ASCA Observations of Cooling Flows in Clusters of Galaxies

A. C. Fabian

K. A. Arnaud

M. W. Bautz

Y. Tawara

Laboratory for High Energy
Astrophysics

ASCA

あすか

SCAN-9410345

CERN LIBRARIES, GENEVA

SW 8444

NASA Goddard Space Flight Center
Greenbelt, MD 20771

ASCA Observations of Cooling Flows in Clusters of Galaxies

A.C. Fabian

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

K.A. Arnaud¹

Laboratory for High Energy Astrophysics, NASA/GSFC, Greenbelt, MD 20771, USA

M.W. Bautz

Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139,
USA

Y. Tawara

Department of Astrophysics, Nagoya University, Chikusa-ku, Nagoya 464-01, Japan

Received _____; accepted _____

¹also Astronomy Department, University of Maryland

ABSTRACT

ASCA spectra of the central regions of three cooling flows, in the Perseus, Centaurus, and A1795 clusters, together with the spectrum of the center of the Coma cluster, are studied. Absorbed, cooler and/or cooling components are required for the cooling flow spectra but not for that of the Coma cluster. Problems have been encountered with the basic plasma emission models in the energy range of the iron-L complex, which preclude further detailed analysis at present. Our results show the potential of ASCA data for revealing the structure of cooling flows.

1. Introduction

X-ray images of the cores of many clusters of galaxies show the emission to be strongly peaked. The radiative cooling time of the X-ray emitting gas within the inner 100-200 kpc is less than a Hubble time. It decreases inward so that it is less than a billion years within the inner few tens of kpc (for reviews see Fabian, Nulsen & Canizares 1984, 1991; Sarazin 1988; Fabian 1994). X-ray spectra from the Einstein Observatory and ROSAT show that the gas temperature decreases inward, thereby confirming that the gas cools (see e.g. Allen et al 1993). This region where the gas loses much of its thermal energy to radiation forms a cooling flow. Detailed studies of the manner in which the gas cools indicate that the cooled gas is deposited in a distributed manner, at a rate $\dot{M} \propto r$, over the whole flow (Thomas, Fabian & Nulsen 1987). $\dot{M}$ may be several hundred $M_{\odot} \text{ yr}^{-1}$ in a large flow. The detection in cooling flows of X-ray absorption in excess of that from the Galaxy (White et al 1991) suggests that some of the cooled gas remains as cold clouds before forming any stars, which from optical constraints must be of low mass (Fabian, Nulsen & Canizares 1982; Sarazin & O'Connell 1983).

In this paper we study ASCA spectra of three cooling flows; in the Perseus (A426), Centaurus, and A1795 clusters. X-ray images from the Einstein Observatory of the Perseus cluster (redshift $z = 0.0183$) indicated a cooling flow of a few hundred $M_{\odot} \text{ yr}^{-1}$ (Fabian *et al.* 1981). This was confirmed by spectra from the Solid State Spectrometer (Mushotzky et al 1981) and Bragg Crystal Spectrometer (Canizares et al 1988). Ginga and EXOSAT data analyzed by Allen et al (1992) gave a cluster temperature of 6.3 keV and mass deposition rate of $\sim 270 M_{\odot} \text{ yr}^{-1}$. BBXRT observations of the core show absorbed cooler gas (Arnaud et al 1992). The Centaurus cluster is closer ($z = 0.0104$), with a mean temperature of 3.5 keV (Hatsukade 1989) and a much weaker flow ($\sim 30 M_{\odot} \text{ yr}^{-1}$; Edge et al 1992; Allen & Fabian 1994). ASCA studies of this cluster reveal a strong abundance gradient, a cool

component and excess absorption in the center (Fukazawa et al 1994). A1795 is the most distant cluster of the three ($z = 0.06334$) with a mean temperature of 5.3 keV (Hatsukade 1989) and a strong cooling flow of $\sim 500 M_{\odot} \text{ yr}^{-1}$ (Edge et al 1992). It is also distinguished by having a low line-of-sight hydrogen column density in our Galaxy ($N_{\text{H}} = 1.2 \times 10^{20} \text{ cm}^{-2}$, compared to 1.37×10^{21} and $8.8 \times 10^{20} \text{ cm}^{-2}$ for the Perseus and Centaurus clusters, respectively; Stark et al. 1992).

