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The Optical Anomalies in Central Cluster Galaxies

C. S. CRAWFORD
Institute of Astronomy, Cambridge University

Abstract
I discuss the luminous line emission and visible star formation seen to occur around many brightest cluster galaxies. Such features are found only in clusters with a cool, high-density core, and may well reflect the final balance between the heating and cooling mechanisms operating in the cluster at higher temperatures. The amount of matter in the cool components matches the revised X-ray cooling rates seen in such clusters. I present a deep *Chandra* image of the central cluster galaxy NGC1275 in the Perseus cluster, that demonstrates a direct link between the emission-line filaments that surround the galaxy and soft X-ray structures seen in the core of the intracluster medium.

1.1 Introduction

The central dominant galaxies in about 20-30 per cent of all rich, relaxed clusters show properties – observed primarily in the optical and ultraviolet wavebands – that are not shared by typical giant elliptical galaxies.

1.1.1 Emission Lines and Massive Star Formation

The most immediate anomaly is the presence of strong, low-ionization emission lines in both the optical and ultraviolet spectrum, prominent in lines of nitrogen, oxygen and the Lyman and Balmer hydrogen series (Fig 1.1). OVI (radiated from gas at 0.05 keV) has been detected by *FUSE* in some central cluster galaxies (Fig 1.1: Oegerle et al 2001). The emission-line systems are very luminous (up to 10^{43} erg s^{-1} in Hα alone), and the total recombination radiation in the UV and optical can be more than 10^{44} erg s^{-1} . The emission-line nebulae are spatially extended over tens of kpc, extending well beyond the optical galaxy into the surrounding intracluster medium. Two famous examples are shown in Fig 1.5 and Fig 1.7: the spectacular Hα filaments extending over 100 kpc around NGC1275, the brightest cluster galaxy (hereafter BCG) of the Perseus cluster, and the $\sim$ 80 kpc-long filament seen in the light of Hα+[NII] extending from the BCG in the A1795 cluster.

The galaxies that display these strong, extended emission lines also show a component of ultraviolet/blue continuum light well in excess of the continuum expected in a normal BCG population (Fig 1.1). The optical continuum is well-fit by a massive stellar population (Allen 95; Crawford et al 1999; Bayer-Kim et al 2002), and have sometimes been resolved by HST into individual blue 'blobs' (McNamara et al 1996; Bayer-Kim et al 2002). This excess blue light is again spatially extended on scales of several kpc, and is sometimes distributed into two lobes bifurcated by a dust lane (eg Fig 1.5; McNamara & O'Connell 1993).

