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Star Formation in Cluster Cooling Flows

B.R. McNamara

Ohio University, Physics & Astronomy, Athens, OH

New X-ray observations from the *Chandra* and XMM-*Newton* observatories have shown that cooling of the intracluster medium is occurring at rates that are now approaching the star formation rates measured in cD galaxies at the bases of cooling flows. Star formation proceeds in repeated episodes, possibly indicating an intermittent fuel supply. Coupled with new evidence for heating by AGN, a new paradigm of self-regulated cooling and star formation in cluster cores is emerging.

1. The Cooling Flow Problem

Little has changed in our understanding of star formation in cooling flows since the topic was last reviewed at the meeting on cooling flows at Haifa in 1996. However, the nature of the so-called "cooling flow problem" has changed dramatically since then. This controversial problem concerns the deficit between the large cooling rates of the keV gas in the centers of clusters and the much smaller star formation rates observed in central cluster galaxies located at the bases of cooling flows (Fabian 1994). While the cooling rates based on *Einstein* and *ROSAT* X-ray observations (but not ASCA, see Makishima this conference) were claimed to be tens to hundreds of solar masses per year, the star formation rates are generally between a few to several tens of solar masses per year. In spite of recent detections of molecular gas in cooling flows (Edge 2001), this apparent violation of mass continuity cannot be reconciled by a repository of molecular gas clouds or star formation with the Local initial mass function in central cluster galaxies.

Adherents of the cooling flow paradigm dodged the problem by appealing to a repository of elusive matter, such as low mass stars or a mist of cold clouds. Others proposed heating mechanisms (e.g., active nuclei, or AGN, heat conduction, cosmic rays, mergers, magnetic reconnection, etc.) with the potential to inject enough energy into the keV gas to balance radiative losses. Nevertheless, these proposals generally suffered various problems, such as the need for fine tuning, but mostly they lacked observational support.

2. The Rumblings of a Paradigm Change

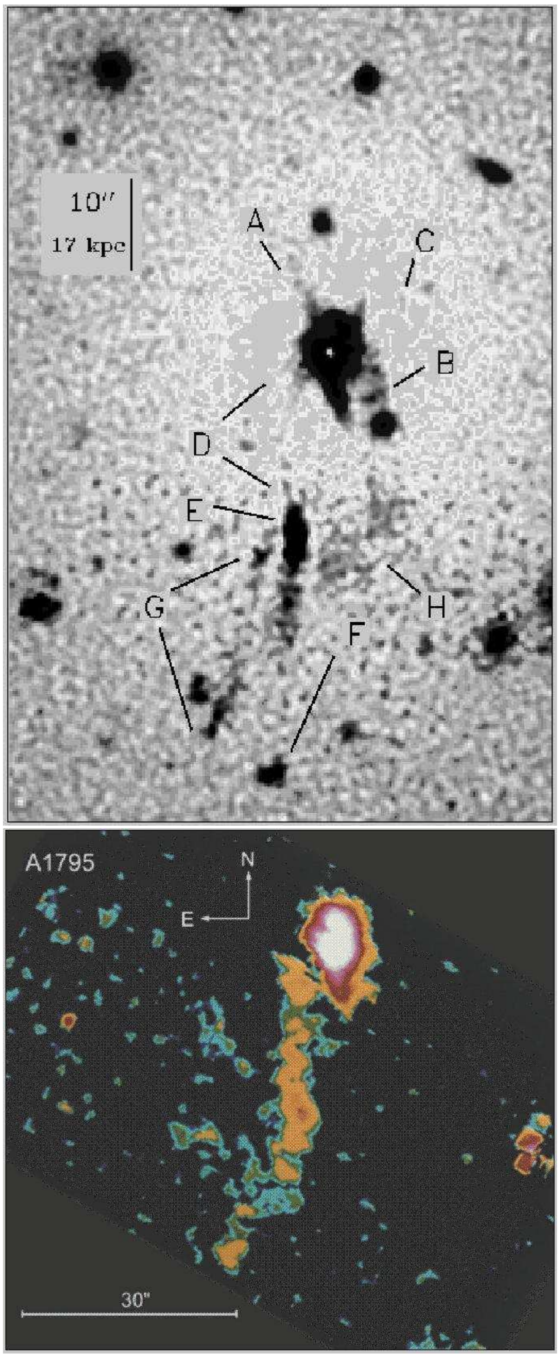
Two recent developments have dramatically changed our view of cooling flows. First, XMM-*Newton* grating spectra of the critical soft X-ray band failed to detect the emission lines that dominate cooling below 2 keV at the predicted levels (Peterson et al. 2003, & this conference). Although the spectra do not exclude cooling entirely, they limit the amount of gas cooling below X-ray temperatures (where it is available to fuel star formation) to be $5-10$ times less than the predicted levels. The spectra imply that most of the cooling gas is maintained above ~ 2 keV (i.e., it is being reheated), or that it is cooling without an obvious spectroscopic signature (Fabian et al. 2000b, Peterson et al. 2003). Similar conclusions have been reached using moderate resolution CCD spectroscopy from *Chandra* and XMM-*Newton* (McNamara et al. 2000, David et al. 2001, Molendi & Pizzolato 2001, Böhringer et al. 2001, Blanton et al. 2003).

