Constraining the cosmic equation of state from old galaxies at high redshift

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ABSTRACT

New limits on the cosmic equation of state are derived from age measurements of three recently reported old high redshift galaxies (OHRG). The results are based on a flat FRW type cosmological model driven by nonrelativistic matter plus a smooth component parametrized by its equation of state $p_x = \omega x \rho_x$ ($\omega \geq -1$). The range of $\omega$ is strongly dependent on the matter density parameter. For $\Omega_M \sim 0.3$, as indicated from dynamical measurements, the age estimates of the OHRG restricts the cosmic parameter to $\omega \leq -0.27$. However, if $\Omega_M$ is the one suggested by some studies of field galaxies, i.e., $\Omega_M \sim 0.5$, only a cosmological constant ($\omega = -1$) may be compatible with these data.

Key words: Cosmology: theory - dark matter - distance scale

Recent distance measurements of some Type Ia supernovae at intermediary and high redshifts indicate that the expansion of the Universe is speeding up, rather than slowing down (Riess et al. 1998; Perlmutter et al. 1999a). Indirectly, these results also mean that the Universe is much older than the one predicted by the standard CDM flat model with a critical deceleration parameter ($q_0 = 0.5$). If confirmed from more accurate observations and/or a different class of phenomena, the existence of these data poses a crucial problem for all CDM models since their generic prediction is a decelerating universe ($q_0 > 0$), whatever the sign adopted for the curvature parameter.

Another source of difficulties for the standard CDM model is related to the “age problem” or its modern variant, the age of old high redshift objects. It should be recalled that some measurements of the Hubble parameter yielded $h = H_0/100 \text{km/sec/Mpc} = 0.7 \pm 0.1$ (Nevalainen & Roos 1998, Friedmann 1998). In particular, this means that the expansion age for a FRW flat manner dominated universe ($t_0 = \frac{3}{2}H_0^{-1}$) falls within the interval $8.3\text{Gyr} \leq t_0 \leq 10.5\text{Gyr}$, while the age inferred from globular clusters lies typically into the range $t_{gc} \sim 13 – 15\text{Gyr}$ or higher (Bolton & Hogan 1995; Pont et al. 1998). As widely known, this conflict is not alliviated if SNe data are considered. In the age analysis of Perlmutter et al. (1998), the favored value is $h = 0.63$, while Riess et al. (1998) found $h = 0.65 \pm 0.02$, from their SNe data.

Age measurements of extragalactic objects at high redshifts also provide an alternative route to the “age problem”. In this case, the discoveries of a 4.0 – Gyr-old galaxy at $z = 1.175$ (Stockton et al. 1995), of a 3.5 – Gyr-old galaxy at $z = 1.55$ (Dunlop et al. 1996; Spinrard et al. 1997), and of a 4.0 – Gyr-old galaxy at $z = 1.43$ (Dunlop 1998) have been even proved to be incompatible with age estimates for a flat Universe unless the Hubble parameter is very low. These constraints are even more stringent than the ones from globular cluster age measurements (Dunlop 1996, Krauss 1997, Roos & Harun-or-Raschid 1998). More recently, it was shown that the existence of the two OHRG discovered by Dunlop would be accommodated in a model with no cosmological constant only if $\Omega_M \leq 0.37$ (Alcaniz and Lima 1999).

In the last few years, flat models with a relic cosmological constant ($\Lambda$CDM) have also been considered as a serious candidate for standard cosmology (Krauss & Turner 1995; Krauss 1997). However, although fitting some observations better than other theoretical models (e.g., the first acoustic peak of the relic radiation angular power spectrum), $\Lambda$CDM cosmologies are reasonably restricted by the statistics of gravitational lenses (SGL) (Kochanek 1996, Falco et al. 1998, Waga and Micieli 1999). On the other hand, though the method based on OHRG have given a lower limit of $\Omega_{\Lambda} \geq 0.5$ (Alcaniz and Lima 1999), from a theoretical viewpoint, these models are plagued by a profound contradiction: in order to dominate the dynamics of the Universe only at recent times, a very small value for the cosmological constant ($\Lambda_0 \sim 10^{-56}\text{cm}^{-2}$) is required from observations, while naive estimates based on quantum field theories are 50-120 orders of magnitude larger, thereby originating an extreme fine tuning problem (Weinberg 1989, Sahni and Starobinsky 1999).