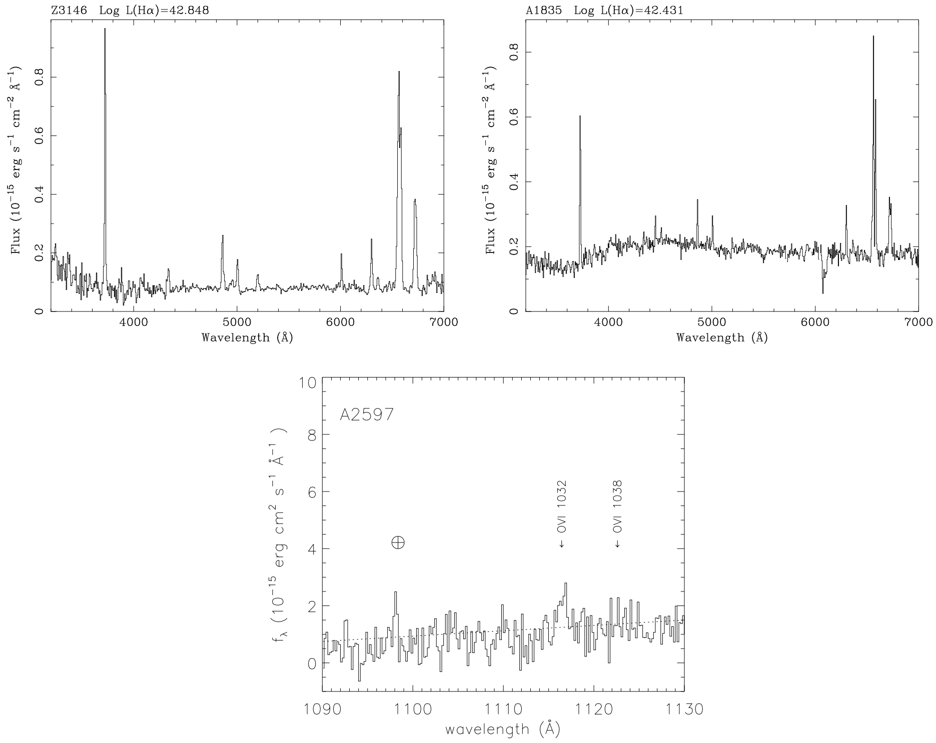

Fig. 1.1. (Top) The (rest-wavelength) emission-line spectrum of two central cluster galaxies showing optical anomalies (from Crawford et al 1999): the BCG of Z3146 at $z \sim 0.3$ (left) and A1835 at $z \sim 0.25$ (right). The slit luminosity of Hα alone is above 10^{42} erg s^{-1} in each galaxy. Note the excess of blue continuum light visible below 4500Å in each galaxy. (Bottom) The *FUSE* detection of OVI in the BCG of A2597 (from Oegerle et al 2001).

Both the properties and the presence of the emission-line nebulae seem correlated with the excess blue continuum. Within a large sample, the strongest line-emitting systems are those that also show the strongest blue continuum (Crawford et al 1999). Within an individual galaxy, the value of the 4000Å break is depressed (implying the presence of more massive stars) only within the regions coincident with the optical emission-line systems (Cardiel et al 1998). Outside these radii, the stellar continuum reverts to 'normal'.

1.1.2 Cooler Components

Detections of infra-red line emission have shown that warm (1000-2500 K) molecular gas is also present around those BCG with 'anomalies' in the optical/UV bands (Jaffe & Bremer 2001; Edge 2001; Edge et al 2002). The detections of both CO and H_2 imply masses of $10^9 - 10^{11}$ $M_\odot$of molecular gas within 50 kpc of the central galaxy. The infrared emission lines are spatially extended, and some show a clear velocity structure (Fig 1.2). There is also evidence for dust ($A_V \sim 2$) in many of these systems, detected from visible dust lanes seen in colour maps (eg Pinkney et al 1996; Edge et al 1999), a depressed Balmer decrement

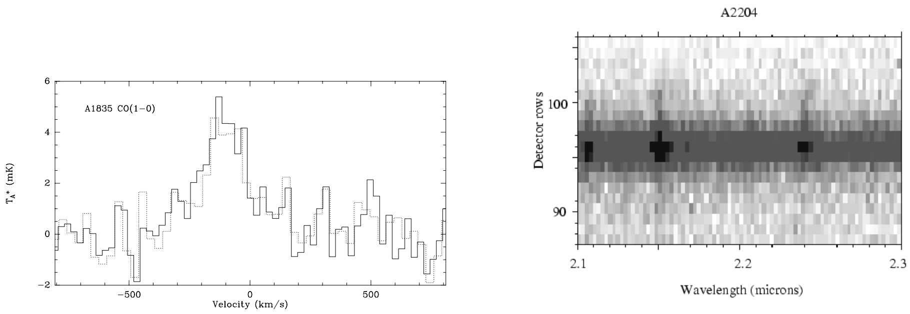

Fig. 1.2. (Left) Detection of CO in the BCG of A1835 (Edge 2001). (Right) Two-dimensional spectral image of the extended infra-red line emission around the BCG of A2204 (Edge et al 2002).

