can be rather dangerous since it has a tend-
dency to lead one to draw conclusions that can be theological in nature. When
some phenomenon cannot be understood simply within a particular system, it is
tempting to ascribe its origin as supernatural, whereas a deeper understanding of physics may allow a perfectly rational description. The history of physical science is littered with examples, from medieval times up to the present.

For some people anthropic reasoning even leads to a “strong form” of the anthropic principle, which argues that our existence places strong restrictions on the types of theories that can be considered to explain the universe and the laws of physics, as well as the fundamental constants of nature. Some would even like to argue that the universe in some sense had to give rise to humans, or even was designed to do that. Many physicists are antagonistic to any version of these stronger arguments. While it is not yet established that the origin of the universe or the origin of the laws of physics can be understood scientifically, attempts to answer those questions are finally in the past decade or so topics of scientific research rather than speculation. It could happen that such questions do not have scientific answers, but until the effort is made and fails we will not know.

One approach to partially unifying the laws of physics is, so-called, “Grand Unification”. In this approach, the weak, electromagnetic, and strong forces are unified into one simple gauge group of which the Standard Model gauge group $SU(3) \times SU(2) \times U(1)$ is a subgroup. In that case it has recently been observed (Hogan [5], Kane [6]) that since the ratios of the coupling strength are fixed, in making anthropic calculations one cannot independently change the strong and electromagnetic forces. (For example, if the strong force strength is increased a little, the diproton could be bound and cut off nuclear burning in stars. It should however be noted that even without unification effects this issue is more subtle than is usually stated [18]). Further, it would be incorrect to argue, as some have done, that various “just so” probabilities should be multiplied together, since the underlying physics effects are correlated.

Increasing the strength of the electromagnetic repulsion is required since its ratio to the strong force strength is fixed by the theory, and that would decrease the diproton binding, so the net effect would be small. Thus in Grand Unified Theories a number of anthropic effects disappear.

Recently, Hogan [5] has argued that some basic microscopic physics should be determined anthropically. He suggests that the Grand Unified theories go about as far as one can hope or expect to go in relating and explaining the fundamental parameters of a basic theory, and emphasizes that the sensitivity of the properties of the universe to a few quantities is very strong. His argument highlights the fact that in Grand Unified theories there are a number of independent parameters (particularly quark and lepton masses) that need to be specified. He argues that it is important that at least some of these parameters cannot be determined by the theory, or else we cannot understand why the universe is “just so”.

The context of the above suggestion is that we are living in one of many universes where these numbers are chosen at random. The reason we see them as being what they are is that if they were different, even very slightly in some cases, then we could not possibly exist. It could be that these many universes are real and emerge as baby universes in some meta-universe as yet unobserved,
or simply as a statistical ensemble of distinct universes. In either case, one is faced with the real difficulty of accounting for why the parameters of the Grand Unified theory are what they are. It turns out that although at first sight there appear to be a myriad of what might be called anthropic coincidences, only four of the parameters appear to be particularly critical, \[20\]. They are \(m_e, m_u, m_d\) and \(g\), the mass of the electron, up and down quarks respectively, and the Grand Unified coupling constant (which determines the strengths of the strong, electromagnetic, and weak forces). Hogan makes the interesting claim that if these parameters were determined by the theory, it would be very hard to understand why the universe is “just so.”

Today, there is a more ambitious approach to understanding and unifying the laws of physics, loosely called “string theory.” We would like to argue precisely the opposite point of view to the one presented by Hogan, based on what is known about string theory, or perhaps more precisely its non-perturbative progenitor, M-theory.

By string theory we mean the effective 10 dimensional theory that incorporates gravity and quantum theory and the particles and forces of the Standard Model of particle physics. Whether string theory really describes our world is not yet known. This is certainly the first time in history when we have a theory to study which could unify and explain all of nature, conceivably providing an inevitable primary theory. Testing string theory ideas may be difficult but is not in any sense excluded – one does not need to be present at the big bang, nor does one need to do experiments at the Planck scale to test them.

Our goals in writing this paper are first to stress that in string theories all of the parameters of the theory – in particular all quark and lepton masses, and all coupling strengths – are calculable, so there are no parameters left to allow anthropic arguments of the normal kind, or to allow the kind of freedom that Hogan has argued for. Second, we want to discuss in what ways, if any, there is room to account for why the universe is “just so”.

