Galaxy Clusters Near the Virial Radius: Some Early Suzaku Results

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Abstract

Suzaku has made some of the first detections of galaxy cluster X-ray e mission in the vicinity of the virial radius. Here I summarize what has been learned to date from a subset of these observations; related observations are discussed by others in these proceedings. Suzaku has expanded the fractional cluster volume within which we can detect the intracluster medium (ICM) by a factor of roughly 8 to 10, and achieved a surface brightness sensitivty limit as low as one-third of the cosmic X-ray background in the 0.5 - 2 keV band. In the cases reviewed here, cluster temperature profiles fall somewhat more rapidly, and entropy profiles rise more slowly, than predicted by some simulations. Evidence for hydrostatic equilibrium near the virial radius is notably absent. In at least one case the metal abundance near the virial radius is relativley large (~ 0.2 solar). I briefly discuss the prospects for future Suzaku work in this area, and consider the potential of future observatories, such as Astro-H and the International X-ray Observatory, for more sensitive observations of low-surface brightness cluster emission.

Key words: galaxy clusters: X-ray emission —

1. Motivation

Although Chandra and XMM-Newton have provided a wealth of information about the structure and physical conditions in the intracluster plasma near the center of galaxy clusters, the majority of the cluster volume is relatively unexplored in X-rays. It is difficult to study clusters at radii greater than $\sim r_{200}/2$ with these observatories because of their relatively high (and, in the case of XMM-Newton, time-variable) instrumental background rates. Here r_{200} is radius within which the mean cluster density is 200 times the critical cosmic density. For massive clusters, $r_{200} \sim 2$ Mpc.

The regions outside of clusters cores are interesting for a number of reasons. Cluster growth is an ongoing process, and to the extent that the virial radius r_{vir} marks the boundary within which accreted matter has reached dynamical equilibrium, observations near and beyond r_{vir} provide a direct view of cluster growth as it occurs[1]. Note that a cluster is expected to have significantly perturbed the Hubble flow to distances as large as $4-5 \times r_{200}$ (Rines et al., 2003). Moreover, radial profiles of the temperature, entropy and abundance of the intracluster medium (ICM) in the outer regions of clusters in principle encode information about such physical conditions as the dynamical state, magnetization, and thermal and enrichment histories of the ICM there. Finally, observations at large radii can improve constraints on dark matter profiles, masses and physical conditions in clusters cores (e.g. at $r < r_{500}$), where precision measurements are especially important for understanding the potential of clusters as cosmological tools.

The relatively low and stable instrumental background of the Suzaku X-ray Imaging Spectrometer has enabled significant progress on this subject. Here we review some of these results; others are presented elsewhere in these proceedings (see, for example, the contributions of Reiprich; Kawaharada et al.; and Hoshino et al.).

2. Selected Early Suzaku Results

2.1. PKS0745-191: the ICM beyond R_{200}

One of the very first Suzaku studies of cluster outskirts, published by George et al. (2009), concerned the cluster surrounding PKS0745-191. This object is among the brightest clusters in its redshift range ($z = 0.1028$), and George et al. use 5 Suzaku pointings to detect X-ray emission to $\sim 1.5 r_{200}$, with $r_{200} \approx 1.7$ Mpc $\approx 15'$. The Suzaku temperature profiles in four distinct azimuthal sectors all fall monotonically at $r > 700$ kpc, and are somewhat steeper than predicted by the simulations of Roncarelli et al. (2006). The observed ICM thermal speed falls faster with radius than the characteristic Ke-

*1 For the case of a uniform, spherical density perturbation collapsing in an Einstein-deSitter universe, $r_{vir} = r_{18\pi^2} \approx r_{180}$. For spherical collapse in a flat universe with $\Omega_\Lambda = 0.7$, as we assume here, $r_{vir} \approx r_{105} \approx 1.3 r_{200}$ for massive clusters. (Bryan and Norman, 1998). Unless otherwise noted we also assume the Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1}.

plerian velocity of a plausible (Navarro, Frenk & White, 1997) dark matter distribution. The rapidly falling temperature profiles lead to a hydrostatic mass estimate that is considerably lower ($M_{200} = 6.1^{+0.5}_{-0.7} \times 10^{14} M_{\odot}$, 1σ errors) but more precise, than previous estimates. However, profiles of the entropy index ($s \equiv kT/n^{2/3}$, where T and n are the temperature and electron density of the ICM, respectively) flatten at $r >\sim 1$ Mpc, and the entropy even drops in one azimuthal sector at the largest radius probe. These results suggest that the ICM is unlikely to be in hydrostatic equilibrium at large radius. George et al. point out that the deficit of thermal energy at large radius may indicate that there is significant bulk motion in these regions of the cluster.