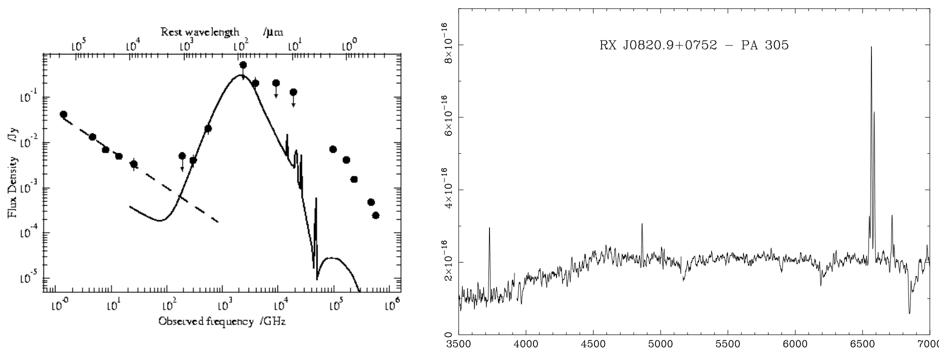

Fig. 1.3. (Left) The spectral energy distribution of the BCG of A1835 between the radio and UV wavebands, showing a detection of excess emission at 850μ (Edge et al 1999). (Right) The (rest-wavelength) optical spectrum of the BCG in the cluster RX J0820.9+0752, where the Balmer decrement implies an intrinsic reddening of $A_{\rm V} \sim 2$ (Bayer-Kim et al 2002).

in the emission lines (eg Allen 95, Crawford et al 1999) and a spectral energy distribution showing a substantial excess emission in the sub-mm (Edge et al 1999: Fig 1.3).

1.2 Relation to the Radio Source Structure

There are several individual cases where the distribution of the optical emission nebula and visible star formation are clearly influenced by the radio source structure. For example, the primary regions of blue continuum around the BCG of A1795 lie along the outside of the radio lobes (McNamara et al 1996), and the warm optically-emitting gas around A2597 is again located around the outside of the radio lobes (Koekemoer et al 2002). Such structures are presumably related to the observed propensity for strong radio sources to evacuate holes in the surrounding X-ray emitting intracluster gas at the core of a cluster (eg in Hydra-A, McNamara et al 2000; Perseus, Fabian et al 2000). In such cases it is clear that the outflowing radio plasma will also displace any cooler components of the intracluster medium, and stars that form from it. What is less obvious is the rôle the radio source may play in actually triggering the star formation.

1.3 The 'Cooling Flow' Connection

The BCG with the optical peculiarities lie *exclusively* in 'cooling flow' clusters – clusters observed in the X-rays to have a cool, high-density core – so their very occurrence appears linked to the properties of the hot gas in the intracluster medium. *XMM-Newton* and *Chandra* results confirm the presence of a range of X-ray temperatures in such clusters, in that the temperatures drops by about a factor of three within the inner ~ 100 kpc radius (eg Peterson et al 2001; Kaastra et al 2001). The radiative cooling time of the gas drops from above 5 Gyr to $\sim 5 \times 10^8$ yr over the same radii. These gradients may possibly be augmented also by contributions from incoming cool sub-clusters. The X-ray spectra from these missions, however, fail to show evidence for gas cooler than about a third of the outer cluster temperature, with upper limits of $\sim 20\%$ of the rate seen at higher temperatures (eg Peterson et al 2001, Kaastra et al 2001). The fact that the gas appears to cool so far but no further has been termed the 'cooling flow problem', and presents a interesting challenge to our understanding of the balance of heating and cooling within the intracluster medium (see Fabian 2003).

Some form of heating is required to reduce the mass cooling rates by a factor of ~ 10 from the simple pre-*Chandra*/*XMM-Newton* values. Without a heat source, the continual accretion of cooling material would cause the BCG to be ten times more massive than observed. Hence the upper mass limit to a BCG (which are the most massive galaxies known) is dictated by the balance of the heating and cooling processes operating in the intracluster medium. Given that most of the gas that forms the baryonic content of galaxies is thought to behave similarly to a cooling flow, understanding this heating/cooling balance has wider ramifications to the whole issue of the galaxy formation (Fabian 2003). There is currently much work in the literature arguing the merits of possible heat sources that could operate in the intracluster medium, such as conduction (Voigt et al 2002; Fabian et al 2002), input of energy by a central radio source (Churazov et al 2002) or indeed combinations of the two (Ruszkowski & Begelman 2002).

