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Proliferation of the Phoenix Universe

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ABSTRACT

Cyclic cosmology, in which the universe will experience alternating periods of gravitational collapse and expansion, provides an interesting understanding of the early universe and is described as "The Phoenix Universe". In usual expectation, the cyclic universe should be homogeneous, however, with studying the cosmological perturbations, we find that the amplification of curvature perturbations on the large scale may rip the homogeneous universe into a fissiparous multiverse after one or several cycles. Thus, we suggest that if the cyclic universe is like the Phoenix, rebirth in the "fire" and will never ended, this Phoenix will also proliferate eternally.

Keywords: Big bang, Cyclic

I. The Cyclic Universe

As a standard model of our universe, the big bang theory has succeed in many aspects, especially in explaining the abundance of primordial elements and prediction of the cosmic microwave background radiation. However, its successes naturally lead the physicists to another confused conception: the big bang, which seems to be the beginning of our universe. Is it really the beginning of our universe when everything suddenly emerged from nothing or the bang? It is a radical notion for most physicists. Actually, in the big bang theory, the big bang is nothing but a moment when the temperature and density are extremely so high that the physical theory, as far as we have known, is not available any more. Then what is the universe before the big bang? The issue is open.

Historically, an idea is that our universe is always existing with no beginning and no ending, and the universe we live in today is just one phase of in¯nite cyclic periods. Physicists revisited this idea in the frame of the Einstein Gravitation, and developed a kind of universe models which are called cyclic universe or oscillating universe. In these models, the universe is homogeneous with a periodical scalar factor and will orderly experience the bounce, expansion, turnaround and contraction in each cycle. Because the universe in cyclic models always rebirths in \¯re" and will never end, it is also named as the Phoenix universe.

In di®erent models, the evolution of cyclic universe is driven by di®erent physics. For example, in (Steinhardt et al. 2002a,b), the authors introduce a cyclic model in high dimensional string theory with an in¯nite and °at universe, while pointed by Brown (Brown et al. 2008) and Baum (Baum et al. 2007) etc, the cyclic evolution of the universe can also be realized with a modi¯ed gravitational equations. For other more cyclic models one can see (Barrow et al. 1995; Kanekar et al. 2001; Piao et al. 2004&2005; Lidsey et al. 2004; Clifton et al. 2007; Xiong et al. 2008; Zhang 2009; Lehners, et al. 2009; Biswas et al. 2009a,b; Cai et al. 2009), and also see (Novello et al. 2008) for review. Although in some of models the physics under such high energy is still uncertain, these studies provide good insights and e®ective theories to describe the dynamics of the cyclic universe.

As an alternate model of the early universe, the studies of cyclic universe model not only bring a distinctive insight for the big bang described in the standard universe model, but also promote the study of and succeed in other problems. The explanation of the primordial perturbations is just one of them.

II. Cosmological Perturbations in Cycle

Today, our universe has a well developed nonlinear structure which takes the form of galaxies, clusters and superclusters of galaxies, and of ¯laments and voids on large scales. However, all the inhomogeneities in the density distribution, when averaged over hundreds mega-parsecs, is very small can be seemed as the perturbations of the homogeneous background. Moreover, if one ascend to the time of recombination, it will be ¯nd that all of these nonlinear inhomogeneous structure has not formation and only a small perturbations, which are called primordial perturbations, remains. By measuring the cosmic microwave background, we can detect and even characterize these primordial perturbations as gaussian, adiabatic °uctuations with a scale-invariant power spectrum. There have been mature theories of explaining how these primordial perturbations evolve and ¯nally leads the structure of our universe today. The details of this process are so complicate that it can only be calculated analytically, but fortunately the current supercomputers are strong enough to deal with these calculations and have given very beautiful results.

On the other hands, as the initial condition of structure formation, the primordial perturbations play an important role in modern cosmology. However, how to understand the origin of primordial perturbations, which is the seed of the structure formation, and why these perturbations are gaussian, adiabatic and scale-invariant are key challenges for the modern cosmology.

According to the present understanding, because the physical wavelength of ¯xed co-moving scales is increasing less fast than the Hubble radius in the late times (times later and including the period of nucleosynthesis)when cosmological evolution is well described in the big bang theory, we must look to the very early universe to ¯nd an explanation for the observed structures. Therefore, a successive model of the early universe must give an appropriate explanation of the origin of primordial perturbations.

Cyclic universe models provide a good explanation about origin of the primordial perturbations. In cyclic universe model, the prime perturbations are generated in the previous cycle. During the contraction, since the Hubble radius shrink faster than the wavelength of the perturbations with ¯xed co-moving scales, the perturbations will leave out

FIG. 1: $\zeta(\vec{x})$ in position space, which reflects the inhomogeneity of two different backgrounds. The length scale is in unit of the Hubble radius at that time.

of the Hubble radius. While after the bounce, which is seems like the big bang of our cycle, the universe expands again, the perturbations leave our the previous Hubble radius will reenter the horizon and then set as the seeds of the structure formation.

