

## Recent CMB Observations Enable to Find the Total Gravitational Energy of a Mass

Valev D.<sup>1</sup>

*Solar-Terrestrial Influences Institute, Bulgarian Academy of Sciences, Stara Zagora, Bulgaria,*

The astronomical observations indicate that the universe expands with acceleration and it has a finite particle horizon. The recent Cosmic Microwave Background (CMB) observations confirm the universe is homogeneous, isotropic and asymptotically flat. The total gravitational energy of an arbitrary body, having mass  $m$ , is the gravitational potential energy originating from the gravitational interaction of the body with all masses of the observable universe, i.e. within the particle horizon. The flat geometry of the universe enables to determine the total gravitational energy of the mass  $m$  within the framework of Newtonian gravity in Euclidean space. By this approach, it has been found the modulus of the total gravitational energy of a mass  $m$  is close to its rest energy  $E=mc^2$ . Therefore, the total energy of an arbitrary mass  $m$ , including its total gravitational energy, is close to zero, which is a substantial result. Besides, the smoothed gravitational potential in an arbitrary point of the observable universe appears close to  $-c^2$ , where  $c$  is the speed of the light.

### Introduction

In Big Bang cosmology, the observable universe consists of the galaxies and other matter that we can in principle observe from Earth in the present day, because light (or other signals) from those objects has had time to reach us since the beginning of the cosmological expansion. The total gravitational energy of a body having mass  $m$  is the gravitational potential energy of the mass  $m$ , originating from the gravitational interaction of the body with all masses in the observable universe. This quantity obtains limited value if the particle horizon of the universe is finite. Besides, to determine the total gravitational energy of a mass  $m$ , the geometry and density of the universe need to be known.

The problem for the total average density of the universe  $\bar{\rho}$  acquires significance when it has been shown that the General Relativity allows to reveal the large-scale structure and evolution of the universe by simple cosmological models [1-3]. Crucial for the geometry of the universe appears dimensionless total density  $\Omega = \bar{\rho} / \rho_c$ , where  $\rho_c$  is the critical density of the universe. The most trustworthy total matter density  $\Omega$  has been determined by measurements of the dependence of the anisotropy of the Cosmic Microwave Background (CMB) upon the angular scale. The recent results show that  $\Omega \approx 1 \pm \Delta\Omega$ , where the error  $\Delta\Omega$  decreases from 0.10 [4, 5] to 0.02 [6]. The fact that  $\Omega$  is so close to a unit is not accidental since only at  $\Omega = 1$  the geometry of the universe is flat (Euclidean) and the flat universe was predicted from the inflationary theory [7]. The total density  $\Omega$  includes densities of baryon matter  $\Omega_b \approx 0.05$ , cold dark matter  $\Omega_c \approx 0.25$  [8] and dark energy  $\Omega_\Lambda \approx 0.70$  producing an accelerating expansion of the universe [9, 10].

The found negligible CMB anisotropy  $\frac{\delta T}{T} \sim 10^{-5}$  indicates that the early universe was very homogeneous and isotropic [11]. Three-dimensional maps of the distribution of galaxies corroborate homogeneous and isotropic universe on large scales greater than 100 Mps [12, 13]. In the present paper, the results of recent CMB observations are used to determine the total gravitational energy of a body having mass  $m$  placed in an arbitrary location, far away from strong local gravitational fields. Such fields appear close to neutron stars, black holes, nuclei of galaxies and quasars.

### Determination of the total gravitational energy of an arbitrary mass

Finite Hubble time  $H^{-1} \sim 1.4 \times 10^{10}$  years (age of the universe) and finite speed of light  $c$  set a finite particle horizon  $R$  beyond which no material signals reaches the observer. Therefore, the possible matter beyond the particle horizon does not affect the observer. As a result, a body having mass  $m$  interacts gravitationally with all masses  $m_i$  at distances  $r_i \leq R$ , where  $R \sim c/H$  is the Hubble distance and  $H = H_0 h \approx 70 \text{ km.s}^{-1} \text{ Mpc}^{-1}$  is the Hubble constant [14]. All these masses form the observable universe. The total gravitational energy of a body having mass  $m$  is the finite gravitational energy of the mass  $m$ , originating from the gravitational interaction of the body with all masses within the particle horizon.

The customary approach used for such cosmological problems is in the framework of the General Relativity, since at cosmological distances the space curvature should be taken into considerations. But, on account of the total density  $\Omega = 1$ , the global geometry of the universe appears flat and the space curvature is zero. This enables to apply Newtonian gravity in Euclidean space for solution of this cosmological problem.

