String Cosmology: A Review

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Abstract

The second string revolution, which begin around 1995, has led to a drastic alteration in our perception of the universe, perhaps even more so than did the first string revolution of 1984. That is, extending 10-dimensional string theory to 11-dimensional M-theory has had more profound implications than did the original extension of 4-dimensional quantum mechanics and relativity to 10-dimensional string theory. After a brief review of M-theory, I discuss some implications of large extra dimensions. I then consider astronomical evidence for, and constraints on, large compactified dimensions. I conclude with a possible resolution to the apparent inconsistency between the MSSM scale and string scale in the weak coupling limit.

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1 Cosmology and the Second String Revolution

The first string revolution began place in 1984 after John H. Schwarz and Michael Green demonstrated anomaly cancellation in the Type I superstring (Green 1984). Similar anomaly cancellation was soon shown, thereafter, for the four other superstring theories, Type IIA, Type IIB, Heterotic $SO(32)$ and Heterotic $E_8 \times E_8$. Superstring theory was quickly recognized as the leading candidate for a “Theory of Everything.” String theory unified the four known forces and explained all particles as different modes of a fundamental “string”. However, it also drastically transformed our understanding of the universe, revealing that it more complex than had ever been imagined prior. For no longer was our universe $(3+1)$-dimensional, instead it became $(9+1)$-dimensional. The six new dimensions were claimed to necessarily be compactified with Planck-scale length to explain the matter and non-gravitational force content of our universe.

The problem with string theory was that it wasn’t a single theory, but actually five. For the next decade one of the primary directions in string research was investigation of the parameter space of each of these five theories and of connections between the theories. While each theory contained only one solution with ten large non-compact dimensions, each time another dimension was compactified the number of solutions grew ever more enormous.

Soon after the first revolution, equivalences were being recognized between different models. The simplest involved models with only one compactified dimension: replacing a compactification radius $R_1$ in one model with radius $R_2 = \alpha' / R_1$, where $\alpha' = \frac{1}{2\pi T}$ is the string slope (with $T$ the string tension) produces another physically equivalent model. In the watershed year of 1995, Ed Witten, Joe Polchinski, Petr Horava and colleagues demonstrated equivalences between models of different string theories (Horava 1996, Polchinski 1996) and even related 10-dimensional string theory to an eleven dimensional supergravity theory. Thus was born the second string revolution. It was soon understood that all five 10-dimensional string theories and 11 dimension supergravity where all part of one more encompassing theory. Each of the old theories were different regions in the parameter space of a single 11-dimensional theory, now known as $M$-theory. In string language, the size of the eleventh dimension was found to corresponded to the string coupling strength. Relatedly, the eleventh dimension also gave strings thickness, thus transforming them into membranes. In models with weak coupling the 11th-dimension is of Planck size or smaller, while in strong coupled string models it is larger than the Planck scale. Thus, the eleventh dimension of spacetime becomes apparent in a ten-dimensional string theory as the string coupling strength becomes strong.

The idea of the 11th dimension growing large led several groups to consider allowing varying numbers of the other six compactified dimensions to also grow large. Two of the first groups were Arkani-Dimopoulos-Dvali (ADD) and Randall-Sundrum (RS). The former group developed models where only gravity propagates in the large ex-
tra dimensions (Arkani-Hamed 1998, Antoniadis 1998). In contrast, the latter group allowed varying combinations of matter and vector boson fields to propagate in all dimensions (Randall 1999). The ADD model allows many dimensions to be much larger than the Planck scale, while the RS model allows only the 11th dimension to grow large.

When gravity propagates in the large extra dimensions the classical gravitational force law goes as $\frac{1}{r^{2+n}}$ (derived from Gauss’ Law in $3+n$ dimensions), where $3+n$ is the number of non-compact and compact dimensions of size significantly greater than $r$. If these $n$ extra dimensions are of the ADD class, then the standard model forces and gravity unify at an energy scale $M^*$ if the size of these dimensions are all of the scale, $R^* \equiv \frac{hc}{M^* c^2} \left(\frac{M_P}{M^*}\right)^{(2/n)}$. In this manner, unification of all forces is possible at a scale as low as a few TeV. This would imply, though, that at least one dimension is of sub-millimeter length. Unification occurs because the gravitational coupling strength grows larger at higher energy scales, increasingly faster as $n$ increases. Although $n = 1$ has been ruled out by astrophysical constraints, $n = 2$ yields $R^* \sim 1$ mm.

