Proceedings of *The Riddle of Cooling Flows in Galaxies and Clusters of Galaxies*: E5
May 31 – June 4, 2003, Charlottesville, Virginia, USA
Ed. T. H. Reiprich, J. C. Kempner, & N. Soker

Meeting Summary: Cluster Cooling Flows Become Modest

Joel N. Bregman

University of Michigan

The *XMM-Newton* observations showing that clusters lack the emission lines predicted from massive cooling flows forced a major revision to the model, although the successor is not yet obvious. One possibility that preserves much of the original model is that the cooling gas mixes with colder gas, spending little time in the 0.2-1 keV range, but passing through the 3×10^5 K range and producing the OVI emission observed in two objects. However, the models attracting the most attention are heating models where most of the gas is prevented from cooling due to a heating agent. The heating agent may be an AGN, which can produce slowly rising radio lobes that do work against the cluster medium, thereby heating it. Weaknesses of this model are that the cooling flow region of clusters are similar, despite large differences between AGNs, and the power that AGNs can impart may be insufficient to balance the radiative losses. Another possible heating mechanism is thermal conduction and in this case, there is an ample heat source and the expected heat flux is approximately the value needed to balance radiative losses, provided that the proper value of the conductive efficiency is chosen. However, it is not clear how different clusters select just the right conductive efficiencies in order to have temperature profiles of nearly identical shape. Another possibility is that the cD galaxy plays an important role and that the stellar mass loss from the stars is heated by conduction and flows outward. Although it is not yet clear if such warming flows occur, it would naturally produce the observed metallicity gradients, which are not produced in most other models.

1. **Setting the Stage**

After several days of presentations, poster sessions, along with some lively debate, it is difficult to summarize everything of importance, so I will try to focus on just a few items. First, I would like to begin by thinking about how an outsider might try to summarize the basic observations of the X-ray observations for the cluster cooling flow paradigm.

An outside observer would notice that every cluster labeled as a cooling flow has a central peak in the X-ray surface brightness distribution, and this central peak is coincident with a central dominant galaxy. This coincidence was not really required in that a central X-ray peak would develop if the cooling time were shorter than a Hubble time as is described by previous models. One might argue that the peak in the hot gas distribution occurs at the bottom of the potential well for the cluster, which is where a central dominant galaxy might lie, but there are examples of X-ray emitting clusters with modest central peaks in the X-ray emission but without a single dominant galaxy, so there are counterexamples. Rather than this coincidence being unrelated, one might suspect that it is the very presence of a central dominant galaxy that is responsible for the central peak in the X-ray surface brightness. If this is the case, then either the additional gravity of the central galaxy is important or the collective mass loss of the stars has an important effect on the surroundings, a theme that we discuss more fully below.

Another general feature of clusters of galaxies is that their temperatures decrease into the central regions. When normalized to the temperature at the radius where the overdensity is 2500 (R_{2500}), Fabian et al. (2003) show that the temperature decreases by about a factor of two into the central region, with a smooth profile that is similar between the clusters that they studied(Figure 1). To an outside observer, this might suggest some sort of steady-state conditions that a cluster moves to quite naturally. This type of profile might not occur if there were periodic outbursts of heating followed by cooling, in which case there could be large differences in the profile from cluster to cluster.

There are other types of common gradients, such as gradients in the metallicity of the gas (e.g., Dupke & White 2000; Irwin & Bregman 2001; De Grandi & Molendi 2001) and the entropy of these systems (e.g., Lloyd-Davies et al. 2000; Pratt & Arnaud 2003; Ponman et al. 2003). The negative metallicity gradient (higher metallicity in the center) is seen in most but not every cluster, and the general trend indicates that there must not be rapid mixing of gas between the inner 50 kpc and the region extending to 100-1000 kpc. There generally is a positive entropy gradient, also suggestive of the lack of rapid mixing, but this is similar to the temperature gradient. One good example of these gradients is the richness class II cluster Abell 2029 (Lewis et al. 2002), where the ambient temperature of the outer region is 8.3 keV beyond about 100 kpc and it drops smoothly until it reaches 3 keV in the inner 5 kpc of the galaxy (deprojected temperature profile). Meanwhile, the Fe abundance increases from about 0.5 of the solar value ($r > 100$

