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DARK ENERGY AND THE ANGULAR SIZE–REDSHIFT DIAGRAM FOR MILLIARCSECOND RADIO SOURCES

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ABSTRACT

We investigate observational constraints on the cosmic equation of state from measurements of angular size for a large sample of milliarcsecond compact radio sources. The results are based on a flat Friedmann-Robertson-Walker (FRW) model driven by nonrelativistic matter, plus a smooth, dark energy component parameterized by its equation of state $p_x = \omega\rho_x$ $(-1 \leq \omega < 0)$. The allowed intervals for ω and Ω_m are heavily dependent on the value of the mean projected linear size l. For $l \simeq$ 20–30h^{-1} pc, we find $\Omega_m \leq 0.62$, $\omega \leq -0.2$, and $\Omega_m \leq 0.17$, $\omega \leq -0.65$ (68% c.l.), respectively. As a general result, this analysis shows that if one minimizes χ^2 for the parameters l, Ω_m, and ω, the conventional flat ΛCDM model ($\omega = -1$) with $\Omega_m = 0.2$ and $l = 22.6h^{-1}$ pc is the best fit for these angular size data.

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

A large body of recent observational evidence strongly suggests that we live in a flat, accelerating universe composed of $\sim$1/3 of matter (barionic + dark) and $\sim$2/3 of an exotic component with large negative pressure, usually called dark energy or "quintessence." The basic set of experiments includes observations from SNe Ia (Perlmutter et al. 1998, 1999; Riess et al. 1998), CMB anisotropies (de Bernardis et al. 2000), large-scale structure (Bahcall 2000), age estimates of globular clusters (Carretta et al. 2000; Krauss 2000; Rengel, Mateu, & Bruzual 2001), and old high-redshift galaxies (OHRGs, see Dunlop 1996; Krauss 1997; Alcaniz & Lima 1999; Alcaniz & Lima 2001). It is now believed that such results provide the remaining piece of information connecting the inflationary flatness prediction ($\Omega_T = 1$) with astronomical observations, and perhaps more important, from a theoretical viewpoint, they have stimulated the current interest in more general models containing an extra component describing this unknown dark energy and simultaneously accounting for the present accelerated stage of the universe.

The absence of convincing evidence concerning the nature of this dark component gave origin to an intense debate and to many theoretical speculations in the last few years. Some possible candidates for "quintessence" are a vacuum-decaying energy density or a time-varying Λ term (Ozer & Taha 1987; Freese et al. 1987; Carvalho, Lima, & Waga 1992; Lima & Maia 1994), a relic scalar field (Peebles & Ratra 1988; Frieman et al. 1995; Caldwell, Dave, & Steinhardt 1998; Saini et al. 2000), or an another extra component, the so-called "X matter," which is simply characterized by an equation of state $p_x = \omega\rho_x$, where $\omega \geq -1$ (Turner & White 1997; Chiba, Sugiyama, & Nakamura 1997), and includes, in this particular case, models with a cosmological constant (ΛCDM) (Peebles 1984). For "X matter" models, several results suggest $\Omega_x \simeq 0.7$ and $\omega \leq -0.6$. For example, studies from gravitational lensing plus SNe Ia provide $\omega \leq -0.7$ at a 68% c.l. (Waga & Miceli 1999; Dev et al. 2001). Limits from age estimates of old galaxies at high redshift require $\omega < -0.27$ for $\Omega_m \simeq 0.3$ (Lima & Alcaniz 2000a). In addition, constraints from large-scale structure (LSS) and cosmic microwave background anisotropies (CMB) complemented by the SNe Ia data require $0.6 \leq \Omega_x \leq 0.7$ and $\omega < -0.6$ (95% c.l.) for a flat universe (Garnavich et al. 1998; Perlmutter et al. 1999; Efstathiou 1999), while for universes with arbitrary spatial curvature, these data provide $\omega < -0.4$ (Efstathiou 1999).

