COSMOLOGICAL CONSTRAINTS FROM COMPACT RADIO SOURCE ANGULAR SIZE VERSUS REDSHIFT DATA

GANG CHEN AND BHARAT RATRA

Department of Physics, Kansas State University, 116 Cardwell Hall, Manhattan, KS 66506

Received 2002 July 1; accepted 2002 September 18

ABSTRACT

We use the Gurvits, Kellermann, & Frey compact radio source angular size versus redshift data to place constraints on cosmological model parameters in models with and without a constant or time-variable cosmological constant. The resulting constraints are consistent with but weaker than those determined using current supernova apparent magnitude versus redshift data.

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

1. INTRODUCTION

Cosmological models now under consideration have a number of adjustable parameters. A simple way to determine whether a model provides a useful approximation to reality is to use many different cosmological tests to set constraints on cosmological model parameter values and to check if these constraints are mutually consistent (see, e.g., Maor et al. 2002; Wasserman 2002).

During the past few years much attention has been focused on the Type Ia supernova apparent magnitude versus redshift test (see, e.g., Riess et al. 1998; Perlmutter et al. 1999; Leibundgut 2001). This cosmological test indicates that the energy density of the current universe is dominated by a cosmological constant, or a term in the material stress-energy tensor that varies only slowly with time and space and so behaves like $\Lambda$.

In conjunction with dynamical estimates that indicate a low nonrelativistic matter density parameter $\Omega_0$ (see, e.g., Peebles 1993), cosmic microwave background anisotropy measurements also suggest the presence of $\Lambda$ or a $\Lambda$-like term (see, e.g., Podariu et al. 2001b; Wang, Tegmark, & Zaldarriaga 2002; Baccigalupi et al. 2002; Durrer, Novosyadlyj, & Apuinevych 2003; Scott et al. 2002; Mason et al. 2002).

However, the observed rate of multiple images of radio sources or quasars produced by gravitational lensing by foreground galaxies appears to favor a smaller value for $\Lambda$ (see, e.g., Ratra & Quillen 1992; Helbig et al. 1999; Waga & Frieman 2000; Ng & Wiltshire 2001) than is indicated by the observations mentioned above. It is therefore of interest to examine the entails of other cosmological tests.

In this paper we consider the redshift–angular size test, using the Gurvits, Kellermann, & Frey (1999) compact radio source measurements. The redshift–angular size relation is measured, for structures a few orders of magnitude larger than those considered by Gurvits et al. (1999), by Buchalter et al. (1998) for quasars and by Guerra, Daly, & Wan (2000) for radio galaxies; we do not use these data sets in our analysis here. Vishvakarma (2001) and Lima & Alcaniz (2002) and references therein use the Gurvits et al. (1999) data to set constraints on cosmological parameters; our results are consistent with but, as discussed next, extend their analyses.2

Cosmological applications of the redshift–angular size test require knowledge of the linear size of the “standard candle” used. Some earlier analyses of the Gurvits et al. (1999) data appear to assume that this linear size will be determined using additional data and so quote limits on cosmological parameters (such as $\Omega_0$ or the cosmological constant density parameter $\Omega_{\Lambda}$) for a range of values of this linear size. Here we note that it is best to treat this linear size as a “nuisance” parameter (for the cosmologically relevant part of this test) that is also determined by the redshift–angular size data and so marginalize over it (using a prior to incorporate other information about it, if needed).3

In § 2 we summarize our computation. Results are presented and discussed in § 3. We present conclusions in § 4.

2. COMPUTATION

For our analyses here we use the redshift–angular size data of Figure 10 of Gurvits et al. (1999), which are binned redshift–angular size data derived from measurements of 145 sources. These measurements are combined in 12 redshift bins, with about the same number of sources per bin, with the lowest and highest redshift bins centered at redshifts $z = 0.52$ and 3.6.

We consider two cosmological models as well as a currently popular parameterization of dark energy. These are low-density cold dark matter (CDM) dominated cases, consistent with current observational indications. The first model is parameterized by two “cosmological” parameters, $\Omega_0$ and $\Omega_{\Lambda}$ (in addition to all the other usual parameters). This model includes, as special cases, two “one-parameter” models: the currently popular $\Lambda$CDM case with flat spatial hypersurfaces and $\Lambda > 0$ (see, e.g., Peebles 1984; Efstathiou, Sutherland, & Maddox 1990; Stompor, Górski, & Bandy

---

1 The proposed SNAP (Supernova Acceleration Probe) satellite should provide much tighter constraints on cosmological parameters from this test (see, e.g., Podariu, Nugent, & Ratra 2001a; Weller & Albrecht 2002; Wang & Lovelace 2001; Gerke & Efstathiou 2002; Eriksson & Amanullah 2002).

2 The Gurvits et al. (1999) data augment those of Kellermann (1993), Stelmach (1994), Stepanas & Saha (1995), Jackson & Dougson (1996), and Kayser (1995) discuss the Kellermann (1993) data.

