A2111: A $z = 0.23$ Butcher-Oemler Cluster with a Non-isothermal Atmosphere and Normal Metallicity

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ABSTRACT

We report results from an X-ray study of the Abell 2111 galaxy cluster using the Advanced Satellite for Astrophysics and Cosmology (ASCA) and the ROSAT Position Sensitive Proportional Counter (PSPC). By correcting for the energy-dependent point-spread function of the ASCA instruments, we have examined the temperature structure of the cluster. The cluster’s core within 3′ is found to have a temperature of 6.46±0.87 keV, significantly higher than 3.10±1.19 keV in the surrounding region of r = 3 - 6′. This radially decreasing temperature structure can be parameterized by a polytropic index of γ ≃ 1.45. The X-ray morphology of the cluster appears elongated and clumpy on scales ≤1′. These results, together with earlier ROSAT and optical studies which revealed that the X-ray centroid and ellipticity of A2111 shift with spatial scale, are consistent with the hypothesis that the cluster is a dynamically young system. Most likely, the cluster has recently undergone a merger, which may also be responsible for the high fraction of blue galaxies observed in the cluster. Alternatively, the temperature structure may also be due to the gravitational potential of the cluster. We have further measured the emission weighted abundance of the X-ray-emitting intracluster medium as 0.25±0.14 solar. This value is similar to those of nearby clusters which do not show a large blue galaxy fraction, indicating that star formation in disk galaxies and subsequent loss to the medium do not drastically alter the average abundance of a cluster. This is consistent with recent results which indicate that cluster abundances have remained constant since at least z ∼0.3.
1. Introduction

Both optical (Geller & Beers 1982) and X-ray (Jones & Forman 1992) morphological studies of galaxy clusters indicate that a significant fraction of nearby clusters have substructures that are possibly due to mergers. Temperature maps derived from spectrospatial X-ray observations are a necessary complement to the X-ray, optical, and radio imaging data in the sense that hydro-dynamical simulations of subcluster mergers show that heating of the cluster atmosphere may be present in a recent post-merger system even when evidence of a merger is not visible in the X-ray surface brightness morphology (Evrard, Metzler, & Navarro 1996). On the other hand, there are clusters such as A2256 which exhibit structure in all three wavebands consistent with a merger yet the temperature map obtained with ASCA indicates a quiescent dynamical state (Markevitch 1996). Spatially resolved spectroscopy can thus help us to find hot spots similar to those seen in the simulations (Roettiger, Loken, & Burns 1997; Evrard, Metzler, & Navarro 1996), which together with the optical, X-ray imaging, and radio observations, provide a detailed description of the dynamical state of the cluster. Such spectral analysis has been carried out for a number of clusters with data from ASCA, which has a broad energy coverage and modest spatial resolution. While the X-ray spectroscopic evidence of merger may be difficult to obtain for some clusters (e.g., A2256) in others the asymmetric X-ray morphology and temperature structure are consistent with those seen in simulations of subcluster merger. Such examples are A754 (Henriksen & Markevitch 1996), the Coma cluster (Honda et al. 1997), and A1367 (Donnelly et al. 1998).

As violent events, subcluster mergers may also affect the evolution of galaxies. Relevant processes include ram-pressure (White et al. 1991), the tidal effect from the cluster potential (Henriksen & Byrd 1996), and “galaxy harassment” (Oemler, Dressler, & Butcher 1997). Consequently, properties of cluster galaxies may be intimately connected to
the changing dynamical state and galaxy environment of clusters (e.g., Kauffmann 1995; Oemler, Dressler, & Butcher 1997). Clusters at early epochs ($z \gtrsim 0.2$) tend to contain higher fractions of blue galaxies — the Butcher-Oemler effect. $HST$ observations indicate that the effect results from a high rate of star formation in spiral galaxies (Dressler et al. 1994; Couch et al. 1994) and from a high fraction of disturbed galaxy systems (Oemler, Dressler, & Butcher 1997). Based on a study of 10 Butcher-Oemler clusters, Wang & Ulmer (1997) have revealed a correlation between the blue galaxy fraction and the X-ray isophote ellipticity. A2111 at $z = 0.23$ is one of the clusters in the sample and contains a high fraction of blue galaxies ($f_b = 0.16$). Based on $ROSAT$ PSPC and HRI observations, Wang, Ulmer, & Lavery (1997; hereafter WUL) have further reported that A2111 has a highly asymmetric X-ray morphology and the X-ray centroid and ellipticity shift with spatial scale, which suggests that the cluster may be undergoing a merger.

In this paper, we present a spatial-spectral analysis, using an $ASCA$ observation, complemented by the $ROSAT$ PSPC data of A2111. This analysis enables us to search for spatial and spectral signatures of a merger over a broad energy band and to compare the metal abundance of A2111 with nearby clusters. Throughout the paper, $H_0 = 50 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ is used, and 90% confidence error bars are quoted on all quantities.