On the other hand, although carefully investigated in many of their theoretical and observational aspects, an overview of the literature shows that a quantitative analysis on the influence of a "quintessence" component ($\omega = p_x/\rho_x$) in some kinematic tests such as angular size-redshift relation still remains to be studied. Recently, Lima & Alcaniz (2000b) studied some qualitative aspects of this test in the context of such models, with particular emphasis for the critical redshift z_m, at which the angular size takes its minimal value. It was generally concluded that this critical redshift cannot discriminate between world models since different scenarios can provide similar values of z_m (see also Krauss & Schramm 1993). This situation is not improved even when evolutionary effects are taken into account. In particular, for the observationally favored open universe ($\Omega_m = 0.3$), we found $z_m = 1.89$, a value that can also be obtained for quintessence models having $0.85 \leq \Omega_x \leq 0.93$ and $-1 \leq \omega_x \leq -0.5$. Qualitatively, it was also argued that if the predicted z_m is combined with other tests, some interesting cosmological constraints can be obtained.

In this paper, we focus our attention on a more quantitative analysis. We consider the $\theta - z$ data of compact radio sources recently updated and extended by Gurvits, Kellerman, & Frey (1999) to constrain the cosmic equation of state. We show that a good agreement between theory and observation is possible if $\Omega_m \leq 0.62$, $\omega \leq -0.2$ and $\Omega_m \leq 0.17$, $\omega \leq -0.65$ (68% c.l.) for values of the mean projected linear size between $l \simeq 20 - 30h^{-1}$ pc, respectively. In particular, we find that a conventional cosmological constant model ($\omega = -1$) with $\Omega_m = 0.2$ and $l = 22.64h^{-1}$ pc is the best-fit model for these data with $\chi^2 = 4.51$ for 9 degrees of freedom.

For spatially flat, homogeneous, and isotropic cosmologies driven by nonrelativistic matter, plus an exotic component with equation of state, $p_x = \omega \rho_x$, the Einstein field equations take the following form:

$$\left(\frac{\dot{R}}{R}\right)^2 = H_0^2\left[\Omega_m\left(\frac{R_0}{R}\right)^3 + \Omega_x\left(\frac{R_0}{R}\right)^{3(1+\omega)}\right], \quad (1)$$

$$\frac{\ddot{R}}{R} = -\frac{1}{2}H_0^2\left[\Omega_m\left(\frac{R_0}{R}\right)^3 + (3\omega+1)\Omega_x\left(\frac{R_0}{R}\right)^{3(1+\omega)}\right], \quad (2)$$

where an overdot denotes derivative with respect to time, $H_o = 100h$ km s^{-1} Mpc^{-1} is the present value of the Hubble parameter, and Ω_m and Ω_x are the present-day matter and quintessence density parameters. As one may check from equations (1) and (2), the case $\omega = -1$ corresponds effectively to a cosmological constant.

In such a background, the angular size-redshift relation for a rod of intrinsic length l can be written as (Sandage 1988)

$$\theta(z) = \frac{D(1+z)}{\xi(z)} \quad . \quad (3)$$

In the above expression, D is the angular-size scale expressed in milliarcseconds (mas)

$$D = \frac{100lh}{c}, \quad (4)$$

where l is measured in parsecs (for compact radio sources) and the dimensionless coordinate ξ is given by (Lima & Alcaniz 2000b)

$$\xi(z) = \int_{(1+z)^{-1}}^{1} \frac{dx}{x[\Omega_m x^{-1} + (1-\Omega_m)x^{-(1+3\omega)}]^{1/2}} . \quad (5)$$

The above equations imply that for given values of l, Ω_m, and ω, the predicted value of $\theta(z)$ is completely determined. Two points, however, should be stressed before discussing the resulting diagrams. First of all, the determination of Ω_m and ω are strongly dependent on the adopted value of l. In this case, instead of assuming a specific value for the mean projected linear size, we have worked on the interval $l \simeq 20$–$30h^{-1}$ pc, i.e., $l \sim O(40)$ pc for $h = 0.65$, or equivalently, $D = 1.4$–2.0 mas. Second, following Kellermann (1993), we assume that possible evolutionary effects can be removed from this sample because compact radio jets are (1) typically less than 100 pc in extent, and therefore, their morphology and kinematics do not depend considerably on the intergalactic medium, and (2) they have typical ages of some tens of years, i.e., they are very young compared to the age of the universe.