The broad bandwidth and moderate spectral resolution of ASCA (Tanaka, Inoue & Holt 1994) enable us to model in detail the cooling spectrum and absorption. We confirm the presence of both cooler gas and excess absorption in cooling flows (see also Fukazawa et al 1994). A spectrum from the center of the Coma cluster shows no evidence for either a cool component or excess absorption. We highlight problems and deficiencies with the theoretical plasma spectral models available so far and demonstrate the complexity of the cooling region. It is our intention to show the potential of ASCA for cooling flow work as well as the need for more detailed physical models.

2. The X-ray data and a two-temperature analysis

The data used here are restricted to ASCA SIS spectra from the central four arcminute diameter regions of the target clusters. The SIS consists of a pair of X-ray CCD cameras, and is described in detail by Burke et al (1991). In these spectra we sample a ‘borehole’ through the centers of the clusters and observe conditions ranging from the outer hot gas to the innermost parts of the flow.

The data have been fitted using the XSPEC package and, except where specified, the thermal plasma models used are from Raymond & Smith (RS: 1977 and modifications), with relative abundances from Anders & Grevesse (1989). The spectra have been binned so that χ^2 statistics can be used (> 20 counts per spectral bin). Background is negligible and

no attempt has been made to subtract it.

Single temperature models give poor fits to the data. The cause of the poor fits can be seen in Fig. 1, which shows the difference between the Perseus cluster data and a single-temperature model (with Galactic absorption) fitted above ~ 3 keV. An excess emission component is required which cannot solely be due to emission lines, given the ASCA spectral resolution. No significant radiation must emerge from this component below about 0.9 keV. The simplest model is a cooler, absorbed thermal plasma.

This is confirmed by fitting the spectra with two-temperature models. The abundances of the two components are set equal and the excess absorption, of column density N_2 , is applied to the cooler component. Our results are gathered in Table 1 and show the big improvement in χ^2 when an absorbed cooler component is added.

We have investigated the effect of adding a power-law component, representing the active nucleus in NGC 1275, to the model for the Perseus spectrum. We have assumed a power-law photon index of 2.0 and used the 0.2 – 2.4 keV flux from the ROSAT High Resolution Imager observations (Böhringer et al 1993) to derive a relation between the absorption and normalization of the active galaxy component. Adding this component to a two-temperature model does not produce a statistically-significant change.

3. Problems and Uncertainties in Plasma models

Additional significant residuals are often found around 1.4 keV. The model predicts more flux than is seen in the data. This is illustrated well by the spectrum of the Centaurus cluster (Fig. 2). Magnesium does contribute line emission at this energy, but the total emission is dominated by 4–2 transitions of iron. Both the RS and Mewe-Kaastra (MEKA: Mewe, Gronenschild & van den Oord 1985; Mewe, Lemen & van den Oord 1986; Kaastra

1992) models overpredict this emission relative to the 3–2 transitions that occur around 1 keV. Kahn (private communication) informs us that this is a problem with the atomic physics in the models (see Liedahl et al 1994). To proceed with low-temperature, high iron abundance clusters we ignore this small part of the spectrum. When this has been done, an L is shown in the model column in Table 1. (Fig. 2 has been constructed by first ignoring the data around the 4–2 transitions, fitting the model, then restoring the data.)

We note that the RS and MEKA models often give significantly different temperatures for the cooler component. The MEKA model typically finds one at about 0.8 keV whereas the RS model shows it to be about 1 keV. This difference is probably due to the MEKA model using the newer Arnaud & Raymond (1992) ionization balance calculations, which have not yet been included in the RS model used by XSPEC. It is likely that both models have further problems for plasma temperatures below 600 eV because recent atomic physics calculations have lowered the predicted Fe-L line power for these temperatures and these results have not yet been included in the plasma codes (Liedahl, private communication).

4. Cooling Flow Models

We have fit the spectra using a model comprising an isothermal model plus an absorbed cooling flow model (consisting of emission from a range of temperatures: Johnstone et al 1992). The isothermal component is included to model the outer, non-cooling-flow gas and the gas in the cooling flow model is assumed to start at the temperature of this component. Fig. 3 shows the spectrum of the Perseus cluster when fit by this model. This model actually gives a worse fit than the simple two-temperature model unless the low end of the range of temperatures used is increased to 0.9–1 keV i.e. there is no observed emission from temperatures below this. We have tried both RS and MEKA models and the differences in fits for the cooling flow models are shown in Table 1; both χ^2 and the excess absorption

have lower values for MEKA spectra. An M is included in the model column where a MEKA model has been fitted.

