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Cool Gas in Clusters of Galaxies

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Abstract

Early X-ray observations suggested that the intracluster medium cools and condenses at the centers of clusters, leading to a cooling flow of plasma in the cluster core. The increased incidence of emission-line nebulosity, excess blue light, AGN activity, and molecular gas in the cores of clusters with short central cooling times seemed to support this idea. However, high-resolution spectroscopic observations from *XMM-Newton* and *Chandra* have conclusively ruled out simple, steady cooling flow models. We review the history of this subject, the current status of X-ray observations, and some recent models that have been proposed to explain why the core gas does not simply cool and condense.

1.1 A Census of Cool Gas

Clusters of galaxies have very deep potential wells with virial velocities equivalent to temperatures of $10^7 - 10^8$ K. Gravitationally driven processes like accretion shocks and adiabatic compression should therefore heat gas accumulating within a cluster to X-ray emitting temperatures. Spectroscopic X-ray observations show that most of a cluster's gas is indeed near the virial temperature $T_{\rm vir} = \mu m_p \sigma_{\rm 1D}^2/k$, equivalent to $7.1 \times 10^7 \sigma_{1000}^2$ K or $6.2\,\sigma_{1000}^2$ keV, where σ_{1000} is the line-of-sight velocity dispersion in units of $1000\,{\rm km\,s^{-1}}$ (Sarazin 1986).

Roughly 10%–20% of the baryons associated with clusters have a temperature significantly less than the virial temperature, qualifying as "cool gas" for the purposes of this review. Much of this gas would be considered quite hot in other astrophysical contexts, but in order to be cooler than the virial temperature today, it must either have avoided the gravitational heating experienced by the rest of the cluster or it must have significantly cooled after entering the cluster.

A large proportion of this cool gas is only moderately cooler than the virial temperature. In the central $\sim$10% of many clusters, corresponding to gas masses of $10^{11} - 10^{13}\,M_\odot$, temperatures dip to $\sim T_{\rm vir}/2$. Because this gas is dense enough to radiate an energy equivalent to its thermal energy in less than a Hubble time, astronomers have long speculated that it cools and contracts, forming a "cooling flow" of condensing gas in the cluster core (Cowie & Binney 1977; Fabian & Nulsen 1977; Mathews & Bregman 1978).

Gas much cooler than the virial temperature is also seen in clusters. For example, all the stars in a cluster's galaxies are made of such gas, implying that at least some cooling and condensation must have occurred during the assembly of the cluster. Applying a standard

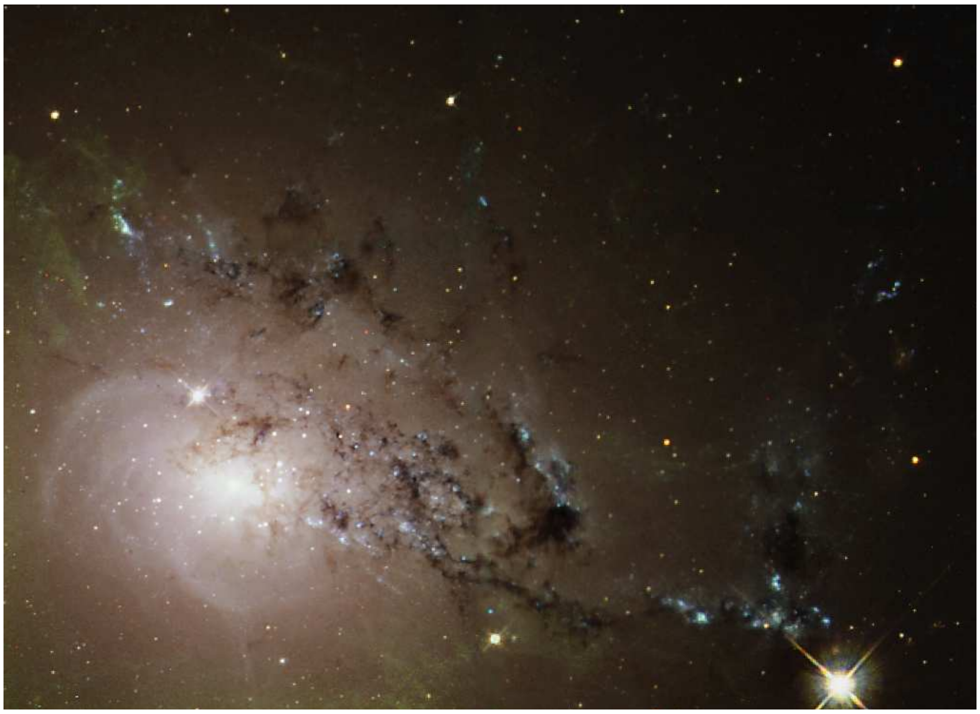

Fig. 1.1. Hubble Heritage image of NGC 1275.

mass-to-light ratio, one finds that $\sim 0.2h^{3/2}$ of a cluster's baryons are "cool gas" of this kind (Arnaud et al. 1992; White et al. 1993; with $h = H_0/100$ km s^{-1} Mpc^{-1}). While it may seem strange to include stars in a census of cool intracluster gas, the total mass of stars does serve as a lower limit to the amount of gas that passed through a cold phase at some point in the cluster's past.

Many clusters also host optical emission-line nebulae within their cores that appear to be associated with the cooler ($\sim T_{\rm vir}/2$) X-ray emitting gas (Fabian & Nulsen 1977; Ford & Butcher 1979; Cowie et al. 1983; Hu, Cowie, & Wang 1985; Heckman et al. 1989; Crawford & Fabian 1992; Donahue, Stocke, & Gioia 1992; Crawford 2004). One could even say that Carnegie Observatories initiated the study of cool gas in clusters. Hubble & Humason (1931) noted that NGC 1275, the central galaxy in the Perseus cluster, had a discrepant color index because of its strong emission spectrum, saying that "it could be classified as an elliptical nebula that has broken up without the formation of spiral arms." Later, Baade & Minkowski (1954) noted that NGC 1275 was unusual among Seyfert galaxies because its emission lines were not restricted to the nuclear regions. Lynds (1970) eventually imaged this amazing Hα emission-line nebula using an interference filter. Figure 1.1 shows a recent Hubble Heritage close-up of NGC 1275, featuring a hint of spiral structure, complex dust lanes, and evidence for recent star formation.

The total amount of $\sim 10^4$ K gas in such nebulae is a mere $\sim 10^4 - 10^7 M_\odot$ (Heckman et al. 1989), but this nebulosity may be only the glowing skin surrounding considerably larger masses of much cooler gas. Clusters with Hα emission also have closely associated

H_2 emission (Elston & Maloney 1994; Jaffe & Bremer 1997; Falcke et al. 1998; Donahue et al. 2000; Jaffe, Bremer, & van der Werf 2001; Edge et al. 2002). Furthermore, recent CO observations of a few cluster indicate that they may contain up to $10^{9-11.5} M_{\odot}$ in the form of cool molecular gas (Edge 2001).

