

CONSTRAINTS ON SCALAR-FIELD DARK ENERGY FROM THE COSMIC LENS ALL-SKY SURVEY GRAVITATIONAL LENS STATISTICS

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Received 2004 March 10; accepted 2004 April 15; published 2004 April 28

ABSTRACT

We use the statistics of strong gravitational lensing based on Cosmic Lens All-Sky Survey (CLASS) data to constrain cosmological parameters in a spatially flat, inverse power-law potential energy density scalar-field dark energy cosmological model. The lensing-based constraints are consistent with, but weaker than, those derived from Type Ia supernova redshift-magnitude data, and mildly favor the Einstein cosmological constant limit of this dark energy model.

Subject headings: cosmological parameters — cosmology: observations — gravitational lensing — large-scale structure of universe

1. INTRODUCTION

Recent cosmological measurements strengthen the evidence from Type Ia supernova redshift-magnitude measurements (Riess et al. 1998; Perlmutter et al. 1999) that the energy density of the current universe is dominated by Einstein’s cosmological constant Λ , or by a dark energy term in the cosmic stress-energy tensor that only varies slowly with time and space and so acts like Λ . These measurements include: (1) more recent Type Ia supernova redshift-magnitude measurements (see, e.g., Knop et al. 2003; Barris et al. 2004); (2) the space-based *Wilkinson Microwave Anisotropy Probe* (WMAP) measurement of the cosmic microwave background (CMB) anisotropy, with some input from other measurements (see, e.g., Page et al. 2003; Spergel et al. 2003; Scranton et al. 2003); and (3) other measurements of CMB anisotropy that indicate the universe is close to spatially flat (see, e.g., Podariu et al. 2001b; Durrer et al. 2003; Melchiorri & Ödman 2003), in combination with the continuing strong evidence for low nonrelativistic matter density (Chen & Ratra 2003b, and references therein). See Peebles & Ratra (2003), Padmanabhan (2003), Bernardeau (2003), Steinhardt (2003), and Carroll (2004) for reviews of the current state of affairs.³

While Einstein’s Λ was the first example of dark energy, nowadays much attention is focused on scalar-field models in which the energy density slowly decreases with time and so behaves like a time-variable Λ (see, e.g., Peebles 1984; Peebles & Ratra 1988, 2003; Padmanabhan 2003; Steinhardt 2003; Carroll 2004). A simple scalar-field dark energy model has scalar-field (ϕ) potential energy density $V(\phi) \propto \phi^{-\alpha}$ at low redshift, with $\alpha > 0$ (see, e.g., Peebles & Ratra 1988; Ratra & Peebles 1988). Podariu & Ratra (2000), Waga & Frieman (2000), and Gott et al. (2001) examine constraints on this model using Type Ia supernova

redshift-magnitude data. They find that a broad range of α is consistent with the supernova data.⁴

It is important that these dark energy models be tested by other independent methods. The redshift–angular size test is one option. Indications from current data, while not as compelling as those discussed above, are consistent with a significant dark energy density at low redshift (see, e.g., Daly & Guerra 2002; Zhu & Fujimoto 2002; Chen & Ratra 2003a; Podariu et al. 2003; Jain et al. 2003; Jackson 2003). Future higher-quality data should turn this into a much more precise cosmological test. The redshift-counts test also appears to be on the verge of becoming a very promising test (see, e.g., Newman & Davis 2000; Huterer & Turner 2001; Podariu & Ratra 2001; Levine et al. 2002). Statistical analyses of strong gravitational lensing can be used to provide constraints on cosmological parameters. Fukugita et al. (1990) and Turner (1990) note that the rate of gravitational lensing increases rapidly with increasing Λ . Ratra & Quillen (1992) and Waga & Frieman (2000) study gravitational lensing in the inverse power-law potential energy density scalar-field dark energy model.

The recently completed Cosmic Lens All-Sky Survey (CLASS) is the largest uniform survey for strong lensing (Myers et al. 2003; Browne et al. 2003). The survey has discovered 22 cases of multiple imaging (that are induced by galaxy-scale lens potentials) out of $\sim 16,500$ extragalactic radio sources. A subsample of 8958 sources containing 13 multiply-imaged sources satisfy well-defined observational selection criteria and is referred to as the CLASS statistical sample (Browne et al. 2003). The CLASS statistical sample has been used to constrain cosmological parameters (see, e.g., Chae et al. 2002; Chae 2003; Kuhlen et al. 2004; Mitchell et al. 2004) and also to constrain global properties of galaxies (Chae 2003; Davis et al. 2003) and galaxy evolution (Chae & Mao 2003). The lensing-based constraints on cosmological parameters are consistent with those based on Type Ia supernova magnitude-redshift data, but have larger statistical errors.