2 The String Theory picture of low energy physics

In non-gravitational physics, the role of spacetime is quite clear. It provides an arena, Minkowski spacetime, in which calculations can be carried out. In classical gravitational physics, spacetime continues to exist, but the backgrounds are in general more exotic, representing diverse situations such as black holes or cosmological models. It is easy to graft onto this edifice the content of Grand Unified theories. However, the philosophy of string unification is to unify all the forces, including gravitation. At some level, one can successfully omit gravitation because the natural scale associated with it is \(\sim 10^{19}GeV\) whereas the other forces become unified at scales noticeably less, around \(10^{16}GeV\). But, if we are to explore energies beyond the unification scale, because we want a general theory, then gravity will become more important and must be included in the overall picture. To do this, one requires a theory of quantum gravity. Treating the gravitational field like a gauge theory leads to an unrenormalizable
theory. To include gravitation, one has to resort to a theory of extended objects: strings. One way to think about string theory is to describe the string as an extended object propagating in a fixed background spacetime. The metric, or gravitational field, is just one of the massless degrees of freedom of the string, and it is possible to extend this picture to include backgrounds that correspond to any of the massless degrees of freedom of the string. One ingredient of string theory is that it is described by a conformally invariant theory on the string world-sheet. This requirement imposes a strict consistency condition on the allowed backgrounds in which the string lives. The backgrounds must have ten spacetime dimensions, and obey the supergravity equations of motion. We therefore regard string theory as a consistent quantum theory of gravity in the sense that the theory of fluctuating strings (including excitations of the string that correspond to gravitons) is finite provided that the background obeys the equations of the supergravity theory that corresponds to particular string theory under discussion.

Next, string theory needs to make contact with the known structure of the universe. There are, apparently, four spacetime dimensions. The six remaining directions of spacetime in string theory need to be removed by a process usually termed compactification. The endpoint of this process usually arrives at simple \( (N = 1) \) supergravity coupled to various matter fields. As a consequence, a severe restriction applies as to how the compactification takes place. One assumes that spacetime takes the form of \( \mathcal{M}^4 \times K \), where \( \mathcal{M}^4 \) is some four-dimensional Lorentzian manifold, and \( K \) is a compact space with six real dimensions. In order to have unbroken simple \( (N = 1) \) supersymmetry, there is a severe restriction on the nature of \( K \). \( K \) must be a so-called “Calabi-Yau” manifold and its spatial extent must be sufficiently small that it has no direct observational signature, which restricts it to scales of around \( 10^{-30} \) cm, or roughly the Planck scale [21].

This in fact is an example of the weak anthropic principle at work. There seems no reason why one should compactify down to four dimensions. From the string theory perspective, there is nothing wrong with having a spacetime of any number of dimensions less than or equal to ten. However, one could certainly not have intelligent life in either one or two spatial dimensions. It is impossible to have a complicated interconnected set of nerve cells unless the number of space dimensions is at least three, since otherwise one is forced only to have nearest neighbor connections. In spatial dimensions greater than three, even if one could have stars, one could not have stable Newtonian planetary orbits or stable atoms [6], and it is presumably impossible for a suitable environment for life to exist. More generally, the compactified dimensions could vary in size.

The Calabi-Yau space is determined by two distinct types of property. Firstly we must specify its topology and then specify the metric on it. The topology determines at least two important properties of the low-energy theory, the number of generations and the Yukawa couplings. The metric can just be one of a family of metrics on the given manifold. The fact that there appears to be some arbitrariness here is reflected in the presence of massless scalars, or moduli fields, in the low-energy theory.
If one were just doing field theory, then the above considerations would really be all that there is to it. However, the geometry of string theory is rather more interesting. In Riemannian geometry, one cannot continuously and smoothly deform a metric so as it interpolates between metrics on two topologically distinct manifolds. If one tries to do this, one ends up finding that there is some kind of singularity in the metric that causes the notion of a manifold to break down. In the background field approximation to string theory, this will also be true. However, we also know that there is more to string theory than that. It appears that one should replace the idea of a classical background geometry with what is usually called quantum geometry. Quantum geometry corresponds to those consistent conformal field theories that define the physics of the string itself. These conformal field theories are intrinsic to the string, and have an existence without any concept of spacetime. Thus, spacetime would be a derived property, rather than being fundamental. This is closer to the true philosophy of a fundamental theory, since we should not be trying to draw a distinction between string physics and the physics of spacetime. A proper discussion of quantum geometry includes an understanding of non-perturbative effects in string theory. However there are two things that we already know for sure that support the viewpoint of spacetime being a derived property. The first is the phenomenon of mirror symmetry. It is known that Calabi-Yau manifolds come in pairs, related by the so-called mirror map, in which the Kahler and complex structures are interchanged. There is no obvious connection between the metrics on pairs of mirror manifolds. However, the conformal field theory associated with the string is in both cases identical. This indicates that the spacetime description is a derived one, rather than being fundamental. A second property is that when non-perturbative phenomena are included, there is no problem from the string theory point of view in effecting continuous transitions between Calabi-Yau spaces of different topology. This shows that stringy ideas about geometry are really more general than those found in classical Riemannian geometry. The moduli space of Calabi-Yau manifolds should thus be regarded as a continuously connected whole, rather than a series of different ones individually associated with different topological objects. Thus, questions about the topology of Calabi-Yau spaces must be treated on the same footing as questions about the metric on the spaces. That is, the issue of topology is another aspect of the the moduli fields. These considerations are relevant to understanding the ground state of the universe.

