Phantom dark energy and the Steady State ’on the average’ universe.

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Abstract. We consider the hypothesis that the dark energy pervading our universe is phantom \((-p > \rho)\). The density of such a substance grows with the cosmological expansion and may become infinite in a finite time producing a Big Rip. In this report we analyze the late stages of the universe evolution and demonstrate that the presence of the phantom energy in the universe is not enough in itself to produce the Big Rip. This singularity occurrence requires the fulfillment of some additional, rather strong conditions. A more probable outcome of the cosmological evolution is the decay of the phantom field into ‘normal’ matter. The second, more intriguing consequence of the presence of the phantom field is the possibility to introduce a cosmological scenario that does not contain a Big Bang. In the framework of this model the universe eternally expands, while its density and other physical parameters oscillate over a wide range, never reaching the Plank values. Thus, the universe evolution has no singularities at all.

1. Introduction

Experimental data [1, 2, 3] indicate convincingly an accelerating cosmological expansion. The substance responsible for this effect is usually called dark energy. If we speculate that the universe is filled with a perfect fluid with equation of state \(p = \alpha \rho\), the accelerating expansion appears if \(\alpha < -1/3\). The case of the dark energy with \(\alpha < -1\) (it is usually called phantom energy) has currently come to the attention. Physical properties of a dark energy with \(\alpha < -1\) differ markedly from the case when \(\alpha \geq -1\). The difference most important for the cosmology becomes apparent when we consider expansion of the universe containing dark energy. If \(\alpha \geq -1\) the dark energy density is not increasing (or even decreasing) as the universe expands. All bound systems (such as the solar one) remain bound forever; the dark energy presence manifests itself only on cosmological scales. If we allow \(\alpha < -1\), the dark energy density grows and becomes infinite in a finite time. Increasing gravitational repulsion produced by the phantom energy will first destroy Galaxies and then any bound systems including elementary particles [4, 5]. This phenomenon is usually called Big Rip. However, as we will see below, realization of such a catastrophic scenario requires the fulfilment of several supplementary conditions. Even if the phantom energy prevails in the universe, the Big Rip does not necessarily occurs.

There is another less evident consequence of \(\alpha < -1\): if dark energy is really the phantom one, the universe evolution needs not to contain a Big Bang.
2. The phantom energy-dominated universe evolution

Presence of the phantom energy in the universe is not enough in itself to produce the Big Rip. This phenomenon appears, for instance, if the coefficient averaged over the universe contents \( \alpha = \text{const} < -1 \). However, it is beyond reason to believe that \( \alpha \) remains constant during the cosmological evolution. In order to illustrate this let us at first consider a very simple situation when a universe contains only uniformly distributed phantom energy with an ordinary Lagrangian

\[
\mathcal{L} = -\frac{\partial \xi \partial \bar{\xi}}{2} - V(\phi)
\]  

(1)

For such a field

\[
\rho = -\dot{\phi}^2/2 + V(\phi), \quad p = -\dot{\phi}^2/2 - V(\phi)
\]

(2)

One can see that \( \alpha \) is not a constant; it depends on the amplitude of the field and on the potential energy density \( V(\phi) \). This question has been discussed in close detail in [6]. To summarize briefly the results: if the potential is not very steep (grows slower than \( V(\phi) \propto \phi^4 \)) then \( \alpha \) tends to \(-1\), and the density becomes infinite only when \( t \to \infty \). So, no Big Rip appears in this case, though the universe reaches the Planck density in a finite time. For steeper potentials a big rip singularity appears even if \( \alpha \to -1 \). Even the parameter \( \alpha \) can tend to \(-\infty \) for a very steep \( V(\phi) \). Finally, if \( V(\phi) \) has a maximum, \( \alpha \to -1 \) and \( \rho \to \text{const} \) [7, 10]. It is important to emphasize that a very steep potential is necessary to provide a constant \( \alpha < -1 \): for any polynomial potential, for instance, \( \alpha \) tends to \(-1 \).

The second effect that is able to prevent the Big Rip is a possible phantom energy interaction generating ‘normal’ particles. The normal substance gives positive contribution to the pressure that decreases the \( \alpha \) value averaged over the universe contents. Eventually the Big Rip may be prevented.