It is not reasonable that the lowest temperature gas is actually at 0.9 keV. At this temperature (and for thermal pressures within this region) the cooling time is $< 6 \times 10^8$ yr and since $> 80\%$ of clusters show the steep profiles of cooling flows (Edge et al 1992) they cannot all be young enough that the gas has not had time to cool further. The most likely explanation is a combination of the plasma code problems alluded to above and the naivety of the simple, constant-pressure, cooling flow model used. Moreover, the assumed geometry is highly oversimplified.

Both A1795 and the Coma cluster (A1656) have low line-of-sight absorption due to our galaxy ($N_1 \sim 10^{20} \text{ cm}^{-2}$; Stark *et al.* 1992) and thus provide a good comparative test for excess absorption. A1795 clearly requires a cooler, absorbed component and is fitted reasonably well by an absorbed cooling flow of $\dot{M} = 130 \text{ M}_\odot \text{ yr}^{-1}$ (Fig. 4). If the start temperature of the gas in the cooling flow component is allowed to decrease below the temperature of the isothermal component then $\dot{M}$ increases to $382 \text{ M}_\odot \text{ yr}^{-1}$ with a marginal drop in χ^2 . We note that A1795, which has the lowest abundance of the cooling flows studied here and thus is least affected by problems in modelling the iron-L emission, has the best value of reduced χ^2 . The Coma cluster, which has no cooling flow inferred from previous X-ray images, does not require any cool component on spectral grounds nor any excess absorption (Figs. 5 and 6). The addition of a cooling flow component to the spectrum gives $\dot{M} = 4 \pm 4 \text{ M}_\odot \text{ yr}^{-1}$.

5. Summary

ASCA spectra confirm the presence of cool components and excess absorption in the innermost regions of cooling flow clusters. The final values of reduced χ^2 do indicate

however that current spectral models are too simple. These are due in part to problems (discovered in the data presented here) with the atomic physics used in the emission models, and in part to a lack of detailed knowledge of the structure of cooling flows. The ASCA data are of such high quality that further work with improved emission models should reveal this structure and help us to understand the origin of the density inhomogeneities in the flow and the distribution and properties of the cooled, absorbing matter.

We thank Steve Kahn and Duane Liedahl for helpful discussions and the entire ASCA team for making this paper possible.

REFERENCES

- Allen, S.W., Fabian, A.C., Johnstone, R.M., Nulsen, P.E.J., Edge, A.C., 1992. MNRAS, 259, 67
- Allen, S.W., Fabian, A.C., Johnstone, R.M., White, D.A., Daines, S.J., Edge, A.C., Stewart, G.C., 1993. MNRAS, 262, 901
- Allen, S. W., Fabian, A.C., 1994. MNRAS, in press
- Anders, E. Grevesse, N., 1989. *Geochem. Cosmochim. Acta.*, 53, 197
- Arnaud, K.A., et al. 1992. In *Frontiers of X-ray Astronomy*, 481, ed. Tanaka, Y., Koyama, K., Universal Acad, Tokyo
- Arnaud, M., Raymond, J.C., 1992. *ApJ*, 398, 394
- Böhringer, H., Voges, W., Fabian, A.C., Edge, A.C., Neumann, D.M., 1993. MNRAS, 264, L25
- Burke, B.E., Mountain, R.W., Harrison, D.C., Bautz, M.W., Doty, J.P., Ricker, G.R., & Daniels, P.J. 1991, *IEEE Trans.*, ED-38, 1069
- Canizares, C.R., Markert, T.H., Donahue, M.E., 1988. In *Cooling Flows in Clusters and Galaxies*, ed A.C. Fabian, Kluwer, 63
- Edge, A.C., Stewart, G.C., Fabian, A.C., 1992. MNRAS, 258,177
- Fabian, A.C., 1994. ARAA, in press
- Fabian, A.C., Hu, E.M., Cowie, L.L., Grindlay, J., 1981. *ApJ*, 248, 47
- Fabian, A.C., Nulsen, P.E.J., Canizares, C.R., 1982. MNRAS, 201, 933
- Fabian, A.C., Nulsen, P.E.J., Canizares, C.R., 1984. *Nature*, 310, 733
- Fabian, A.C., Nulsen, P.E.J., Canizares, C.R., 1991. *AaA Rev*, 2, 191

