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NEW PERSPECTIVES ON COOLING FLOWS AND CLUSTER RADIO SOURCES

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We discuss new results from the Chandra X-ray Observatory and XMM-Newton on cluster cooling flows, emphasizing early results from our Chandra programs. We find cooling rates reduced by factors of 5–10 compared to those from earlier missions. Nevertheless, substantial amounts of keV gas appear to be cooling and fueling star formation in central dominant cluster galaxies (CDGs). The structure of the keV thermal gas is remarkably complex, particularly in regions surrounding the the radio source and sites of star formation in CDGs. The radio sources are displacing the thermal gas leaving cavities filled with radio emission. The cavities are apparently supported against the local gas pressure by magnetic fields and cosmic rays. In addition, radio-faint, "ghost" cavities are seen in some clusters. They may be relics of earlier radio outbursts rising buoyantly in the intracluster medium. The radio sources may reduce the mass deposition rates by mechanical heating, and by inducing convective currents that move cool material outward.

1 The Cooling Flow Problem

Roughly half of clusters of galaxies have bright cusps of X-ray emission in their central ~ 100 kpc. The cusps are associated with so-called cooling flows: regions of dense gas with short radiative cooling times (Fabian 1994). Absent a significant source of heat, the gas will cool to low temperatures and accrete onto the cluster's central dominant galaxy (CDG). The cooling gas will presumably accumulate there in atomic and molecular clouds and form stars. Indeed, the likelihood that a CDG has detectable levels of cold gas and star formation increases dramatically with the X-ray cooling rates (McNamara 1997; Cardiel et al. 1998). However, the cooling rates always exceed the observed levels of cold gas and star formation by large factors. Cooling rates of hundreds to as much as two thousand solar masses per year have been reported from analyses of *ROSAT* data. By comparison, the star formation rates are generally one to two orders of magnitude less than the cooling rates. Furthermore, the systems with the largest star formation rates appear to have experienced bursts or episodes of star formation lasting $\lesssim 100$ Myr or so (McNamara 1997). Therefore, unless cooling is likewise episodic, cold gas would accumulate to the observed levels in much less than 100 Myr, which in turn is much less than the probable $1-10$ Gyr ages of cooling flows. This troubling situation leads to the view that either the matter is accumulating in a dark or otherwise unusual physical state, cooling flows are young, or the cooling rates have been substantially overestimated.

Progress on this problem stagnated through much of the 1990s because the previous generations of X-ray telescopes left the cooling regions for the most part unresolved. The new Chandra X-ray Observatory breathed new life into this problem with remarkably crisp spectral images of clusters resolved on kiloparsec (arcsec) scales, the same scales on which cold, freshly-accreted gas, star formation, and powerful radio activity is observed. In addition, high resolution spectra from Chandra's High Energy Transmission Grating (HETG) and XMM-Newton's Reflection

Grating Spectrometer (RGS) are probing the spectral lines responsible for cooling through temperatures shortward of 1 keV. In this respect, the Fe XVII and O VII lines are particularly important (Peterson et al. 2000).

2 Reduced Cooling Rates from Chandra and XMM-Newton

It would be premature to comment definitively on the broad trends in cooling flows, other than to point out that the early Chandra and XMM results for several clusters do not confirm the huge cooling rates derived from *ROSAT* and *Einstein* data. The radially decreasing temperature gradients and short central cooling times $t_{\rm cool} \sim 5 \times 10^8$ yr are certainly observed in several clusters. However, the spectroscopically derived cooling rates are factors of 5–10 less than earlier estimates. For instance, the first cooling flow observed with Chandra during its orbital verification phase was the Hydra A cluster. The *spectroscopic* cooling rate derived from spectral imaging on the ACIS S3, back-illuminated CCD is $\dot{M} \simeq 35$ $M_\odot$ yr^{-1} (McNamara et al. 2000; David et al. 2000), while earlier studies reported cooling rates of $\dot{M} \sim 300-600$ $M_\odot$ yr^{-1} (David et al. 1990; Peres et al. 1998, but see Ikebe et al. 1997). Similarly, a preliminary analysis of a Chandra image of Abell 2597 gives $\dot{M} \simeq 40-80$ $M_\odot$ yr^{-1} (McNamara et al. 2001), compared to the *ROSAT* PSPC value of $\dot{M} \simeq 280-350$ $M_\odot$ yr^{-1} (Sarazin & McNamara 1997; Peres et al. 1998). Furthermore, including a cooling flow component in the spectral models improves the fits to the data only in the central few tens of kpc, and then only marginally.

