RADIO SOURCE SURVEYS

Mergers at high redshifts?

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1. Introduction

The early study of radio sources at visible wavelengths and the first empirical evidence that galaxies can have strong dynamical interactions are closely intertwined. Baade & Minkowski's (1954) model of Cygnus A as a pair of galaxies in collision, while now believed to be incorrect, presaged the merger-driven picture for the generation of radio sources (e.g. Heckman et al. 1986) by some 30 years. Morphological evidence for an association between mergers and radio loud AGN is seen in both the nearest radio galaxies (e.g. Cen A; Schweizer 1986) and in the most powerful sources at $z \sim 0.1 - 0.3$ (Stockton & Mackenty 1983; Hutchings et al. 1988; Heckman et al. 1986).

When the first radio galaxies with redshifts beyond ~ 2 were identified, their properties were viewed from a perspective that was heavily colored by the merger induced starburst/AGN paradigm. Thus Lilly & Longair (1984) and Spinrad & Djorgovski (1984) cited the complex morphologies, strong and spatially extended emission lines, UV excesses, and large amplitude velocity fields as signs of strong dynamical interactions. While this view may ultimately have considerable validity, we have learned that there a number of physical processes at play in producing the colors and morphologies of radio galaxies. From a variety of observations we now know with some confidence that there are both local and scattered sources of UV continuum (Dey et al. 1997; Cimatti et al. 1997), that recombination can produce much of the UV continuum in some objects (Dickson et al. 1995) and that there is a complex interplay between the extended radio source and its environment.

The discovery of the alignment of the UV continuum and emission-lines with the radio source axes lead people to reconsider strongly held views regarding these objects and ultimately, to question the stellar origin of the

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UV continuum. Our present understanding of the rest-frame visible continuum is not much more sophisticated than our early 1980's understanding the UV continuum. Most who work in this field are comfortable with the idea that the bulk of the light at $\lambda > 4000\,\text{Å}$ arises from cool stars and that the radio galaxies form a fairly homogeneous population that is drawn from the larger population of massive ellipticals. The passively evolving old galaxy model for radio galaxy hosts is clearly laid out in Lilly (1988). There are now spectra of weak radio sources at $z > 1$ that show convincing evidence for stars with ages of more than 1 Gyr (Dunlop et al. 1996 ; Spinrad et al. 1997). There is at present no demonstration that the K-band light of radio galaxies with $z > 2$ is dominated by stars of any age. The latest generation of near-IR arrays on large apertures and the advent of NICMOS on *HST* are now providing us with data that has the potential to seriously challenge the status quo.

2. The MRC/1 Jy Radio Survey

Over the past several years Kapahi, van Breugel, Persson, Athreya and I have carried out a large survey of radio galaxies with flux densities near the peak of the 408 MHz source counts. The MRC/1Jy sample (McCarthy et al. 1996; Kapahi et al. 1997) is the largest sample of sources for which essentially complete optical and near-IR identifications are available. Its flux limit ($S_{408} > 0.95\,\text{Jy}$) is roughly a decade below and 3CRR (Laing et al. 1985) and while its redshift content ($\sim 75\%$) is less than optimal, it is nevertheless, well suited to a number of statistical investigations. In Figure 1 I show the run of $P(408)$ vs. z for the MRC/1Jy and 3CRR samples. The strong, but spurious, correlations within each sample is the Malmquist bias, the gap between the two tracks results from the different solid angle coverages. The combination of the 3CRR and MRC/1Jy samples allows us to span a decade in power at any z and a wide range of z for a fixed radio power. Athreya et al. (1998) and McCarthy (1998) have used the combined samples to examine the evolution and luminosity dependences of sources size and Athreya (1998) has determined the redshift dependence of the rest-frame radio spectral indices. The quasar sample has been compiled by Kapahi et al. (1997) and spectroscopy of nearly all of the QSR and BL Lac identifications were obtained by Hunstead et al. (1998). Baker & Hunstead (1996) have produced composite rest-frame UV spectra of the CSS, and core and lobe-dominated MRC/1Jy quasars.

