Comments On String Theory

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March 27, 2022

Abstract

String theory avoids the ultraviolet infinities that arise in trying to quantize gravity. It is also more predictive than conventional quantum field theory, one aspect of this being the way that it contributed to the emergence of the concept of “supersymmetry” of particle interactions. There are hints from the successes of supersymmetric unified theories of particle interactions that supersymmetry is relevant to elementary particles at energies close to current accelerator energies; if this is so, it will be confirmed experimentally and supersymmetry is then also likely to be important in cosmology, in connection with dark matter, baryogenesis, and/or inflation. Magnetic monopoles play an important role in the structure of string theory, and thus should certainly exist, if string theory is correct, though they may have been diluted by inflation to an unobservable level. The monopole mass in many attractive models is near the Planck mass, but, if unification of elementary particle forces with gravity occurs near TeV energies through large or warped extra dimensions, as in some recent models, then monopoles should be below 100 TeV and in an astrophysical context would be ultrarelativistic. In such models, supersymmetry would definitely be expected at TeV energies.

*Research supported in part by NSF Grant PHY-0070928. This manuscript is based on a lecture presented at the Sackler Colloquium on Challenges to the Standard Paradigm (National Academy of Sciences, October 2002).
In string theory, at the most basic level, an elementary particle is treated as a vibrating string, rather than a point particle. A string has many different harmonics of vibration, and in this context different elementary particles are interpreted as different harmonics of the string.

In a Feynman diagram of ordinary quantum field theory, there are interaction vertices at which particles split and rejoin (figure 1(a)). These are definite spacetime events that every Lorentz observer can agree upon. By contrast, in the splitting and rejoining of a string (figure 1(b)), there is no definite moment at which an interaction occurred. If one looks at the whole history, it is clear that one string split into two, but nevertheless any small piece of the history looks like any other. This is a hint of one of the most important facts about the theory: once one decides what the string is, the interactions follow; they need not be separately postulated, as is the case in quantum field theory.

Quantizing a relativistic string proves to be very subtle. When this was done in the 1970’s, some highly unusual features appeared. Perhaps the most dramatic is that the ground state of the (closed) string proves to be a massless spin two field, i.e. a graviton. The interactions do mimic those of general relativity at long wavelengths, so string theory proves to be a quantum theory of gravity. This is something that we need in physics – since both quantum mechanics and gravity are present in nature – and it is something that we otherwise do not have, since conventional attempts at quantizing general relativity are thwarted by ultraviolet divergences.

The ultraviolet divergences of quantum general relativity disappear when one replaces a particle by a string. This is so roughly because of the fact that was illustrated in figure 1: replacing particles by strings has the effect of smearing out the interaction vertex in a Feynman diagram.

String theory also leads to gauge symmetry in much the same way that it leads to gravity. For example, the ground state of an open string turns out to be a gauge field. (A closed string is a loop of string that closes on itself without ends; an open string does have ends.)

Supersymmetry

Along with gauge theory and gravity, string theory generates “supersymmetry,” which is symmetry between bosons and fermions. In fact, the appearance around 1970 of what we now call worldsheet supersymmetry in the Ramond model of string theory was part of the historical origin of the idea of supersymmetry. Nature does not have exact supersymmetry. But it is possible that nature does have an underlying supersymmetry which
is “spontaneously broken,” like the $SU(2) \times U(1)$ gauge symmetry of the standard model of particle physics. In fact, it may be that supersymmetry is detectable at energies relevant to current and planned accelerator experiments. There are a few hints of this.

One is the “hierarchy problem,” which is a modern version of Dirac’s “problem of large numbers.” In Dirac’s formulation, why is the gravitational force between two protons $10^{-38}$ times weaker than the electric force? The appearance of such a tiny dimensionless number in the laws of physics seems to require some explanation. An updated version of the question is to ask why the $W$ and $Z$ bosons (the gauge bosons whose masses are ultimately linked to the mass scale of other particles) have masses $10^{-17}$ times smaller than the Planck mass. At any rate, supersymmetry offers a possible solution to this problem, because supersymmetry removes the quadratic divergences that otherwise affect the Higgs boson mass.

