Physics Letters B 778 (2018) 332–338

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

On the cosmological gravitational waves and cosmological distances

V.A. Belinski [a,b,*], G.V. Vereshchagin [c,d]

[a] ICRANet, P.le della Repubblica 10, 65100 Pescara, Italy
[b] IHES, 35, Route de Chartres, F-91440 Bures-sur-Yvette, France
[c] ICRANet, Piazza della Repubblica, 10, 65100 Pescara, Italy
[d] ICRANet-Minsk, NASB, Nezavisimosti av. 68, 220072 Minsk, Belarus

ARTICLE INFO

Article history:
Received 27 November 2017
Received in revised form 17 January 2018
Accepted 18 January 2018
Available online xxxx
Editor: M. Trodden

Keywords:
Dark energy
Gravitational waves

ABSTRACT

We show that solitonic cosmological gravitational waves propagated through the Friedmann universe and generated by the inhomogeneities of the gravitational field near the Big Bang can be responsible for increase of cosmological distances.

1. Introduction

At present the most popular cosmological model — ΛCDM model successfully explains a wealth of cosmological observations. However, it involves a hypothetical substance, “dark energy”, having unusual physical properties. According to interpretation of various data, there is a need for accelerated expansion in the recent history of the universe, and hence dark energy is required to dominate the energy budget of the universe.

So far the main cause of introduction of dark energy was the discrepancy between observations of distant type Ia supernovae [1,2] and Friedmann cosmological models with ordinary matter. Additional arguments include: tension between age estimates of globular clusters [3] and the age of the Universe, determined thanks to the measurement of the Hubble parameter [4–6] measurement of the baryon acoustic oscillations signature [7] providing the ratio of absolute distances in different cosmological epochs, and the inference from X-ray observation of massive galaxy clusters of the evolution of their number density [8], all consistent with recent accelerated expansion. Moreover, measurements of anisotropy spectrum of the cosmic microwave background [9,5] suggest that observed universe is nearly spatially flat, while accounting for matter usually gives about one third of the critical density [10], requiring additional unknown component.

Alternatives to dark energy, discussed in the literature, include modification of gravity, for review see e.g. [11], and back-reaction of density perturbations on the Friedmann background [12,13].

However, all these approaches do not take into account traces the strong gravitational waves of cosmological origin left in space. In the present paper we propose the point of view that such traces could in principle be a cause for the aforementioned discrepancy (if so there is no need to search for any enigmatic substance filling the universe). At present this idea represents only a “proof of principle” and cannot be considered as a realistic alternative to dark matter. The proof that this effect can indeed replace the concept of dark energy is left for the future work. The sources of the long-lived cosmological waves are the solitonic type inhomogeneities of the gravitational field near the Big Bang. In general the inhomogeneities are unavoidable near the initial cosmological singularity and some subset of them has the solitonic structure. Due to expansion of the universe these inhomogeneities decay but expel solitonic gravitational waves which also decay in course of propagation through the expanding space transferring, however, their energies to the Friedmann background deforming it and making the distances different compared with those which would be observed without such waves.[1] The gravitational solitons are most

[1] The phenomenon we describe here is due to the strong non-linear gravitational waves of cosmological origin, however, it is akin to the Zeldovich–Polnarev [14] memory effect produced by the weak linear gravitational waves generated by the colliding astrophysical objects.

* Corresponding author.
E-mail addresses: belinski@icra.it (V.A. Belinski), veresh@icra.it (G.V. Vereshchagin).

https://doi.org/10.1016/j.physletb.2018.01.051

important among all possible types of waves because such disturbances are more stable and survive longer time than others in the course of expansion. This effect has been described in the paper [15] by example of single-soliton cylindrical wave propagating on the Friedmann background where the background is supported by the matter in the form of massless scalar field φ. The particular kind of matter is of a little importance since constructed solutions contain only gravitational waves and matter field remains unperturbed, it serves only to support the background. In the case of flat model the background solution of the Einstein equations in cylindrical coordinates is:

$$-ds^2 = t(-dt^2 + dz^2 + z^2dx^2 + dy^2)\,, \varphi = (3/2)^{1/2}\ln t\,, \tag{1}$$

and exact solution [15] containing one gravitational soliton propagating on this background has the form:

$$\begin{aligned}-ds^2 =& f\,(t,z)\left(-dt^2 + dz^2\right) \\ &+ g_{11}\,(t,z)\,dx^2 + g_{22}\,(t,z)\,dy^2 + 2g_{12}\,(t,z)\,dxdy\,,\end{aligned} \tag{2}$$

with the same unperturbed scalar field φ as in (1). Here $\left(x^0, x^1, x^2, x^3\right) = (t, x, y, z)$ and metric has the following structure:

$$\begin{aligned}g_{11} =& \frac{t}{s^2t^2 + \left(t^2+\mu\right)^2} \\ &\times\left[s^2t^2z^2 + z^2\left(t^2+\mu\right)^2 + qz^2\left(t^2+\mu\right) - q^2\mu\right],\end{aligned} \tag{3}$$

$$g_{22} = \frac{t}{s^2t^2 + \left(t^2+\mu\right)^2}\left[s^2t^2 + \left(t^2+\mu\right)^2 - q\left(t^2+\mu\right)\right], \tag{4}$$

$$g_{12} = \frac{tqs\mu}{s^2t^2 + \left(t^2+\mu\right)^2}\,, \tag{5}$$

$$f = \frac{tl^2[s^2t^2 + \left(t^2+\mu\right)^2]}{s^2[l^2t^2 + \left(t^2+\mu\right)^2]} \tag{6}$$