The modified cooling flow rates have, however, provided a solution to the long-running debate about the eventual fate of the gas expected to have cooled from X-ray temperatures. Current spectroscopic limits allow modest levels of cooling (at rates of a few tens of $M_\odot\,yr^{-1}$) to continue into the inner few tens of kpc, and such rates now neatly match the amount of gas required to produce the line emission and star formation observed in other wavebands. We are no longer seeking to 'hide' much larger quantities of cooled matter in the core of a cluster. By studying these cool gas components and recently formed stars around BCG, we are directly observing that part of the X-ray gas which 'escaped' the heat source, to continue on and contribute to the underlying BCG. Comparison of X-ray properties of a cluster to the quantity of material involved in the star formation and cool line emission should enable us to assess how well the heating balances the cooling at intermediate temperatures.

1.4 The X-ray-optical Connection

The optical line-emitting filaments often spatially coincide with the soft (cooling) X-ray structures around a BCG, although this is commonly due to the displacement of both by outflowing plasma from a central radio source (eg in A2052, Fig 1.4: Blanton et al 2001). For clarification of the link between the cooling X-ray gas and the cooler components, we should seek examples of spatial coincidences away from the influence of the radio source.

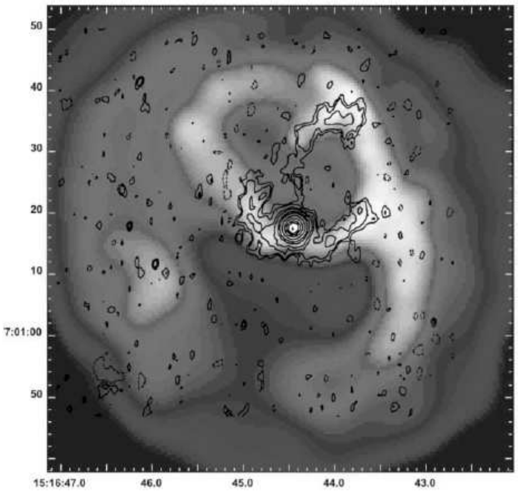

Fig. 1.4. The background greyscale image shows the distribution of the X-ray emission in the vicinity of the BCG in A2052 (Blanton et al 2001). The brightest part of the X-ray structures (shown as white) is coincident with the Hα+[NII] line emission (contour lines).

For example, whilst there is a clear radio-cool cloud interaction close to the BCG in A1795 (Crawford 2004), most of the long emission-line filament is well displaced from the radio source (Fig 1.5), including discrete blue blobs of massive star formation along its length (McNamara et al 1996), whose formation is unlikely to have been triggered by the radio source.

Another example lies in the cluster RX J0820.9+0752 at $z = 0.11$ (Fig 1.6: Bayer-Kim et al 2002) which shows an extended component of soft X-ray emission towards the NW. The Hα nebula around the BCG is spatially extended in the same direction, and the NW side is also coincident with a region of strong intrinsic dust absorption and CO emission (which shares the velocity structure of the optical emission lines). An *HST* image reveals two arcs of blue, star-forming blobs extending from the NW to the SE around the BCG. The exciting thing about this particular galaxy, however, is that although it shares all the optical peculiarities we are discussing, it does *not* contain a central radio source (or at least one that is still active). The inferred star formation rates and mass in cooler components around this galaxy are well matched to the X-ray (*Chandra*) inferred cooling rates of a few tens of solar masses a year. It is thus clear that it is possible to produce all the optical anomalies from the cooling processes in the intracluster medium alone, without interference from a powerful central radio source.

