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The Evolution of Cluster Radio Galaxies at $0.5 < z < 1$

E. S. PERLMAN[1], C. FRYE[1], H. EBELING[2], L. R. JONES[3], C. A. SCHARF[4], and D. HORNER[5]
(1) University of Maryland, Baltimore County, Baltimore, MD, USA
(2) University of Hawaii, Honolulu, HI, USA
(3) University of Birmingham, Birmingham, UK
(4) Columbia University, New York, NY, USA
(5) Space Telescope Science Institute, Baltimore, MD, USA

Abstract

We are conducting a deep radio survey of a sample of 25 distant ($0.5 < z < 1$) clusters of galaxies. Here we present a progress report. So far 17 of 25 clusters have been observed, to varying depths. We have found 33 radio sources within 0.3 Abell radii of the cluster center, of which 28 are likely associated with cluster member galaxies. A comparison of the radio luminosity function of these clusters with the results of two surveys at lower redshift, reveals no evidence for strong evolution in the population of cluster radio galaxies at $z \sim 0.65$.

1.1 Introduction

Rich clusters have long been known as the homes for powerful radio galaxies. Several of the first radio sources known lie in clusters (e.g., Perseus A, Virgo A, Cygnus A), and surveys of nearby Abell clusters have discovered and mapped many radio sources (e.g., Ledlow & Owen 1996 and references therein). In low-redshift clusters, the radio sources have been found to be almost exclusively of the lower power, edge-dimmed Fanaroff & Riley (1974) class I (FR I) variety, rather than more powerful, edge-brightened FR II sources. It was therefore a surprise when deep optical imaging of the fields surrounding $z \sim 0.5-1$ radio sources found clusters around both FR Is and FR IIs (Prestage & Peacock 1988, Hill & Lilly 1991, Ellingson et al. 1991; see also Harvanek & Stocke 2002). Coupled with the then-prevalent notion that the X-ray luminosity function of clusters evolved strongly at moderate redshifts (Henry et al. 1992 and references therein), by the mid-1990s it appeared that at $z \sim 0.5$ radio sources in rich environments were responding to the changes around them.

Since that time, our view of clusters and their radio sources has changed significantly. The most recent evidence on cluster environments seems to indicate at most weak negative evolution since $z \sim 0.8$ (e.g., Jones et al. 1998, Borgani et al. 1999, Rosati, Borgani & Norman 2002 and references therein), both in the X-ray luminosity function as well as in the X-ray luminosity/temperature relation (Ettori, Tozzi & Rosati 2003; Fairley et al. 2000). This appears to contradict the earlier findings of the EMSS, albeit mostly at 4-10 $\times$ lower X-ray luminosities given the greater depth but smaller area of the more recent ROSAT-based surveys. However, reanalyses of the EMSS cluster data now also suggest weak or no evolution in the cluster X-ray luminosity function at higher luminosities out to $z = 0.8$ (Nichol et al. 1997, Ellis & Jones 2001, Lewis et al. 2002), although the error bars in the high redshift bin are large. It was therefore apparently consistent with this trend of finding little cosmological evolution in $z \sim 0.5$ cluster environments when Stocke et al. (1999) found no evolution in either the luminosity function or morphology of radio sources in clusters, from a deep VLA survey of 19 clusters at $0.3 < z < 0.83$ from the EMSS sample.

It was against this backdrop that we decided to use the WARPS sample (Scharf et al. 1997, Perlman et al. 2002, Horner et al. in prep.) to re-examine the issue of radio source evolution in clusters. Due to its depth (0.5–2.0 keV flux limit of $\sim 6.5 \times 10^{-14}$ erg cm^{-2} s^{-1}) and sky coverage (~ 70 deg^2) WARPS has a much larger sample of high-z clusters than existed only a few years ago. At $z \gtrsim 0.5$, WARPS has 25 clusters, with a maximal redshift of 1.013. By comparison, the EMSS in 1999 had only 6 clusters at $z > 0.5$, with a maximal redshift of 0.829 (an additional $z \sim 0.8$ cluster was added to the EMSS by Lewis et al. 2002; this cluster is also part of WARPS and was in fact discovered by us. See Ebeling et al. 2000.). With WARPS we therefore had the tool to not only attempt to confirm the findings of Stocke et al., but also extend their result to significantly greater lookback times.