The primary question concerning cool gas in clusters is whether these pieces—cool X-ray gas, stars, nebulae, molecular clouds—all fit together into a single coherent picture of condensation and star formation. If so, then studies of cluster cores may have much to teach us about the processes that govern galaxy formation. In this review, we will first recap the cooling flow hypothesis, now over 25 years old, suggesting that X-ray gas should cool and flow into cluster cores (see also Fabian, Nulsen, & Canizares 1984, 1991; Fabian 1994). Then we will present evidence showing that simple cooling flows, in which cooling proceeds unopposed by heating or feedback, do not occur (Molendi & Pizzolato 2001; Peterson et al. 2001, 2003). Supernovae and AGN activity must provide at least some feedback during the history of the cluster. In fact, *the global properties of clusters cannot be understood without accounting for radiative cooling and subsequent feedback* (Lewis et al. 2000; Pearce et al. 2000; Voit & Bryan 2001; Voit et al. 2002). Conduction may also suppress cooling in cluster cores (Bertschinger & Meiksin 1986; Bregman & David 1988; Sparks, Macchetto, & Golombek 1989), and this possibility has received renewed attention in recent years (Malyshkin 2001; Narayan & Medvedev 2001; Fabian, Voigt, & Morris 2002; Voigt et al. 2002). However, we do not yet know which is the dominant mechanism opposing cooling—feedback, conduction, or perhaps a combination of the two (Ruskowkski & Begelman 2002; Brighenti & Mathews 2003). We close the review by summarizing a few clues that might help answer this question.

1.2 The Cooling Flow Hypothesis

The road from the discovery of hot gas in clusters to the cooling flow hypothesis was rather short. Clusters of galaxies were first confirmed to be sources of X-ray emission in 1971 by the *UHURU* satellite (Gursky et al. 1971). Thermal emission from hot intracluster gas seemed like a natural interpretation (Lea et al. 1973; Lea 1975) given the extent of the emission (e.g., Forman et al. 1972; Kellogg et al. 1972) and the spectrum (e.g., Gorenstein et al. 1973; Davidsen et al. 1975; Kellogg, Baldwin, & Koch 1975), but it was not confirmed until the 6.7 keV iron-line complex from helium-like and hydrogen-like ions was discovered in the Perseus cluster by Mitchell et al. (1976) using *Ariel V*, and in Virgo, Perseus, and Coma by Serlemitsos et al. (1977) using *OSO-8*.

Simple calculations of radiative cooling at the centers of clusters like Perseus revealed that the cooling time, t_c, was probably less than a Hubble time (Cowie & Binney 1977; Fabian & Nulsen 1977). These authors suggested that, in the absence of a compensating heat source, the core gas ought to cool and condense at the cluster's center. Thus, the centers of all clusters with $t_c < H_0^{-1}$ soon became known as "cooling flows," even though there was not yet any firm evidence for either cooling or flowing. The main piece of circumstantial evidence was the close association between a short central cooling time and the presence of an optical emission-line nebula at the cluster's center, presumed to be generated by gas cooling through $\sim 10^4$ K. Hu et al. (1985) showed that these nebulae are frequently found in clusters with $t_c \lesssim H_0^{-1}$, but never in clusters with $t_c > H_0^{-1}$.

A simple estimate of the implied cooling rate can be drawn from the X-ray luminosity of the cooling region by assuming the gas cools from the virial temperature at constant pressure:

$$\dot{M}_X \approx \frac{2}{5}\frac{\mu m_p}{kT_X} L_X(< r_c) \ . \tag{1.1}$$

Here, $L_X(< r_c)$ is the X-ray luminosity coming from inside the cooling radius r_c, at which $t_c \approx H_0^{-1}$. Estimates for $\dot{M}$ derived from X-ray imaging often exceed $100 M_\odot \, \mathrm{yr}^{-1}$ (Fabian et al. 1984), even approaching $1000 M_\odot \, \mathrm{yr}^{-1}$ in some extreme cases (e.g., White et al. 1994).

The X-ray surface brightness distributions of cooling flow clusters are inconsistent with steady flows in which $d\dot{M}/dr = 0$ because such flows produce exceedingly strong central peaks in brightness. To obtain better-fitting surface brightness profiles, cooling flow modelers allowed for spatially distributed mass deposition that led to a decline in $\dot{M}$ as the flow approached $r = 0$ (Fabian et al. 1981; Stewart et al. 1984). Models of this kind fit the data best if $\dot{M}(r) \propto r$ (Fabian et al. 1984), implying that the flow must be inhomogeneous, with a range of cooling times at any given radius, because only a subset of the inflowing gas manages to condense within each radial interval (e.g., Thomas, Fabian, & Nulsen 1987). However, the overall $\dot{M}$ values derived from such models are similar to the simple estimates based on $L_X(< r_c)$.

Individual X-ray emission lines could, in principle, be used to estimate the rate at which matter is cooling (Cowie 1981). For cooling at constant pressure, the luminosity of emission line i is

$$L_i = \dot{M}\frac{5k}{2\mu m}\int \frac{\epsilon_i(T)}{\Lambda(T)} dT, \tag{1.2}$$

where T is the plasma temperature, $\epsilon_i(T)/\Lambda(T)$ is the fraction of the cooling emissivity function owing to emission line i as a function of T, μm is the mean mass per particle, and k is the Boltzmann constant. In the steady cooling flow model, this expression is integrated from $T = 0$ to $T = T_{hi}$. There were two high-resolution spectrometers on board the *Einstein* Observatory, and results (with rather low signal-to-noise ratio) from both of those spectrometers seemed to confirm the rates inferred from X-ray surface brightness distributions (Canizares et al. 1982; Canizares, Markert, & Donahue 1988; Mushotzky & Szymkowiak 1988).

1.3 The Trouble with Cooling Flows

X-ray astronomers have historically been quite fond of the cooling flow hypothesis but have had trouble convincing colleagues who work in other wavebands because no one has ever found a central mass sink containing the $\dot{M}_X H_0^{-1} \approx 10^{11-13} M_\odot$ implied by the simplest interpretation of the X-ray observations. Now that *Chandra* and *XMM-Newton* are providing high-resolution spectra of cluster cores, X-ray astronomers themselves have become convinced that cooling flows are not that simple, if indeed they occur at all, because the cooling rates derived from spectroscopy do not agree with simple cooling flow predictions.

