1 Radio Feedback in Clusters and Galaxies

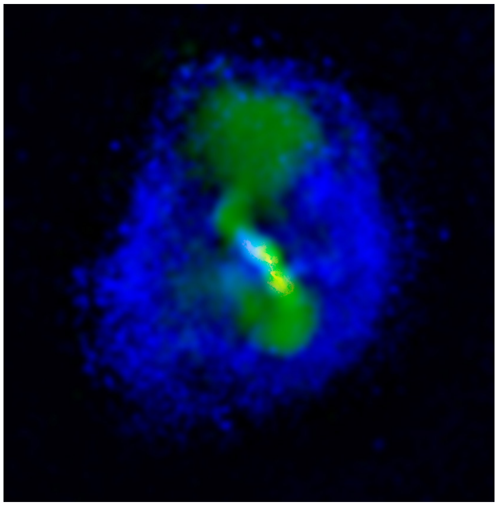
X-ray images of hot halos surrounding elliptical and central cluster galaxies have revealed a wealth of structure associated with their radio sources. The most interesting of these structures are buoyant X-ray cavities and shock fronts. Measurements of the pV work required to inflate cavities and to drive shocks provide reliable estimates of the mechanical energy associated with radio jets and lobes (Fig. 1). These energies range from 10^{54} erg in giant ellipticals to 10^{62} erg in the cores of rich clusters. Their ages, estimated independently using buoyant rise times and shock speeds, have yielded mean jet powers large enough to offset cooling flows in normal elliptical galaxies and in rich clusters (see McNamara & Nulsen 2007 for a review). This has significant consequences for understanding the evolution of galaxies and clusters. For example, the suppression of star formation by AGN feedback at late times in the so-called "radio mode" (as opposed to the early "quasar mode" that imprinted the Magorrian relation on bulges) may be responsible for the turnover at the bright end of the galaxy luminosity function and the dearth of bright, blue galaxies that are present in standard cold dark matter models (Croton et al. 2006). Furthermore, the energy released in these outbursts contributes to the excess entropy in clusters, and may lead to the breaking of self similarity in the scaling relations between, X-ray luminosity, gas temperature, and mass (Voit 2005).

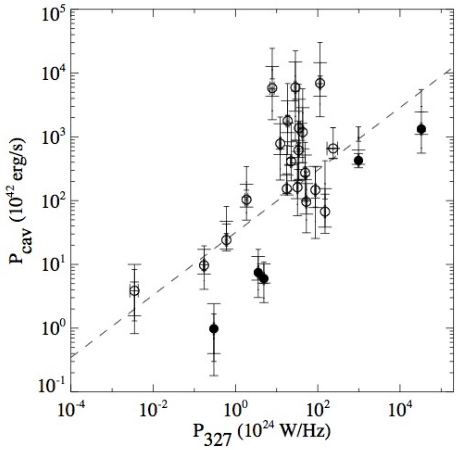
X-ray and radio studies of cavities and shock fronts have also yielded direct measurements of the radiative efficiencies of extragalactic radio sources, and their energetics have placed strong constraints on the contents of extragalactic radio sources (Dunn et al. 2005, De Young 2006). Combining VLA observations at several frequencies with Chandra imagery of 18 clusters, Bîrzan et al. (2004, 2008 — B04, B08) found radiative efficiencies ranging from unity to a few parts in 10^5, with median values of approximately one part in a few thousand. Their measurements show that even weak radio sources are often associated with powerful AGN outbursts, whose energies and momenta are carried primarily by heavy, non-radiating particles, such as protons (Dunn et al. 2005, De Young 2006, B08). Furthermore, B04 and B08 found that jet (mechanical) power correlates with radio power approximately as $L_{\rm jet} \sim L_{\rm radio}^{1/2}$ in clusters, but with a large intrinsic scatter. This important correlation provides the means to use radio observations to estimate the mechanical feedback power in galaxies over large volumes of the Universe, where X-ray measurements cannot be made. Applying this relationship to NVSS radio sources in Sloan ellipticals, Best et al. (2006) showed that radio-mode feedback is energetically important in distant giant ellipticals. However, Best's study was based on B04's cluster measurements, and not on lower luminosity ellipticals whose numbers dominate in the Universe, and are the focus of this proposal.

B08 found that VLA imaging at 320 MHz provides the best tracer of jet power by providing a relationship between radio and jet power with lower scatter than is found at 1.4 and 8 GHz. This is because 320 MHz is sensitive to the aging electron population that dominates the emission of the cavities and radio lobes (Fig. 1). We propose to extend our VLA imaging survey of cavity systems to groups and isolated giant ellipticals with lower jet and radio powers. In particular, we wish to determine whether the power law relationships found by B04 and B08 apply over 8 orders of magnitude in jet power from giant cD galaxies in clusters to to isolated galaxies. The observations proposed here will yield calibrated scaling relationships between jet power and radio power that can be used to study feedback through much of cosmic history. It will also provide the larger sample necessary to study and understand the primary factors that cause the scatter in this relationship, that may include aging, adiabatic expansion, variations in magnetic field strength, and particle content.

2 Targets & Strategy

Our sample of 16 ellipticals was drawn from the 109 nearby giant elliptical galaxies found by Christine Jones and collaborators to have X-ray emitting hot atmospheres. All have been observed with *Chandra*. Our targets consist of a subsample of the 27 with detected cavity systems (Nulsen et al. 2007). Our long term goal is to obtain high signal to noise radio images of the entire subsample at at least three frequencies: 327 MHz, 1.4 GHz, 8 GHz. Most of these targets have been observed at one or more frequencies with the VLA, but they have not been imaged at 327 MHz with the VLA. 327 MHz is most sensitive to cavity systems, primarily because cavity systems are typically several tens to a few hundred Myr old, so that their radio emission is dominated by an aging electron population. Thus 320 MHz is sensitive to the history of AGN





*L*eft: Chandra image of the shock and cavity system (blue) in Hydra A (Wise et al. 2007) with 327 MHz image (green) from Lane et al. (2004) shown completely filling the cavity system. The sharp edges surrounding the radio source is a weak shock, and the dark areas filled in green are the cavities. *R*ight Correlation between cavity (jet) power and 327 MHz power with best fit power law superposed (from Birzan et al. 2008). The proposed sample will extend this relation below cavity powers of 10^{42} erg s^{-1}.

activity not just the most recent outburst. Our strategy, as we adopted for B08, is to reduce and analyze the existing observations in the VLA archive and fill in the frequency gaps in future observing cycles. Of the 27 systems with cavities, 14 are being observed with the Indian GMRT as part of another program (Vrtilek, PI), and we are proposing here for the remaining 13. The two samples will be combined to form a complete sample. The estimated 320 MHz fluxes are typically 0.5 Jy. NGC 4261, NGC 4782, and NGC 4374 have total fluxes estimated to be roughly 25 Jy. Our targets are listed in order of decreasing priority in the Source List.

We will use the standard P band observing mode (4IF, 3.125MHz per IF, 32 channels, Hanning smoothed). The total flux density of all sources is larger than 100 mJy, assuming a standard spectral index of -0.8. We are asking for 3 hours per source, which will lead to a sensitivity limit of 0.3 mJy/beam, and provide adequate uv coverage for imaging with reasonable dynamic range (~ 1000). Our experience with the previous sample of radio galaxies (B08) has shown that the proposed observations will be adequate to detect the extended emission in the sources associated with the X-ray cavities. The VLA-A array resolution of 4.5 arcsec at 320 MHz is comparable to or smaller than the cavities in our targets, so most will be well resolved.

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