GLOBAL COSMOLOGICAL PARAMETERS
MEASURED USING CLASSICAL DOUBLE RADIO SOURCES

RUTH A. DALY, ERICK J. GUERRA, & LIN WAN

Department of Physics, Princeton University,
Princeton NJ 08544, USA

Fourteen classical double radio galaxies with redshifts between zero and two were used to determine the cosmological parameters $\Omega_m$, $\Omega_\Lambda$, and $\Omega_k$, where these are the normalized values of the mean mass density, cosmological constant, and space curvature at the present epoch. A low value of $\Omega_m$ is obtained, and $\Omega_m = 1$ is ruled out with 97.5% confidence. The low value of $\Omega_m$ determined using the radio source method described here is also indicated by several independent tests. Thus, it appears that either a cosmological constant, or space curvature, is significant at the present epoch. This means that the universe is undergoing, or has recently undergone, a transition away from a state of matter domination and into a state where either a cosmological constant or space curvature is determining the expansion rate of the universe. The low value of $\Omega_m$ presented here and by Guerra & Daly (1998) means that we can state with 97.5% confidence that the universe will continue to expand forever.

1 Introduction

The structure and fate of the universe can be described by the cosmological parameters $\Omega_m$, $\Lambda$, and $k$, where $\Omega_m$ is the average density of matter in the universe at the present time divided by the critical density, $\Lambda$ is the current value of the cosmological constant (generally, though not always, taken to be time-independent), and $k$ describes the global geometry of the universe. The normalized values of $\Lambda$ and $k$ are denoted $\Omega_\Lambda$, and $\Omega_k$ (e.g. Peebles 1993). Assuming that any relativistic component, such as the microwave background radiation, has a negligible contribution to the total mass-energy density at the present time, the following equation must be satisfied: $\Omega_m + \Omega_\Lambda + \Omega_k = 1$.

As originally discussed by Dicke (1970), and later by Peebles (1993), each term evolves differently with redshift, so it is unlikely that two terms will be comparable at any given time. However, if $\Omega_m < 1$, then, the universe is undergoing a transition away from a state of matter domination into a state where either space curvature or the cosmological constant is dominant. Following Dicke’s argument, it is rather unlikely that all three terms will be significant at the present time.

The cosmological parameters can only be believably determined when several independent methods of estimating the parameters all yield similar values, both within each category of test, and comparing results from different categories. At present, there are three main categories of estimates of $\Omega_m$: (1) local, low-redshift dynamical tests; (2) tests that depend on the coordinate distance to high-redshift sources through the angular size distance or the luminosity distance;
and (3) tests using the fluctuations of the microwave background radiation on different angular scales. At the present time, values of $\Omega_m$ have been determined using methods (1) and (2); results obtained using method (1) are mentioned below. Method (2) has been applied to radio galaxies with redshifts between zero and two by Daly (1994, 1995), Guerra & Daly (1996, 1998), and is applied here to radio sources with redshifts between zero and two. Method (2) has also been applied to supernovae by Garnavich et al. (1998) and Perlmutter et al. (1998), who study sources to a redshift of about one. At some point in the future, there may be independent constraints from measurements of fluctuations of the microwave background radiation on different angular scales.

Several local, low-redshift estimates of $\Omega_m$ indicate that it is significantly less than unity (Hudson et al. 1995; Shaya, Peebles, & Tully 1995; Carlberg et al. 1997; Bahcall & Fan 1998). These tests are interesting and important, though they are all subject to caveats. Many depend on whether the mass is distributed like the light, known as “biasing,” and many local measurements only indicate the amount of mass that is clustered on the scales of galaxies and clusters of galaxies. The concordance of many local, low-redshift tests suggests that the amount of mass that clusters with galaxies is significantly less than the critical value.

Estimates of cosmological parameters that utilize the coordinate distance to sources at high redshift (category [2] defined above), such as tests involving angular size distance or luminosity distance, are fundamentally different from local, low-redshift tests. The value of $\Omega_m$ estimated through the coordinate distance, the angular size distance, or the luminosity distance, is truly the global value of $\Omega_m$. The test is independent of any biasing of matter relative to light, of how or whether the mass is clustered, of the nature of the dark matter (e.g. baryonic, cold dark matter, hot dark matter, etc.), and of the origin of fluctuations that lead to galaxy formation (e.g. cosmic strings, textures, adiabatic or isocurvature fluctuations, etc.).

Two tests currently being used to determine global cosmological parameters through the coordinate distance to high-redshift sources (category [2] defined above) are the radio source method, and the supernova method.

2 The Radio Source Method

A new way in which powerful classical double radio sources can be used to determine global cosmological parameters is described in detail by Daly (1994, 1995), and Guerra & Daly (1996, 1998). The idea is to use two independent measures of the average size of a given radio source, where the size is measured by the separation of the two radio hot spots. The two measures depend on the angular size distance to the source in different ways, so equating them allows a determination of the coordinate distance to the source, which in turn can be used to determine values for cosmological parameters.