In this work we use the CLASS statistical sample to constrain

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³ Specific dark energy models and observational measurements are considered in Munshi et al. (2004), Barreiro et al. (2003), Mainini et al. (2003), Lima et al. (2003), Silva & Bertolami (2003), Amendola et al. (2003), Linder & Jenkins (2003), Makler et al. (2003), Bean & Doré (2004), Łokas et al. (2004), Alam et al. (2003), Choudhury & Padmanabhan (2003), Zhu & Fujimoto (2004), and Macció (2004), from which the earlier literature may be accessed.

⁴ The proposed *SNAP* space mission (see <http://snap.lbl.gov> and Schubnell 2003 and Annis et al. 2003) will provide significantly tighter constraints on such models (Podariu et al. 2001a; Erickson & Amanullah 2002; Caresia et al. 2003; Wang & Mukherjee 2004, and references therein). Mukherjee et al. (2003b, 2003a), Spergel et al. (2003), Caldwell & Doran (2003), Weller & Lewis (2003), Giovi et al. (2003), and references therein, discuss constraints on scalar field and related dark energy models from CMB anisotropy measurements; upcoming *WMAP* and other CMB data will improve these constraints.

the inverse power-law potential scalar-field dark energy model (Peebles & Ratra 1988). In linear perturbation theory, a scalar field is mathematically equivalent to a fluid with time-dependent equation-of-state parameter $w = p/\rho$ and speed of sound squared $c_s^2 = \dot{p}/\dot{\rho}$, where p and ρ are the pressure and energy density, respectively, and the overdot denotes a time derivative (see, e.g., Ratra 1991). The Λ CDM parameterization of this dark energy model approximates w as a constant, which is accurate during the radiation- and matter-dominated epochs, but not in the current scalar-field dark energy dominated epoch. This Λ CDM approximation thus leads to inaccurate predictions for the gravitational lensing considered here, which probes the low-redshift universe. We emphasize, however, that unlike a lot of earlier work, we do not work in the Λ CDM approximation; instead, we explicitly integrate the scalar-field dark energy equations of motion.

In § 2 we summarize the data and method used. Results are presented and discussed in § 3.

2. DATA AND METHOD

We use the data listed in Chae (2003), except for the following modifications owing to the very recent spectroscopic observations of several CLASS lens systems by McKean et al. (2004). The 13 lens systems in the CLASS statistical sample (Table 1 of Chae 2003) are 0218+357, 0445+123, 0631+519, 0712+472, 0850+054, 1152+199, 1359+154, 1422+231, 1608+656, 1933+503, 2045+265, 2114+022, and 2319+051. From McKean et al. (2004) we adopt the following lens redshifts: $z_l = 0.558, 0.620,$ and $0.588,$ respectively, for 0445+123, 0631+519, and 0850+054. We also use the finding by McKean et al. (2004) that the lenses for 0445+123 and 0631+519 are early-type galaxies, while that for 0850+054 is a spiral-type galaxy.

Sheth et al. (2003) directly estimate the velocity (dispersion) function (VF) of early-type galaxies based on the Sloan Digital Sky Survey (SDSS) data; a correction to their normalization is reported in Mitchell et al. (2004). It would be desirable to use the Sheth et al. (2003) VF for lensing analyses. However, we find a posteriori that the maximum likelihood for the Sheth et al. (2003) VF is far worse than that for the Chae (2003) inferred VF based on the Second Southern Sky Redshift Survey (SSRS2). This implies that the SSRS2 VF is more consistent with the image separations in the CLASS statistical sample (K.-H. Chae 2004, in preparation). In this work we use the SSRS2 VF as in Chae et al. (2002), Chae (2003), and Chae & Mao (2003).