However we reach the final picture of what happens at low energies in four dimensions, the end point does not contain any massless scalar fields. That in turn means that when the final $N = 1$ supersymmetry is broken, all of the fields must be associated with effective potentials. The only exceptions are the genuinely massless fields associated with unbroken gauge symmetries. These are the photon for electromagnetic $U(1)$, the gluons for $SU(3)$ of color, and the graviton with diffeomorphism invariance. One could very plausibly conclude that all of the low energy physics must be determined as a result of this type of compactification plus supersymmetry breaking process.

Thus we have relegated most of the traditionally anthropic quantities to
physics that we know, at least in principle, even if as yet the calculations are too technically complex to carry out. For example in the scheme sketched here, it now seems perfectly possible to compute from first principles quantities like $m_d$ and $m_u$ (see below). In fact, it would seem that all of low-energy physics is computable. This leads us to ask about the small number of possible remaining anthropic quantities. For example, what about the number of the non-compact dimensions of spacetime. Whilst in string theory, there seems to be no obvious reason why four should be singled out, in M-theory there is. One’s usual attitude to string theory is that it can be derived from M-theory, whose low-energy limit is $d = 11$ supergravity, by compactifying on a circle, and then saying that the resultant ten-dimensional spacetime is the arena for string theory. However, in $d = 11$ supergravity theory there is a four-form field strength that could pick out four dimensions as being different from the remaining seven if it has a vacuum expectation value. Thus, a four-seven split seems quite natural. In cosmological models, the observed universe is described by the Friedmann-Robertson-Walker models, and they have the property of being conformally flat. This means that they can be described most simply as a four-dimensional spacetime of constant curvature, together with a time-dependent scale factor. Whilst it is not presently understood how one might realize these ideas in practice, it is beginning to seem plausible that even something like the dimensionality of the large directions of spacetime might eventually be understood in M-theory without recourse to any anthropic arguments at all. Another observed fact is that there seems to be a small cosmological constant with a magnitude similar to the energy density of observed matter in the Universe. Most string theorists think it is likely, or at least possible, that a better understanding of string theory will lead to an understanding of the small size of the cosmological constant, and possibly also its actual value. It is not inconceivable that a solution to the dimension problem would come together with a solution to the cosmological constant problem in M-theory.

3 The role of parameters in string theory

As discussed in the previous section, before string theory can be applied to our actual world several problems have to be solved. They include compactification to four dimensions, breaking the full supersymmetry of the theory that is a hidden symmetry in our world, and finding the correct ground state (vacuum) of the theory. These problems are logically independent, though it could happen that one insight solves all of them. We assume here that ongoing research will find solutions to these problems, and consider the implications for our view of the world and for anthropic ideas.

Assuming (as described above) that the theory is successfully formulated as a 4D effective theory near the Planck scale, we describe qualitatively how force strength and masses are viewed in string theory.

In the string theory one can think of the theory as having only a gravitational force in 10D. The other forces arise in a way analogous to what happens
in the old Kaluza-Klein theory, where one has a 5D world with only a 5D gravitational force, which splits into a 4D gravitational force plus electromagnetism when one dimension is compactified. Thus in the string theory all of the force strength ratios are fixed by the structure of the theory. In string theory the coupling strengths, including that of gravity, are viewed as vacuum expectation values of scalar fields, so the overall force strengths are calculable too (though how to evaluate those vacuum expectation values is not yet known). If the string approach is correct there is no room for any coupling strength to vary anthropically.

The situation is similar for masses, though more subtle. Physical masses are written as Yukawa couplings (determined by the compactification) times the electroweak Higgs field vacuum expectation value. The quarks and leptons are massless at high temperature scales, until the universe cools through the electroweak phase transition (at 100 GeV), at which point the quarks and leptons acquire mass. At higher scales one speaks of the Yukawa couplings. The string theory determines a function called the superpotential, and the coefficients of terms in the superpotential are the Yukawa couplings. In general the theory determines the Yukawa couplings and thus the masses. The way in which this comes about is directly from the topology of the Calabi-Yau space itself. Given its topological nature, the Yukawa couplings are determined. Thus, there is really not much freedom left at this level.

