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Radio galaxies and the acceleration of the universe beyond a redshift of one

Ruth A. Daly *

Department of Physics, Berks-Lehigh Valley College, Penn State University, Tulpehocken Road, Reading, PA 19610-6009, USA

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Abstract

Radio galaxies provide a means to determine the coordinate distance, the luminosity distance, the dimension-less luminosity distance, or the angular size distance to sources with redshifts as large as two. Dimensionless coordinate distances for 55 supernovae and 20 radio galaxies are presented and discussed here. The radio galaxy results are consistent with those obtained using supernovae, suggesting that neither method is plagued by unknown systematic errors. The acceleration parameter $q(z)$ and the expansion rate $H(z)$ or dimensionless expansion rate $E(z)$ can be determined directly from the data without having to make assumptions regarding the nature or evolution of the ‘‘dark energy’’. The expansion rate $E(z)$ can be determined from the first derivative of the dimensionless coordinate distance, $(\mathrm{d}y/\mathrm{d}z)^{-1}$, and the acceleration parameter can be determined from a combination of the first and second derivatives of the dimensionless coordinate distance. A model-independent determination of $E(z)$ will allow the properties and redshift evolution of the ‘‘dark energy’’ to be determined, and a model-independent determination of $q(z)$ will allow the redshift at which the universe transitions from acceleration to deceleration to be determined directly. Determination of $E(z)$ and $q(z)$ may also elucidate possible systematic errors in the determinations of the dimensionless coordinate distances.

Keywords: Radio galaxies; Acceleration of the universe; Redshift of one

1. Introduction

A primary goal of current cosmological studies is to determine whether the expansion of the universe is accelerating or decelerating at the present epoch, and what the acceleration or deceleration rate is. From this, we can determine the global cosmological parameters, and study how structure evolved.

One way to improve our understanding of the recent history of the universe, and begin to quantify the properties of the ‘‘dark energy’’, is to observationally determine the redshift at which the universe transitions from acceleration to deceleration if is established that the expansion of the universe is accelerating at the present epoch. ‘‘dark energy’’ is discussed, for example, by Caldwell et al. (1998), Turner and Riess (2002), Frieman et al. (2002), Peebles and Ratra (2002), and Peebles (2002).

Since astrophysics is a ‘‘spectator science’’, for which we can only collect data but cannot design and control experiments, unknown systematic errors are always a worry. The only way to convincingly establish a result is to have independent determinations that agree.

2. The basics

The Robertson–Walker metric describes an expanding (or contracting) homogeneous and isotropic spacetime, and has the line element

$$\mathrm{d}\tau^2 = \mathrm{d}t^2 - a^2(t)\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\theta^2 + r^2\sin^2\theta\,\mathrm{d}\phi^2\right) \quad (1)$$

* Tel.: +1-610-396-6273; fax: +1-610-396-6024.
E-mail address: rdaly@psu.edu.

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(see, for example, Weinberg, 1972), where the cosmic scale factor $a(t)$ is related to the source redshift z and the current value of the cosmic scale factor a_0: $(a(t)/a_0) = (1 + z)^{-1}$. For light traveling from a source with redshift z along a radial path, Eq. (1) implies that the coordinate distance to the source, $a_0 r$ can be obtained by integrating the equation

$$dr/\sqrt{1-kr^2} = dt/a(t). \tag{2}$$

In this universe, a source at redshift z, with intrinsic physical size D, and luminosity L, will have an observed angular size θ given by $\theta = D(1 + z)/(a_0 r) = D/d_A$, where d_A is the "angular size distance" $d_A = (a_0 r)/(1 + z)$ and $(a_0 r)$ is the coordinate distance to the source. The flux f that could be detected from the source is given by $f = L/[4\pi(a_0 r)^2(1+z)^2] = L/[4\pi d_L^2]$, where d_L is the "luminosity distance", $d_L = (a_0 r)(1+z) = H_0^{-1} y(z)(1+z)$; $y(z) = H_0 a_0 r$ is the dimensionless coordinate distance (see for example, Peebles, 1993).

Thus, if d_A or d_L to a source at redshift z can be observationally determined, then the coordinate distance $(a_0 r)$ and the dimensionless coordinate distance $y(z)$ to that redshift are known.

