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OBSERVED NON–STEADY STATE COOLING AND THE MODERATE CLUSTER COOLING FLOW MODEL

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ABSTRACT

We examine recent developments in the cluster cooling flow scenario following recent observations by *Chandra* and *XMM-Newton*. We show that the distribution of gas emissivity versus temperature determined by *XMM-Newton* gratings observations demonstrates that the central gas, when the cooling time is less than the age of the cluster, in cooling flow clusters cannot be in simple steady state; i.e., $\dot{M}$ is not a constant at all temperatures. On the basis of the measured gas emissivity, the gas can be in steady state only if there exists a steady heating mechanism that scales as $H(T) \propto T^{\alpha}$, where $\alpha = 1$–2. A heating mechanism that preferentially targets the hottest and highest entropy gas seems very unlikely. Combining this result with the lack of spectroscopic evidence for gas below one-third of the ambient cluster temperature is strong evidence that the gas is heated intermittently. While the old steady state isobaric cooling flow model is incompatible with recent observations, a moderate cooling flow model in which the gas undergoes intermittent heating that effectively reduces the age of a cooling flow is consistent with observations. Most of the gas within cooling flows resides in the hottest gas, which is prevented from cooling continuously and attaining a steady state configuration. This results in a mass cooling rate that decreases with decreasing temperature, with a much lower mass cooling rate at the lowest temperatures. Such a temperature-dependent $\dot{M}$ is required by the *XMM-Newton* RGS data and will produce an increasing amount of intermediate-temperature gas that will then be reheated during the next heating cycle. We show the compatibility of this model with the cooling flow cluster A2052. This paper strengthens the moderate cooling flow model, which can accommodate the unique activities observed in cooling flow clusters.

Subject headings: cooling flows — galaxies: clusters: general — intergalactic medium — X-rays: galaxies: clusters

1. INTRODUCTION

Several recent papers have shown that the predictions of the steady state cluster cooling flow (CF) model is inconsistent with *Chandra* and *XMM-Newton* X-ray observations (see review by Fabian 2003). *Chandra* observations show that the gas in the central regions of relaxed clusters with central dominant galaxies can be described as homogeneous single-temperature gas with a positive temperature gradient. Ettori (2002) showed that the *ASCA* evidence for multiphase CFs was due to the poor spatial resolution of *ASCA*, which could not distinguish between multiphase gas and single-phase gas with a temperature gradient. *Chandra* observations show that only within the central few tens of kiloparesecs in clusters does the spectroscopy require additional components above a single temperature. Of course, this could simply be due to statistical and spatial resolution limitations in the *Chandra* data. The strongest evidence against the steady state isobaric CF model is the lack of observed line emission in *XMM-Newton* RGS spectra from gas cooler than about one-third of ambient cluster temperatures (Kaastra et al. 2001; Peterson et al. 2001; Fabian 2003). In the standard steady state CF model, the age of a CF is assumed to be similar to the age of the cluster; namely, the gas has been cooling for a long time. In the moderate CF model (Soker et al. 2001), heating is intermittent, and the hot gas is not in steady state in the sense that its cooling time is longer than the time elapsed since the gas was last heated. Many reheating scenarios of the central gas in CFs have been proposed in the past with the aim of suppressing CFs altogether or significantly reducing the average mass cooling rate (see Binney & Tabor 1995; Tucker & David 1997; Ciotti & Ostriker 2001; David et al. 2001; Quilis, Bower, & Balogh 2001; Brüggen & Kaiser 2001; Ruszkowski & Begelman 2002; Nulsen et al. 2002). These scenarios can be divided into models with steady heating by conduction or active galactic nuclei (AGNs), or nonsteady, self-regulating models heated by nuclear outbursts. The moderate CF model is in the class of nonsteady models in which the cooling gas is periodically heated by nuclear outbursts. We present below the evidence for nonsteady CFs. The frequent occurrence of X-ray cavities coincident with radio lobes around the central dominant galaxy in CFs (e.g., A496, Dupke & White 2002; Perseus [A426], Fabian et al. 2002; Hydra A, McNamara et al. 2000) demonstrates that AGNs have a significant impact on the X-ray morphology of the hot gas. However, there are still significant uncertainties in the detailed physics of how the relativistic and thermal plasmas interact and how much heat is deposited into the hot gas.

