Some remarks on the observational constraints on the self-interacting scalar field model for dark energy

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Abstract – We consider a cosmological model containing a dust fluid and self-interacting scalar field, with an exponential potential, the first component representing dark matter and the second dark energy. The model is tested against supernova type-Ia (Constitution and Gold sample) and the 2dFGRS matter power spectrum data. The results are crossed with the recent seven-year WMAP estimations for the dark-energy equation-of-state parameter \(\alpha\) using CMB, BAO and \(H(z)\). The final results indicate, at 1\(\sigma\) level, \(\alpha = -1.049^{+0.105}_{-0.154}\) when the Constitution sample is used, and \(\alpha = -1.050^{+0.132}_{-0.220}\) when the Gold sample is employed. The implications for a dark-energy component composed of phantom field is discussed.

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Observations indicate that the Universe today must be in a phase of accelerated expansion \([1-5]\). In order to explain the evidences for an accelerated Universe, keeping the traditional general relativity theory untouched, it is necessary a fluid with negative pressure, generally called dark energy, since it must not emit any kind of electromagnetic radiation. At the same time, dark energy must remain a smooth component of the cosmic budget, since it does not appear in the dynamics of local virialized systems, like galaxy and clusters of galaxies. This feature requires also a negative pressure.

Considering a fluid with an equation of state of the type \(p = \alpha \rho\), \(p\) being the pressure and \(\rho\) the density, the parameter \(\alpha\) must satisfy the condition \(\alpha < -1/3\) in order to drive the accelerated expansion of the Universe remaining at same time an unclustered component of the cosmic budget: dark energy must violate the strong energy condition.

There are some claims that the observational data favors negative values for \(\alpha\) such that the dominant energy condition \(p + \rho \geq 0\) (\(\alpha < -1\)) is also violated \([6]\). If this is the case, the Universe may evolve towards dominant future singularity, since the violation of the dominant energy condition may lead to the divergence of the curvature invariants in a future finite proper time. This is due to the fact that the violation of the dominant energy condition implies that the density of the fluid grows as the Universe expands —it is remarkable that the divergence in the density, and consequently in the curvature, happens in finite proper time and not asymptotically.

It is essential to verify the strength of the evidences for a violation of the dominant energy condition. A lot of work has been devoted to this question, see for example \([7]\) and references there in. The most simple representation of dark energy is through a fluid with an equation of state of the type \(p = \alpha \rho\), \(\alpha\) constant, with \(\alpha < -1/3\), the phantom case corresponding to \(\alpha < -1\). In what concerns the SN Ia test, that is all it is needed as far as the equation of state of the dark-energy component does not evolve with time. But, for the other tests, like those requiring perturbative analysis, the real nature of phantom field is crucial, that is, it is essential to know if the results are obtained considering the dark-energy component (and in special the phantom fluid) as a self-interacting scalar field or a scalar field with non-canonical kinetic term, etc. There are many works exploring different possibilities, see for example refs. \([8-10]\), to quote just the more recent ones. In some cases, a phantom phase can be represented in such a way that it can evolve towards a non-phantom configuration in the future \([11,12]\), leading to the avoidance of the future singularity. This possibility requires, of course, a non-constant \(\alpha\).

In what follows we will consider this simplest case where dark energy, at least at background level, must satisfy an equation of state of the type \(p = \alpha \rho\), \(\alpha\) being a constant. Hence, no evolution of the equation-of-state parameter \(\alpha\) with time will be allowed. Evidently, in such situation, the precise value of \(\alpha\) is very important in order to extrapolate...
the evolution of the Universe for the very distant future. For example, if \( \alpha < -5/3 \), there can appear instabilities in the perturbations in the very large-wavelength limit, inducing an avoidance of big rip due to violation of the homogeneity and isotropic conditions [13,14]. Moreover, \( \alpha = -1 \) represents the cosmological constant, and its crucial to understand to which extend it is a special value in the, otherwise, continuous parameter. In considering a constant equation of state for the dark-energy fluid, the question of the future singularity is not addressed.

