High-redshift objects and the generalized Chaplygin gas

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Motivated by recent developments in particle physics and cosmology, there has been growing interest in a unified description of dark matter and dark energy scenarios. In this paper we explore observational constraints from age estimates of high-z objects on cosmological models dominated by an exotic fluid with an equation of state $p=-A/\rho^{\alpha}$ (the so-called generalized Chaplygin gas) which has the interesting feature of interpolating between nonrelativistic matter and negative-pressure dark energy regimes. As a general result we find that, if the age estimates of these objects are correct, they impose very restrictive limits on some of these scenarios.

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I. INTRODUCTION

The question about the nature of the energy content of the Universe has always been a central topic in cosmology. In the last few years, however, this discussion has become even more critical due to a convergence of observational results that strongly support the idea of an accelerated universe dominated by cold dark matter (CDM) and an exotic fluid with a large negative pressure. Dark matter is inferred from galactic rotation curves which show a general behavior that is significantly different from that predicted by Newtonian mechanics. The most direct evidence for the dark energy component or ''quintessence'' came from distance measurements of type Ia supernovae (SNe Ia) which indicate that the expansion of the Universe is speeding up, not slowing down [1]. Another important piece of evidence arises from a discrepancy between the measurements of the cosmic microwave background (CMB) anisotropies which indicate $\Omega_{\rm total}=1.1\pm0.07$ [2] and clustering estimates providing $\Omega_m=0.3\pm01$ [3]. While the combination of these two latter results implies the existence of a smooth component of energy that contributes with $\simeq 2/3$ of the critical density, the SNe Ia results require this component to have a negative pressure, which leads to a repulsive gravity.

The main distinction between these two dominant forms of energy (or matter) existent in the Universe is manifested through their gravitational effects. Cold dark matter agglomerates at small scales whereas the dark energy seems to be a smooth component, a fact that is directly linked to the equation of state of both components. Recently, the idea of a unified description for the CDM and dark energy scenarios has received much attention [4–7]. For example, Wetterich [5] suggested that dark matter might consist of quintessence lumps, while Kasuya [6] showed that spintessencelike scenarios are generally unstable to formation of Q balls, which behave as pressureless matter. More recently, Padmanabhan and Choudhury [7] investigated this possibility via a string theory motivated tachyonic field.

Another interesting attempt of unification was suggested by Kamenshchik *et al.* [8] and developed by Bilić *et al.* [9]. It refers to an exotic fluid, the so-called Chaplygin gas, whose equation of state is given by [10]

$$p=-A/\rho^{\alpha}, \tag{1}$$

with $\alpha=1$ and A a positive constant. In actual fact, the above equation for $\alpha\neq 1$ constitutes a generalization of the original Chaplygin gas equation of state recently proposed in Ref. [10]. By inserting Eq. (1) into the energy conservation law we find the following expression for the density of this generalized Chaplygin gas:

$$\rho_{Cg}=\left[A+B\left(\frac{R_o}{R}\right)^{3(1+\alpha)}\right]^{1/(1+\alpha)}, \tag{2}$$

or, equivalently,

$$\rho_{Cg}=\rho_{Cg_o}\left[A_s+(1-A_s)\left(\frac{R_o}{R}\right)^{3(1+\alpha)}\right]^{1/(1+\alpha)}, \tag{3}$$

where the subscript o denotes present-day quantities, $R(t)$ is the cosmological scale factor, $B=\rho_{Cg_o}^{1+\alpha}-A$ is a constant, and $A_s=A/\rho_{Cg_o}^{1+\alpha}$ is a quantity related to the sound speed for the Chaplygin gas today. As can be seen from the above equations, the Chaplygin gas interpolates between nonrelativistic matter $[\rho_{Cg}(R\rightarrow 0)\simeq\sqrt{B}/R^3]$ and negative-pressure dark component regimes $[\rho_{Cg}(R\rightarrow\infty)\simeq\sqrt{A}]$.