In these formulas l and s are two arbitrary real constants and

$$q = s^2 - l^2\,. \tag{7}$$

The function μ (representing the pole trajectory in the inverse scattering method by which this solution was found) is:

$$\mu = -\frac{1}{2}\left(l^2 + t^2 + z^2\right) + \frac{1}{2}\left[\left(l^2 + t^2 + z^2\right)^2 - 4t^2z^2\right]^{1/2}, \tag{8}$$

It is easy to see that everywhere in space-time the square root in this expression is real and without loss of generality we can define it as positive. In the limit when parameter q tends to zero ($s^2 \to l^2$) the solution gives the background metric (1). It is this fact that permits to interpret the solution as an exact solitonic gravitational perturbation on the Friedmann background. It is convenient to characterize the solitonic field as exact deviation of the metric (2) from its background, which we designate by the upper index (0). For the g-components of the metric (2) this field is represented by the symmetric matrix H_{ab} $(a, b = 1, 2)$:

$$H_{11} = \left(g_{11} - g_{11}^{(0)}\right)\left(g_{11}^{(0)}\right)^{-1}, \tag{9}$$

$$H_{22} = \left(g_{22} - g_{22}^{(0)}\right)\left(g_{22}^{(0)}\right)^{-1}, \tag{10}$$

$$H_{12} = H_{21} = g_{12}\left(g_{11}^{(0)}g_{22}^{(0)}\right)^{-1/2}, \tag{11}$$

and in the same way can be defined the perturbation F for the f-component of the metric (2):

$$F = \left(f - f^{(0)}\right)\left(f^{(0)}\right)^{-1} \tag{12}$$

Then in case of the background (1) we have:

$$H_{11} = \frac{g_{11} - tz^2}{tz^2}, \quad H_{22} = \frac{g_{22} - t}{t}, \quad H_{12} = \frac{g_{12}}{tz}, \quad F = \frac{f - t}{t}. \tag{13}$$

The solution (3)–(8) contains no singularities other than the usual cosmological singularity already present in the background (1). The axis of cylindrical symmetry $z = 0$ is regular. All fields and its derivatives on the axis take some finite values. The solitonic excitations at the initial time $t = 0$ are concentrated around the axis $z = 0$ with the width $\delta z \sim l$ and disappear at infinity $z \to \infty$. Hence, observers at the initial stage of expansion located far enough from the axis see no difference from the usual Friedmann universe with metric (1). During expansion the disturbance H_{ab} around the axis vanish but produces a solitonic gravitational wave moving away from the axis to infinity, with amplitude decreasing in time. This wave propagates along light-like line (in two-dimensional section) $t = z$ inside the strip with the same width $\delta z \sim l$ as initial disturbances have (see Fig. 1). It turns out that for the same observers located far from the axis but at the final stages of the expansion, that is after the wave passed the region around them, the solution describes again the flat Friedmann model, however, with different measure for the time intervals and space distances in the longitudinal z-direction (measures of the distances in the transversal directions x and y do not change). From (8) it follows that at $t \to 0$ the function μ tends to zero as t^2 and in this limit for the metric coefficient f (6) we have $f = t$. In the limit $t \to \infty$ (and $t \gg z$) the function μ in the main approximation does not depend on time and at the late phases of expansion we have $f = tl^2s^{-2}$. Consequently, passing of a cosmological gravitational wave through the universe makes the scale factor in the measure of the longitudinal distances for the initial and final Friedmann backgrounds different because perturbation F of this factor makes the jump (see Fig. 1):

$$\lim_{t\to 0} F = 0\,, \quad \lim_{t\to\infty,\, t\gg z} F = \frac{l^2 - s^2}{s^2}\,. \tag{14}$$

This jump disappears if $l = s$ that is when the constant q defined in (7) vanish, but in such case, as we already mentioned, the solution (2)–(6) coincide identically with the background (1), that is the case $l = s$ means the absence of any waves in the course of evolution.

Now the reasonable question to ask is whether such longitudinal memory effect is only due the cylindrical symmetry and single-solitonic structure of the chosen solution but can be absent in the more general cases. Let's show that the same effect arises in the solutions containing double-solitonic waves and no matter under which symmetry, cylindrical or planar. These facts suggest a hint that the longitudinal memory effect is the general phenomenon of solitonic waves propagating on an isotropic homogeneous cosmological background. Some general consequences of this phenomenon we will discuss in the section "Summary".