Enlightening the primordial dark ages

Iarygina, O.

Summary

From a time of ancient gods, warlords and kings people were curious about the origin of our Universe. Nowadays, with the theoretical and experimental tools of modern cosmology the scientific community is breaking the boundaries of the previously unsolved questions, pushing forward our understanding of the Universe. From the myths that our world is located on the backs of four elephants, who are standing themselves on a turtle, humanity has arrived at the era of precision cosmology that allows us to talk about previously philosophical questions in scientific terms with further confirmation or falsification by observational experiments.

Our current understanding is that about 13.77 billion years ago the Universe began from a dense and hot state, that expanded and continues to expand today. The leading paradigm in the physics of the early universe is called cosmological inflation. It describes the earliest stage of the Universe's expansion that happened about 10^{-36} seconds after the moment we call the "Big Bang". Quantum fluctuations produced during inflation serve as the source for the density inhomogeneities that became stars, galaxies, clusters of galaxies and, in turn, formed the large scale structure. To connect the inflationary era with the Universe we observe nowadays, the energy that drives inflation must be transferred to elementary particles and to radiation. This process is called reheating. When particles settle into thermal equilibrium, the formation of chemical elements starts, which is followed by the rest of cosmic evolution.

This thesis is dedicated to the exploration of *the primordial dark ages*: unknown physics during the inflationary and reheating eras that has not been *directly* probed by observations. We focus on novel effects in inflation and reheating in multi-dimensional field spaces, with the aim to provide new connections to astrophysical observables and reduce theoretical uncertainties, in order to properly test inflationary models and understand the physics of the early universe. In particular, the unknown expansion

history of the universe during the reheating era connects the cosmic microwave background observations to inflationary physics. The cosmic microwave background is the oldest light in the universe that was emitted about 380.000 years after the beginning of the universe's evolution and provides us a snapshot of the primordial universe. In addition to that, both the inflationary and reheating eras generate various signatures to be seen in upcoming experiments, for instance, via gravitational waves and cosmic microwave background polarization.

The first part of the thesis studies inflation with multiple scalar fields as well as covers the physics of gauge fields during the inflationary era. Gauge fields are unavoidable components of any successful field theory. They describe fundamental forces of nature and explain the dynamics of elementary particles. On the other hand, the studies of multi-field inflation are motivated by high energy completions of low energy field theories. Since energies in the primordial universe are extremely high, it is natural to assume that multiple fields may participate in inflationary dynamics.

In Chapter 2 we present a new class of inflationary models that is called "shift-symmetric orbital inflation". The field that drives inflation in this case orbits along an angular direction with a constant arbitrary radius. In this model the extra degree of freedom is responsible for the primordial observables at the end of inflation. Nevertheless, it governs single-field-like predictions that are favoured by observations. We explicitly prove the neutral stability of the attractor solution.

Chapter 3 is dedicated to the study of the predictions for the amplitude and tensor tilt of chiral gravitational waves produced by a non-Abelian gauge field sector that is realised as a spectator for a standard scalar single-field inflation. We find a maximum allowed value for the gravitational wave enhancement with respect to the standard vacuum predictions, that could be potentially distinguishable in future cosmic microwave background polarization experiments.

The second part of the thesis explores reheating in multi-field models of inflation with curved field-space geometries. A knowledge of the physics of the reheating era is crucial since its efficiency and duration significantly influences the cosmic microwave background predictions and may affect primordial nucleosynthesis.

Chapter 4 studies preheating in one broad family of multi-field models of inflation that is called α-attractors. We show analytically a simple scaling behaviour that allows for an easy estimate of the reheating efficiency for large values of the field-space curvature.

Chapter 5 investigates and compares the dynamics during inflation and reheating for the multi-field α-attractor model with prototype potentials that are symmetric and asymmetric around the minimum. We explicitly show the significance of the asymmetry and its influence on the reheating efficiency.

The aim of this thesis is to shed light on the primordial dark ages of cosmology, push forward their frontier and motivate further development. We live in an exciting time of precision measurements in modern cosmology that may disclose previously unknown physics of the early universe. However, a correct interpretation of the observations significantly relies on theoretical understanding of the early universe physics. Below we outline a few directions that require a deep investigation in the coming years.

- *Gravitational wave* experiments opened a new window for probing the physics of the early Universe via the stochastic gravitational wave background. It is important to deeply understand their production mechanisms in order to correctly interpret the measurements of the upcoming experiments.

- *Features in the primordial power spectrum* are exciting signatures from both the inflationary and reheating eras that may be potentially visible in the cosmic microwave background and large scale structure spectra. This subject requires a thorough analytical understanding and future research.

- *An effective theory of reheating* is essential for the correct understanding of the cosmic microwave background predictions. In turn, predictions for inflationary models strongly depend on the physics of the reheating era. Hence, the development of the effective field theory of reheating for curved field-space manifolds is an important goal for theoretical physics. Special attention would require incorporating the non-linear effects and systematic analytical studies of stable long-lived spatially localized structures such as oscillons, especially in the general multi-field set-ups.

In order to keep the motivation for further exciting explorations it is good to remember:

"The cosmos is within us. We are made of star-stuff.
We are a way for the universe to know itself."

Carl Sagan