String/M-theory considerations can modify the inverse $r^{2+n}$ form of the force law to a more general expression with potential $V(r) = -G_m m_2 r (1 + \alpha e^{-r/\lambda})$. Two large extra dimensions yields $\lambda = R^*$ and $\alpha = 3 (4)$ for compactification on a 2-sphere (2-torus). Dilaton and moduli exchange correspond to $\alpha$ as large as $10^5$ and $\lambda \sim 0.1$ mm.

While the unification of forces via dimensions of sub-millimeter scale eliminates the hierarchy between the weak and the Planck distance scales, it creates another: that between the weak scale and the much larger compactification scale $R^*$. In their model Randall-Sundrum sought to avoid introducing this new hierarchy, so they allowed only the eleventh dimension to grow beyond Planck scale and only by a factor of $M_{\text{Plank}}/M_{\text{GUT}}$. Near the Planck scale, spacetime appears 5-dimensional, but it’s metric is “warped”: $ds^2 = e^{-2k r c \phi} \eta_{\mu \nu} dx^\mu dx^\nu + r_c^2 d\phi^2$, where $k$ is of Planck scale order, $x^\mu$ are coordinate for our four dimensions, and $0 \leq \phi \leq \pi$ is the coordinate of the 11th dimension, for which $r_c$ is the size scale. This metric was shown to be a solution to Einstein’s equations with two 3-branes (tensored with six compactified dimensions) separated along the direction of $\phi$. In this model the large hierarchy between the Planck and weak scales does not require $r_c$ to be extremely large compared to the Planck scale, but only larger by a factor of around 50. The hierarchy is generated by the exponential term that decreases in values as $\phi$ increases. This corresponds to movement away from one 3-brane (a hidden universe) towards the other 3-brane (our universe).

1.1 Varying Physical Constants

In string/M-theory the traditional physical constants in nature, such as the speed of light, are not fundamental constants. Their values depend upon the geometry of the extra spatial dimensions, specifically their size and arrangement. Thus, these
physical "constants" may be dynamical during different phases of an evolving string universe. The sizes of the compactified dimensions correspond to scalar (moduli) fields of the theory.

Recent astronomical evidence suggests that at least one of the extra spatial dimensions, in particular the 11th, in string theory might indeed be very large. The first piece of evidence originates in magnesium and iron atom absorption lines in the light emitted by quasars billions of light years away. The absorption lines are created as the emitted light passes through interstellar gas. The positions of the lines are functions of the fine-structure constant. Based on their analysis of light from over 30 distant quasars that contain these absorption lines, Jack Webb et al. have concluded that the fine-structure constant, $\alpha_{em}$, has been varying significantly only a few billion years ago (Webb 1999, 2000). When the wavelengths for specific quasar absorption lines was compared to those in absorption lines produced in a laboratory, a consistent shift in the quasar lines from four independent sets of data was found suggesting that a few billion years ago $\alpha_{em} \equiv \frac{e^2}{\hbar c}$ was about smaller than it is now. Comparison of the lab value of $\alpha$ to the value of $\alpha$ from quasars within the red shift domain $z \sim 0.6$ to 2 indicated a 4$\sigma$ deviation, $\delta \alpha/\alpha = (0.72 \pm 0.18) \times 10^{-5}$. This implies $e$ has increased and/or $c$ has decreased over the last few billion years. Changes in $c$ in particular suggest a low energy M-theory scale and a related long time before some compactified dimensions stabilized.

