RXTE Observations of A2256

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ABSTRACT

The cluster of galaxies A2256 was observed by the PCA and HEXTE experiments aboard the RXTE satellite during the period July 2001 - January 2002, for a total of $\sim$343 ks and $\sim$88 ks, respectively. Most of the emission is thermal, but the data analysis yields evidence for two components in the spectrum. Based on statistical likelihood alone, the secondary component can be either thermal or power-law. Inclusion in the analysis of data from ASCA measurements leads to a more definite need for a second component. Joint analysis of the combined RXTE-ASCA data sets yields $kT_1 = 7.9^{+0.5}_{-0.2}$ and $kT_2 = 1.5^{+1.0}_{-0.4}$, when the second component is also thermal, and $kT = 7.7^{+0.3}_{-0.4}$ and $\alpha = 2.2^{+0.9}_{-0.3}$, if the second component is fit by a power-law with (photon) index $\alpha$; all errors are at 90\% confidence. Given the observed extended regions of radio emission in A2256, it is reasonable to interpret the deduced power-law secondary emission as due to Compton scattering of the radio producing relativistic electrons by the cosmic microwave background radiation. If so, then the effective, mean volume-averaged value of the magnetic field in the central 1\textdegree region of the cluster – which contains both the ‘halo’ and ‘relic’ radio sources – is $B \sim 0.2^{+1.0}_{-0.1}$ $\mu$G.

Subject headings: Galaxies: clusters: general — galaxies: clusters: individual (A2256) — galaxies: magnetic fields — radiation mechanisms: non-thermal
1. Introduction

The improved spatial resolution and wider spectral coverage of current X-ray satellites provide further motivation for a less simplified description of the properties of intracluster (IC) gas, and the consideration of additional cluster phenomena, such as non-thermal (NT) processes. An obvious generalization of the simple isothermal model for the gas is made by allowing for a more realistic temperature structure. This has, in fact, been considered in quite a few analyses of cluster X-ray data, leading to clear evidence for radial variation of the gas temperature in some clusters (e.g., Honda et al. 1996, Watanabe et al. 1999, Markevitch et al. 1998). Somewhat less obvious is the need to include a NT component in the X-ray spectra of (at least some) clusters. Such emission has long been predicted (e.g., Rephaeli 1977; for a review, see Rephaeli 2001), and recent observations give appreciable evidence for its likely detection in a few clusters.

It is of considerable interest to know if IC gas within the central (\(\sim 1\) Mpc) cluster region is non-isothermal. In addition to insight gained from the form of the temperature profile on physical processes in the gas, and its cosmological evolution, knowledge of the density and temperature distributions is clearly very important not only for the determination of basic cluster properties, such as the gas and dark matter masses, but also for the use of phenomena in clusters to determine cosmological parameters (e.g., from measurements of the Sunyaev-Zeldovich effect and gravitational lensing). On the other hand, measurement of a NT spectral component – especially in clusters in which extended regions of radio emission have been measured – is essential for the characterization of NT quantities and phenomena in clusters, such as the strength and morphology of magnetic fields, densities and energy content of relativistic electrons and protons, and the interaction of these particles with the gas.

Measurements with RXTE and BeppoSAX satellites are particularly useful in the search for NT spectral components in cluster spectra. First attempts to detect NT emission from a few clusters with the HEAO-1, CGRO, and ASCA satellites were unsuccessful (Rephaeli, Gruber & Rothschild 1987, Rephaeli & Gruber 1988, Rephaeli, Ulmer & Gruber 1994, Henriksen 1998). The improved sensitivity and wide spectral band of the RXTE and BeppoSAX seem to have resulted in the detections of NT emission in Coma (Rephaeli, Gruber & Blanco 1999, Fusco-Femiano et al. 1999, Rephaeli & Gruber 2002), and A2319 (Gruber & Rephaeli 2002). A NT component was also deduced in the BeppoSAX spectra of A2256, A119, and A754 (Fusco-Femiano et al. 2002). Here we report the results from a long RXTE observation of A2256, possibly a merging cluster with complex X-ray (Sun et al. 2002) and radio (Giovannini, G., et al. 1999) morphologies.

2. Observations and Data Reduction

A2256 is a rich radio and X-ray bright cluster at \(z = 0.0581\), with complex morphology. Extended radio emission from A2256 was measured by Bridle & Fomalont (1976), Bridle et al. (1979), Giovannini et al. (1999), and most recently by Clarke & Ensslin (2001). In addition to emission from several strong radio sources in the central region of the cluster, there is a centrally located extended emission region, as well as regions of extended emission (located in the northern side of the cluster) that are thought to be radio relics. The
centrally located emission is characterized by a spectral (energy) index $\alpha_C \sim 2.0$ in the $\sim 1.4 - 5$ GHz band, while the main relic has a flatter spectrum with index $\alpha_R \sim 1.0$ (Clarke & Ensslin (2001)).

