THE INTERACTION BETWEEN THE CENTRAL GALAXY AND THE INTRACLUSTER MEDIUM IN COOL CLUSTER CORES.

N.A. Hatch and C.S.Crawford, A.C Fabian, R.M.Johnstone, J.S. Sanders

Institute of Astronomy, University of Cambridge, Madingley Road, UK

ABSTRACT

The extended emission-line nebulae surrounding the central galaxies of the Perseus and Centaurus clusters show a direct association with soft X-ray filaments indicating an energy exchange between the hot intracluster medium and the warm ionized gas. Radial gradients in the [NII]/Hα ratio imply the ionization state of the line-emitting gas is coupled to the global properties of the intracluster medium or the gas contains significant metallicity variations. The velocity field of filaments within the Perseus cluster core indicate that the filaments are most likely to be galactic gas drawn out of the central galaxy by the buoyant rise of under-dense bubbles.

Key words: ICM; central cluster galaxies.

1. INTRODUCTION

At the centre of galaxy clusters in which the X-ray emitting intracluster medium has a short radiative cooling time, lies the most massive galaxies known. Approximately a third of these central cluster galaxies exhibit line-emission, emitting predominantly in Lyα, Hα and collisionally excited lines e.g. [NII] (Crawford et al., 1999). Deep narrow-band imaging has revealed that these emission-line nebulae can extend over 30 kpc from the central galaxy core in the form of long, narrow filaments (e.g. Perseus: Conselice et al. (2001) [Fig. 1]; M87: Sparks et al. (2004); Centaurus: Crawford et al. (2005)[Fig. 1]). The emission line nebulae are extremely luminous, requiring a constant source of excitation. Despite many studies (e.g. Hu et al. (1985); Heckman et al. (1989); Donahue et al. (2000)) the origin, nature and excitation of these nebulae remain a mystery.

Two well-studied clusters which host line-emitting nebulae around their central galaxies are the Perseus cluster with NGC 1275 residing in the core, and the Centaurus cluster with NGC 4696 in the core. Both clusters have centrally peaked X-ray emission with a short radiative cooling time and like $\sim$70 per cent of central cluster galaxies, they both harbour an active radio source (Burns, 1990). Both cluster cores exhibit cavities in the X-ray emission that spatially coincide with GHz radio-emission (Fabian et al., 2003a; Sanders & Fabian, 2002); these X-ray cavities are known as radio bubbles. Two ICM-confined bubbles of radio plasma surround NGC 4696 to the east and west, whilst two X-ray cavities exhibiting GHz radio-emission lie to the north and south of NGC 1275 in the Perseus cluster core. In addition to the radio bubbles, there are two outer cavities in the Perseus intracluster medium that lie approximately 30 kpc to the northwest and south which do not exhibit GHz radio emission. These cavities, known as ghost bubbles, are interpreted as radio-bubbles that were inflated during a previous epoch of activity, that have detached and risen buoyantly through the intracluster medium.

NGC 1275 is host to the most spectacular emission line nebula imaged so far (see Fig. 1; Conselice et al. (2001)). The nebula is extremely luminous ($>4.1\times10^{41}$ erg s^{-1} in Hα and [NII]; Heckman et al. 1989) and consists mostly of radial filaments. A large reservoir of cool molecular gas has been detected in the core of NGC 1275 as is commonly found in the core of many central cluster galaxies (Edge, 2001; Edge et al., 2002). Warm molecular hydrogen is also observed associated with the outer nebula, 25 kpc from the galaxy core (Hatch et al., 2005a).

2. NEBULA-INTRACLUSTER MEDIUM INTERACTION

High resolution, deep *Chandra* images show that soft X-ray emission is associated with some of the optical and UV line-emitting filaments of the nebula surrounding NGC 1275 (Fabian et al., 2003b). Similar soft X-ray emission is found associated with the nebula surrounding M87 at the core of the Virgo cluster (Sparks et al., 2004) and with the 45 kpc filament trailing the central galaxy of Abell 1795 (Fabian et al., 2001).