1.5 A Special Case: The Perseus Cluster

A recent 200 ksec *Chandra* observation of the nearby Perseus cluster shows a wealth of fascinating features – such as a clear shadow from the small foreground ('high velocity') system, emission from the central active nucleus, holes evacuated by bubbles of radio plasma displacing the X-ray intracluster medium, detached (presumably buoyant) holes at larger radii, and sharp azimuthal ridge structures (Fabian et al 2004). At soft ener-

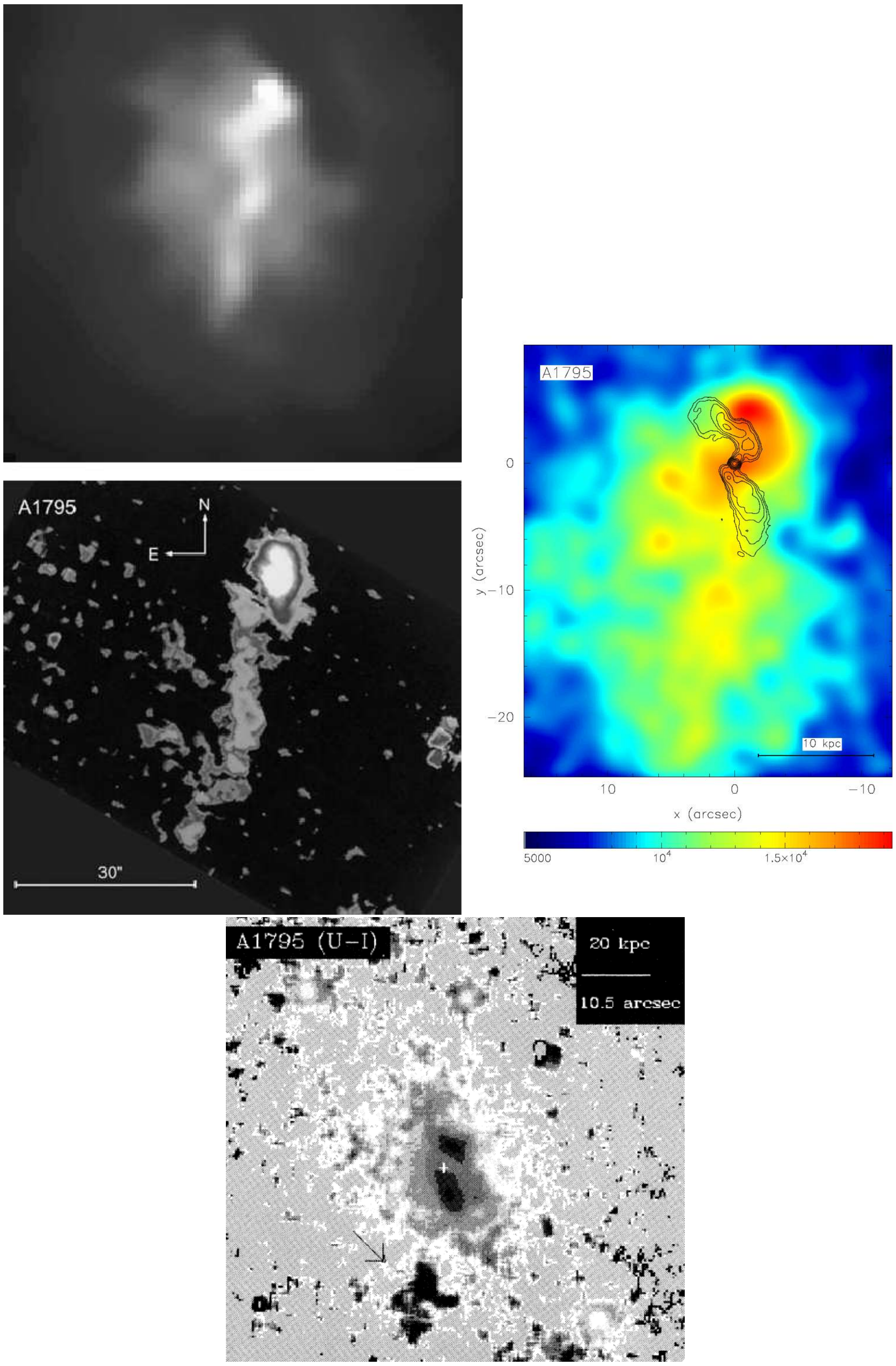

Fig. 1.5. The central cluster galaxy of A1795. (Top left) The soft X-ray filament observed with *Chandra* (Fabian et al 2001). (Bottom left) The optical filament in the light of Hα+[NII] (Cowie et al 1983). (Top right) The contours of radio emission overlayed on the *Chandra* emission (Fabian et al 2001). (Bottom right) Colour map (in which dark colours correspond to