Chandra Observations of Cold Fronts in Cluster of Galaxies

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Abstract.

High-resolution Chandra images of several clusters of galaxies reveal sharp, edge-like discontinuities in their gas density. The gas temperature is higher in front of the edge where the density is low, corresponding to approximately continuous pressure across the edge. This new phenomenon was called “cold fronts”, to contrast it to shock fronts that should look similar in X-ray images but where the temperature should jump in the opposite direction. The first cold fronts were discovered in merging clusters, where they appear to delineate the boundaries of dense cool subcluster remnants moving through and being stripped by the surrounding shock-heated gas. Later, Chandra revealed cold fronts in the central regions of several apparently relaxed clusters. To explain the gas bulk motion in these clusters, we propose either a peculiar cluster formation history that resulted in an oscillating core, or gas sloshing (without the involvement of the underlying dark matter peak) caused by past subcluster infall or central AGN activity. We review these observations and discuss their implications for the X-ray cluster mass estimates.

1. Introduction

In the hierarchical cosmological scenario, clusters of galaxies grow through gravitational infall and merging of smaller groups and clusters (e.g. White & Rees 1978). During a merger, a significant fraction of the kinetic energy of the colliding subclusters dissipates in the intracluster medium. If unperturbed by further major mergers for few Gyr the cluster eventually relaxes and the intracluster medium reaches hydrostatic equilibrium. This status is the basic condition needed to derive the total cluster mass distribution from X-ray observations (e.g. Bahcall & Sarazin 1997). For years clusters with azimuthally symmetric X-ray morphology and with X-ray brightness strongly picked on a cD galaxy have been thought to be the prototype of relaxed clusters and, consequently, the best candidates for cluster mass measurements. Many of these clusters, however, show systematic discrepancy between the X-ray and the independent strong lensing derived masses inside the cluster core (see e.g. Miralda-Escudé, & Babul 1995 and later works). While this discrepancy may be the result of systematic effects such as line of sight substructure and/or inadequate X-ray modeling, it may also indicate that the hydrostatic equilibrium in the cluster center may have not been achieved yet.
Recently, Chandra discovered a new phenomenon, sharp gas density discontinuities or “cold fronts” that may form as a result of the relative motion of a merging subclump (or just a distinct gas cloud) with respect to the gas of the main cluster. Surprisingly Chandra discovered that a number of previously thought relaxed clusters host cold fronts. This finding, beside raising important questions about the individual cluster formation history, indicates that the hydrostatic equilibrium in the central region of such clusters may have not been achieved yet. In this paper we briefly review the observational evidences of cold fronts in both merging and quasi-relaxed clusters and discuss the implications for X-ray mass estimate.

2. Observation of Cold Fronts in Merger Clusters

The firsts cold fronts were discovered in the merging cluster A2142 (Markevitch et al. 2000). How can be seen in Fig. 1a, the Chandra image of this cluster reveals the presence of two sharp surface brightness edges on opposite sides of the X-ray peak that indicate density profile discontinuities. From the temperature map it is clear that the temperature profiles across both edges are discontinuous (see Fig. 1b). Moreover the brightest regions across the edges are also the coldest. A similar surface brightness edge, with much better statistics, was subsequently discovered by Chandra in the cluster of galaxies A3667 (Vikhlinin, Markevitch, & Murray 2000a; see Fig. 2). The surface brightness and temperature profile across the edge are shown in Fig. 2ab. These figures show that, while the brightness profile at the edge drops by a factor $\approx 5$, the temperature discontinuously increases by a factor $\approx 2$. It is particularly important to stress that the tem-
temperature variation across all these edges goes exactly in the opposite direction to what predicted in a shock front. In fact, the temperature in front of the edge is higher than that inside where the density is higher. For this reason these newly discovered edges have been called “cold fronts” (Vikhlinin, Markevitch, & Murray 2000a). One particularly interesting aspect of the cold front is that the width of the discontinuity is much less than the Coulomb free mean path. This finding represents a direct observation that, in the cold front region of the cluster, the transport processes in the intergalactic medium are highly suppressed and, thus, the gasses inside and outside the edge are thermally isolated (Ettori & Fabian 2000; Vikhlinin et al. 2000a). The most natural interpretation for the presence of these cold fronts is that they represent the boundaries of cold dense gas bodies moving (together with their underlying dark matter concentrations) inside more diffuse hotter intracluster medium (Vikhlinin et al. 2000a). Indeed, from the pressure profile across the front in A3667, Vikhlinin et al. have derived the subcluster velocity which corresponds to Mach number $1 \pm 0.2$. As result of this motion the magnetic field lines stretch along the front forming an amplified parallel magnetic field that suppresses stripping of the cool gas and stops transport processes across the boundary (Vikhlinin et al. 2000b).