The coordinate distance is related to the cosmological parameters through the equations $a_0 \int dr/\sqrt{1-kr^2} = \int (a/\dot{a}) dz$, and $(\dot{a}/a) = H_0 E(z)$. For $k = 0$, the coordinate distance is $(a_0 r) = H_0^{-1} \int dz/E(z)$. For a universe with components for which the equations of state w_i are time independent, such as a universe with quintessence (Caldwell et al., 1998) $E^2(z) = \sum \Omega_i (1+z)^{n_i}$, where $w_i = P_i/\rho_i$, and $n_i = 3(1 + w_i)$ for a component with non-evolving equation of state (see, for example, the Appendix of Daly and Guerra, 2002). The deceleration parameter at the present epoch is $q_0 = -\ddot{a} a_0/\dot{a} = 0.5 \sum \Omega_i (1 + 3w_i)$, when w_i is time independent.

Thus, one way to determine the cosmological parameters Ω_i and the equations of state w_i, is to determine the coordinate distance to high-redshift sources, then use equations given above, and solve for the cosmological parameters that yield the observed coordinate distances. If the equation of state is time-dependent, or if a rolling scalar field such as that proposed by Peebles and Ratra (1988) is considered, then these equations must be modified accordingly as discussed, for example, by Peebles and Ratra (2002).

The cosmological parameters determined using this method then go into the equation for q_0 to determine whether the universe is accelerating or decelerating today. The equation for $q(z)$, which is very similar to that for q_0, then allows a determination of the redshift at which the acceleration is expected to go through zero, which marks the redshift at which the universe transitions from acceleration to deceleration.

A method of using the observed coordinate distances to go directly to the acceleration parameter as a function of redshift will be described below. And, a method of using the data directly to determine the function $E(z)$ without making any assumptions about the nature or redshift evolution of the dark energy will also be discussed.

The beauty of using coordinate distance measurements to determine the cosmological parameters Ω_i is that the true global cosmological parameters are determined; no corrections need to be made for the clustering properties of matter, so that contributions to Ω_i cannot be missed or miscounted, and there are no biasing issues.

3. The radio galaxy and supernova methods

Two methods currently being used to constrain global cosmological parameters through the determination of the coordinate distance to high-redshift sources are the Type Ia Supernova method (e.g., Perlmutter et al., 1999; Riess et al., 1998), and the Type FRIIb Radio Galaxy method (e.g., Daly and Guerra, 2002).

For Type Ia Supernovae, there is one model parameter α, which goes into the determination of m_B^{eff}, the effective apparent B band magnitude of the supernova at maximum brightness. This is related to the Hubble-constant free luminosity distance D_L via the equation

$$m_B^{\text{eff}}(\alpha) = \mathscr{M}_{\mathscr{B}} + 5 \log (D_L[\Omega_i, w_i]). \tag{3}$$

If quintessence is being considered (e.g., Caldwell et al., 1998), then w_i would represent the equation of state, and if an evolving scalar field is being considered, such as that proposed and studied by Peebles and Ratra (1988), then w_i would be evolving with redshift (and would represent their parameter α).

$\mathscr{M}_{\mathscr{B}}$ is a constant obtained by fitting all of the data; it is related to the standard absolute magnitude of the peak brightness of a supernova M_B : $\mathscr{M}_{\mathscr{B}} = M_B + 25 - 5\log(H_0)$ (see Perlmutter et al., 1999). For $k = 0$, and allowing for non-relativistic matter and quintessence, there are $(N - 4)$ degrees of freedom; this is also the case for a universe with an evolving scalar field such as that discussed by Peebles and Ratra (1988), or a universe with space curvature, a cosmological constant, and non-relativistic matter.

The Hubble-constant-free luminosity distance D_L is related to the dimensionless coordinate distance $y(z)$ via the relation $y(z)(1 + z) = D_L = H_0 d_L$.

For FRIIb radio galaxies, there is one model parameter *beta*, which goes into the determination of the ratio $R_* = \langle D \rangle / D_*$ (Daly, 1994). This ratio also depends on the dimensionless luminosity distance D_L:

$$R_*(\beta, D_L[\Omega_i, w_i]) = \kappa. \tag{4}$$

where κ is a constant obtained by fitting all of the radio galaxy data. This fit also has $(N - 4)$ degrees of freedom.