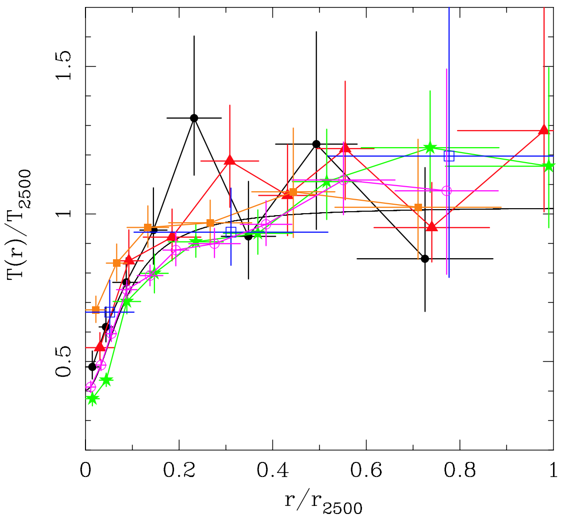

FIG. 1.— The temperature profile for six massive galaxy clusters, normalized to the radius at which the overdensity is 2500 (Allen et al. 2001); the profiles are remarkably similar.

kpc), up to 2-3 times the solar value in the inner 5 kpc (Figure 2). A dramatic example of the entropy gradient is found in Abell 1983 (Pratt & Arnaud 2003), where the entropy rises more than an order of magnitude between 25 kpc and 500 kpc (also, see Ponman et al. 2003,for the discussion of a large sample).

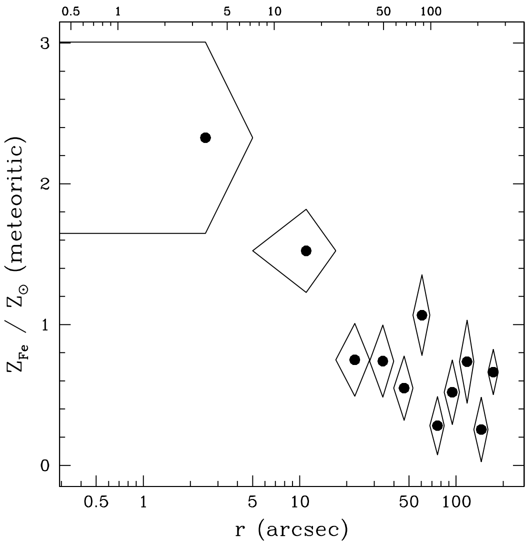

FIG. 2.— The metallicity profile for Abell 2029 shows that the metallicity decreases by about a factor of five from the central 10 kpc to the ambient cluster medium (Lewis et al. 2002).

2. The Demise of "Classic" Cooling Flows

Much of this information was emerging prior to the launch of *Chandra* and *XMM-Newton* when the "classic" picture of cooling flows was in vogue. The term "classic" usually refers to something that has been around for a while, and in the Charlottesville area, we have such classics as the University of Virginia (a beautiful campus and excellent university) and Big Jim's Barbeque, which is not approved by the American Heart Association. In terms of it's virtues, the case of "classic cooling flows" lies somewhere between the Mr. Jefferson's university and Mr. Jim's grub joint. One of the most straightforward predictions was that of the cooling rate, which is simply proportional to the ratio of two observables (L_X/T_X), under the assumption of negligible heating. The cooling rate had an enormous range, from 10-3000 $M_\odot$ yr^{-1}, so attention was generally focused on either the highest cooling rate systems or the nearest ones, with the Perseus cluster being the "poster child" as it is nearby and has a high inferred cooling rate.

