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Cosmic Scalar Field

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We investigate the hypothesis that missing matter and energy in the Cosmos could be a scalar field, which it would compose about 95% of the matter of the Universe. We show that this hypothesis agrees quite well with the recent observations on type Ia supernovae.

Recent observations of the luminosity-redshift relation of Ia Supernovae suggest that distant galaxies are moving slower than predicted by Hubble's law, that is, the Universe seems to be in an accelerating stage of its evolution.[1] On the other hand, measurements of the Cosmic Microwave Background Radiation (CMBR) and the Mass Power Spectrum indicate that the Universe has a critical density $\Omega_0 = 1$. There must exist a kind of matter possessing a negative velocity dispersion $p/\rho = \omega < 0$[2] which would be responsible for accelerating the Universe. These observations suggest that the components of the Universe are matter and vacuum energy $\Omega_0 = \Omega_M + \Omega_V$, being $\Omega_M = \Omega_b + \Omega_\nu + \cdots \sim 0.05 + \Omega_{DM}$, where Ω_{DM} represents the dark matter part of the matter contributions which has a value $\Omega_{DM} \sim 0.35$. Models such as the quintessence (a scalar field rolling down a potential) imply $-1 < \omega < 0$ and the one using a cosmological constant, requiring $\omega = -1$, appea+r to be strong candidates to be the missing vacuum energy, because both of them satisfy an equation of state concerning an accelerated behavior of the Universe.[2] But we do not know what the composition of $\Omega_{DM} + \Omega_V \sim 0.95$ is, *i.e.*, the 95% of the whole matter in the Universe. In a previous work two of us have shown that the scalar field is a strong candidate to be the dark matter in spiral galaxies,[3] where the scalar potential arising for the explanation of rotation curves of galaxies is exponential.[4] In this letter we show that the hypothesis that the scalar field is the most of matter and vacuum energy of the Universe is consistent with Ia supernovae observations and then this would imply that the scalar field is the dominant matter in the Universe, determining its structure at a cosmological and galactic level.

Assuming the Universe is homogenous and isotropic, we use the FRW metric $ds^2 = -dt^2 + a^2(t)\left[dr^2(1-kr^2)^{-1} + r^2\left(d\theta^2 + \sin^2(\theta)d\phi^2\right)\right]$. The evolution equations for the Universe with a scalar field Φ and a scalar potential $V(\Phi)$ are

$$\ddot{\Phi} + 3\frac{\dot{a}}{a}\dot{\Phi} + \frac{dV}{d\Phi} = 0, \quad \left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{\kappa_o}{3}\left(\rho + \rho_\Phi\right) \tag{1}$$

where $\rho_\Phi = \frac{1}{2}\dot{\Phi}^2 + V(\Phi)$ is the density of the scalar field, ρ is the density of the baryons, plus neutrinos, plus radiation, etc, and $\kappa_o = 8\pi G$. We define a function $F(a)$ such that $V(\Phi(a)) = F(a)/a^6$. Then, if the scale factor is considered as the independent variable,

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it is possible to integrate the field equations up to quadratures and to find a first integral of the field equations (1). Thus, $\rho_\Phi = \frac{6}{a^6}\int da \frac{F}{a} + \frac{C}{a^6}$, being C an integration constant.[5]

In order to fit the data obtained from the Ia supernovae observations, we write the magnitude-redshift relation $m_B^{effective} = \check{M}_B + 5\log D_L(z;\Omega_i,\Omega_\Phi)$ with an equation of state $p_x = w_x\rho_x$ for the unknown energy, where $D_L = H_0 d_L$ is the "Hubble-constant-free" luminosity distance.[1] If we compare this luminosity distance with a theory defining a scalar field as the missing energy and matter, we obtain that $C = 0$ and $F(x) = V_o x^s$, with V_o and s constants. Moreover, a flat Universe dominated by a scalar field with the function $F(a) = V_0 a^s$ ($s = constant$) has a very important property: the scalar field potential $V(\Phi)$ is essentially exponential in the regions where the scalar energy density dominates, that is, $V(\Phi) = F(a)/a^6 \simeq V_0 \exp\left(-\sqrt{3(1+\omega_\Phi)\kappa_0}\Phi\right)$ where ω_Φ is the scalar equation of state.[3] Fitting the data of Ia supernovae[1] we found that $w_\Phi = -0.636 = constant$ and $V_o = 0.78\rho_c$ for $\rho_{0\Phi} \sim 0.95\rho_c$ being ρ_c the critical density ($\rho_c = 0.92\times 10^{-29} gcm^{-3}$) (see Fig.1).