The only evidence for massive cooling is found using morphological cooling rates, calculated essentially by dividing the central gas mass by the cooling time. This method gives $\dot{M}$s that are roughly consistent with results from earlier X-ray missions. However, the morphological $\dot{M}$s vastly exceed the spectroscopic $\dot{M}$s in the same systems (David et al. 2000). The inconsistency between these methods suggests that either the cooling gas is being reheated or maintained at keV temperatures by some poorly understood process (David et al. 2000; Fabian et al. 2000a), or the cooling model is wrong.

The most compelling evidence for reduced cooling is found in XMM's RGS and Chandra's HETG spectra for the massive cooling flow in Abell 1835. Abell 1835 has a putative $\dot{M} \sim 2300$ $M_\odot$ yr^{-1} cooling flow (Allen et al. 1996). However, high dispersion spectroscopy with the RGS and HETG provide upper limits of $\dot{M} \lesssim 200-300$ $M_\odot$ yr^{-1}, based primarily on Fe XVII emission limits (Peterson et al. 2000; Wise et al. 2001). While this $\dot{M}$ is certainly large, the data imply that either most of the cooling gas is maintained above ~ 1 keV, or that gas is cooling below 1 keV without an obvious spectroscopic signature (Fabian et al 2000a).

3 Star Formation as the Repository of the Cooling Gas

Even though the huge cooling rates reported in the last 20 years appear to have subsided, there is evidence for substantial cooling. Nonetheless, the the mass budgets in the few systems studied thus far do not balance. In Hydra A, the strongest spectroscopic evidence for cooling gas is found in the central 30 or so kpc (David et al. 2000; McNamara et al. 2000). Within this region sits a 9 kpc diameter circumnuclear disk of young stars and gas (McNamara 1995; Hansen et al. 1995; Melnick et al 1997). The star formation history of the disk, i.e. burst or continuous star formation, remains sketchy. However, the disk's mass as measured by its rotation curve and luminosity is $10^{8\rightarrow 9}$ $M_\odot$. This mass is consistent with the present rate of cooling throughout the entire volume of the disk over the Hubble time. On the other hand, if all 35 $M_\odot$ yr^{-1} of material cooling within a 70 kpc radius is accreting onto the disk, it would double its mass in only 30 Myr. This would be implausible unless the accretion began recently. Hydra A's stellar halo is also unusually blue (Cardiel et al. 1998; McNamara 1995), so distributed star formation at some level could account for at least some of the cooling gas.

The CDG in Abell 2597 likewise is experiencing vigorous star formation with a total mass of $\sim 10^{8\rightarrow 9}$ $M_\odot$ (McNamara & O'Connell 1993; Koekemoer et al. 1999). Although we have not completed our Chandra analysis of Abell 2597 (McNamara et al. 2001), the preliminary estimate of $\dot{M} \sim 40 - 80$ $M_\odot$ yr^{-1} would be capable of fueling star formation for $\sim 10^7$ yr or so depending on the star formation history. Therefore, while the reduced accretion rates certainly reduce the mass deficit, most of the cooling mass remains unseen.

3.1 X-ray Structure Near the Sites of Star Formation

The Chandra images of cooling flows we have seen thus far show surface brightness irregularities and structure in the inner few tens of kpc. Much of the structure is associated with the radio sources, nebular emission, and sites of star formation. For instance, a bright, irregular X-ray structure is associated with the disk of star formation and nebular emission in Hydra A (McNamara et al. 2000). (The structure surrounding Hydra A's radio lobes is discussed below.) In addition, bright knots of X-ray emission (McNamara et al. 2001 in prep.) accompany the regions of ongoing star formation, nebular emission, and molecular gas in Abell 2597 (Voit & Donahue 1997; Donahue et al. 2000). These structures are seen in Figure 1 with the radio contours superposed on the X-ray image.