There was some unease about this picture in that one does not observe the end state of the cooling gas either in the form of star formation or in the form of cold gas. Nevertheless, many X-ray astronomers expected that *XMM-Newton* would detect gas at a wide range of temperatures in the cooling flow clusters, as the gas cooled from the ambient cluster temperature to 10^4 K or less. Therefore it was shocking when the *XMM-Newton* cluster observations failed to show the presence of the OVII and the Fe XVII lines (recent compilation by Peterson et al. (2003).

There were a number of reactions to these observations and it was clear that a major revision was in store for the cooling flow model. One approach, which has received little attention at this meeting, was that the gas passes through the 0.1-1 keV region rather quickly so that relatively little emission is produced in these intermediate temperature lines. One way of accomplishing this is if the cooling gas begins to mix with cold gas once it reaches a temperature of about 1 keV, as suggested by Fabian et al. (2002). If the gas were to be mixed down to a temperature of $10^{5.2}$ - 10^6 K and then resume cooling, it would produce OVI emission as it cooled through the temperature regime near $10^{5.3}$ K. Emission from OVI mainly occurs through the doublet at 1032 Å, 1038Åand thus far, three clusters have been observed by the *Far Ultraviolet Explorer* (*FUSE*). Two of those clusters have been detected, Abell 2597 by Oegerle et al. (2001), and Abell 426 (Perseus, by Bregman, Miller, and Irwin; in preparation; Figure 3), and for both cases, the inferred OVI line strength corresponds to about 40 $M_\odot$ yr^{-1}. While this is about an order of magnitude less than the original predicted rate, only a fraction of the cooling region is being imaged by *FUSE*, so the total rate may be significantly larger. More observations by *FUSE* are planned and they should reveal whether OVI emission is a common feature of galaxy clusters, even if OVII is nearly absent. If OVI emission is common, it would encourage us to retain the "classic cooling flows" at a cooling rate given by the strength of the OVI emission lines.

3. Reheating the Cooling Flows

The majority "opinion" from this meeting appears to be to ditch the "classic" model and find suitable ways of preventing the gas from cooling in the first place. There are two primary models suggested to prevent the gas from cooling: heating by an active galactic nucleus; and thermal conduction. There are problems and virtues to each model, so I will consider them in turn, focusing on general aspects that must be satisfied, such as energy

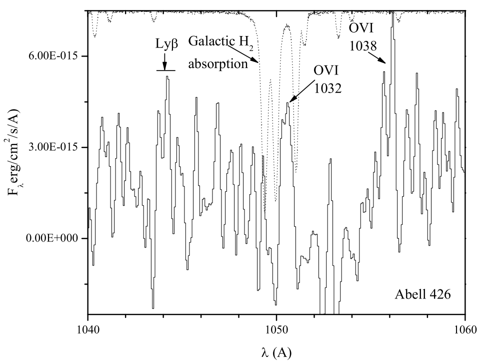

FIG. 3.— The *FUSE* spectrum of Abell 426 shows both the strong OVI line (1032 Å; partly absorbed by Galactic H_2), the weak OVI line (1038 Å) and a Lyβ emission line. When corrected for the considerable Galactic extinction, the cooling rate inferred from the OVI lines is about 40 $M_\odot$ yr^{-1}.

budget considerations.

AGN models

Perhaps the model most discussed in this meeting features heating by an AGN in some fashion (Churazov et al. 2000; Ciotti & Ostriker 2001; Kaiser & Binney 2003), which often include thermal conduction to move the energy around (e.g., Brighenti & Mathews 2003; Brüggen 2003). In this model, the AGN provides rapid feedback to prevent a cooling flow from continuing. If a cooling flow were to begin producing cold "fuel" for the AGN, it leads to a powerful AGN that subsequently heats the surroundings and reduces or shuts off further cooling. One of the suggestions that has been discussed at this meeting is that slowly moving radio lobes provide the heat input by creating acoustic noise that is damped (Binney, this meeting), although there are other possibilities.