In order to clarify the situation concerning the evidences for a phantom cosmology, at least in the framework considered here, we will concentrate initially on two observational tests: the matter power spectrum and the supernova type-Ia data. For the first case, we will consider the data from the 2dFGRS observational program [15]. For the second, we will use two samples of data: Gold sample [4] and the Constitution sample [16]. The aim is to compare the predictions for different samples. We will see that there are strong divergences on the parameter estimations using one sample or the other. Later on, we will combine the predictions here obtained with those estimations using one sample or the other. Later on, we will compare the predictions for different samples. We will see that there are strong divergences on the parameter estimations using one sample or the other. Later on, we will combine the predictions here obtained with those obtained from the seven-year WMAP observations [17], this for the particular case of a flat model with a constant obtained from the, otherwise, continuous parameter. In considering a

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With the two components described above, Einstein’s equations for a flat, isotropic and homogenous universe described by the Friedmann-Robertson-Walker metric, reduce to the following expression:

\[
H^2 = \Omega_{m0}a^{-3} + \Omega_x0a^{-3(1+\alpha)},
\]

where \( \Omega_{m0} = \Omega_{dm0} + \Omega_{b0} \) is the ratio of matter component to the critical density today, including dark matter (\( \Omega_{dm0} \)) and baryons (\( \Omega_{b0} \)), while \( \Omega_x0 \) is the dark-energy ratio to the critical density.

The SN Ia observational test constrains only the background relation, through the luminosity distance function. However, the matter power spectrum analysis depends strongly on the nature of the components. For example, a fluid or a scalar field representation leads to complete different results for the parameter estimations. The situation is more delicate when components with negative pressure are considered, as it is the case for dark energy: a fluid description leads to an imaginary sound velocity, being unstable at small scales, while a field description through self-interacting scalar field implies positive sound velocity at sub-horizon scales [20]. Since the observational data for the matter power spectrum concerns sub-horizon modes, the specific descriptions for dark energy and dark matter are fundamental to interpret the observational constraints.

To cope with the instability problem described above (which to some extend excludes the possibility of an ordinary fluid description for the dark-energy component), the dark-energy field will be described through a self-interacting scalar field. This is the simplest field description of a given component in cosmology. If it is a realistic description or a unique one (certainly, to some extent, it is not) is outside the aims of the present work: it would require, to answer this question, to know the origin of the dark-energy field, which is object of speculation, with no clear candidate. A comparison of the specific model with the observational data aids, of course, in shedding some light on this question.

In the absence of matter field, it is quite easy to reproduce the behaviour of a dark-energy field through a self-interacting scalar field. The Friedmann equation coupled to a self-interacting scalar field and the Klein-Gordon equation for the scalar field reads,

\[
3\left(\frac{a'}{a}\right)^2 = \frac{\phi'^2}{2} + V(\phi)a^2,
\]

\[
\phi'' + 3\frac{a'}{a}\phi' = -\epsilon\frac{dV(\phi)}{d\phi}a^2,
\]

where the primes mean derivative with respect to the conformal time \( \eta \) defined by the expression \( dt = a(\eta)d\eta \), and \( \epsilon = +1 \) is required to describe a “normal” dark-energy fluid, while for a phantom fluid \( \epsilon = -1 \): for a phantom field, the kinetic term must have the “wrong” sign. For a general equation of state \( p = \alpha \rho \), the scale factor behaves as \( a = a_0\eta^{2/(1+3\alpha)} \). This behaviour can be reproduced by a self-interacting scalar field with the form [13,14],

\[
V(\phi) = V_0 \epsilon^\pm \sqrt{3\epsilon(1+\alpha)}\phi,
\]

\[
\phi(\eta) = \pm 2\sqrt{3\epsilon(1+\alpha)}\ln\eta/
\]

\[
1 + 3\alpha,
\]

\[
V_0 \text{ being a constant. It is not a surprise the appearence of an exponential potential, see for example ref. [21]. An interesting analysis for a power law potential, implying a non-constant equation of state, has been performed in ref. [22].}