blue regions) regions, showing the excess blue light to have a double structure around the radio source (the centre of which is marked by the white cross). There is a significant blue excess (marked by the arrow) lying half-way along the filament. (McNamara & O'Connell 1993).

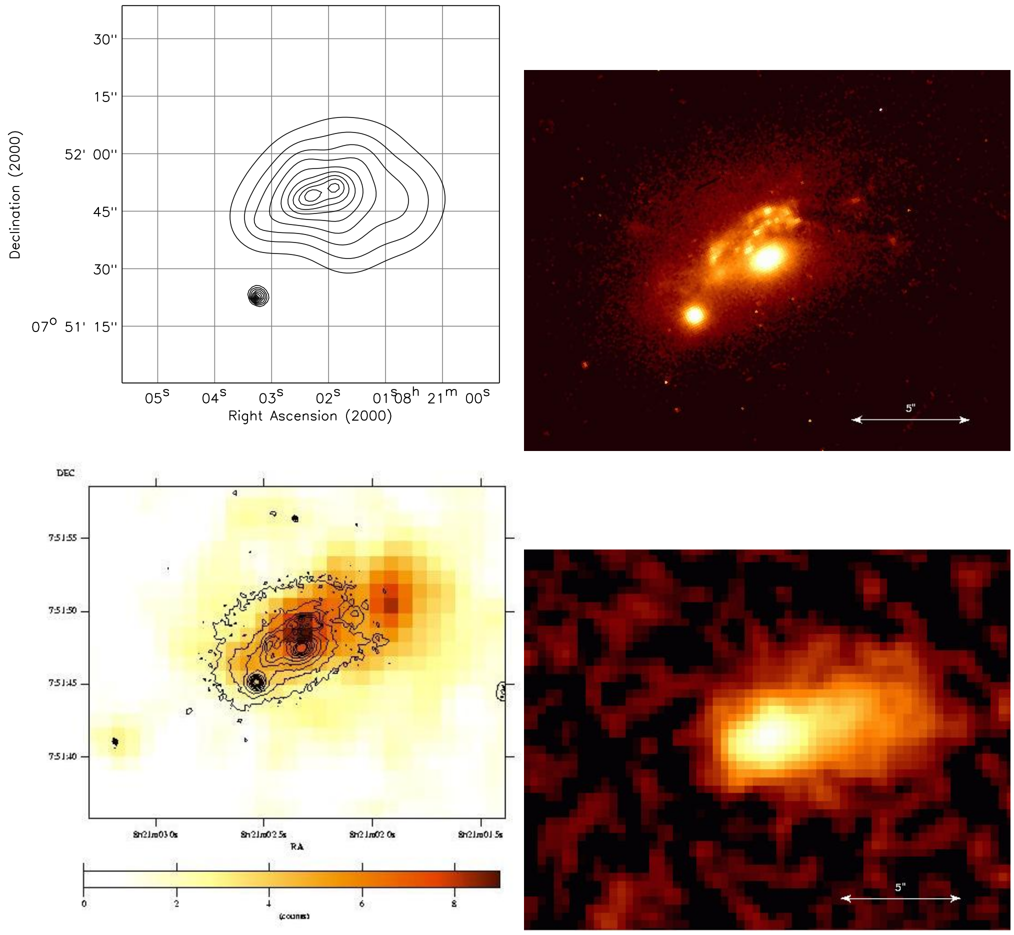

Fig. 1.6. (Top left) Contour plot of the 0.3-7 keV *Chandra* emission from the RX J0820.9+0752 cluster, showing it to be extended to the NW. (Top right) *HST* (F606W) image of the central regions around the BCG, showing the dust absorption to the NW, and the blobby arcs of young star formation. (Lower left) A slightly smoothed image of the 0.5-2 keV X-ray cluster emission (greyscale) with the contours of the *HST* optical emission overlaid. (Lower right) An image of the (continuum-subtracted) Hα emission around the BCG. All images are taken from Bayer-Kim et al (2002).

