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Ekpyrotic and cyclic cosmology

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A R T I C L E   I N F O

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A B S T R A C T

Ekpyrotic and cyclic cosmologies provide theories of the very early and of the very late universe. In these models, the big bang is described as a collision of branes — and thus the big bang is not the beginning of time. Before the big bang, there is an ekpyrotic phase with equation of state $w = \frac{\mathcal{P}}{\rho} \gg 1$ (where $\mathcal{P}$ is the average pressure and ρ the average energy density) during which the universe slowly contracts. This phase resolves the standard cosmological puzzles and generates a nearly scale-invariant spectrum of cosmological perturbations containing a significant non-Gaussian component. At the same time it produces small-amplitude gravitational waves with a blue spectrum. The dark energy dominating the present-day cosmological evolution is reinterpreted as a small attractive force between our brane and a parallel one. This force eventually induces a new ekpyrotic phase and a new brane collision, leading to the idea of a cyclic universe. This review discusses the detailed properties of these models, their embedding in M-theory and their viability, with an emphasis on open issues and observational signatures.

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1. Introduction

The evolution of our universe is very well understood from the time of big bang nucleosynthesis until the present. However, if we go beyond these time frontiers, almost nothing is known with a great amount of certainty. We know that the early universe must have been in a very special state (very homogeneous and flat, but with tiny fluctuations in curvature), but we do not know why. The theory of inflation [41,69,4] provides a possible explanation by means of a period of rapid expansion preceding nucleosynthesis, but it has not yet been possible to test inflation conclusively, which is why it is important to keep an open mind. Also, we know that dark energy has come to dominate the energy density of the universe [86,85] and that it will determine the expansion of the universe in the near future. If dark energy turns out to be a cosmological constant, which is the theoretically simplest way of modeling it, then the universe will continue to expand at an accelerating pace and become increasingly dilute and cold, making life very difficult, if not impossible. However, it should be borne in mind that we have no fully convincing explanation of dark energy at present.

This review will be concerned with a set of ideas, strongly inspired by string theory, that suggests alternative solutions to the early universe puzzles mentioned above, and considers an alternative fate for the future of our universe. What makes these ideas exciting is that, on one hand, they provide a theoretical playground for applying string theory to cosmology, and, on the other hand, certain observational signatures predicted from these models are in a range that will be tested by near-future satellite experiments. This provides a certain timeliness to a subject concerned with eras far removed from everyday experience.

Ekpyrotic[1] and cyclic cosmology are based on the braneworld picture of the universe, in which spacetime is effectively 5-dimensional, but with one dimension not extending indefinitely, but being a line segment,[2] see Fig. 1. The endpoints of this line segment (orbifold) are two $(3 + 1)$-dimensional boundary branes. All matter and forces, except for gravity, are localized on the branes, while gravity can propagate in the whole spacetime. Our universe, as we see it, is identified with one of the boundary branes and, as long as the branes are far apart, can interact with the other brane only via gravity. The ekpyrotic model assumes that there is an attractive force between the two branes, which causes the branes to approach each other. This ekpyrotic phase has the rather non-intuitive property that it flattens the branes to a very high degree. Eventually the two branes collide and move through each other (since there is no space "outside" of the boundary branes, it makes no difference whether we say that the branes bounce off each other or move through each other). It is this collision that, from the point of view of someone living on one of the branes, looks like the big bang. The collision is slightly inelastic and produces matter and radiation on the branes, where the standard cosmological evolution now takes place. However, due to quantum fluctuations, the branes are slightly rippled and do not collide everywhere at exactly the same time. In some places, the branes collide slightly earlier, which means that the universe has a little bit more time to expand and cool. In other places, the collision takes place slightly later, and those regions remain a little hotter. This provides a heuristic picture of the way temperature fluctuations are naturally produced within the model. Shortly after the brane collision, the distance between the boundary branes gets almost stabilized, but the branes start attracting each other again very slightly. This very slight attraction acts as quintessence, and is identified with the dark energy observed in the universe. After a long time and as the branes become closer again, they start attracting each other more strongly so that we get a new ekpyrotic phase and eventually a new brane collision with the creation of new matter. In this way, a cyclic model of the universe emerges.

The preceding description of course only provided a very rough outline of the main ideas. All of this will be made precise in the following. However, at this stage it is already clear that conceptually the cyclic universe differs substantially from the standard big bang picture. For one thing, the big bang is seen as a physical event and not a mysterious moment of creation. As such, it does not represent the beginning of time (note that if quantum gravity is unitary, this point of view seems unavoidable). Thus there was plenty of time before the big bang for the universe to be in causal contact over large regions, and in this way the horizon problem is automatically solved. The long timescales existing before the big bang also imply that other cosmological puzzles don't have to be solved in the extremely short time interval between the big bang and nucleosynthesis. What is more, properties of the very early universe (such as cosmological perturbations) and properties of the late universe (such as dark energy) are described by the same ingredients, namely the motion of branes.

In the description above, the higher-dimensional interpretation was emphasized. This higher-dimensional viewpoint is useful for understanding the origin of the ideas, and provides a concrete realization of them. However, it is important to realize that many of the processes mentioned above can also be discussed purely in a 4-dimensional effective theory. Some processes, such as the ekpyrotic period of slow contraction before the big bang, are quite general and could have a different origin than the brane motion just described. Therefore, the four subsequent sections of this review, which describe the fundamentals of ekpyrotic and cyclic cosmology, are phrased mostly in terms of a 4-dimensional effective theory. Section 2 describes the ekpyrotic phase and the way it resolves the standard cosmological puzzles. Section 3 describes the approach to the big crunch in more detail. The cosmological fluctuations generated by the model are discussed in Section 4. This includes a treatment of scalar perturbations with their second-order non-gaussian corrections as well as tensor perturbations. The following section is concerned with the details of the cyclic universe, such as its relationship to

[1] The name ekpyrosis can be translated as all-engulfing cosmic fire. In Stoic philosophy, it represents the contractive phase of eternally-recurring destruction and re-creation [1].

[2] This setting will be discussed in detail in Section 6, along with its motivation from and embedding in heterotic M-theory.