Secondly, strong interactions (Carilli et al. 1994, Böhringer et al. 1993) between radio sources and the intracluster medium are now commonly seen in *Chandra* images (McNamara et al. 2000, Fabian et al. 2000, and see McNamara 2002, and Nulsen et al. 2003 for reviews). These interactions are creating X-ray surface brightness depressions or cavities that, like bubbles in soda water, move buoyantly through the intracluster medium. The bubbles in some (but not all) systems, contain enough energy to balance radiative losses emerging from the centers of clusters in the X-ray band. This, along with the discovery of very short central cooling timescales, and at the same time, the lack of evidence for strong cooling below X-ray temperatures, have renewed interest in feedback-driven heating mechanisms capable of balancing radiation losses (Nulsen, this conference). It is now an established fact that the keV gas in clusters with cooling times approaching 100 Myr are frequently associated with the sites of star formation. Therefore, this star formation may have been fueled during the cooling phase of the feed-back loop.

3. Properties of Star Formation in Clusters

I list below a few of the key observational facts about star formation in cooling flows. (I use the term "cooling flow" to refer to clusters with short central cooling times.) For more detailed discussions and additional references, see recent reviews by Böhringer et al. (2001), Crawford (2003 & this conference), Fabian (1994), and McNamara (1997, 2002).

1. A trend exists between cooling flows and the occurrence and amplitude of blue color excesses associated with star formation in central cluster galaxies (Johnstone et al. 1987, McNamara & O'Connell 1989, Cardiel et al. 1998, Crawford et al. 1999). *Chandra* has shown that the regions of star formation are associated with bright lumps and filaments of gas whose radiative cooling times approach $\sim 10^8$ yr (McNamara et al. 2000, Fabian et al. 2001, McNamara et al. 2004, Blanton et al.



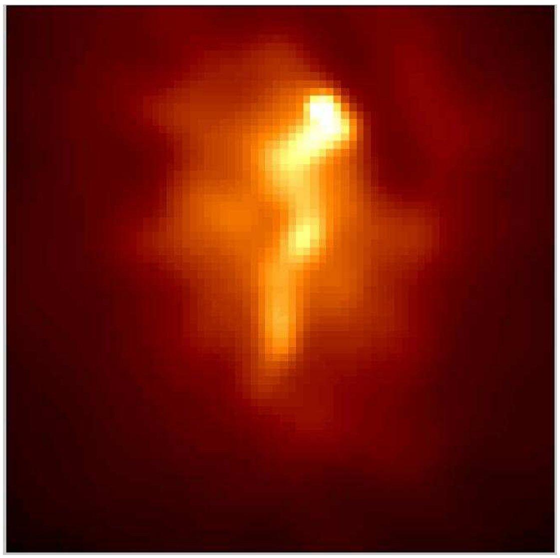


FIG. 1.— **Upper Left:** Star formation map (McNamara et al. 1997), **Upper Right:** Hα map (Cowie et al. 1983), and **Lower Right:** Chandra X-ray map of the center of the Abell 1795 cluster (Fabian et al. 2001). The trail of star formation, indicated by lettering, is traced using a processed, deep U-band image (McNamara et al. 1997). The U-band, Hα, and X-ray trails are clearly correlated.