In the Centaurus core, filaments of soft X-ray emission are clearly visible spiralling east from NGC 4696, the central cluster galaxy (Sanders & Fabian, 2002; Fabian

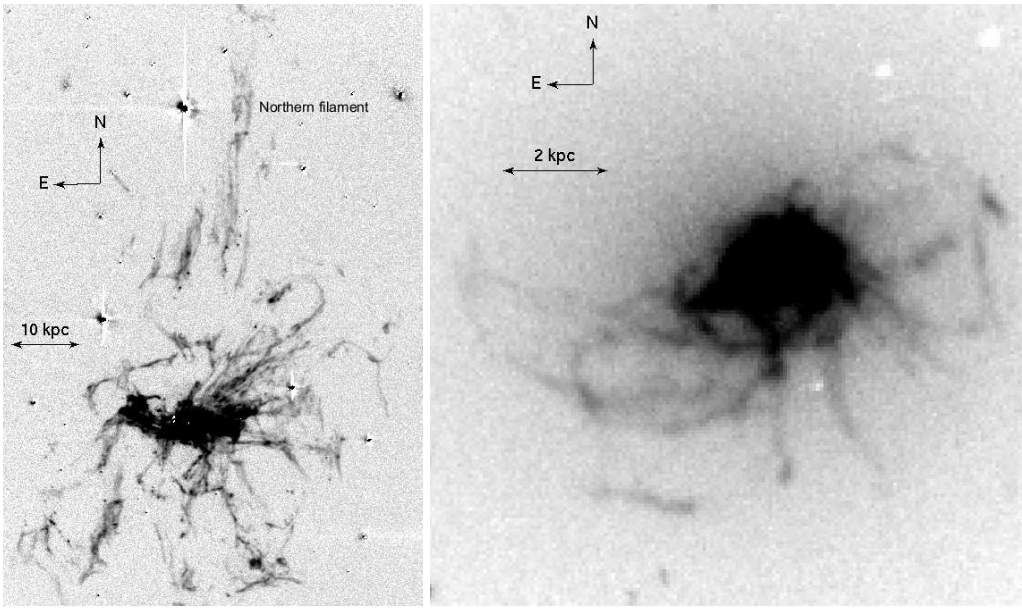

Figure 1. Left: Continuum subtracted Hα emission from NGC 1275 at the core of the Perseus cluster. Data from Conselice et al. (2001). Right: Continuum subtracted Hα emission from NGC 4696 at the core of the Centaurus cluster. Data from Crawford et al. (2005).

et al., 2005a). Comparison with an Hα image of the extended optical nebula that surrounds NGC 4696 shows that the soft X-ray filaments directly align with the optical line-emitting filaments (see Fig. 2). The optical line-emission and the soft X-ray emission share the same spiral structure that is suggestive of a bulk laminar flow and the presence of strong magnetic fields acting on the nebula. Not all bright line-emitting filaments surrounding NGC 4696 have associated soft X-ray emission. Toward the west lies a ring of optical line-emitting gas that surrounds the bubble of radio-emitting plasma. This ring exhibits no clearly associated soft X-ray emission and therefore has a much lower X-ray/Hα ratio than the spiral filaments in the east.