3 The situation here is similar to that for the redshift–magnitude test (e.g., Riess et al. 1998; Perlmutter et al. 1999) where one must marginalize over the magnitude of the standard candle used, treating it as a nuisance parameter. In fact, Gurvits et al. (1999) determine the linear size from the redshift–angular size data by using the model of Gurvits (1994).
We also derive constraints on the parameters of a spatially flat model with a dark energy scalar field \( \phi \) with scalar field potential energy density \( V(\phi) \) that at low \( z \) is \( \propto \phi^{-\alpha} \), \( \alpha > 0 \). The energy density of the scalar field decreases with time, behaving like a time-variable \( \Lambda \) (see, e.g., Ratra 1988; Ratra & Peebles 1988; Steinhardt 1999; Brax, Martin, & Riazuelo 2000; Carroll 2001). 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 \( c_s^2 = dp/d\rho \), where \( p \) is the pressure and \( \rho \) is the energy density (see, e.g., Ratra 1991). The XCDM parameterization for dark energy approximates \( w \) for dark energy (see, e.g., Ratra 1991). The XCDM parameterization is recommended by its simplicity, so we also determine redshift–angular size constraints on its parameters.

We want to determine how well the Gurvits et al. (1999) redshift–angular size measurements distinguish between different cosmological model parameter values. To do this we pick one of the above models or the XCDM parameterization and a model with open spatial hypersurfaces and no \( \Lambda \) (see, e.g., Gott 1982; Ratra & Peebles 1995; Cole et al. 1997).

and 161 points, respectively; while for the XCDM parameterization we compute over the ranges \( 0 \leq \Omega_0 \leq 1 \) and \( -1 \leq w \leq 0 \), both sampled at 201 points. The confidence limits are computed from the distribution of equation (2), and we typically show 1, 2, and 3 \( \sigma \) confidence contours that correspond to enclosed probabilities of 68.27%, 95.45%, and 99.73%, respectively.

Since \( \Omega_0 \) is a positive quantity, we also consider the noninformative or logarithmic prior \( p(\Omega_0) \propto 1/\Omega_0 \) (Berger 1985; Gott et al. 2001) and compute confidence regions for the probability distribution \( L(P)/\Omega_0 \), where \( L(P) \) is given in equation (2).

3. RESULTS AND DISCUSSION

Figure 1 shows the Gurvits et al. (1999) redshift–angular size constraints on the general two-dimensional constant \( \Lambda \) case. Apparently these have not previously been published. These constraints are consistent with but mostly not as constraining as those from Type Ia supernova redshift-magnitude data, except at larger values of \( \Omega_0 \) and \( \Lambda_0 \) (see, e.g., Podariu & Ratra 2000, Fig. 5).

Figure 2 shows the redshift–angular size constraints on the XCDM parameters. Lima & Alcaniz (2002, Fig. 2) show related constraints computed at the fixed physical length \( l \) for the same Gurvits et al. (1999) data. While the shapes are similar, the Lima & Alcaniz (2002) contours are much more constraining than those found here, largely because our procedure of marginalizing over the physical length \( l \) also accounts for the uncertainty in the determination of \( l \).

Fig. 1.—Contours of 1, 2, and 3 \( \sigma \) confidence for the constant-\( \Lambda \) model. Solid lines are contours computed using the uniform prior \( p(\Omega_0) = 1 \), while short-dashed lines show the case using the logarithmic prior \( p(\Omega_0) \propto 1/\Omega_0 \) (with three contours lying on each other at the left edge). The horizontal dot-dashed line demarcates models with a vanishing cosmological constant, \( \Lambda = 0 \); the dot-dashed line running from the point \( \Omega_0 = 0, \Lambda_0 = 1 \) to the point \( \Omega_0 = 2, \Lambda_0 = -1 \) indicates the spatially flat \( \Omega_0 + \Lambda_0 = 1 \) case, and models lying in the upper left-hand corner beyond the dotted line do not have a big bang.

4 Here the Hubble constant \( H_0 = 100 \) km s\(^{-1}\) Mpc\(^{-1}\).
Podariu & Ratra (2000, Fig. 2) show corresponding constraints on the XCDM parameters from the Type Ia supernova redshift-magnitude data, which are significantly more constraining than those shown in Figure 2 here.

Figure 3 shows the constraints on the dark energy scalar field model with potential energy density $V = c_1 \phi^{c_2}$, $c_1 > 0$ (Peebles & Ratra 1988). They are consistent with but not as constraining as those from the Type Ia supernova redshift-magnitude data (Podariu & Ratra 2000; Waga & Frieman 2000).

4. CONCLUSION

Constraints on cosmological model parameters derived from the redshift–angular size compact radio source data of Gurvits et al. (1999) are consistent with but less constraining than those derived from the redshift-magnitude Type Ia supernova data of Riess et al. (1998) and Perlmutter et al. (1999).

Higher quality redshift–angular size data will more significantly constrain cosmological models and, in combination with high-quality redshift-magnitude data, will provide a check of conventional general relativity on cosmological length scales.