2003). Abell 1795, shown in Figure 1, is a good example (Fabian 2001).

2. Bright, spatially extended nebular emission is seen preferentially in clusters (e.g. Perseus) with central cooling times below ~ 1 Gyr (Hu 1988; Heckman et al. 1989). Recent comparisons between optical emission line maps and *Chandra* X-ray maps have shown spatial correlations between nebular emission and bright lumps and filaments of gas (Figure 1) where the radiative cooling time approaches $\sim 10^8$ yr (Fabian et al. 2003, Blanton et al. 2001).

3. The star formation histories vary between short duration bursts $\lesssim 10$ Myr of age, or more extended episodes lasting between 0.1-1 Gyr; such histories are inconsistent with steady cooling and accretion that has endured for the ages of clusters (Allen 1995, Crawford et al. 1999, McNamara 1997, McNamara et al. 2004). The short duration bursts are, in some cases, triggered by the central radio source (McNamara & O'Connell 1993).

4. A Comparison Between the Cooling and Star Formation Rates

A clean demonstration of equality between the level of cooling and star formation plus its associated gas would be a critical test of the new, self-regulated cooling paradigm. More importantly, if it can be shown that the cooling upper limits are systematically below the star formation levels, a possibility that is now within reach, we would be in a position to reject the link between cooling and star formation, with some measure of confidence.

Cooling rates have now been estimated for several clusters with *Chandra* and XMM-*Newton*. As I discussed above, they are systematically below the classical values. This trend is shown in Figure 2, where I plot cooling rate ($\dot{M}$) versus star formation rate (SFR), in solar masses per year, for five clusters. The solid squares show the morphological cooling rates from the *ROSAT/Einstein* era, calculated essentially by dividing the central gas mass by the cooling time. The modern cooling rates fall well below these values and are shown along with their measurement uncertainties. Only Abell 1795 and Abell 2597 have independent cooling measurements from *FUSE* spectra of the O VI λ1032 feature (Oegerle et al. 2001). In both cases, the ultraviolet cooling rates, shown as filled dots in Figure 2, lie within the uncertainties of the X-ray cooling

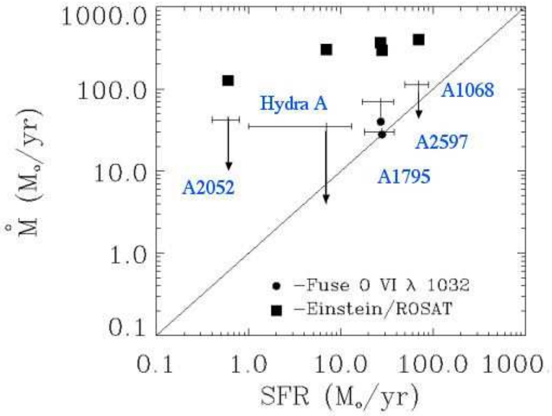


Fig. 2.— Plot of X-ray cooling rate versus star formation rate. The line represents equality between the rates. An explanation of this figure is given in the text.

rates, represented as vertical bars. The cooling rates for the remaining objects are presented as upper limits because the *Chandra*-ACIS spectral cooling rates represent the "maximum cooling" models consistent with the data (Wise et al. 2004), and they should not be misconstrued as the unique spectral signatures of cooling below one or two keV. In other words, in spite of the very short cooling time of the keV gas, single temperature model plasmas provided acceptable fits to the data at each radius.

The star formation rates owe their uncertainties (horizontal bars) primarily to the difficult problem of measuring the intrinsic colors of young accretion populations against the background glare of the cD galaxy, mismeasuring extinction, and degeneracies in the population models themselves (cf., McNamara et al. 2004).

Figure 2 shows that the cooling and star formation rates are generally converging, and in some cases they agree to within the (substantial) measurement errors. This is evident in Abell 1068, Abell 2597, and Abell 1795. While I don't regard this as proof positive that the cooling flow problem has been solved, we are clearly on the right track. The challenges ahead include improving our understanding of the star formation rates and histories, and obtaining higher precision (deeper) X-ray spectra capable of turning the current upper limits into cooling detections, or excluding cooling entirely at levels below the star formation rates.