3. Color and Luminosity Evolution of the Host Galaxies

The large formation redshift and passive evolution paradigm for radio galaxies is based largely on the uniformity of the $K-z$ relation and the evolution

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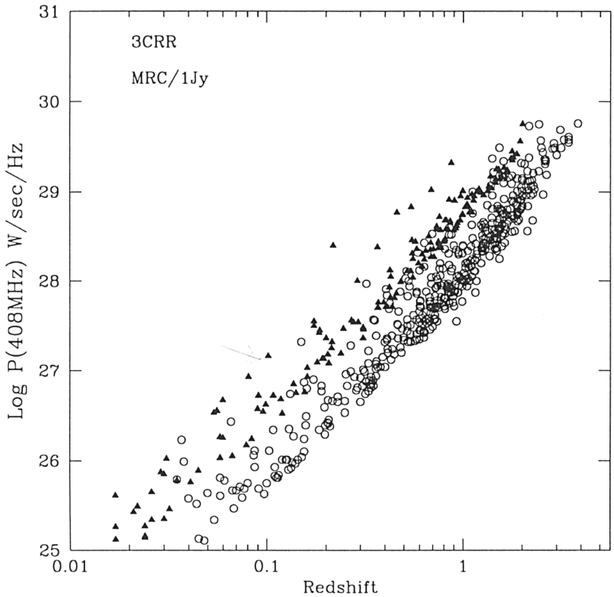

Figure 1. The run of 408MHz power with redshift for the 3CRR (filled symbols) and MRC/1Jy (open symbols) surveys.

of the red envelope in the visible and near-IR colors in the 3CRR sample (e.g. Lilly & Longair 1984; Eisenhardt & Lebofsky 1986). A similar behavior is seen in other samples (e.g. Dunlop et al. 1989). I illustrate this behavior for the MRC/1Jy sample in Figures 2 & 3 where I plot the K magnitudes and $r-K$ colors against z. The model curves show the apparent magnitudes and colors of passively evolving systems with formation redshifts from 10 to 2 in a low Ω, H_0 Universe. For any redshift below ~ 2 there are galaxies with $r-K$ colors are red as the passive evolution model and in $J-K$ the galaxies continue to get red to $z \sim 2.5$.

4. Velocity fields in the extended emission-line regions

Baum, Spinrad and I have measured the extranuclear velocity fields in the emission-line gas for a large sample of radio galaxies. At redshifts below ~ 0.8 the typical radio galaxy has a velocity field with an amplitude of $100 - 300$ km s^{-1}. At larger redshifts the amplitudes increase to typically 800 km s^{-1}, with a number of systems having gas moving at more than 1000 km s^{-1}s. Baum & McCarthy (1998) speculate that the apparently sudden change in velocity amplitudes reflects the change in galaxy environments.

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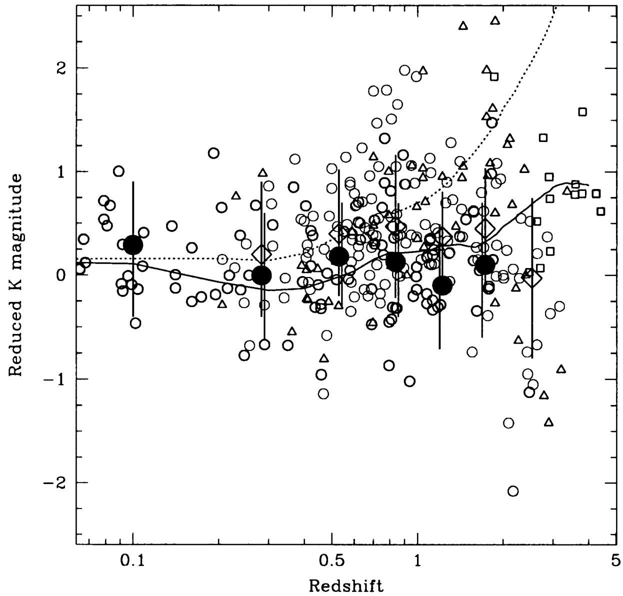

Figure 2. The K-band Hubble diagram for radio galaxies from the 3CRR, MRC/1-Jy surveys and a number of $z > 3$ radio galaxies taken from the literature. The dotted line is a no-evolution model with $H_0 = 50$ and $q_0 = 0.1$; the solid line is a BC96 passive evolution model with $z_f = 20$. A low order polynomial has be subtracted from both the data and the models to compress the scale.

