On the influence of radio galaxies on cooling flows: M87 and Cygnus A

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Abstract. Results from Chandra studies of the intracluster medium around M87 and Cygnus A are summarized.

1. Introduction

In most clusters of galaxies, the X-ray surface brightness rises steeply towards the center. The radiative cooling time of the gas typically drops below 10 Gyr at 70 - 150 kpc and 1 Gyr at 5 - 30 kpc from the center (Fabian 2002). X-ray spectra do show declines in the gas temperature with decreasing radius within these central regions. These observational results provide the primary support for the existence of cooling flows. As the gas loses its energy to radiation, the weight of the overlying gas produces a subsonic infall. In the traditional picture, non-uniformity of the density is argued to cause denser, cooler matter to form cold clouds or stars in the flow, and these are supposed to be deposited over an extended region in the center of the cluster (Fabian 1994). Most published models of cooling flows are steady-state ones.

The major technological advances achieved by Chandra and XMM are enabling much more critical scrutiny of cooling flows, including not only whether the intracluster medium (ICM) is, in fact, multiphase but also their relationship to the radio source often associated with the central galaxy. The latter relationship bears on the long controversy over the importance of heating processes on the intracluster medium (contrast Fabian 2002 and Binney 2002). M87 (Virgo A) and Cygnus A were among the first identified extragalactic radio sources and are located near the centers of rich clusters. In this note, we summarise some of our ongoing work with Chandra in which we attempt to shed light on the interaction between these radio sources and the ICM.

2. M87

A Chandra study of the X-ray core of the Virgo cluster is given in Young, Wilson & Mundell (2002). The main conclusions are as follows.

The inner radio lobes are aligned with depressions in the X-ray surface brightness and there is no evidence of shock heating in the X-ray emission immediately surrounding the inner radio lobes, suggesting that the radio plasma has gently pushed aside the X-ray emitting gas. These cavities cannot have been inflated much slower than the sound speed, however, or they would have risen...
too far from the nucleus due to buoyancy effects. We estimate the jet power to be $L_{\text{jet}} \simeq 3 \times 10^{42}$ erg s$^{-1}$.

On larger scales, the most striking feature is the X-ray arc running from the east, across the central regions of M87, and off to the southwest (Fig. 1). The gas in the arc has at least two temperatures, with one component at the temperature of the ambient ICM and a cooler component at $\simeq 1$ keV. The gas in the arcs is probably over-pressured with respect to, and somewhat more metal rich than, the ambient ICM.

Abrupt changes in surface brightness, or “fronts”, are seen at nuclear distances slightly larger than the nuclear distances of the inner radio lobes and intermediate radio ridges. Within the inner front, at nuclear distances $\leq 45''$ ($\leq 3.5$ kpc) the gas has at least two temperatures, with the cooler component at $\simeq 1$ keV, similar to the X-ray arc. This cooler region is concentrated more to the north than the south of the nucleus and is correlated with the H$\alpha +$ [NII] emission-line distribution.
We suggest that a model based on the hydrodynamical simulations of Reynolds, Heinz & Begelman (2002), scaled to a lower power radio source such as M87, may explain the observed phenomena. Intermittent jet activity has two effects on the cluster. Firstly, it inflates buoyant bubbles of radio plasma that trail cold gas from the central regions in their wakes as they rise at \( \sim \) 0.6 – 0.7 times the sound speed, thereby producing the X-ray arcs. The gas dredged up from the nucleus is expected to have higher metal abundances than the ICM at large nuclear distances. Secondly, at late times in the evolution of the radio source, the injection of energy into the cluster core produces a “pulse” that expands at the sound speed into the ICM. We suggest that such pulses produce the observed X-ray “fronts”. Detailed numerical simulations tailored to the Virgo cluster are required to explore this hypothesis.

3. Cygnus A

Discussions of Chandra results on the radio hot spots, the galactic nucleus and the large scale ICM are given by Wilson, Young & Shopbell (2000), Young et al. (2002) and Smith et al. (2002). Fig. 2 shows the inner regions of the X-ray image with temperatures indicated for various regions of thermally-emitting gas. We may bear in mind that an extrapolation inward of the temperature of the ICM indicates a temperature at the edge of the cavity of about 4.7 keV (Smith et al. 2002, improved by better calibration). It is striking that the temperatures measured in the bands of emission which project across the minor axis of the prolate spheroidal cavity are lower, in the range 3.8 - 4.4 keV (red polygons). It is tempting to interpret these structures as “belts” of gas extending around the equator of the prolate spheroidal cavity. This gas is cooling while being accreted by the Cygnus A galaxy, is likely falling through the cavity and may well continue inwards to form the accretion disk around the nuclear black hole.

In contrast, the temperatures of the limb-brightened edges of the cavity are 5.2 - 6.8 keV (blue polygons), which is hotter than the inward extrapolation of the cluster gas. If we assume that this high temperature is the result of a strong shock driven into the surrounding cluster gas by the expanding cavity, it is possible to estimate the power needed to drive the expanding cavity, and hence the minimum power of the jets, as \( L_{\text{jet}} \approx 0.5 \rho_{\text{ICM}} V_S^3 A \), where \( \rho_{\text{ICM}} \) is the pre-shock density, \( V_S \) the shock velocity and \( A \) the total surface area of the prolate spheroid. Numerically we have \( n_{\text{ICM}} \approx 0.02 \, \text{cm}^{-3} \) (from the density profile of the cluster - Smith et al. 2002), \( V_S \approx 2,000 \, \text{km} \, \text{s}^{-1} \) (to get a postshock temperature of 6 keV), \( A = 4 \times 10^{47} \, \text{cm}^2 \), giving \( L_{\text{jet}} \approx 6 \times 10^{46} \, \text{erg} \, \text{s}^{-1} \). This number exceeds, by almost a factor of 100, the total radio emission of Cygnus A (\( L_R \approx 7 \times 10^{44} \, \text{erg} \, \text{s}^{-1} \)) and that of the total cluster X-ray emission (\( L_X(2 - 10 \, \text{keV}) \approx 1 \times 10^{45} \, \text{erg} \, \text{s}^{-1} \)). The cooling time of the shocked gas exceeds the age of the radio source, so the jet is heating up the inner part of the cluster. This argument is, to our knowledge, the first to estimate the jet power from measurements of purely thermal processes, a method which should be inherently more reliable than previous estimates involving synchrotron radiation. Nevertheless, our method revolves around the assumption that the temperature measured at the limb-brightened edges represents that behind a strong shock driven by the expanding cavity. We believe the difference between the temperature obtained
Figure 2. The Chandra X-ray image of the central regions of Cygnus A. The spectra of emission from within the indicated polygons have been modelled with a MEKAL plasma and the temperatures (in keV) are given. Red boxes and labelled temperatures represent the “bands”, while blue boxes and labelled temperatures represent the limb-brightened edges of the cavity.

by inward extrapolation of the temperature of the large-scale ICM – 4.7 keV – and those measured around the limb-brightened cavity – 5.2 to 6.8 keV – is real. If these numbers are taken literally, the shock may be weak. A more complete discussion of the cavity will be published elsewhere (Wilson & Smith 2003, in preparation).

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