When matter is present, the potential (4) does not represent anymore exactly the dynamics of the dark-energy fluid. In fact, this representation is exact only in the asymptotic limit. When pressureless matter is present the potential that reproduces the coupled system dark energy/matter is more complicated, and it cannot be represented, apparently, in a closed form using elementary functions. However, the scalar field and the potential for this case can be implicitly expressed in terms of the scale
factor. The overall dynamics is accounted by the following expressions:

\[
\left( \frac{a'}{a} \right)^2 = \Omega_{m0}a^{-1} + \Omega_{x0}a^{-(1+3\alpha)}, \tag{5}
\]

\[
\Omega_x = \Omega_{x0}a^{-3(1+\alpha)} = \epsilon \phi'^2 / 2 + Va^2, \tag{6}
\]

\[
\phi' = \sqrt{38\Omega_0} \sqrt{\epsilon(1+\alpha)a^{-(1+3\alpha)/2}}, \tag{7}
\]

\[
V = \frac{3}{2}(1-\alpha)a^{-3(1+\alpha)}. \tag{7}
\]

The relation between the scalar field and its potential to the scale factor is obtained by imposing that

\[
\epsilon \phi'^2 / 2 + Va^2 = 8\pi G\rho_x = 8\pi G\rho_0a^{-(1+3\alpha)}, \tag{8}
\]

\[
\epsilon \phi'^2 - Va^2 = 8\pi G\rho_x = 8\pi G\alpha\rho_0a^{-(1+3\alpha)}. \tag{9}
\]

When \(\Omega_{m0} = 0\) these expressions can be re-inserted in the Einstein’s equation in order to have the explicit dependence of the potential in terms of the scalar field \(\phi\). The cosmological constant case is reproduced in the sense that the kinetic term becomes zero for \(\alpha = -1\), and we remain only with a constant potential term.

The supernova type-Ia analysis can be performed by using the moduli distance quantity defined by

\[
\mu = 5 \log_{10}(D_L/Mpc) + 25, \tag{10}
\]

where the luminosity distance \(D_L\) is given by

\[
D_L = (1+z) \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + (1-\Omega_m)(1+z')^{3(1+3\alpha)}}}, \tag{11}
\]

where \(z\) is the redshift. This expression is valid for a flat universe for which \(\Omega_m + \Omega_{x0} = 1\). We parametrize the Hubble parameter today writing \(H_0 = 100 h\) km/(Mpc s). The model contains three free parameters, \(\alpha, \Omega_{m0}\) and \(h\), while the baryonic component is fixed such that \(\Omega_0 = 0.04\). We will use, separately, the SN Ia Gold sample and the Constitution sample. The \(\chi^2\) statistics is defined by

\[
\chi^2_{SN} = \sum_{i=1}^{N_s} \frac{(\mu_i - \mu_i^0)^2}{\sigma_i^2}, \tag{12}
\]

where \(\mu_i^0\) is the observational data for the moduli distance for the \(i\)-th supernova, \(\mu_i\) the corresponding theoretical prediction, \(\sigma_i^2\) is the observational bar error including the dispersion velocity and \(N_s\) is the number of supernova data, which is 157 for the Gold sample and 397 for the Constitution sample. The probability distribution function (PDF) is obtained through the expression

\[
P(h, \Omega_{m0}, \alpha) = A e^{-\chi^2_{SN}/2}, \tag{13}
\]

where \(A\) is a normalization constant. In evaluating the probabilities, we use the total \(\chi^2\) which is statistically more relevant than the reduced \(\chi^2\) quantity (the \(\chi^2\) by degree of freedom). The PDF is three-dimensional. Two-dimensional and one-dimensional PDF can be obtained integrating in one or two variables.

Let us now turn to the perturbative analysis. We will use the Bardeen’s gauge-invariant formalism. For the case including pressureless matter and a self-interacting scalar field, the perturbed equations read (see [23]):

\[
\nabla^2 \Phi - 3H \Phi' - \left[ 3H^2 - \frac{\phi'^2}{2} \right] \Phi = 4\pi G a^2 \delta \rho + \epsilon \phi' / 2 \delta \phi' + V_\phi a^2 \delta \phi, \tag{14}
\]

\[
\Phi'' + 3H \Phi' + \left[ 2H'H + H^2 + \frac{\phi'^2}{2} \right] \Phi = 4\pi G a^2 \delta \rho + \epsilon \phi' / 2 \delta \phi' - V_\phi a^2 \delta \phi, \tag{15}
\]

\[
\delta \phi'' + 2H \delta \phi' - \nabla^2 \delta \phi + \epsilon V_{\phi\phi} a^2 \delta \phi = 4\phi' \Phi' - 2c \nu \phi \delta \phi. \tag{16}
\]

In these expressions, \(H = a'/a\), and the subscript \(\phi\) indicates derivative with respect to \(\phi\). Since the fluid represents matter, \(\delta p = 0\). The anisotropic pressure is made equal to zero in these equations.

