Closing the Universe by relaxing the cosmological constant

JORGE L. LOPEZ and D. V. NANOPoulos

Center for Theoretical Physics, Department of Physics, Texas A&M University
College Station, TX 77843-4242, USA
and
Astroparticle Physics Group, Houston Advanced Research Center (HARC)
The Mitchell Campus, The Woodlands, TX 77381, USA

ABSTRACT

We propose a string-inspired model which correlates several aspects of particle physics and cosmology. Inspired by the flat directions and the absence of adjoint Higgs representations found in typical string models, we consider a no-scale $SU(5) \times U(1)$ supergravity model. This model entails well determined low-energy phenomenology, such as the value of the neutralino dark matter relic abundance and a negative contribution to the vacuum energy. A positive contribution to the vacuum energy is also typically present in string theory as a consequence of the running of the fundamental constants towards their fixed point values. If these two contributions cancel appropriately, one may end up with a vacuum energy which brings many cosmological observations into better agreement with theoretical expectations. The present abundance of neutralinos would then be fixed. We delineate the regions of parameter space allowed in this scenario, and study the ensuing predictions for the sparticle and Higgs-boson masses in this model.

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There are two fundamental problems in cosmology today which are intimately related to particle physics: the dark matter problem and the cosmological constant problem. Indeed, almost any extension of the minimal Standard Model ($SU(3) \times SU(2) \times U(1)$) predicts some new particles which can be identified as viable candidates for hot (e.g., massive neutrinos and axions) or cold (e.g., neutralinos and cryptons) dark matter. Concerning the cosmological constant problem, there are not that many satisfactory solutions. Recent developments at the cosmological and particle physics fronts indicate a possible correlation between dark matter and the cosmological constant ($\Lambda$). In this note we allow the cosmological constant to contribute to the cosmic energy density, thus reducing the corresponding dark matter contribution such that the latest cosmological observations are best fit.

The standard cold dark matter model (with $\Omega = 1$ and $h = 0.5$) has had great success, but as observations have improved various discrepancies with the data have started to appear [1]. Recent observations of X-rays from the gas surrounding galaxy clusters indicate that $\Omega$ (visible plus dark) is $\mathcal{O}(0.2)$, implying $\Omega_{\text{CDM}} \lesssim 0.2$ [2]. On the other hand, an $\Omega = 1$ Universe is not only appealing in the inflationary scenario, but it may also arise under more general circumstances (as we discuss below). Thus, the phenomenological suggestion has been made that a Universe with $\Omega_{\text{CDM}} \approx 0.2$, $\Omega_\Lambda \approx 0.8$, and $h \approx 1$ should be seriously considered [3]. Indeed, such a cosmological scenario is claimed to be consistent with a varied set of cosmological observations [4]: the APM galaxy angular correlation function, the rich cluster correlation function, the mass function and power spectra from clusters, the CfA slices, and the Southern Sky redshift survey.

The presently unique candidate for the unification of all fundamental interactions, including gravity, is string theory. There are a few generic properties of string theory which are relevant to our cosmological scenario. First, string theory is characterized by flat directions, which implies that certain parameters of the theory can only be determined dynamically at the quantum level. This fundamental property of string theory [5] appears from the low-energy effective field theory point of view as the so-called no-scale structure [6]. This mechanism can explain the smallness of the electroweak scale (i.e., $M_W = \mathcal{O}(e^{-1/\alpha t}) M_{Pl}$), and yields a negative cosmological constant $\mathcal{O}(-M_W^4)$ (much smaller than the usual $M_W^2 M_{Pl}$ or $M_{Pl}^4$ results). Second, the simplest and most studied string models (i.e., those based on level-one Kac-Moody algebras) do not contain adjoint Higgs representations at the field theory level [7]. This result precludes the traditional grand unified gauge groups (i.e., $SU(5)$, $SO(10)$, $E_8$), but allows the $SU(5) \times U(1)$ or flipped $SU(5)$ gauge group, since it only requires the allowed $10, \overline{16}$ representations for symmetry breaking down to the Standard Model gauge group [8]. There are many interesting properties of $SU(5) \times U(1)$ which do not impact directly on our present discussion, but when combined with the no-scale structure result in rather restricted three-parameter models (compared with the more than 20 parameters of the Minimal Supersymmetric Standard Model) [9]. As a result, the dependence of the neutralino relic abundance $\Omega_\chi$ on the few model parameters can be studied in detail. It is important to point out that a cosmologically desirable value of $\Omega_\chi h^2$ (i.e., $\Omega_\chi h^2 \lesssim 1$) is not a guaranteed prediction of supersymmetric
models, as values of $\Omega_\Lambda h^2$ as large as 100 are not uncommon [10]. However, in the three-parameter models which we consider, $\Omega_\Lambda h^2 < 1$ is automatic.