Cosmologies containing an extra component describing
the dark matter, and simultaneously accounting for the present accelerated stage of the universe have also been widely discussed in the literature. Indeed, the absence of a convincing evidence on the nature of the dark component has stimulated the debate and theoretical speculations. Some possible candidates are: a time varying A-term (Ozer & Taha 1986, 1987; Freese et al. 1987; Carvalho et al. 1992; Waga 1993; Lima and Maia 1994; Lima and Trodden 1996; Lima 1996; Silveira and Waga 1997), a relic scalar field (Peebles 1984; Ratra and Peebles 1988; Caldwell et al. 1998; Maia and Lima 1999; Lima et al. 2000). Sometimes, the extra component is named “X-matter”, or “quintessence”, which is simply characterized by an arbitrary equation of state $p_x = \omega p_x$, where $\omega \geq -1$ (Turner and White 1997; Chiba et al. 1997; Efstathiou 1999; Lima and Alcaniz 2000). In this case, constraints from large scale structure (LSS) and cosmic microwave background anisotropies (CMB) complemented by the SN Ia data, require $0.6 \leq \Omega_x \leq 0.7$ and $\omega < -0.6$ (95% C.L.) for a flat universe (Perlmutter et al. 1999b; Efstathiou 1999), while for universes with arbitrary spatial curvature the limit is $\omega < -0.4$ (Efstathiou 1999).

In the present work, we focus our attention to this kind of “quintessence” or “X-matter” cosmology. As a matter of fact, due to their generality these models merit a broader discussion. In principle, to check the validity of a theory or model (for instance, the $\Lambda$CDM model), it is interesting to insert it in a more general framework, herein quantified or modelled. As one may check from (1) and (2), the case $\omega = -1$ is special. Let us now introduce the dimensionless ratio

$$f(\Omega_M, \omega, z) = \frac{t(z)}{H_o t_g} \geq 1 ,$$

where $t_g$ is the age of an arbitrary object, and $f(\Omega_M, \omega, z)$ is the dimensionless integral factor appearing in the expression for $t(z)$. For each extragalactic object, this inequality defines a dimensionless parameter $T_g = H_o t_g$. In particular, for the LBDS 53W091 radio galaxy discovered by Dunlop et al. (1996), the lower limit to the age of this galaxy yields $T_G(1.55) = 3.5H_o\text{Gyr}$, which take values on the interval $0.21 \leq T_G \leq 0.28$. The extreme values of $T_G$ have been determined by the error bar of $h$. It thus follows that $T_G \geq 0.21$, and from (2) we see that at this $z$ the matter dominated flat FRW model furnishes an age parameter $T_F = 0.16$, which is far less than the previous value of $T_G$. Naturally, for a given value of $h$, only models having an expanding age parameter bigger than the corresponding value of $T_G$ at $z = 1.55$ will be compatible with the existence of this galaxy. The standard Einstein-de Sitter FRW model is (beyond doubt) ruled out by this test (Alcaniz and Lima 1999).

In order to assure the robustness of the limits, two conditions have systematically been adopted in our computations:

(i) The minimal value for the Hubble parameter. In this case, we use the one obtained by the HST Key project, i.e.,

$$t(z) = H_o^{-1} \int_0^{(1+z)^{-1}} \frac{dx}{x^{(1+\omega)} \Omega_M x^{-3} + \Omega_z x^{-3(1+\omega)}} = H_o^{-1} f(\Omega_M, \omega, z) ,$$

where the flat condition constraint, $\Omega_M = 1 - \Omega_z$, has been inserted.