From the theoretical viewpoint, an interesting connection between the Chaplygin gas equation of state and string theory has been identified [11,12] (see also [13] for a detailed review). As explained in these references, a Chaplygin gas-

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type equation of state is associated with the parametrization invariant Nambu-Goto d-brane action in a $d+2$ spacetime. In the light-cone parametrization, such an action reduces itself to the action of a Newtonian fluid which obeys Eq. (1) with $\alpha=1$ so that the Chaplygin gas corresponds effectively to a gas of d-branes in a $d+2$ spacetime. Moreover, the Chaplygin gas is the only gas known to admit supersymmetric generalization [13]. From the observational viewpoint, these cosmological scenarios have interesting features [14] which make them in agreement with the most recent observations of SNe Ia [15–17] the location of the CMB peaks [18], age estimates of globular clusters, as well as with the current gravitational lensing data [19] (see, however, [20]).

In this paper we discuss new observational constraints on Chaplygin gas cosmologies from age considerations due to the existence of three recently reported old high-redshift objects, namely, the LBDS 53W091, a 3.5-Gyr-old radio galaxy at $z=1.55$ [21], the LBDS 53W069, a 4.0-Gyr-old radio galaxy at $z=1.43$ [22], and a quasar, the APM 08279+5255 at $z=3.91$ whose age is estimated between 2 and 3 Gyr [23]. Two different cases will be studied: a flat scenario in which the generalized Chaplygin gas together with the observed baryonic content are responsible by the dynamics of the present-day Universe (unifying dark matter-energy) (UDME) and a flat scenario driven by nonrelativistic matter plus the generalized Chaplygin gas (GCGCDM). For UDME scenarios we adopt in our computations $\Omega_b=0.04$, in accordance with the latest measurements of the Hubble parameter [24] and of the baryon density at nucleosynthesis [25]. For GCGCDM models we assume $\Omega_m=0.3$, as suggested by dynamical estimates on scales up to about $2h^{-1}$ Mpc [3]. For the sake of completeness an additional analysis for the conventional case ($\alpha=1$) is also included.

The plan of this paper is as follows. In Sec. II we present the most relevant formulas for our analysis, as well as the main assumptions for the age-redshift test. We then proceed to discuss the constraints provided by this test on the cosmological scenarios described above in Sec. III. We end this paper by summarizing the main results in the Conclusion section.

II. AGE-REDSHIFT TEST

The general Friedmann equation for the kind of model we are considering is

$$\left(\frac{\dot{R}}{R}\right)^2 = H_o^2\left\{\Omega_j\left(\frac{R_o}{R}\right)^3 + (1-\Omega_j)\left[A_s + (1-A_s)\times\left(\frac{R_o}{R}\right)^{3(\alpha+1)}\right]^{1/(\alpha+1)}\right\}, \tag{4}$$

where H_o is the present value of the Hubble parameter and Ω_j stands for the baryonic matter density parameter ($j=b$) in UDME scenarios and the baryonic + dark matter density parameter ($j=m$) in GCGCDM models.

The age-redshift relation as a function of the observable parameters is written as

$$t_z = \frac{1}{H_o}\int_0^{(1+z)^{-1}} \frac{dx}{x f(\Omega_j, A_s, \alpha, x)} = \frac{1}{H_o} g(\Omega_j, A_s, \alpha, z), \tag{5}$$

where x is a convenient integration variable and the dimensionless function $f(\Omega_j, A_s, \alpha, x)$ is given by

$$f(\Omega_j, A_s, \alpha, x) = \sqrt{\frac{\Omega_j}{x^3} + (1-\Omega_j)\left[A_s + \frac{(1-A_s)}{x^{3(\alpha+1)}}\right]^{1/(\alpha+1)}}. \tag{6}$$

The total expanding age of the Universe is obtained by taking $z=0$ in Eq. (5). As one may check, for $\alpha=1$ and $A_s=1$ Eq. (5) reduces to the CDM with a cosmological constant (ΛCDM) case while for $\alpha=1$ and $A_s=0$ the standard relation $[t_z=\frac{2}{3}H_o^{-1}(1+z)^{-3/2}]$ is recovered. A recent discussion about the globular cluster constraints on the total expanding age in the context of Chaplygin gas cosmologies can be found in [19].

