The electromagnetic coupling and the dark side of the Universe

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Abstract

We examine the properties of dark energy and dark matter through the study of the variation of the electromagnetic coupling. For concreteness, we consider the unification model of dark energy and dark matter, the generalized Chaplygin gas model (GCG), characterized by the equation of state $p = -\frac{A}{\rho^\alpha}$, where p is the pressure, ρ is the energy density and A and α are positive constants. The coupling of electromagnetism with the GCG's scalar field can give rise to such a variation. We compare our results with experimental data, and find that the degeneracy on parameters α and A_s, $A_s \equiv A/\rho_{ch0}^{1+\alpha}$, is considerable.

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1. Introduction

It is well known that, if four-dimensional physics arises from higher-dimensional theories, then the presumably fundamental constants of the four-dimensional theory are actually time dependent. It is therefore particularly relevant to search for these variations and for possible correlations with striking features of the Universe evolution. Characterization of these correlations may, in turn, provide relevant hints on the nature of the main constituents of the Universe, namely dark matter and dark energy.

Evidence suggesting that, for instance, the proton–electron mass ratio has varied has been recently reported [1]. This arises from comparison of the absorption spectra of H_2 in the laboratory with that of two clouds of H_2 about 12×10^9 light years away. Furthermore, the observation of the spectra of quasars (QSOs) seems to indicate a time-dependent fine structure parameter [2–4]. Such observations lead to, for $0.2 < z < 3.7$ [2],

$$\frac{\Delta\alpha_{\text{em}}}{\alpha_{\text{em}}} = (-0.54 \pm 0.12) \times 10^{-5}, \tag{1}$$

at $4, 7\sigma$.

More recent observations suggest, however, that for $0.4 < z < 2.3$ [3,4],

$$\frac{\Delta\alpha_{\text{em}}}{\alpha_{\text{em}}} = (-0.06 \pm 0.06) \times 10^{-5}, \tag{2}$$

at 3σ.

The Oklo natural reactor also provides a bound on the variation of the electromagnetic coupling, at 95% CL, for $z = 0.14$ [5–7]

$$-0.9 \times 10^{-7} < \frac{\Delta\alpha_{\text{em}}}{\alpha_{\text{em}}} < 1.2 \times 10^{-7}. \tag{3}$$

Estimates of the age of iron meteorites, corresponding to $z = 0.45$, combined with a measurement of the Os/Re ratio resulting from the radioactive decay $^{187}\text{Re} \rightarrow {}^{187}\text{Os}$, yields [8,10,11]:

$$\frac{\Delta\alpha_{\text{em}}}{\alpha_{\text{em}}} = (-8 \pm 8) \times 10^{-7}, \tag{4}$$

at 1σ, and

$$-24 \times 10^{-7} < \frac{\Delta\alpha_{\text{em}}}{\alpha_{\text{em}}} < 8 \times 10^{-7}, \tag{5}$$

at 2σ.

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Observations of the hyperfine frequencies of the ^{133}Cs and ^{87}Rb atoms in their electronic ground state, using several laser cooled atomic fountain clocks, gives, at present ($z = 0$):

$$\left|\frac{\dot{\alpha}_{\text{em}}}{\alpha_{\text{em}}}\right| < 4.2 \times 10^{-15} \text{ yr}^{-1}, \tag{6}$$

where the dot represents differentiation with respect to cosmic time. Stricter bounds arise from the measurement of the $1s$–$2s$ transition of the atomic hydrogen and comparison with a previous measurement with respect to the ground state hyperfine splitting in ^{133}Cs and combination with the drift of an optical transition frequency in ^{199}Hg^{+}, which yields:

$$\frac{\dot{\alpha}_{\text{em}}}{\alpha_{\text{em}}} = (-0.9 \pm 4.2) \times 10^{-15} \text{ yr}^{-1}. \tag{7}$$

As already pointed out, a spacetime dependence on the fine structure parameter arises naturally in higher-dimensional fundamental theories, as shown in several theoretical investigations [12]. It is therefore relevant to deepen the experimental observations and search for realistic models that allow for such variation.

