POWERFUL EXTENDED RADIO SOURCES: A GOLDMINE FOR COSMOLOGY

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Abstract.

The radio properties of powerful extended radio sources may be used to study the environments of the sources, the source energetics, a characteristic length-scale that can be used as a cosmological tool, and the relation between radio galaxies and radio loud quasars. Thus, these sources offer a rich variety of diagnostics, both direct and indirect, of the cosmological model that describes our universe. They, indeed, are a goldmine for cosmology.

Perhaps the most significant result of the investigations mentioned here is the use of the radio properties of the sources to estimate the ambient gas density in the vicinity of the radio lobe. As discussed below, the ambient gas densities estimated using the strong shock jump conditions across the radio lobe indicate that these sources lie in relatively dense gaseous environments, similar to the intracluster medium found in clusters of galaxies at low redshift. Thus, the observations suggest that at least some clusters with their intracluster medium in place exist at high redshift.

1. Introduction

Several key cosmological questions remain unanswered at the present time. One piece of the cosmological puzzle is the history of the formation and evolution of structure in the universe. Radio sources can be used to study gas-rich environments and the evolution of these environments with redshift. This has implications for the epoch of cluster formation, which in

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turn has implications for models of structure formation and evolution. For example, structure formation is expected to occur rather late in models with $\Omega = 1$, and relatively early in open models with low values of Ω.

To study the distant universe, it is necessary to understand the sources that we use as probes of the state and structure of the distant universe. Radio observations may be used to estimate the rate at which energy is deposited to the radio hotspot, and to study whether the source energetics vary systematically with redshift, as described below.

At the present time it is unknown whether the universe is open and will continue to expand forever, $\Omega < 1$, the universe is of critical density, $\Omega = 1$, or the expansion will halt and the universe recollapse, $\Omega > 1$; here Ω refers to the ratio of the mean mass density of the universe to the critical density. The remarkable properties of powerful extended radio sources suggest that these sources may be used to define a calibrated yardstick for each source (Daly 1994a). The comparison of the physical size of the radio source, estimated from the angular size of the source and the coordinate distance to the source, with the calibrated yardstick indicates whether the universe is open or closed, since the calibrated yardstick is independent of the angular source size and is either independent of or inversely proportional to the coordinate distance to the source (Daly 1994a,b).

Finally, the detailed comparison of radio galaxies and radio loud quasars sheds light on the similarities and differences between these types of active galactic nuclei (AGN). It is of interest to know whether both types of source are drawn from a single parent population. If the sources emit radiation anisotropically, then the observer might identify the source as a radio galaxy or a radio loud quasar depending on their orientation relative to the source. Alternatively, it is possible that some radio galaxies are intrinsically different from radio loud quasars, and that orientation effects plus other parameters are needed to describe the differences between powerful extended radio sources that are galaxies and quasars.

Many of the results discussed here are presented and discussed in more detail by Daly (1990, 1994a,b).

2. The Basic Model and Summary of Results

The basic model for double-lobe radio sources has been discussed by many authors (see Begelman, Blandford, & Rees 1984 and references therein). The AGN emits a highly collimated outflow in two opposite directions; this causes a strong shock wave to propagate into the ambient medium and the source size grows with time. This also provides the energy needed to produce relativistic electrons and magnetic fields that cause the source to be a powerful radio emitter. Radio sources with 178 MHz radio powers greater than about (10^{26} to 10^{27}) h^{-2} W Hz^{-1} sr^{-1} have morphologically simple and regular radio bridges indicating little backflow and little lateral expansion (Leahy & Williams 1984), in which case the rate of growth of the source estimated from the synchrotron and inverse Compton aging of the relativistic electrons across the radio bridge is a measure of the rate of growth of the radio bridge, which is referred to as the lobe propagation velocity. The lobe propagation velocities of these powerful sources indicate that they propagate supersonically relative to the ambient medium (Alexander & Leahy 1987). Thus, the strong shock jump conditions can be applied to these types of sources.

The strong shock jump conditions indicate that: $n_a v_L^2 \propto P_L \propto B^2$ where n_a is the ambient gas density just beyond the radio lobe, v_L is the lobe propagation velocity, P_L is the pressure in the lobe, and B^2 is a measure of the lobe pressure when the magnetic field B in the radio lobe is in rough equipartition with the relativistic electrons. Thus, n_a can be estimated from

$$n_a \propto (B/v_L)^2 \; . \tag{1}$$

Daly (1994a,b) uses this method to estimate ambient gas densities for the radio sources in the Leahy, Muxlow, & Stephens (1989) data set and finds that: many powerful extended radio sources, including radio galaxies and radio loud quasars, are similar to Cygnus A in that they sit near the base of the gravitational potential well of a cluster of galaxies that has a high-density gaseous intracluster medium in place. Wellman & Daly (1994) have applied eq. (1) to the Liu, Pooley, & Riley (1992) data and find very similar results.

The observations suggest that radio galaxies and radio loud quasars inhabit very similar environments, and these environments exhibit little evolution with redshift over the redshift range from about zero to 2 (Daly 1994a,b). This may be related to the conditions required for the existence of a powerful extended radio source; it could well be that if a source with a given highly collimated outflow is moved to a lower density, lower pressure environment, it will not produce a powerful radio source. However, irrespective of selection effects, the observations suggests that at least some clusters with their intracluster medium in place exist at fairly large redshift. The existence of cluster-like, extensive, gaseous environments at large redshift suggests that structure formation is well under way at early epochs. This is expected in models of structure formation in an open universe, that is, in a universe with a relatively low value of the density parameter Ω.

The physics of strong shocks also indicates that the rate at which energy is deposited to the hotspot L_j and drives the shock wave is very simply related to observable quantities: $L_j \propto v_L^3 \; n_a \; a_L^2$ or

$$L_j \propto v_L \; B^2 \; a_L^2 \; , \tag{2}$$

where a_L is the lobe radius (Daly 1990, 1994a,b). Note that this equation is completely consist with the familiar expression $L_j \propto v_j\ v_h^2\ n_a\ a_h^2$, which involves parameters that are not accessible observationally: the jet velocity v_j, the velocity of the head or hotspot v_h and the area of the head a_h^2, where a_h is the radius of the hotspot or head of the jet. The consistency of the two equations is discussed in detail by Daly (1994b), and can be seen by noting that $v_h \propto v_j$; Daly (1994b) shows that several models are simultaneously consistent with both equations.

Equation (2) has been applied to the data of Leahy, Muxlow, & Stephens (1989) to study source energetics (Daly 1994b). The range and upper envelope of L_j for the 10 radio galaxies in the sample, that spans redshifts from zero to 2, does not evolve with redshift, and the range of L_j spans about an order of magnitude. This suggests that the sources are remarkably homogeneous, and exhibit little evolution with redshift. Further, it is interesting to note that L_j for the radio galaxies is independent of lobe-lobe separation, suggesting that L_j is relatively constant over the lifetime of an individual radio source.

Powerful extended radio sources exhibit remarkable properties that suggest a time-independent characteristic source size can be estimated for each source, and this source size is independent of the angular source size. The comparison of this calibrated yardstick with the physical sizes of sources estimated from their angular sizes may provide a very useful cosmological tool (Daly 1994a,b). This method is still undergoing extensive testing; preliminary results indicate that the model is internally consistent, and applications to various data sets indicate that an open universe with a relatively low value of Ω is favored by the data analyzed to date (Daly 1994a,b; Guerra & Daly 1994).

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