P.C.W. Davies et al. have recently argued that black hole thermodynamics suggests that only $c$ changed (Davies 2002). Otherwise, they claim that an increase in $e$ would have decreased the entropy of black holes, violating the generalized second law of thermodynamics. However, S. Carlip and S. Vaidya have contested this claim, arguing that when the full thermal environment of a black hole is considered, thermodynamics is consistent with a decrease in $c$, an increase in $e$, or both (Carlip 2002). Further, for a certain class of charged dilaton black holes related to string theory, M. Fairbairn and M. Tytgat have shown that the entropy does not change under adiabatic variations of $\alpha$ and one might expect it to increase for non-adiabatic changes (Fairbairn 2002).

M. Duff has also argued that, while the possible time variation of dimensionless fundamental constants of nature, such as the fine structure constant $\alpha$, is a legitimate subject of physical enquiry, the time variation of dimensional constants, such as $\hbar$, $c$, $G$, $e$, $k$, ..., has no operational meaning, since the latter are merely human constructs whose number and values differ from one choice of units to the next (Duff 2002).

P. Brax et al. have investigated under what conditions masses or gravitational constant or any of the three Standard Model coupling constants, including $\alpha$, might vary (Brax 2002). They determined that in the brane world scenario, an evolution of masses or of the gravitational constant (which one depends on the frame) is generally predicted when the moduli fields are not stabilized, whereas an evolution of a coupling constant is predicted only under more special circumstances (Brax 2002). Only if vector bosons are directly coupled to the bulk scalar field in a string/M-theory model,
which is often the case, would the corresponding coupling constants vary. Thus, a
time-variation of coupling constants is a prediction of string/M-theory (Brax 2002).

1.2 The GZK Paradox

A current astrophysical paradox is the detection on earth of ultra high energy cosmicrays with energies beyond the Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen
1966, Zatsepin 1966). There are no known astrophysical sources in the local region
of our galaxy that can account for these streams of particles, which appear to be
hadrons, rather than photons or neutrinos, based on the signatures of shower events
as these high energy particles interact with our atmosphere. However, if the particles
are truly hadronic in nature, then their propagation over astrophysical distances is
strongly influenced by the cosmic background radiation. These interactions result in
the GZK cutoff on the maximum energy of cosmic ray hadrons, with $E_{\text{MAX}} \leq 10^{20}$
eV. Further, if the particles were photonic, rather than hadronic, then they would be
expected to have a mean free path of less than 10 Mpc due to scatter with the cosmic
background radiation and radio photons (Coriano 2002). Therefore, unless the
cosmic ray particles are neutrinos, their origin must be nearby. However, neutrinos
would interact very weakly in our atmosphere, not producing the signatures seen.

String/M-theory offers at least two distinct solutions to the GZK paradox. The
first proposal is that the ultra high energy cosmic rays originate from the decay of
long-lived super-heavy matter states with mass of order $10^{12-15}$ GeV, which simulta-
neously are good candidates for cold dark matter (Coriano 2001, 2002). Then these
cosmic rays could have their origin in decays within our galactic halo and escape GZK
bounds (Coriano 2002). Matter with the basic properties required to produce such
cosmic rays are inherent to a class of (semi)-realistic models derived from the heterotic
string and originate from Wilson line breaking of GUT symmetries. More specifically,
though, the super-heavy states must have a lifetime of order $10^{17}$ seconds to $10^{28}$
seconds and their abundance should satisfy the relation, $(\Omega_X/\Omega_0)(t_0/\tau_X) \sim 5 \times 10^{-11}$ to
account for the observed flux of cosmic rays through the earth’s atmosphere. $t_0$ is the
age of the universe, $\tau_X$ is the lifetime of the meta-stable state, $\Omega_0$ is the critical mass
density, and $\Omega_X$ is the relic mass density of the meta-stable state (Coriano 2002).
Whether or not these latter properties are specifically satisfied is very string model
dependent. Potential ultra high energy ray producing candidates include “cryptons”
in the flipped $SU(5)$ model (Antoniadis, Lopez), which are condensates of $\mathbf{4}$ and $\bar{\mathbf{4}}$
reps of the hidden sector $SU(4)_H$, “unitons”, which are exotic standard model quarks
and carry a fractional $U(1)_{Z'}$ charge, and “singletons”, which is a standard model
singlets but carry a fractional $U(1)_{Z'}$ charge (Coriano 2001).