gies, very faint radial spurs can also be seen stretching to the North of the BCG. These appear more clearly in an unsharp-masked image of the soft energy emission (Fig 1.7). Comparison to the Hα image of Conselice et al (2001: Figs 1.7,1.8) demonstrates that many of these faint features correspond directly to structures seen in the emission-line gas.

Some of these X-ray/optical filaments also seem to show curious relations with the intracluster environment, and do not show any direct correspondence to the radio source structure. In particular:

1. To the NW, two filaments appear to be deflected and curl back where they meet the inner

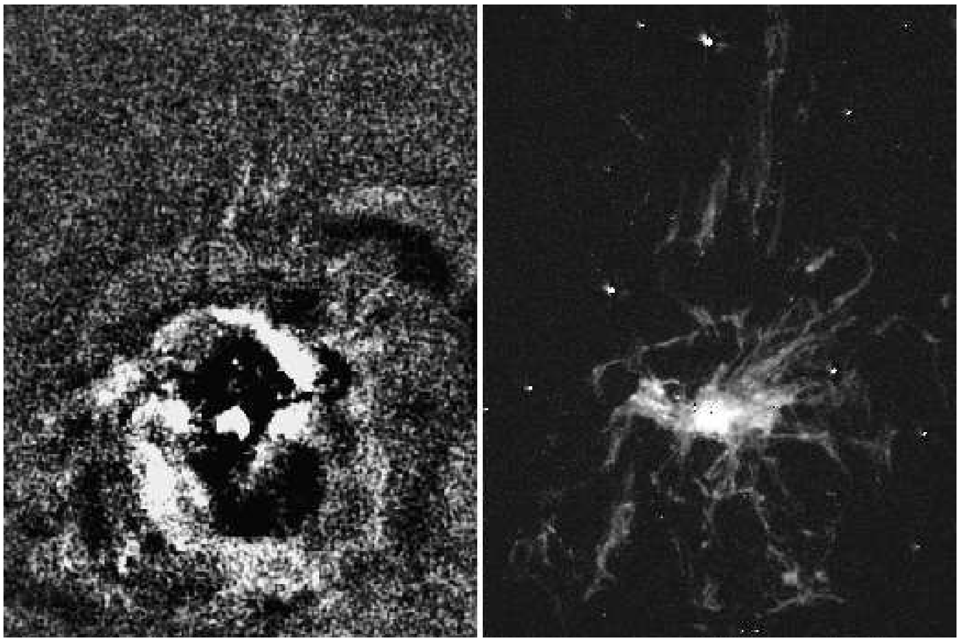

Fig. 1.7. (Left) A slightly-smoothed, unsharp-masked image of the *Chandra* soft energy X-ray emission around NGC1275, the BCG of the Perseus cluster. (Right) The image of NGC1275 in the light of (continuum-subtracted) Hα, at the same scale and alignment as the X-ray image from Conselice et al (2001).

edge of an outer buoyant cavity in the intracluster medium.
2. The northern radial filaments appear to terminate at an azimuthal edge or ‘shell’ feature seen in the X-ray emission.
3. A loop in both the X-ray and line emission to the SE corresponds to the position of the long-known star-forming ‘blue loop’.
4. A thin X-ray/optical filament is seen crossing the SW radio cavity (though presumably it only crosses it in projection, and not in three-dimensions).

