

A Decade of Dark Energy: 1998 - 2008

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Abstract. The years 1998 to 2008 were very exciting years for cosmology. It was a pleasure to accept this invitation to describe my contributions to the development of our knowledge and understanding of the universe over the course of the past decade. Here, I begin by describing some of my work on radio galaxies as a modified standard yardstick and go on to describe model-independent studies of the accelerating universe and the properties of the dark energy. During the course of these studies, I came upon interesting ways to study the spin and other properties of supermassive black holes, some of which are briefly mentioned.

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THE EARLY YEARS

Many scientists have contributed to our knowledge and understanding of the accelerating universe and the properties of the dark energy. In keeping with the request of the conference organizers, this paper only addresses my contributions to this field.

The years 1997 and 1998 were exciting times for cosmology! I had been studying powerful classical double radio galaxies since the early 1990s [1], and had proposed a new method of using radio galaxies as a modified standard yardstick in 1994 [2]. This work continued with Princeton University PhD thesis students Eddie Guerra, Lin Wan, and Greg Wellman, and some of this work included cosmological studies ([3], [4], [5], [6], [7]), and studies of outflows from the supermassive black holes that power the radio sources ([8], [9], [10], [11], [12]). The cosmological studies were done in the context of two cosmological world models: one that included non-relativistic matter, a cosmological constant, and space curvature, and another that included “quintessence” with constant equation of state, non-relativistic matter, and zero space curvature. Later, radio galaxies were studied in the context of a cosmological model that included a rolling scalar field, non-relativistic matter, and zero space curvature [13], [14].

The cosmological results eventually published by [6] were presented on January 9, 1998 at the AAS meeting in Washington, D. C.; the sample of twenty radio galaxies studied is briefly mentioned in AAS Bulletin Abstract 95.04. These results indicated that a cosmological constant provided a good fit to the radio galaxy data. In late 1997, Steve Maran from the AAS press office invited me to prepare a press release on cosmological studies with radio galaxies to be presented on January 8, 1998, and I accepted this invitation. The press release ¹ explains how distant radio galaxies can be used to study

¹ available at <http://www.princeton.edu/pr/news/98/index1.html> under “The Ultimate Fate of the Universe” (1/8/1998) and at <http://www.bk.psu.edu/faculty/daly>

the expansion history of the universe. For a given observed angular size of the radio source, a large intrinsic size meant that the coordinate distance to the source was large, and that the universe was accelerating in its expansion, or, in the words of the release, “the expanding universe will continue to expand forever, and will expand more and more rapidly as time goes by.” This is explained again later in the release where it states “the universe will continue to expand forever and will expand at a faster and faster rate as time goes by.”

The press release session included supernova results presented by Adam Riess and Saul Perlmutter, and I had an opportunity to discuss my conclusions with Adam and Saul in detail. They were surprised to hear that a cosmological constant provided a good fit to the radio galaxy data, which implied the universe would expand at an ever increasing rate. Each expressed a similar concern, this concern being the dependence of the result on the cosmological model or world view under consideration. The result that I was reporting on was obtained in the context of a cosmological model that allowed for non-relativistic matter, a cosmological constant, and space curvature. If different components were present in the universe, would the data still imply that the universe was accelerating? In fact, addressing this concern was part of the motivation for developing a completely model-independent approach to the analysis and interpretation of radio galaxy and supernova data (described below).

Two supernova groups showed that a cosmological constant provides a good description of the supernova data (e.g. [15], [16]). As time passed and more data were analyzed, it became clear that these two completely independent methods, FRIIb radio galaxies and type Ia supernovae, based on totally different types of sources and source physics, yield very similar results [17], [18], [19], [20], [21], [22], [23]. This was important because it suggested that neither method was plagued by unknown systematic errors.

One of the reasons the radio galaxy method provides interesting results with a relatively small number of sources is that many of the radio sources are at relatively high redshift. For example, the highest redshift source in either the radio galaxy or supernovae samples is the radio galaxy 3C 239 at a redshift of 1.79, which has been included in the radio galaxy studies since 1998 [3]. Differences between predictions of various cosmological models become large at high redshift, so high redshift data points can have a strong impact on results.