A more quantitative hint of supersymmetry comes from the measured values of the strong, weak, and electromagnetic coupling constants. They agree at about the 1% level with a relation that follows from supersymmetry together with grand unification of the elementary particle forces.

If supersymmetry is discovered (presumably at Fermilab or at the LHC, the new accelerator that is being built at CERN), there is much to be learned about the masses and couplings of the supersymmetric particles. Theoretical models of the details of the supersymmetric world are currently all over the
map. Even if one of the them is on the right track, we have no idea which one.

Discovering supersymmetry would undoubtedly give string theory a big boost, showing that the three structures – gravity, gauge theory, and supersymmetry – that arise from string theory in roughly the same way are all part of the description of nature. It is impossible right now to guess how big a boost string theory might get from the discovery and exploration of supersymmetry, because we do not know what the pattern of supersymmetric masses would turn out to be and therefore what clues we would get about physics at still higher energies.

There are also several possibilities for how discovering supersymmetry might be relevant to cosmology:

(1) Some of the supersymmetric particles make plausible dark matter candidates, as calculations show that they would have just about the right mass and abundance to agree with observation. (However, supersymmetric particles are not the only plausible particle physics candidates for dark matter, and some supersymmetric models do not have such candidates.)

(2) If supersymmetry is correct, this must be taken into account in theories of baryogenesis in the early universe. In fact, supersymmetric theories have scalar fields with baryon number that might very well have played an important role.

(3) Supersymmetric scalar fields might also be relevant to inflation (this was discussed in L. Randall’s talk), though supersymmetry and strings have not given a clear picture yet.

In 1984, string-based models of particle physics became much more interesting when Green-Schwarz anomaly cancellation and the construction of the heterotic string by Gross, Harvey, Martinec, and Rohm made possible models of particle physics plus quantum gravity that are elegant and semi-realistic. In this context, “semirealistic” means that one neatly gets the right particles and gauge forces, but one does not have a reasonable picture of particle masses, because these involve supersymmetry breaking, for which we have no sensible model.

A good model of supersymmetry breaking ought to shed light on the extreme smallness (or vanishing?) of the cosmological constant, since in our semi-realistic models, the cosmological constant vanishes when supersymmetry is unbroken. Thus, not only is the extreme smallness of the cosmological constant a big mystery – sharpened by observations suggesting that it is not zero – but not understanding the cosmological constant makes it hard to improve the models of particle physics.
Supersymmetry breaking models that we have now lead to quintessence-like behavior (an evolving scalar field and no stable vacuum) but with highly unrealistic parameters and couplings. In general, quintessence with a scalar field seems troublesome due to coherent couplings that would likely already have been detected, notably in tests of the equivalence principle. In that respect, quintessence with an evolving pseudo-scalar (an axion-like field with a potential like $V(a) = \Lambda^4(1-\cos(a/F))$ with some constants $\Lambda$ and $F$) seems more attractive, given the absence (or extreme suppression, given that parity is not an exact symmetry of nature) of coherent couplings for pseudoscalars. There have only been a few papers on quintessence-like models based on pseudoscalars [4], [5].

Five String Theories

By 1984, there were five string theories, differing by very general properties of the string:

1. In Type IIA and Type IIB, the strings are closed, oriented, and insulating.
2. Type I strings are open or closed and insulating; open Type I strings have electric charges at the ends. (This model has an analogy with strong interaction physics, with the open and closed strings corresponding respectively to mesons and glueballs; the analogy played a role in the discovery of string theory and continues to motivate much current research.)
3. Finally, heterotic $SO(32)$ and $E_8 \times E_8$ strings are closed, oriented, and superconducting.

Five string theories, each of which includes gravity, is four too many, but it is much better than the situation in pre-string physics, where there are infinitely many possible quantum field theories, none of which include gravity.