In our analysis, we consider the angular size data for milliarcsecond radio sources recently compiled by Gurvits et al. (1999). This data set, originally composed by 330 sources distributed over a wide range of redshifts ($0.011 \leq z \leq 4.72$), was reduced to 145 sources with spectral index $-0.38 \leq \alpha \leq 0.18$ and total luminosity $Lh^2 \geq 10^{26}$ W Hz^{-1} in order to minimize any possible dependence of angular size on spectral index and/or linear size on luminosity. This new sample was distributed into 12 bins with 12–13 sources per bin (see Fig. 1). In order to determine the cosmological parameters Ω_m and ω, we use an χ^2 minimization, neglecting the unphysical region $\Omega_m < 0$,

$$\chi^2(l, \Omega_m, \omega) = \sum_{i=1}^{12} \frac{[\theta(z_i, l, \Omega_m, \omega) - \theta_{oi}]^2}{\sigma_i^2}, \quad (6)$$

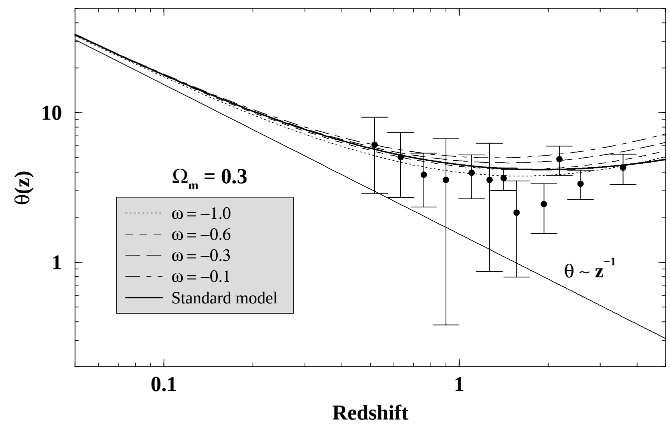

FIG. 1.—Angular size versus redshift for 145 sources binned into 12 bins (Gurvits, et al. 1999). Curves correspond to the characteristic linear size $l = 22.64h^{-1}$ pc. Thick solid curve is the prediction of the standard open model ($\Omega_m = 0.3$).

where $\theta(z_i, l, \Omega_m, \omega)$ is given by equations (3) and (5) and θ_{oi} is the observed values of the angular size with errors σ_i of the ith bin in the sample.

Figure 1 displays the binned data of the median angular size plotted against redshift. The curves represent flat quintessence models with $\Omega_m = 0.3$ and some selected values of ω. As discussed in Lima & Alcaniz (2000b), the standard open model (*thick line*) may be interpreted as an intermediary case between ΛCDM ($\omega = -1$) and quintessence models with $\omega \leq -0.5$. In Figure 2, we show contours of constant likelihood (95% and 68%) in the plane ω-Ω_m for the interval $l \simeq 20$–$30h^{-1}$ pc. For $l = 20.58h^{-1}$ pc ($D = 1.4$ mas), the best fit occurs for $\Omega_m = 0.26$ and $\omega = -0.86$. As can be seen there, this assumption provides $\Omega_m \leq 0.62$ and $\omega = -0.2$ at 1σ. In the subsequent panels of the same figure, similar analyses are displayed for $l \simeq 22.05h^{-1}$ pc ($D = 1.5$ mas), $l \simeq 23.53h^{-1}$ pc ($D = 1.6$ mas), and $l \simeq 29.41h^{-1}$ pc ($D = 2.0$ mas), respectively. As should be physically expected, the limits are now much more restrictive than in the previous case, because for the same values of θ_{oi}, larger $\xi(z)$ (for larger l) is needed, and therefore, smaller values of ω. For $l \simeq 29.41h^{-1}$ pc, we find $\Omega_m = 0.04$ and $\omega = -1$ as the best-fit model. For intermediate values of l, namely, $l = 22.0h^{-1}$ pc ($D = 1.5$ mas) and $l = 23.5h^{-1}$ pc ($D = 1.6$ mas), we have $\Omega_m = 0.22$, $\omega = -0.98$ and $\Omega_m = 0.16$ and $\omega = -1$, respectively. In particular, for smaller values of l, e.g., $l \simeq 14.70h^{-1}$ pc ($D = 1.0$ mas), we find $\Omega_m = 0.36$, $\omega = -0.04$. As a general result (independent of the choice of l), if we minimize χ^2 for l, Ω_m, and ω, we obtain $l = 22.64h^{-1}$ pc ($D = 1.54$ mas), $\Omega_m = 0.2$, and $\omega = -1$ with $\chi^2 = 4.51$ for 9 degrees of freedom (see Table 1). It is worth noting that our results are rather different from those presented by Jackson & Dodgson (1996), which are based on the original Kellermann data (Kellermann 1993). They argued that Kellermann's compilation favors open and highly decelerating models with negative cosmological constant. Later on, they considered a bigger sample of 256 sources selected from the compilation of Gurvits (1994) and concluded that the standard flat CDM model is ruled out at 98.5% confidence level, whereas low-density models with a cosmological constant of either sign are favored (Jackson & Dodgson 1997). More recently, Vishwakarma (2001) used the updated data of Gurvits et al. (1999) to compare varying and constant