The significance of these spatial correlations are just beginning to be explored. However, it has been known for some time that star formation and nebular emission in cooling flows are found preferentially along the edges of the radio sources (Heckman et al. 1989; Baum 1992; McNamara 1997; Cardiel et al. 1998). Star formation occurs in repeated bursts (McNamara & O'Connell 1993; Allen 1995; McNamara 1997) and in many instances, the radio source seems to be triggering it by some mechanism (e.g. De Young 1995; McNamara 1999). The bright X-ray emission may be from dense, cool gas that was compressed and displaced by the expanding radio lobes, or back-flowing material along the radio lobes. The fact that the brightest structure is seen in similar configurations between the radio lobes in several objects with a broad range of radio power (e.g. Hydra A, Abell 2597, M84) supports this general picture.

In Hydra A, the cooling time of the gas reaches a minimum of $\sim 300 - 600$ Myr surrounding the blue optical disk where star formation is observed. Whether this means star formation is being fueled by cooling is not clear. A remarkable correlation between X-ray structure, star formation, and nebular emission is seen in the Chandra image of Abell 1795 (Fabian, this conference). Abell 1795 has a tail of U-band continuum and Hα emission extending roughly 70 kpc to the south of the CDG (Cowie et al. 1983; McNamara et al. 1996). The Chandra image shows this optical emission embedded in a bright X-ray filament. This feature is unrelated to the radio source, but may be associated with a group merger or a cooling filament of gas.

4 Interactions Between Radio Sources and the ICM

4.1 Radio-Bright Cavities in the keV Gas

Chandra observations show a strong interaction between the keV gas and the powerful radio source Hydra A. The most striking features are 30 kpc diameter depressions in the X-ray emission that coincide with the radio lobes (McNamara et al. 2000). Similar surface brightness depressions in Perseus seen in *ROSAT* HRI images (Böhringer et al 1993) are beautifully seen in Chandra images (Fabian et al. 2000b). The radio lobes appear to be excavating cavities in the keV gas. The cavities are presumably supported against the ambient gas pressure by magnetic fields and cosmic rays. The density within the cavities, or bubbles, is much less than their surroundings, so the bubbles rise outward by buoyancy (McNamara et al. 2000; Churazov et al. 2000). Using hydrodynamic models, Heinz, Reynolds, & Begelman (1998) have proposed that cavities would form in the ICM during the supersonic expansion of the radio cocoon. In this case, the models predict high-entropy, shocked gas surrounding the radio lobes. This is not observed. In fact the gas in the shell around Hydra A's radio lobes is cooler than the surrounding material. Fabian et al. (2000b) likewise found cool gas surrounding NGC 1275's radio cavities. David et al. (2000) and Reynolds, Heinz, and Begelman (2000) have argued that Hydra A is in the weak shock regime of its expansion, when the radio lobes are moving at the local sound speed.

Assuming the radio-bright cavities are in pressure balance with the surrounding gas, we can derive several interesting properties (see McNamara et al. 2000; Reynolds, Heinz, and Begelman 2000). For instance, the mechanical power required to inflate the cavities $P = pV/t_{\rm b} \simeq 6 \times 10^{43}$ ergs s^{-1} is comparable to Hydra A's total radio power. Here, p is the ambient pressure, V is the volume of the cavities, and $t_{\rm b}$ is the local buoyancy timescale. (A similar figure is obtained assuming the cavities expanded at the local sound speed.) This shows that the radio source is indeed capable of displacing the keV gas, and that there is little evidence for radio kinetic luminosity substantially in excess of the luminous radio power. Radio-filled cavities are also seen in low radio power ellipticals such as M84 (Finoguenov & Jones 2000). Strong interactions are evidently occurring in systems covering a wide range of gas density and radio power.