Here is another characteristic difference between string theory and pre-string physics. In quantum field theory, we generally have adjustable dimensionless parameters, such as the fine structure constant $e^2/4\pi \hbar c \sim 1/137$ or the electron-muon mass ratio $m_e/m_\mu$, which is about 1/200. These adjustable parameters mostly appear at the interaction vertices of figure 1, and they disappear in going to string theory. In string theory, there are no adjustable dimensionless parameters, but instead there are scalar fields $\phi_i$ whose expectation values determine $e^2/4\pi \hbar c$, $m_e/m_\mu$, etc.

This means that in principle $e^2/4\pi \hbar c$, $m_e/m_\mu$, and the rest might be computed by minimizing the energy as a function of the $\phi$’s. In practice, to do this we would have to understand supersymmetry breaking and the cos-
mological constant, since in the absence of supersymmetry breaking, \( V(\phi) \) is identically zero. This is another reason that it would be good to discover supersymmetry at accelerators and thus have the chance to explore supersymmetry breaking experimentally.

**Strong Coupling**

In trying to answer any of the really big questions in string theory, we run against the fact that we do not really understand what the theory is. In contrast to (say) general relativity, where the big ideas came first, string theory emerged, originally in the early 1970’s, by a process of tinkering without anyone having the big picture. At first, one could see only the loftiest peaks above the clouds. For thirty years now, we have chipped away, uncovering some of the underlying structure, but with much still unclear.

One important development in the 1990’s was that, as long as one can ignore supersymmetry breaking, we learned to extrapolate to large values of parameters such as \( e^2/4\pi\hbar c = \phi \). We always could calculate for \( e^2/4\pi\hbar c << 1 \); now we can say something for \( e^2/4\pi\hbar c >> 1 \).

The basic technique is to study magnetic monopoles and other non-perturbative excitations. For \( e^2/4\pi\hbar c \) the monopoles are extremely heavy compared to the ordinary particles, and this makes them less important. However, for \( e^2/4\pi\hbar c \) large, the monopoles become light and we should find a description of the theory in terms of monopoles.

At the cost of oversimplifying things a bit, I will give a qualitative explanation of this. According to Dirac, the magnetic charge of a magnetic monopole is \( g = 2\pi\hbar c/e \). This shows that \( g \) is much larger than \( e \) when \( e \) is small, and much smaller than \( e \) when \( e \) is large. So to the extent that the mass of an electron or a magnetic monopole has an electromagnetic origin, one would expect that monopoles are the light objects for \( e \to \infty \).

So for \( e^2/4\pi\hbar c \to \infty \), we need to use a description that favors monopoles rather than electrons, but this turns out to be another string theory, or a close cousin. Thinking along these lines led to the understanding that there is only one string theory: the five string theories as traditionally understood are different limiting cases of one more complete theory, sometimes called \( M \)-theory. \( M \)-theory is the candidate for superunification, though we still do not really understand it.

**Magnetic Monopoles**

Monopoles have played an important role in developing this picture, so in particular, if string theory is correct, they should exist. Where are they?
Inflation may have made the monopole density unobservably small; this was plausible when first proposed over 20 years ago, and remains plausible. But it would be a shame, so let us hope that a reasonable number of monopoles survived somehow.

What is the monopole mass? The standard picture based on GUT-like models leads to monopole masses above the GUT scale, say in the range of $10^{17}$ to $10^{20}$ GeV. (The upper bound is the mass of a Reissner-Nordstrom black hole carrying magnetic charge; the lightest monopole could scarcely be heavier than this.)

Monopoles of such high mass are not affected by the Parker bound on monopole flux, because in a galaxy the gravitational force on such a monopole is much greater than the magnetic force. As far as I know, they would have been viable dark matter candidates, except that bounds from MACRO [4] and other experiments exclude the hypothesis that monopoles, even at the highest plausible mass, are the dominant component of the galactic halo.

Along with GUT-like models, we also should consider models in which a low scale unification with gravity is achieved, via large extra dimensions [5] or a warped scenario [6]. For example, if such unification occurs at energies of a few TeV, we should expect monopoles at perhaps 10 - 100 TeV. Such light monopoles would be accelerated in the galactic magnetic field to ultrarelativistic energies, so their experimental signatures are completely different from those of the GUT-scale monopoles. (For a recent assessment, see [7].) Also, they might not have been diluted by inflation. It is hard to be specific on this last point, as current ideas for low-scale unification are really scenarios more than detailed models.

