Virtual gravitational dipoles as alternative to cosmic inflation in the primordial Universe

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Abstract. In March 2014 the BICEP Collaboration has announced the discovery of the primordial gravitational waves. The hypothetical cosmic inflation (of unknown origin) is widely acclaimed as the cause of these waves. We suggest that the quantum vacuum enriched with the virtual gravitational dipoles might be an alternative to cosmic inflation with three significant advantages. First, there is no need for a mysterious scalar field that produces the exponential expansion of the Universe. Second, there is no initial singularity. Third, there is an elegant explanation of the matter-antimatter asymmetry in the Universe: our Universe is dominated by matter because the previous cycle of the Universe was dominated by antimatter.

1. Introduction

Recently, astronomers working on the Background Imaging of Cosmic Extragalactic Polarisation 2 (BICEP2) telescope have reported results [1] which are apparently the discovery of the primordial gravitational waves. In fact, the primordial B-mode polarisation of the cosmic microwave background (CMB) has been observed; the key point is that B-mode polarisation can be created only by very strong primordial gravitational waves. Hence, a background of strong gravitational waves existed in the Universe at the moment of the "birth" of CMB (by the way at that moment the Universe was already much bigger than our Galaxy). The existence of strong primordial gravitational waves proves that a mysterious cataclysmic event happened before the birth of CMB.

Let us underline that the Big Bang model of the Universe *contradicts* observations without *invoking* cosmic inflation (See [2] for a review) or an appropriate alternative to inflation. According to the dominant inflation scenario (the chaotic inflation) our Universe is born with a microscopic mass as a quantum vacuum fluctuation within a single Planck size domain. Within the first 10^{-30} seconds this small Universe was subject to inflation i.e. an extremely rapid exponential expansion, blowing the size of what is now the observable Universe from a size much smaller than an electron to the macroscopic size of order of metres (or even bigger); hence the expansion happened with a speed many orders of magnitude faster than the speed of light. Of course, the cause of this hypothetical inflation remains a mystery; in theoretical work the starting point is an ad hoc introduction of a scalar field. Creation of matter of our Universe has happened *after* inflation when the energy concentrated in the inflation field was converted into particle-antiparticle pairs (this is radically different from Big Bang model without inflation in which the totality of mass of the Universe was created in the initial singularity). From this time on, the universe can be described by the usual Big-Bang theory.

Of course, conversion of the energy of the scalar inflation field into the enormous quantity of matter in our Universe (and all that in a tiny fraction of one second) is a cataclysmic event inevitably accompanied with creation of the primordial gravitational waves, the strongest gravitational waves in the history of the Universe. However it is premature to conclude that the inflation theory is confirmed by the discovery of the primordial gravitational waves; the existence of the waves and the physical source of the waves are two different things. The BICEP2 results tell us *only* that much before the birth of the CMB there was a cataclysmic event as the source of the primordial gravitational waves; what was the event, the inflation or something else, remains an open question. In the present Essay we suggest an alternative to inflation based on the assumption that the quantum vacuum contains virtual gravitational dipoles.

2. The cosmological equation for acceleration

In contemporary cosmology (See for instance [3]) the "mass-energy content" of the Universe is successfully modelled as a perfect "cosmological fluid", which consists of a mixture of several distinct components (hereafter denoted by the subscript n) having density ρ_n and pressure p_n in the instantaneous rest frame.

The cosmological principle leads to the Friedman-Robertson-Walker metric [3]. The dynamics of that metric (i.e. the space-time geometry) is entirely characterized by the scale factor $R(t)$ which depends on the content of the Universe. For the purpose of the present paper it is important that the scale factor satisfies [3] the following cosmological field equation

$$\ddot{R} = -\frac{4\pi G}{3} R \sum_n \left(\rho_n + \frac{3p_n}{c^2} \right) \tag{1}$$

Within the Standard Cosmological Model, densities ρ_n follow the power-law

$$\rho_n = \rho_{n0} \left(\frac{R_0}{R} \right)^n \tag{2}$$

where index 0 denotes the present-day values.

Each component of the cosmological fluid obeys an equation of state of the form $p_n = w_n \rho_n c^2$ with constant equation-of-state parameter $w_n = (n-3)/3$. The cases $n = 4, 3, 0$ (with $w = 1/3, 0, -1$) correspond respectively to relativistic particles, pressureless matter (including both ordinary matter and dark matter) and a cosmological constant Λ (as one plausible candidate for dark energy).

Today $\ddot{R}$ has a small value of the order of $10^{-9}\, m/s^2$. However (and it is crucial for our arguments), in the primordial Universe soon after inflation acceleration $\ddot{R}$ was extremely big. For instance, if we limit only to the effects of the pressureless matter, equations (1) and (2) lead to the following lower bound $\ddot{R}_{lb}$ for acceleration

$$\ddot{R}_{lb} = -\frac{4\pi G \rho_{m0}}{3} \frac{R_0^3}{R^2} = -\frac{4\pi G \rho_{m0}}{3} \left(\frac{c}{H_0} \right)^3 \frac{1}{(\Omega_{tot} - 1)^{3/2}} \frac{1}{R^2} \tag{3}$$

The second equality in (3) is a consequence of well-known relation [3] $c^2 / H^2 R^2 = \Omega_{tot} - 1$ where the usual dimensionless parameter $\Omega_{tot} \approx 1.002$ denotes the total energy density of the Universe. For example, if $R = 1m$, $\ddot{R}_{lb}$ has tremendous value of the order of $10^{45}\, m/s^2$.