In these fits the dimensionless luminosity distance D_L, and the dimensionless coordinate distance $y(z)$, is implicitly determined for each source, though it only factors out as a separate term when synchrotron cooling dominates over inverse Compton cooling with CMB photons in the radio bridge of the source, in which case $R_* \equiv \langle D\rangle/D_* = (\text{observables})(D_L)^{g(\beta)}$, where $g(\beta) = 3/7 + 2\beta/3$ (Guerra and Daly, 1998). This is not a valid approximation for all of the sources in the sample. Here, this approximation has not been adopted, and an iterative technique has been used to determine the dimensionless coordinate distance to each source. Thus, these coordinate distances are valid for all of the sources in the sample.

The dimensionless luminosity distance D_L and coordinate distance $y(z)$ has been determined using Eq. (3) for each source using the best fit value for $\mathcal{M}_{\mathcal{B}}$, obtained with the 54 supernovae in the "primary fit C" of Perlmutter et al. (1999) and the 1 high-redshift supernova published by Riess et al. (2001), with the magnitude of this source corrected for gravitational lensing (Benitex et al., 2002). The dimensionless coordinate distance $y(z)$ has been determined for each radio galaxy using Eq. (4) and the best fit values for κ and β (along with their one sigma error bars) for the 20 radio galaxies presented by Guerra et al. (2000). These dimensionless coordinate distances are shown in Figs. 1–3.

The dimensionless coordinate distances obtained for the radio galaxies are completely independent of those obtained for the supernovae. The conclusion from Figs. 1–3 is that there is good agreement between results obtained using Type Ia SN and FRIIb RG. This has also been demonstrated through detailed analyses. It is clearly the case when a cosmological constant and non-relativistic matter are considered (Guerra et al., 2000), when quintessence is considered (Daly and

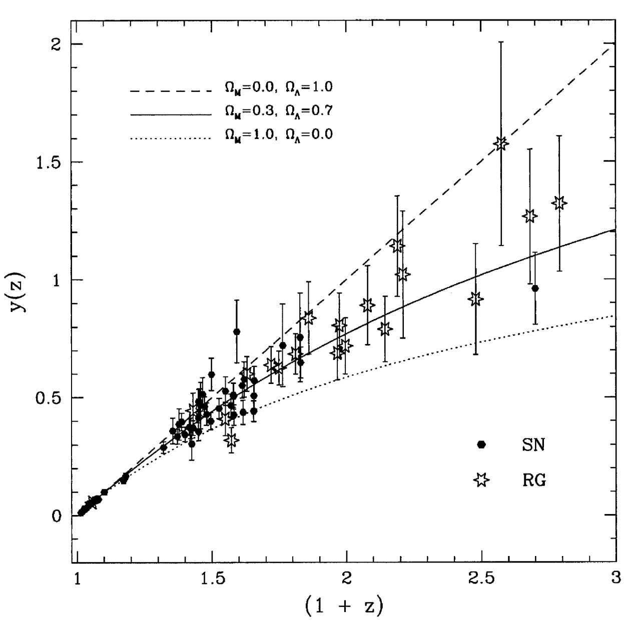

Fig. 1. Dimensionless coordinate distances $y(z)$ to 20 radio galaxies and 55 supernovae as a function of $(1 + z)$. Note that the radio galaxy and supernovae determinations of $y(z)$ are *completely independent*. Radio galaxies are shown as open stars and supernovae are shown as solid circles.