In order to constrain the cosmological parameters from the age estimates of the above mentioned high-z objects we take for granted that the age of the Universe at a given redshift is bigger than or at least equal to the age of its oldest objects. In this case, the comparison of these two quantities implies a lower (upper) bound for A_s (α), since the predicted age of the universe increases (decreases) for larger values of this quantity (see Fig. 1). Note also that the age parameter $H_o t_o$ is almost insensitive to the parameter α but it depends strongly on variations of A_s. This means that age considerations will be much more efficient in constraining the sound speed A_s than the values of the parameter α.

To quantify the above considerations we follow [26] and introduce the expression

$$\frac{t_z}{t_g} = \frac{g(\Omega_j, A_s, \alpha, z)}{H_o t_g} \geqslant 1, \tag{7}$$

where t_g is the age of an arbitrary object, say, a galaxy or a quasar at a given redshift z, and $g(\Omega_j, A_s, \alpha, z)$ is the dimensionless factor defined in Eq. (5). For each extragalatic object, the denominator of the above equation defines a dimensionless age parameter $T_g=H_o t_g$. In particular, the 3.5-Gyr-old galaxy (53W091) at $z=1.55$ yields $T_g=3.5H_o$ Gyr which, for the most recent determinations of the Hubble parameter $H_o=72\pm8$ km s^{-1} Mpc^{-1} [24] takes values in the interval $0.229\leqslant T_g\leqslant 0.286$. It thus follows that $T_g\geqslant 0.229$. Therefore, for a given value of H_o, only models having an expanding age bigger than this value at $z=1.55$ will be compatible with the existence of this object. Naturally, similar considerations may also be applied to the 4.0-Gyr-old galaxy (53W069) at $z=1.43$ and to the 2-Gyr-old quasar (APM 08279+5255) at $z=3.91$. In this case, we obtain, respectively, $T_g\geqslant 0.261$ and $T_g\geqslant 0.131$. To assure the robustness of the limits, we have systematically adopted in our computations the minimal value of the Hubble parameter, i.e., $H_o=64$ km s^{-1} Mpc^{-1}, as well as the underestimated age of