It is convenient to use the scale factor \(a\) as the new variable. The perturbed equations and the background relations can be re-expressed in terms of this new variable. For the perturbed equations we find

\[
\Phi + \frac{3}{a} \frac{a''}{a^2} \Phi + \frac{2}{a^2} \frac{1}{a^2} + \epsilon \phi'^2 / 2a^2 \Phi = \frac{1}{2} \phi' \lambda - \frac{V_\phi}{2} a^2 \lambda, \tag{17}
\]

\[
\lambda + \frac{2}{a^2} \frac{a''}{a^2} \lambda + \left( \frac{k \nu}{a^2} \right)^2 + \epsilon V_{\phi\phi} a^2 \lambda = 4\phi' \Phi' - 2c \nu \phi \delta \phi, \tag{18}
\]

where \(\lambda = \delta \phi\) and the dots mean now derivative with respect to \(a\). We have the following definitions:

\[
a' = \sqrt{\Omega_{m0}a + \Omega_{x0}a^{1-3\alpha}}, \tag{19}
\]

\[
a'' = \frac{1}{2} [\Omega_{m0} + (1-3\alpha) \Omega_{x0}a^{-3\alpha}], \tag{20}
\]

\[
\phi' = \sqrt{3(1+\alpha) \Omega_{x0}a^{-3(1+3\alpha)/2}}, \tag{21}
\]

\[
V(a) = \frac{3}{2} \Omega_{x0}(1-\alpha)a^{-3(1+\alpha)}, \tag{22}
\]

\[
V_\phi(a) = -\frac{3}{2}(1-\alpha) \sqrt{3\Omega_{m0}(1+\alpha)a^{-(7+3\alpha)/2}a'}, \tag{23}
\]

\[
V_{\phi\phi}(a) = a' \frac{d}{da} V_\phi(a), \tag{24}
\]

where the subscript \(\phi\) means derivative with respect to the scalar field. Moreover, \(k\) is the wave number of the perturbation coming from the Fourier decomposition with \(l_0 = 3.000 \cdot h\) Mpc is the Hubble radius today.

We will perform a numerical integration of eqs. (17), (18). The initial conditions are fixed employing the BBKS transfer function, and supposing a Harrison-Zeldovich
primordial spectrum [24–26]. The implementation of the initial conditions is described in ref. [27]. We will compute the matter power spectrum, defined as

$$P_k = |\delta_k|^2,$$  \hspace{1cm} (25)

$\delta_k$ being the Fourier component of the density contrast. As in the preceding SN case, we can evaluate the $\chi^2$ parameter that gives the quality of the fitting of the observational data by the theoretical model:

$$\chi^2_{PS} = \sum_{i=1}^{N_{\text{obs}}} \frac{(P_{k_i}^{\text{th}} - P_{k_i}^{\text{obs}})^2}{\sigma_i^2},$$  \hspace{1cm} (26)

where $k_i$ corresponds to the $i$-th Fourier mode, $P_{k_i}^{\text{th}}$ is the theoretical prediction for this mode, $P_{k_i}^{\text{obs}}$ is the corresponding observational data, $\sigma_i$ its observational uncertainty and $N_{\text{obs}}$ is the number of observational data for the power spectrum, which for the 2dFGRS sample is 39. The quantity $P_{k_i}^{\text{th}}$ is evaluated by integrating numerically eqs. (17), (18), with the initial conditions specified as described in ref. [27], obtaining finally the quantity (25). Since we use modes corresponding to the linear regime (scales larger than 10 Mpc), it is not necessary to use the full correlation matrix. Moreover, a constant prior will be used.