Powerful classical radio sources form an unusually homogeneous population, and the average size, or separation between the two radio hot spots, of the sources at any given redshift exhibits a rather small dispersion. One measure of the average size of a given source is $<D>$, the average size of similar sources at the same redshift. Another measure of the average size of a source is $D_* = v_L t_*$, where $v_L$ is the average rate of growth of that source, and $t_*$ is the total time for which the highly collimated outflows of that source are powered by the AGN; this outflow leads to the large scale radio emission. Several observational properties of powerful classical double radio sources can be explained by setting $t_* \propto L_j^{-\beta/3}$ (Daly 1994). Given this parameterization, it is straight-forward to show that $D_* \propto (B_L a_L)^{-2\beta/3} v_L^{(1-\beta/3)}$, where $B_L$ and $a_L$ are the magnetic field strength and width of the radio lobe, located just behind the radio hot spot. Each of these parameters, $B_L$, $a_L$, and $v_L$ can be determined using radio data (e.g. Wellman, Daly, & Wan 1997). The best fit value of $\beta$ is about 2, in which case $D_* \propto (B_L a_L)^{-4/3} v_L^{1/3}$, as discussed in
Figure 1: The data are compared with expectations in different cosmological models on the left hand panel. Note how well the data track the curves expected in a low density universe all the way from a redshift of zero to a redshift of about 2. The one-dimensional confidence contours on the parameters $\Omega_m$ and $\Omega_\Lambda$ are shown on the right hand panel; one and two sigma constraints on either parameter can be obtained by projecting onto the appropriate axis. A universe with $\Omega_m = 1$ is ruled out with 97.5 % confidence. Lines indicating zero space curvature, zero cosmological constant, and $\Omega_m = 1$ are drawn on figure 1b. The location of the minimum of the reduced $\chi^2$ is indicated by a star.


3 Results

Clearly, $<D>$ for sources at a given redshift is proportional to the angular size distance, luminosity distance, or coordinate distance $(a_o r)$ to the sources. For $\beta \simeq 2$, $D_\ast \propto (a_o r)^{-0.8}$, so the ratio $<D>/D_\ast \propto (a_o r)^{1.8}$. For the correct choice of cosmological parameters, the ratio $<D>/D_\ast = 1$, at all redshifts. Thus, one way to compare the data with the cosmological models is to compare $(<D>/D_\ast)(a_o r)^{-1.8}$ with the curves $(a_o r)^{-1.8}$ assuming different values for the cosmological parameters. This is shown in figure 1a. It is clear that a low value of $\Omega_m$ is favored, and $\Omega_m = 1$ does not fit the data well at all. In fact, it is shown in figure 1b that $\Omega_m = 1$ is ruled out with 97.5 % confidence.

Allowing for error bars on all quantities, the best fit values of the cosmological parameters are: $\Omega_m = 0.2^{+0.3}_{-0.2}$ assuming zero space curvature ($k = 0$, $\Omega_\Lambda = 1 - \Omega_m$), and $\Omega_m = -0.1^{+0.5}_{-0.4}$ assuming zero cosmological constant ($\Lambda = 0$, $\Omega_k = 1 - \Omega_m$). These values can be obtained by projecting the one-dimensional fits, shown in figure 1b, onto their respective axes. Allowing $\Omega_\Lambda$ and $\Omega_k$ to vary simultaneously, the confidence levels for each parameter are shown on figure 1b in such a way that the one and two sigma constraints on each can be obtained by projecting onto the appropriate axis.
4 Discussion

The constraints on cosmological parameters obtained here arise primarily from the relative position of the data points as a function of redshift, and are not sensitive to any particular point, or to the normalization of the curves (which is left as a free parameter in the fits). For example, if the one low-redshift point near $z = 0$ is excluded, the results do not change (see Guerra & Daly 1998). It is clear from figure 1a that the radio source model is working extremely well; the data fall right along the cosmological curves all the way from zero redshift to a redshift of about two. It is clear from figure 1b that, given this data, it is very unlikely that $\Omega_m = 1$.

The results presented here are very similar to those obtained by the supernovae groups. Any potential problems, such as dust extinction or evolution, are completely different for the two methods. The fact that they yield nearly identical results suggests that both are correct. In addition, the low value of $\Omega_m$ obtained using this method agrees with the low values indicated by local dynamical tests, which further suggests that $\Omega_m$ is low, and the universe will continue to expand forever.

We are in the process of obtaining radio information on 67 additional radio galaxies with redshifts between zero and two. With these additional sources we will be able to constrain cosmological parameters to very high accuracy.

Acknowledgments

It is a pleasure to thank Rick Perley and Ruth Durrer for helpful conversations. This work was supported in part by the US National Science Foundation, the Independent College Fund of New Jersey, and a grant from Mark M. Wheeler III.

References