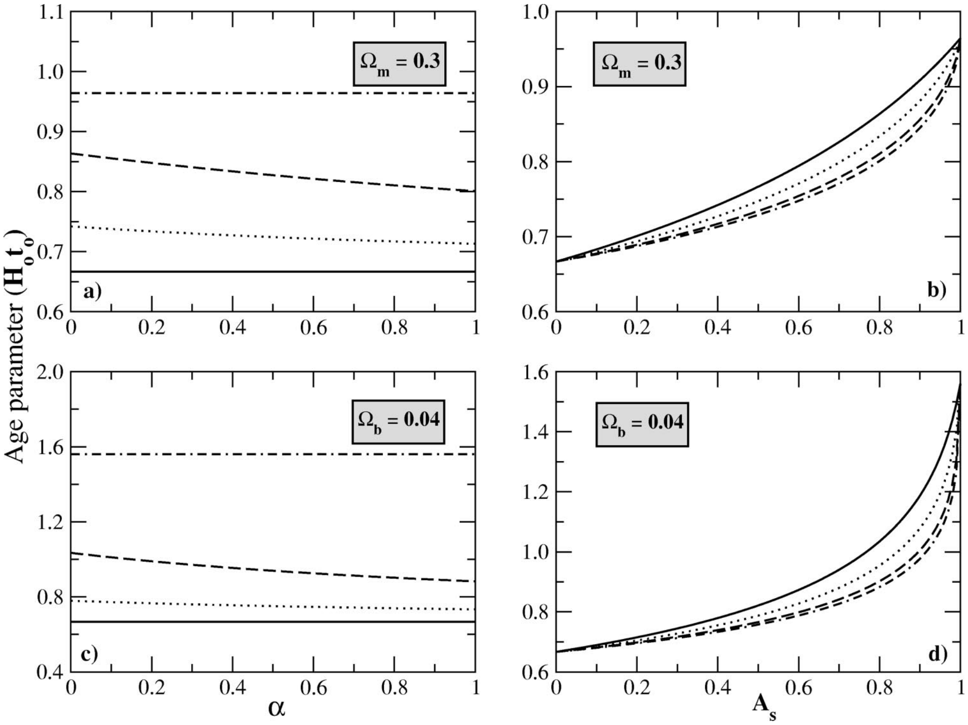

FIG. 1. Dimensionless age parameter as a function of α and A_s for UDME and GCGCDM scenarios. In order to have a bidimensional plot we have fixed some selected values of A_s in panels (a) and (c) and α in panels (b) and (d). From top to bottom the curves correspond to the following values of these parameters: 1.0, 0.8, 0.4, and 0.0.

the objects. In other words, this means that conservative bounds are always favored in the estimates presented here (see [24] for details).

III. DISCUSSION

Figures 2(a) and 2(b) show the parameter space A_s-α for a fixed value of the dimensionless age parameter $H_o t_z$ for UDME and GCGCDM scenarios, respectively. For a given object, each contour represents the minimal value of its age parameter at the corresponding redshift with the arrows indicating the available parameter space allowed by each object. As discussed earlier, the main constraints from this kind of cosmological test are on the value of the parameter A_s (see Fig. 1). Note also that the allowed range for this parameter is reasonably narrow. For example, for UDME scenarios the age-redshift relation for LBDS 53W091 and LBDS 53W069 require, respectively, $A_s \geqslant 0.52$ and $A_s \geqslant 0.58$, while the same analysis for GCGCDM models provides $A_s \geqslant 0.72$ and $A_s \geqslant 0.80$. As physically expected, the limits from age consid-

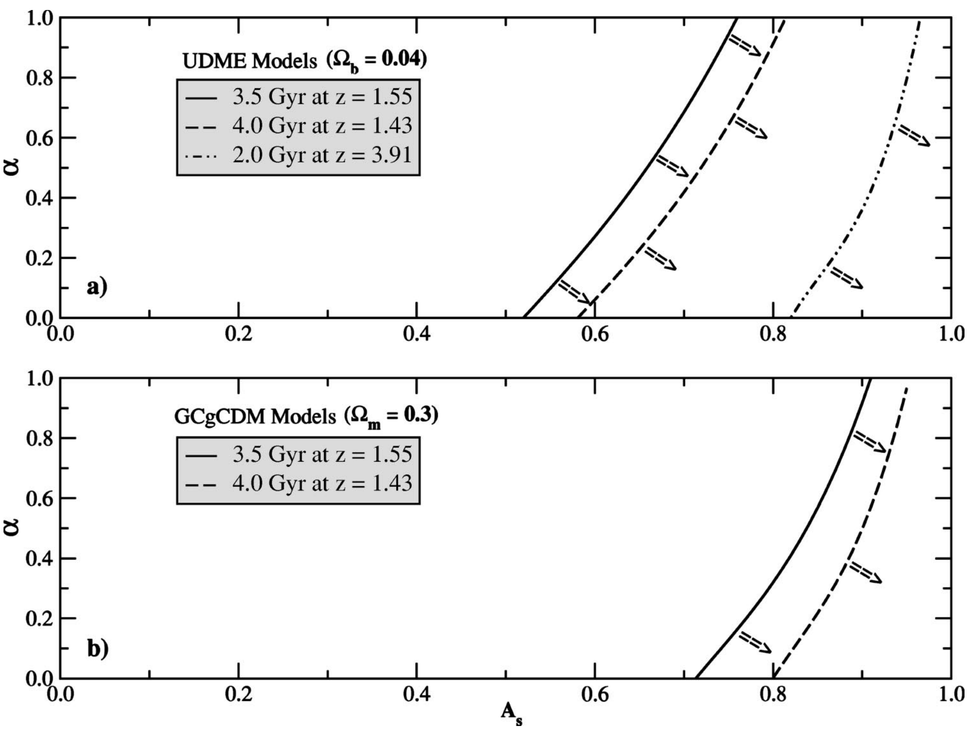

FIG. 2. (a) Contours of fixed age parameter $H_o t_z$ for the three high-z objects discussed in the text for UDME models. The contours are obtained for the minimal values of T_g. For each contour the arrows point to the allowed parameter space. (b) The same as in panel (a) for GCGCDM scenarios.

