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ON THE RELATIONSHIP BETWEEN COOLING FLOWS AND BUBBLES

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ABSTRACT

A common feature of the X-ray bubbles observed in *Chandra* images of some "cooling flow" clusters is that they appear to be surrounded by bright, cool shells. Temperature maps of a few nearby luminous clusters reveal that the shells consist of the coolest gas in the clusters — much cooler than the surrounding medium. Using simple models, we study the effects of this cool emission on the inferred cooling flow properties of clusters. We find that the introduction of bubbles into model clusters that *do not* have cooling flows results in temperature and surface brightness profiles that resemble those seen in nearby "cooling flow" clusters. They also approximately reproduce the recent *XMM-Newton* and *Chandra* observations of a high minimum temperature of ∼1-3 keV. Hence, bubbles, if present, must be taken into account when inferring the physical properties of the ICM. In the case of some clusters, bubbles may account entirely for these observed features, calling into question their designation as clusters with cooling flows. However, since not all nearby "cooling flow" clusters show bubble-like features, we suggest that there may be a diverse range of physical phenomena that give rise to the same observed features.

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

1. INTRODUCTION

Observations obtained with the *Chandra* and *XMM-Newton* X-ray Observatories have yielded a number of important results that have changed our view of galaxy groups and clusters, especially those systems that have been termed "cooling flow" clusters[5]. For example, *Chandra*'s exquisite spatial resolution has allowed for much more detailed analyses of the X-ray surface brightness depressions (referred to as "bubbles" or "holes") discovered in earlier *ROSAT* images of several nearby "cooling flow" clusters (Fabian et al. 2000; Schmidt et al. 2002; Heinz et al. 2002; Blanton et al. 2001; 2003). High quality *Chandra* data is also responsible for the discovery of many new bubbles (or bubble-like features) in a number of other groups and clusters (e.g., McNamara et al. 2000; 2001; Schindler et al. 2001; Mazzotta et al. 2002; Johnstone et al. 2002; Young et al. 2002; Sanders & Fabian 2002; Smith et al. 2002). It now seems that such bubbles are a fairly common constituent of "cooling flow" clusters.

Another important result, derived with *XMM-Newton* data, is the lack of spectral evidence for gas cooling to temperatures below a few keV (e.g., Peterson et al. 2001; 2003; Kaastra et al. 2001; Tamura et al. 2001). Possible explanations for this unexpected behavior include heating of the cooling flows by AGN outflows and/or thermal conduction, rapid mixing of the low temperature gas, and inhomogeneous metallicity distributions in the ICM (e.g., Peterson et al. 2001; Ciotti & Ostriker 2001; Narayan & Medvedev 2001; Fabian et al. 2002a; 2002b; Churazov et al. 2002; Ruszkowski & Begelman 2002; Kaiser & Binney 2003; Morris & Fabian 2003).

The near simultaneous discovery of the connection between bubbles and "cooling flow" clusters, and the high minimum temperatures in clusters raises the question: are these phenomena related? As we already mentioned, it has been hypothesized that heating by a central AGN could quench the cooling flows. Recent numerical simulations show that heating the ICM near the cluster core can also give rise to bubble-like features that resemble those seen in the *Chandra* images (e.g., Churazov et al. 2001; Quilis et al. 2001; Brighenti & Mathews 2002a). However, it still is not clear *how* the AGNs or the bubbles they produce could heat up cooling flows, e.g. through shocks, cosmic rays, or Compton heating, or whether this heating would be sufficient to offset the radiative losses and establish the observed high minimum temperature (see, e.g., Fabian et al. 2002a; Brighenti & Mathews 2002b). We speculate that there could be an even simpler connection between the bubbles, "cooling flow" clusters, and the high minimum temperatures of clusters.