The optical emission-line filaments around NGC1275 thus appear to arise directly from conditions originating in the hot cluster gas. The process giving rise to the X-ray and optical filaments is also related to the recent star formation, as exemplified by the blue star clusters seen in the ‘blue loop’ region 30 kpc to the SW of NGC1275 (eg Conselice et al 2001). We plan to investigate whether the connection of the recent star formation holds for all the optical/X-ray filaments in this system, although this will require some detailed quantification of intrinsic reddening across the system.

1.6 Conclusions

There is increasing evidence directly linking the luminous line emission and recent massive star formation seen around some brightest cluster galaxies to cooling features seen in deep X-ray images. In particular, soft X-ray structures around NGC1275 can be seen to match much of the Hα filamentation around this galaxy. Both from this source, and our

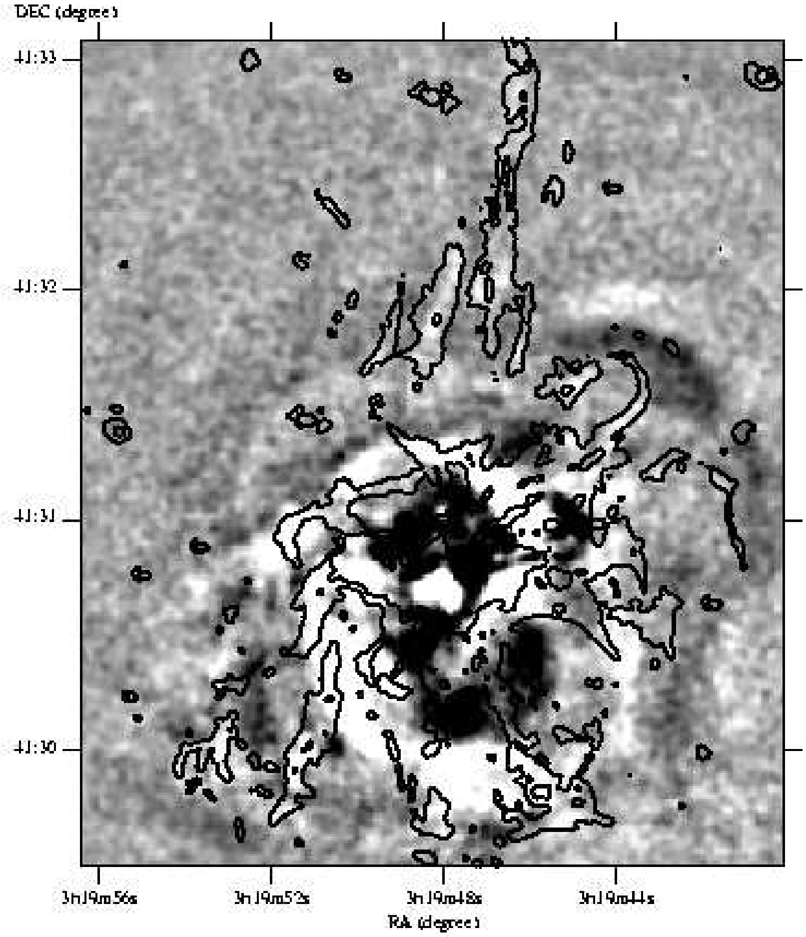

Fig. 1.8. the unsharp-masked image of the *Chandra* soft X-ray emission around NGC1275, with the outline of the Hα filaments (from Conselice et al 2001) marked by the superimposed contours.

observations of the BCG in RX J0820.9+0852 we suggest that an interaction from the central powerful radio source is not necessary to produce these features. The amount of matter involved in creating the observed cooler components is comparable to the reduced, post-*XMM*/*Chandra* cooling rates seen in such clusters, and reflect the outcome of the delicate balance of cooling and heating in the intracluster medium at higher temperatures. Perhaps conditions in those clusters which show X-ray cooling but no lower temperature components reflect a different cooling-heating balance in the surrounding intracluster medium. It will be of interest to re-quantify the role of the optical anomalies in the light of the reduced cooling rates seen in clusters of galaxies; they may represent a much clearer tracer of clusters with cool cores than previously thought.

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