Constraining Multiphase Gas in Cooling Flows

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abstract

We present a spectral analysis of the central X-ray emission for a sample of galaxy clusters observed with Chandra. We constrain the quantity of a second cospatial temperature component using Markov Chain Monte Carlo (MCMC) sampling and discuss the implications for our understanding of cooling flows.

the cooling flow problem

The cores of many galaxy clusters are sufficiently dense and cool that the plasma cooling time is shorter than a Hubble time. For many years it was thought that runaway cooling would result in in a large central mass deposition rate (Fabian 1994; Allen & Fabian 1997; Peres et al. 1998; White 2000; Allen 2000). Chandra and XMM observations have altered this picture significantly – there appears to be a core temperature floor of 1-2 keV, and inferred mass deposition rates have been reduced by an order of magnitude (Peterson et al. 2001; Fabian et al. 2001; Peterson et al. 2002). Several mechanisms have been proposed to explain the lack of colder gas, including heating by AGN, heat conduction from cluster halo plasma, and small-scale variations in the cooling and metallicity structure of the plasma. Each of these processes can potentially leave a specific observational signature. For example, if conduction provides enough energy to arrest the cooling rate the core plasma would be single-phase, but if AGN and/or small-scale inhomogeneities are responsible, one might expect to see observational signatures indicating the presence of multiphase plasma.

the method

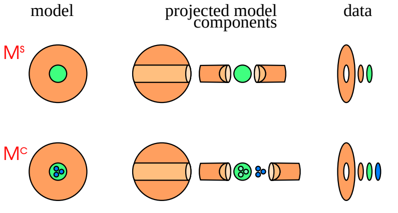

Figure 1. Core/halo geometry used for the spectral modelling.

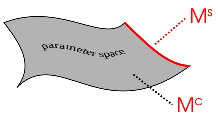

Figure 2. Schematic parameter space morphology of the simple and complex models.

We use a simple core-halo geometry and MCMC simulations to assess the statistical significance of the presence of multiphase plasma in a sample of Chandra observations. We compare two models of the emssion: a simple model M^s which contains one emission component in the halo and one in the core, and a complex model M^c which contains one in the halo and two in the core. Each model is fit to a data set consisting of two spectra, one from the outer annulus and one from the inner annulus. Because M^s lies on a boundary of the parameter space of M^c (i.e. the normalization of the second core component goes to zero), the standard F-test cannot be used (Protassov et al. 2002) since the F statistic may deviate considerably from its nominal distribution. We must instead construct an empircal F distribution to which we apply the F-test. We do this by creating a set of MCMC simulations. This process is essentially a semi-random walk through the N-dimensional parameter space of the simple model, the creation of a fake data set D_i at each sampled point in the parameter space, and the application of M^s and to each of these. The F-statistic,

$$F_i = \frac{\chi^2(M^s \mid D_i) - \chi^2(M^c \mid D_i)}{\chi^2(M^s \mid D_i) \,/\, \nu(M^s)} \quad ,$$

is tabulated for each model pair, and the significance of the second core component is determined by the location of the F value of the data within the empirical F distribution. (Here χ^2 is the variance of the model, and ν is the number of degrees of freedom.) The resulting significance S is the fraction of MCMC samples exceeded by the F value of the data, and is thus a measure of the statistical significance of the inclusion of a second cospatial core component – i.e. a multiphase treatment of the core plasma.

application to Chandra clusters

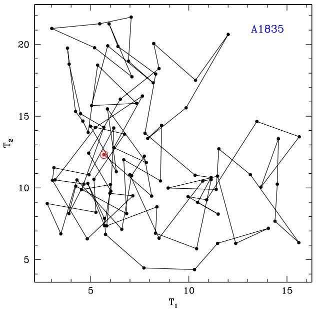

Figure 3. MCMC temperatures for A1835.

We apply this method to 12 clusters observed with Chandra. As an example we show in Figure 3 the simulated M^s temperatures at each step in the Markov Chain for A1835. The red point shows the M^s fit to the original data, which we use as the starting point of the MCMC simulations. (Note that there is a corresponding set of model normalizations in this MCMC sample that we have not shown.) The resulting F distributions for the entire sample are shown in Figure 4. The sample consists of 10 cooling flow and two non-cooling flow (CL0024 & A2104) clusters. Statistics for each cluster are shown below, including the pre-Chandra/XMM cooling rates and the multiphase plasma signficance.

cluster	dM/dt ($M_\odot$/y)	reference	S
A1689	$118 \pm^{375}_{118}$	White (2000)	21%
A1795	$453 \pm^{86}_{90}$	White (2000)	83%
A1835	$683 \pm^{677}_{677}$	White (2000)	36%
A1942	$817 \pm^{118}_{741}$	White (2000)	1%
A2029	$547 \pm^{72}_{81}$	Allen (2000)	98%
A2104	$0 \pm^{94}_{0}$	White (2000)	68%
A2204	$984 \pm^{583}_{653}$	White (2000)	96%
CL0024	0	–	16%
HydraA	$264 \pm^{81}_{60}$	Allen (2000)	–
MS1358	$691 \pm^{348}_{287}$	Allen (2000)	68%
MS2137	$1467 \pm^{880}_{726}$	Allen (2000)	2%
ZW3146	$2228 \pm^{357}_{636}$	Allen (2000)	99%

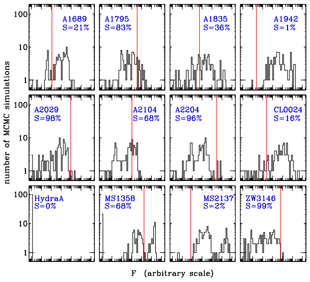

Figure 4. Empirical F distributions for the cluster sample. Red lines represent F(data).

discussion

Of the 10 cooling flow clusters in the sample, only three – A2029, A2204, and ZW3146 – show evidence for multiphase gas in the core. Perhaps more surprising is the fact that the clusters with the largest pre-Chandra/XMM mass deposition rates – MS2137 and ZW3146 – show such disparate evidence for multiphase plasma. It could be that, in the absence of core merging events, the equilibrium state of the plasma is uniphase, and that core gas mixing from merging events is responible for some clusters showing multiphase cores. We note that these results are preliminary, and that this exercise is being performed again with 1000 MCMC simulations per cluster. For example, MS1358 shows S=87% for 1000 samples. Regardless, it is safe to say that cooling flow cluster cores are as inhomogeneous a class as clusters are in general.

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