UNDERSTANDING THE RADIO GALAXY METHOD

The methods of using type Ia supernova and type IIb radio galaxies for cosmological studies are empirically based. It could be empirically demonstrated that the methods worked well, but the underlying physical processes were not understood well enough to explain why the methods worked so well. This changed in 2002 for the radio galaxies, when the reason that the radio galaxy method works so well began to become clear [7]. The radio galaxy method is applied to very powerful classical double radio galaxies, such as the radio source Cygnus A (3C 405). These FRIIb radio galaxies are powered by very energetic, highly collimated outflows from regions very close to a supermassive black hole located at the center of a galaxy. When the collimated outflow impacts the ambient gas, a strong shock wave forms, and a shock front separates the radio emitting

material from the ambient gas [1]. The physics of strong shocks is fairly simple and straight-forward, and makes these systems ideal for cosmological studies.

Large-scale outflows from supermassive black holes are thought to be powered by the spin energy of the hole (e.g. [24], [25], [26]). When [7] cast the radio galaxy method in the language of the Blandford-Znajek model to extract the spin energy from a rotating black hole [24], it became clear that the outflow from the hole occurs when the strength of the magnetic field near the hole reaches a maximum or limiting value. This value can be written as a function of the black hole mass, spin, and the radio galaxy model parameter, β . When the radio galaxy model parameter has one particular value, $\beta = 1.5$, the relationship between the magnetic field strength and the properties of the rotating hole is greatly simplified, and the field strength depends only upon the black hole spin. Empirical studies by [7] and [14] found that the value of β is very close to 1.5, $\beta \simeq 1.5 \pm 0.15$. Thus, the reason the radio galaxy model works so well is that the outflow from the supermassive black hole is triggered when the magnetic field strength reaches a maximum or limiting value that depends only upon the black hole spin. Interestingly, other models, such as that by [27], have the same functional form as the Blandford-Znajek model [24] but with a different constant of proportionality, and the results of [7] apply to any model with the same functional form as the Blandford-Znajek model.

THE MODEL- INDEPENDENT APPROACH

From 1998 to 2002 the study of the acceleration of the universe was done in the context of particular cosmological world models, and the question of whether the acceleration of the universe could be studied independent of a particular cosmological model and independent of a theory of gravity captivated my interest. To address this question, I worked to develop an assumption-free, or model-independent, method of analyzing supernova, radio galaxy, or other data sets that provide coordinate distances. The method was proposed in 2002 [18], and, in collaboration with George Djorgovski, was developed and applied to supernova and radio galaxy data sets [19], [20], [21], [22], [23].

Assuming only that the Friedmann-Lemaître-Robertson-Walker (FLRW) line element is valid, coordinate distance measurements can be used to obtain the expansion and acceleration rates of the universe as functions of redshift. Coordinate distance measurements are easily obtained from luminosity distances or angular size distances to any type of source (e.g. supernovae or radio galaxies). The FLRW line element is the most general metric describing a homogeneous and isotropic four-dimensional space-time. These determinations of the expansion and acceleration rates of the universe are independent of a theory of gravity, and independent of the contents of the universe ([18], [19]). It was shown by [23] that the zero redshift value of the dimensionless acceleration rate of the universe is independent of space curvature, and that very similar results are obtained for the dimensionless acceleration rate $q(z)$ and the expansion rate of the universe $H(z)$ for zero and reasonable non-zero values of space curvature. Thus, the model-independent method can be applied without requiring that space curvature be set equal to zero.

It was shown by [19], [20], [21], [22], and [23] that the universe is accelerating today and was most likely decelerating in the recent past, and this result is independent of a theory of gravity, of the contents of the universe, and of whether space curvature is

non-zero (for reasonable non-zero values).