Recent observations clearly indicate that the Universe is undergoing a period of accelerated expansion [13], which suggests that it is dominated by a form of energy density with negative pressure usually referred to as dark energy. The most obvious candidate to explain this accelerated expansion is an uncanceled cosmological constant [14]. This is, of course, problematic as it involves a serious fine-tuning difficulty. Other possible explanations include quintessence-type models [15] with one [16] or two [17] scalar fields, k-essence [18] and exotic equations of state like in the case of the Chaplygin gas and its generalized version [19,20].

In this context, it is relevant to question whether these two observational facts are related. This issue has already been addressed in the context of quintessence models [21], $N = 4$ supergravity models [22], Dirac–Born–Infeld inspired models [23] and a Lorentz violating model to generate primordial magnetic fields [24].

Given that scalar fields are a common feature in most of the above mentioned approaches, one considers the coupling of such a scalar field to electromagnetism and hence a variation of the fine structure parameter, α_{em}, can arise [25]. The bounds expressed in Eqs. (1)–(5) allow one to place constraints on the coupling.

For sure, the Standard Model of particle physics does not fix the coupling between the scalar field and electromagnetism, hence it is relevant to analyze some realistic alternatives. In particular, we consider the generalized Chaplygin gas (GCG) since it is a promising possibility from the phenomenological point of view [26–32].

This Letter is organized as follows: In Section 2 we review the GCG model and study the coupling with electromagnetism. In Section 3 we use experimental data to constrain the model. We present our conclusions in Section 4.

2. Description of the Chaplygin gas model

The GCG model considers an exotic perfect fluid described by the equation of state [19]

$$p = -\frac{A}{\rho_{\text{ch}}^{\alpha}}, \tag{8}$$

where A is a positive constant and α is a constant in the range $0 \leqslant \alpha \leqslant 1$. The covariant conservation of the energy–momentum tensor for a homogeneous and isotropic spacetime implies that in terms of the scale factor, a:

$$\rho_{\text{ch}} = \left[A + \frac{B}{a^{3(1+\alpha)}}\right]^{\frac{1}{1+\alpha}}. \tag{9}$$

2.1. Real scalar field

Following Ref. [28], we describe the GCG through a real scalar field. We start with the Lagrangian density

$$\mathcal{L} = \frac{1}{2}\dot{\phi}^2 - V(\phi), \tag{10}$$

where the potential, for a flat Universe, has the form [28]

$$V = V_0 e^{3(\alpha-1)\phi}\left[\cosh^{\frac{2}{\alpha+1}}\left(\frac{m\phi}{2}\right) + \cosh^{-\frac{2\alpha}{\alpha+1}}\left(\frac{m\phi}{2}\right)\right], \tag{11}$$

where V_0 is a constant, the field ϕ is expressed in some suitable mass unit so that the arguments of the cosh function are dimensionless, and $m = 3(\alpha + 1)$.

For the energy density of the field we have

$$\rho_{\phi} = \frac{1}{2}\dot{\phi}^2 + V(\phi) = \left[A + \frac{B}{a^{3(1+\alpha)}}\right]^{\frac{1}{1+\alpha}} = \rho_{\text{ch}}. \tag{12}$$

Using Eq. (8), we can write the pressure as follows

$$p_{\phi} = \frac{1}{2}\dot{\phi}^2 - V(\phi) = -\frac{A}{\left[A + \frac{B}{a^{3(1+\alpha)}}\right]^{\frac{\alpha}{1+\alpha}}}, \tag{13}$$

and then

$$\dot{\phi}^2 = \frac{B}{a^{3(1+\alpha)}\left[A + \frac{B}{a^{3(1+\alpha)}}\right]^{\frac{\alpha}{1+\alpha}}}, \tag{14}$$

which, after integration, yields in terms of the redshift, once one assumes that at present, $a_0 = 1$:

$$\phi(z) = \frac{1}{3(1+\alpha)}\ln\left[\frac{\sqrt{\frac{A_s}{1-A_s}(1+z)^{-3(1+\alpha)} + 1} - 1}{\sqrt{\frac{A_s}{1-A_s}(1+z)^{-3(1+\alpha)} + 1} + 1}\right]. \tag{15}$$

It is easy to show that, at present

$$\phi_0 = \frac{1}{3(1+\alpha)}\ln\left(\frac{1 - \sqrt{1-A_s}}{1 + \sqrt{1-A_s}}\right). \tag{16}$$