It is generally believed that the phantom energy does not interact with ‘normal matter’, but it cannot be absolutely true, if for no other reason than the gravitational interaction. Let us consider a toy illustration for a start. As noted above, in the phantom scenario increasing gravitational repulsion produced by the phantom energy will finally destroy even elementary particles. We consider a hadron (more precisely, a quark-antiquark pair \( q\bar{q} \)) ripped by the gravitational forces. When the distance between the quark and antiquark increases, the color field lines of force between them are pressed together into a string-like region. The gravitational repulsion stretches the color lines of force until the increasing potential energy becomes sufficient to create another \( q\bar{q} \) pair. It divides the string on two strongly-coupled \( q\bar{q} \) pairs, but they are also ripped up by the gravitational repulsion. So, this leads to intensive hadron production in the moments just before the Big Rip.

Another mechanism of ‘normal’ matter generation in the phantom-dominated universe is particle production in the cosmological gravitational field. In [11] the process was considered under assumption that the universe is filled with a perfect fluid with \( \alpha = \text{const} < -1 \). The generated ‘normal’ matter density can be written as

\[
\rho_{\text{norm}} = C\eta^\beta, \quad \text{where} \quad \beta = \frac{4}{1 + 3\alpha}
\]

(3)

In order to examine the problem in more detail we consider a universe, initially filled with a perfect fluid with \( \alpha = -4/3 \). Integration of the system of cosmological equations [8] shows that the Hubble constant grows progressively slower, reaches its maximum \( H_{\text{max}} \), and begins to decrease. On the contrary, \( \alpha \) constantly increases from the initial value that is close to \(-4/3 \). Finally it becomes positive. Of course, both the effects result from the high growth fraction of the ‘normal’ matter in the universe that makes a positive contribution to the pressure. It seems reasonable to contend that in the course of the phantom-dominated universe evolution
the quantity of 'normal' matter becomes comparable with the phantom one, and the value of \( \alpha \) grows hindering from the Big Rip. To this we can add that we have considered the case of \( \alpha = \text{const} \), which claims an extremely steep phantom field potential \( V(\phi) \), as we could see above. For a more realistic case of the polynomial potential \( \alpha \) tends to zero even in the absence of 'normal matter'. This makes the occurrence of the Big Rip highly unlikely.

### 3. Discussion

Of course, the suggested model is ingenuous. Intensive phantom field may interact in some other way decaying into 'normal' matter. Whatever the mechanism of the transformation may be, the universe after it has the following properties:

(i) It has just passed through the stage of very rapid (at least, exponential) expansion.
(ii) It is flat and homogeneous.
(iii) It is 'normal' matter-dominated.
(iv) The Hubble constant is very large.

It is precisely these physical conditions that existed in our universe \( \sim 13.7 \) milliard years ago, just after the inflation. If we assume that the inflation was caused by the phantom field (the equations of the phantom cosmology can be closely analogous to those of the chaotic inflation \[8\]), this makes possible to construct a model of universe evolution that does not contain a Big Bang. The universe leaves inflation being matter-dominated. As it expands the density of matter decreases, while the phantom density grows: eventually the universe passes into the phantom-dominated stage. As this takes place, the total density and the Hubble constant stop diminishing and begin to increase. Gradually the expansion becomes very fast, leading to an inflation-lake stage. Finally the phantom field decays into 'normal' matter, and the cycle repeats. Thus, the universe eternally expands, while its density and other physical parameters oscillate over a wide range, never reaching the Plank values. The universe evolution has no singularities like a Big Bang or a Big Rip. By analogy with the Steady State theory \[12, 13, 14, 9\], the considering model may be called the Steady State on the average universe.

If the phantom energy does exist, the considering model is an interesting instance of cosmological solutions containing no singular points like a Big Bang or a Big Rip. It is worthy of note that, though in our case the universe density never reaches infinity (or, more precisely, Planck density), all the physical parameters vary over a very wide range and amount up to extremal values. So, the universe passes through the stages that can be called physically critical.

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