Before proceed further, we call attention for an important point: for a fixed value of the density parameter $\Omega_M$, the age of the Universe predicted by this “quintessence” model decreases with the increasing of $\omega$. Hence, taking for granted that the age of the Universe in a given redshift is bigger than or at least equal to the age of its oldest objects, the existence of these OHNG yield rise to an upper bound for $\omega$. Let us now introduce the dimensionless ratio
the round number value $H_o = 60 \text{km/sec/Mpc}$ (Friedmann 1998).

ii) The underestimated age for all old high redshift galaxy.

The above conditions are almost self-explanatory when interpreted in the spirit of inequality (4). First, the smaller the value of $H_o$, the larger the age predicted by the model, and, second, objects with smaller ages are more easily accommodated, thereby guaranteeing that the model is always favored in the estimates presented here. Indeed, concerning the value of $h$, and specially its lower bound, we are being rather conservative since it was recently updated to nearly 10% of accuracy ($h = 0.71 \pm 0.07$, 1$\sigma$) by Friedman and collaborators (1999), and the data from SNe also point consistently to $h > 0.6$ or even higher (Perlmutter et al. 1998, Riess et al. 1998). On the other hand, we also recall that the best-fitting spectral synthesis models has indicated strong evidence for a minimum age of 4.0 Gyr for the 3C 65 ($z = 1.175$) (Stockton et al. 1995), of 3.5 Gyr for the LBDS 53W091 ($z = 1.55$), and 4.0 Gyr for the LBDS 53W069 ($z = 1.43$) (Dunlop et al. 1996; Spinrad et al. 1997; Dunlop 1998; Dunlop 1999). Even taking into account the above conditions, the discrepancy between these observational values and the predictions of a flat matter dominated model is evident. For instance, if $h = 0.6$, the age predicted by this model for an object at $z = 1.175$ is $t_o \leq 3.35$ Gyr, while for an object at $z = 1.55$ is $t_o \leq 2.66$ Gyr. For a flat universe with cosmological constant ($\omega = -1$), these data may be fitted only if the vacuum energy contribution is $\Omega_{\Lambda} \geq 0.29$ and $\Omega_{\Lambda} \geq 0.42$, respectively. The situation is even worse if one considers the object at $z = 1.43$ with a minimal age of 4.0 Gyr (LBDS 53W069). In this case, the age predicted is $t_o \leq 2.85$ Gyr and the vacuum energy contribution should be $\Omega_{\Lambda} \geq 0.5$ (Alcaniz & Lima 1999).

In Fig. 1, we display the parameter space $\Omega_M - \omega$. For a given OHRG, each contour represent the minimal value of its age parameter ($T_o = H_o t_o$) in the respective redshift. If this parameter is greater, the curves are displaced as suggested by the arrows in the picture, that is, for the inner region of each contour. Thus, if $T_o$ increases the available parameter space is diminished, or equivalently, for a given redshift $z$, older galaxies require smaller values of the pair $(\Omega_M, \omega)$. The shaded horizontal region corresponds to the observed range $\Omega_m = 0.2 - 0.4$ (Dekel et al. 1996), which is used to fix the upper limit to the cosmic parameter. Note that the allowed range for $\omega$ is reasonably large. For example, if $\Omega_M \sim 0.3$, as suggested by dynamical estimates on scale up to about $2 h^{-1}$ Mpc (Calberg et al.1996; Bahcall &Fan 1998), the age-redshift relation for the LBDS 53W091 constrains $\omega$ to be $\leq -0.20$. If $\Omega_M$ is the one derived by some analyses of large-scale structure and field galaxies, i.e., $\Omega_M \sim 0.5$ (Tammann 1998), we find $\omega \leq -0.4$. For the radio galaxy 3C 65 at $z = 1.175$, the corresponding interval $\Omega_M = 0.3 - 0.5$ provides $\omega \leq -0.12$ and $\omega \leq -0.20$, respectively. The most restrictive upper bounds on $\omega$ comes from the radio galaxy LBDS 53W069. In this case, for $\Omega_M \sim 0.3$, we have $\omega \leq -0.27$ whereas for $\Omega_M \sim 0.5$, only a $\Lambda$CDM model ($\omega = -1$) is compatible with the minimal value of its age parameter $t_o$. In particular these results agree with the $1\sigma$ upper limit derived by Waga and Miceli (1999) using statistics of strong gravitational lenses (SGL) and high-z type Ia supernovae ($\omega < -0.7$), as well as with the $2\sigma$ upper limit obtained by Efstathiou (1999) and Perlmutter et. al (1999b) using high-z type Ia supernovae and cosmic microwave background anisotropies ($\omega < -0.6$). As one may see from Fig. 1, for $\omega = -1$ (cosmological constant) the results above mentioned are recovered (for more details see Alcaniz & Lima 1999).