1.3.1 The Mass-Sink Problem

The trouble with cooling flows began when optical observers could not locate all the stars that ought to be formed in the prodigious cooling flows ($> 100 M_\odot \, \mathrm{yr}^{-1}$) of some clusters (Fabian et al. 1991). Star formation rates derived from observations of excess blue light and Hα nebulosity, assuming a standard initial mass function, amounted to only $\lesssim 0.1\dot{M}_X$

(Johnstone, Fabian, & Nulsen 1987; McNamara & O'Connell 1992; Allen 1995; Cardiel, Gorgas, & Aragón-Salamanca et al. 1995, 1998). While it remains possible in principle that star formation in cooling flows is heavily skewed toward unobservable low-mass stars (Fabian, Nulsen, & Canizares 1982), there is still no compelling theoretical justification for this idea.

Initial enthusiasm about the Hα emission representing $\sim 10^4$ K cooling flow gas (e.g., Cowie, Fabian, & Nulsen 1980) abated when it was realized that the $\dot{M}$ implied by the Hα luminosity in some clusters was $\sim 10^2 \dot{M}_X$ (Cowie et al. 1983; Heckman et al. 1989). Models have been proposed in which the Hα is boosted by absorption of EUV and soft X-ray emission from cooling gas (Voit & Donahue 1990; Donahue & Voit 1991) or by cooling through turbulent mixing layers (Begelman & Fabian 1990). However, it now seems likely that most of the Hα emission comes from photoionization by OB stars (Johnstone et al. 1987; Voit & Donahue 1997; Cardiel et al. 1998; Crawford et al. 1999).

Hope for a solution to the mass-sink problem rose with the apparent discovery of excess soft X-ray absorption in cooling flow clusters, which would require $\sim 10^{12} M_\odot$ of cold gas distributed over the central $\sim$ 100 kpc (White et al. 1991; Allen et al. 1993). Yet, dogged pursuit of this cold gas by radio astronomers failed to find either 21 cm emission (Dwarakanath, van Gorkom, & Owen 1994; O'Dea, Gallimore, & Baum 1995; O'Dea, Payne, & Kocevski 1998) or CO emission (O'Dea et al. 1994; Braine et al. 1995) with the necessary covering factor and beam temperature. Some clusters do have significant amounts of molecular gas, but detections so far generally find it only within the central $\sim$ 20 kpc (Donahue et al. 2000; Edge 2001; Edge et al. 2002).

One explanation for the undetectability of the cooling flow sink is that this gas may become so cold that it produces no detectable emission (Ferland, Fabian, & Johnstone 1994, 2002). However, cold clouds bathed in the X-rays found in cluster cores must reradiate the X-ray energy they absorb in some other wave band. At minimum, these clouds should have an observable warm skin of detectable H I if they do indeed cover the central regions of clusters (Voit & Donahue 1995). Cold clouds with a low covering factor may still evade current radio observations but would not produce appreciable soft X-ray absorption.

Soft X-ray absorption itself is probably now a phenomenon that no longer needs explaining. Recent cluster observations with *Chandra* and *XMM-Newton* are failing to confirm the levels of absorption suggested by lower-resolution X-ray observations (McNamara et al. 2000; Blanton, Sarazin, & McNamara 2003; Peterson et al. 2003). If these observations are correct, then there is no evidence at all, in any waveband, for a large mass sink in cooling flow clusters.

1.3.2 The Spectroscopic $\dot{M}$ Problem

A recent breakthrough in X-ray astronomy is reframing the whole debate about cooling flows. In a simple, steady-state cooling flow one expects to see emission from gas over the entire range of temperature from $T_{\rm vir}$ to the sink temperature, whatever that may be. Because the thermal energy lost as gas cools from T to $T - \Delta T$ is proportional to ΔT, the luminosity coming from gas within that temperature interval is expected to be $\Delta L \propto \dot{M} \Delta T$. Thus, X-ray spectroscopy of the emission lines characteristic of gas at each temperature can be used to test whether $\Delta L / \Delta T$ is constant with temperature (Cowie et al. 1980). For example, we can use Fe XVII to track gas at $\lesssim 10^7$K, O VIII to track gas at $\lesssim 2 \times 10^7$, and UV observations of O VI to track gas at $\sim 10^6$ K. Figure 1.2 shows the predicted spectrum if

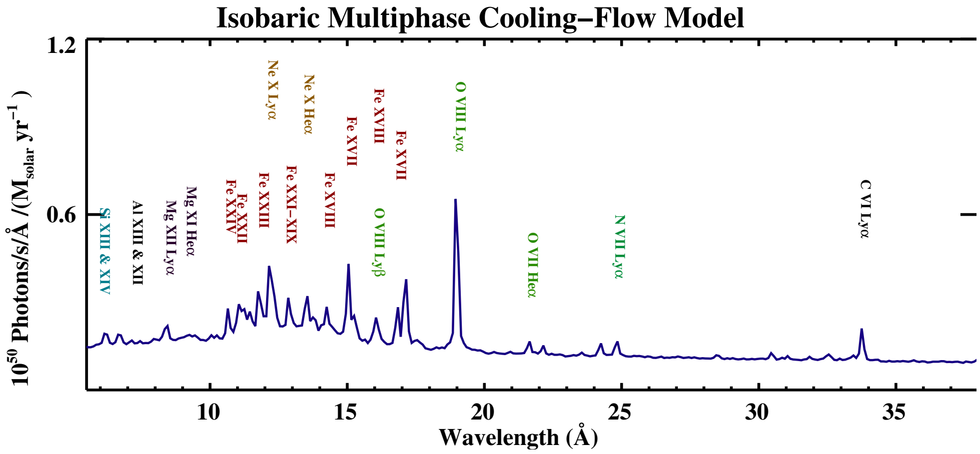

Fig. 1.2. Spectrum emitted by gas cooling from 6 keV at constant pressure. Because the gas recombines as it cools, the relative strengths of the emission lines reveal how much gas cools through each temperature. (Figure from Peterson et al. 2003.)

the cooling gas is assumed to be an inhomogeneous (multiphase) medium, as inferred from $\dot{M} \propto r$, that cools at constant pressure.