Recent determinations of $H(z)$ and $q(z)$ obtained using the model-independent method are compared with predictions in a standard Lambda Cold Dark Matter (LCDM) model in Fig. 1 (the thin solid line shows the LCDM prediction). These results indicate that the LCDM model provides a good description of the data to a redshift of about one (e.g. [19], [20], [21], [22], [23]). The LCDM model assumes that General Relativity (GR) is the correct theory of gravity, space curvature is equal to zero, and two components contribute to the current mass-energy density of the universe, a cosmological constant and non-relativistic matter with 70 % and 30 %, respectively, of the normalized mean mass-energy density of the universe at the current epoch. As discussed by [23], a comparison of model-independent determinations of $H(z)$ and $q(z)$ with predictions in the LCDM and other models provides a large-scale test of GR. Current observations suggest that GR provides an accurate description of the data over look back times of about ten billion years [23]. There is a hint of a deviation of the data from predictions in the LCDM model at redshifts of about one ([20], [23]).

The model-independent approach can be extended to solve for the properties of the dark energy as a function of redshift [20], where the “dark energy” is the name given to whatever is causing the universe to accelerate. Assuming that GR is valid on very large length scales, and that space curvature is zero, supernova and radio galaxy data can be used to solve for the pressure, energy density, equation of state, and potential and kinetic energy densities of the dark energy as functions of redshift ([20], [23]), as shown in Fig. 2. Results obtained using the model-independent approach can provide valuable information to theorists developing new ideas to explain the acceleration history of the universe and the properties of the dark energy. This is complementary to the commonly adopted approach of assuming a particular dark energy model and cosmological world model and solving for best fit model parameters (e.g. [15], [16], [4], [6], [7], [13], [14]).

In studies of the properties of the dark energy, the equation of state of the dark energy has surfaced as an important parameter. A cosmological constant has an equation of state that is always equal to -1 . To study the equation of state of the dark energy in a model-independent manner, [23] defined a new model-independent function, called the dark energy indicator. The dark energy indicator provides a measure of deviations of the equation of state from -1 as a function of redshift. Current data suggest that a value of $w = -1$ provides a good description of data at redshift less than 1 (see Fig. 2).

SUPERMASSIVE BLACK HOLES AND THEIR SPINS

The radio galaxies described above are powered by large-scale outflows from the vicinity of supermassive black holes. Studies of the properties of a radio galaxy allow the energy per unit time, known as the “beam power,” that is being channeled from the vicinity of the supermassive black hole to the large-scale outflow to be determined. Studies of the beam power and other source properties provide important insights and information on these black hole systems (e.g. [12], [28], [29]).

For example, the beam power can be combined with the radio galaxy model parameter β to solve for the total energy that will be channeled away from the vicinity of the supermassive black hole over the full lifetime of the outflow (e.g. [12], [7], [29]). The

