Paulo Rodrigues Lima Vargas Moniz

Research Programme - *November 2002*

Superstrings, Branes, Cosmology and Large Extra Dimensions

A number of recent measurements points to the growing evidence that the expanding universe is currently accelerating. Those observations comprise the luminosity-redshift relation observed from type Ia supernovae. Such conclusion has been strenghten by the study of the accoustic peak in the cosmic microwave background and the mass power spectrum [1].

Other class of quite recent observations using quasars seem to point with growing strength to the possibility that the fine-structure constant α changes in cosmological time [2]. However, one of the problems that cosmologists have faced in their attempts to assess the astronomical consequences of a time variation in the fine structure constant has been the absence of an exact theory describing such cosmological models [3].

These examples from current observational cosmology clearly point to a "golden age". Together with increasingly more reliable data for parameters like matter the density or the Hubble factor H, new and *unexpected* information is being retrieved to which new chalenges to our so far accepted models for the universe [4].

Hence, how will the scientific community explain (from our current understanding of modern theories of physics, involving the unification of the gravitational, strong and electro-weak interactions) the cosmological implications of recent observational data?

A very promising framework where to investigate the above issues is superstring theory, which basically describes particles and interactions by way of the oscillation modes of different types of strings [5]. In this sense it provides the foundation for an ultimate unified theory of the fundamental interactions, where the gravitational field would be consistently quantized. Five distinct 10-dimensional string theories are known, being considered equivalent and related by a particular type of symmetry transformation designated as *dualities* [6]. This attractive description has led to the emergence of a novel understanding of our Universe. In fact, these 10-dimensional string theories constitute different realisations of a more fundamental 11-dimensional scenario called M-theory. The presence of duality transformations are at the basis of this achievement. In addition, they also brought 11-dimensional supergravity as another realisation of M-theory, which will embody the eagerly sought unification [7] of all interactions.

There are significant reasons why these ideas should be enthusiastically tested in the very early Universe (ranging from a quantum origin up to structure formation, involving a crucial inflationary stage). On the one hand, the field equations in string theory have a different structure from Einstein equations. Moreover, important new symmetries provide a new picture where the presence of higher spatial dimensions, fermions and supersymmetry are mandatory. On the other hand, string theory also admits a wide range of solutions, classified as $p-$(mem)branes (where typical strings are a particular case). In this line, actions of the Born-Infeld (BI) type have been the subject of wide interest. This comes from the result that the effective action for the open string ending on D-branes (higher dimensional solutions found in string theory, satisfying specific boundary conditions) can be written in a BI form.

All these and many other features determine that there are plenty of issues to explore. To be more precise, the physical behaviour of strings/branes from a gravitational perspective and towards the early universe might be worthy to analyse [8]-[11]. If either string or brane effects are present, it can be expected that may bring modifications and elucidate on current problems, such as the observational issues above mentioned.

For some cosmological scenarios, the string dualities may correspond to $a \mapsto a^{-1}$ (for the scale factor of a cosmological model) and $\Phi \mapsto \Phi - 6 \ln a$ (for the corresponding scalar dilaton field), playing thereby an important role: it maps an expanding onto a contracting cosmological solution, leaving the string action invariant. Moreover, it provides an inflationary scenario (driven by the dilaton field) designated as a *Pre Big-Bang* scenario. The basic assumption is that the Universe starts at a flat, empty, string vacuum state and then evolves accelerating (kinetically driven) towards a state of increasing curvature and typically a non-perturbative regime. A transition (yet to be fully clarified) should then occur, leading the universe to the Standard (*Post* Big Bang) phase of evolution. However, this transition involves another type of singularity, where both the curvature and strong coupling increase to infinity [12, 13].

A possible way out is to include corrections, either in the form of higher curvature terms or additional fields [12, 13]. These can be justified through a dimensional reduction to a 4-D Friedmann-Robertson-Walker (FRW) model derived from the 11- dimensional M-theory effective action. In this framework we could study whether axions and $p-$form fields determine a four-dimensional FRW spacetime admits an inflationary stage followed by radiation-matter dominance, while the internal space ever contracts [14]. Other type of corrections may occur when considering D-brane effects *effectively* described by actions of the Born-Infeld (BI) type [8]-[11].