5. What is Preventing Most of the Gas from Cooling?

Essentially all indicators are telling us that the enormous radiation losses in cluster cores are balanced, or nearly so, by some form of heating. Clear-cut evidence now exists that interactions between radio sources and the surrounding gas are supplying some of this heat in many clusters and perhaps all of it in others (see Nulsen and Blanton this conference). Cavities have been identified in nearly two dozen clusters over the past three years (Bîrzan et al. 2004). The archetypes, Hydra A (McNamara et al. 2000) and Perseus (Böhringer et al. 1993, Fabian et al. 2000), are typical of most systems: twin surface brightness depressions 10 – 20 kpc in diameter lying at distances of 10 – 30 kpc from the nucleus of the cD. Cavities have also been observed in giant elliptical galaxies, such as M84 (Finoguenov & Jones 2001), and groups, such as HGG 62 (Bîrzan et al. 2004). Cavity ages range between $\sim 10^7$ yr – 10^8 yr. Their enthalpy ranges between $\gamma pV/(\gamma - 1) \sim 10^{55}$ erg in isolated galaxies and groups to $\sim 10^{60}$ erg in rich clusters. The total energy input from each AGN outburst may be several times these figures when shocks are included (Fabian 2003, Forman et al. 2004). The total energy deposited into the intracluster medium integrated over the lifetime of the AGN can greatly exceed 10^{61} erg (McNamara et al. 2001, and see Nulsen et al. 2003 for a review). Nevertheless, while AGN may be able to retard or quench cooling in many systems, they would do so with great difficulty in others. Only $\sim 25\%$ of clusters in the *Chandra* archive have obvious cavity systems, and many of these systems contain too little energy to balance radiative losses at the current time (Bîrzan et al. 2004).

Other heating agents could be assisting the AGN at balancing radiative losses. Of these, heat conduction between the cool cores and hot outer layers of clusters has received a good deal of attention (Voigt et al. 2002). But this model has problems. In order to work effectively, most studies have concluded that conduction must be suppressed by several times the Spitzer rate. While this may be true in special cases, it cannot be easily demonstrated observationally. In other systems, heat conduction acting alone at the Spitzer rate is incapable of balancing radiative losses (Voigt et al. 2002, Zakamska & Narayan 2003, Wise et al. 2004). Additional agents acting together to a greater or lesser degree, such as mergers (Motl et al. 2003) and supernovae associated with star formation (McNamara et al. 2004), must be assisting the AGN.

6. Conclusions & Speculations about a New Cooling Flow Paradigm

I have shown that the star formation rates estimated with optical, ultraviolet, and infrared observations are within factors of several of the new cooling limits, and in some cases, agree to within their errors. What we know about the star formation histories in cooling flows points to repeated bursts of star formation lasting $10^7 - 10^9$ yr. In some cases, the starbursts are triggered by the central radio sources. Constant star formation over the ages of clusters, the history of star formation predicted by steady cooling flow models, is inconsistent with most data.

The overall picture of star formation in cooling flows is consistent with, and indeed has helped to shape, the emerging paradigm of self-regulated cooling in clusters. The X-ray, optical, and radio data taken together point to episodes of cooling and periodic reheating by radio outbursts and their associated bubbles. This scenario (e.g., Churazov et al. 2002) has received observational support from the newly-discovered trend between central X-ray luminosity and the instantaneous kinetic luminosity of bubbles in clusters (Bîrzan et al. 2004). Thermal conduction may be an additional element of the feedback loop that regulates cooling (Ruszkowski & Begelman 2002, Nulsen 2003). This emerging picture of cooling flows has broad implications for theories of structure formation and evolution. Feed-back processes may have been important during the early development of galactic bulges and their central black holes, and they may regulate the thermal balance of the hot gas in giant elliptical galaxies today (Nulsen, this conference). The possibility that such processes are active in large, bright, relatively nearby clusters provides a unique opportunity to test these models in detail.

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