DARK ENERGY AND THE EPOCH OF GALAXY FORMATION
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ABSTRACT
The influence of a dark component on the first epoch of galaxy formation is analyzed by using the ages of the three oldest high-redshift galaxies known in the literature. Our results, based on a spatially flat accelerated universe driven by a “quintessence” component ($p_x = \omega p_x$), show that, if the inferred ages of these objects are correct, the first formation era is pushed back to extremely high redshifts. For the present best-fit quintessence model ($\Omega_r = 0.7$, $\omega < -0.6$), we find a lower bound of $z_f \geq 7.7$, whereas in the extreme case of the $\Lambda$ + cold dark matter model ($\omega = -1$) the limit is slightly smaller ($z_f \geq 5.8$). The case for open cold dark matter models has also been discussed. For $\Omega_m = 0.3$, the formation redshift is restricted by $z_f \geq 18$. As a general result, if $\Omega_x \geq 0.37$, these galaxies are not formed in FRW cosmologies with no dark energy since for all these cases $z_f \rightarrow \infty$.

Subject headings: cosmology: theory — dark matter — distance scale — galaxies: formation

In the last decade, the remarkable observational progress in addressing the question of the origin, early evolution, and ages of galaxies, as well as the expected rapid improvement of these data coming from the next generation of space telescopes, may provide the key for a precise determination of the epoch when the most of the galaxies in the universe were formed.

Recently, different groups (Stockton, Kellogg, & Ridgway 1995; Dunlop et al. 1996; Spinrad et al. 1997; Dunlop 1999) announced the discoveries of three extremely red radio galaxies at $z = 1.175$ (3C 65), $z = 1.55$ (LBDS 53W091), and $z = 1.43$ (LBDS 53W069) with minimal stellar ages of 4.0, 3.5, and 4.0 Gyr, respectively. These discoveries accentuated even further the already classical “age crisis” and gave rise to a new variant of this problem, which could be named the high-$z$ time-scale crisis: the underestimated ages of these galaxies contradict the predictions of the standard Einstein–de Sitter model for the formation redshift. Furthermore, for $\Lambda$ + cold dark matter (LCDM) scenarios, the age-redshift relation for these old high-redshift galaxies (OHRGs) requires $\Omega_m \geq 0.50$ if the universe is assumed to be spatially flat (Alcaniz & Lima 1999; Lima & Alcaniz 2000a). The problem raised by the ages of these galaxies to the standard CDM model suggests that OHRGs may be an important piece of the missing information related to the galaxy formation process and, in a similar vein, may constrain the epoch when the first structures were actually formed.

On the other hand, recent measurements of some Type Ia supernovae (SNe) at intermediate and high redshifts (Riess et al. 1998; Perlmutter et al. 1999a) also indicate that the bulk of energy in the universe is repulsive and appears like a “quintessence” component, that is, an unknown form of dark energy (in addition to the ordinary CDM matter) probably of primordial origin (see also Turner 2000 for a review). Together with the observations of cosmic microwave background (CMB) anisotropies (de Bernardis 2000), these results provide the remaining piece of information connecting the inflationary flatness prediction ($\Omega_r = 1$) with the astronomical observations. This state of affairs has stimulated the interest for more general models containing an extra component describing this dark energy and simultaneously accounting for the present accelerated stage of the universe. In recent years, the absence of convincing evidence on the nature of the dark component gave origin to an intense debate and mainly to theoretical speculations. Some possible candidates for “quintessence” are: a vacuum-decaying energy density or a time-varying A-term (Ozer & Taha 1987; Freese 1987; Carvalho, Lima, & Waga 1992), a relic scalar field (Ratra & Peebles 1988; Peebles & Ratra 1988; Frieman et al. 1995; Caldwell, Dave, & Steinhardt 1998; Saini et al. 2000), or still an extra component, the so-called X-matter, which is simply characterized by an equation of state $p_x = \omega p_x$, where $\omega \geq -1$ (Turner & White 1997; Chiba, Sugiyama, & Nakamura 1997; Lima & Alcaniz 2000b), and includes, as a particular case, models with a cosmological constant (LCDM; Turner, Steigman, & Krauss 1984; Peebles 1984; Krauss & Turner 1995). For X-matter models, constraints from large-scale structure (LSS) and cosmic microwave background (CMB) anisotropies 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, Turner, & White 1999b; Efstathiou 1999; Garnavich et al. 1998), while for universes with arbitrary spatial curvature the limit is $\omega < -0.4$ (Efstathiou 1999).