High-resolution spectroscopic observations with *XMM-Newton* and *Chandra* are now revealing a deficit of emission from gas below $\sim T_{\rm vir}/3$, relative to this predicted spectrum. Peterson et al. (2003) compiled Reflection Grating Spectra (RGS) spectra of 12 cooling flow clusters, the single largest collection to date. We plot an example from the Perseus cluster in Figure 1.3. None of the clusters hotter than 4 keV show evidence for Fe XVII emission from gas below 1 keV, and Fe XVII is weaker than expected in cluster with global temperatures of 2–4 keV. This line does appear in the spectra of supernova remnants, so its absence in cluster spectra is not a shortcoming of the plasma codes or the detectors. Furthermore, the early *XMM-Newton* RGS results (Peterson et al. 2001) have been confirmed by *Chandra* grating spectroscopy (e.g., Hicks et al. 2002). Gas at $\lesssim 1$ keV apparently does not exist in the amounts predicted by simple cooling flow models. Even the data from instruments with lower spectral resolution, such as the ACIS-S detector on board *Chandra*, suggest significantly lower mass cooling rates than obtained from previous analyses of *ROSAT* and *ASCA* data (e.g., McNamara et al. 2000; Wise & McNamara 2001; Lewis, Stocke, & Buote 2002). Faint detections and strong limits on O VI emission from the *FUSE* satellite (Oegerle et al. 2001) also imply lower mass cooling rates (Fig. 1.4).

Two *ad hoc* models for cool gas do fit the high-resolution observations obtained with the *XMM-Newton* RGS instrument reasonably well (Kaastra et al. 2001; Peterson et al. 2001, 2003). One is a two-temperature model, in which some gas is at $T_{\rm vir}$ and some is at $\sim T_{\rm vir}/2$. The other is a modified cooling flow model, in which the amount of cooling gas tapers off from $T_{\rm vir}$ to a minimum temperature $\sim T_{\rm vir}/3$ (Peterson et al. 2003). Because the temperature floor in these models seems to scale with $T_{\rm vir}$, it would appear that whatever prevents the gas from cooling further is sensitive to the depth of the cluster potential.

The assumption that cooling flows contain inhomogeneous, multiphase gas, as implied by their surface brightness profiles, has also been called into question. *XMM-Newton* observa-

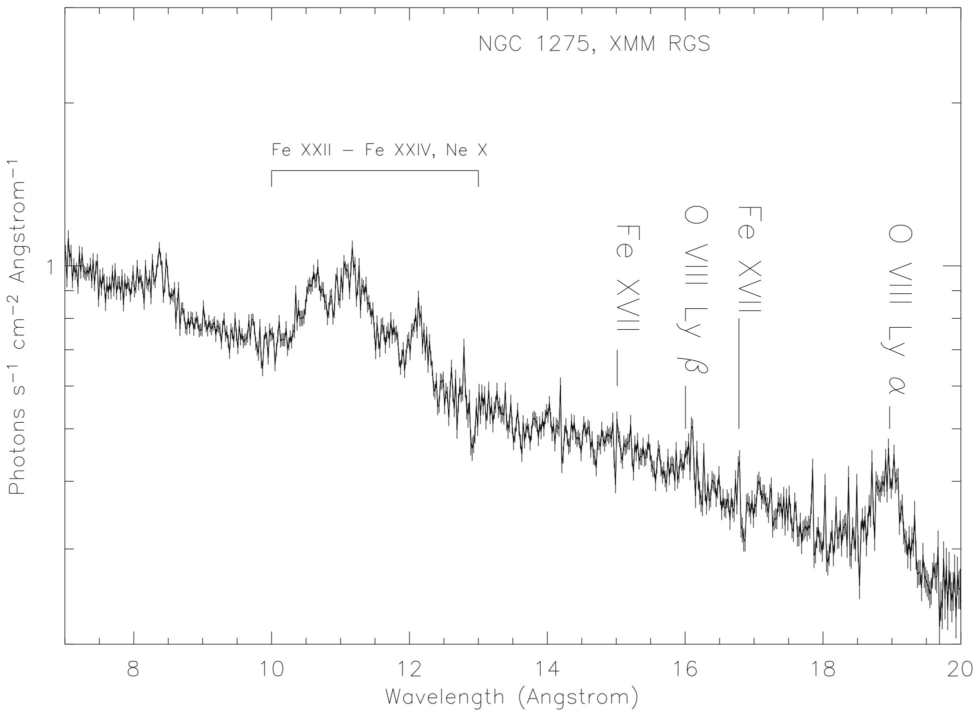

Fig. 1.3. Figure based on *XMM-Newton* RGS data for NGC 1275 in the Perseus cluster. The O VIII Lyα and Lyβ lines were detected, but no Fe XVII is apparent at the expected wavelengths of 15.014 Å or 16.78 Å. (Data courtesy J. Peterson; Peterson et al. 2003.)

tions of M87, at the center of the nearest cooling flow cluster, indicate that the surrounding intracluster medium consists of a single temperature plasma, except for those regions of the cluster associated with the M87 radio source (Matsushita et al. 2002).

1.3.3 Time for a New Name

What should we call these clusters in which gas no longer appears to be cooling and flowing? The close association between short central cooling times, Hα nebulosity, and H_2 emission strongly suggests that something unusual is happening in their cores. Star formation in some cases is rapid enough to qualify as a starburst (e.g., McNamara & O'Connell 1992; Cardiel et al. 1995), even though it cannot solve the mass-sink problem. The goings-on in the cores of these clusters certainly qualify as an important astrophysical puzzle that may have far reaching implications for galaxy formation. However, as we search for a new name for "cooling flow" clusters, we should perhaps settle for an observable, such as "cool core" clusters, as has been also suggested by others (Molendi & Pizzolato 2001).

Adopting a name less freighted with theoretical assumptions might promote more balanced consideration of alternatives to the cooling flow hypothesis. Any successful model must explain the following features of cool core clusters:

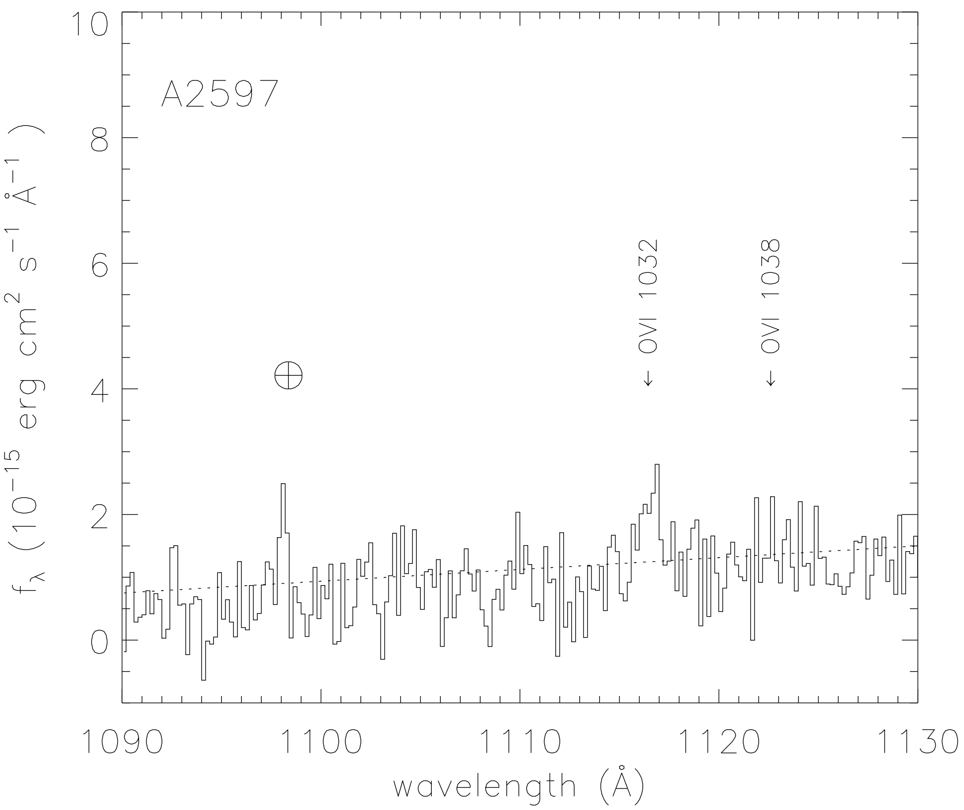

Fig. 1.4. *FUSE* detection of O VI in the central 36 kpc of the cooling flow cluster Abell 2597. The line flux is consistent with the luminosity expected from $\sim 40 M_\odot$ of gas cooling through $\sim 10^6$ K. (Figure from Oegerle et al. 2001.)

- The apparent lack of a mass sink comparable to $\dot{M}_X H_0^{-1}$.
- The positive core temperature gradients extending to $\sim 10^2$ kpc in clusters with $t_c < H_0^{-1}$.
- The frequent incidence of emission-line nebulae, dust lanes, and molecular gas in clusters with $t_c < H_0^{-1}$ and their absence in clusters with $t_c > H_0^{-1}$.
- The tendency for radio sources to be present in clusters with $t_c < H_0^{-1}$.

In light of the new X-ray observations, many of the competing ideas that have previously received less attention and testing than the cooling flow hypothesis are now being revisited. The next section discusses how feedback from supernovae and AGNs might limit the amount of gas that condenses in clusters, and the following section outlines the potentially important role of electron thermal conduction.

1.4 The Galaxy-Cluster Connection

Simple cooling flows may be disproven, but cooling in general plays a major role in determining the global X-ray properties of clusters. Cosmological models of cluster formation that do not include radiative cooling and the ensuing feedback processes fail to produce realistic clusters (Lewis et al. 2000; Pearce et al. 2000; Muanwong et al. 2001; Voit & Bryan 2001). The most glaring failure is in predictions of the L_X-T_X relation. Models without galaxy formation predict $L_X \propto T_X^2$ (Kaiser 1986; Borgani et al. 2001; Muanwong et al. 2001), while observations indicate $L_X \underset{\sim}{\propto} T_X^3$ (Mushotzky 1984; Edge & Stewart 1991; David et al. 1993; Markevitch 1998; Arnaud & Evrard 1999; Novicki, Sornig, & Henry 2002). Ignoring cooling and feedback also causes problems with the slope and normalization of the $M_{\rm vir}$-T_X relation between virial mass and temperature (Horner, Mushotzky, & Scharf 1999; Nevalainen, Markevitch, & Forman 2000; Finoguenov, Reiprich, & Böhringer 2001), which is a fundamental ingredient in efforts to constrain cosmological parameters with cluster observations.

Recent work has shown that tracing the development of intracluster entropy is a powerful way to understand how cooling, supernova feedback, and perhaps energy injection by AGNs conspire to determine both the L_X-T_X and $M_{\rm vir}$-T_X relations of present-day clusters (Ponman, Cannon, & Navarro 1999; Bryan 2000; Voit & Bryan 2001; Voit et al. 2002, 2003; Wu & Xue 2002a,b). Here we briefly outline some connections between a cluster's galaxies and its intracluster medium and show how these connections manifest themselves in the intracluster entropy distribution. Then we focus on some particular models for how AGNs might quench cooling in clusters.

1.4.1 The Theoretical Cooling Flow Problem

Cosmological models for cluster formation that do not include cooling are clearly too simplistic because they do not spawn galaxies. Radiative cooling initiates galaxy birth but is responsible for the now-classic overcooling problem (White & Rees 1978; Cole 1991). If no form of feedback opposes cooling, then at least 20% of the baryons in the Universe, and maybe more, should have condensed into stars. Yet, the observed fraction of baryons in stars is $\lesssim 10\%$ (see Fig. 1.5; Balogh et al. 2001). This overcooling problem is even more acute in clusters, where primordial densities are higher, enabling even more of the baryons to condense.

One could also call this problem the "theoretical cooling flow problem" because far too many baryons cool and condense if there is no heat source to compensate for radiative cooling. Supernova feedback is generally assumed to provide the requisite heat to halt overcooling in galaxies, although the precise mechanism remains murky (e.g., Kay et al. 2002). However, supernovae might not provide enough heat to halt overcooling in clusters, where the binding energy per particle exceeds the mean supernova energy per particle (~ 1 keV), as measured from the intracluster metallicity (e.g., Finoguenov, Arnaud, & David 2001). Thus, feedback from AGNs may be necessary to suppress cluster cooling flows.

1.4.2 Cooling, Feedback, and Intracluster Entropy

The slope of the observed L_X-T_X relation has long been assumed to reflect an early episode of feedback that imposed a universal entropy floor throughout the intergalactic medium (Evrard & Henry 1991; Kaiser 1991). An entropy floor steepens the L_X-T_X relation from $L_x \propto T_X^2$ to $L_X \underset{\sim}{\propto} T_X^3$ because the extra entropy stiffens the intracluster medium