III. Proliferation of the Phoenix Universe

Before we discuss the proliferation of the Phoenix Universe, we would like to address a little further about the behaviors of the cosmological perturbations as preparation. Although there are many cyclic universe models, for the generality of the results, we will not involve the details of the cyclic model building. Actually, it is not difficult, since behaviors of the perturbations is mainly dependent on the background evolution, namely the evolution of the scale factor. To be more specifical, we would like to consider the universe is dominated by a matter with equation of state ω, and the scale factor can be described as $a \sim \eta^{\frac{n}{n-1}}$ where η is the conformal time. If we solve the equation of the curvature perturbations ζ in momentum space, we can find that the linear perturbation with each k evolves dependently. For the perturbations with wavelength smaller than Hubble radius, the amplitude of ζ_k evolves in inverse proportion to the scale factor. While for perturbations with wavelength larger than Hubble radius, we can find that the solution of k-mode curvature perturbation ζ_k can be written into two terms which can be denote them as D_1 and D_2 term, and D_1 is constant term while D_2 is depended on the background evolution.

Then we can discuss perturbations in the cyclic universe by considering a cyclic universe model, starting with the turnaround. The universe is homogeneous with small perturbations generated by the quantum fluctuations inside the Hubble radius. During the contraction with $n > \frac{1}{3}$, some perturbations leave out the Hubble radius and the amplitude of ζ will be dominated by D_2 term, which is increased during this time. After the bounce, the universe comes into the expanding phase in which the D_2 term is decreasing while the D_1 term dominates ζ_k. Thus, perturbations with wavelength large than Hubble radius keep constant during expanding until they reenter the Hubble radius and leading the formation of the large structure. In a word, for a cycle of cyclic universe during the contraction ζ_k is increased on super Hubble radius scale, up to the end of contracting phase in corresponding cycle, while during the expansion it becomes constant. Thus the net result is that ζ_k on large scale is inevitably amplified.

As an application, we can find that for non-scale-invariant quantum fluctuation spectrum, this process will change the spectrum index of ζ as

$$n_\zeta - 1 = 3 - \left|\frac{3n-1}{n-1}\right| , \qquad (1)$$

which is scale invariant for $n \simeq \frac{2}{3}$, i.e. the contraction with $\omega \simeq 0$. The above estimation shows a way of how the primordial perturbation with a scale invariant power spectrum be gained in the cyclic models.

However, the picture may be not that simple as our usual expectation. As we have concluded, the amplitude of the perturbations may be amplified during the contraction, and in (Piao 2009; Zhang et al. 2010) we suggest that, this amplification may change the global picture of our cyclic universe. We would like to recheck the above process. One should notice that during the hole process mentioned above, the universe is supposed to be homogeneous, and evolves with the same background, from the beginning of contraction to the time of turnaround, which denotes the end of one cycle, the net increasing of amplitude of the perturbations in one cycle, say the j^{th} cycle, can be described as

$$\mathcal{P}_\zeta^{j+1}(k, \eta_B^{j+1}) \sim k^{\text{¢} n_s} \mathcal{P}_\zeta^{j}(k, \eta_B^{j}), \tag{2}$$

where ¢n_s is negative for most of cyclic models. We can imagine that, due to the ampli¯cation, the modes on large scale will have the amplitude be about order one after many cycles. This will lead to $\frac{\delta\rho}{\rho} \sim 1$ on corresponding super horizon scale at this time. Here we use horizon scale, a di®erent conception with Hubble radius but with same scale in most of cases, since region outside horizon is causally uncorrelated.

In this case, it is obviously impossible that the di®erent regions of global universe will evolve synchronously, even if it is synchronous in previous cycle. This indicates that the global universe at the beginning time of this cycle will be separated into many di®erent parts, each of which will evolve independently of one another. While inside any given part, all perturbation modes origin from the interior of horizon, which is causally correlative. Thus in this sense, each of such parts actually corresponds to a new universe. To illustrate this e®ect of the perturbation on background, we show the distribution of curvature perturbation, which is homogeneous at the very beginning, by transforming the power spectrum into position space after many cycles in Fig.1.

In principle, each of these new universes will experience the contraction, bounce and expansion, hereafter all or some of them will enter into next cycle and proliferate again, and then the above course is repeated again. This means the proliferation will inevitably occur cycle by cycle. Thus we can have a cyclic multiverse scenario. In this cyclic multiverse, the experience of each universe after proliferation is generally not expected to be synchronous. Thus when some universe are in a period of matter domination, it is possible that there are many other universes which are in the period of contraction or bounce or others. There is also the proliferation of global universe in chaotic eternal in°ation, in which it is induced by the large quantum °uctuation of in°aton ¯eld in its horizon scale. Here, however, the proliferation is induced by the cyclical ampli¯cation of perturbation on super horizon scale, which is in classical sense, thus it occurs cycle by cycle.

In conclusion, we have showed that the global con¯guration of cyclic universe is more complex than expected ever, which actually shows itself a cyclic multiverse. It is found that if the contracting phase with $w \simeq 0$ is included in each cycle of a cycle universe, the increasing mode of metric perturbation is inherited by the constant mode of curvature perturbation that lead the ampli¯cation of metric perturbation on super horizon scale cycle by cycle. Therefore after few cycles the universe will be inevitably separated into many parts independent of one another, each of which corresponds to a new universe and evolve up to next cycle, and then is separated again. Thus a cyclic multiverse scenario, in which the universe proliferates cycle by cycle, is actually presented. If the cyclic universe is like the Phoenix, rebirth in the \¯re" and will never ended, this Phoenix will also proliferate eternally.

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