In the moderate CF model where the intermittent heating is generated by AGN activity in the central dominant galaxy, it is expected that the amount of cooling gas increases sharply with increasing temperature. Only at very low temperatures is there a steady state situation (i.e., where the cooling time is short compared to the time between nuclear outbursts). In Soker et al. (2001), we presented the arguments for a moderate CF in which the actual mass cooling rate is significantly below that derived under the

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assumption of the standard model, but a nonsteady CF still exists. Soker et al. (2001) estimate that in the moderate cluster CF model, the required kinetic energy of the AGN is $\sim 10^{47}$ ergs s^{-1}, and its strong activity should last $\sim 10^7$ yr and occur every $\sim 10^9$ yr. Only $\sim 1\%$ of all CF clusters should be found during that stage. In Cygnus A, there is a strong radio source that heats the intracluster medium (Smith et al. 2002). Wilson, Young, & Smith (2003) estimate the mechanical power of the jets in Cygnus A to be $L_{\rm jet} \simeq 6 \times 10^{46}$ ergs s^{-1}. This is ~ 100 times larger than the radio emission, and it is in the range required by the moderate CF model.

In recent analyses of *XMM-Newton* RGS data by Kahn et al. (2003) and Peterson et al. (2003, hereafter P2003), they find that there is less gas than predicted by the steady state isobaric CF model at all temperatures below the ambient gas temperature. Also, the discrepancy increases with decreasing temperature. There is not just a deficit in gas below about one-third of the ambient cluster temperature: there is a deficit of gas at all temperatures below the ambient temperature. They conclude that their results are difficult to reconcile with the newly proposed alternatives to the standard CF model, including those that completely suppress radiative cooling with some form of steady state heating, and that new physics may be required. Our goal in this paper is to show that the *XMM-Newton* results are consistent with the expectations of the moderate CF model presented in Soker et al. (2001).

We convert the differential luminosity as a function of temperature as derived from the RGS data on cluster CFs into the distribution of gas mass versus temperature in § 2. We also derive $\dot{M}$ as a function of temperature in this section and show that the gas in CFs cannot be in steady state. In § 3, we apply the moderate CF model to a recent *Chandra* observation of A2052, and in § 4, we summarize our main results.

2. DISTRIBUTION OF GAS MASS WITH TEMPERATURE

We show, in this and the next sections, that the distribution of gas mass with temperature within cluster CFs found by P2003 can be incorporated into a model with intermittent heating such that the effective age of the cooling gas is only $\sim(1\text{–}3) \times 10^9$ yr. On the basis of RGS spectra of 14 CF clusters, P2003 find that the variation in the differential luminosity with gas temperature can be characterized by the following expression:

$$\frac{dL}{dT} = \frac{5}{2}\frac{\dot{M}_{\rm ocf} k}{\mu m_p}(\alpha+1)\left(\frac{T}{T_0}\right)^{\alpha} , \tag{1}$$

where k, μ, and m_p have their usual meanings, $\dot{M}_{\rm ocf}$ is the inferred mass cooling rate based on the assumptions inherent in the steady state isobaric CF model, T is the gas temperature, and T_0 is the maximum or ambient cluster temperature. In general, the luminosity of gas cooling isobarically within a temperature interval dT is

$$dL = \frac{5}{2}\frac{k}{\mu m_p}\dot{M}(T)\,dT . \tag{2}$$

In steady state, the rate at which gas cools into a given temperature interval must equal the rate at which gas cools out of the same temperature interval. In other words, $\dot{M}(T)$ must be constant and equal to $\dot{M}_{\rm ocf}$. Comparing equations (1) and (2) shows that the gas can be in steady state only if $\alpha = 0$. Fitting the RGS data on their sample of 14 CF clusters, P2003 find that $\alpha \sim 1\text{–}2$. Within the old CF radius—where cooling time equals the cluster age—most of the radiation comes in the X-ray band. Only in the very inner region of $r \lesssim 10\text{–}30$ kpc may a significant fraction of the energy lost by the cooling gas be emitted in the optical and UV bands (Fabian et al. 2002; Soker, Blanton, & Sarazin 2003).

The mass cooling rate as a function of temperature can be written as

$$\dot{M}(T) = \frac{dM}{dT}\frac{dT}{dt} = \frac{dM}{dT}\frac{T}{\tau_{\rm cool}} , \tag{3}$$

where we define the cooling time to be

$$\tau_{\rm cool}(T) \equiv \frac{T}{dT/dt} . \tag{4}$$

From equations (2) and (3), we obtain

$$\frac{dL}{dT} = \frac{5}{2}\frac{k}{\mu m_p}\frac{dM}{dT}\frac{T}{\tau_{\rm cool}} . \tag{5}$$

Combining equations (1) and (5) gives

$$\frac{dM}{dT} = \dot{M}_{\rm ocf}\tau_{\rm cool}(\alpha+1)\left(\frac{T}{T_0}\right)^{\alpha-1}\frac{1}{T_0} . \tag{6}$$

