Big Bang

Latest news from the Big Bang theory

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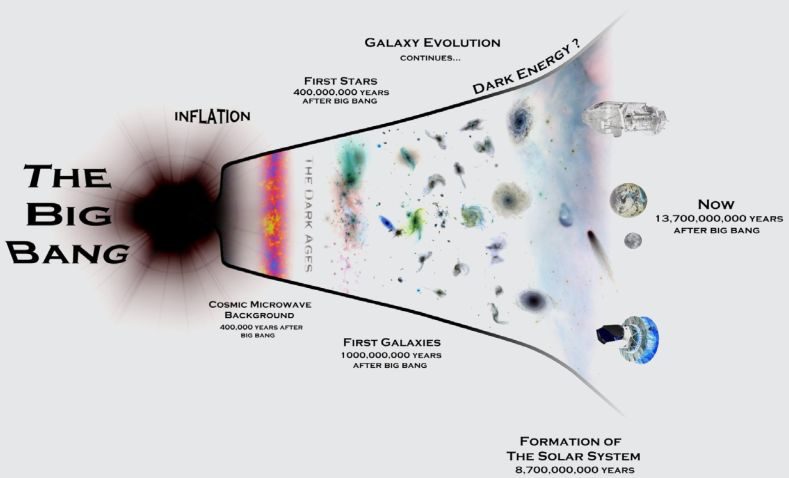
Edwin Hubble was amongst the first to observe, via the Doppler shifts of emitted radiation, that galaxies are moving away from us. The only reasonable way to explain this is by accepting that the entire Universe is expanding: as time goes by, the universe becomes ever larger. Reversing this logic, one concludes that by going back in time, the Universe becomes smaller and smaller.

According to the standard equations of General Relativity, this reversed logic leads to a singularity at the earliest instance, that is referred to as the Big Bang. At this moment, the size of the Universe would have been infinitely small, while its energy density would have been infinitely large.

Soon after this realization the Big Bang theory was constructed, which encompasses both this initial moment and the subsequent, steady, expansion and evolution of the Universe. While this paradigm of cosmology has very strong observational support - from, for instance, nucleosynthesis, i.e., the formation of protons and neutrons during the first three minutes -, and explains a large number of features, it falls short in providing an explanation for others. The common denominator of the latter is the surprising smoothness of the Universe on large scales.

- First of all, the galaxy distribution over distances larger than 100 Mpc (1 Mpc ≈ 3.3 million light years) is too homogeneous for the Big Bang theory.
- Secondly, one would expect the cosmic microwave background (more details later) to be isotropic over angles of at most 1 degree on the sky, in contrast to the fact that its temperature is observed to be very nearly the same (approximately 2.7 K) on the entire sky.



FIGUUR 1 An artist's impression of the evolution of the Universe, running from left to right.

- Finally, Grand Unified Theories of high-energy physics (theories that aim to unify the known forces other than gravity, i.e., the two nuclear forces and the electromagnetic force) predict the existence of ultra-heavy magnetic monopoles (objects that have either an isolated South or North pole), which would create unobserved density accumulations.

To tackle these problems of the Big Bang theory, Guth and Linde proposed in the early 1980s that the Universe did not just start to steadily expand after the Big Bang. Instead of steady growth, a period of rapid accelerated expansion was postulated, a mere fraction of a second following the Big Bang, after which the steady expansion of the Big Bang theory would resume. This initial period of exponential growth is referred to as inflation (see figure 1).

"Instead of steady growth, a period of rapid accelerated expansion was postulated."

Quantum fluctuations

At first, the status of inflation was hypothetical at best, as it only provided an explanation for already observed, large-scale features of the Universe. This changed dramatically with the realisation that inflation has a much further-reaching implication: in addition to smoothing out the Universe at large scales, it also provided the initial seeds for all the inhomogeneities, such as galaxy clusters, that make the Universe such an interesting place today. During the phase of furious growth, short-scale quantum fluctuations were stretched out to macroscopic sizes. These inflated fluctuations would then result into perturbations in the energy density, and effectively became classical initial conditions for the evolution of the Universe. During the ensuing 13.8 billion years, these diluted quantum effects were magnified under the influence of gravity: dense areas attract the matter from less dense parts, amplifying the differences in density between different areas. Over time, these initial fluctuations evolved into the entire large-scale structure of the Universe as observed today!