An alternate or complimentary explanation for the GZK paradox is based upon
M-theory space-time foam effects studied by Ellis et al. They model spacetime foam
using a non-critical Liouville-string model for the quantum fluctuations of $D$-branes
with recoil. Ellis et al. argue that particle momentum could be conserved exactly
during propagation but only on the average during interactions with a D-brane, while energy is conserved only on the average during interactions and, in general, is not conserved during interactions with a brane because of changes in the background metric. Ellis et al. conclude that D-brane recoil effects provide another means by which the GZK cut-off can be avoided (Ellis 2001).

2 Constraints on Sizes of Extra Dimensions

The scale below which deviation from \(1/r^2\) begins corresponds to the size of the largest compactified string or M-theory dimension. Hoyle et al. at the University of Washington have verified from a Cavendish torsion-type experiment that gravity keeps its \(1/r^2\) form down to 0.218 mm. This translates into a 95% confidence upper limit of .150 mm. on the size of two compact dimensions and a 95% confidence that the largest compact dimension of any number is less than .2 mm. (Hoyle 2000, Adelberger 2002).

Even stronger constraints have been imposed from neutrino flux measurements of the SN 1987a supernova. Hanhart et al. have developed self-consistent simulations of the early, neutrino-emitting phase of a proto-neutron star which include energy losses due to the coupling of Kaluza-Klein modes of a graviton which arise with ADD compactified dimensions. They compared the neutrino signals from their simulations to that from SN 1987a and from a probabilistic analysis determined the upper bound for two compact extra dimensions to be 0.66 \(\mu\)m at the 95% confidence level and, similarly, an upper bound of 0.8 nm. for three extra dimensions (Hanhart 2001).

Milton has placed not upper, but lower limits on large compactified dimensions. Since quantum fields in extra compact dimensions should give rise to a quantum vacuum or Casimir energy and supernova and cosmic microwave background data indicate that the cosmological constant is of the same order as the critical mass density of the universe, Milton argues a lower bound of around 10 \(\mu\)m. to the size of large compact dimensions (Milton 2000). Otherwise he claims the Casimir energy would produce too large of a cosmological constant.

3 MSSM and String Scales Consistency

Strong coupling effects of M-theory can lower (Witten) heterotic string scale \(\Lambda_H\) down to \(\Lambda_U\). However, when a weak string coupling is assumed, that is, \(R_{11} \approx 10^{-33}\) cm., an enduring issue has been the discrepancy between the \(SU(3)_C \times SU(2)_L \times U(1)_Y\) (\([321]\)) gauge coupling unification scale, \(\Lambda_U \approx 2.5 \times 10^{16}\) GeV (Ellis 1990, Amaldi 1991, Langacker 1991), for the the MSSM with intermediate scale desert and the string scale, \(\Lambda_H \approx 5 \times 10^{17}\) GeV (Kaplunovsky 1988), for the weakly coupled heterotic string.
Two weak coupling solutions have been proposed to resolve this factor of 20 disagreement (Dienes 1995a, 1995b, 1997). One proposal is a grand unified theory between $\Lambda_U$ and $\Lambda_H$. Here the MSSM couplings merge at $\Lambda_U$ and then run together within a GUT to $\Lambda_H$. However, with the exception of flipped $SU(5)$ (Antoniadis 1989, Lopez 1993) (or partial GUTs such as the Pati-Salam $SU(4)_C \times SU(2)_L \times SU(2)_R$ (Pati 1975, Chang 1984) string GUT models based on level-one Kač-Moody algebras encounter a difficulty: they lack the required adjoint higgs (and higher representations). Alternately, intermediate scale exotics could shift the MSSM unification scale upward to the string scale (Chang 1997).