Given the context above outlined, this research proposal is aimed at investigating specific cosmological models retrieved within superstring theory features. In particular, identifying whether string theory and related features could be present or determine some of the properties present in the the observable universe. A detailed description of the research programme is presented in the following:

I. Cosmological Implications of Superstring Theory :

- (I.1) Analyse models arising from the bosonic sector of string effective actions with potentials derived from the requirement of S and T duality [13]. Namely, by employing inhomogenous perturbations of the metric and dilaton fields. In that context, we expect to find *new* (quantum) states. These would have a physical significance regarding (a) a period of evolution from a string (Pre Big Bang) phase towards a semi-classical stage, together with (b) identifying the existence of any (quantum) state associated with (dilaton driven) inflation and to structure formation.
- (I.2) Numerical simulations regarding inhomogenous cosmological models in string cosmology have been considered [15]. However, they have not provided a full agreement or a consistent scenario. Our purpose is to further investigate these models but within the more general scenario of scalar-tensor theories, where the dilaton kinetic term in the action is multiplied by a constant factor ω. These include low-energy string actions as a particular case ($\omega = -1$), as well as a cosmological constant. Examining such a general scenario where string theory fits, will clearly assist us in identifying the reasons(s) for those apparent differences. Moreover, it will provide a relevant picture of the dynamical processes that are involved.
- (I.3) Another line of research that we aim to analyse is the recent cosmological scenario within the Horava-Witten formulation of M-theory [7, 13]. This is an active and

most innovative area of research where a fundamental description for the origin and subsequent evolution of the very early Universe ought to be addressed. In particular, since cosmological solutions may entail as a direct consequence a particle physics framework where the standard model of strong-electro-weak interactions seem a natural consequence. Our aim is to investigate new ansatze (choices) when solving the cosmological equations, inquiring whether satisfactory inflationary stages are present.

(I.4) Pre Big-Bang cosmologies have also been quantized from the point of view of a Broglie-Bohm approach [16]. We would like to further investigate these systems in the presence of a potential for the dilaton. Early indications point to cosmological effects similar to those retrieved from the presence of extra dimensions.

(I.5) Issues relating (A)dS stability and large extra dimensions are interesting within string/M-theory, because of recent aspects dealing with the AdS/CFT conjecture and the possibility of large extra dimensions (solving the hierarchy problem). For this context, we want to consider a non-linear multidimensional gravitational model. More precisely, we will include higher-order terms in the curvature, with a warped product geometry [17], together with $p-$form fields. For certain parameter ranges, we wish to investigate if the extra dimensions are stabilized when the internal spaces have constant curvature. Our purpose is to to establish rigourously in which conditions the 4–dimensional effective cosmological constant as well as the bulk cosmological constant may become asymptotically negative or positive. In the latter case, the homogeneous and isotropic external space may become asymptotically dS_4, similarly to a (late) inflationary or accelerated expansion stage, with large extra dimensions becoming admissible.

There are further lines where string theory and cosmology can be explored. In particular, it has been suggested in recent years or so that the presence of dualities in quantum cosmological models *induce* the existence of quantum states that have invariance under *supersymmetry* (SUSY) [18]-[20].

The presence of SUSY invariance in a description of the very early universe represents an element of the uppermost value. In fact, SUSY plays a crucial role in Supergravity (that is, local SUSY) and Superstring theory by inducing the cancellation of divergences that would otherwise be present in plain quantum gravity theories. Moreover, some supergravity theories represent a "square-root" of Einstein gravity: to determine physical states it is sufficient to employ the Lorentz and Supersymmetry invariances. This constitutes the setting of *Supersymmetric (Quantum) Cosmology* (SQC) [18]-[20],[21]-[24].

