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Cosmic inflation / Inflation cosmique

Bouncing alternatives to inflation

Rebond primordial comme alternative à l'inflation

Marc Lilley [a,b], Patrick Peter [a,b]

[a] *Sorbonne Universités, UPMC (Université Paris-6), UMR 7095, Institut Lagrange de Paris, 75014 Paris, France*
[b] *CNRS, UMR 7095, Institut d'astrophysique de Paris (GReCO), 75014 Paris, France*

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ABSTRACT

Although the inflationary paradigm is the most widely accepted explanation for the current cosmological observations, it does not necessarily correspond to what actually happened in the early stages of our Universe. To decide on this issue, two paths can be followed: first, all the possible predictions it makes must be derived thoroughly and compared with available data, and second, all the imaginable alternatives must be ruled out. Leaving the first task to all other contributors of this volume, we concentrate here on the second option, focusing on the bouncing alternatives and their consequences.

RÉSUMÉ

Quoique le paradigme inflationaire soit maintenant communément accepté comme représentant la meilleure explication des données cosmologiques, il n'est pas pour autant possible de dire qu'une telle phase soit avérée. Pour s'approcher d'une telle conclusion, on peut suivre deux chemins différents : on peut explorer les conséquences de l'inflation pour la pousser dans ses derniers retranchements, ou bien, au contraire, étudier en détail les alternatives possibles. La première option faisant l'objet de la plupart des contributions de ce volume, nous nous concentrons ici sur la seconde, et présentons les modèles dans lesquels une phase de contraction est suivie d'un rebond conduisant à notre époque d'expansion.

1. Introduction

Starting out in a dense state some 13.8 billion years ago, our Universe and its evolution since this initial time are well understood, with an initially almost scale-invariant, but not quite, spectrum of primordial perturbations condensing into the presently observed large-scale structures by means of gravitational collapse. The very high densities of the early stages provide initial conditions to explain the relative amounts of different nuclei, and the ensuing phases, being controlled by well-known physical mechanisms, permit to reconstruct, from the cosmic microwave background (CMB) observations, the

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E-mail address: lilley@iap.fr (M. Lilley).

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properties of the last scattering surface. We have arrived at the point [1,2] where cosmological data can be used to probe the earliest conceivable phases.

The most widely accepted paradigm for describing the earliest phases of the Universe, when the energy density was a mere few orders of magnitude below the Planck scale, is inflation [3,4]. Easily implemented by means of a scalar field, this almost exponentially expanding era rapidly leads to a flat Friedmann–Lemaître (FL) spacetime with a very slightly reddish spectrum of initial perturbations, from which the rest of the history of the Universe ensues. As is, such a scenario is compatible with all currently available data.

This contribution reviews some properties of some non-inflationary bouncing models. The first natural question that comes to mind before going any further is: why should we bother with possible alternatives to a working scenario? There are in fact many reasons, the first of which being that the phase of inflation is silent relative to the primordial singularity, as we discuss in Section 2 below. The second is that there is no way we will ever be able to assert that a phase of inflation did actually take place, except through its presently observable consequences. But then the question arises as to whether other competing theories could induce similar consequences. Thus, examining all plausible scenarios in detail seems to be the only way to assert whether inflation is the unique possibility leading to our observable Universe. In the end, ruling out alternatives, or not, increases or decreases our level of confidence in inflation until it becomes, if ever, recognized as valid beyond any reasonable doubt. As we shall see in Section 3, there are bouncing alternative explanations to the standard model puzzles of homogeneity, flatness, isotropy, horizon and the overproduction of relics, as well as many models, some of which are listed in Section 4, in which those bounces can be implemented.

Getting a background-compatible model is however not the end of the story: the recently released PLANCK data [5,6] confirm what was suggested by previous experiments, namely that the spectrum of primordial perturbations was almost scale invariant: slightly red, with a spectral index $n_s = 0.9639 \pm 0.0047$, excluding exact scale invariance at the 5σ level. The level of non-gaussianity is compatible with zero, and the contribution of tensor modes remains below the $\sim$10% limit relative to the scalar amplitude. All these facts are compatible with the perturbations having been produced by quantum vacuum fluctuations of a single scalar degree of freedom, a natural consequence of slow-roll single-field inflation. Can a non-inflationary bouncing model reproduce such results? As of now, there is no definite answer to this question. For this reason, and for lack of space in the present article, we shall not discuss these points below, and instead refer the reader to a recent review [7] in which all the relevant constraints for the models exhibited below are derived.

2. The singularity

The fact that cosmology, or at least its classical implementation in terms of general relativity (GR), always leads to the existence of singularities stems from the well-known singularity theorems [8]. A general argument was proposed in Ref. [9]: in an FL spacetime with metric

$$ds^2 = -dt^2 + a^2(t)\gamma_{ij}^{\mathcal{K}}(\boldsymbol{x})\, dx^i dx^j = a^2(\eta)\left[-d\eta^2 + \gamma_{ij}^{\mathcal{K}}(\boldsymbol{x})\, dx^i dx^j\right] \tag{1}$$

with $\gamma_{ij}^{\mathcal{K}}$ the constant-curvature ($\mathcal{K} = 0, \pm 1$) spatial metric, let $\mathcal{U}^\mu \equiv dx^\mu/d\lambda$, with λ an affine parameter, be a lightlike tangent to a geodesic curve, i.e. $\mathcal{U}^\mu \mathcal{U}_\mu = \gamma_{ij}^{\mathcal{K}} a^2 \mathcal{U}^i \mathcal{U}^j - \left(\mathcal{U}^0\right)^2 = 0$ and $\mathcal{U}^\mu \nabla_\mu \mathcal{U}^\alpha = 0$. Expanding the geodesic equation in terms of the connections associated with the metric (1) and taking into account the lightlike character of $\mathcal{U}$, one finds that

$$\frac{d\mathcal{U}^0}{d\lambda} + H\left(\mathcal{U}^0\right)^2 = 0$$

which implies that

$$\frac{d}{d\lambda}\left(\frac{dt}{d\lambda}\right) + H\left(\frac{dt}{d\lambda}\right)^2 = 0 \tag{2}$$

where the Hubble scale is $H = d\ln a/dt$. Eq. (2) is solved by choosing the affine parameter λ to satisfy $d\lambda = [a(t)/a(t_f)]dt$, with t_f a reference time, today say. We now assume our spacetime to begin at some initial coordinate time t_i, which can take any value between 0 say, to $-\infty$; this depends on the actual cosmological realization. The average Hubble rate along the geodesic parameterized by λ is found to be

$$H_{\text{average}} \equiv \frac{1}{\lambda(t_f) - \lambda(t_i)} \int_{\lambda(t_i)}^{\lambda(t_f)} H(\lambda) d\lambda = \frac{1}{\lambda(t_f) - \lambda(t_i)} \left\{1 - \frac{a[\lambda(t_i)]}{a[\lambda(t_f)]}\right\} \leq \frac{1}{\lambda(t_f) - \lambda(t_i)} \tag{3}$$

so that in order for H_{average} to be strictly positive, a condition that is generally satisfied in inflationary models, one finds that the interval in affine parameter must be finite, and therefore that the spacetime under consideration is not geodesically complete. This argument can be extended to timelike geodesics and more arbitrary cosmological models, i.e. with no specific assumptions regarding homogeneity and isotropy. This requires the definition of a local expansion rate that is not dependent on the special FL metric solution; in this case, it is the deviation between neighboring geodesics that needs to be used