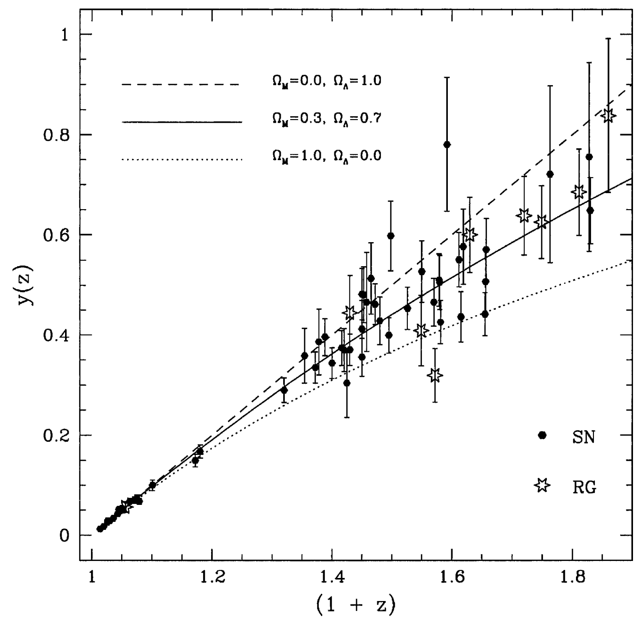

Fig. 2. Focus on the low redshift end of Fig. 1. Radio galaxies are shown as open stars and supernovae are shown as solid circles.

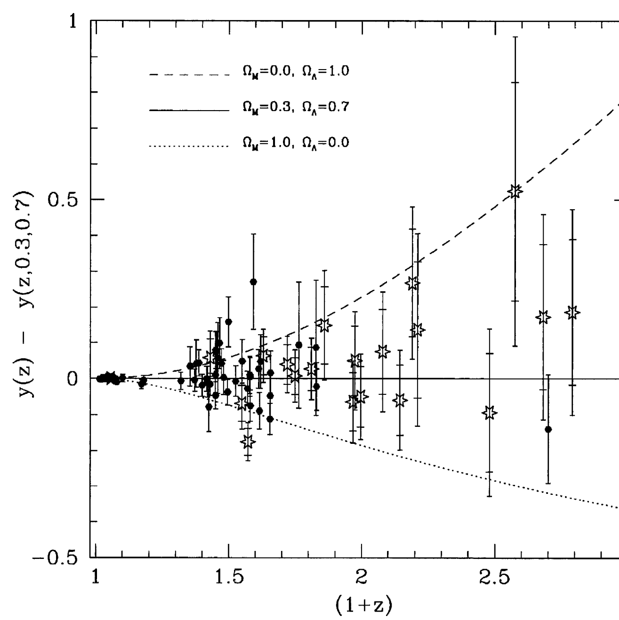

Fig. 3. The residuals between $y(z)$ and those expected in a universe with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$, where $y(z)$ is the dimensionless coordinate distance, shown as a function of $(1 + z)$. The error bars on the radio galaxies could be reduced by a factor of 1.4 as indicated on the figure if the source 3C427.1 is excluded and the reduced χ^2 is normalized to one, as discussed in detail by Podariu et al. (2003). Radio galaxies are shown as open stars and supernovae are shown as solid circles.

Guerra, 2002), and when the evolving scalar field model of Peebles and Ratra (1988) is considered (Podariu et al., 2003).

The results shown here, obtained using 20 FRIIb radio galaxies obtained from the published literature and the VLA archive, will be improved and extended with 10 new sources that will be observed by O'Dea, Guerra, Daly, and Donahue at the VLA.

Radio sources are observed out to very high redshift, and it would be easy to push this test to redshifts of three or four. The only thing that would be required would be a week or two of observing time at the VLA, followed by data analysis. This is not very demanding in terms of time, manpower, and funding.

4. A model-independent determination of *q*(*z*)

The current method used to study the acceleration of the universe is to take the measured $y(z)$ or $D_L(z)$, determine best-fitting global cosmological parameters, and then use these global cosmological parameters to determine the acceleration of the universe as a function of redshift. In this process, assumptions must be made concerning the nature and redshift evolution of the mass–energy density of the "dark energy".

A direct, empirical determination of the acceleration of the universe as a function of redshift can be determined using the data, without making any assumptions about the nature or evolution of the "dark energy". This can be done using the equation

$$-q(z) \equiv \ddot{a}a/\dot{a}^2 = 1 + (1+z)(\mathrm{d}y/\mathrm{d}z)^{-1}(\mathrm{d}^2y/\mathrm{d}z^2) \qquad (5)$$

valid for $k = 0$; if $k \neq 0$, another term $[kr(1+z)/(1-kr^2)](\mathrm{d}r/\mathrm{d}z)$ must be added to the right hand side. Here, y is the dimensionless coordinate distance $y = H_0(a_0r)$.