2.2. Coupling with electromagnetism

We consider now the interaction between the scalar and the electromagnetic field following a proposal by Bekenstein [25]

$$\mathcal{L}_{em} = \frac{1}{16\pi} f(\phi) F_{\mu\nu} F^{\mu\nu}, \tag{17}$$

where f is an arbitrary function. Given that observational bounds indicate that the variation of the electromagnetic coupling is fairly small, we expand this function up to first order

$$f(\phi) = \frac{1}{\alpha_{em0}} \big[1 + \xi(\phi - \phi_0)\big], \tag{18}$$

where ξ is a constant. It follows that fine structure parameter, α_{em}, is given by

$$\alpha_{em} = \big[f(\phi)\big]^{-1} = \alpha_{em0} \big[1 - \xi(\phi - \phi_0)\big], \tag{19}$$

and hence, for its variation, we obtain

$$\frac{\Delta\alpha_{em}}{\alpha_{em}} = \xi(\phi - \phi_0). \tag{20}$$

The rate of variation of α at present is given by

$$\frac{\dot{\alpha}_{em}}{\alpha_{em}} = -\xi \frac{d\phi}{dy} H_0, \tag{21}$$

where $y \equiv 1 + z$ and $H_0 = 100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ is the Hubble constant.

We should take in account the equivalence principle experiments, which implies [9]

$$\xi \leqslant 7 \times 10^{-4}, \tag{22}$$

where ξ gives, at first order, the coupling between the scalar and electromagnetic fields.

3. Results

We choose the Hubble constant, $h = 0.71$, and adjust the coupling parameter, ξ, for different values of α and A_s in order to satisfy the bounds on the evolution of α_{em}.

Considering the set of parameters A_s and α, with $0.7 \leqslant A_s < 1$ and for $\xi \simeq 10^{-5}$, we find consistency with both meteorite and atomic clocks bounds. However, the model does not fit QSO and Oklo data with this set of parameters. We have to take $\xi \simeq 10^{-6}$ to obtain consistency with all bounds considered here. In this case, however, the degeneracy on both parameters, α and A_s, is considerable, that is, any values in the range $0 \leqslant \alpha \leqslant 1$ and $0 < A_s < 1$ are consistent with data. Figs. 1–4 summarize our results for $\xi = 10^{-6}$ and $A_s = 0.8$, for several values of α in the range $0 \leqslant \alpha \leqslant 1$.

4. Discussion and conclusions

In this work, we have investigated the implications of the coupling to electromagnetism of a scalar field model that describes in an unified fashion dark energy and dark matter, the GCG model. The experimental bounds provided for such variation, namely QSOs, Oklo's natural reactor, meteorite and
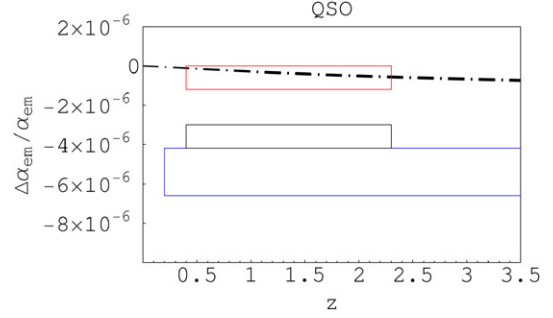

Fig. 1. Evolution of $\frac{\Delta\alpha_{em}}{\alpha_{em}}$ for $\xi = 10^{-6}$, $\alpha = 0, 0.2, 0.4, 0.6, 0.8, 1$ (top to bottom). The lines overlap because of the degeneracy on α (see Fig. 5). The box corresponds to QSO bounds of Refs. [3,4] and [2] (top to bottom).
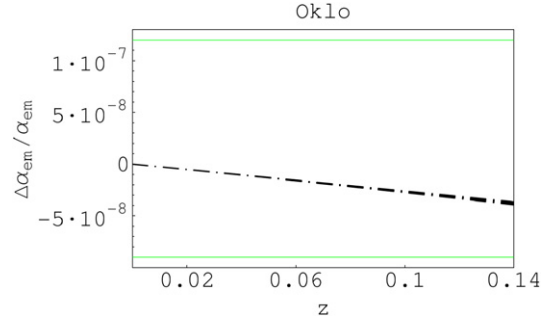