We use the method of statistical analysis of lensing described in Chae (2003,) except we now work in the spatially flat scalar-field dark energy cosmological model (Peebles & Ratra 1988). In particular, as in Chae (2003) we assume that the comoving number density of early-type galaxies is constant from $z \sim 1$ to the present epoch, and the characteristic velocity dispersion for $0.3 \lesssim z \lesssim 1$ is not assumed to be known a priori, but is determined from the image-splitting sizes of the multiply imaged systems.⁵ Here we briefly review essential concepts in lensing statistics (Chae 2003) and the spatially flat scalar-field dark energy cosmological model (Peebles & Ratra 1988). Let the differential probability for a cosmologically distant source to be multiply imaged with image-splitting size $\Delta\theta$ to $\Delta\theta + d(\Delta\theta)$ by a lens at redshift z to $z + dz$ be δp , and the probability

of multiple imaging be the integral of δp over $\Delta\theta$ and z . Then for a statistical sample that contains N_L lensed sources and N_U unlensed sources, the likelihood L of the observation given the statistical lensing model, including the background cosmology, is

$$\ln L = \sum_{k=1}^{N_L} \ln(1 - p_k) + \sum_{l=1}^{N_U} \ln \delta p_l. \quad (1)$$

The differential and integrated lensing probabilities depend on both the properties of galaxies and on the underlying cosmological model through proper time element and angular-diameter distances (see, e.g., Chae 2003), so that the above likelihood has dependence on cosmological parameters under consideration.

The action for the scalar-field model of Peebles & Ratra (1988) is given by

$$S = \int d^4x \sqrt{-g} \left[\frac{m_p^2}{16\pi} \left(-R + \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} \kappa m_p^2 \phi^{-\alpha} \right) + \mathcal{L} \right], \quad (2)$$

where ‘‘natural units’’ (i.e., $\hbar = c = 1$) are adopted, the Planck mass $m_p = G^{-1/2}$ (G is Newton’s gravitational constant), \mathcal{L} is the Lagrangian density for matter and radiation, and $\kappa > 0$ and $\alpha > 0$ are the parameters characterizing the scalar-field inverse power-law potential energy density. For a spatially flat cosmological model, equation (2) yields the following equations of motion:

$$\begin{aligned} \ddot{\phi} + 3 \frac{\dot{a}}{a} \dot{\phi} - \frac{\kappa\alpha}{2} m_p^2 \phi^{-(\alpha+1)} &= 0, \\ \left(\frac{\dot{a}}{a} \right)^2 &= \frac{8\pi}{3m_p^2} (\rho + \rho_\phi), \\ \rho_\phi &= \frac{m_p^2}{32\pi} [(\dot{\phi})^2 + \kappa m_p^2 \phi^{-\alpha}], \\ p_\phi &= \frac{m_p^2}{32\pi} [(\dot{\phi})^2 - \kappa m_p^2 \phi^{-\alpha}], \end{aligned} \quad (3)$$

where overdots denote derivatives with respect to time, $a = a(t)$ is the cosmological scale factor, and ρ_ϕ and p_ϕ are respectively the energy density and pressure of ϕ . Cosmological quantities in the above model are computed through a combination of numerical integration, tabulation, and interpolation. Specifically, we numerically integrate the equations of motion given by equation (3) to compute $|dl/dz|$, where l is the proper time normalized by the Hubble time (see § 2.1.2 of Chae 2003). We compute and tabulate the values of $|dl/dz|$ in the three-dimensional grid spanned by $\Omega_{m,0}$, α , and z . Then the value of $|dl/dz|$ for any $\Omega_{m,0}$, α , and z is obtained by interpolation, and the angular-diameter distance between two redshifts is obtained as usual by the trivial numerical integration of $(1+z)|dl/dz|$.

3. RESULTS AND DISCUSSION

Figure 1 shows the CLASS lensing-based constraints on the parameters of the spatially-flat inverse power-law potential scalar-field dark energy cosmological model. The likelihood is maximized for $\Omega_{m,0} = 0.34$ and $\alpha = 0$ (i.e., a conventional cosmological constant). At 68% confidence, $\alpha < 2.7$ and

⁵ Chae & Mao (2003) find that if a spatially flat universe with $\Omega_{m,0} = 0.3$ and Einstein’s Λ is assumed, the CLASS data are consistent with nonevolution of early-type galaxies, since $z \sim 1$.