SQC is usually retrieved from supergravity theory by restricting it to spatially homogeneous cosmological models. The reduction of $N = 1$ supergravity in four space-time dimensions usually leads to one-dimensional with $N = 4$ local SUSY and time-invariance reparametrization. FRW models are the simplest, but Bianchi models enable us to consider anisotropic degrees of freedom and more gravitino modes. An important feature in some of these superspaces is that the fermion number can be conserved [22, 23]. More precisely, each sector with a fixed fermion number may be treated separately.

In essence, SQC constitutes an interesting and rewarding research topic. It provides the

Table 1: SUSY solutions in the metric representations.

Content $\rightarrow$ **Solutions** $\searrow$ **Models** $\downarrow$	Empty	Λ	ϕ, ϕ $(P=0)$	ϕ, ϕ $P(\phi, \bar{\phi})$	Yang Mills	Generic
$k=+1$ FRW	NB, WH	NB, WH,	NB, WH	?	NB	?
Bianchi – A	NB, WH	CS	NB, WH	?	?	?
PerturbedFRW	?	?	NB	?	?	?
FullTheory	WH	?	?	?	?	?

opportunity, on the one hand, to perform calculations that may be relevant for phenomenology and, on the other hand, it has a close connection to exciting new areas of fundamental research such as quantum gravity, M/string theory and theoretical high energy physics in general [23]. Table 1 summarizes the type of solutions found so far within the canonical quantization of $N = 1$ supergravity and restricted to the metric and connection representation approach. The initials NB, WH, CS and "?" stand for No-Boundary (Hartle-Hawking), Wormhole (Hawking-Page), Chern-Simmons and "not yet found", respectively. The latter means there is open ground for considerable improvement and new contributions[1]:

Within the physical context of SQC this research programme also includes the following lines of investigation:

II. Supersymmetric Quantum Cosmology (SQC) (II.1) Examine *how* the presence of duality transformations induces the existence of SUSY invariance [18]-[20]. Applying methods used for FRW models where duality seems to imply the existence of $N = 2$ SUSY, we will investigate this assertion towards a considerable larger range by analysing a broader class of homogeneous cosmologies (that is, Bianchi models, which are <u>not</u> isotropic).

(II.2) Address the same Bianchi models indicated in (II.1) but derived *directly* from $N = 1$ supergravity, where a fermionic matter sector is *explicitly* present. This an urgent and pertinent issue: results with other models and different matter contents have pointed instead to $N = 4$ SUSY . Our purpose is then to compare these results with (II.1), discussing the physical reasons for any possible differences. In particular, regarding the level of SUSY and its relation with the existence of dualities: *how does duality relates to supersymmetry*?

(II.3) Further analyse the retrieval of semi-classical features and origin of structure formation in SQC [24]. Is it possible to identify a consistent quantum to classical transitions in SQC? How does this compare to plain gravitational theories with matter fields but *no* SUSY? That is, which additional feature(s) does the presence of SUSY invariance brings about in a quantum mechanical description of the very early universe? *Is there an imprint of an early SUSY quantum epoch into the observed universe*?

(II.4) We also propose to use a perturbative expansion for the superpotential $P(\phi, \overline{\phi})$ mentioned in table 1 and the bosonic functionals in powers of a parameter $\lambda \ll 1$.

[1]For further details, the interested reader could consult ref. [19, 23, 24].

This could allow us to write the constraints in a power series, which can be solved to find new non-trivial solutions. Therefore, we would advance and extend the current spectrum of solutions present in table 1.

(II.5) Another important issue facing theories of fundamental interactions (e.g., supergravity, superstring and M-theory) is the problem of spontaneous supersymmetry breaking [25]. It is crucial to explain under which conditions it can occur: supersymmetry, if it exists, has to broken at low energies and several different mechanisms have been proposed. Somewhat related scenarios have been recently discussed within supersymmetric quantum mechanics or supersymmetric (minisuperspaces) cosmologies. Regarding $N = 4$ SUSY spaces with time-reparametrization invariance, we propose to investigate if non-trivial states are possible with a suitable superpotential $P(\phi, \overline{\phi})$.