The fluctuations predicted by inflation come in two flavours: scalar fluctuations, which give rise to the density fluctuations, and tensor fluctuations, corresponding to gravitational waves. These perturbations are predicted to have very specific properties, and are characterized via the so-called scalar power spectrum $P_s(k)$ and tensor power spectrum $P_t(k)$. These power spectra quantify the amplitude of fluctuations with different length scales, as captured by the wavenumber $k = 2\pi/\lambda$. They thus give us a measure of scale dependence of the fluctuations, and generically inflation predicts that the fluctuations are nearly independent of scale. For instance, for the scalar perturbations one finds: $P_s(k) \propto k^{n_s - 1}$. Most models of inflation predict that the so-called spectral index, n_s, is close to 1, resulting in a nearly scale independent scalar power spectrum. The precise details may vary amongst different models. The case of the tensor perturbations is similar.

Cosmic Microwave Background

This mind-boggling interplay between quantum fluctuations, inflation and structure formation can be tested by comparing predictions with observations. In principle, this can be done at any stage of the Universe's evolution; however, it is very difficult to extract accurate information on the state of the Universe for most periods. There is one moment for which we do have a treasure trove of information: recombination, taking place around 380.000 years after the Big Bang, when neutral hydrogen was first formed.

At earlier times, light could not travel freely due to constant scattering interactions with the high number of charged plasma particles present in the Universe. After the formation of neutral hydrogen, such scattering processes no longer dominated and light could move freely. Thus, at this moment the Universe became transparent. The light that was emitted at this moment is called the Cosmic Microwave Background (CMB) and can be observed from every direction in the sky. In fact, the CMB photons are so abundant that they are responsible for 1 percent of the background noise on analogue televisions.

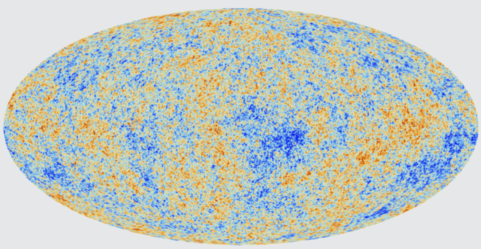
As the Universe became transparent, information on the state of the Universe (at that time) was stored in the CMB. By observing this remnant radiation, we can retrieve an accurate picture of the Universe during its early stages, when all inhomogeneities had only evolved for a few hundreds of thousands of years.

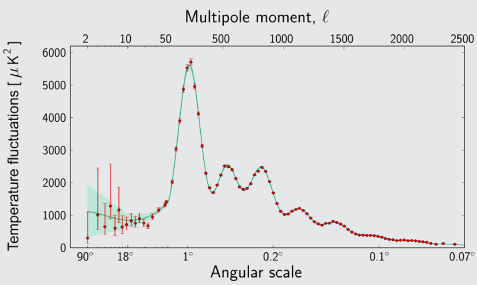
The CMB has two important physical traits: frequency dependence and polarisation patterns. The former of these translates, via Planck's law of the blackbody spectrum, into temperature variations. These variations are a direct consequence of the quantum fluctuations predicted by inflation. They have been looked for from the 1980s onwards, and indeed the COBE satellite discovered them in 1992. This is indicated by the so-called T-T power spectrum of the CMB (figure 2). The T-T power spectrum gives a measure of the correlation of temperature perturbations along different directions on the sky, and it can be directly related to the scalar power spectrum. Thus, comparing the observed properties of the temperature variations with those predicted theoretically provides a great test of inflation. Subsequent studies by the WMAP and Planck satellites have confirmed that the statistical properties of these variations are in full agreement with the predictions of inflation!

An equally generic prediction of inflation concerns the second property, related to the polarisation of the CMB photons. Inflation predicts particular patterns in the polarisation; moreover, it predicts very specific correlations between the temperature and the polarisation modes. The latter consists of two polarisation components: E- and B-modes. During recombination, when the CMB was formed, the tensor perturbations left a specific B-mode polarization pattern, with a corresponding B-B power spectrum. Similar to the T-T power spectrum, the B-B power spectrum simply gives a measure of correlation between B-mode polarisations at different points on the sky. As far as we know, tensor perturbations are the only primordial source for such a pattern, and detection thereof therefore corresponds to the discovery of primordial gravitational waves!