Finally, it has been recently argued that string theory in an expanding Universe cannot be considered to be in “equilibrium”, but that it rather “runs” towards a fixed point [11]. The renormalization group scale which characterizes this “running” is identified as a statistically-defined universal “time”. The arrow of time is thus explained. This scenario entails that all dimensional fundamental constants of Nature actually “run” until they reach the equilibrium (fixed) point of this flow. The cosmological constant obeys a simple relaxation equation $\Lambda(t) = \Lambda(0)/[1 + t\Lambda(0)]$, where all quantities are given in Planck (“natural”) units (i.e., $t \rightarrow tM_{Pl}$, $\Lambda \rightarrow \Lambda/M_{Pl}^2$, $G_N = 1$). The vacuum energy is then given by $\rho_{VAC} = \Lambda/8\pi$.

For the present epoch $t_0 \sim 10^{60}$, and with $\Lambda(0) \sim 1$ one gets $\Lambda(t_0) \sim 10^{-60}$. Combining our above discussion on the no-scale supergravity prediction for the standard contribution to the vacuum energy (i.e., $\rho_{VAC} \sim -(M_W/M_{Pl})^4 \sim -10^{-60}$) with the string-theoretic contribution (i.e., $\rho_{VAC} \sim 10^{-60}$), it may be possible to obtain a cancellation of the total vacuum energy. This argument is only suggestive, although encouraging. Once the effective field theory from string is completely understood, it should be possible to explain what symmetry principle is behind the phenomenological requirement of $\rho_{VAC}^{tot} \approx 0$. Note that since the Universe has yet to relax completely to its true vacuum state, it is possible that $\rho_{VAC}^{tot}(t_0) \sim O(10^{-123})$, in agreement with present experimental limits, and yet eventually it would relax to $\rho_{VAC}^{tot}(t_{equil}) \approx 0$.

Interestingly enough, this dynamical out-of-equilibrium → equilibrium string scenario provides an appealing alternative to conventional inflation, resolving the standard cosmological problems (horizon, flatness, large entropy) automatically [11]. For instance, the running of the fundamental constants implies that the speed of light $c$ becomes infinite in the early Universe, thus solving the horizon problem. For our present purposes, $\Omega = 1$ is then a string-derived property.

In view of the above discussion, we then propose a string-inspired cosmological model: no-scale $SU(5) \times U(1)$ supergravity with $\Omega_\Lambda = 0.8$ and $h = 1$, as preferred by cosmology, and $\Omega_{CDM} = 0.2$ so that $\Omega = \Omega_\Lambda + \Omega_{CDM} = 1$, as preferred by string theory.

For practical purposes, the most important feature of no-scale $SU(5) \times U(1)$ supergravity is the minimalism of parameters needed to describe the complete low-energy supersymmetric spectrum and its interactions. The constraints of supergravity and radiative electroweak symmetry breaking reduce the number of parameters to four: the ratio of Higgs-boson vacuum expectation values ($\tan \beta$) and three universal soft-supersymmetry breaking parameters $(m_{1/2}, m_0, A)$. In addition, the top-quark mass ($m_t$) plays an important role through the running of the mass parameters from the unification scale down to the electroweak scale. In no-scale $SU(5) \times U(1)$ supergravity [9] we consider two string-inspired scenarios for the universal soft-supersymmetry-breaking parameters: (i) the moduli scenario [12], where $m_0 = A = 0$, and (ii) the dilaton scenario [13], where $m_0 = \frac{1}{\sqrt{3}} m_{1/2}$, $A = -m_{1/2}$. In this case, the number of