The model using heating by radio lobes permits investigators to examine whether there is an adequate amount of energy available for this process (Birzan-Rafferty et al. 2003; this meeting). For nearly all of the systems that they examined, the power available from the radio lobe was below the radiative loss rate, usually by an order of magnitude. If this work stands up to further scrutiny, it would be a very serious problem for this model. Another concern about this model is that there seems to be no relationship between the radiative loss rate in the X-rays and the luminosity of a central AGN. Unless the feedback between the AGN and the hot gas is very rapid, one might have expected an AGN to overheat the central region occassionally, eliminating the observed temperature gradient that is so common.

There are a number of other potential problems, such as demonstrating that the energy from the lobes can be distributed azimuthally while maintaining the observed radial temperature gradient and not having a hot region near the radio lobe. The region near radio lobes appear to be cooler, rather than hotter than their surroundings, which does not seem to support the model.

This model, if broadly applicable to AGNs, is a significant change to the proposed feeding mechanism for these objects. Generally, it has been thought that stars feed the black hole in the center of AGNs (e.g., David et al. 1987) as their mean density is greater than the typical gas densities in the center. The rate of accretion seems to about the correct value and it predicts a distribution of AGNs with redshift that is consistent with the data (many more AGNs in the past). The model proposed here has AGNs, or at least those in the centers of clusters, fed by cooling gas, and since clusters and groups are predicted to be less common at higher redshift ($z > 1$), one might expect that cluster-fed AGNs to become less common with redshift. Furthermore, if AGNs are cluster-fed, the cooled gas would need to lose essentially all of its angular momentum to make it into the vicinity of the black hole.

Conduction Models

The motivation for the thermal conduction model is that the central cooling region, 100–200 kpc in size, is surrounding by a vastly greater mass of gas ($r > 200$ kpc) that acts as a nearly infinite bath of thermal energy. As the temperature drops into the central region, the conductive heat flux rises to oppose the change and prevent the gas from cooling below 1-2 keV. The heat flux is not only proportional to the temperature gradient, but it is sensitive to the temperature, going as $T^{2.5}$, so it works well at high temperatures and poorly at lower temperatures. For gas at constant pressure, the radiative cooling function increases toward lower temperature, so there appears to be a bit of a mismatch. Also, thermal conduction is carried by the electrons, whose mean free path is reduced enormously if there is a tangled magnetic field, thereby reducing the heat flux vector. Since the magnetic topology is not know, workers in the field usually leave the conductive efficiency to be a parameter that is fit (or free), with the upper limit being the value with no magnetic field (Spitzer conductivity). This idea was first proposed during the days when the "classic" cooling flow model was popular (e.g., Bertschinger & Meiksin 1986; Bregman & David 1988) and it has become the topic of much study now that a revised model is necessary (e.g., Narayan & Medvedev 2001; Voigt et al. 2002; Brighenti & Mathews 2003; Brüggen 2003; Voigt & Fabian 2003).

The next test that can be done is to examine whether the radiative loss rate can be balanced by the conductive heat flux, as a function of radius, and for any value of the conductive efficiency up to the Spitzer value. A few workers have done this and they find that the heat flux is adequate to explain the high temperature clusters, but not some of the lower temperature clusters (Zakamska & Narayan 2003; Voigt & Fabian 2003). However, it is precisely the high temperature clusters that are the ones with the enormous cooling flows, whereas the lower temperature clusters have rather low cooling rates anyway (e.g., 20 $M_\odot$ yr^{-1}), so this may not be a critical shortcoming of the model.

A modification of these models is where thermal conduction occurs in a magnetized turbulent gas, an area in which there has been some recent work (Cho et al. 2003; Kim & Narayan 2003; Voigt & Fabian 2003). The authors suggest that turbulence in the gas would mix the gas on a mixing length scale, which is argued to be some fraction of a pressure scale height (Kim & Narayan 2003). The resulting turbulent conduction coefficient can be an order of magnitude greater than the Spitzer value and it depends less strongly on temperature, so it can be more effective in the lower temperature clusters. The authors are able to obtain solutions for the temperature distribution of clusters, provided they can choose a particular value of the turbulent conduction coefficient. A possible shortcoming is that a great deal of turbulence will eliminate some of the structures that we see in clusters, such as the relics of old radio lobes and quasi-linear optical filaments, such as in the Perseus cluster (Conselice et al. 2001).