Observational status

As already noted, the general predictions of inflation as captured in the temperature fluctuations are confirmed by actual observations. This is of course already a major milestone. However, more strikingly, given the highly accurate measurements on the temperature fluctuations, it has in addition proven possible to put





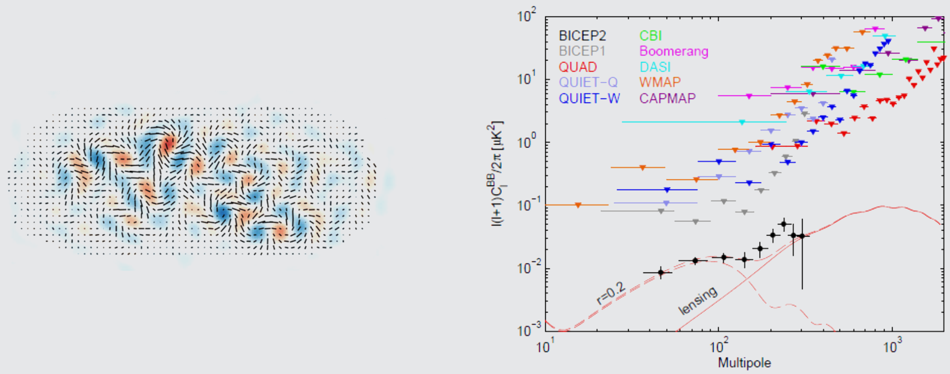
FIGUUR 2 Left panel: the temperature anisotropies δT of the CMB. Right panel: the power spectrum of δT - red points indicate Planck data while the green line is the inflationary prediction for $n_s = 0.9603$.

strong constraints on the inflationary parameters. That is, we can perform precise measurements that allow us to discern between different models of inflation. In particular, the green line in the right panel of figure 2 is the prediction of the concordance model (Λ-CDM) of cosmology supplemented with a single inflationary parameter: the scale dependence of the initial scalar fluctuations, as encoded in the spectral index n_s. The impressive agreement over three decades of wavenumbers requires this scale dependence to be equal to $n_s = 0.9603 \pm 0.0073$, ruling out the scale-invariant case $n_s = 1$ at a certainty of 99.99994 percent. Another parameter one can measure is the so-called tensor-to-scalar ratio, r, defined as: $r = P_t(k)/P_s(k)$. This parameter thus gives a measure of the amount of gravitational waves relative to the amount of scalar perturbations, and hence any non-zero value would imply quantum gravitational waves. The value of r can in principle be extracted from the B-B power spectrum; however, this proves much more finicky from an observational point of view. Amazingly, the team of the BICEP2 telescope has claimed to be able to measure it and found $r = 0.20^{+0.07}_{-0.05}$ without foreground subtraction (figure 3). However, it is currently heavily debated whether the BICEP2 signal is indeed of primordial origin, or whether it could also (partially) stem from more mundane sources such as dust in our own galaxy. Hopefully, this matter will be resolved in the coming months, and then we finally might know more about the rôle of gravity's quantum fluctuations after the Big Bang...

In our research group on Quantum Gravity at the newly found Van Swinderen Institute for Particle Physics and Gravity, we are trying to provide a sound theoretical basis for theories of inflation and their resulting predictions. If you want to know more, or if you are interested in doing your BSc or MSc research in this direction, pass by in the theoretical physics corridor - building 11 of Nijenborgh 4!

Concluding remarks

Observations of the CMB contain a great promise towards discovering more about the physics of inflation, which has taken place at very high energy, around or just below the grand unified scale. As such, it is unprecedented as an observational window in this energy range, and can be used complementary to traditional particle physics approaches. In this article, we have reported on the latest observational progress in this direction •



FIGUUR 3 Left panel: the B-mode polarization of the CMB. Right panel: the power spectrum of B-black points indicate BICEP2 data while the red line is the inflationary prediction for $r = 0.2$.