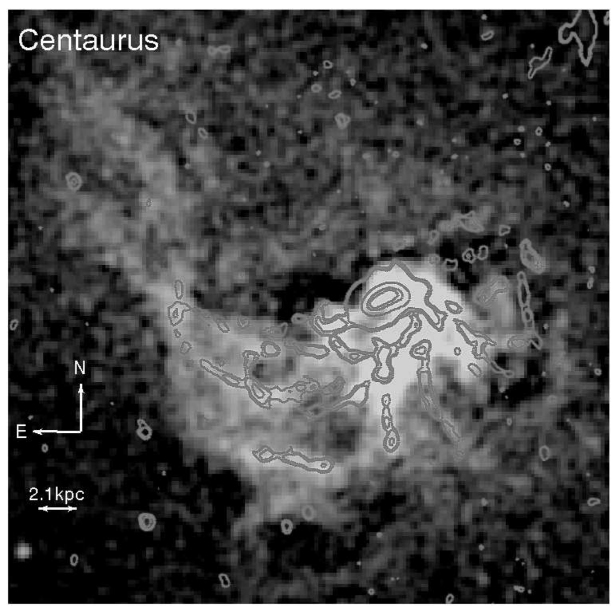

Figure 2. Contours of Hα emission from NGC 4696 overlaid on a soft X-ray image of the core of the Centaurus cluster. X-ray data from (Fabian et al., 2005a). The Hα filaments that spiral east from the central galaxy have spatially associated soft X-ray emission. The filaments are X-ray bright rather than UV bright (unlike the Perseus cluster core).

Whereas there is no clear evidence of dust in the nebula surrounding NGC 1275 in the Perseus cluster, the Centaurus core shows clear evidence of dusty filaments. A $B-I$ image of the Centaurus core maps out the distribution of the absorbing dust and shows there are dust features associated with many of the bright nebula filaments (see Fig. 3). The optical/soft X-ray filaments that spiral east match the strong dust features. The prominent innermost dust lane spirals all the way into the galaxy core (Crawford et al., 2005). A bright filament that stretches northwest across the emission-line ring surrounding the radio bubble corresponds to a dust feature, however, there is no absorbing dust associated with the ring of line-emission that also lacks soft X-ray emission. As it is unlikely for dust to form within gas that is condensing from the intracluster medium, the presence of dust within the filaments means it is probable that the Centaurus filaments were not formed *in situ*, but were extracted from a reservoir within the dusty galaxy environment.

Figure 3. Contours of Hα emission from NGC 4696 in the Centaurus cluster overlaid on B-I greyscale indicating presence of dust. North is up, east is right. The two filaments stretching east from the central galaxy show correlations with strong dust features, as does a shorter filament that stretches west across the ring of Hα emission surrounding the radio bubble. The ring itself does not correlate with any clear dust features.

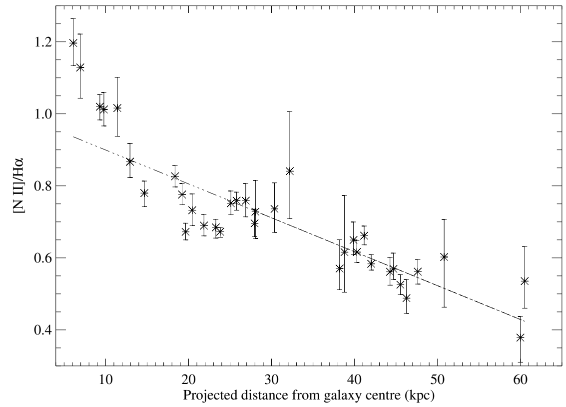

Figure 4. [NII]λ6584/Hα line intensity ratio against projected distance from the core of NGC 1275. The clear radial gradient is difficult to produce from metallicity variations alone, therefore the correlation implies the excitation of the nebula gas is connected to the global properties of the surrounding intracluster medium.

The direct spatial correlation between the optical line-emitting gas and the soft X-ray emission implies an energy exchange between the nebula gas and the surrounding intracluster medium. The intracluster medium that surrounds the central galaxy is very hot, having a temperature greater than 10^7 K, whereas the temperature of the ionized optical and UV line-emitting gas is cooler at $\sim 10^4$ K. Such large temperature gradients may cause conduction to be an efficient heat transport mechanism. Conduction could transfer heat to the optical nebula from the intracluster medium where there is enough energy to ionize the extended nebula (Sparks et al., 2004). Alternatively the energy exchange can be due to a mixing process which would produce the same features (Fabian et al., 2005b). Whilst both the Perseus and Centaurus cluster cores have soft X-ray emission associated with some of the optical line-emitting filaments, the soft X-ray luminosity of the Perseus filaments is only a few per cent of the total optical and UV line-emission luminosity, whereas the Centaurus filaments are twice as luminous in soft X-rays compared to optical and UV line-emission. Neither of these values have been corrected for intrinsic absorption, therefore this variation may be due to the large dust content of the Centaurus nebula reducing the observed Hα flux relative to the X-ray flux. The dusty regions (spiral features) exhibit strong soft X-ray emission, whereas the regions apparently free from large quantities of dust (western ring) do not exhibit strong X-ray emission.