2.2. Abell 1795: asymmetry at R_{200}

Bautz et al. (2009) observed Abell 1795 with Suzaku. At $z = 0.063$ and with $r_{200} \approx 1.9$ Mpc $\approx 26'$, this cluster subtends a larger solid angle than does PKS0745-191, so five Suzaku pointings were arranged along a line to cover a rectangular field extending ± 2.6 Mpc ($\pm 35'$) from the cluster center, but with relatively limited azimuthal coverage. X-ray emission is detected above background nearly to r_{200} north of the cluster, but only to about 1.3 Mpc south of the cluster. The observed temperature profiles north and south of the cluster, along with inferred entropy profiles, are shown in Figure 1. The (deprojected) temperature is observed to fall as $\sim r^{-0.8}$ outside of the cluster core, which is marginally steeper than the simulation results of Roncarelli et al. (2006). The rapid temperature drop leads to a hydrostatic mass profile which rises quite slowly with radius; this is similar to the result obtained by George et al. (2008) for PKS 0745-191. By the same token, the entropy profile in Abell 1795 rises as $s \sim r^{0.74}$, somewhat less rapdily than the $r^{1.1}$ rate predicted from adiabatic simulations (e.g. Voit, 2005).

Given the azimuthal asymmetry of the cluster brightness near r_{200}, and the relatively low temperature and entropy there, Bautz et al. suggest that the observed plasma at the largest radii may be relatively cool, infalling material that is not in hydrostatic equilibrium in the cluster's gravitational potential. Additional Suzaku observations, covering a larger range of azimuth at r_{200}, are planned to test this suggestion.

The observations of Abell 1795 do confirm Suzaku's remarkable surface brightness sensitivity. Bautz et al. estimate a limiting (3σ) detection sensitivity of $B_{0.5-2keV} = 1.8 \times 10^{-12}$ erg s^{-1} cm^{-2} deg^{-2}, less than 20% of the observed brightness of the cosmic X-ray background. Even at this level, the surface brightness sensitivity is limited by spatial fluctuations in the number density of unresolved background sources in the relatively small ($< 3 \times 10^{-2}$ deg^2) regions sampled, and by temporal fluctuations in the diffuse foreground due to geocoronal X-ray emission from solar wind charge exchange processes.

2.3. Abell 399/401: iron at R_{200}

The surface brightness at r_{200} of the two clusters discussed above is too low to provide interesting constraints on the iron abundance of the ICM there with available data. Fujita et al. (2008) have exploited the unusual configuration of the two clusters Abell 399 and Abell 401 to detect substantial iron abundance ($\sim 0.2 Z_{\odot}$) at a distance of ~ 2 Mpc from the cluster centers. The projected distance between these two objects is less than $r_{200} \approx 2.3$ Mpc, and they are thought to be approaching one another for the first time. As a result, the ICM between the clusters is compressed and relatively hot (~ 6 keV) , and therefore relatively luminous. It is thus possible to detect iron line emission at large distances from the centers of these clusters.

This presence of substantial iron abundance in outskirts of these clusters is interpreted by Fujita et al. as evidence that the ICM was enriched early in the clusters' history, possibly by galactic outflows operating before the clusters collpsed.

2.4. Other Results

A number of other clusters have been studied near the virial radius with Suzaku. These include Abell 2204 (Reiprich, et al. 2009; Reiprich, 2010), Abell 1689 (Kawaharada et al., 2010), Abell 1413 (Hoshino, et al., 2010), Abell 2218 (Takei, et al., 2007) and Abell 2052 (Tamura et al., 2007).

3. Discussion

These results demonstrate that Suzaku is capable of sampling as much as 10 times more cluster volume that has typically been observable with prior instrumentation. Surface brightness sensitivity to as low as 1/3 of the cosmic X-ray background (at 3σ significance) has been achieved. In general, radial temperature profiles are apparently steeper, and entropy profiles flatter, than expected from theoretical studies of the ICM. Disequilibrium near r_{200} seems common, and in at least one object the iron abundance in this region can be comparable to that observed near the cluster center.

Parrish et al. (2008) have argued that the presence of a negative radial, a magneto-thermal instability will tend to align the intracluster magnetic field along the radial direction, enhancing thermal conductivity and tending to flatten the temperature profile on timescales of a few Gyr. The observed temperature profiles discusssed here provide no evidence of the flattening that might be expected from the operation of this instability, in spite of the fact that at least two of these objects (PKS0745-191 and Abell 1795) show relatively regular and presumably undisturbed morphologies.