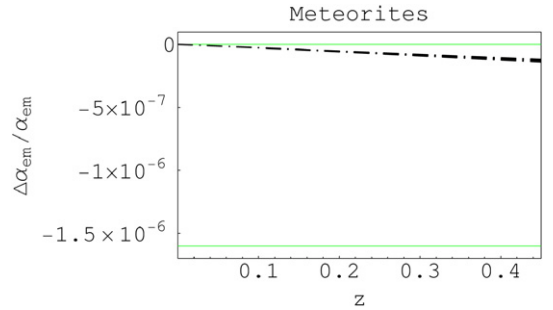Fig. 2. As for Fig. 1. The box and the redshifts correspond to Oklo bounds.

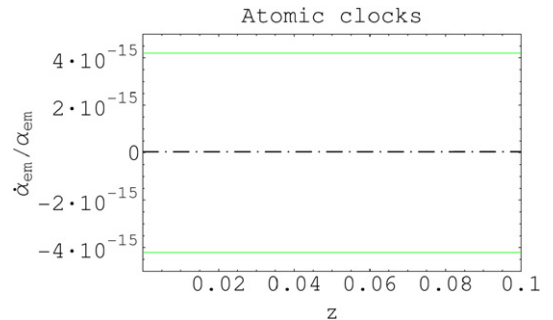Fig. 3. As for Fig. 1. The box and the redshifts correspond to Meteorites bounds.

Fig. 4. As for Fig. 1. The box and the redshifts correspond to the bounds provided by atomic clocks ($\alpha = 0, 0.2, 0.4, 0.6, 0.8, 1$; bottom to top).

atomic clocks, were used to constrain the model. We find that the model is consistent with QSO, Oklo, meteorite and atomic clocks bounds simultaneously for $\xi \simeq 10^{-6}$, for any value of the GCG's parameters α and A_s in the ranges $0 \leqslant \alpha \leqslant 1$ and $0 < A_s < 1$, respectively. Moreover, in order to be consis-
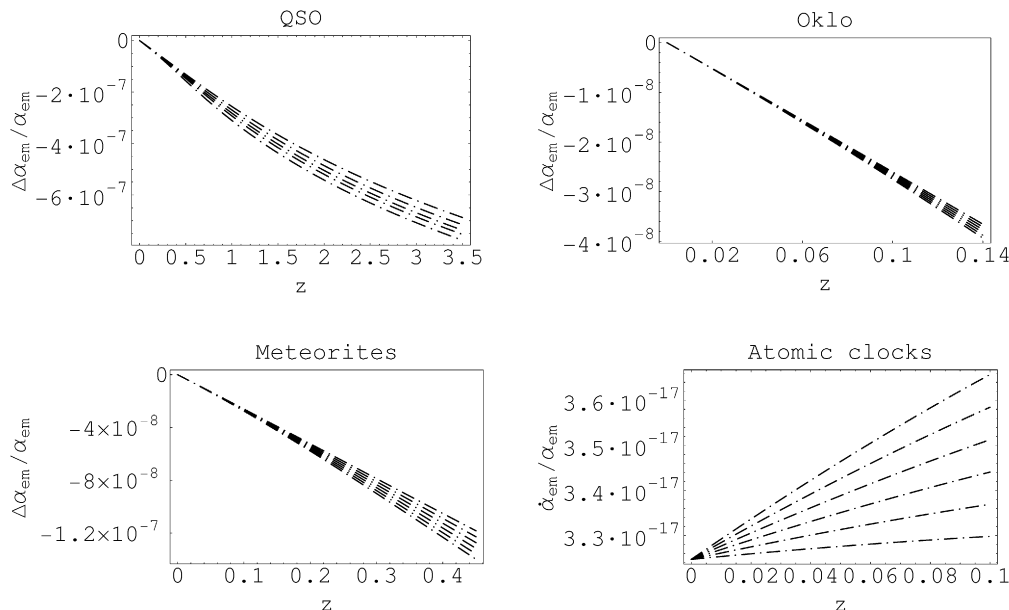
Fig. 5. As for Figs. 1–4, but without the experimental bounds.

