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Inflation in the standard cosmological model

L'inflation dans le cadre du modèle cosmologique standard

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ABSTRACT

The inflationary paradigm is now part of the standard cosmological model as a description of its primordial phase. While its original motivation was to solve the standard problems of the hot big bang model, it was soon understood that it offers a natural theory for the origin of the large-scale structure of the universe. Most models rely on a slow-rolling scalar field and enjoy very generic predictions. Besides, all the matter of the universe is produced by the decay of the inflaton field at the end of inflation during a phase of reheating. These predictions can be (and are) tested from their imprint of the large-scale structure and in particular the cosmic microwave background. Inflation stands as a window in physics where both general relativity and quantum field theory are at work and which can be observationally studied. It connects cosmology with high-energy physics. Today most models are constructed within extensions of the standard model, such as supersymmetry or string theory. Inflation also disrupts our vision of the universe, in particular with the ideas of chaotic inflation and eternal inflation that tend to promote the image of a very inhomogeneous universe with fractal structure on a large scale. This idea is also at the heart of further speculations, such as the multiverse. This introduction summarizes the connections between inflation and the hot big bang model and details the basics of its dynamics and predictions.

RÉSUMÉ

Le paradigme de l'inflation fait aujourd'hui partie intégrante du modèle cosmologique standard en tant que modèle de la phase primordiale de son évolution. Bien que sa formulation originelle ait été motivée par la résolution de problèmes du modèle du big bang chaud, on réalisa rapidement que l'inflation offrait un méchanisme naturel pour l'origine des grandes structures de l'univers. La plupart des modèles reposent sur la dynamique d'un champ scalaire en roulement lent et fournissent des prédictions génériques et robustes. De plus, toute la matière de notre univers serait produite par la désintégration de l'inflaton à la fin de l'inflation dans une phase de réchauffement. Ces prédictions peuvent être (et sont) testées par l'étude de leurs signatures sur les grandes structures et, en particulier, sur le fond diffus cosmologique. L'inflation est une fenêtre sur un domaine où relativité générale et théorie quantique des champs sont conjointement à l'œuvre et qui peut être étudiée observationnellement. Elle connecte la cosmologie

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à la physique des hautes énergies. Aujourd'hui, la plupart des modèles sont construits dans des extensions du modèle standard, comme la supersymétrie ou la théorie des cordes. L'inflation bouleverse aussi notre représentation de l'univers, en particulier par les idées d'inflation chaotique et d'inflation éternelle, qui tendent à révéler un univers très hétérogène à grande échelle, avec une structure fractale. Cette introduction résume les liens entre inflation et modèle du big bang chaud et détaille ses propriétés dynamiques et ses prédictions.

1. Modern cosmology and the inflationary paradigm

A cosmological model is a mathematical representation of our universe that is based on the laws of nature that have been validated locally in our Solar system and on their extrapolations (see Ref. [1] for a detailed discussion). It thus seats at the crossroad between theoretical physics and astronomy. While a topic of interest for many centuries, we can safely state [2] that scientific cosmology was born with Albert Einstein's general relativity a century ago, a theory of gravitation that made the geometry of spacetime dynamical physical fields that need to be determined by solving equations known as Einstein field equations. Each solution of the theory is a spacetime, a universe and the question arose to determine the solutions [3] which are good approximations of the geometry of our universe.

This led to the construction of a standard cosmological model, mostly through four phases.

1.1. The basis of the standard cosmological model

The first era of relativistic cosmology started in 1917 with the seminal paper by Einstein [3], in which he constructed, at the expense of the introduction of a cosmological constant, a static solution to its equations in which space enjoys the topology of a three-sphere. This paved the way to the derivations of exact solutions to the Einstein equations that offer possible world models. Alexandr Friedmann and independently Georges Lemaître [4] developed the first dynamical models [5], hence discovering the cosmic expansion as a prediction of the equations of general relativity. An important step was provided by Lemaître, who connected the theoretical prediction of an expanding universe with an observations by linking it to the redshifts of electromagnetic spectra, and thus of observed galaxies. This was later confirmed by the observations by Edwin Hubble [6], whose *Hubble law*, relating the recession velocity of a galaxy to its distance from us, confirms the cosmological expansion. The law of expansion derives from the Einstein equations and thus relates the cosmic expansion rate, H, to the matter content of the universe, offering the possibility to "weight the universe". This solution to a spatially homogeneous and isotropic expanding spacetime, referred to as Friedmann–Lemaître (FL) universe, serves as the reference background spacetime for most later developments of cosmology. It relies on the so-called Copernican principle stating that we do not seat in a particular place in the universe, and introduced by Einstein [3]. While difficult to test, since we observe the universe from a special spacetime position, it has been shown in the past years that this hypothesis holds on the scale of the observable universe [7].

In a second era, starting in 1948, the properties of atomic and nuclear processes in an expanding universe were investigated (see, e.g., Ref. [8] for an early textbook). This allowed Ralph Alpher, Hans Bethe and George Gamow [9] to predict the existence of a cosmic microwave background (CMB) radiation (and to estimate its temperature), and to understand the synthesis of light nuclei, the big bang nucleosynthesis (BBN), in the early universe. Both have led to theoretical developments compared successfully to observation. It was understood that the universe is filled with a thermal bath with a black-body spectrum, the temperature of which decreases with the expansion of the universe. The universe cools down and has a thermal history, and more importantly it was concluded that it emerges from a hot and dense phase at thermal equilibrium (see, e.g., Ref. [10] for the details). This model has however several drawbacks, such as the fact that the universe is spatially extremely close to Euclidean (*flatness problem*), the fact that it has an *initial spacelike singularity* (known as big bang), and the fact that thermal equilibrium, homogeneity and isotropy are set as initial conditions and not explained (*horizon problem*). It is also too idealized, since it describes no structure, i.e. does not take into account the inhomogeneities of the matter, which is obviously distributed in galaxies, clusters and voids. The resolution of the naturalness of the initial conditions was solved by the postulate [11] of the existence of a primordial accelerated expansion phase, called *inflation*.

The third and fourth periods were triggered by an analysis of the growth of the density inhomogeneities by Lifshitz [12], opening the understanding of the evolution of the large-scale structure of the universe, that is of the distribution of the galaxies in clusters, filaments and voids. Technically, it opens the way to the theory of cosmological perturbations [13–15], in which one considers the FL spacetime as a background one, the geometry and matter content of which are perturbed. The evolution of these perturbations can be derived from the Einstein equations. For the mechanism studied by Evgeny Lifshitz to be efficient, one needed initial density fluctuations large enough so that their growth in an expanding universe could lead to a non-linear structure at least today. This motivated the question of the understanding of the origin and nature (amplitude, statistical distribution) of the initial density fluctuations, which turned out to be the second success of the inflationary theory, which can be considered as the onset as the third era, the one of *primordial cosmology*. From a theory point of view, the origin of the density fluctuation lies into the quantum properties of matter [16]. From an observational