In the ensuing sections, we assume a Hubble constant of $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$ for consistency with Stocke et al. (1999) and Ledlow & Owen (1996).

1.2 Observations and Results

To date, we have observed 17 of the 25 WARPS clusters at $z \gtrsim 0.5$. The observed clusters range in redshift from $z = 0.490$ to $z = 0.92$, with a mean of $\langle z \rangle = 0.65$. But unfortunately the time awards for this project did not allow us to observe the most distant cluster in the WARPS sample, WARPJ1415.1+3612 at $z = 1.013$ (Perlman et al. 2002). The observations used the VLA in either B or C configuration at a frequency of 1.4 GHz. The observations varied in depth because the time allocations occurred at LST $\sim 19h - 10h$; however, they have averaged about 90 minutes, with multiple observations that were well distributed in hour angle. The typical 5σ flux limit within the central 2-3$'$ was 0.3-0.6 mJy.

These observations detected 33 radio sources within 0.3 Abell radii (A_c) in these 17 clusters. This survey radius was chosen to match the work of Stocke et al. (1999) and Ledlow & Owen (1996). Only two clusters (WARPJ0152–1357 and WARPJ0216–1747) did not have a radio source within 0.3 A_c. To decide if these radio sources were associated with cluster member galaxies, we used moderately deep R or I band images obtained at a variety of optical telescopes, and made radio-optical overlays. We also compared to the results of our optical spectroscopy (Perlman et al. 2002, Horner et al. in prep.). This allowed us to identify with reasonable certainty 21 of 33 radio sources with galaxies that are likely cluster members. The identifications of another six radio sources with cluster member galaxies is less secure. Three radio sources appear to be associated with optical blank fields, while three radio sources were identified with either foreground or background galaxies. In Figure 1 we show two sample overlays of optical and radio images.

Once it is known which radio sources are associated with cluster members, it is possible to compute their power at 1.4 GHz. This was done assuming a spectral index of 0.7 ($S_\nu \propto \nu^{-\alpha}$) for k-correction. All but four of the radio sources found within 0.3 A_c have radio power figures consistent only with those of FR I radio galaxies, which typically have $\log P(1.4\ \mathrm{GHz},\ \mathrm{W\ Hz^{-1}}) = 23 - 26$). The remainder lie in the grey area occupied by both FR I and FR II radio galaxies (the latter have typically $\log P(1.4\ \mathrm{GHz}) = 25 - 28$).

The luminosity function for cluster radio galaxies is typically expressed in terms of the fraction of radio-loud, bright ellipticals in each bin of radio power at 1.4 GHz. Because we do not have complete spectroscopy for every galaxy within $0.3 A_c$, we estimated the number