Whilst the process by which the nebula interacts with the intracluster medium is uncertain, it is probable that the nebula cools the intracluster medium in its vicinity, producing the soft X-ray emission observed. The effect of the interaction on the nebula is apparent through the variation in the nebula ionization state. The nebula of NGC 1275 in the Perseus cluster displays a radial variation of the line intensity ratio [NII]λ6584/Hα implying that the intracluster medium affects the excitation of the nebula (see Fig. 4). [NII]λ6584 line emission is produced through collisional excitation, hence is a measure of the thermal energy of the ionized gas, whereas the Hα line intensity is a measure of the ionization rate. Therefore the [NII]/Hα line intensity ratio measures the heat input to the gas per hydrogen ionization. The inner nebula displays emission-line ratios of gas in a very low ionization state, whereas the extended regions display emission-line ratios of a much higher ionization state. The large variation in the [NII]/Hα ratio observed in Perseus is difficult to produce through metallicity variations alone. If the relative abundance of oxygen and nitrogen is fixed, an increase in the total metallicity of the gas reduces the [NII]/Hα ratio. In order to produce the observed range in ratio, there must be a radial increase in oxygen abundance with the largest oxygen fraction at the outer edges of the nebula, whilst the nitrogen abundance must fall. Although a certain process may be able to change the relative abundances in such a way to produce the ratio variation, it seems plausible that the radial gradient in the [NII]λ6584/Hα ratio is a product of an interaction between the nebula and the global properties of the surrounding intracluster medium which vary smoothly (Hatch et al., 2005b).

3. ORIGIN OF THE PERSEUS-NGC 1275 NEBULA

The nebulae surrounding both the Perseus and Centaurus central galaxies have a filamentary morphology, which implies that the intracluster medium cannot be turbulent on scales grater than a few kpcs (Fabian et al., 2003b). On larger scales the emission-line filaments are coupled

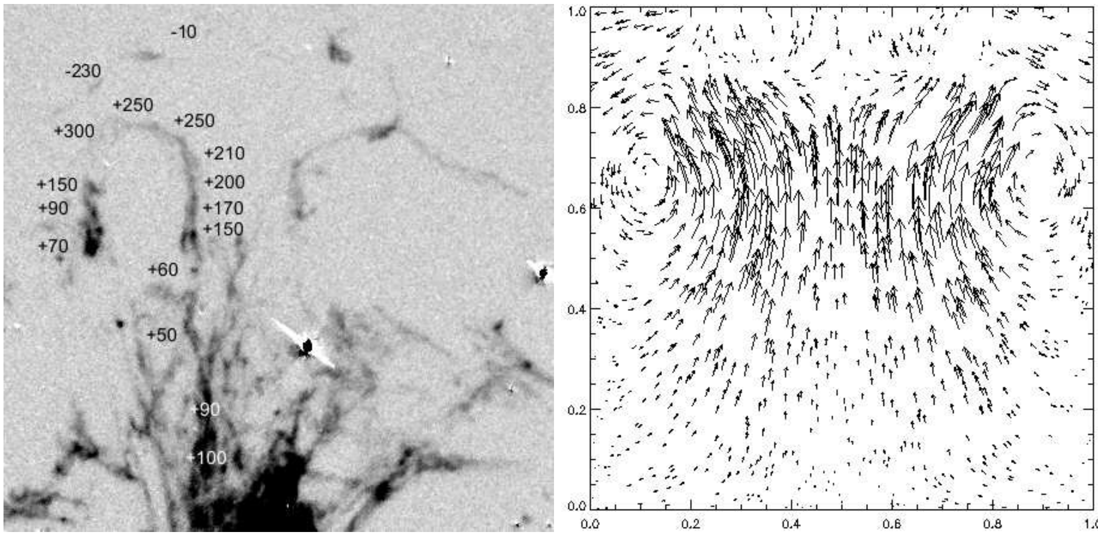

Figure 5. Left: Detail of northwest filaments that lie beneath the ghost bubble. Numbers indicate approximate line-of-sight velocities of the long radial filament. Data from Hatch et al. (2005b). Right: Simulated velocity field of a bubble rising buoyantly through a viscous fluid. Adapted from data of Reynolds et al. (2005)