Thus, Eq. (5) can be used to empirically determine the redshift at which the universe transitions from acceleration to deceleration without requiring assumptions regarding the nature and redshift evolution of the "dark energy". The supernova and radio galaxy data allow a determination of the dimensionless coordinate distance y to each source, at redshift z. These data can then be used to determine $\mathrm{d}y/\mathrm{d}z$, and $\mathrm{d}^2y/\mathrm{d}z^2$; these can then be substituted into Eq. (5) to determine $q(z)$.

Eq. (5) follows from the RW line element and the relation $(1+z) = a_0/a(t)$. Our measurements of the coordinate distance (a_0r) move along the negative direction of $\mathrm{d}r$, so Eq. (2) with $k = 0$ implies that $a_0\mathrm{d}r = -(1+z)\mathrm{d}t$, or $(\mathrm{d}z/\mathrm{d}t) = -a_0^{-1}(1+z)(\mathrm{d}r/\mathrm{d}z)^{-1}$. Differentiating $(1+z) = a_0/a(t)$ with respect to time implies that $\dot{a} = -a_0(1+z)^{-2}(\mathrm{d}z/\mathrm{d}t)$. Substituting in for $(\mathrm{d}z/\mathrm{d}t)$, we find $\dot{a} = (1+z)^{-1}(\mathrm{d}r/\mathrm{d}z)^{-1}$. Differentiating again with respect to time, we find $\ddot{a} = -(1+z)^{-2}(\mathrm{d}z/\mathrm{d}t)(\mathrm{d}r/\mathrm{d}z)^{-1} \times [1 + (1+z)(\mathrm{d}r/\mathrm{d}z)^{-1}(\mathrm{d}^2r/\mathrm{d}z^2)]$, which simplifies to Eq. (5) using the expressions given here, and the relation $y(z) = H_0(a_0r)$. Note, these expressions include the well-known equation (e.g., Peebles, 1993; Weinberg, 1972)

$$H(z) = \dot{a}/a = \sqrt{1-kr^2}[d(a_0r)/\mathrm{d}z]^{-1}, \qquad (6)$$

or, for $k = 0$ and with $H(z) = H_0E(z)$,

$$E(z) = (\mathrm{d}y/\mathrm{d}z)^{-1}. \qquad (7)$$

Since Eqs. (5)–(7) are derived without any assumptions regarding the mass–energy components of the universe or their redshift evolution, they can be used to directly determine the function $E(z)$, which contains important information on the "dark energy" and its redshift evolution, and to determine the dimensionless acceleration parameter $q(z)$ directly from measurements of $y(z)$. The use of the data to directly determine $E(z)$ and $q(z)$ is underway.

5. Details of the Radio Galaxy Method

The Radio Galaxy Method relies on a comparison of the average size of an FRIIb source determined by the mean size $\langle D\rangle$ of the full population at that redshift $[\langle D\rangle \propto (a_0r)]$, and the average source size, D_*, determined using a physical model that describes the evolution of the source. The two measures of the average source size should track each other, so $\langle D\rangle/D_*$ should remain constant, independent of redshift. The ratio depends upon observed quantities, the coordinate distance and the model parameter β. When inverse Compton cooling with CMB photons is negligible, then $R_*\langle D\rangle/D_* = (\mathrm{Observables})(a_0r)^{2\beta/3+3/7}$ (Guerra and Daly, 1998). However, this is not a good approximation for all of the sources in the radio galaxy sample. Therefore, this approximation has not been adopted here, and the full equation $R_* = k_0y^{(6/\beta-1)/7}(k_1y^{-4/7}+k_2)^{(\beta/3-1)}$, where k_0, k_1, and k_2 represent directly observed quantities, has been used to solve for $y(z)$ to each source.

Details of the model are discussed by Daly and Guerra (2002), Guerra et al. (2000), Guerra and Daly (1998), and Daly (1994). The physics of FRIIb sources is discussed at length by Daly (2002).