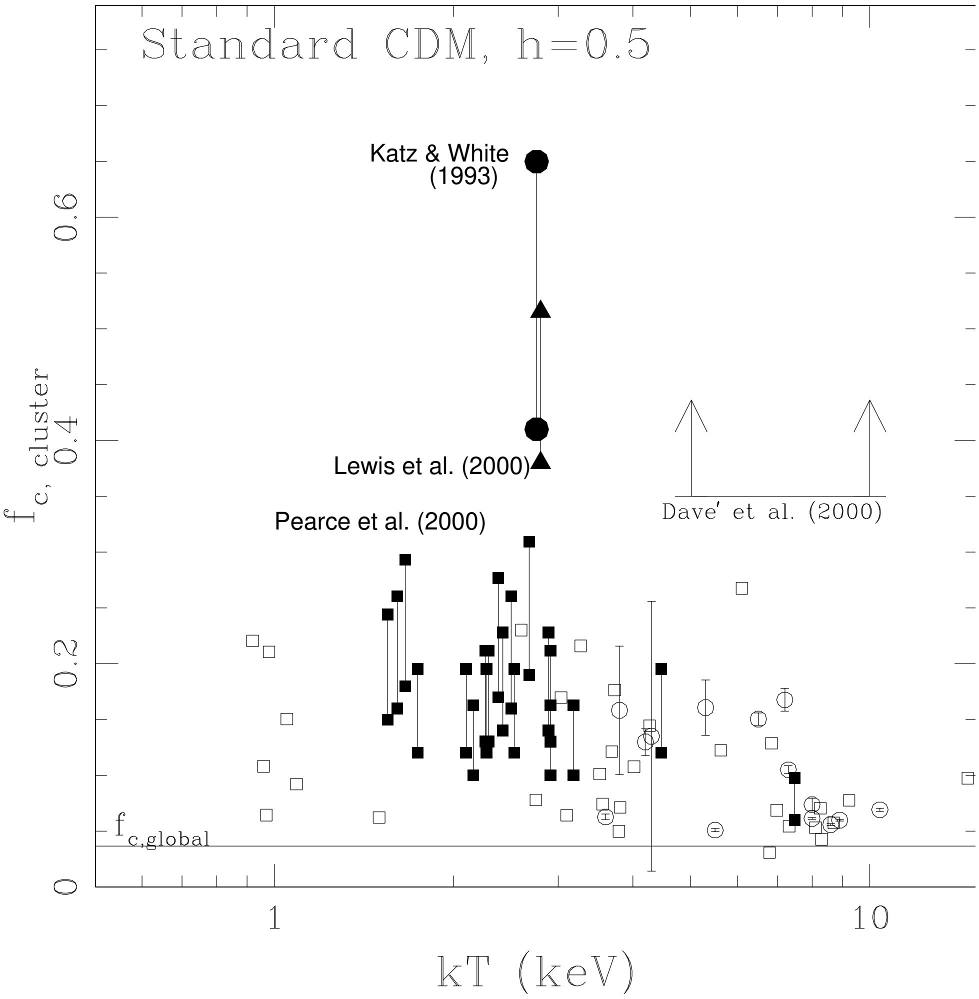

Fig. 1.5. The global overcooling problem. High-resolution cosmological simulations including cooling, represented by the labeled solid points, predict that at least 20% of the Universe's baryons should have condensed into stars or cold clouds, if feedback is ineffective. However, the global condensed baryon fraction $f_{c,\mathrm{global}}$ inferred from large-scale surveys is ∼5%–10%, depending on the initial mass function, and the condensed baryon fractions inferred from cluster observations (empty squares) are ∼10%–20%. (Figure from Balogh et al. 2001.)

against compression. Lower temperature clusters with shallower potential wells therefore have a harder time compressing their core gas, leading to lower core densities and smaller X-ray luminosities than expected in models without cooling and feedback.

Measurements of intracluster entropy in the vicinity of the X-ray core radius support this notion because they indicate elevated entropy levels in groups and poor clusters, corresponding to $Tn_e^{-2/3} \approx 100-150\,\mathrm{keV\,cm^2}$ (Ponman et al. 1999; Lloyd-Davies, Ponman, & Cannon 2000). In order to produce such an entropy floor through supernova heating alone, a large proportion of the available supernova energy is needed (Kravtsov & Yepes 2000). Even then, the required supernova heating efficiency may be unrealistic, in which case additional heat input from AGNs would be required (Valageas & Silk 1999; Wu, Fabian, & Nulsen 2000). However, there is another way to interpret these entropy measurements that does not involve global heating of the intergalactic medium.

Instead, the L_X-T_X relation may reflect a conspiracy between cooling and feedback that regulates the core entropy of clusters and groups (Voit & Bryan 2001). Figure 1.6 shows measurements of core entropy from Ponman, Sanderson, & Finoguenov (2003) along with the locus in T-$Tn_e^{-2/3}$ space at which the cooling time equals a Hubble time. The way in which core entropy tracks this locus suggests that gas with a short cooling time is eliminated from clusters by a combination of cooling and feedback.

A parcel of gas with entropy ($Tn_e^{-2/3}$) below this threshold must condense unless feedback intervenes. If feedback is effective, then it will raise the entropy of the gas parcel until it exceeds the threshold, where it is no longer subject to cooling. If feedback is ineffective, then most of the parcel's gas will cool and condense. Either way, both cooling and feedback remove gas from the region below the threshold, establishing a core entropy at the level of the threshold.

This mechanism explains why simulations that include cooling produce clusters with reasonably realistic L_X-T_X and $M_{\rm vir}$-T_X relations, regardless of the efficiency of feedback (Muanwong et al. 2001; Borgani et al. 2002; Davé, Katz, & Weinberg 2002). However, the amount of baryons that end up in galaxies is very sensitive to how feedback is implemented (Kay, Thomas, & Theuns 2003). Thus, it would appear that cooling is essential to a proper understanding of cluster properties and that the details of how cooling flows are suppressed are crucial to understanding hierarchical galaxy formation in the context of clusters.

1.4.3 AGNs and Cooling Flows

Many cooling flow clusters also contain radio sources indicative of recent nuclear activity (e.g., Burns 1990). This close association between AGNs and clusters with short central cooling times supports the idea that feedback from AGNs helps to suppress cooling. Some authors have proposed that radiation from the active nucleus heats the cluster core (e.g., Ciotti & Ostriker 1997, 2001), but far more attention has been paid to the possibility that radio jets somehow heat the intracluster medium (e.g., Binney & Tabor 1995; Churazov et al. 2001; Soker et al. 2001; Brüggen & Kaiser 2002; Reynolds, Heinz, & Begelman 2002). Such heating was originally not considered to be a viable solution to the mass-sink problem because the total amount of energy needed to stabilize a strong cooling flow is quite large ($\sim 10^{62}$ erg), and the spatial deposition of that heat would need to be precisely matched to local cooling rates in order to maintain thermal stability (Fabian 1994). However, *Chandra* and *XMM-Newton* observations showing widespread interactions between radio plasma and the intracluster medium (e.g., Fabian et al. 2000; McNamara et al. 2000) have stimulated new interest in connections between radio jets and cooling flows.