Now when we know how strong the gravitational field in the primordial universe might be we need to remember an important mechanism coming from quantum electrodynamics.

3. The Schwinger mechanism in quantum electrodynamics

A virtual electron–positron pair (and in fact any charged particle-antiparticle pair) from the quantum vacuum, might be *converted* into a real one by a sufficiently strong external electric field which accelerates electrons and positrons in *opposite* directions. For a constant acceleration *a* (which corresponds to a constant electric field), the particle creation rate per unit volume and time, can be written [4, 5] as:

$$\frac{dN_{m\bar{m}}}{dtdV} = \frac{c}{\lambda_m^4} \left(\frac{a}{a_{cr}} \right)^2 \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n \frac{a_{cr}}{a} \right), \; a_{cr} \equiv \frac{\pi c^2}{\lambda_m} \tag{4}$$

which is the famous Schwinger formula [4 , 5], with λ_m being the reduced Compton wavelength of a particle with mass m . In simple words, a virtual pair can be converted to a real one (i.e. real particle–antiparticle pairs can be created from the quantum vacuum!), by an external field which, during their short lifetime, can separate particle and antiparticle to a distance of about one reduced Compton wavelength. Let us note that according to (4) the critical accelerations for creation of electron-positron and proton-antiproton pairs are respectively $7.4\times 10^{29}\ m/s^2$ and $1.4\times 10^{33}\ m/s^2$. These accelerations are much smaller than the gravitational accelerations which might exist in the primordial Universe!

It is important to understand, the Schwinger mechanism is valid *only* for an external field that has the tendency to *separate* particles and antiparticles. Hence, Eq. (4) can be used for the gravitational field, *only if*, particles and antiparticles have *gravitational charge of the opposite sign.* Well, why not? The existing experimental evidence does not and cannot preclude the hypothesis that the quantum vacuum contains virtual gravitational dipoles. The hypothesis can be confirmed or dismissed only by forthcoming experiments at CERN [6, 7, 8] and astronomical observations [9, 10]. So, we continue our considerations assuming that virtual gravitational dipoles exist, and consequently that there is the gravitational version of the Schwinger's mechanism.

4. Big Crunch and virtual gravitational dipoles

According to astronomical observations we live in an expanding Universe; hence, the size of the Universe was smaller in the past. How much smaller? At what size would an imagined trip backward in time end?

In the framework of contemporary physics there is no known mechanism to stop the gravitational collapse; hence, our imagined trip backward in time must end with a *singularity* as is the case in the Old Big Bang theory (i.e. the theory before the invention of the inflation scenario). As noted there is no singularity in chaotic inflation but the initial quantum vacuum fluctuation is roughly within a single Planck size domain.

However, if the quantum vacuum contains virtual gravitational dipoles, there is a physical mechanism to prevent gravitational collapse to microscopic size. Through the gravitational version of the Schwinger mechanism *at a macroscopic size* the matter of our Universe would be converted to antimatter leading to a new cycle of the Universe dominated by antimatter.

The qualitative picture of the expected phenomena is very simple and beautiful. An extremely strong gravitational field (estimated by Eq. 3) would create a huge number of particle-antiparticle pairs from the physical vacuum; with the additional feature that matter tends to reach toward singularity while antimatter is violently ejected farther and farther from singularity. The amount of created antimatter is equal to the decrease in the mass of the collapsing matter Universe. Hence, the quantity of matter decreases while the quantity of antimatter increases for the same amount; the final result might be conversion of nearly all matter into antimatter. If the process of conversion is very fast, it may look like a Big Bang starting with a macroscopic initial size many orders of magnitude greater than the Planck length, which may be a viable alternative to inflation in Cosmology.

The particle-antiparticle creation rate per unit volume and time can be estimated using the Eq. (4). For instance, if the scale factor of the Universe is $R = 1m$, Eq. (4) gives the following order of the magnitude for neutron-antineutron pairs

$$\frac{dN_{n\bar{n}}}{dtdV} \sim 10^{96}\ \frac{pairs}{sm^3} \tag{5}$$

which corresponds to a mass of $10^{69}\,kg$ per second and cubic meter. With such an enormous conversion rate the matter of our Universe can be transformed into antimatter in a tiny fraction of second.

In the inflation scenario at a macroscopic size the energy of the hypothetical scalar field converts to an initial matter-antimatter mixture, from which somehow only matter will survive. In our scenario, instead of the energy of the scalar field the existing matter of the Universe converts to antimatter; there is no need for inflation and for any additional mechanism to explain the matter-antimatter asymmetry of the Universe. Of course conversion of matter to antimatter is a cataclysmic event of the same order of magnitude as the supposed conversion of scalar field to matter; hence the strong primordial gravitational waves (revealed by results of BICEP2 Collaboration) are inherent part of both theories.

5. Concluding comments

Inflation is a mature theory more than 30 years old and developed by the work of hundreds of top theorists. It is a theory which proposes elegant mathematical solutions to the problems of the Old Big Bang theory. However we must stay open to alternatives.

Of course it would be wrong to confront this initial paper with the already well developed inflation theory. It would be more reasonable to compare this paper with the first paper proposing the idea of inflation (just imagine that both proposals have appeared at the same time, one paper proposing inflation and the other proposing virtual gravitational dipoles). Hopefully this short paper would stimulate detailed theoretical study of the proposed mechanism; only after a fair development must it be confronted with inflation and both of them with observations.

In this paper the virtual gravitational dipoles were considered as an eventual alternative to inflation but it is worth noting that as recently suggested [11, 12, 13] they also have the potential to explain phenomena usually attributed to dark matter and dark energy.

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