At these redshifts radio galaxies are, on average, in richer environments than the low redshift FR II sources that comprise the bulk of the 3CRR and 1Jy sources with $0.2 < z < 0.5$. The merger picture for radio galaxies at these low redshift is quite consistent with the range of velocities seen in the ionized gas. The large amplitudes in the more distant systems are comparable to the velocity dispersions of rich clusters and suggest that galaxy collisions, rather than actual mergers, may be a more common form of dynamical interaction.

5. WFPC2 & NICMOS Imaging of Radio Galaxies with $z > 2$

Miley, Fosbury, van Breugel, Rottgering and I have imaged several $z > 2$ radio galaxies with NICMOS in the F160W bandpass. These images benefit both from the large reduction in background compared to the ground and from diffraction limited images. In several cases we find that the H-band light is dominated by a nuclear point source. In other cases we have detected resolved emission and have attempted to separate the contributions

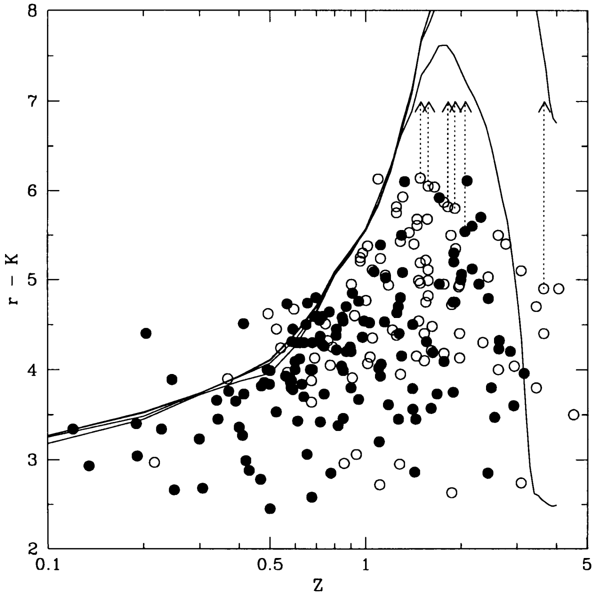

Figure 3. (a) The $r - K$ colors for galaxies in the MRC/1Jy sample. The filled symbols are objects with secure spectroscopic redshifts, the open symbols are objects for which the redshift has been estimated from the K magnitude. The solid lines are the same passive evolution model as above, but with formation redshifts ranging from 20 to 3.

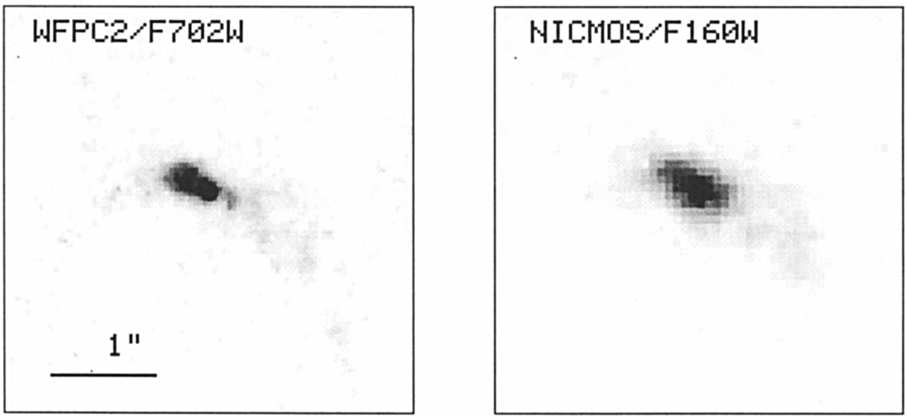

Figure 4. WFPC2/F702W and NICMOS/F160W images of the radio galaxy MRC 0943-242 ($z = 2.93$).