to the motion of the intracluster medium, therefore they may act as streamlines tracing the bulk flow of the intracluster medium. Fabian et al. (2003b) remark on the similarity of the northwest filaments that lie underneath the ghost bubble to streamlines of flow beneath a spherical cap bubble rising through a fluid. As these ghost bubbles rise they may entrain significant quantities of cool metal-rich intracluster medium from the core (Churazov et al., 2001). The long narrow structure of the filaments suggest that the primary direction of flow is along the filament's length. Doppler shifts of the emission-line gas can be used to measure the velocity field, which can determine whether the filaments have condensed from the intracluster medium and are accreting onto the galaxy, or whether they are galactic gas drawn out from the central galaxy by buoyantly rising ghost bubbles.

Fig. 5 details the heliocentric line-of-sight velocities of the horseshoe shaped filament that lies beneath the northwest ghost cavity. From the bottom of the image, the filament emission is redshifted with a line-of sight velocity of $\sim$+100 kms^{-1} with respect to the central galaxy. The velocity dips slightly before increasing rapidly to $\sim$+250 kms^{-1} further up the filament. The highest velocity occurs on the curved part of the loop, with velocities reaching +300 kms^{-1}. Above the loop (and ghost bubble) lies line-emitting gas which exhibits blueshifted emission with a line-of-sight velocity of $-230\,\mathrm{kms}^{-1}$. This flow pattern qualitatively matches the velocity field of simulations made by Reynolds et al. (2005) of a bubble rising through a viscous intracluster medium. The similarities include:

- The velocity of gas within the filament increases with distance from the central galaxy, with the highest velocities occurring directly underneath the rising bubble/ghost cavity
- The gas flow above the bubble is in the opposite direction to gas flow below the bubble
- The short side of the horseshoe loop is blueshifted relative to the long-side of the loop as expected if the gas flows up the long straight side, over the loop and down the short straight side.

Both the morphology and velocity field of these filaments suggest that they were drawn out of the central galaxy by the rise of the northwest ghost bubble. The spherical cap appearance of the ghost bubble, the morphological structure and the low line-of-sight velocities suggest that the northwest filaments are orientated such that they are close to being in the plane of the sky. Within the interpretation that the filaments are entrained by the ghost bubble, the Doppler shifts indicate that the filaments must be orientated slightly away from the observer.

Direct outflow from NGC 1275 in the Perseus cluster can be observed in a 35 kpc long, thin ($<$1 kpc) filament that stretches radially north from the central galaxy (filament marked in Fig. 1). The filament is unlikely to be in projection with another filament as it is the only structure detected so far out from the central galaxy, and we assume the filament is intrinsically straight as it is improbable that we are observing an intrinsically-curved filament at a particular angle such that it appears straight. Fig. 6 details the line-of-sight velocity of the filament. The upper half of the filament (above a projected distance of 40 kpc from the galaxy centre) displays blueshifted emission whereas the lower half displays redshifted emission. As the predominant flow direction is along the filament, the gas in the lower half must be moving in the opposite direction to the gas at the top of the filament. If the filament is orientated toward the observer, the filament will be collapsing. If the filament is orientated away from the