Thus, the problem of the total gravitational energy of a mass  $m$  transforms into the classical problem of the gravitational potential in the centre of a homogeneous isotropic sphere having a finite radius  $R \sim c/H$  and density  $\bar{\rho} = \Omega \rho_c$ . Therefore, the total gravitational energy  $U$  of a mass  $m$  in the homogeneous and isotropic universe, far away from strong local gravitational fields, would be expressed by equation:

$$U = -Gm \sum_i \frac{m_i}{r_i} = -4\pi m G \bar{\rho} \int_0^R r dr = -2\pi m G \bar{\rho} R^2 \quad (1)$$

where 0 is an arbitrary location of an observer and  $R \sim c/H$  is his particle horizon, i.e. 'radius' of the observable universe. The integration of (1) is made in Euclidean 3-dimensional space.

Similar approach has been used in [15]. According the authors, Newtonian gravity is acceptable for the calculation of the total gravitational energy even in the case of  $\Omega \ll 1$ . Still more the applied approach would be adequate in the case of  $\Omega \approx 1$  [16].

The critical density of the universe  $\rho_c$  determines [17] from equation:

$$\rho_c = \frac{3H^2}{8\pi G} \quad (2)$$

where  $G$  is the gravitational constant.

In view of  $\bar{\rho} = \Omega\rho_c$  and (2), the equation (1) transforms into:

$$U = -\frac{3}{4}\Omega m R^2 H^2 \quad (3)$$

In consideration of  $R \sim c/H$ , we obtain:

$$U \approx -\frac{3}{4}\Omega mc^2 = -\frac{3}{4}mc^2 \quad (4)$$

The equation (4) shows that the modulus of the gravitational energy of a body, originating from the gravitational interaction of the body with all masses within the particle horizon, is approximately (with accuracy to a factor 3/4) equal to its rest energy  $E = mc^2$ . Thus, the rest energy of an arbitrary mass  $m$  is approximately balanced with its total gravitational energy. Therefore, the total energy of an arbitrary mass  $m$ , including its total gravitational energy, is close to zero, which is a substantial result.

The factor 3/4 in (4) most likely arises as a result of the use of approximation  $R \sim c/H$  in equation (3). This approximation is valid with accuracy to the coefficient  $k \sim 1$  depending on the specific cosmological model of the expansion, i.e.  $R = kc/H$ . Clearly, for  $k = \sqrt{4/3} \approx 1.155$  the equation (4) of the total gravitational energy of a mass  $m$  will be replaced from equation:

$$U = -\frac{3}{4}k^2\Omega mc^2 = -\Omega mc^2 = -mc^2 \quad (5)$$

According to the definition, the total gravitational energy  $U$  of the mass  $m$  is equal to the work, which does the gravity originating by all masses in the observable universe for a removal of the mass  $m$  from its current location to the infinity. Therefore, the rest energy  $E = mc^2 \sim -U$  of a mass  $m$  is close to the gravitational energy, which would be released if the mass were moved from the infinity to its current location.

The smoothed gravitational potential  $\varphi$  in an arbitrary point of the homogeneous and isotropic universe, far away from strong local gravitational fields, follows from (4):

$$\varphi = \frac{U}{m} \approx -\frac{3}{4}\Omega c^2 \sim -c^2 \quad (6)$$

The equation (6) shows that the smoothed gravitational potential in an arbitrary point of the observable universe appears close to  $-c^2$ , where  $c$  is the speed of the light. Since the observable universe appears equipotential 3-dimensional sphere, no additional (cosmological) gravitational force acts on the masses.

According (6), the smoothed gravitational potential  $\varphi$  in an arbitrary point of the homogeneous and isotropic universe depends linearly from the density of the universe  $\Omega$ . Clearly, only in a case of  $\Omega \sim 1$ , the smoothed gravitational potential is

$\varphi \sim -c^2$ . If the universe was consisted of baryonic matter only, than total density  $\Omega \approx 0.05$  and  $|\varphi| \ll c^2$ , but the high densities of the cold dark matter and dark energy increase the density to  $\Omega = 1$ . In result, the universe appears flat and the modulus of the gravitational energy of a body having mass  $m$  is close to its rest energy.

## Conclusions

The astronomical observations indicate that the accelerating universe has a finite particle horizon. The recent CMB observations confirm the universe is homogeneous and isotropic on large scales and the geometry is asymptotically flat. The flat geometry of the universe enables to determine the total gravitational energy of an arbitrary mass  $m$  within the framework of Newtonian gravity in Euclidean space. Thus, the problem of the total gravitational energy of a mass  $m$  transforms into the classical problem of the gravitational potential in the centre of a homogeneous isotropic sphere having a finite radius  $R \sim c/H$ .

By this approach, it has been found the modulus of the gravitational energy of a body, originating from the gravitational interaction of the body with all masses of the observable universe, is close to its rest energy  $E = mc^2$ . Thus, the rest energy of an arbitrary mass  $m$  is approximately balanced with its total gravitational energy. Therefore the total energy of an arbitrary mass  $m$ , including its total gravitational energy, is close to zero, which is a substantial result. Besides, the smoothed gravitational potential  $\varphi$  in an arbitrary point of the universe is close to  $-c^2$ . Finally, it has been shown that these evaluations are valid only in a case of  $\Omega \sim 1$ , i.e. in a flat universe.

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