The cooling time varies as

$$\tau_{\rm cool} = \tau_0\frac{\Lambda_0}{\Lambda}\frac{T}{T_0}\frac{n_0}{n} = \tau_0\frac{\Lambda_0}{\Lambda}\frac{P_0}{P}\left(\frac{T}{T_0}\right)^2 , \tag{7}$$

where τ_0 is the cooling time of gas at T_0, n is the total number density, P is the gas pressure, and Λ is the radiative cooling function, such that Λn^2 gives the energy radiated per unit volume per unit time. The last two equations can be combined to give

$$\frac{dM}{dT} = \dot{M}_{\rm ocf}\tau_0(\alpha+1)\left(\frac{T}{T_0}\right)^{\alpha+1}\frac{1}{T_0}\frac{\Lambda_0}{\Lambda}\frac{P_0}{P} . \tag{8}$$

The cooling function can be characterized as

$$\frac{\Lambda}{\Lambda_0} = \left(\frac{T}{T_0}\right)^{\eta}, \tag{9}$$

where $\eta \simeq \frac{1}{2}$ for $T \gtrsim 2 \times 10^7$ and $\eta \simeq -\frac{1}{2}$ at lower temperatures. For consistency with the expressions derived above, assuming isobaric cooling and integrating equation (8) over temperature gives

$$M(<T) = \dot{M}_{\rm ocf}\tau_0\frac{\alpha+1}{\alpha-\eta+2}\left(\frac{T}{T_0}\right)^{\alpha-\eta+2} . \tag{10}$$

Setting $\alpha \simeq 1.5$ in the last equation, the average value found by P2003, and assuming bremsstrahlung cooling ($\eta = 0.5$) gives

$$M(<T) \simeq \dot{M}_{\rm ocf}\tau_0\left(\frac{T}{T_0}\right)^3 . \tag{11}$$

If we add a heating mechanism to equation (2), then a steady state condition can be established only if

$H(T) \propto T^{\alpha}$. It is difficult to conceive of a heating mechanism that preferentially heats the hottest and highest entropy gas in a CF. The RGS data show that $\dot{M}(T)$ increases with increasing temperature. If this was true over the lifetime of a cluster, there would be a large reservoir of gas at intermediate temperatures, which is also inconsistent with the RGS data. This gas must be periodically removed from these intermediate temperatures by either cooling sporadically to very low temperatures (which simply returns us to the classic CF problem, i.e., the lack of a significant reservoir of cool gas) or intermittent heating back to roughly the ambient temperature. We therefore examine the nonsteady moderate CF model.

3. MODERATE COOLING FLOW MODEL

As an example, we consider the CF cluster A2052, which was included in the P2003 *XMM-Newton* sample and whose X-ray structure as observed by *Chandra* was discussed in detail by Blanton et al. (2001, 2003). P2003 assume a cooling radius of $r_0 = 51''$ and find $\alpha \simeq 3$ for this cluster. Hence, from equation (10), $M(< T) \propto T^{4.5}$, and most of the mass is in the hottest gas.

Indeed, from Figure 4 of Blanton et al. (2003), we find that the mass within $30''$ consists of $\sim$30% of the total gas mass within $50''$. The temperature of the gas at $30''$ is 2.5 keV (Blanton et al. 2003). Using this along with an ambient temperature of $kT_0 = 3.3$ keV (Blanton et al. 2003) implies that $(2.5/3.3)^{4.5} = 29\%$ of the total gas mass up to T_0 resides at temperatures lower than 2.5 keV. Considering the uncertainties, these two numbers are in excellent agreement. A small fraction of the gas still resides at lower temperatures, presumably because the shock that heated the gas, $\sim 10^9$ yr ago, could not increase the cooling time of the lowest entropy gas above the time between outbursts (Soker et al. 2001).

P2003 did not compare their *XMM-Newton* results directly to the *Chandra* data. We find the cooling time at $30''$, with $kT = 2.5$ keV and $n_e = 0.02$ cm^{-3} (Blanton et al. 2001), to be $\tau_{\rm cool}(30\ {\rm kpc}) = 1.5 \times 10^9$ yr. Interior to this radius, the intracluster medium is disturbed by two large radio bubbles (Blanton et al. 2001). In the moderate CF model, the time interval between intermittent energy deposition is $(1\text{–}4) \times 10^9$ yr; hence, the gas is prohibited from settling into a steady state configuration at $r > 30''$. Although the gas continues to cool, and its cooling time gets shorter, it is unable to reach a steady state before the next nuclear outburst.