However, a subtlety may arise. At the most basic level of the theory it could happen that some Yukawa couplings were of the same order as the gauge couplings, giving the masses of the heavier particles such as the top quark, but some Yukawa couplings corresponding to lighter particles were zero. The lighter masses only arise when the full symmetry group of the theory is broken, perhaps when supersymmetry is broken or when the compactification occurs. Then calculating the lighter masses is technically more challenging. Nevertheless, it is expected that in principle, and eventually in practice, all of the masses are calculable, including the up and down quark masses, and the electron mass. There is not any room for anthropic variation of the masses in a string theory.

4 What is left that could be anthropic?

String theory can be any one of the five consistent perturbative superstring theories that contain gravitation. These are the two types of closed superstring, the two heterotic strings, and the open superstring. Each of them is characterized by a single dimensionful parameter, usually called $\alpha'$, the inverse string tension. This sets the scale for all observations and is as a consequence not a measurable parameter — it simply sets the scale for units. Each string theory has a second dimensionless parameter, the string coupling constant, that determines the strength with which strings interact. This constant is freely specifiable, and thus manifests itself as a massless scalar field in the theory, the dilaton. However, like all other massless scalar fields, it must acquire a mass through some quantum effects. The fact that such a massless scalar field has not been observed
argues in support of this conclusion. Thus the string coupling constant must be determined intrinsically by the theory — in any given vacuum it is calculable. So, all that is left is $\alpha'$ which is unobservable anyway. There still appears to be a choice of which string theory one should pick. However, the discovery of M-theory shows that in fact all string theories are equivalent and so no choice needs to be made.

There are two issues associated today with the cosmological constant. The first is to explain why the actual cosmological constant is tiny compared to the amounts of vacuum energy generated by the electroweak vacuum or the QCD vacuum or other sources of vacuum energy. The second issue is why there is apparently a residual non-zero small vacuum energy which at the present epoch is of the same order as the contributions to the total energy density. The two issues are logically independent, and could be physically independent. We will not try to deal with the second issue, even though it could be an anthropic question because of the apparent coincidence that the cosmological energy density is of the same order as the combined forms of matter at the present time even though the two forms depend differently on time. The first issue has been discussed as an anthropic one \cite{8, 9, 10}. However, the string theory point of view is outlined in the previous section. Another possibility \cite{11, 12} is that there might be very light scalars left over in the theory. Standard wisdom has it that such objects would by now have been detected, but there is always the possibility that they couple so weakly to gravitation that they would not have been seen. What is interesting about the above scenario is that the potential for such a scalar field would look very much like an ordinary cosmological constant except that the value of the scalar itself could very both in time and space on cosmological distances or timescales. Under these circumstances, it is thus a possibility that the effective cosmological constant here and now is anthropically determined.

Another possibility at our present state of knowledge for understanding how not to be uncomfortable with a universe that seems to be “just so” arises from the observation that universes could be arising with different initial conditions and early histories, leading to different parameters. There are several approaches today to how universes might begin \cite{13, 14, 15, 16}, and of course additional approaches may be required. Some or none of them could be correct. If many universes arise, various initial conditions could lead to various resulting sets of parameters. It is then like a random lottery in that someone wins, and even though they may feel singled out, from a broader viewpoint there is nothing special about whomever won.

Finally, the vacuum structure of string theory is expected to be very complicated. A 10D world is a consistent one as far as is known, and perhaps so are many compactified ones. There may be many stable solutions (local minima), each with different dimensions, topological characteristics, and parameters. Once a universe falls into one of those minima the probability of tunneling to a deeper minimum may be extremely small, so that the lifetime in many minima is large compared to the lifetime needed for life to arise in those minima. For a discussion of such phase transitions see Adams and Laughlin \cite{17}.\footnote{\textcopyright{} 2000 by the American Physical Society.}
Then life would actually arise in those minima that were approximately “just so”. Thus the “just so” issue is resolved by having a large number of possible vacua in which universes can end up. Eventually understanding of M-theory may reach the stage where it is possible to calculate in practice all the possible vacua. In each vacuum, all of the quantities needed for a complete description of the universe, including the masses and couplings that Hogan argues need to be “just so”, are calculable.

5 Concluding Remarks

We have argued that the usual anthropic arguments cannot be relevant to understanding our world if string theory is the right approach to understanding the law(s) of nature and the origins of the universe. Our arguments are predicated on this hypothesis. If the type of unification found in string theory is not an appropriate description of nature, then we are back to the beginning in trying to understand why the universe has been kind enough to us to allow us to live here. If any parameters such as force strengths or quark masses or the electron mass must be somehow adjustable and not fixed by the theory in order to understand why the universe is “just so”, then string theory cannot be correct. We discuss various ways consistent with string theory in which different universes with different parameters could arise, so that the apparent “just so” nature of a number of parameters can be understood.

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