4.2 Radio-Faint Cavities in the keV Gas

Cavities in the X-ray emission that lack bright radio emission above ~ 1 GHz have been discovered in a few clusters. For example, Abell 2597 harbors a powerful radio source PKS 2322-122 (Sarazin et al. 1995). The radio source is relatively compact in the CDG's inner 10 kpc, where it is colliding with cold, dusty gas clouds (Sarazin et al. 1995). Although the X-ray surface brightness decreases at the locations of the radio lobes, cavities are not as obvious as those seen in Hydra A and Perseus. However, a prominent, circular cavity is seen 30 kpc to the southwest of the CDG, and possibly another to the northeast. The cavity to the southwest is roughly 12 kpc in diameter and is aligned with the axis of Abell 2597's inner radio jets. A 15 minute VLA, A configuration image at 8.44 GHz clearly shows the inner radio source (Sarazin et al. 1995), but fails to reveal any emission from the cavities. Although the origin of these cavities is unknown, they may possibly be the outwardly-moving remnants of a previous radio outburst: a radio fossil or "ghost" (Enßlin & Gopal-Krishna 2000; Medina-Tanco & Enßlin 2000). Assuming they are propelled outward by buoyancy, the causal radio outburst would have occurred ~ 100 Myr ago. If the cavities are filled with magnetic field and cosmic rays with a decaying synchrotron flux, radio emission may be detectable at lower frequencies.

Abell 2597 is not unique. Similar, radio-faint cavities are seen in Perseus beyond its radio-filled, inner cavities (Fabian et al. 2000b). The outer cavities in Perseus have, however, been detected at 74 MHz, which suggests that they are devoid of energetic electrons (Fabian et al. 2000b). These bubbles of magnetic field and cosmic rays are presumably lifted into the outer regions of clusters where, rejuvenated, they may contribute to the formation of cluster-scale radio halos (Kempner & Sarazin 2000; Enßlin & Gopal-Krishna 2000).

4.3 Evidence for Repeated Radio Outbursts

That nearly 70% of CDGs in cooling flows are radio-bright (Burns 1990) implies that radio sources live longer than about 1 Gyr, or they recur with high frequency. Our interpretation of the cavities implies the latter, with a recurrence approximately every 100 Myr. This would have significant implications for understanding energy feedback to the ICM, the star formation histories of cooling flows, and the nature and fueling of radio sources. Feedback between the central black hole and cooling flow may be occurring at some level (Tucker & David 1997; Soker et al. 2000). Furthermore, star formation occurs in repeated, short duration bursts (McNamara