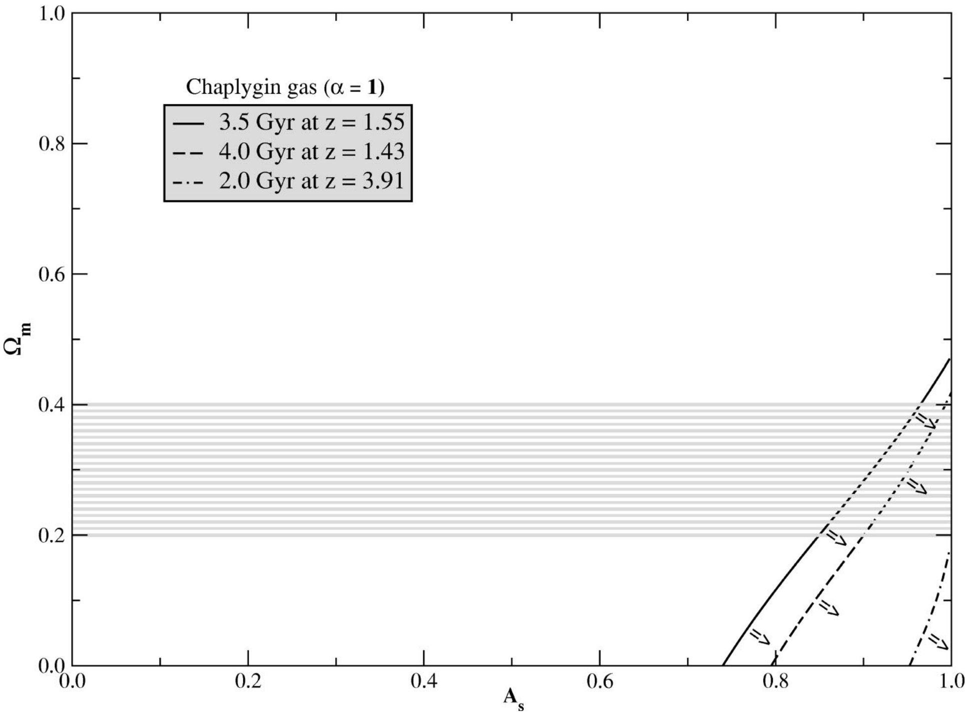

FIG. 3. A_s-Ω_m plane allowed by the age estimates of the high-z objects in the framework of Chaplygin gas cosmologies $(\alpha=1)$. The shadowed region corresponds to the observed interval of the matter density parameter $\Omega_m=0.3\pm0.1$ [3]. Arrows delimit the available parameter space. The curves are defined by the underestimated values of t_g and the observed lower limit of H_o.

erations are much more restrictive for GCGCDM models than for UDME scenarios. It happens because the larger the contribution of nonrelativistic matter (Ω_j) the smaller the predicted age of the Universe at a given redshift and, as a consequence, the larger the value of the parameter A_s that is required in order to fit the observational data. The most restrictive bounds on A_s are provided by the quasar APM 08279+5255 at $z=3.91$ whose age is estimated to be $\geqslant 2.0$ Gyr [23]. In this case, we find $A_s\geqslant 0.81$ for UDME models. Our analysis also reveals that GCGCDM scenarios with $\Omega_m=0.3$ are not compatible with the existence of this quasar once the predicted age of the universe at $z=3.91$ is smaller than the underestimated age for this object. The maximum age predicted by this model at this redshift is 1.7 Gyr $(H_o=64\ \mathrm{km\,s^{-1}\,Mpc^{-1}})$ for values of $\alpha=0$ and $A_s=1$ (the point of maximum age; see Fig. 1). By inverting the analysis, i.e., by fixing the values of α and A_s, it is also possible to infer the maximum allowed value of the matter density parameter in order to make GCGCDM models compatible with the existence of this particular object. For $\alpha=0$ and $A_s=1$, we find $\Omega_m\leqslant 0.21$. In other words, it means that if the age estimates for the quasar APM 08279+5255 are correct there is an "age crisis" in the context of GCGCDM models for values of the matter density parameter $\Omega_m\geqslant 0.21$. We still recall, in line with the arguments presented in [23], that recent x-ray observations show an Fe/O ratio for this object that is compatible with an age of 3 Gyr. In this case, GCGCDM models are compatible with the existence of such an object only for values of $\Omega_m<0.1$. The restrictive bounds imposed by the age estimates of the quasar APM 08279+5255 on ΛCDM models, on quintessence scenarios with an equation of state $p=\omega\rho$ $(-1\leqslant\omega<0)$, as well as on the first epoch of quasar formation can be found in [27].