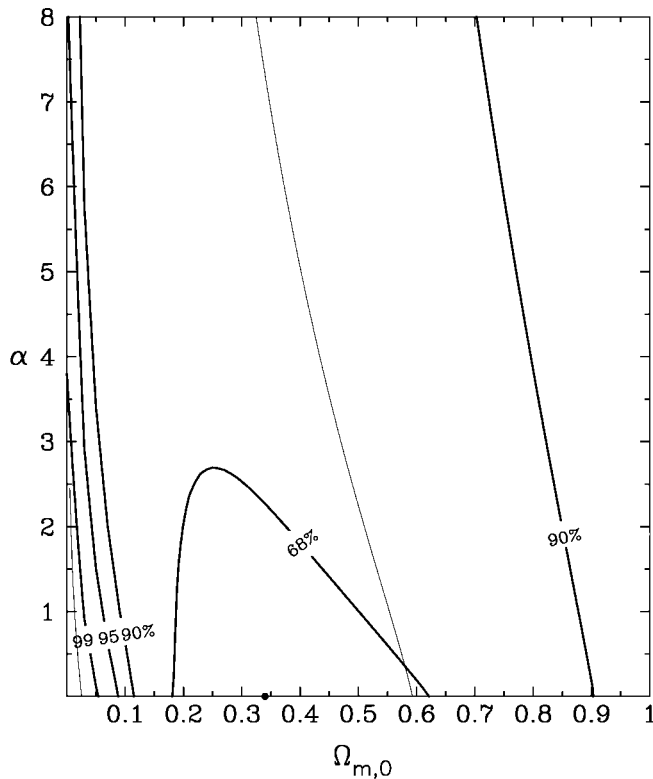


FIG. 1.—Contours of 68%, 90%, 95%, and 99% confidence based on a likelihood ratio test (only the left parts of the last two are shown, near the left-hand edge of the plot) for the spatially flat scalar-field dark energy model with potential energy density $V(\phi) \propto \phi^{-\alpha}$ at low redshift. The black dot on the horizontal axis near nonrelativistic matter density parameter $\Omega_{m,0} = 0.34$ denotes where the likelihood is maximized. Overplotted thin lines represent a 68% confidence limit by recent redshift–angular size data (Chen & Ratra 2003a), which are given for comparison. Here the confidence contours are based on the same likelihood ratio test as for the lensing data. These contours are, however, different from those of Chen & Ratra (2003a), because they are from fractions of the integrated likelihood over the whole plane, assuming a priori that the likelihood is zero outside the range $0 < \Omega_{m,0} < 1$ and $0 < \alpha < 8$.

$0.18 < \Omega_{m,0} < 0.62$.⁶ However, at 95% confidence, both $\alpha = 8$ and $\Omega_{m,0} = 1$ are allowed. As mentioned in § 2, these results are based on the assumption that the comoving number density of early-type galaxies is unchanged from $z \sim 1$. However, if there were fewer early-type galaxies at intermediate redshifts compared with the present epoch, the maximum likelihood estimate of $\Omega_{m,0}$ would become lower, and the confidence ranges for α and $\Omega_{m,0}$ would become narrower. The above results are consistent with, but not as constraining as, those derived from Type Ia supernova redshift–magnitude data (Podariu & Ratra 2000; Waga & Frieman 2000). They are also consistent with, but more constraining than, those determined using measurements of angular size as a function of redshift (Chen & Ratra 2003a; Podariu et al. 2003).

It is interesting to note that various disparate data sets give consistent constraints on the inverse power-law potential energy density scalar-field dark energy model that weakly favor the conventional cosmological constant over a dynamical scalar-field dark energy. However, current results are tentative, and future, much larger data sets are required to resolve this issue. Future lensing data (e.g., CLASS2; see § 6 of Chae 2003) would be valuable in this respect and are eagerly anticipated.

We thank the anonymous referee for constructive comments. K.-H. C. and D.-W. L. acknowledge support from the ARCSEC of KOSEF. G. C. and B. R. acknowledge support from NSF Career grant AST 98-75031 and DOE EPSCoR grant DE-FG02-00ER45824.

⁶ If the SDSS-measured VF (Sheth et al. 2003; Mitchell et al. 2004) were used instead of the SSRS2 inferred VF (Chae 2003), these ranges would be narrower, and the maximum likelihood estimate of $\Omega_{m,0}$ would be ~ 0.2 . See § 2 and K.-H. Chae (2004, in preparation) for why we choose to use the SSRS2 VF.

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