One of the problems with conduction models is that the heat flux balances the radiative cooling for a particular value of the thermal conductivity, but for a value that is a factor of two different, one obtains an unviable model or one that is inconsistent with the data. Furthermore, there is some concern that a steady-state solution will move away from some equilibrium value (Bregman & David 1988). This raises the question of how galaxy clusters became "smart" enough to arrange for the thermal conduction coefficient to be 19% of the Spitzer value for one cluster and 83% of the Spitzer value for another, poorer cluster (Brighenti & Mathews 2003). Not only would it need to be stable over time, the conductive efficiency would need to adjust as the cluster grows through accretion.

There are other problems that need to be kept in mind, such as the metallicity. One issue is that the for models with a central heat source (an AGN) and conductive heating, the metallicity of the groups would become excessive, so now there would need to be some mechanism to prevent the Type Ia SNe material from going into the gas phase (Brighenti & Mathews 2003). Another issue is whether these models reproduce the metallicity gradient seen in the cooling region. Achieving the metallicity gradient would require either selective cooling that leaves the metals in the gas phase (the reverse of the expected result) or the metal-rich gas from the cD galaxy plays an important role, which seems more likely to me. There would probably be mixing between the higher metallicity gas of the cD and the lower metallicity gas of the ambient cluster material, but if the mixing is too rapid, it might reduce the strength of the gradient below that observed (this may be a concern for the turbulent mixing model, but the details would need to be calculated).

A suggestion that I would like to propose for a model is "warming flows", in which gas from the cD galaxy flows outward rather than inward (see also the contribution by Thomas, this meeting; Bregman 1992; Canizares et al. 1993). The gas within the cD comes from stellar mass loss and becomes thermalized, so it would be at about the velocity dispersion of the galaxy, 1 keV, and with moderately high metallicity, as observed. Initially, mass loss from a star has magnetic field lines that are not connected to the ambient medium, so conduction is suppressed at first, but if magnetic reconnection occurs with the ambient medium, this material can be conductively heated by the ambient medium. Consequently, the conductively heated gas flows outward and merges with the ambient medium. This picture would naturally produce an inner temperature near 1 keV and a positive temperature gradient, without fine-tuning the conductive efficiency, provided that it is above a critical value (about 0.3 of the Spitzer value). The temperature gradient should be stable in time since the inner and outer boundary values of the temperature are fixed, and this should lend stability to the model. Also, the model explains why cooling flows occur only when there is a cD at the center of the cluster.

There are a few concerns about this model, which I might as well get into the open. In some calculations that a student (Ryan Foley) and I have carried out, the temperature gradient becomes steeper than observed (in the model shown at this meeting by Brighenti and Mathews, the temperature at the center can be very high, but they do not include a reconnection timescale). Also, the metallicity of the gas would decrease slowly in the outward flow until it mixes with the surrounding medium, which would lead to a sharp metallicity drop at some radius. As this is not observed, there must be mixing of this outward flow with the ambient cluster medium, and to treat this, one would probably need to introduce a mixing length, which becomes an important free parameter not know from first principles. Nevertheless, I hope that this model will be investigated further to determine if it is a viable alternative, or if it is an additional aspect of some of the models already discussed. In general, if the cD plays an integral role in cooling (or warming) flows, various properties should be correlated with the mass of the cD, such as the metallicity.

4. Cooled Gas and Star Formation at the Bottom of Cooling Flows

One of the important lines of study has been the presence of cooled gas and star formation in some of the galaxy clusters. This is just the finding that one might associate with a cooling flow, albeit a modest one. One of the striking aspects of the presence of this material is that it is a "package deal" in that you find together the molecular gas (Donahue et al. 2000; Edge et al. 2002), the Hα emitting gas (Crawford et al. 1999,Baum, this meeting), star formation, and usually an AGN to boot. The mass of the molecular gas can be difficult to determine because it relies on a ratio between the CO intensity and the H_2 gas mass, which has been estimated for giant molecular clouds in the Milky Way, but may be significantly different in the environment of a cluster of galaxies. With this warning in mind, the derived molecular masses are typically 10^9-10^{10} $M_\odot$, and some are higher.