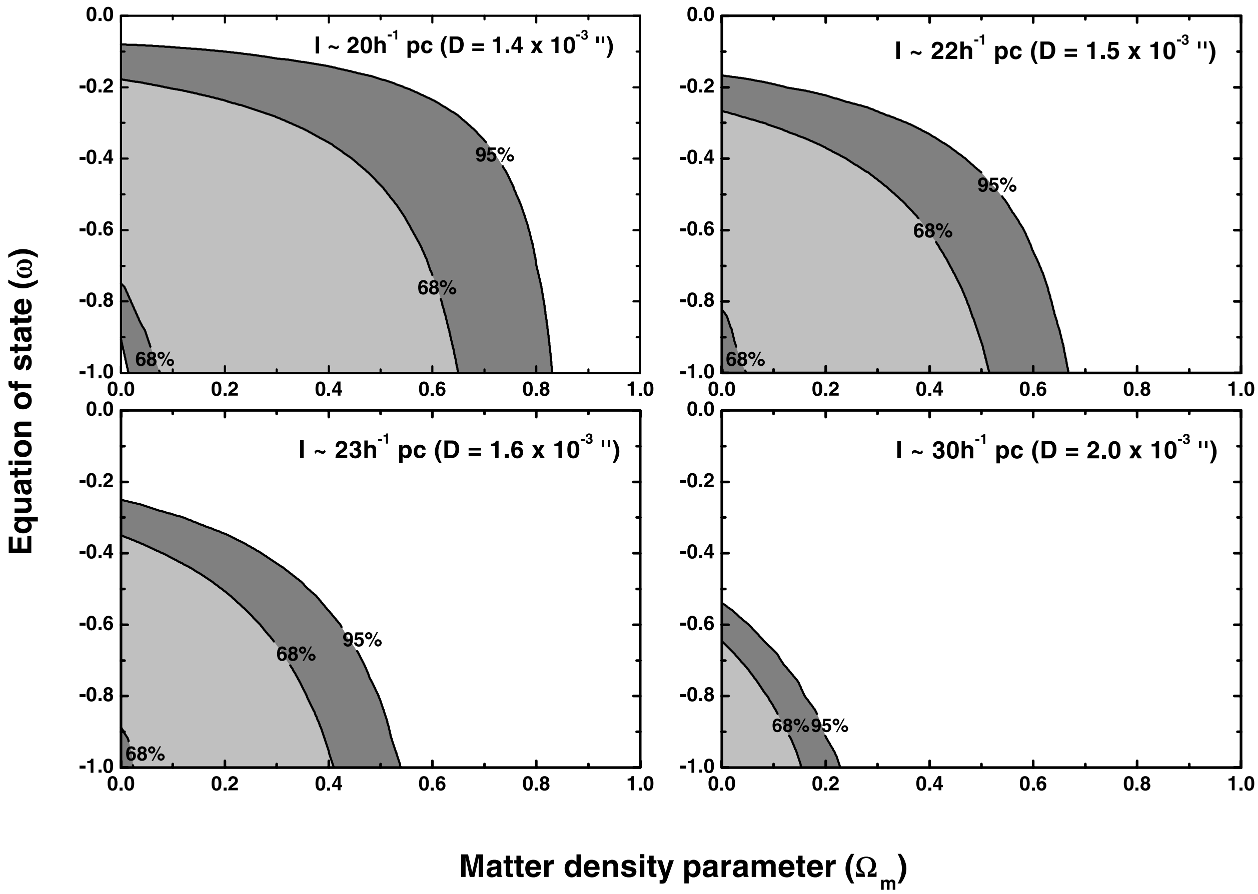

FIG. 2.—Confidence regions in the ω-Ω_m plane according to the updated sample of angular size data (Gurvits et al. 1999). Solid lines in each panel show the 95% and 68% likelihood contours for flat quintessence models.