tent with the data, ξ must be about three orders of magnitude smaller than the upper bound implied by the equivalence principle (cf. Eq. (22)). This small values for ξ indicate that the first order expansion (cf. Eq. (18)) is a quite good approximation, meaning that the functional form of function $f(\phi)$ does not affect our conclusions. As a final comment, it is interesting to point out that a coupling like the one of Eq. (17) can be used, in an inflationary set up, for generating primordial magnetic fields provided function $f(\phi)$ changes abruptly during the process [24]. This is, for instance, the case of the model discussed in Ref. [33], where $f(\phi)$ is an exponentially decaying function.

Acknowledgements

References

[1] E. Reinhold, et al., Phys. Rev. Lett. 96 (2006) 151101.
[2] M.T. Murphy, J.K. Webb, V.V. Flambaum, Mon. Not. R. Astron. Soc. 345 (2003) 609;
M.T. Murphy, J.K. Webb, V.V. Flambaum, S.J. Curran, Astrophys. Space Sci. 283 (2003) 577;
J.K. Webb, et al., Phys. Rev. Lett. 87 (2001) 091301;
M.T. Murphy, et al., Mon. Not. R. Astron. Soc. 327 (2001) 1208;
M.T. Murphy, J.K. Webb, V.V. Flambaum, J.X. Prochaska, A.M. Wolfe, Mon. Not. R. Astron. Soc. 327 (2001) 1237;
M.T. Murphy, J.K. Webb, V.V. Flambaum, M.J. Drinkwater, F. Combes, T. Wiklind, Mon. Not. R. Astron. Soc. 327 (2001) 1244;
J.K. Webb, et al., Phys. Rev. Lett. 82 (1999) 884.
[3] H. Chand, R. Srianand, P. Petitjean, B. Aracil, Astron. Astrophys. 417 (2004) 853.
[4] R. Srianand, H. Chand, P. Petitjean, B. Aracil, Phys. Rev. Lett. 92 (2004) 121302.
[5] T. Damour, F. Dyson, Nucl. Phys. B 480 (1996) 37.
[6] Y. Fujii, et al., Nucl. Phys. B 573 (2000) 377.
[7] Y. Fujii, Phys. Lett. B 573 (2003) 39.
[8] K.A. Olive, M. Pospelov, Y.Z. Qian, E. Vangioni-Flam, A. Coc, M. Casse, Phys. Rev. D 66 (2002) 045022.
[9] K.A. Olive, M. Pospelov, Phys. Rev. D 65 (2002) 085044.
[10] Y. Fujii, A. Iwamoto, Phys. Rev. Lett. 91 (2003) 261101.
[11] K.A. Olive, M. Pospelov, Y.Z. Qian, G. Manhes, E. Vangioni-Flam, A. Coc, M. Casse, Phys. Rev. D 69 (2004) 027701.
[12] See, e.g., E. Cremmer, J. Scherk, Nucl. Phys. B 118 (1977) 61;
A. Chodos, S. Detweiler, Phys. Rev. D 21 (1980) 2167;
W.J. Marciano, Phys. Rev. Lett. 52 (1984) 489;
T. Damour, A.M. Polyakov, Nucl. Phys. B 423 (1994) 532;
P. Loríen-Aguilar, E. García-Berro, J. Isern, Y.A. Kubyshin, Class. Quantum Grav. 20 (2003) 3885.
[13] S.J. Perlmutter, et al., Supernova Cosmology Project Collaboration, Astrophys. J. 483 (1997) 565;
S.J. Perlmutter, et al., Nature (London) 391 (1998) 51;
A.G. Riess, et al., Supernova Search Team Collaboration, Astron. J. 116 (1998) 1009;
P.M. Garnavich, et al., Astrophys. J. 509 (1998) 74.
[14] See, e.g., M.C. Bento, O. Bertolami, Gen. Relativ. Gravit. 31 (1999) 1461;
M.C. Bento, O. Bertolami, P.T. Silva, Phys. Lett. B 498 (2001) 62.
[15] For early work on the subject, see, e.g., M. Bronstein, Phys. Z. Sowjetunion 3 (1933) 73;
O. Bertolami, Nuovo Cimento B 93 (1986) 36;
O. Bertolami, Fortschr. Phys. B 34 (1986) 829;
M. Ozer, M.O. Taha, Nucl. Phys. B 287 (1987) 776;
B. Ratra, P.J.E. Peebles, Phys. Rev. D 37 (1988) 3406;
B. Ratra, P.J.E. Peebles, Astrophys. J. 325 (1988) L17;
C. Wetterich, Nucl. Phys. B 302 (1988) 668.
[16] R.R. Caldwell, R. Dave, P.J. Steinhardt, Phys. Rev. Lett. 80 (1998) 1582;
P.G. Ferreira, M. Joyce, Phys. Rev. D 58 (1998) 023503;
I. Zlatev, L. Wang, P.J. Steinhardt, Phys. Rev. Lett. 82 (1999) 896;
J.E. Kim, JHEP 9905 (1999) 022;
J.P. Uzan, Phys. Rev. D 59 (1999) 123510;
T. Chiba, Phys. Rev. D 60 (1999) 083508;
O. Bertolami, P.J. Martins, Phys. Rev. D 61 (2000) 064007;
A.A. Sen, S. Sen, S. Sethi, Phys. Rev. D 63 (2001) 107501;
A. Albrecht, C. Skordis, Phys. Rev. Lett. 84 (2000) 2076.
[17] A. Masiero, M. Pietroni, F. Rosati, Phys. Rev. D 61 (2000) 023504;
Y. Fujii, Phys. Rev. D 62 (2000) 044011;