- Fukazawa, Y., et al. 1994. PASJ in press
- Johnstone, R.M., Fabian, A.C., Edge, A.C., Thomas, P.A., 1992. MNRAS, 255, 431
- Hatsukade, I., 1989. PhD Thesis, Osaka University
- Kaastra, J.S., 1992. Internal SRON-Leiden report, version 2.0
- Liedahl, D., Osterheld, A.L., Mewe, R., Kaastra, J.S., 1994, Preprint
- Mewe, R., Gronenschild, E.H.B.M., van den Oord, G.H.J., 1985. AaAS, 62, 197
- Mewe, R., Lemen, J.R., van den Oord, G.H.J., 1986. AaAS, 65, 511
- Mushotzky, R.F., Holt, S., Smith, B.W., Serlemitsos, P., 1981. ApJ, 278, 536
- Raymond, J.C., Smith, B.W., 1977. ApJS, 35, 419
- Sarazin, C.L., 1988. X-ray emissions from clusters of galaxies, CUP
- Sarazin, C.L., O'Connell, R.W., 1983. ApJ, 268, 552
- Stark, A.A., Gammie, C.F., Wilson, R.W., Bally, J., Linke, R.A., Heiles, C., Hurwitz, M., 1992. ApJS, 79, 77
- Tanaka, Y., Inoue, H., Holt, S.S., 1994. PASJ, 46, L37
- Thomas, P.A., Fabian, A.C., Nulsen, P.E.J., 1987. MNRAS, 228, 973
- White, D.A., Fabian, A.C., Johnstone, R.M., Mushotzky, R.F., Arnaud, K.A., 1991. MNRAS, 252, 72

TABLE 1
RESULTS

Model ^a	N_1^b (10^{22}cm^{-2})	N_2^c (10^{22}cm^{-2})	T_1 (keV)	T_2 (keV)	A	$\dot{M}^d$ ($M_\odot \text{ yr}^{-1}$)	χ^2/bins
Perseus	...	...	...	...	...	...	...
...	0.137	...	4.15	...	0.48	...	866/442
...	0.137	0.11	5.62	2.05	0.39	...	667/442
CF	0.137	0.41(0.05) ^e	4.21(0.10)		0.46(0.04)	138(18)	705/442
CF, M	0.137	0.30	4.20		0.43	122	685/442
...	...	...	...	...	...	...	...
Centaurus	...	...	...	...	...	...	...
...	0.088	...	2.12	...	0.86	...	812/226
L	0.088	0.15	3.37	1.30	0.82	14	268/198
CF, L	0.088	0.46(0.05)	2.14(0.09)		0.99(0.12)	19.2(3)	389/198
CF, M, L	0.088	0.26	2.39		1.05	15.6	332/202
...	...	...	...	...	...	...	...
A1795	...	...	...	...	...	...	...
...	0.011	...	5.27	...	0.31	...	572/386
...	0.011	0.25	6.23	1.60	0.26	...	448/386
CF	0.011	0.35(0.08)	5.25(0.23)		0.30(0.04)	131(22)	468/386

^aCF is cooling flow model, M is MEKA, and L is Fe 4-2 transitions ignored.

^bGalactic column, held fixed during the fitting.

^cExcess absorption column density in the rest-frame of the cluster.

^dThe restricted geometry of the regions used for the spectra here mean that caution is needed in comparing the above values of $\dot{M}$ with those from other, more complete, analyses.

^eNumbers in parentheses are 90% confidence uncertainties for one interesting parameter.

Figure Captions

Fig. 1. Residuals for SIS0 after fitting the Perseus cluster data with an isothermal model, with Galactic absorption, above 3 keV and extrapolating it to the lower energy band.

Fig. 2. The best fit MEKA cooling flow model for the SIS0 spectrum from the Centaurus cluster. The Fe 4-2 transition line at 1.4 keV was not included in the fit.

Fig. 3. The best fit cooling flow model for the SIS0 spectrum from the Perseus cluster.

Fig. 4. The best fit cooling flow model for the SIS0 spectrum from the A1795 cluster.

Fig. 5. The best fit isothermal model for the SIS0 spectrum from the Coma cluster.

Fig. 6. Confidence contours for the acceptable range in kT and excess N_H in the Coma cluster.

Fig 2.

fig 6