References

[1] For a review, see V. Sahni, *Class. Quantum Grav.* **19** (2002) 3435

[2] For a review, see J. Webb *et al*, astro-ph/0210532

[3] J. Barrow, J. Magueijo and M. Sandvik, *Phys. Lett.* **B541** (2002) 201

[4] For a review, see E. Kolb and M. Turner, *Eur. J. Phys.* **C15** (2000) 125

[5] M. Green, J. Schwarz and E. Witten, *Superstring Theory*, C.U.P. (Cambridge, 1992); J. Polchinski, *String Theory* C.U.P. (Cambridge, 1999)

[6] P. West and K. Olive, *Duality and Supersymmetric Theories*, C.U.P. (Cambridge, 2001); For a review, see also J. Polchinski, *Rev. Mod. Phys.* **68** (1997) 1245

[7] M. Duff, *The World in Eleven Dimensions*, IOP (Bristol, 2001)

[8] P. Vargas Moniz, FRW Quantum Cosmology in the Non-Abelian Born-Infeld Theory, *Class. Quantum Grav.* **19** (2002) L127

[9] P. Vargas Moniz, FRW Wormhole Instanton solutions in the non-Abelian Born-Infeld Theory, *Phys. Rev.* **D66** (2002) 064012

[10] P. Vargas Moniz, Quintessence and non-Abelian Born-Infeld theory, *Phys. Rev.* **D66** (2002), to appear

[11] P. Vargas Moniz, Cosmological Aspects of the Born-Infeld theory, to appear in the Proceedings of 13th National Conference of the Portuguese Physical Society

[12] A relevant list of references on Pre Big Bang (String) Cosmology can be found at http://www.to.infn.it/gasperin/;

[13] For a review, see E. Copeland, J. Lidsey and D. Wands, et al, *Phys. Rep.* **337** (2000) 343 as well as M. Gasperini and G. Veneziano, hep-th/0207130.

[14] P. Moniz and M. Cavaglia, Canonical and Quantum FRW Cosmological solutions in M-Theory, *Class. Quantum Grav.* **18** (2001) 95.

[15] T. Chiba, *Phys. Rev.* **D59** (1999) 083508; J. Maharana, E. Onofri and G. Veneziano, *JHEP* **01** (1998) 004.

[16] P. Moniz and J. Marto de Broglie-Bohm FRW Universe in Quantum String Cosmology, *Phys. Rev.* **D65** (2002) 023516

[17] A. Zhuk, P. Vargas Moniz and U. Guenther, Asymptotical AdS space from nonlinear gravitational models with stabilized extra dimensions, *Phys. Rev.* **D66** (2002) 044014

[18] J.E. Lidsey, *Phys. Rev.* **D52** (1995) R5407.

[19] P.V. Moniz, A Tale of Two Symmetries – The Observed Universe from Duality and Supersymmetry, Nuc. Phys. Proc. Supplements **B88** (2000) 57 (2000)

[20] J. Lidsey and P. V. Moniz Supersymmetric Quantization of Anisotropic Scalar Tensor Cosmologies *Class. Quantum Grav.* **17** (2000) 4823.

[21] J. Bene and R. Graham, *Phys. Rev.* **D49** (1994) 799.

[22] A. Cheng, P. D Eath and P. Moniz, *Phys. Rev.* **D49** (1994) 5246;

[23] For a review, see P. Vargas Moniz, Supersymmetric Quantum Cosmology - Shaken, not Stirred, [qr-qc/9605025], *Int. J. Mod. Phys.* **A11** (1996) 4321

[24] Origin of structure in Supersymmetric Quantum Cosmology, Essay awarded an Honourable Mention in the 1997 Gravity Research Essays competition , *Phys. Rev.* **D57** (1998) R7071

[25] E. Donets *et al*, *Phys. Rev.* **D61** (2000) 043512