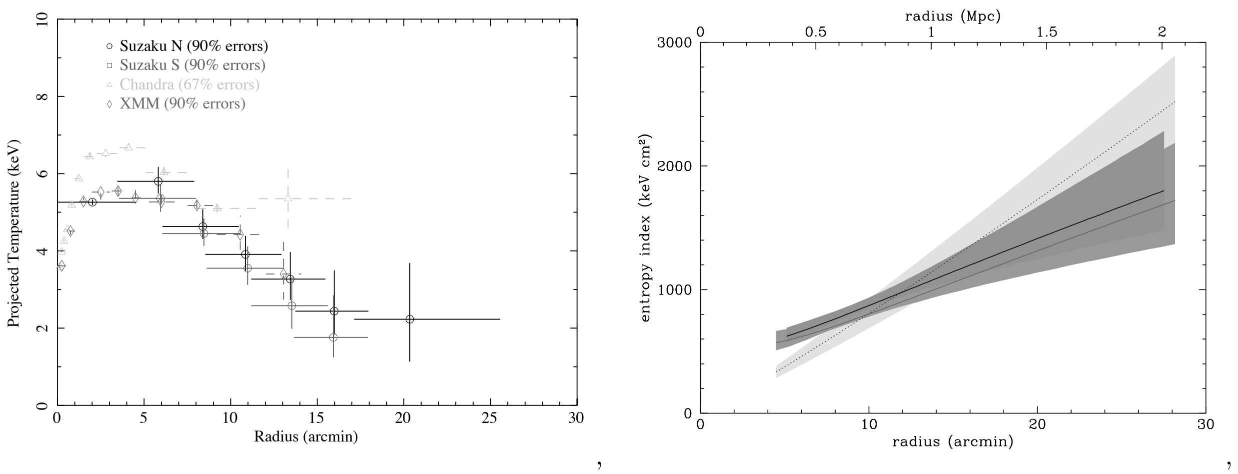

Fig. 1. Projected temperature profiles (left) and (deprojected) entropy profiles (right) of Abell 1795 (from Bautz et al. 2009). In the right panel, the red and black lines show the estimated entropy profiles to north and south of the cluster center, respectively; the shaded regions indicated 90% confidence intervals on the profiles. The dotted curve and blue shading are results of non-radiative, hierarchical cluster formation simulations reported by Voit (2005).

If a spherical, homogeneous and polytropic ICM is in hydrostatic equilibrium, then its temperature cannot fall any faster than r^{-1}. The results discussed above do not violate this limit, but the observed temperature profiles are somewhat steeper than expected from simulations. One possible interpretation is that the X-ray emission from the outer regions of any of the observed clusters are dominated by relatively cool, infalling clumps or subclusters of plasma that are not in hydrostatic equilibrium in the main cluster potential. To the extent that clusters grow at the intersections of filaments in the matter distribution, anisotropic accretion of such cool substructures may be expected. Such accretion might also disrupt the magnetic fields in the cluster outskirts, and disrupt the operation of the magneto thermal instability there.

4. Prospects

Suzaku has so far observed the outer regions of only a few clusters. Additional observations of more clusters, with more complete azimuthal coverage, are certainly warranted.

Astro-H should allow significant progress in these studies. The Soft X-ray Imager (SXI) will have roughly four times the field of view of the Suzaku XIS, reaching a radius of 2 Mpc for clusters at z> 0.08, and should feature a low background level quite similar to that of the XIS. In addition, with a sharper telescope point spread function than Suzaku XIS, the Astro-H SXI will be more sensitive to unresolved background sources. This will reduce the background uncertainty arising from statistical fluctuations in the number of such sources, which is a significant factor limiting Suzaku's sensitivity. We note also that Astro-H is likely to perform deep exposures of the central regions of clusters to exploit the unprecedented spectral resolution of the Soft X-ray Spectrometer (SXS). The long exposure times required for SXS observations will yield very sensitive SXI surface photometry in the outskirts of many clusters. The SXS itself may also be sufficiently sensitive to detect bulk motion of the ICM in the outskirts in a few clusters where the emission near r_{200} is exceptionally bright, such as the Abell 399/ Abell 401 system. Such observations would provide a powerful test of the picture that accreting subclusters dominate the X-ray emission from these regions. In the more distant future, the enormous collecting area of the International X-ray Observatory, coupled with spectral resolution of its X-ray Microcalorimeter Spectrometer, will allow detailed mapping of the ICM velocity field well beyond the virial radius in a large number of clusters.

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