Some of these systems have evidence of very high ionization emission lines, such as from Si VI in Abell 1068 and RXJ 0747-19, and S XI in NGC 1275, indicative of gas above 10^5 K, so this is consistent with gas cooling from higher temperatures and may indeed be evidence for the end product of modest cooling flows. Also, the gas is within several kpc of the center of the central dominant galaxy in the cluster, which also supports the cooling flow interpretation, because if gas were torn out of a passing galaxy, it would need to have exquisite aim to fall so close to the center. However, there may be a different explanation for much of this emission, as was suggested by Sparks (this meeting).

The amount of cool gas along with its size and star formation rate are all typical of a single spiral galaxy. This raises the possibility that it was once associated with a spiral galaxy that passed through the core of the cluster and had its gas removed through ram-pressure stripping. Shocks in the gas could lead to star formation and the related Hα emission, while the gravitational disturbance of the central galaxy by the passing galaxy would ignite the AGN. In this picture, the X-ray emission has little to do with the cooled gas in the center except that it provides the medium against which ram-pressure stripping occurs (and it should be more efficient in clusters with denser gas and therefore higher implied cooling flow rates). This picture has some compelling aspects because cool gas has clear evidence of dust, which is unlikely to survive for very long in the hot environment of galaxy clusters (Sparks 1992; Sparks et al. 1997; Donahue et al. 2000). Largely because of the presence of dust, I favor the stripping model, although it is not without problems.

5. A Few Final Comments

To explain the variety of observations bearing upon cooling flows, we have at least two popular models and several other candidates as well, which is far too many. Our main goal is to rule out as many of the models as possible, so I have a "wish list" of what I would like to see occur. Beginning with theoretical calculations of the AGN heating picture, I would like to see predictions about the temperature distribution within the cooling radius and in the vicinity of radio lobes. There must be some generic predictions that could be tested with the emerging temperature maps of these regions. Also, we have seen that there may be an apparent energy budget failure for this model, which needs to be investigated further.

The conduction model has many attractive features and appears to me to be the leading model at this time. Some of the issues that need to be further investigated is the mechanism by which the cluster arrives at the correct coefficient of thermal conduction. Also, heating from magnetic reconnection may be important and investigations along these lines should be continued. Any of the models must fit all the relevant data, including the temperature gradient, metallicity gradient, and surface brightness distribution.

Regarding observational programs, we probably do not need many more RGS cluster observations that fail to show the intermediate temperature lines, but there are a number of other observations that I would like to see. Regarding the X-ray observations, high S/N observations of a few typical objects would permit one to determine temperature maps both azimuthally as well as radially. This would allow for comparisons with the AGN models in which the heating near radio lobes is transported azimuthally around the cluster. Also, high resolution observations, such as those of Perseus, allow one to identify old radio lobes for which we might have an estimate of its age. The longevity of such structures may place important constraints on the degree of turbulent mixing that occurs.

Another item on my observational wish list is a larger set of OVI emission line measurements. If these emission lines are common and the cooling rate is moderate ($\sim$30 $M_\odot$ yr^{-1}), it would help establish the presence of cooling flows, probably at a level below the original predictions.

Finally, I am very interested in knowing the origin of the cool gas (H_2). If this gas was shed by a passing galaxy, it should be possible to identify the galaxy in some cases and the presence of a "smoking gun" would help to distinguish between the cooling flow origin and the ram pressure stripping origin. Investigators should be able to calculate the frequency at which the galaxy would be close enough to the stripped material that an association can be made. Also, it may be possible to predict certain characteristics for the shape of the stripped material, such as the axial ratio. I hope that the problems raised above, and other problems discussed at this meeting will be resolved by the next meeting, although I am sure that new issues will emerge.

I would like to thank the meeting organizers for their efforts in making this meeting scientifically memorable as well as enjoyable. Support for this work was provided by NASA, under programs NAG5-11483, G01-2089X, GO1-2087X, NAG5-10765, and NAG5-12841.