A common feature of the X-ray bubbles present in the *Chandra* images is that they appear to be partially or fully surrounded by cool, bright shells. In fact, high resolution cluster temperature maps of Perseus and A2052 (see Fig. 6. of Schmidt et al. 2002; Fig. 10. of Blanton et al. 2003), two nearby X-ray bright clusters which have probably yielded the best constraints on bubble properties, reveal that the shells consist of the coolest gas in the

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[5] The designation *"cooling flow" cluster* refers to a system that has a sharply rising surface brightness profile and a declining temperature profile towards the center. These observational characteristics have typically been interpreted as manifestations of an ICM that is radiatively cooling on short timescales. The cooling gas flows inward toward the cluster center (hence, the name cooling flow). When we use the phrase "cooling flow" (in quotation marks) we are referring to the observational characteristics and not a physical model.

clusters; much cooler than surrounding ambient medium. What are the effects of these bright, cool shells on the inferred cooling flow properties of clusters? It is clear that if the emission from the bubbles is relatively important, it will have an impact on both the azimuthally-averaged surface brightness and emission-weighted temperature profiles. Since the cooling flow properties of clusters (e.g., the cooling time, mass deposition rate, age and size of the cooling flow) are deduced from these profiles, they will also be affected. To date, however, the effects that bubbles have on the inferred properties of gas in the cores of clusters have not been studied theoretically or observationally.

In this Letter, we explore how the presence of bubbles affects the surface brightness and temperature (kT_{ew}) profiles of clusters. We show that the introduction of bubbles into non-cooling flow model clusters results in profiles that closely resemble those observed in nearby "cooling flow" clusters that clearly contain bubbles (but which have not been excised from the analysis of those clusters). This implies that the bubbles have a significant impact on the inferred cooling flow properties of these clusters and, in the case of some clusters, may account for the entire "cooling flow".

2. MODEL CLUSTERS WITH BUBBLES

To ascertain the effects of bubbles on the general appearance of clusters, we make use of analytic "preheated" cluster models developed in Babul et al. (2002). Since an in-depth discussion of the models can be found in that study, we give only a very brief description here.

The distribution of the dark matter in the model clusters is assumed to be the same as that found in recent high resolution numerical simulations. The intracluster gas, preheated to a uniform 'entropy' ($\equiv kT_e n_e^{-2/3}$) of 300 keV cm^2, is assumed to be in hydrostatic equilibrium within the cluster potential well. The preheated models (with entropy floors $\gtrsim 300$ keV cm^2) have been shown to provide an excellent match to the observed *global* X-ray and thermal Sunyaev-Zeldovich effect properties of groups and clusters (Balogh et al. 1999; Babul et al. 2002; McCarthy et al. 2002; 2003). A welcome by-product of the high level of preheating is that the cooling timescale of the ICM is greater than the age of the Universe (for $H_0 = 75$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ at $z = 0$, which we assume throughout) for groups up to moderate mass clusters. Thus, the complicated effects of radiative cooling and cooling flows (which are neglected by the Babul et al. 2002 models) are unimportant for these model clusters. Because there are no cooling flows, it is straightforward to quantify the effects of the cool bubble shells on the surface brightness and emission-weighted temperature profiles.

For the bubbles, we use the *Chandra* images of Perseus and A2052 as a guide. Each model bubble consists of a spherical 'cavity' surrounded by a spherical shell[6]. Schmidt et al. (2002) and Blanton et al. (2001; 2003) argue that any gas filling the 'cavities' must be hot ($kT_e \gtrsim 20$ keV) and have a low density. We assume a constant cavity temperature of 20 keV. The density distribution of the cavities is set by requiring that they are in pressure equilibrium with the bubble shells and the ambient ICM.

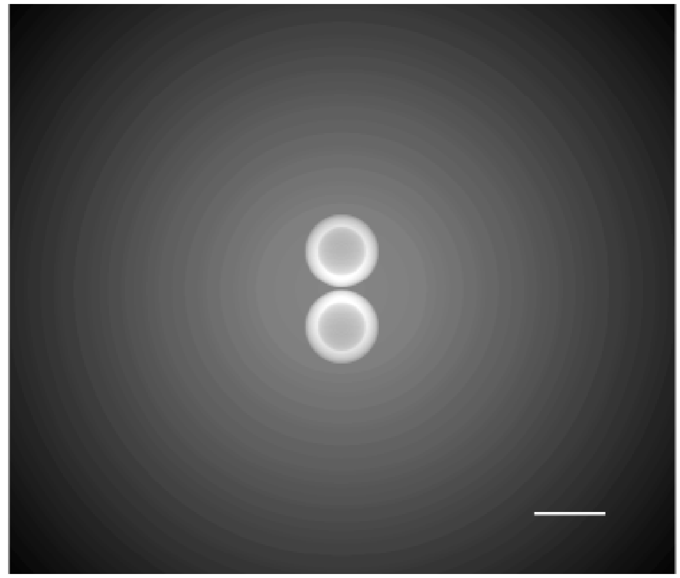

Fig. 1. Bolometric surface brightness map of a typical model cluster. The surface brightness is displayed in logarithmic scale. The solid white line indicates a length of 20 kpc.