ΛCDM models. He concluded that flat ΛCDM models with $\Omega_m = 0.2$ are favored.

At this point, it is also interesting to compare our results with some recent determinations of ω derived from independent methods. Recently, using the SNe Ia data from the high-z supernova search team, Garnavich et al. (1998) found $\omega < -0.55$ (95% c.l.) for flat models whatever the value of Ω_m, whereas for arbitrary geometry they obtained $\omega < -0.6$ (95% c.l.). As commented there, these values are inconsistent with an unknown components such as topological defects (domain walls, string, and textures) for which $\omega = -n/3$, n being the dimension of the defect. The results by Garnavich et al. (1998) agree with the constraints obtained from a wide variety of different phenomena using the "concordance cosmic" method (Wang et al. 2000). In the latter case, the combined maximum likelihood analysis suggests $\omega \leq -0.6$, which is less stringent than the upper limits derived here for values of $l \geq 20h^{-1}$ pc. More recently, Balbi et al. (2001) investigated CMB anisotropies in quintessence models by using the MAXIMA-1 and BOOMERANG-98 published band powers in combination with the *COBE* differential microwave radiometer results (see also Corasaniti & Copeland 2001). Their analysis suggests $\Omega_x > 0.7$ and $-1 \leq \omega \leq -0.5$, whereas Jain et al. (2001) found, by using image separation distribution function of lensed quasars, $-0.75 \leq \omega \leq -0.42$ for the observed range of $\Omega_m \sim 0.2$–0.4 (Dekel, Burstein, & White 1997). These and other recent results are summarized in Table 2.

TABLE 1

LIMITS ON ω FROM θ-z RELATION

D (mas)	lh (pc)	Ω_m	ω	χ^2
1.4	20.58	0.26	−0.86	4.56
1.5	22.05	0.22	−0.98	4.52
1.6	23.53	0.16	−1	4.54
2.0	29.41	0.04	−1	5.57
Best fit: 1.54......	22.64	0.2	−1	4.51

Let us now discuss briefly these angular size constraints where the adopted "X matter" model is replaced by a scalar field-motivated cosmology; for instance, the one proposed by Peebles & Ratra (1988). These models are defined by power-law potentials, $V(\phi) \sim \phi^{-\alpha}$, in such a way that the parameter of the effective equation of state ($w_\phi = p_\phi/\rho_\phi$) may become constant at late times (or for a given era). In this case, as shown elsewhere (Lima & Alcaniz 2000c), the dimensionless quantity ξ defining the angular size reads

$$\xi(z) = \int_{(1+z)^{-1}}^{1} \frac{dx}{x[\Omega_m x^{-1} + (1-\Omega_m)x^{(4-\alpha)/(2+\alpha)}]^{1/2}} . \quad (7)$$

Comparing the above expression with equation (5), we see that if $\omega = -2/(2+\alpha)$, this class of models may reproduce faithfully the "X matter" constraints based on the angular

TABLE 2

LIMITS TO ω FOR A GIVEN Ω_m

Method	Author	Ω_m	ω
CMB+SNe Ia......	Turner & White (1997)	$\simeq 0.3$	$\simeq -0.6$
	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, Turner, & White (1999)	$\sim$	< -0.6
Various.............	Wang et al. (2000)	0.2–0.5	< -0.6
OHRG's............	Lima & Alcaniz (2000a)	0.3	≤ -0.27
CMB	Balbi et al. (2001)	0.3	≤ -0.5
	Corasaniti & Copeland (2001)	$\sim$	≤ -0.96
SGL	Jain et al. (2001)	0.2–0.4	≥ -0.75, ≤ -0.55

size observations presented here. However, as happens with the SNe Ia data (Podariu & Ratra 2000), the two sets of confidence contours may differ significantly if one goes beyond the time-independent equation of state approximation. Naturally, a similar behavior is expected if generic scalar field potentials are considered.

Finally, we stress that measurements of angular size from distant sources provide an important test for world models. However, in order to improve the results, a statistical study describing the intrinsic length distribution of the sources seems to be of fundamental importance. On the other hand, in the absence of such analysis, but living in the era of *precision cosmology*, one may argue that reasonable values for astrophysical quantities (such as the characteristic linear size l) can be inferred from the best cosmological model. As observed by Gurvits (1994), such an estimative could be useful for any kind of study involving physical parameters of active galactic nuclei (AGN). In principle, by knowing l and assuming a physical model for AGN, a new method to estimate the Hubble parameter could be established.