We are indebted to L. Gurvits for providing the binned redshift–angular size data. We acknowledge helpful discussions with J. Alcaniz, R. Daly, J. Lima, and J. Peebles, and support from NSF Career grant AST 98-75031.

REFERENCES

Baccigalupi, C., Balbi, A., Matarrese, S., Perrotta, F., & Vittorio, N. 2002, Phys. Rev. D, 65, 063520
Berger, J. O. 1985, Statistical Decision Theory and Bayesian Analysis (New York: Springer), 82
Brax, P., Martin, J., & Riazuelo, A. 2000, Phys. Rev. D, 62, 103505
Buchalter, A., Helfand, D. J., Becker, R. H., & White, R. L. 1998, ApJ, 494, 503
Carroll, S. M. 2001, Living Rev. Relativity, 4, 1
Cole, S., Weinberg, D. H., Frenk, C. S., & Ratra, B. 1997, MNRAS, 289, 37
Durrer, R., Novosyadlyj, B., & Apurweych, S. 2003, ApJ, in press
Efstathiou, G., Sutherland, W. J., & Maddox, S. J. 1990, Nature, 348, 705
Eriksson, M., & Amanullah, R. 2002, Phys. Rev. D, 66, 023530
Gerke, B., & Efstathiou, G. 2002, MNRAS, 335, 33
Gott, J. R. 1982, Nature, 295, 304
Gott, J. R., Vogeley, M. S., Podariu, S., & Ratra, B. 2001, ApJ, 549, 1
Guerra, E. J., Daly, R. A., & Wan, L. 2000, ApJ, 544, 659
Gurvits, L. I. 1994, ApJ, 425, 442
Gurvits, L. I., Kellermann, K. I., & Frey, S. 1999, A&A, 342, 378
Helbig, P., Marlow, D., Quast, R., Wilkinson, P. N., Browne, I. W. A., & Koopmans, L. V. E. 1999, A&A, 136, 297
Huterer, D., & Turner, M. S. 2001, Phys. Rev. D, 64, 123527
Jackson, J. C., & Dodgson, M. 1996, MNRAS, 278, 603
Kayser, R. 1995, A&A, 294, L21
Kellerman, K. I. 1993, Nature, 361, 134
Leibundgut, B. 2001, ARA&A, 39, 67
Lima, J. A. S., & Alcaniz, J. S. 2002, ApJ, 566, 15
Maor, I., Brustein, R., McMahon, J., & Steinhardt, P. J. 2002, Phys. Rev. D, 65, 123503
Mason, B. S., et al. 2002, ApJ, submitted (astro-ph/0205384)
Ng, S. C. C., & Wiltshire, D. L. 2001, Phys. Rev. D, 63, 023503
Peebles, P. J. E. 1984, ApJ, 284, 439
Peebles, P. J. E. 1993, Principles of Physical Cosmology (Princeton: Princeton Univ. Press)
Peebles, P. J. E., & Ratra, B. 1988, ApJ, 325, L17
Perlmutter, S., et al. 1999, ApJ, 517, 565
Podariu, S., Nugent, P., & Ratra, B. 2001a, ApJ, 553, 39
Podariu, S., & Ratra, B. 2000, ApJ, 532, 109
Podariu, S., Souradeep, T., Gott, J. R., Ratra, B., & Vogeley, M. S. 2001b, ApJ, 559, 9
Ratra, B. 1991, Phys. Rev. D, 43, 3802
Ratra, B., & Peebles, P. J. E. 1988, Phys. Rev. D, 37, 3406
Ratra, B., & Peebles, P. J. E. 1995, Phys. Rev. D, 52, 1837
Ratra, B., & Quillen, A. 1992, MNRAS, 259, 738
Ratra, B., Sugiyama, N., Banday, A. J., & Górski, K. M. 1997, ApJ, 481, 22
Riess, A. G., et al. 1998, AJ, 116, 1009
Sahni, V., & Starobinsky, A. 2000, Int. J. Mod. Phys. D, 9, 373
Scott, P. F., et al. 2002, MNRAS, submitted (astro-ph/0205380)
Steinhardt, P. J. 1999, in Proc. of Pritzker Symp. Status of Inflationary Cosmology, in press
Stelmach, J. 1994, ApJ, 428, 61
Stepanas, P. G., & Saha, P. 1995, MNRAS, 272, L13
Stompor, R., Górski, K. M., & Banday, A. J. 1995, MNRAS, 277, 1225
Vishwakarma, R.G. 2001, Classical Quantum Gravity, 18, 1159
Waga, I., & Frieman, J.A. 2000, Phys. Rev. D, 62, 043521
Wang, X., Tegmark, M., & Zaldarriaga, M. 2002, Phys. Rev. D, 65, 123001
Wang, Y., & Lovelace, G. 2001, ApJ, 562, L115
Wasserman, I. 2002, preprint (astro-ph/0203137)
Weller, J., & Albrecht, A. 2002, Phys. Rev. D, 65, 103512