M.C. Bento, O. Bertolami, N.M.C. Santos, Phys. Rev. D 65 (2002) 067301.

[18] C. Armendriz-Picon, V. Mukhanov, P.J. Steinhardt, Phys. Rev. Lett. 85 (2000) 4438.

[19] A. Kamenshcik, U. Moshella, V. Pasquier, Phys. Lett. B 511 (2001) 265;
M.C. Bento, O. Bertolami, A.A. Sen, Phys. Rev. B 235 (2002) 043507.

[20] N. Bilic, G.B. Tupper, R.D. Viollier, Phys. Lett. B 535 (2002) 17.

[21] S.M. Carroll, Phys. Rev. Lett. 81 (1998) 3067;
M.C. Bento, O. Bertolami, N.M.C. Santos, Phys. Rev. D 70 (2004) 107304;
P.P. Avelino, C.J.A.P. Martins, N.J. Nunes, K.A. Olive, Phys. Rev. D 74 (2006) 083508.

[22] O. Bertolami, R. Lehnert, R. Potting, A. Ribeiro, Phys. Rev. D 69 (2004) 083513.

[23] R.G. Mohammad, M. Sami, S. Tsujikawa, Phys. Rev. D 71 (2005) 083005.

[24] O. Bertolami, R. Monteiro, Phys. Rev. D 71 (2005) 123525.

[25] J.D. Bekenstein, Phys. Rev. D 25 (1982) 1527.

[26] M.C. Bento, O. Bertolami, A.A. Sen, Phys. Rev. D 67 (2003) 063003;
M.C. Bento, O. Bertolami, A.A. Sen, Phys. Lett. B 575 (2003) 172;
M.C. Bento, O. Bertolami, A.A. Sen, Gen. Relativ. Gravit. 35 (2003) 2063.

[27] P.T. Silva, O. Bertolami, Astrophys. J. 599 (2003) 828.

[28] O. Bertolami, A.A. Sen, S. Sen, P.T. Silva, Mon. Not. R. Astron. Soc. 353 (2004) 329.

[29] M.C. Bento, O. Bertolami, A.A. Sen, Phys. Rev. D 70 (2004) 083519.

[30] M.C. Bento, O. Bertolami, N.M.C. Santos, A.A. Sen, Phys. Rev. D 71 (2005) 063501.

[31] M.C. Bento, O. Bertolami, M.J. Rebouças, P.T. Silva, Phys. Rev. D 73 (2006) 043504.

[32] O. Bertolami, P.T. Silva, Mon. Not. R. Astron. Soc. 365 (2006) 1149.

[33] B. Ratra, Astrophys. J. 391 (1992) L1.