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REFERENCES

Alcaniz J. S. & Lima J. A. S. 1999, ApJ, 521, L87
———. 2001, ApJ, 550, L133
Bahcall, N. A. 2000, Phys. Rep., 333, 233
Balbi, A., Baccigalupi, C., Matarrese, S., Perrotta, F., Vittorio, N. 2001, ApJ, 547, L89
Caldwell, R. R., Dave, R., & Steinhardt, P. J. 1998, Phys. Rev. Lett., 80, 1582
Carretta E., et al. 2000, ApJ, 533, 215
Carvalho, J. C., Lima, J. A. S., & Waga, I. 1992, Phys. Rev., D46, 2404
Chiba, T., Sugiyama, N., & Nakamura, T. 1997, MNRAS, 289, L5
Corasaniti, P. S., & Copeland, E. J. 2001, Phys. Rev. D, in press
de Bernardis, P., et al. 2000, Nature, 404, 955
Dekel, A., Burstein, D., & White, S. 1997, in Critical Dialogues in Cosmology, ed. N. Turok (Singapore: World Scientific), 175
Dev, A., Jain, D., Panchapakesan, N., Mahajan, M., & Bhatia, V. preprint (astro-ph/0104076)
Dunlop, J. S., et al. 1996, Nature, 381, 581
Efstathiou, G. 1999, MNRAS, 310, 842
Freese, K., Adams, F. C., Frieman, J. A., & Mottola, E. 1987, Nucl. Phys. B, 287, 797
Frieman, J. A. , Hill, C. T., Stebbins, A. & Waga, I. 1995, Phys. Rev. Lett., 75, 2077
Garnavich, P. M. et al. 1998, ApJ, 509, 74
Gurvits, L. I. 1994, ApJ, 425, 442
Gurvits, L. I., Kellermann, K. I., & Frey, S. 1999, A&A, 342, 378
Jackson, J. C., & Dodgson, M. 1996, MNRAS, 278, 603
———. 1997, MNRAS, 285, 806
Jain, D., Dev, A., Panchapakesan, N., Mahajan, M., & Bhatia, V. preprint (astro-ph/0105551)
Kellermann, K. I. 1993, Nature, 361, 134
Krauss, L. M. 1997, ApJ, 480, 466
———. 2000, Phys. Rep., 333, 33
Krauss, L. M., & Schramm, D. N. 1993, ApJ, 405, L43
Lima, J. A. S., & Alcaniz, J. S. 2000a, MNRAS, 317, 893
———. 2000b, A&A, 357, 393
———. 2000c, Gen. Relativ. Gravitation, 32, 1851
Lima, J. A. S., & Maia, J. M. F. 1994, Phys. Rev. D, 49, 5597
Ozer, M., & Taha, O. 1987, Nucl. Phys., B287, 776
Peebles, P. J. E. 1984, ApJ, 284, 439
Peebles, P. J. E., & Ratra, B. 1988, ApJ, 325, L17
Perlmutter S., et al. 1998, Nature, 391, 51
———. 1999, ApJ, 517, 565
Perlmutter, S., Turner, M. S., & White, M. 1999, Phys. Rev. Lett., 83, 670
Podariu, S., & Ratra, B. 2000, ApJ, 532, 109
Rengel, M., Mateu, J., & Bruzual, G. 2001, in IAU Symp. 207, Extragalactic Star Clusters, ed. E. Grebel, D. Geisler, D. Minniti (Cambridge: Cambridge Univ. Press), in press
Riess A. et al. 1998, AJ, 116, 1009
Saini, T. D., Raychaudhury, S., Sahni, V., & Starobinsky, A. A. 2000, Phys. Rev. Lett., 85, 1162
Sandage, A. 1988, ARA&A, 26, 561
Turner, M. S., & White, M. 1997, Phys. Rev., D56, R4439
Vishwakarma, R. G. 2001, Classical Quantum Gravity, 18, 1159
Waga, I., & Miceli, A. P. M. R. 1999, Phys. Rev., D59, 103507
Wang, L., Caldwell, R. R., Ostriker, J. P., & Steinhardt, P. J. 2000, ApJ, 530, 17