The high spatial resolution of the *Chandra* observations reveals that jets do not simply shock-heat the surrounding intracluster medium, because the gas surrounding the lobes appears somewhat cooler and denser than the undisturbed gas farther from the lobes (McNamara et al. 2000). Thus, because cluster cores do not appear to be shock heated, most of the recent theoretical models have focused on mixing and turbulent heating stirred up

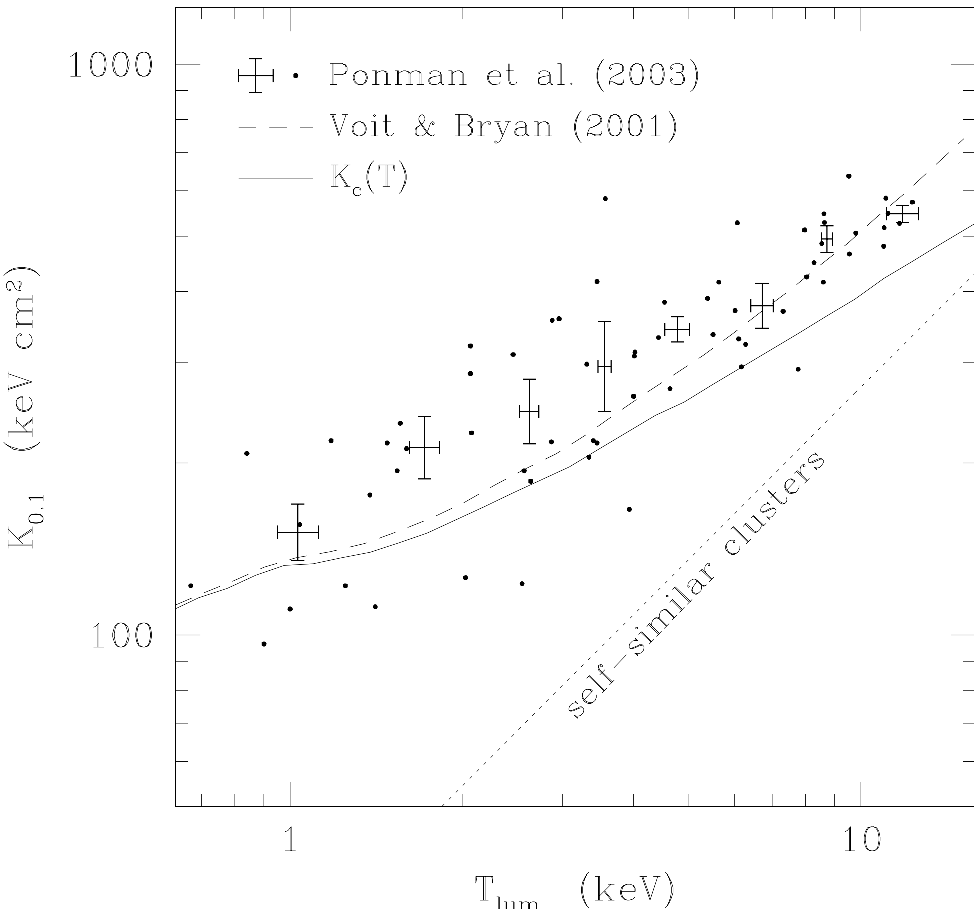

Fig. 1.6. Relationship between core entropy and the cooling threshold. Each point with error bars shows the mean core entropy $K_{0.1}$, measured at $0.1r_{200}$, for eight clusters within a given bin of luminosity-weighted temperature $T_{\rm lum}$, and small circles show measurements for individual clusters (Ponman et al. 2003). The dotted line shows a self-similar relation calibrated using the median value of $K_{0.1}$ measured in simulation L50+ of Bryan & Voit (2001), which does not include cooling or feedback. The solid line shows the cooling threshold $K_c(T)$, defined to be the entropy at which the cooling time equals 14 Gyr, assuming the cooling function of Sutherland & Dopita (1993) for 0.3 solar metallicity. The dashed line shows the entropy at $0.1r_{200}$ in the model of Voit & Bryan (2001) when this cooling function is used.

as the buoyant radio plasma rises through the intracluster medium (e.g., Quilis, Bower, & Balogh 2001; Brüggen & Kaiser 2002; Reynolds et al. 2002). Both mixing and heating raise the entropy of the core gas, consequently raising its cooling time as well. These models circumvent the local fine-tuning problem by distributing heat over a large region through convection, and they add additional thermal energy to the core beyond that supplied by the AGN itself by mixing the core gas with overlying gas of higher entropy.

However, not all clusters with short central cooling times have obvious nuclear activity. Thus, if AGN heating is the solution to the cooling flow puzzle, then it must be episodic.

A recent model by Kaiser & Binney (2003) shows how the central entropy profile would evolve under episodic heating. Because cooling rates rise dramatically as isobaric gas cools to lower temperatures, an episodically heated medium usually contains very little gas below $\sim T_{\rm vir}/3$. When the central gas reaches this temperature it is assumed to cool very quickly to even cooler temperatures and accrete onto the AGN, triggering another episode of heating. This feature of episodic heating may explain the absence of line emission from colder gas in cool core clusters.

1.5 The Revival of Conduction

During the first two decades of the cooling flow hypothesis, the idea that electron thermal conduction might somehow suppress cooling was a minority viewpoint, despite the fact that it has many attractive features. Because conduction carries heat from warmer regions to cooler regions, it naturally directs thermal energy into regions that would otherwise condense. Also, it taps the vast reservoir of thermal energy in the intracluster medium surrounding the cluster core, which is more than sufficient to resupply the radiated energy.

Many models invoking conduction have been developed (e.g., Tucker & Rosner 1983; Bertschinger & Meiksin 1986; Bregman & David 1988; Rosner & Tucker 1989; Sparks 1992), but conduction has often been dismissed as a global solution on the grounds that it is not stable enough to preserve the observed temperature and density gradients for periods of order $\gtrsim$ 1 Gyr (Cowie & Binney 1977; Fabian 1994). The heat flux from unsaturated conduction proceeding uninhibited by magnetic fields is $\kappa_s \nabla T$, with $\kappa_s \approx 6 \times 10^{-7} T^{5/2}\,{\rm erg\,cm^{-1}\,s^{-1}\,K^{-7/2}}$, the so-called Spitzer rate (Spitzer 1962). Because of this extreme sensitivity to temperature, it is difficult for radiative cooling and conduction to achieve precise thermal balance with a globally stable temperature gradient (Bregman & David 1988; Soker 2003). However, any mechanism that places cool gas at the center of a cluster, such as a merger of a gas-rich galaxy with the central cluster galaxy, sets up a temperature gradient that would cause uninhibited conduction to proceed until either the cool gas has evaporated or the hot gas has condensed (Sparks et al. 1989). As long as a temperature gradient exists, a certain amount of conduction has to occur.

In order for a standard, steady cooling flow alone to produce the temperature gradients observed in cool core clusters, conduction must be highly suppressed by at least 2 orders of magnitude below the Spitzer rate, presumably by tangled magnetic fields (Binney & Cowie 1981; Fabian et al. 1991). Yet, recent theoretical analyses of conduction have concluded that this level of suppression is unrealistically high (Malyshkin 2001; Malyshkin & Kulsrud 2001; Narayan & Medvedev 2001). These studies suggest that magnetic field tangling may only suppress conduction by a factor ~3–10, implying that it may be important in the cores of clusters.