From the $\chi^2_{PS}$, we can define the probability density function (PDF) as

$$P(\Omega_{dm0}, \alpha) = A e^{-\chi^2_{PS}/2},$$  \hspace{1cm} (27)

where $A$ is a normalization factor. Again, the total $\chi^2_{PS}$ to evaluate the probability distribution will be used. It depends, as indicated, on two free parameters, the dark-matter fractional density $\Omega_{dm0}$ and on the equation-of-state parameter, $\alpha$. The baryonic density is fixed as before. Again, a constant prior will be used.

We will consider generally the range of $0 < \Omega_{dm0} < 0.95$ for the dark-matter parameter density. For, the equation-of-state parameter, the situation is more delicate, since the PDF for the Gold sample and the Constitution sample is relevant in different ranges, $-9 < \alpha < -0.35$ for the Gold sample and $-1.8 < \alpha < -0.5$ for the Constitution sample. In a matter of fact, for the Gold sample we should extend the lower extreme to very deep negative values, due to the existence of a plateau in the PDF curve. But, this is computationally unrealistic, so we stop the computation at $\alpha = -9$. The different ranges of value of $\alpha$ may be considered as a kind of “weak prior”, that may affect slightly not only the estimation of the parameter $\alpha$ itself, but also the estimation of $\Omega_{dm0}$. But, its final influence on the final results is very small, at least for the range of the parameters considered in this work. The restrictions in the range of the parameter $\alpha$ aid to understand the upper error bar in the estimations of $\Omega_{dm0}$ to be presented later.

The matter power spectrum analysis contains two free parameters, $\alpha$ and $\Omega_{dm0}$. Using a flat prior, these parameters are not tightly constrained using this test. This can be seen by inspecting fig. 1: the one-dimensional probability displayed in these figures seems to favor the extreme parameters, in these case, $\Omega_{dm0} \sim 0.95$, and $\alpha = -0.35$ when using the Gold sample and $-0.50$ when using the Constitution sample. Inspecting more carefully fig. 1, it can be verified that the difference between the maximum and minimum of the probability distribution, for both parameters, is of the order of 5%.

If the different supernova samples are now used, without crossing with any other test, and again with a flat prior, the results are quite surprising. The supernova test in our case contains three free parameters: the reduced Hubble parameter $h$, $\Omega_{dm0}$ and $\alpha$. The Gold sample predict that the value of $\alpha$ can extend to very high negative values and a higher value for the dark-matter density parameter $\Omega_{dm0}$ compared to the $\Lambda CDM$ model ($\Omega_{dm0} \sim 0.217$, see [17]). In fact, at 1σ level (68% confidence level), the prediction are the following: $\alpha = -2.292^{+0.989}_{-2.149}$, $\Omega_{dm0} = 0.486^{+0.037}_{-0.054}$ and $h = 0.659^{+0.014}_{-0.012}$. Using the Constitution sample we obtain $\alpha = -0.897^{+0.105}_{-0.274}$, $\Omega_{dm0} = 0.277^{+0.081}_{-0.109}$ and $h = 0.661^{+0.011}_{-0.021}$. This reveals a “tension” between the two samples. This is somewhat expected since each sample is obtained with specific methods of calibration. What is surprising here is the extension of this “tension”: the Gold sample favors phantom scenarios ($\alpha < -1$) while the Constitution sample favors a scenario around the cosmological constant ($\alpha = -1$), which includes a region corresponding to phantom scenarios. The corresponding one-dimensional PDF are shown in fig. 2. Crossing now the
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matter power spectrum and the supernova tests, we obtain essentially the same as in the pure supernova case, see fig. 3, this being due to the high degeneracy of parameter estimations using only matter power spectrum.