This, combined with the high temperature, insures that the density is quite low and, consequently, the cavities are X-ray-deficient (as observed). As expected, use of higher cavity temperatures (i.e., lower densities) gives very similar results. The radius of the cavities is assumed to be 7 kpc, approximately the mean value of the bubbles observed in Perseus and A2052 (scaled to our assumed cosmology). For the shells, Blanton et al. (2001; 2003) find a deprojected temperature of about 1 keV. We assume this temperature, although changing the temperature by up to 50% does not significantly modify the results (see Fig. 2). Again, the density distribution is set by requiring that the shells are in pressure equilibrium with the surroundings. A shell thickness of 3.5 kpc is assumed. Two of these (identical) bubbles are placed near the center of each model cluster. The bubbles are placed in opposite hemispheres with equal distances from the cluster center, and perpendicular to the line-of-sight. We have also experimented with other orientations (e.g., bubbles overlapping) but the qualitative results remain generally unaffected.

A surface brightness map of a typical model cluster with bubbles is displayed in Figure 1. As observed, the shells have been significantly 'limb-brightened' (especially near the cluster center). With an emission-weighted temperature of ~ 3 keV at a projected radius of about 50 kpc, beyond the outer radius of the bubble shells, this particular model cluster roughly resembles A2052.

3. RESULTS

In Figure 2, we plot the predicted emission-weighted temperature profiles of two model clusters. As expected, the addition of the bubbles with cool shells leads to a decrease in the emission-weighted temperature towards the center of the cluster. The magnitude and scale over which the drop occurs, however, is surprising. The temperature, kT_{ew}, declines from ≈ 3 keV to ≈ 2 keV in the case of the lower mass cluster and from ≈ 6 keV to ≈ 2.5 keV for the

[6] For simplicity, we assume that the shells completely surround the cavities, even though this does not appear to be the case for all of the observed bubbles.

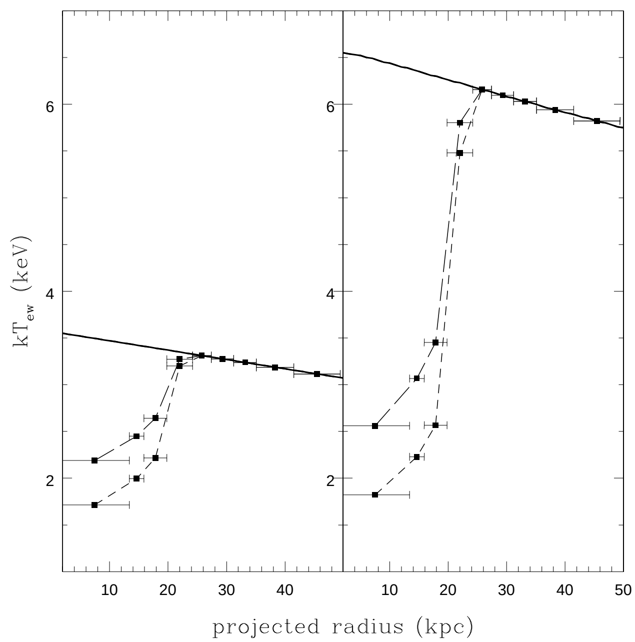

Fig. 2. Predicted emission-weighted temperature profiles. *Left:* Profile of the cluster displayed in Fig. 1. *Right:* Profile of a more massive cluster. The thick solid lines are the profiles *prior* to placing the bubbles in the cluster. The long-dashed and short-dashed lines are the profiles assuming shell temperatures of 1 keV and 0.8 keV, respectively. The solid squares indicate the radial bins from which the temperatures were extracted, while the error bars indicate the bin widths (which are similar to those used in the analyses of Perseus and A2052).