In Fig. 3 we show the A_s-Ω_m diagram allowed by the age estimates of the above mentioned objects for the specific case in which $\alpha=1$ (Chaplygin gas cosmologies). As in Fig. 2, the arrows indicate the available parameter space allowed by each object. The shadowed horizontal region corresponds to the observed interval $\Omega_m=0.2$–0.4 [3] which now is used to fix the lower bounds to A_s. By considering this interval, LBDS 53W091 and LBDS 53W069 provide, respectively, $A_s\geqslant 0.85$, $A_s\geqslant 0.96$ and $A_s\geqslant 0.90$, $A_s\geqslant 0.99$. These values are even more restrictive than those obtained in the previous analyses because the predicted age of the Universe is smaller for larger values of α. Such limits also provide a minimal total age of the Universe of the order of 13 Gyr. Finally, as expected from previous analyses, the quasar APM 08279+5255 provides the most restrictive bounds on these cosmologies. In reality, its existence is not compatible with Chaplygin gas cosmologies $(\alpha=1)$ unless the matter density parameter is $\leqslant 0.17$. Such a result may be used to reinforce the idea of dark matter–energy unification if UDME models are not only compatible with the existence of these high-z objects (and, as a consequence, with general age consider-

TABLE I. Limits to A_s.

Object	UDME	GCGCDM
LBDS 53W091	$A_s\geqslant 0.52$	$A_s\geqslant 0.58$
LBDS 53W069	$A_s\geqslant 0.72$	$A_s\geqslant 0.80$
APM 08279+5255	$A_s\geqslant 0.81$	— [a]
	Chaplygin gas $(\alpha=1)$	
	$\Omega_m=0.2$	$\Omega_m=0.4$
LBDS 53W091	$A_s\geqslant 0.85$	$A_s\geqslant 0.96$
LBDS 53W069	$A_s\geqslant 0.90$	$A_s\geqslant 0.99$
APM 08279+5255	— [a]	— [a]

[a]The entire range is incompatible.

ations) but also provide the best fit for the SNe data [15]. The main results of the present paper are summarized in Table I.

IV. CONCLUSION

We have investigated new observational constraints from age estimates of high-z objects on generalized Chaplygin gas cosmologies. Two different cases have been analyzed, namely, UDME scenarios in which the dynamics of the present day Universe is completely determined by the generalized Chaplygin gas and the observed baryonic content ($\Omega_b=0.04$), and GCGCDM models in which the generalized Chaplygin gas plays the role of dark energy only and is responsible for the dynamics of the Universe together with the dark matter ($\Omega_m=0.3$). The former kind of cosmological scenario is inspired by the ideas of dark matter–energy unification while the latter follows the conventional ''quintessence'' program. By considering the age estimates of the radio galaxies LBDS 53W091 and LBDS 53W069 and of the quasar APM 08279+5255, we derived very restrictive constraints on the free parameters of these models (see Table I). In particular, we found that, similarly to models with a relic cosmological constant, there is no ''age of the Universe problem'' in the context of UDME scenarios while GCGCDM models are incompatible with the age estimates of the quasar APM 08279+5255 for values of $\Omega \geqslant 0.21$. This result may be understood as a backup to the idea of dark matter–energy unification if UDME models also provide the best fit for SNe Ia data [15]. However, we emphasize that only with new and more precise sets of observations will it be possible to show whether or not this class of models constitutes a viable possibility for unification of the dark matter and dark energy scenarios.

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