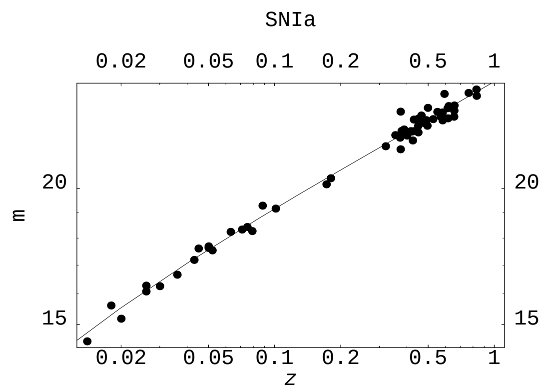

Figure 1: Fit of the solution obtained for the value $\omega_\Phi = -0.636$. The dots represent the observational results and the solid line means $m(z) = \check{M} + 5\log D_L$ for a scalar field dominated Universe.

We obtain that the deceleration parameter is $q_o = -0.45 = constant$, which really implies that the Universe is accelerating. For the density of the scalar field we obtain $\rho_\Phi = 0.95\rho_c a^{-1.09}$.[3] See[2] for a scalar field with equation of state $w = -2/3$ and Ω_Φ up to 0.8, where it is concluded that the scalar field fits CMBR and Mass Power Spectrum too. We can now speculate about the evolution of the Universe. A general integration of the conservation equation for a perfect fluid made of radiation (dust), indicates that the density scales as $\rho_r = \rho_{or}a^{-4}$ ($\rho_m = \rho_{om}a^{-3}$), with $\rho_{or} = 10^{-5}\rho_c$ ($\rho_{om} = 0.05\rho_c$). Recalling our result $\rho_\Phi = \rho_{o\Phi}a^{-1.09}$, the Universe was matter dominated until $a \sim 0.21$, the time of matter and scalar field equality (for this time the radiation energy density is negligible). This corresponds to a redshift $z = 3.7$. Since this time (approximately 14×10^9 yr. ago for this model), the scalar field began to dominate the expansion of the Universe and then the later entered in its actual acceleration phase. This is most of the history of the Universe, then we wonder if the scalar field is the responsible for the formation of structure too.[6] Some final remarks. The solution is singular, i.e., $a(t)$ vanishes at some finite time, *i.e.*, there was a big bang. Also, the solution has no particle horizon because $\omega_\Phi < -1/3$.[5] The question why nature uses spin 1 and spin 2 fundamental interactions over the simplest spin 0 interactions becomes clear with our result. In fact, Nature has preferred the spin 0 interaction over the other two, then scalar field interactions would determine the structure of the Universe.

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References

1. Perlmutter *et al.*, ApJ **483**, 565 (1997); Perlmutter *et al.* ApJ **517**, 565 (1999); A. G. Riess *et al.*, Astron. J. **116**, 1009-1038 (1998)
2. J. P. Ostriker and P.J. Steinhardt, *Nature* (London) **377**, 600 (1995); R. R. Caldwell, Rahul Dave and Paul J. Steinhardt, Phys. Rev. Lett. **80**, 1582-1585 (1998); Ivaylo Zlatev, Limin Wang and Paul J. Steinhardt, Phys. Rev. Lett. **82**, 896-899 (1999).
3. F. Siddhartha Guzmán and Tonatiuh Matos, Class. Quant. Grav. 17, L9-L16 (2000); Tonatiuh Matos, F. Siddhartha Guzmán and L. A. Ureña-López, available at astro-ph/9908152.
4. Dragan Hurterer and Michael S. Turner, astro-ph/9808133. Pedro G. Ferreira and Michael Joyce, Phys. Rev. D **58**, 023503 (1998); A. de la Macorra and G. Piccinelli, hep-ph/9909459; T. Barreiro, E.J. Copeland and N.J. Nuñes, astro-ph/9910214.
5. Luis P. Chimento, Alejandro S. Jakubi, Int. J. Mod. Phys. **D5**, 71 (1996).
6. Madau, P. *Physica Scripta*, (1999), in press.