Only within $r \sim 30''$ may the gas have reached a steady state; however, the *Chandra* data show that it was recently disrupted by the two radio bubbles. We therefore expect that the actual cooling rate is much smaller than that in the old (standard) CF model. On the basis of a spectral analysis of the *Chandra* data, Blanton et al. (2003) find the mass cooling rate to be $26 < \dot{M} < 42\ M_\odot$ yr^{-1}, which is about one-third of the old value within $r \sim 140''$ (Peres et al. 1998). Taking the actual cooling radius to be the radius within which steady state has been established on the basis of the shorter age in the moderate CF model, the cooling rate will be even lower than the value found by Blanton et al (2003); i.e., we argue for a mass cooling rate of $\dot{M} \lesssim 10\ M_\odot$ yr^{-1}.

Although we only study one cluster as an example, we note the following. (1) In the moderate CF model suggested by Soker et al. (2001), the heating does not inhibit the CF in the very inner region $r \lesssim 10$ kpc. In this region, the gas continues to cool to temperatures of $T \sim 10^4$ K, even after a heating event. Only in the outer regions does the heating event prevent the gas from cooling to low temperatures. Therefore, we do not expect the gas to be isothermal. The heating event cannot heat the gas to extremely high temperature, either, because this requires AGN energy output much larger than typically observed values. (2) The moderate CF model thus predicts that α in equation (1) or $\alpha - \eta + 2$ in equation (10) will not take extreme values. We cannot predict the exact range of values of α in the present study: this requires numerical simulations with variable conditions in the intracluster medium before each heating event, the energy supplied by the event, the time elapsed between events, and other processes, e.g., mergers. (3) Some CF clusters have central cooling times shorter than those in A2052. This does not pose a problem for the moderate CF model since the central regions of clusters still harbor a CF. (4) In light of the uncertainties, e.g., the temperature profile in the inner regions, the presence of X-ray cavities, and in the model parameters mentioned in point 2 above, it does not warrant a more extensive comparison with other clusters at this point. Future work, in particular numerical simulations of heating events, will include a greater comparison between the moderate CF theory and cluster observations.

4. SUMMARY

We show that the differential luminosity of the gas in cluster cooling flows as a function of temperature, as derived from RGS *XMM-Newton* observations, is inconsistent with steady state cooling flow scenarios but is consistent with nonsteady heating or moderate cooling flow models. The findings of P2003 imply that most of the gas in cooling flows resides in the highest temperature phase (eqs. [10] and [11] above). Within the context of the moderate cooling flow scenario (Soker et al. 2001), at these temperatures and densities, the CF cannot reach a steady state, and if the intermittent heating continues, it cannot attain such a state. Therefore, the rate of gas cooling at high temperatures is much higher than at lower temperatures.

We demonstrate the applicability of this model to the cooling flow cluster A2052 (§ 3). We argue for a mass cooling rate of $\lesssim 10\ M_\odot$ yr^{-1} in this cluster, which is compatible with the upper limit found by P2003 for lowest temperature gas. This is much lower than the cooling rate of hotter gas, $\gtrsim 100\ M_\odot$ yr^{-1}, found by P2003 or deduced in the old CF model by Peres et al. (1998) and somewhat lower than the cooling rate derived recently by Blanton et al. (2003) of $\sim$26–42 $M_\odot$ yr^{-1}. Overall, intermittent heating in the moderate CF model (Soker 2001; Fabian 2003) or more frequent heating (Blanton et al. 2003 for A2052) may account for the P2003 findings without invoking new processes. The intermittent heating model, with time intervals between major heating events of $\sim(1\text{–}3) \times 10^9$ yr, has the advantage that no fine tuning is required to balance heating and cooling since the gas is heated to relatively high temperatures and then starts cooling. Most of the heated gas does not cool to low temperatures before the next major heating event. Different values of the physical parameters, e.g., energy input and time intervals between heating events as well as a cluster's properties, will give different values of α in equations (1) and (10). Indeed, a large range of values is observed, $\alpha \sim 1\text{–}3$, hinting at a wide range in the physical parameters mentioned above, such that no fine tuning is observed or required. As shown in Soker et al. (2001), it is difficult to prevent the lowest entropy gas from complete cooling (i.e., increasing the cooling time above the time between heating events). Hence, a low $\dot{M}$ cooling flow can be sustained in the very central region of clusters.

This paper strengthens the moderate cooling flow model (Soker et al. 2001) by supporting the claim that the unique activities observed in cooling flow clusters (e.g., McNamara 2002 and references therein) can be accommodated within its framework. The problems that need to be solved, e.g., the exact nature of the heating events, are less severe than the crisis encountered in the old cooling flow model.

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