In this Letter we focus our attention on this kind of “quintessence” or X-matter cosmology. As is widely known, because of their generality these models also merit a broader discussion. In principle, to check the validity of a theory or model (e.g., the LCDM model), it is interesting to insert it in a more general framework, herein quantified by the $\omega$ parameter. In this context, we derive new lower limits to the formation redshift $z_f$ from ages of the oldest high-redshift objects known in the literature. The main consequences of this approach for the standard open FRW model (open cold dark matter [OCMD]) are also briefly analyzed.

For passively evolving elliptic radio galaxies, almost the entire amount of gas is believed to be processed into stars in a single episode of star formation, in such a way that the assumption of an instantaneous burst is considered a good approximation for modeling their evolution (Jimenez et al. 1999). For look-back time calculations, the hypothesis of an instantaneous burst of star formation means that the age of these OHRGs can be expressed as being almost exactly the time taken by the universe to evolve from $z_f$ to the observed redshift $z_{obs}$. In the framework of flat Friedmann-Robertson-Walker (FRW) models with nonrelativistic matter plus a quintessence component ($p_x = \omega p_x$, $\omega \geq -1$), such a condition can be trans-
Fig. 1.—ω-zf plane for quintessence models allowed by the existence of OHRGs. The value of ω is indicated in the figure, and the shaded region corresponds to the range of ω as determined from LLS + CMB + SNe Ia analysis (Perlmutter et al. 1999b; Efstathiou 1999; Garnavich et al. 1998). As explained in the text, for each high-redshift object, the arrows delimit the available parameter space. The curves are defined by the underestimates of tf and the indicated lower limit of H0. For the best-fit model (ω = 0.7, ω < −0.6), the corresponding lower limit is zf ≥ 7.7 (see also Table 1).

lated as

\[ t_{\text{sim}} - t_{z_f} = H_0^{-1} \int (t_{z_f})^{-1} \frac{dx}{x^{\Omega} \alpha^{3} + \Omega_{\alpha} x^{-3 + (1+\omega)}} \geq t_f, \]

where \( \Omega \) stands for the present-day quintessence density parameter. The inequality signal on the right-hand side of the above expression comes from the fact that the universe is older than or at least has the same age as any observed structure. Since this natural argument also holds for any time interval, a finite value for the redshift \( z_f \) provides the lower bound for the galaxy formation allowed by the aged object located at \( z_{\text{Obs}} \).

Models for which \( z_f \to \infty \) are clearly incompatible with the existence of the specific galaxy, being ruled out in a natural way. Indeed, as argued by Peebles (1989), any model is already in trouble if \( z_f \) is bigger than the finite redshift for which the mean density of the universe was equal to the mean density of the aged high-redshift galaxy (null contrast density).

Before discussing the resulting diagrams, an important point of principle should be stressed. To ensure the robustness of the limits on \( z_f \), we adopt (1) the minimal value for the Hubble parameter and (2) the underestimated age for all OHRGs. Both conditions are almost self-exploratory. First, as we know, the smaller the value of \( H_0 \), the larger the age predicted by the model and, second, objects with smaller ages are theoretically more easily accommodated, thereby guaranteeing that the models are always favored in the present estimates. For the Hubble parameter we consider the value obtained by the Hubble Space Telescope Key project, which is in agreement with other independent estimates (Giovanelli et al. 1997), i.e., the round number value \( H_0 = 60 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (Freedman 1998). Indeed, we are being rather conservative since this lower limit was recently updated to within nearly 10% of accuracy (\( h = 0.70 \pm 0.07, 1 \sigma \)) by Freedman (2000), and the data from SNe also point consistently to \( h > 0.6 \) or even higher (Riess et al. 1998; Perlmutter et al. 1999a).

At this point, some few words concerning the ages of these galaxies and their consequences are also appropriate. Since its discovery, the age estimates for LBDS 53W091 (at \( z = 1.55 \)) have stimulated considerable debate and controversy in the literature. Initially, by analyzing the strong transition breaks existing in the spectrum at 2640 and 2900 Å, Dunlop et al. (1996) and Spinrad et al. (1997) found a best-fitting age of 3.5 Gyr. Later on, Bruzual & Magris (1997) and Yi et al. (2000), using different arguments, claimed to have derived an age as young as 1.5 Gyr. More recently, we witnessed a new chapter on this controversy. Through a more detailed analysis of the different evolution models (based on \( \chi^2 \) minimization), the minimum age of 3.0 Gyr has again been clearly favored (Nolan, Dunlop, & Jimenez 2001). For the radio galaxy 3C 65 at \( z = 1.175 \), we adopt the estimated age from the analysis by Stockton et al. (1995), which has indicated strong evidence for a minimum stellar age of 4.0 Gyr. However, as we shall see, since the redshift of this galaxy is comparatively low, the corresponding constraint on the first epoch of formation is the less restrictive one. Finally, the remaining galaxy (LBDS 53W069, \( z = 1.43 \)) is an even redder galaxy that is 1.0 Gyr older than 53W091 and whose inferred age seems to be essentially unchanged for different solar metallicity models (Nolan et al. 2001). Actually, for a given value of \( \Omega_m \), the tighter constraints on \( z_f \) come from this object.