Recently, the seven-year analysis of the WMAP mapp has been released [17]. For the kind of model we considered in the present work, fiat space and constant $\alpha$, it is found $\alpha = -1.10 \pm 0.14$ at $1\sigma$ level using CMB, BAO and $H_0$. A full comparison between our results and their results must be made with care due to the fact that our scalar model has very specific properties at perturbative level, and a full CMB analysis requires a perturbative computation. But, we can use the results of ref. [17] to obtain tighter constraints. In doing so, the result for this joint SN Ia, PS, CMB, BAO and $H_0$ leads to $\alpha = -1.050^{+0.132}_{-0.220}$ using the Gold sample and $\alpha = -1.049^{+0.105}_{-0.154}$. Hence, in any case, the results of ref. [17] are displaced in the direction of the phantom scenario using both SN Ia samples. The

![Figure 2](image2.png)

Fig. 2: (Colour on-line) The one-dimensional PDF using the SN Ia data of the Gold sample are shown in the top panels. The bottom panels display the corresponding one-dimensional PDF when the Constitution sample is used.

![Figure 3](image3.png)

Fig. 3: (Colour on-line) The one-dimensional PDF using the power spectrum and SN Ia data of the Gold sample are shown in the left panels. The right panels display the corresponding one-dimensional PDF when the Constitution sample is used.

![Figure 4](image4.png)

Fig. 4: (Colour on-line) The figures show the different estimations for the equation-of-state parameter $\alpha$, using the combination of SN Ia and matter power spectrum (dot-dashed line), the estimations from CMB, BAO and $H(z)$ (full line), and a combination of SN Ia, matter power spectrum, CMB, BAO and $H_0$ (dashed line). In the left figure, the Gold sample has been used, while in the right figure the Constitution sample has been considered.
different estimations for $\alpha$ using different tests are shown in fig. 4. All the results are summarized in table 1.

The analysis here is restricted to the case where the dark-energy component is described by a self-interacting scalar field leading to a constant equation of state. In this model, the evolution with a constant equation of state corresponds to a critical point in the phase space, but it is not the only possibility. Introducing perturbations, the effective equation of state changes, and that is why instabilities do not appear even when $\alpha$ is negative. This is convenient in order to perform the power spectrum analysis. The main message encoded in the results obtained here, concerning the self-interacting scalar field model for dark energy analysed in this work, seems to be the following: there are strong evidences for a phantom fluid with a very negative value for the equation-of-state parameter $\alpha$, mainly due to the SN Ia constraint, especially when using the Gold sample; otherwise, using only matter power spectrum, the only clear restriction is that $\alpha$ must be smaller than $\alpha \sim -1/3$. It is important to stress that no special prior has been used, in opposition with the analysis made, for example, in refs. [3,4]. If we particularize the value of the dark-energy component for that used in the prior of [3,4] we find essentially their results, with a peak in the probability distribution for $\alpha$ around $-1$. Introducing the results of the seven-year WMAP for CMB, BAO and $H_0$, the distribution is near the $\Lambda$CDM model, at least at $1\sigma$ level, covering the region corresponding to phantom scenarios. As a secondary product of the analysis, we remark the existence of a “tension” between observational data samples when only the SN Ia test is used, at least in what concerns the Gold sample and the Constitution sample.

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Table 1: Estimations of the cosmological parameters at $1\sigma$ level according to the different cosmological observational data.

| Parameter       | PS            | SN            | SN+PS         | SN+PS+CMB+BAO+$H_0$ |
|-----------------|---------------|---------------|---------------|---------------------|
| $\alpha$ (Constitution) | $-0.500^{+0.000}_{-1.382}$ | $-0.897^{+0.185}_{-0.274}$ | $-0.897^{+0.185}_{-0.274}$ | $-1.049^{+0.105}_{-0.154}$ |
| $\Omega_{dm0}$ (Constitution) | $0.932^{+0.018}_{-0.056}$ | $0.277^{+0.081}_{-0.109}$ | $0.276^{+0.081}_{-0.109}$ | - |
| $h$ (Constitution) | - | $0.661^{+0.011}_{-0.021}$ | - | - |
| $\alpha$ (Gold) | $-0.350^{+0.000}_{-1.192}$ | $-2.292^{+0.989}_{-2.148}$ | $-2.288^{+0.986}_{-2.213}$ | $-1.050^{+0.132}_{-0.220}$ |
| $\Omega_{dm0}$ (Gold) | $0.951^{+0.000}_{-0.041}$ | $0.486^{+0.037}_{-0.054}$ | $0.486^{+0.037}_{-0.054}$ | - |
| $h$ (Gold) | - | $0.659^{+0.016}_{-0.012}$ | - | - |

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