Another interesting property of monopoles in string models [8] is that in many models, the minimum magnetic charge is not the Dirac quantum $2\pi \hbar c/e$, but is larger than this by an integer $n$ that depends on the model. Reciprocally, these models have unconfined massive particles with electric charge $e/n$. These particles would have GUT-like masses in the GUT-scale models and would be at the TeV energy scale in models with low energy unification. The cosmic ray flux of particles with electric charge equal to or greater than $e/5$ and $\beta > 1/4$ has been significantly constrained by MACRO [9].

Ironically, though models with TeV scale unification with gravity are sometimes seen as making TeV scale supersymmetry unnecessary, they also make it inevitable, if string theory is correct. To see this, let us perform a simple thought experiment (which we could have considered earlier in
the case of the monopoles). Suppose that accelerator experiments at TeV energies do discover a unification with quantum gravity and an effective higher-dimensional Planck scale of a few TeV. Then, if it is true (as string theory seems to tell us) that quantum gravity requires supersymmetry at the fundamental Planck scale, we should expect to find supersymmetry at energies of a few TeV, if not less!

A nice illustration of this last point is in a recent paper by Giddings and DeWolfe [10]. (See also [11] for a related discussion.) They consider a warped scenario with an underlying ten-dimensional Planck mass that for most of the states is effectively at or above the usual GUT scale; moreover, supersymmetry is broken at this high scale. However, because of the warping of the metric, some of the states survive down to TeV energies and below. In this model, the TeV scale particles include some excited gravitons, and by experiments at TeV energies involving this low energy sector (which is assumed to contain the familiar particles), one could observe unification of elementary particles with gravity. And sure enough, as our heuristic argument would predict, Giddings and DeWolfe find that although the GUT-scale particles have GUT-scale supersymmetric mass splittings, the TeV scale particles have TeV-scale supersymmetric splittings. Thus, experiments that uncover unification with gravity would also have the energy to uncover supersymmetry.

So in short, weak scale monopoles and weak scale supersymmetry breaking should be general consequences of models with weak scale unification with gravity.

Where else might we see signatures of string theory? It would be nice to detect some of the numerous stringy scalar fields either because of changes in time of natural constants (because of evolution of scalar fields in the vacuum) or because of departures from the equivalence principle, or deviations from Newton’s law of gravity at short distances. Concerning the changes in natural constants, I am personally a little pessimistic because I suspect that scalars whose evolution causes a detectable change in natural constants might have already shown up in tests of the equivalence principle. But let’s

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1To spell this out a bit, scalars that are evolving so slowly as to produce a change in natural constants on cosmic time scales are so light that their Compton wavelengths are far greater than any length scale that is relevant in tests of the equivalence principle or general relativity. Such particles would therefore be detected in such experiments unless their couplings are significantly weaker than gravitational. By contrast, since current laboratory tests of gravity involve shorter distances than those explored in the other experiments, a scalar of the right mass might produce a detectable departure from Newton’s laws of
hope.

Among various other conceivable possibilities, I will only add that the very name “string theory” suggests that if this theory is right, strings may exist in the heavens. (Again, the cosmic strings may be greatly diluted by inflation; this remark applies especially to heavy ones.) One can imagine elementary strings stretching across the sky, and other conceivable objects with GUT-like tension, possibly visible in the CMB maps. But also plausible are other, lighter objects, perhaps all the way down to the TeV scale (which corresponds to a string tension of roughly $10^{-4}$ gm/cm). The light objects might arise, for example, from spontaneous breaking of extra $U(1)$ factors of the gauge group that we do not yet know about. The light ones would not be detectable gravitationally, but they might be detected if they are abundant in the Milky Way (or the Solar System? [12]), in which case, if they are superconducting (not unlikely for strings that arise from breaking of extra $U(1)$’s [13]), they might be detectable by causing magnetic disturbances and creating antimatter clouds when they interact with a magnetic field.

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