In Figure 1 we show the \( \omega-zf \) plane allowed by the existence of these OHRGs for quintessence models. In order to have a bidimensional plot, one needs to fix the value of one of the parameters (\( \Omega \), or \( \omega \)). Here we use the observational limits from LLS + CMB + SNe Ia, i.e., \( \Omega_m = 0.7 \) and \( \omega < −0.6 \) at 95% c.l. (Perlmutter et al. 1999; Efstathiou 1999; see also Wang et al. 2000 for limits from the “concordance cosmic” method). This constraint is represented by the shaded horizontal region and is used to determine the lower limits on \( z_f \). Since the effect of the equation of state associated with the quintessence component (\( \omega = p/\rho_c \)) is to accelerate the cosmic expansion, this means that the look-back time between \( z_{\text{Obs}} \) and \( z_f \) is larger than in the standard scenario and, therefore, the galaxy formation process may start relatively late in comparison with the corresponding standard CDM model. For example, for the interval considered here (−0.6 ≤ \( \omega \) ≤ −1) the estimated ages of 3C 65, 53W091, and 53W069 provide, respectively, \( z_f \geq 3.6 \), \( z_f \geq 5.2 \), and \( z_f \geq 3.8 \), with the lower values of \( z_f \) corresponding to the lower \( \omega \). These lower bounds are also heavily dependent on the Hubble parameter. For instance, on the interval 0.6 ≤ \( h \) ≤ 0.7, the formation redshift for the best-fit quintessence model (\( \Omega_m = 0.7 \), \( \omega < −0.6 \); Turner & White 1997; Perlmutter et al. 1999b; Efstathiou 1999; Garnavich et al. 1998) varies from \( z_f \geq 7.7 \) to \( z_f \geq 30 \) when the age of LBDS 53W069 is considered. Naturally, if the inferred ages of these OGHGs were smaller, the corresponding formation redshifts should be relatively smaller (for fixed values of the other parameters) in comparison with the limits derived. For example, by taking the estimated age for LBDS 53W091 given by Bruzual & Magris (1997) and Yi et al. (2000), i.e., \( t_f \sim 1.5 \) Gyr, the formation redshift is reduced from \( z_f \geq 6.4 \) to \( z_f \geq 2.3 \) for the interval of parameters considered above. However, if the age of this object is greater than 2.5 Gyr (J. S. Dunlop 2000, private communication), the corresponding lower bound is \( z_f \geq 2.9 \).

Figures 2 and 3 display the \( \Omega_m-zf \) plane for the OCDM and ΛCDM models, respectively. The shaded horizontal region corresponds to the observed range \( \Omega_m = 0.2−0.4 \) (Dekel, Burstein, & White 1997), which is also used to fix the lower limits on \( z_f \). As should be physically expected, in the case of OCDM
models (Fig. 2), if the matter contribution increases, a larger value of \( z_f \) is required in order to account for the existence of these OHRGs within these models. Conversely, for each object, the absolute minimal value of \( z_f \) is obtained for an empty universe (\( \Omega_m \to 0 \)). In the observed range of \( \Omega_m \), the allowed values for the formation redshift are unexpectedly high. For example, by considering \( \Omega_m = 0.3 \), as indicated from dynamic estimates on scales up to about 2 \( h^{-1} \) Mpc (Calberg et al. 1996), the ages of 3C 65, 53W091, and 53W069 provide, respectively, \( z_f \geq 6.3 \), \( z_f \geq 10.5 \), and \( z_f \geq 18 \). Such values suggest that these galaxies were formed about 12.5 Gyr ago, or, if we consider the most recent lower limits for the age of the universe (Carretta et al. 2000; Krauss 2000), that such objects were formed when the universe was \( \sim 1.0 \) Gyr old. However, since almost all the age of the universe is at low redshifts (\( z = 0 \)–2), these galaxies may have been formed at nearly the same epoch, regardless of their constraints on the redshift space. It is also interesting to note that the value of \( z_f \) is proportional to the quantity of dark matter. As one may verify, in the limiting case of a universe dominated only by dark energy (\( \Omega_m = 0, \omega = -1 \)), the lower limit is \( z_f \geq 2 \) (see Fig. 3).