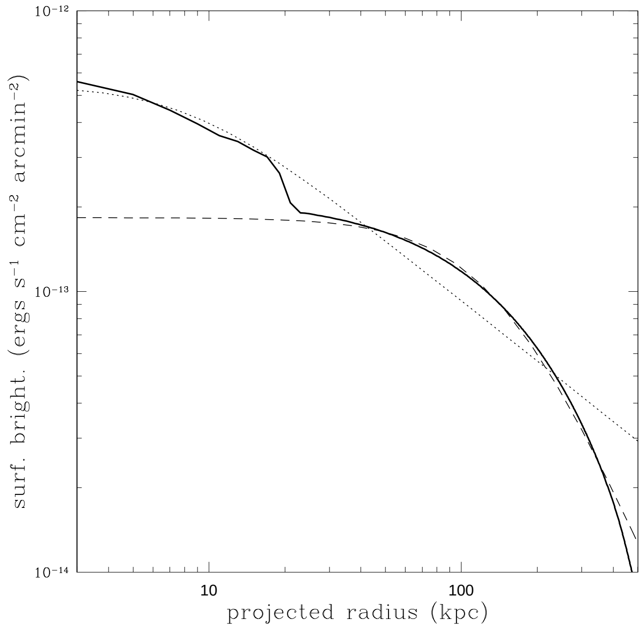

Fig. 3. Predicted bolometric surface brightness profile of the cluster displayed in Fig.1. The thick solid line is the resulting profile after the bubbles have been placed in the cluster. The dotted line is the best-fit isothermal β model, while the dashed line is the best-fit isothermal β model excluding the central 30 kpc. The sharp kink at $\approx$ 20 kpc is an artifact of the simplistic geometry we have assumed for the bubbles. A more realistic geometry would result in a smoother surface brightness profile.

more massive cluster. Furthermore, both model clusters (in fact, all of the model clusters that we examined) show a slow decline, almost a core, in the temperature profile near the very centers of the clusters and the minimum temperatures are quite similar ($\sim$ 2 keV). These predicted trends roughly match those seen in nearby "cooling flow" clusters (that contain bubbles). This is surprising since it implies that the cool shells alone could be entirely responsible for the observed temperature dips and the surface brightness peaks (i.e., cooling flows may not be necessary for these clusters). It should be kept in mind that the bubble shells have very low masses ($\sim 10^9 M_\odot$) and only occupy $\approx$ 18% (combined) of the total volume within the central 21 kpc. Any mass deposition rates inferred from such clusters that do not excise the cool shell emission will grossly overestimate the true cooling rate.

The temperature dips seen in Fig. 2 are obviously confined within the (projected) outer radius of the bubble shells (in this case about 21 kpc). An interesting question, therefore, is do the observed temperature gradients in clusters with bubbles extend beyond the outer radius of the observed bubbles? If so, this would immediately imply that the bubble shells cannot be *solely* responsible for the gradients. A close examination of Fig. 2 of Blanton et al. (2001) suggests that the gradient of A2052 does, indeed, begin very near the outer edge of the bubble shells. Similar, although somewhat less clear-cut, trends are seen in Virgo (Fig. 5 of Young et al. 2002), Hydra A (Figs. 1 & 3 of McNamara et al. 2000), A133 (Figs. 1 & 9 of Fujita et al. 2002), MKW3S (Figs. 1 & 3 of Mazzotta et al. 2002), Cygnus A (Figs. 1 & 8 of Smith et al. 2002) and A2199 (Figs. 2 & 3 of Johnstone et al. 2002). Thus, the simplistic model we have proposed seems to provide a viable explanation for the gradients in these clusters. However, the model does not appear to be compatible with the *Chandra* observations of Perseus (Schmidt et al. 2002). The gradient in that cluster extends well beyond the outer radius of the two bubbles situated near the center of the cluster. We note that there are at least two other bubbles at larger radii but they do not seem to have bright shells. Unless the bubbles *had* bright shells that somehow became dissociated from the cavities and were distributed throughout the ambient ICM, it is difficult to see how our model could reproduce the entire temperature gradient of Perseus. Even so, the shells of the two interior bubbles certainly influence the gradient near the center of the cluster (note the temperature jump at 50 kpc in Fig. 2 of Schmidt et al. 2002).