2. Observations and Analysis

A2111 was observed on January 15-16, 1997 with $ASCA$ for 30,000 seconds. Data was obtained with both the GIS and SIS; each has two sensors. The GIS has a higher effective area at higher energies ($> 5 \text{ keV}$) than the SIS so that use of all 4 data sets is optimum for studies of multi-component emission. The data were filtered using the REV2 criteria utilized by the $ASCA$ Data Processing Center. Data were excluded under the following conditions: with a radiation belt monitor (RBM) count $> 100 \text{ cts/s}$, during earth occultation or at low
elevation angle to the Earth (\(< 5\) degrees for the GIS and \(< 10\) degrees for the SIS), when the pointing was not stable (deviation of \(> 0.01\) degrees), during South Atlantic Anomaly passage, and when the cutoff rigidity (COR) was \(> 6\) GeV/c. Additionally, the SIS was required to be \(> 20\) degrees to the bright earth and were cleaned to remove hot pixels. The resulting good exposure times are given in Table 1. The ROSAT PSPC observations have been discussed in WUL. Briefly, the observations have an exposure of 7511s, a spatial resolution of \(\sim 0.5\)’, and about 7 overlapping energy bands in the 0.1-2 keV range.

To obtain an emission weighted spectrum for the cluster, we first conducted a joint fit to the spectra from the ROSAT PSPC and the ASCA GIS and SIS detectors. Extracted from a region within 6’ from the assumed cluster centroid at 15\(^h\)39\(^m\)36.554\(^s\); +34\(^\circ\)25\('\)31\(''\).16 (R.A.; Dec.; J2000), the spectra include essentially all of the cluster emission. Background for the PSPC, taken from source-free regions of the image, is calculated from 4 circular regions of radius 7.3’ located at: (15:40:56.408, +34:50:13.32), (15:36:41.344, +34:27:59.74), (15.38:16.532, +33:51:05.97), and (15:42:17.971, +34:10:45.85). The SIS data was taken in 1-ccd mode and the cluster essentially fills the chip, we thus utilized blank sky, deep ASCA observations taken at high Galactic latitudes for background subtraction. The GIS background was extracted similarly to avoid uncertainties related to vignetting, shadowing of the instrument supports, and gain variations with radius from the detector center. The energy bands used are: 0.1 - 2 keV for the PSPC, 0.3 - 10 keV for the SIS, and 0.7 - 10 keV for the GIS. We adopted the Raymond & Smith thermal plasma model. The two GIS normalizations were fixed to have the same emission integral, as were the two SIS normalizations. The redshift of the cluster was taken to be 0.23. The abundance, column density, and temperature were left as free parameters giving a total of 5 free parameters. We fit this model to the 2 GIS data sets with free normalizations and found that the normalizations were essentially identical, as expected. This test was repeated for the 2 SIS data sets yielding the same result justifying tying the normalizations as described above.
The fit to all 5 data sets is not acceptable with a reduced $\chi^2 = 344.2$ for 311 degrees of freedom. The data and the best model fit are presented in the top panel of Fig. 1 and the residuals are shown in the bottom panel.

While the above analysis was not sensitive to any temperature structure in A2111, we measured the ICM temperature of the cluster in two regions, with radii 0-3' and 3-6'. Further dividing the regions was not practical due to the limited extent of the cluster compared to the XRT+GIS PSF and the limited counting statistics of the ASCA observation. The temperature measurement used a PSF modeling technique described in Markevitch (1996) and Takahashi et al. (1995). This technique has been successfully used in similar analyses for several relatively low redshift clusters (see references in Markevitch, Sarazin, & Henriksen 1997). Briefly, the PSPC image is used as a model surface brightness template which is convolved with the ASCA mirror effective area and PSF to produce model spectra in the two regions. The ROSAT image was flat fielded, background subtracted, and rotated to match the GIS roll angle. The PSPC energy range used is 0.5 - 2.0 keV and the emission measure is corrected to the ASCA energy band. Since the PSPC is used as a surface brightness template to get the EM for the spectral fits, a slightly higher band (0.5 - 2 keV) was used to better match the GIS and SIS. Channels for each data set are grouped to contain at least 20 counts. The model PSF, which is based on GIS observations of Cyg X-1 at various radii from the detector center (Takahashi et al. 1995), is increasingly uncertain at low energies so the minimum energy used was 1.5 keV to minimize this uncertainty. To maintain greater than approximately 20 counts in any fitted energy bin, the data were grouped to give energy bins of 1.5-2.5, 2.5-4., 4.-7. keV in the SIS and 1.5-2.5, 2.5-3., 3.-5., 5.-7., 7.-11 keV in the GIS. Markevitch (1996) discussed in detail various consistency checks performed in validating the use of the method for ASCA data.