\footnote{For the $\Omega_\Lambda = 0.8$, $h = 1$ cosmological constant model, $\rho_{VAC} = 3 \times 10^{-123}$.}
parameters is just two \((\tan \beta, m_{1/2})\) plus the top-quark mass. For the typical value of \(m_t = 150\) GeV we find the following allowed range of \(\tan \beta\): \(2 \lesssim \tan \beta \lesssim 26\) (40) in the moduli (dilaton) scenario. The resulting parameter space for the moduli \([14]\) and dilaton \([15]\) scenarios consists of discrete pairs of points in the \((\tan \beta, m_{1/2})\) plane. In practice, we trade the \(m_{1/2}\) supersymmetric mass scale parameter for the more readily measurable lightest chargino mass \(m_{\tilde{\chi}_1^\pm}\). An extensive study of the various experimental constraints and experimental predictions in \(SU(5) \times U(1)\) supergravity has been recently given in Ref. \([16]\). We refer the reader to that reference for further details.

The computation of the neutralino relic abundance, following the methods of Ref. \([10]\), shows that \(\Omega_{\chi} h^2 \lesssim 0.25\) (0.90) in the moduli (dilaton) scenario. On the other hand, the cosmological model with a non-zero cosmological constant fits observations best for \(\Omega_{\text{CDM}} \approx 0.2\) and \(h \approx 1\), that is \(\Omega_{\chi} h^2 \approx 0.2\). This constraint can be applied to the still-allowed parameter space in both moduli and dilaton scenarios. In Fig. 1 we show the still-allowed points in parameter space \([16]\). The areas of the plots which do not contain any points are theoretically or experimentally excluded. In the figure we have delineated the region where \(\Omega_{\chi} h^2 = 0.2\) (the boundary between the pluses + and the diamonds \(\diamond\)). The cosmological constraint then allows one to determine \(\tan \beta\) for a given chargino mass. Moreover, we can compute the sparticle and Higgs-boson masses along this boundary, \(i.e.,\) when the relation \(\Omega_{\chi} h^2 = 0.2\) is satisfied. These are shown in Fig. 2 for the moduli and dilaton scenarios. The resulting spectra indicate that the gluino, squarks, sleptons, and charginos should be accessible at the LHC, but not at LEPII. On the other hand, the lightest Higgs boson \((h)\) may be accessible at LEPII \([16]\).

In sum, our proposed string-inspired model correlates several aspects of particle physics and cosmology. Inspired by the string flat directions and the absence of adjoint Higgs representations, we have considered a no-scale \(SU(5) \times U(1)\) supergravity model. This entails well determined low-energy phenomenology, such as the value of the neutralino dark matter relic abundance and a negative contribution to the vacuum energy. A positive contribution to the vacuum energy is also typically present in string theory as a consequence of the running of the fundamental constants towards their fixed point values. If these two contributions cancel appropriately, one may end up with a vacuum energy which brings many cosmological observations into better agreement with theoretical expectations. The present abundance of neutralinos would therefore be fixed and this entails clear predictions for the sparticle and Higgs-boson masses in the model.

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Figure Captions

1. The still-allowed points in the parameter space of no-scale $SU(5) \times U(1)$ supergravity in the (a) moduli and (b) dilaton scenarios, for $m_t = 150$ GeV. The cosmological constraint $\Omega_{\chi} h^2 = 0.2$ is satisfied along the boundary between the pluses (+) and the diamonds (⋄).

2. The predicted values for the gluino, squark, slepton, and lightest Higgs-boson masses in no-scale $SU(5) \times U(1)$ supergravity in the moduli and dilaton scenarios, when the cosmological constraint $\Omega_{\chi} h^2 = 0.2$ is satisfied.
\[ \tan \beta \]

\[ m_{\tilde{t}}^* \text{ (GeV)} \]

\[ m_t = 150 \text{ GeV} \]

\[ : \Omega_{x,h}^2 > 0.25 \text{ or } \Omega_{x,h}^2 < 0.15 \]

\[ \Diamond : 0.20 < \Omega_{x,h}^2 < 0.25 \]

\[ + : 0.15 < \Omega_{x,h}^2 < 0.20 \]

Figure 1a

\[ \mu > 0 \]

no-scale SU(5) × U(1)

moduli scenario

\[ \mu < 0 \]

\[ m_{\tilde{t}}^* \text{ (GeV)} \]

\[ m_t = 150 \text{ GeV} \]

Figure 1b