What about the surface brightness profiles? Figure 3 is a plot of the predicted bolometric surface brightness profile of the model cluster displayed in Fig. 1. It is readily apparent that the addition of bubbles with bright shells results in a sharp peak in the surface brightness profile of the model cluster. This trend holds true for both higher and lower mass model clusters as well. Use of the isothermal β model reveals an emission excess at the cluster center. Near the cluster center, the surface brightness has been enhanced by a factor of three, which is very similar to what is observed in A2052. Such excess emission is often interpreted as an indicator for the presence of cooling flows (e.g., Blanton et al. 2003) but there are no cooling flows in our model clusters.

4. DISCUSSION

We have developed a simple toy model that qualitatively reproduces the surface brightness and temperature trends of nearby "cooling flow" clusters that contain bubbles. Because our models do not have cooling flows, this suggests that the bubbles have significant effects on the observed profiles and perhaps explain them entirely (without the need for a massive cooling flow). Without taking into account the cool emission from the bubble shells, estimates of the total mass drop out due to radiative cooling would be orders of magnitude too high. Thus, our model potentially explains the longstanding problem of why only relatively small amounts of atomic and molecular gas have been found in the centers of "cooling flow" clusters (e.g., Donahue et al. 2000), at least for some clusters (such as A2052). However, there do exist some "cooling flow" clusters that do not have bubbles. Abell 2029, for example, is a seemingly relaxed cluster with a temperature gradient that extends out to nearly 260 kpc (Lewis et al. 2002). This suggests that observational features that have come to be characterized as manifestations of cooling flows may in fact be due to a wider range of physical phenomena. As noted earlier, the observed properties of Perseus, for example, may be due to several processes, of which the bubbles are one.

The results of the present study hinge on the properties of our model bubbles and, in particular, their shells. For the purposes of simplicity, the shell properties (i.e., geometry, size, temperature) were *chosen* to roughly match the *Chandra* images of Perseus and A2052, probably the most clearcut cases. But what physical mechanism(s) can give rise to such cool shells? A number of proposals have recently been put forward. The shells could consist of low entropy gas that was lifted by the bubble from the cluster center and cooled through adiabatic expansion as the bubble floated to larger cluster radii (e.g., Churazov et al. 2001; Soker et al. 2002; Nulsen et al. 2002). Alternatively, the shells (or shell-like structures) could be cool gas from the central cD galaxy that was displaced by a recent merger event (Ricker & Sarazin 2001), the result of instabilities that were induced by the interaction between the gas around the cD galaxy and the ICM (Fujita et al. 2002), or the result of thermal instabilities that were triggered by radio jets. Whatever the mechanism, the shells should not be regarded as merely re-organized cooling flows, since the radiative cooling time of the gas in the shells is apparently larger than the age of the bubbles, at least for the limited number of bubbles studied in detail to date (Soker et al. 2002; Nulsen et al. 2002).

The cooling time of the gas in the shells may not necessarily be long relative to the age of the bubbles for all clusters. In the absence of a significant source of heating, the gas would cool quickly. This would obviously conflict with the lack of X-ray emission lines below ~ 1 keV or so in "cooling flow" clusters (e.g., Peterson et al. 2001). Thermal conduction has been proposed as a way of explaining the lack of very cool gas in clusters (e.g., Narayan & Medvedev 2001; Fabian et al. 2002b), but this is over large scales. In the case of cool shells, conduction would be more efficient since it would be acting over smaller scales with a much steeper temperature gradient. In addition, the process of bubble formation itself could help to disentangle the magnetic fields in and around the bubbles shells, perhaps allowing conduction to proceed near the Spitzer rate. We suggest the shells could be reheated through conduction and eventually disappear when, for example, the jets causing the thermal instabilities cease or when the magnetic fields become disentangled enough to allow conduction to overwhelm the cooling.

Ultimately, any detailed model of the ICM must include the natural formation and evolution of bubbles with cool shells in realistic galaxy clusters. High resolution hydrodynamic simulations are required and we anticipate that a thorough check of our hypothesis will be possible in the not too distant future. A detailed and explicit accounting of the full instrumental response of *Chandra*, which has been ignored in the present study, should be included in such an analysis. Hence, we regard the present study as a first step towards understanding how bubbles influence the inferred properties of the gas in the cores of clusters. We expect that the results and conclusions presented here are generally robust, since the bubble models are based, to a large extent, on observations of *real* bubbles. Just how remarkably well this simplistic model works is, in our opinion, a strong testament to the hypothesis that bubbles significantly affect the observed properties of clusters and must be taken into account when inferring the physical properties of the ICM.

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