Since the A2111 observation and the deep, blank sky observations used in the
background subtraction were taken at different times, their COR values are different. We thus subtracted the background using blank sky images, each at a specific COR value, weighted to the amount of source data obtained at that COR value. The SIS background image was normalized by exposure time. A 20% systematic error in the SIS and a 5% error in the GIS background normalization were included in the fitting procedure. The SIS error was estimated at 20% based on a day-to-day variation in the GIS background of \( \sim 20\% \) for a specific COR value. By using a composite background consisting of GIS observations with the same COR values as the data, the GIS background was better determined and the error in the normalization was estimated at 5% (Markevitch 1996 and references within). There errors were then added in quadrature with the random errors. Table 1 presents the resulting number of background subtracted counts in each of the regions from each detector integrated over the full energy band.

We simultaneously fitted the four spectra from each region using the Raymond & Smith model while fixing the abundance at the best fit value from the single region fit, 0.25 Solar. We fixed the column density at the measured 21 cm value, \( 1.9 \times 10^{20} \text{ cm}^{-2} \), because the data used, \( >1.5 \text{ keV} \), are insensitive to the exact value.

Confidence intervals on temperature were estimated by the following procedure. A Monte-Carlo simulation of the number of counts in each energy band of the spectra, assuming a Gaussian distribution of counts around the observed value, was carried out and the spectra were fitted to obtain the best-fit temperature. Two hundred simulated spectra were fit and the variance of the distribution of best-fitting temperatures was calculated to obtain the 90% confidence range. A systematic error of 5% each for the PSF and effective area are included in the error simulation.

The best fit models and GIS2 data are presented in Figs. 2 and 3 for the 0-3’ and 3-6’ regions respectively.
3. Results and Discussion

We present in Figs. 4 and 5 the exposure-corrected SIS and GIS contour maps. Both maps show an overall elongation of the cluster X-ray morphology. The X-ray intensity distribution in the SIS map is very clumpy, compared to that in the GIS map. Similar features also appear in the PSPC data. The statistical significance of individual features is marginal, however. But the overall clumpiness of the X-ray distribution is real, since the SIS and GIS maps were smoothed in the exactly same way to have the same noise level. The PSF of the ASCA X-ray telescopes (XRT) has a relatively sharp core (FWHM of ~50 arcsec) but broad, energy dependent wings which extend to a half-power diameter of 3 arcmin. The intrinsic spatial broadening of the SIS is negligible compared to that of the XRT. The GIS has its own PSF characterized by broad low energy wings which adds to the XRT PSF. Thus, the clumpy structure appears much more clearly in the SIS map. The clumpy X-ray morphology may arise from the presence of multiple components of the ICM. Assuming an approximate pressure balance, the temperature inhomogeneity could naturally result in large emission measure differences in the ICM, which is manifested in the X-ray emission.

The results from our spectral modeling are summarized in Table 2. The emission weighted temperature for the cluster derived from a joint fit of the ROSAT and ASCA data is 4.9 - 5.9 keV (90% limit), which overlaps the results reported by WUL based solely on the PSPC (2.1 - 5.3 keV). The 90% confidence range on the column density, 1.03 - 1.36×10^{20} cm^{-2} is slightly below that measured from 21 cm, 1.9×10^{20} cm^{-2}. However, refitting the model with the column density fixed at the Galactic value gives a $\chi^2$ is 378.2/312 degrees of freedom, an increase in $\chi^2$ of 33.4. The preference for a column density below Galactic for the single temperature component model may be due to the overall poor fit of an isothermal model.
Our spatial-spectral analysis of A2111 further suggests that the average temperature of 6.46±0.87 keV in the central region (r < 1 Mpc) of A2111 is significantly higher than 3.10±1.19 keV in its surrounding, r = 3 - 6’. A higher temperature in the central region is consistent with the results from simulations after a subcluster has passed through the core of the main cluster (Roettiger, Loken, & Burns 1993), supporting the hypothesis that A2111 is undergoing a merger. Using only the PSPC data, WUL found that if the column density is fixed at the Galactic value, the subcomponent has a higher temperature than the rest of the cluster. This is consistent with the heating in the ASCA temperature map. Thus, A2111 is the first intermediate redshift cluster which contains a large blue galaxy fraction for which the optical, X-ray imaging, and X-ray spectral data are all consistent with the interpretation of a merger.

As a test of the robustness of the ASCA PSF correction, Donnelly et al. (1998) applied two independent methods of correcting for the ASCA PSF (one of which was used for this paper) in analyzing the A1367 data. Similar features in the derived temperature maps were obtained using each methods.