References

Allen, S.W., Schmidt, R.W., & Fabian, A.C. 2001, MNRAS, 328, L37

Bertschinger, E., & Meiksin, A. 1986, ApJ, 306, L1

Bregman, J.N., & David, L.P. 1988, ApJ, 326, 639

Bregman, J.N. 1992, in "Clusters & Superclusters of Galaxies", NATO ASI (Kluwer: Dordrecht), vol. 366, 19

Brighenti, F., & Mathews, W.G. 2003, apJ, 587, 580

Brüggen, M. 2003, ApJ, 593, 700

Canizares, C.R., Markert, T.H., Markoff, S., & Hughes, J.P. 1993, ApJ, 405, L17

Cho, J., Lazarian, A., Honein, A., Knaepen, B., Kassinos, St. And Moin, P. 2003, ApJ, 589, L77

Churazov, E., Forman, W., Jones, C., & Böhringer, H. 2000, A&A, 356, 788

Ciotti, L., & Ostriker, J.P. 2001, ApJ, 551, 131

Conselice, C.J., Gallagher, J.S., & Wyse, R.F.G. 2001, AJ, 122, 2281

Crawford, C.S., Allen, S.W., Ebeling, H., Edge, A.C., & Fabian, A.C. 1999, MNRAS, 306, 857

David, L.P., Durisen, R.H., & Cohn, H.N. 1987, ApJ, 313, 556

Donahue, M., Jennifer, M., Voit, G.M., Sparks, W., Elston, R., & Maloney, P.R. 2000, ApJ, 545, 670

Dupke, R.A., & White, R.E., III 2000, ApJ, 537, 123

De Grandi, S., & Molendi, S. 2001, ApJ, 551, 153

Edge, A.C., Wilman, R.J., Johnstone, R.M., Crawford, C.S., Fabian, A.C., & Allen, S.W. 2002, MNRAS, 337, 49

Fabian, A. C., & Allen, S. W. 2003, in the XXI Texas Symposium on Relativistic Astrophysics held on December 9–13 2002, in Florence, Italy, astro−ph/0304020

Fabian, A. C., Allen, S. W., Crawford, C. S., Johnstone, R. M., Morris, R. G., Sanders, J. S., Schmidt, R. W. 2002, MNRAS, 332, L50

Irwin, J.A., & Bregman, J.N. 2001, ApJ, 546, 150

Kaiser, C.R., & Binney, J. 2003, MNRAS, 338, 837

Kim, W.-T., & Narayan, R. 2003, ApJ, 596, L139
Lewis, A.D., Stocke, J.T., & Buote, D.A. 2002, ApJ, 573, L13
Lloyd-Davies, E.J., Ponman, T.J., & Cannon, D.B. 2000, MNRAS, 315, 689
Narayan, R., & Medvedev, M.V. 2001, ApJ, 562, L129
Oegerle, W.R., Cowie, L., Davidsen, A., Hu, E., Hutchings, J., Murphy, E., Sembach, K., Woodgate, B. 2001, ApJ, 560, 187
Peterson, J.R., Kahn, S.M., Paerels, F.B.S., Kaastra, J.S., Tamura, T., Bleeker, J.A.M., Ferrigno, C., & Jernigan, J.G. 2003, ApJ, 590, 207
Ponman, T.J., Sanderson, A.J.R., & Finoguenov, A. 2003, MNRAS, 343, 331
Pratt, G.W., Arnaud, M. 2003, 408, 1
Sparks, W.B. 1992, ApJ, 399, 66
Sparks, W.B., Carollo, C.M., & Macchetto, F. 1997, ApJ, 486, 253
Voigt, L.M., & Fabian, A.C. 2003, astro-ph/0308352
Voigt, L. M., Schmidt, R. W., Fabian, A. C., Allen, S. W., Johnstone, R. M. 2002, MNRAS, 335, L7
Zakamska, N. L., & Narayan, R. 2003, ApJ, 582, 162