In brief, the average size of a given source is $D_* = v_Lt_*$, where t_* is the total time that the AGN produces large-scale jets. Several different lines of argument, reviewed by Daly and Guerra (2002), suggest that $t_* \propto L_j^{-\beta/3}$, where L_j is the beam power of the source. If this relation is assumed, then $D_* \propto (B_La_L)^{-2\beta/3} v_L^{1-\beta/3} \propto y^{-6\beta/7+8/7}(k_1y^{-4/7}+k_2)^{1-\beta/3}$. For a typical value of β of 1.7, $D_* \propto (B_La_L)^{-1.1}v_L^{0.4}$.

Note that the length of the source, D, does not enter into our determination of D_*. Of course, D does enter into the determination of $\langle D\rangle$.

The determination of the most uncertain of these parameters, v_L, can be studied using Chandra data, since Chandra data can be used to determine or constrain the ambient gas density n, and the radio galaxy model assumes that $v_L^2 \propto B_L^2/n$. This is discussed in Section 6.

The assumption that $t_* \propto L_j^{-\beta/3}$ is consistent with models of jet production via the electromagnetic extraction of the spin energy from a rotating black hole. Daly and Guerra (2002) show that this relation results if the magnetic field strength in the vicinity of the rotating black hole is given by $B \propto (a/m)^{\beta/(3-\beta)} \times M^{(2\beta-3)/(2(3-\beta))}$, or $B \propto (a/m)$ for $\beta = 1.5$, and $B \propto (a/m)^2 M^{0.5}$ for $\beta = 2$, where a is the spin angular momentum per unit mass, m is the gravitational radius of the black hole, and M is the mass of the black hole (see Blandford, 1990).

The two other key assumptions of the radio galaxy model, that all FRIIb classical doubles at a given redshift have a similar maximum or average size so that the average size of a given source will be close to that of full population at that redshift, and that strong shock physics applies near the forward region of the radio source, have been tested empirically, and are consistent with the data.

6. Tests of the radio galaxy model

Three tests of the radio galaxy model and method are underway. These are tests using Chandra X-ray data; tests based on a detailed analysis of radio maps at multiple frequencies; and tests using a detailed comparison of radio maps with results from numerical simulations.

Chandra X-ray data can be used to study the ambient gas density, which can be compared with that predicted. Donahue et al. (2003) have completed Chandra studies of 3C 280 (a radio galaxy) and 3C 254 (a radio loud quasar). The predicted ambient gas densities are consistent with the three sigma upper bounds placed by the Chandra data. Other radio predicted ambient gas densities will be compared with Chandra observations and bounds.

Ten new RG with redshifts between 0.4 and 1.3 will be observed with the VLA in collaboration with Chris O'Dea, Eddie Guerra, and Megan Donahue. These high-resolution observations will allow several tests of the RG model, and will be compared with detailed numerical simulations tailored to match the properties of these sources, which is being done in collaboration with Joel Calvalho and Chris O'Dea. These studies will be based on the numerical work of Carvalho and O'Dea (2002a,b), and will help to identify the physical processes that must be accounted for the in modeling FRIIb sources.

In addition, complete radio galaxy samples of FRIIb sources that go to redshifts of three or four will be investigated. These could serve as the parent populations in the application of the RG method to redshifts greater than two. This could take us to very high redshift very quickly since radio observations are relatively quick, easy, and do not require major new instruments.

7. Conclusions

In a spatially flat universe with non-relativistic matter and quintessence, radio galaxies alone indicate with 84% confidence that the universe is accelerating in its expansion at the present epoch (Daly and Guerra, 2002). Results obtained using the Radio Galaxy Method out to redshifts of two are consistent with those obtained using the Supernova Method out to redshifts of about one.

A model-independent way to use the supernova and radio galaxy data to determine the dimensionless expansion rate $E(z)$ and acceleration parameter $q(z)$ is presented and discussed. A direct determination of $q(z)$ that is independent of assumptions regarding the nature and evolution of the "dark energy" would allow the transition redshift from acceleration to deceleration to be determined, and would help to identify any systematic errors that might plague either the radio galaxy or supernova methods. A direct determination of $E(z)$ would help to quantify the properties and redshift evolution of the "dark energy" and to identify potential systematic errors in the methods used to determine $y(z)$.

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