Tables 1 and 2 summarize the estimated values of \( z_f \) for quintessence and CDM models. In the former case the matter density parameter has been fixed in its central observed value (\( \Omega_m = 0.3 \)), with \( z_f \) determined for several values of \( \omega \) (see Table 1). As explained before, since the look-back time between \( z_f \) and \( z_{\text{obs}} \) increases for lower values of \( \omega \), it is physically expected that the value of \( z_f \) diminishes for smaller values of \( \omega \). The remaining cases, OCDM and ACDM, are displayed for the entire observed range of the matter density parameter (\( \Omega_m = 0.2 \)–0.4). Note that, for \( \Omega_m \geq 0.37 \), the lower limit inferred from the age of 59W069 is \( z_f \to \infty \). This result is consistent with recent studies based on the age-redshift relation (Alcaniz & Lima 1999) and means that the standard cosmological model with \( \Omega_m \geq 0.37 \) and \( h \geq 0.6 \) is (beyond doubt) incompatible with the existence of this galaxy. Our results are also in line with the claims of Kashlinsky & Jimenez (1997) that the galaxy 53W091 represents a very rare and unlikely event in the density field of such models. In principle, they also imply that quintessence models constitute a potential alternative to conciliate the observed excess of power observed in galaxy surveys without requiring too late galaxy formation (as it happens in ACDM models). It should be stressed that the present constraints on \( z_f \) are indeed rather conservative since the lower limit on \( H_0 \) has been considered in all the estimates. Furthermore, the inferred ages for these galaxies refer to the end of the star formation episode that dominates the spectrum and not to the first epoch of star formation in the galaxy, which, therefore, provides only a lower limit to the age of the galaxy. Finally, these high limits on \( z_f \) provide new theoretical evidence that galaxies are not uncommon objects at very large redshifts, say, at \( z > 5 \), and also reinforce the interest in the observational search for galaxies and other collapsed objects within the redshift interval (\( 5 \leq z \leq 10 \)), which nowadays delimits the last

![Fig. 2—Ωₘzₜ plane allowed by the existence of OHRGs in the framework of open cold dark matter models. The shadowed horizontal region corresponds to the observed range of Ωₘ. The arrows delimit the available parameter space. The curves are also defined by the underestimated values of (a), and the indicated lower limit is provided by the radio galaxy 53W069.](image1)

![Fig. 3.—Same as Fig. 2 but for ACDM models. Again, the contours are obtained by considering the minimal value of Ωₘ, and the shadowed horizontal region corresponds to the observed range of Ωₘ. In comparison with the corresponding OCDM model, we see that all curves have been shifted for smaller redshifts (see also Table 2).](image2)

| Table 1 | Limits to \( z_f \): Quintessence Models |
|---------|----------------------------------------|
| Galaxy  | \( \omega \) | \( z_f \) |
| 3C 65   | 0.2 | \( \geq 5.0 \) | \( \geq 3.0 \) |
|         | 0.3 | \( \geq 6.3 \) | \( \geq 3.6 \) |
| 53W091  | 0.4 | \( \geq 8.6 \) | \( \geq 4.8 \) |
|         | 0.3 | \( \geq 10.5 \) | \( \geq 5.2 \) |
| 53W069  | 0.4 | \( \geq 20.7 \) | \( \geq 7.4 \) |
|         | 0.2 | \( \geq 9.3 \) | \( \geq 3.9 \) |
|         | 0.3 | \( \geq 18.0 \) | \( \geq 5.8 \) |
|         | 0.37 | \( \to \infty \) | \( \geq 10 \) |

| Table 2 | Limits to \( z_f \): OCDM and ACDM Models |
|---------|----------------------------------------|
| Galaxy  | \( \Omega_m \) | OCDM | ACDM |
| 3C 65   | 0.2 | \( \geq 5.0 \) | \( \geq 3.0 \) |
|         | 0.3 | \( \geq 6.3 \) | \( \geq 3.6 \) |
| 53W091  | 0.4 | \( \geq 8.6 \) | \( \geq 4.8 \) |
|         | 0.3 | \( \geq 10.5 \) | \( \geq 5.2 \) |
| 53W069  | 0.4 | \( \geq 20.7 \) | \( \geq 7.4 \) |
|         | 0.2 | \( \geq 9.3 \) | \( \geq 3.9 \) |
|         | 0.3 | \( \geq 18.0 \) | \( \geq 5.8 \) |
|         | 0.37 | \( \to \infty \) | \( \geq 10 \) |
frontier to a more complete understanding of the galaxy formation process.

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