The only cluster with a similar redshift for which a similar spatial-spectral study using ASCA data has been conducted, is the z = 0.2 cluster, A2163 (Markevitch 1996). In A2163, the temperature drops with radius out to 3 Mpc, consistent with a polytropic index (γ) of 1.9. The cluster atmosphere is apparently convectively unstable after a very recent major merger. The temperature profile for A2111 is less steep than A2163, the equivalent γ is = 1.45 (using the density parameters from WUL: β = 0.54 and core radius = 0.21 Mpc); perhaps this cluster has passed the stage of convective instability or involves less massive subclusters. Alternatively, a temperature drop with radius may reflect a more centrally concentrated gravitational potential of the cluster rather than shock heating from a merger. However, the case for A2111 being a merger candidate is strengthened by the spectral and
spatial results taken together.

The best fit abundance of A2111, 0.11 - 0.39 solar (90% confidence), is typical of low z clusters and is consistent with the studies of large samples (Allen & Fabian 1998; Mushotzky & Loewenstein 1997) which indicate that metallicity in galaxy clusters in essentially constant out to $z \sim 0.3$. A2111 is unlike the nearby clusters which show a similar abundance because it has a high frequency of star forming galaxies, while the nearby clusters do not. While increased star formation will increase the metallicity of the interstellar medium and subsequent enrich the intergalactic medium by a variety of processes, including ram-pressure and tidal stripping, the similarity in abundance argues against this episodic star formation having a significant effect on the overall metallicity of the cluster gas.

In conclusion, our ASCA data show that A2111 has an elongated and clumpy X-ray morphology as well as a relatively high temperature core, compared to the surrounding regions. These results, together with the apparent substructure observed in the ASCA and ROSAT observations, strongly suggest that the cluster is undergoing a merger, which is likely responsible for the observed large blue galaxy fraction of the cluster. Future X-ray observations will be necessary to study the relationship between possible element abundance gradients in the intergalactic medium and the blue galaxy distribution in the cluster.

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Table 1. ASCA Data

| Detector | Region | Counts | Exposure (sec) |
|----------|--------|--------|----------------|
| GIS 2    | 0-3'   | 644.5  | 23707          |
|          | 3-6'   | 402.8  |                |
| GIS 3    | 0-3'   | 533.4  | 23370          |
|          | 3-6'   | 335.9  |                |
| SIS 0    | 0-3'   | 494.0  | 13562          |
|          | 3-6'   | 294.0  |                |
| SIS 1    | 0-3'   | 350.4  | 14314          |
|          | 3-6'   | 217.6  |                |

Table 2. Spectral Modeling Results

| Region(s) | $\chi^2$/dof | kT(keV) | $n_H\text{cm}^{-2}$ | Abundance |
|-----------|--------------|---------|----------------------|-----------|
| 0-6'      | 344.8/311    | 5.38 $^{+0.50}_{-0.47}$ | 1.19 $^{+0.17}_{-0.16} \times 10^{20}$ | 0.25 $^{+0.14}_{-0.14}$ |
| 0-3'      | 8.6/17       | 6.46±0.87 | -                    | -         |
| 3-6'      | 9.4/17       | 3.10±1.19 | -                    | -         |
Fig. 1.— The data for the PSPC, GIS2, GIS3, SIS0, and SIS1 and best fit single component Raymond and Smith model are shown in the upper panel. The reduced $\chi^2$ is 1.11. $\chi^2$ vs. energy is plotted in the lower panel with the sign of the residual.

Fig. 2.— The best fit model, background subtracted counts and error are shown in each of the energy bins fit for the G2 in the inner, 0-3′ region of the cluster. The triangles are model counts while the data is shown as a histogram with 1σ error bars. The errors are the statistical and systematic errors (effective area, PSF, and background normalization) added in quadrature. This is representative of the data quality and the goodness of fit since the spectrum from the G3, SIS0, and SIS2 were also fit but are not shown.

Fig. 3.— The same as is shown in figure 2 for the outer, 3-6′ region of the cluster.

Fig. 4.— The exposure corrected SIS intensity map is adaptively smoothed with a Gaussian function, adjusted to achieve a uniform signal-to-noise of 6. The contour levels are 2σ higher than the next lower one and have values of: 1.6, 2.1, 2.8, 3.8, and $5.0 \times 10^{-3}$ counts arcmin$^{-2}$ sec$^{-1}$. The background level is $1.2 \times 10^{-3}$ counts arcmin$^{-2}$ sec$^{-1}$.

Fig. 5.— The GIS map is prepared similarly to the SIS map in figure 4. The contour levels have values of: 2.0, 2.7, 3.6, 4.7, 6.3, 8.4, 11.2, 14.9, and $20.0 \times 10^{-4}$ counts arcmin$^{-2}$ sec$^{-1}$. The background level is $1.5 \times 10^{-4}$ counts arcmin$^{-2}$ sec$^{-1}$. 