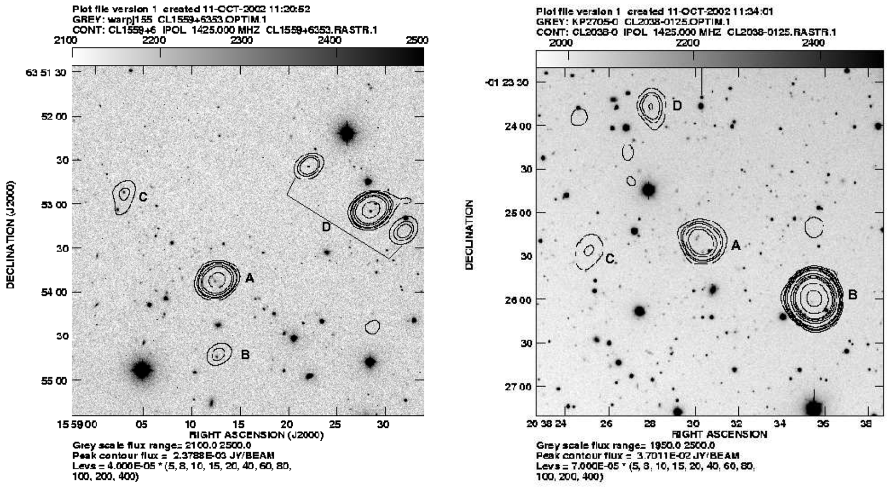

Fig. 1.1. Overlays of VLA radio images (as contour maps) over optical images (greyscale) for two WARPS clusters of galaxies: WARPJ1559.3+6353 (left, z = 0.81 :) and WARPJ2038.1–0125 (right, z = 0.679). Contours are given at 3,5,8,12,16,24,32,48,64,128,256 $\times$ the rms noise. Both of these clusters have multiple radio sources located in their cores, as do most of the clusters in our sample. The radio sources are mostly associated with cluster member galaxies, but some are associated with galaxies in the cluster's background or foreground (e.g., WARPJ1559.3+6353D, at left).

of bright galaxies within $0.3A_c$ using the tight correlation between X-ray luminosity and galaxy counts from Abramopoulos & Ku (1983). These figures were then multiplied by a factor 2.2, in accordance with the standard form of the two-point correlation function, to correct from a radius of 0.5 Mpc (used in Abramopoulos & Ku 1983) to $0.3A_c$. We then subtracted 20% to account for the bright cluster spirals and S0s, which do not contribute to the radio galaxy population. This method follows the analysis of Stocke et al. (1999) and Ledlow & Owen (1996). The luminosity function achieved so far is shown in Figure 2.

1.3 Discussion

As can be seen in Figure 2, from our survey there is no evidence for strong evolution of the luminosity function of cluster radio galaxies out to $\langle z \rangle = 0.65$, i.e., a lookback time 50% greater than that which was achievable with the EMSS (Stocke et al. 1999). Thus our work has both confirmed and extended to higher redshifts the result of Stocke et al. (1999), which used a strategy similar to ours. These results contrast with those obtained through deep optical surveys of the environments around bright radio sources (Prestage & Peacock 1988, Hill & Lilly 1991, Ellingson et al. 1991, Harvanek & Stocke 2002), which favor similar, moderately rich ($\sim$ Abell class 0) environments for both FR I and FR II radio sources at z=0.5-1. It does, however, agree with the most recent results on the evolution of BL Lac objects (Rector et al. 2000, Rector & Stocke 2001), which now show that both radio and X-ray selected samples have $\langle V/V_{max} \rangle \approx 0.5$.

Our data, as well as those of Stocke et al. (1999) are suggestive of weak negative evo-