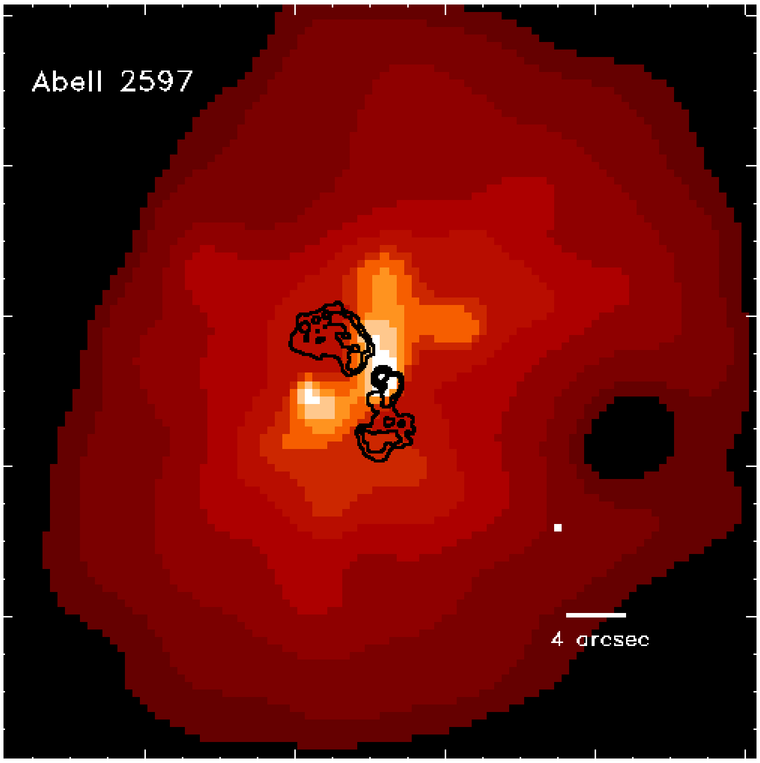

Figure 1: 40 ksec Chandra image of the center of Abell 2597 (grayscale) with 8.4 GHz radio contours superposed (McNamara et al. 2001 in prep). Note the radio-faint hole 17 arcsec to the southwest.

1997; Allen 1995; Cardiel et al. 1998), and there is strong evidence in several objects that the starbursts were triggered by their radio sources (McNamara 1997). The starburst ages are generally consistent with the radio-burst ages implied by the cavities in Hydra A and Abell 2597. It therefore seems that repeated radio outbursts affect both the structure and dynamics of the keV gas and the star formation histories of cooling flows. However the physical mechanisms driving these process are poorly understood.

4.4 Radio Heating and Convection in Clusters

It is too early to tell whether the mechanical energy of radio sources is heating the ICM and lowering the cooling rates (Soker et al. 2000). On the one hand, Hydra A's entropy profile flattens near the center of the cluster, which suggests the gas is indeed being heated (David et al. 2000). Furthermore, the energy input required to substantially reduce the cooling rate is only four times the current radio power. Therefore, a plausible amount of mechanical energy above the radio luminosity would be required to heat the gas. On the other hand, the decreasing temperature gradient in the vicinity of the radio source is inconsistent with heating, nor is there evidence for strong shocks (McNamara et al. 2000). Weak shocks, which are difficult to detect, may be important, however (David et al. 2000). So although radio sources are obviously having a substantial impact on the dynamics of the ICM, it is not yet clear that they are heating the gas significantly.

Finally, David et al. (2000) proposed that convective currents driven by Hydra A's radio source are removing cooling material from the core of the cluster and transporting it outward. However, the pronounced metallicity gradient in the cluster's core (David et al. 2000; Fukazawa et al. 2000) is a problem for this scenario. Convection should remove a metallicity gradient, unless the excess metals are rapidly replenished. Although ongoing star formation is occurring in Hydra A, the present day star formation rate is too low to replenish the metals at the required rate.

5 Low Luminosity AGN

Chandra is revealing low luminosity AGN in CDG nuclei. In addition to being powerful radio sources, both Hydra A (Sambruna et al. 2000; McNamara et al. 2000) and Abell 2597 (McNamara et al. 2001) have unresolved nuclear X-ray sources. Hydra A's spectrum can be modeled as a heavily absorbed power law with a total unabsorbed luminosity of $L_{2-10\mathrm{keV}} \simeq 1.3 \times 10^{42}$ ergs s^{-1}, and an absorbing column of $N_{\mathrm{H}} \simeq 4 \times 10^{22}$ cm^2 (Sambruna et al. 2000). Hydra A would have a $\sim 10^9$ M$_\odot$ nuclear black hole were it to lie on the velocity dispersion–black hole mass relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000). The observed nuclear X-ray flux would then correspond to $\sim 10^{-5}$ times the Eddington luminosity, which is consistent with its being a low radiative efficiency, advection dominated accretion flow, i.e. ADAF (Sambruna et al. 2000). Furthermore, Hydra A and Abell 2597 both have deep H I absorption features seen against their nuclear radio sources and jets (Taylor 1996; Taylor et al. 1999), which is rare in the general population of ellipticals (Morganti et al. 2000). In Hydra A, the hydrogen column density in front of the radio core roughly matches the column density derived from the X-ray spectrum of the AGN. This implies that the cold material is within 24 pc of the central black hole (McNamara et al. 2000). These properties taken together support models for AGN fueled by accretion of cold gas onto a super massive black hole, although the hot Bondi accretion favored by ADAF models may also be important (Di Matteo et al. 2000).

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