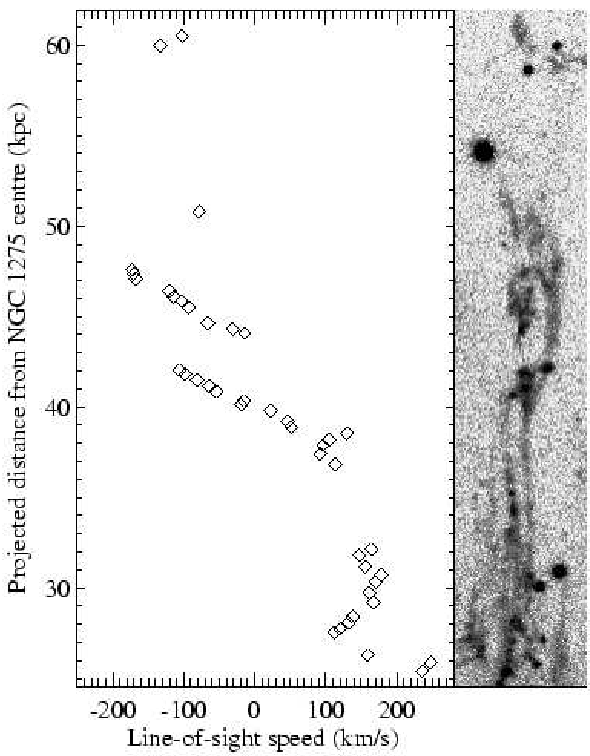

Figure 6. Line-of-sight velocity of the northern filament. Above 40 kpc the filament exhibits blueshifted emission, below 40 kpc, the filament exhibits redshifted emission. Data from Hatch et al. (2005b).

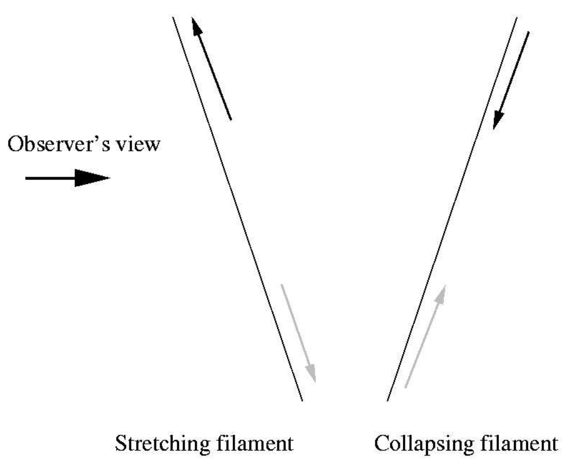

Figure 7. Graphic representing the possible configurations of the northern filament. The bottom of the filament exhibits redshifted lines, the top exhibits blueshifted emission lines. Thus the filament may be stretching or collapsing depending on the orientation. In both scenarios line-emitting gas must have been drawn away from the galaxy.

observer, the filament will be in the process of stretching (see Fig. 7). In both stretching and collapsing scenarios a portion of the filament is flowing away from the central galaxy. In addition to outflowing gas, part of the filament is falling back into the galaxy. These extended nebulae are complex dynamical systems; if the filaments survive in the intracluster medium, we may be observing filaments drawn out from the galaxy over 2 (if not 3; Fabian et al. 2005b) epochs of bubble formation. These filaments may eventually fall back into the galaxy, evaporate due to interactions with the intracluster medium or condense into stellar clusters.

4. SUMMARY

The velocity structure of the northern filament shows that gas more than 30 kpc from the central galaxy is flowing away from the galaxy. The morphology and velocity field of the filaments suggests the most probable dynamical model is one in which the filaments are galactic gas entrained by buoyantly-rising bubbles inflated by the central engine. As the nebula's filaments are coupled to the bulk flow of the intracluster medium on scales larger than a few kpc, the filaments may trace a larger flow of the intracluster medium away from the cluster core.

Direct spatial correlation between the optical line-emitting filaments and soft X-ray emission in both the Perseus and Centaurus cluster cores, imply that an energy exchange is occurring between the two gas phases. Conduction by thermal electrons (Sparks et al., 2004) or mixing (Fabian et al., 2005b) are both possible mechanisms by which the optical nebula can cool the surrounding intracluster medium. Although the mechanism by which the Perseus intracluster medium interacts with the line-emitting nebula is uncertain, the radial gradient in the [N II]/Hα line intensity ratio indicates a possible link between the global properties of the intracluster medium and the ionization state of the nebula gas.

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