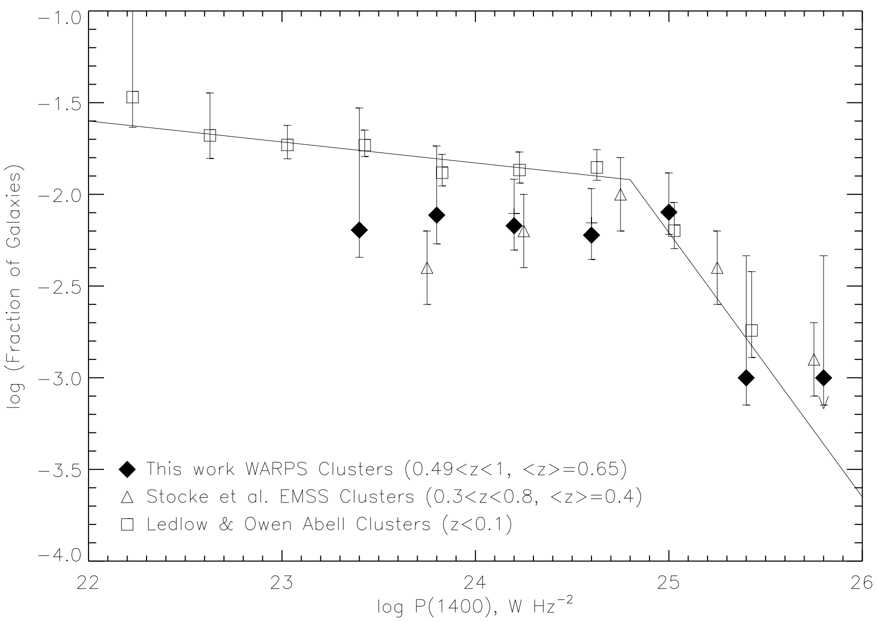

Fig. 1.2. The luminosity function of cluster radio galaxies in the inner $0.3A_c$. The points shown in all but the highest power bin represent our best estimates for radio source counterpart identification, while the marks on the upper error bars represent the effect of adding in blank field sources. The point shown in the highest luminosity bin represents a blank field source in one cluster (WARPJ2302.7+0844) which is located very near the cluster center. As shown, we do not see evidence for strong evolution in the population of cluster radio galaxies out to $\langle z \rangle = 0.65$. The data may indicate weak negative evolution, but at powers below the knee our results are likely affected by incompleteness (see text).

lution, as in both surveys the points at luminosities below the knee lie below those seen at $z < 0.1$. However we believe this is due to incompleteness. The real problem with doing sensitive surveys of high-z clusters lies in the dual issues of FR I sources' diffuse, edge dimmed morphology (where the lobes tend to have $> 90\%$ of the flux) and cosmological $(1+z)^{-4}$ surface brightness dimming. These two effects combine to effectively lower the sensitivity of any survey to FR I - type sources. Unfortunately, since the effect is highly morphology dependent, it is difficult to model. Simulations were done for two prototype sources by Perlman & Stocke 1993, but that work needs to be repeated on a much larger scale. Whatever the magnitude of the final effect of surface brightness dimming, we do know that it would tend to move points towards artificially low densities in the FR I-only bins. Deeper VLA observations would help to address this problem. To firm up either result (i.e, no or negative evolution), we also need better optical observations, to firm up the identifications of radio sources with cluster members. As already discussed, for about 25% of the radio sources found in this survey, the nature of the optical counterpart (i.e., whether or not it is associated with the cluster) is questionable. In deriving the luminosity function shown in Figure 2 we have used our best judgment; however, it is possible that better optical imaging could change the identifications assigned to the more questionable cases and thus push the result towards one of negative evolution. Similar suggestions were made by Stocke et al. (1999) to explain the fact that their lowest-luminosity point falls below the Ledlow & Owen (1996) curve.

The finding of weak negative or no evolution up to $z = 0.65$ presents us with a paradox, as not only does it conflict obtained by optical surveys around radio sources, it also appears inconsistent with that observed in most AGN (La Franca & Cristiani 1997, Ciliegi et al. 1995), which evolve positively, i.e., up to $z \approx 2$ AGN were either more luminous or more numerous at higher redshifts than in the present epoch. Stocke et al. (1999) suggested that this might be explained by a higher density of FR Is in poor clusters. This was prompted by the evidence which then existed regarding the evolution of BL Lac objects, which at that time suggested negative evolution. Our sample, which covers X-ray luminosities 4 times lower than the EMSS at similar redshifts, does not support this notion. We cannot, however, comment on issues of morphology, as we have no A-array data.

This apparent paradox is resolved by considering the likely association of FR II radio galaxies with radio-loud quasars, which (like other quasars) appear to evolve positively. This is significant because the most recent evidence suggests that FR IIs have lifetimes $\lesssim 10^{7-8}$ years, up to 5-10 times shorter than those of FR Is, and that most radio sources do not evolve from FR II to FR I before they fade away (e.g., Parma et al. 2002). If – as seems likely – the evolution of the radio sources in clusters is intimately related to the evolution of the cluster environment, one might expect the majority of the evolution from FR II to FR I to take place at higher redshifts and yet still find both types of radio sources in rich cluster environments. We can then predict that deep radio surveys of clusters at $z = 1-2$ will find an increasing prevalence of FR II-type objects. This has not been seen in current samples because very few (less than five) confirmed clusters of galaxies exist at $z > 1$. Thus to tie in the evolution of the active fraction in clusters with the evolution of the cluster environment, it is of key importance that future samples of clusters which do reach $z \sim 2$ be surveyed with the VLA.

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