At this point it is interesting to compare our results with some recent determinations of $\omega$ derived from independent methods. Recently, Garnavich et al. (1998) using the SNe Ia data from the High-Z Supernova Search Team (Riess et al. 1998) found $\omega < -0.55$ (95% C.L.) for flat models whatever the value of $\Omega_M$ whereas for arbitrary geometry they obtained $\omega < -0.6$ (95% C.L.). As commented there, these values are inconsistent with a unknown component like topological defects (domain walls, string, and textures) whose $\omega = -\frac{2}{n}$, being $n$ the dimension of the defect. The results by Garnavich et al. (1998) agree with the constraints obtained from a wide variety of different phenomena (Wang et al., 2000), using the “concordance cosmic” method. Their combined maximum likelihood analysis suggests $\omega \leq -0.6$, which is more stringent than the upper limits derived here, unless the density parameter is slightly larger than the observed range $(\Omega_M = 0.2 - 0.4)$. The main results of the present paper together with other determinations of $\omega$ are summarized in Table 1.

Finally, we stress that the new constraints on the “quintessence” parameter presented here reinforce the importance of old high redshift galaxies as special probes to the late stages of the universe. Even taking a too conservative viewpoint that such constraints are only suggestive (perhaps due to an unknown systematic effect on the data), our results point consistently to the same direction, namely: if $\Omega_M > 0.4$ a cosmological constant ($\omega = -1$) is favored by the existence of OHGRs (see Table 1). This conclusion is also supported by a more detailed analysis combining the age of the universe problem and the $H_o - \omega$ diagram. Thus, it should be interesting to insert this high redshift method and the related constraints within the large set of quintessence cosmological tests recently discussed by Wang et al. (2000).

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### Table 1. Limits to $\omega$ for a given $\Omega_M$

| Method                  | Reference                     | $\Omega_M$ (flat) | $\omega$ |
|-------------------------|-------------------------------|--------------------|----------|
| CMB + SNe Ia:........... | Turner & White (1997)         | $\approx 0.3$      | $\approx -0.6$ |
|                         | Efstathiou (1999)             | $\sim$             | $< -0.6$  |
| SNe Ia................... | Garnavich et al. (1998)       | $\sim$             | $< -0.55$ |
| SGL + SNe Ia............. | Waga & Miceli (1999)          | 0.24               | $< -0.7$  |
| SNe Ia + LSS............. | Perlmutter et al. (1999)      | $\sim$             | $< -0.6$  |
| Various.................. | Wang et al. (2000)            | 0.2 − 0.5          | $< -0.6$  |
| Old High-z Galaxies:    |                               |                    |          |
| $z = 1.43$............... | This paper                    | 0.3                | $< -0.27$ |
| $z = 1.43$............... | This paper                    | $\geq 0.5$         | $-1$      |
| $z = 1.55$............... | This paper                    | 0.3                | $< -0.20$ |
| $z = 1.55$............... | This paper                    | 0.5                | $< -0.40$ |
| $z = 1.175$............. | This paper                    | 0.3                | $< -0.12$ |
| $z = 1.175$............. | This paper                    | 0.5                | $< -0.20$ |

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