This finding, coupled with the X-ray spectroscopic observations showing little evidence for cooling gas, has helped to spur a remarkable revival of the idea of conduction, with notable assistance from some of its harshest earlier critics (Fabian et al. 2002; Voigt et al. 2002; Zakamska & Narayan 2003; but see Loeb 2002). One can analyze the observed temperature gradients of clusters by defining an effective conduction coefficient $\kappa_{\rm eff}(r) \equiv L(<r)/4\pi r^2 (dT/dr)$ that would lead to balance between radiative cooling and conductive heating. The values of $\kappa_{\rm eff}$ measured at $\sim$ 100 kpc in cool core clusters are typically $\sim (0.1-0.3)\kappa_{\rm S}$, suggesting that electron thermal conduction is a plausible mechanism for counteracting radiative cooling over much of the region where $t_c < H_0^{-1}$ (Fig. 1.7).

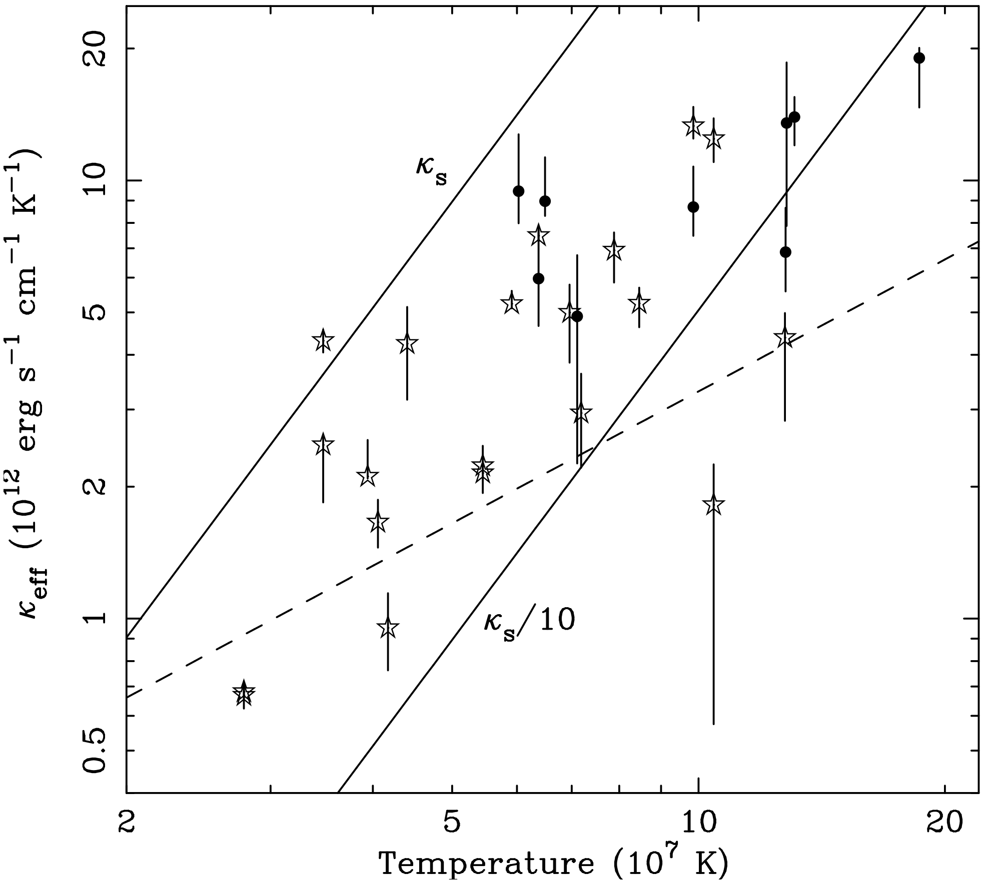

Fig. 1.7. Effective conduction coefficients $\kappa_{\rm eff}$ required for conduction to compensate for radiative cooling within the central regions of clusters, plotted as a function of cluster temperature. The required conductivity generally does not exceed the Spitzer rate κ_S at radii $\sim$ 100 kpc, implying that conduction is potentially important in cluster cores. (Figure from Fabian et al. 2002.)

Even though conduction may be important at $\sim$ 100 kpc, the required effective conductivity exceeds the Spitzer rate at radii $\sim$ 10 kpc (Ruszkowski & Begelman 2002; Voigt et al. 2002), a result presaged by the analysis of Bertschinger & Meiksin (1986). Thus, a modest amount of feedback may be necessary to offset cooling in the centers of cool core clusters. Hybrid models involving conduction in the outer parts of the core and AGN feedback in the inner parts have been developed by Ruszkowski & Begelman (2002) and Brighenti & Mathews (2003).

1.6 Paths to a Resolution

Observations from the present generation of X-ray telescopes have dethroned the cooling flow hypothesis, but what will take its place? Star formation, radio jets, and conduction may all have important roles to play in the development of cluster cores. Conduction is notoriously hard to test because the rate at which it proceeds depends on the unknown geometry of intracluster magnetic fields and uncertain factor by which these fields suppress heat flow. Looking for hallmarks of episodic feedback, from both AGNs and supernovae, may be more fruitful, at least in the short term.

If feedback is episodic, then the state of the central intracluster medium should be closely related to other goings-on in the cluster core. Thus, it would be interesting to test whether the $\sim T_{\rm vir}/3$ scaling of the minimum plasma temperature apparent in the early sample of *XMM-Newton* clusters from Peterson et al. (2003) holds for a large sample of cool core clusters with various levels of core activity. How do the X-ray emission-line spectra of clusters with radio-loud nuclei differ from those of clusters with radio-quiet nuclei? Are there any correlations between X-ray line emission and the presence of obvious star formation or emission-line nebulae? Episodic heating also leads to a predictable pattern in the evolution of the core entropy distribution (Kaiser & Binney 2003). Thus, studying the core entropy distributions of a large sample of clusters may reveal a telltale pattern of entropy evolution with time.

In order to look for evidence of a feedback duty cycle in cluster cores and to study how their properties depend on AGN and star formation activity, we are now in the midst of an archival *Chandra* study of cluster cores. The result of this program will be a publicly available library of entropy distributions showing how the entropy of intracluster gas depends on radius and enclosed gas mass within that radius (Horner et al., in preparation.) We are focusing on entropy because it is the thermodynamic quantity most closely related to heat input and radiative cooling. We invite all who are interested in the vexing problem of cooling flows to take advantage of this database.

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