The near ubiquitous appearance of MSSM-charged exotics in heterotic string models adds weight to this third proposal. If MSSM exotics exist with intermediate scale masses of order $\Lambda_I$, then the actual $[321]$ running couplings are altered above $\Lambda_I$. It is then, perhaps, puzzling that the illusion of MSSM unification should still be maintained when the intermediate scale MSSM exotics are ignored (Giedt 2002). Maintaining this illusion likely requires very fine tuning of $\Lambda_I$ for a generic exotic particle set and $\Lambda_H$. Slight shifting of $\Lambda_I$ would, with high probability, destroy appearances. Thus, in some sense, the apparent MSSM unification below the string scale might be viewed as accidental (Ghilencea 1999, Giedt 2002).

A mechanism whereby the appearance of a $\Lambda_U$ is not accidental would be very appealing. Just such a mechanism, entitled “optical unification,” has recently been discussed by J. Giedt (Giedt 2002). Optical unification results in $\Lambda_U$ not disappearing under shifts of $\Lambda_I$. Instead, $\Lambda_U$ likewise shifts in value. This effect is parallel to a virtual image always appearing between a diverging lens and a real object, independent of the position of the lens or real object. Hence, Giedt’s choice of appellation for this mechanism.

Successful optical unification requires three things (Giedt 2002). First, the effective level of the hypercharge generator must be the standard $k_Y = \frac{5}{3}$. This is a strong constraint on string-derived $[321]$ models, for the vast majority have non-standard hypercharge levels. Only select classes of models, such as the NAHE-based free fermionic class, can yield $k_Y = \frac{5}{3}$. Second, optical unification imposes the relationship $\delta b_3 = \frac{7}{12} \delta b_3 + \frac{1}{4} \delta b_Y$, between the exotic particle contributions $\delta b_3$, $\delta b_2$, and $\delta b_1$ to the $[321]$ beta function coefficients. Each $SU(3)_C$ exotic triplet or anti-triplet contributes $\frac{1}{2}$ to $\delta b_3$; each $SU(2)_C$ doublet contributes $\frac{1}{2}$ to $\delta b_2$. With the hypercharge of a MSSM quark doublet normalized to $\frac{1}{6}$, the contribution to $\delta b_Y$ from an individual particle with hypercharge $Q_Y$ is $Q_Y^2$. $\delta b_3 > \delta b_2$ is required to keep the virtual unification scale below the string scale. Combining this with the second constraint imposes $\delta b_3 > \delta b_2 \geq \frac{7}{12} \delta b_3$, since $\delta b_Y \geq 0$.

To acquire intermediate scale mass, the exotic triplets and anti-triplets must be equal in number. Similarly, the exotic doublets must be even in number. Hence, $\delta b_3$ and $\delta b_2$ must be integer (Giedt 2002). As Giedt pointed out, the simplest solution to optical unification three exotic triplet/anti-triplet pairs and two pairs of doublets. One pair of doublets can carry $Q_Y = \pm \frac{1}{2}$, while the remaining exotics carry no
hypercharge. Alternately, if the doublets carry too little hypercharge, some exotic $SU(3)_C \times SU(2)_L$ singlets could make up the hypercharge deficit. The next simplest solution requires four triplet/anti-triplet pairs and three pairs of doublets that yield $\delta b_Y = \frac{2}{3}$ either as a set, or with the assistance of additional non-Abelian singlets. Cleaver et al. presents a standard-like model that has the potential to realize the latter optical unification solution, with the required hypercharge carried by the (anti)-triplets and one additional pair of singlets (Cleaver 2002). Detailed analysis of this model is underway.

4 Concluding Comments

The second string revolution answered many of the fundamental questions of string theory, in particular, the relation between the five former string theories. But M-theory has also raised more questions than it has answered. What M-theory truly is, is not known. String theory, even with ten-dimensions, presented a much less complicated picture of the universe than M-theory does. The drastically different string cosmologies that the ADD and RS theories present give a hint to the vast array of possibilities allowed perturbatively by $M$-theory. For now we can only wonder about the form of the true $M$-theory universe.

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