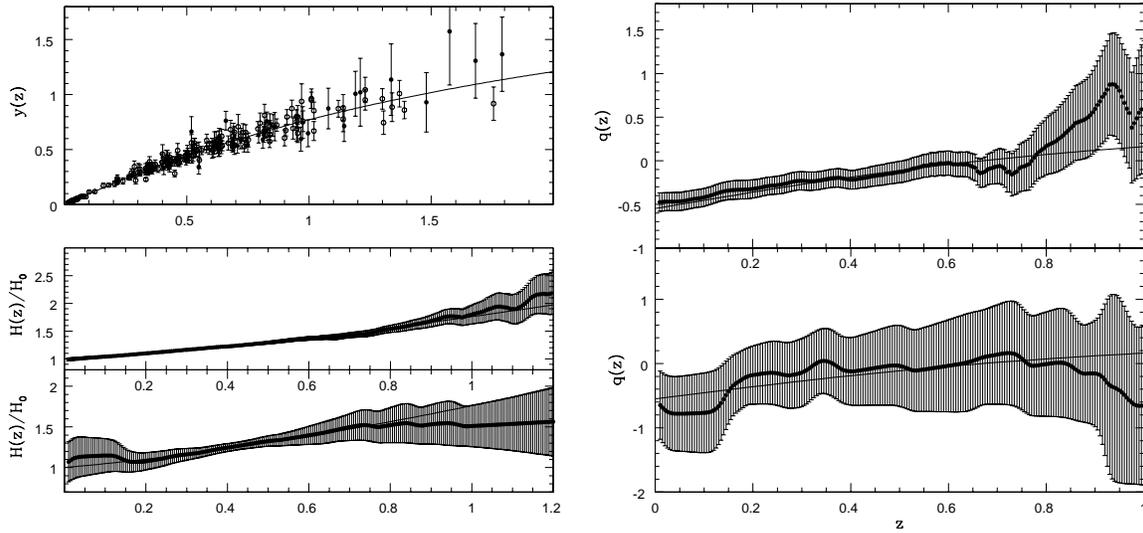


FIGURE 1. Dimensionless coordinate distances (filled symbols indicate radio galaxies and open symbols indicate supernovae), $H(z)$ for supernovae (middle left panel) and radio galaxies (bottom left panel), and $q(z)$ for supernovae (top right panel) and radio galaxies (bottom right panel); from Daly et al. (2008).

total energy of the outflow can be combined with the black hole mass to obtain a lower bound on the spin of the supermassive black hole [30], assuming only that the highly collimated outflow is powered by the spin energy of the supermassive black hole. This is one of the very few direct indications of the spin of supermassive black holes known at present. The ratio of the total outflow energy to the black hole mass appears to be constant for these black hole systems. This ratio provides an important diagnostic of the physical state of the black hole system at the time the outflow is generated, and the results of [30] indicate that each system is in a similar physical state when the outflow is triggered. Thus, these studies provide insights into the physical conditions of supermassive black holes systems and their state at the time powerful outflows are generated.

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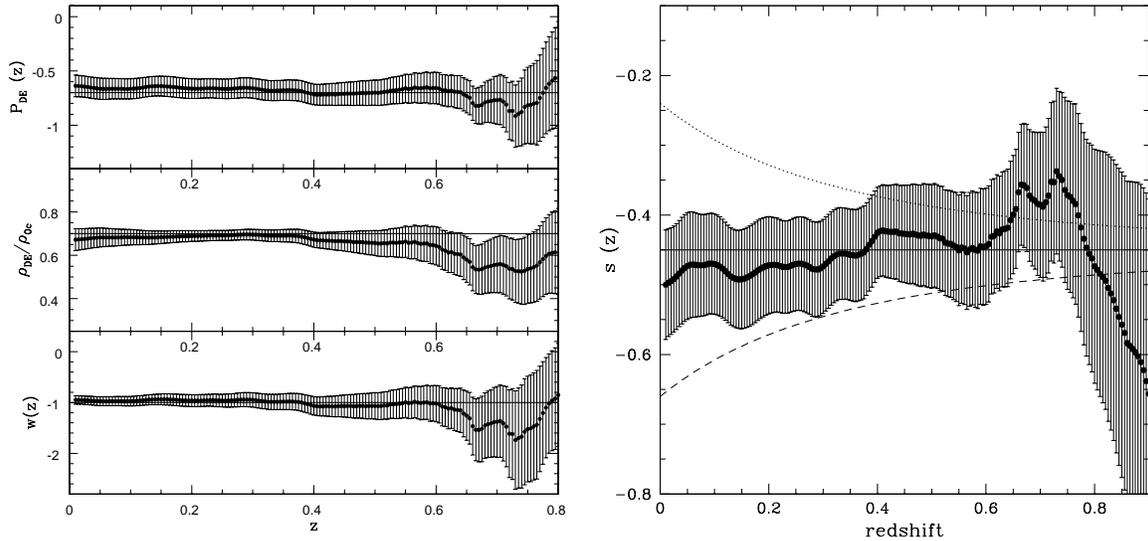


FIGURE 2. Dark energy pressure (top left panel), energy density (middle left panel), and equation of state (bottom left panel), and the dark energy indicator (right panel) as functions of redshift for a combined sample of supernovae and radio galaxies; from Daly et al. (2008).

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