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from a symmetric host galaxy and a component aligned with the radio axis. This separation is accomplished by using the WFPC2 and NICMOS images to iteratively solve for linear combinations of aligned and host galaxy contribution. In Figure 4 I show the WFPC2 and NICMOS images of MRC 0943-242 ($z = 2.93$). One can easily see that the F160W image contains an strong aligned component, the underlying symmetric component is less obvious. We find that the fractional contribution of the symmetric component, assumed to be stellar, is roughly 10% at F702W and 25% at F160W. In Figure 5 I show the spectral energy distribution of 0943-242 derived from ground-based imaging and from *HST*. The solid line is a Bruzual-Charlot model for the 1.5 Gyr population and it is fitted to the photometry of the symmetric component. The dotted line is the observed composite SED for a core dominated MRC/1Jy quasar, as derived by Baker & Hunstead (1996), the upper solid line is the sum of the two components. The good agreement between the $4''$ aperture photometry and the model suggests that 0943-242 contains a large contribution from quasar continuum that is scattered by a nearly grey scattering medium. Extrapolating the model fit from the H-band to K-band yields a 30% contribution from the symmetric component.

In the case of 0943-242 was are confident that much of the observed H and K light is not associated with stars in a normal elliptical galaxy. The objects found to be dominated by nuclear point sources must also contain substantial non-stellar contributions. Thus the meaning of the colors and K magnitudes of the $z > 2$ galaxies with high radio powers is no longer clear. Our thinking regarding the evolution of the stellar populations in terms of an early formation redshift and subsequent passive evolution needs revision.

In Figure 6 I show an F160W image of MRC 0406-244 recently obtained with NICMOS. At $z = 2.43$ this image contains a contribution from the nebular lines. The striking bipolar morphology revealed in this image is reminiscent of the wind-blown bubbles associated with Arp 220 and other ULIRGs. Deep WFPC2 imaging of this object by Rush et al. (1997) reveal an apparent double nucleus and continuum features suggestive of tidal tails. It is tempting to speculate that this object may by a high redshift radio-loud analogue of the powerful ULIRGs and SNe driven outflows.

6. Summary

Our understanding of powerful radio sources and their relationship to other classes of AGN and star forming galaxies is undergoing considerable evolution at the present. The paradigms that work well for the local population of radio sources, and merger-driven activity in particular, may not be valid at early epochs. Imaging and spectroscopic observations show that the

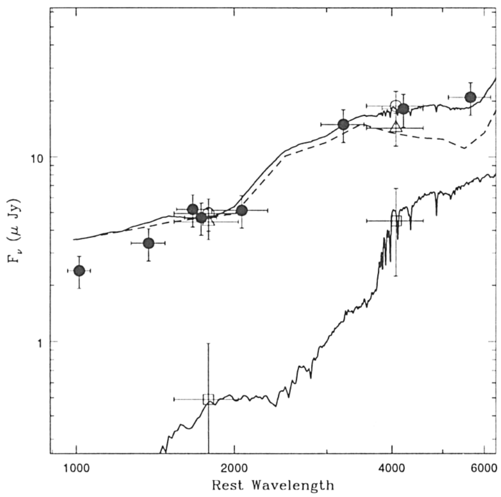

Figure 5. The derived SED for 0943-242. The open squares are the NICMOS and WFPC2 magnitudes for the host galaxy, the open triangles are the aligned component. The filled circles are the ground-based photometry. The model curves are described in the text.

Figure 6. A NICMOS/F160W image of MRC 0406-244 (z = 2.44). The large bubble-like structures are aligned with the radio source axis and are likely to be composed of [OIII]5007,4959 and Hβ emission lines. The total size of the bipolar structure is 3.5$''$ or $\sim$ 30 kpc.

environments and dynamical states of radio galaxies evolve with look-back time. The application of NICMOS and ground-based near-IR imaging to the most distant radio galaxies has lead us to reexamine the basic assumptions that underly our interpretation of the apparent color and luminosity evolution of these objects and their relation to early type galaxies. I thank my collaborators, as listed in the text, for allowing the use of previously unpublished data.

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