3. Observation of Cold Fronts in “quasi-relaxed” Clusters

Beside the merger clusters, 	extit{Chandra} discovered cold fronts also in more round and apparently “relaxed clusters”. The first evidence of a cold front in a round clusters was observed in RXJ1720.1+2638 (Mazzotta et al. 2001a). The 	extit{Chandra} image of this cluster shows a surface brightness edge with a jump factor of $\approx 8$ at $\approx 250$ kpc south-east of the X-ray peak (see Fig.4b). This surface brightness edge corresponds to a density jump of a factor $\approx 2.8$. Even though the statistics are rather poor, the temperature profile across the edge allows us to exclude at $> 3 \sigma$ significance level that the observed edge is a shock front and
strongly indicate that it is a cold front. A similar, but stronger, edge was discovered later in the cluster of galaxies MS 1455.0+2232 (Mazzotta et al. 2001b). The Chandra image of this cluster shows a surface brightness edge with a jump factor of $\approx 10$ at $\approx 190$ kpc to the north of the X-ray peak (see Fig.4a) which corresponds to a density jump of a factor $\approx 3$. Chandra data on a number of other relaxed clusters at low (e.g. A1795 at $z=0.062$; Markevitch, Vikhlinin, & Mazzotta 2001) as well as at high redshift (e.g. 1WGAJ1226.9+3332 at $z=0.89$; Mazzotta et al. in preparation) exhibit similar fronts in their central region indicating that such a phenomenon may be quite common in clusters.

3.1. Cold fronts and cluster dynamic

The presence of cold fronts indicate that these apparently relaxed clusters host moving group-size (80–250 kpc) gas clouds. The gas velocity in relaxed clusters should be low; indeed, in A1795, it is near zero (Markevitch, Vikhlinin & Mazzotta 2001). The upper limit on the cloud speeds for both RXJ1720.1+2638 and MS 1455.0+2232 show that they are moving subsonically, although the statistical accuracy for these clusters is poor. As the shape of the surface brightness profile is a strong function of the direction of motion (Mazzotta et al. 2001a), we know that the central gas clouds in these two clusters are moving in a direction close to the plane of the sky.

At the moment it is not clear why such round clusters host moving group size gas clouds. For both RXJ1720.1+2638 and MS 1455.0+2232 it has been assumed that the gas traces the dark matter so that the clouds are moving with their own distinct dark matter halos. If this is the case the most natural explanation for the presence of a moving subclumps is that these two clusters are actually merging clusters. This scenario, however appears to be unlikely.
as both clusters show no further signs of ongoing merger as, for example, the
typical X-ray elongation in the merger direction and/or the displacement of the
cD galaxy with respect to the X-ray peak. Moreover, while the speed of a mass
point free falling from infinity into the cluster center should be $\approx 3$ times the
speed of sound, the observed subclump speed is clearly subsonic. In addition
we notice that MS 1455.0+2232 hosts one of the most massive cooling flows
observed ($\dot{M} \approx 1500 M_\odot \text{yr}^{-1}$; Allen et al. 1996) and it is not clear if that a
massive cooling flow (or cool central core) would have survived the merger (see
e.g. Roettiger, Loken, & Burns 1997, but Fabian & Daines 1991).

An alternative scenario is that, as proposed by Mazzotta et al. 2001a,
both clusters are the result of the collapse of two different perturbations in the
primordial density field on two different linear scales at nearly the same location
in space. As the density field evolves, both perturbations start to collapse. The
small scale perturbation collapses first and forms a central group of galaxies
while the larger perturbation continues to evolve to form a more extended cluster
potential. The central group of galaxies could have formed slightly offset from
the center of the cluster and is now falling into or oscillating around the minimum
of the cluster potential well. This motion is responsible for the observed surface
brightness discontinuity. As the initial position of the subclump lies well within
the main cluster, we may also expect the velocity of the infalling subclump to
be subsonic.

Another possibility is that, as proposed for A1795, the dark matter distribu-
tion is near-stationary, but the gas is decoupled from it and sloshing in the
cluster gravitational potential (Markevich et al. 2001). Such gas bulk motion
might be caused by a disturbance of the central gravitational potential by past
subcluster infall. Alternatively, in clusters where the central AGN produces
large bubbles of hot plasma (e.g., McNamara et al. 2000), such activity could
supply kinetic energy to the surrounding cool gas. This scenario seems to be
supported by simulations of cluster mergers (that did not include AGN activity)
showing that in the final stages of a merger, the gas decouples from dark matter
and sloshes in the cluster gravitational potential for a significant time before
coming to a hydrostatic equilibrium (e.g. Roettiger et al. 1997).

4. Cold fronts and X-ray mass estimates

Regardless of the origin of the cold fronts in round clusters Mazzotta et al. 2001a
and Markevitch et al. 2001 showed that its presence affects the estimate of the
total mass in the inner regions of the clusters. In particular they showed that
the mass estimate derived from the cluster sector containing the cold front and
assuming hydrostatic equilibrium has an unphysical discontinuity at the surface
brightness edge. Moreover the inferred mass inside the edge is much lower than
the value derived using sectors of the cluster containing no cold fronts (see Fig. 4
of Mazzotta et al. 2001a and Fig. 2e of Markevitch et al. 2001). As a result
of this effect, measurements of the total mass using the hydrostatic equation in
Circular annuli would result in a underestimate of the total mass at small radii.
Thus, such a phenomenon may explain, in part, the discrepancy between the
X-ray and the strong lensing mass determinations found in some systems (e.g.
Miralda-Escudé, & Babul 1995, but see Allen et al. 2001 and reference therein).
Figure 4. (a) Photon image of RXJ1720.1+2638 in the 0.5-5 keV band. Note the sharp edge SE of the X-ray peak. (b) Photon image of MS 1455.0+2232 in the 0.5-5 keV band. Note the sharp edge to the North.

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