The cluster was observed by most previous X-ray satellites, most recently by XMM and Chandra. Several emission regions were resolved by Chandra, yielding further evidence for the view that the cluster is undergoing a merger (Sun et al. 2002). These measurements also indicate considerable variation of the temperature in the central region, with a mean value of $\sim 6.7$ keV, but with hotter ($\sim 10$ keV) and colder ($\sim 5$ keV) regions. Of particular interest to us here are BeppoSAX observations with the MECS and PDS detectors: From an analysis of these measurements Fusco-Femiano et al. (2000) deduced the presence of a NT spectral component at a $\sim 4.6\sigma$ confidence, with a (photon) index roughly in the range $0.3 - 1.7$, in addition to the main thermal component with a temperature of $7.4 \pm 0.2$ keV. A short, $\sim 30$ ks, observation of A2256 by RXTE yielded only an upper limit on a NT flux, $\sim 2.3 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 30 keV, and a lower limit of $\sim 0.36 \mu$G on the mean magnetic field (Henriksen 1999).

A2256 was observed with RXTE for a nominal total observation time of 400 ks between July 2001 and January 2002. After the application of data selection criteria recommended by the RXTE project, 343 ks of screened data were collected with the PCA in 111 one-orbit observations, spaced irregularly over the seven-month campaign. For the HEXTE, which beam-switches observations with 32-second dwells between source and background fields, and has in addition about 50% detector dead time, the net observation time was 88 ks with each of the two clusters. On time scales of two weeks or longer, the limit to variability observed with PCA was less than 1%. Because of the much lower signal to background, corresponding HEXTE limits to variability are larger, about 20%.

Following project practice at the time, PCA data were collected in two of the 5 detectors. One of these, PCU 0, had lost its propane guard layer by the time of the A2256 campaign, but the net flux and spectral shape differed negligibly from those obtained with PCU 2, which indicates that the project has very successfully produced modifications for the response matrix and background estimation tool for PCU 0.

ASCA observations of A2256 have been archived for several observations, the longest of which was 36 ks on 22 July 1993, and the next-longest, 26 ks, was carried out on 8 April 1993. Standard archival GIS and SIS spectra and matrices were provided. Preliminary spectral study of the two observations gave very similar best fits of an isothermal spectral model. However, there was large non-statistical scatter of about 10% in the SIS data of the longer July observation. For this reason the July data were considered less reliable, and the April data alone were employed in the joint analysis with the RXTE data.

### 3. Spectral Analysis

The combined ASCA and RXTE data provide spectral information on the rather broad energy range of 0.6 to 100 keV. The four ASCA detectors, two PCA detectors and two HEXTE clusters, with thousands of energy channels combined, rather heavily oversample this range. After pilot spectral studies revealed no evidence for sharp features in the raw data, we proceeded to reduce the spectral oversampling to a reasonable level by com-
bining counts from similar detectors and by 
summing counts in adjacent spectral chan-
nels into groups whose energy width was set 
at about one half of the FWHM detector en-
ergy resolution at the given energy. Approp-
riate response matrices were also generated, 
and standard ftools were employed. The final 
spectral set contained 44 energy bands for the 
ASCA data and 44 for the RXTE data.

An additional systematic error of 0.5% per 
ergy channel was added in quadrature to 
the statistical error of the PCA data (e.g 
Wilms et al. 1999). No systematic error 
was used with HEXTE data, and 2% sys-

tematic error was used for both the ASCA 
SIS and GIS data. Spectral analysis was per-
formed separately on the RXTE data, jointly 
on the RXTE and ASCA data sets, and in a 
restricted analysis, also on just the HEXTE 
data above 15 keV.

Spectral models were limited to three cases: 
an isothermal thermal spectrum (based on a 
Raymond-Smith emission code), two-temperature 
thermal, and a thermal plus a power-law. The 
RXTE data by themselves provide only weak 
evidence of the need for an extra component 
beyond isothermal. The $\chi^2$ of 46.8 (40 de-
grees of freedom [dof]) for an isothermal fit 
is acceptable; however inclusion of a second 
component reduces $\chi^2$ modestly to 40.2 (38 
dof) with an extra 0.9 keV thermal compo-
nent, or to 40.4 (38 dof) with an extra power-

law, whose best-fit photon index is a rather 
steep 4.0. For four “interesting” parameters, 
the change in $\chi^2$ (Lampton et al. 1976) gives 
90% error limits for the 4-20 keV power-law 
flux of $(0.5 - 4.8) \times 10^{-11}$ erg-cm$^{-2}$ s$^{-1}$. The 
temperature for the main spectral component 
is in the range $\sim 7.7 - 7.9$ keV for all three 
cases, with formal (1$\sigma$) errors of $\sim 0.1 - 0.3$

By fitting jointly with the ASCA data 
one obtains much more decisive results. An 
isothermal fit is ruled out both by a high 
$\chi^2$ of 155.4 for 82 dof, and by much im-
proved fits with a second component, $\chi^2 = 
96.9$ with a second thermal at 1.4 keV, and 
$\chi^2 = 104.5$ with a power-law component with 
best-fit photon index 2.2. For both of these 
cases the $\chi^2$ is somewhat high for 80 dof, 
but this may reflect slight under-correction 
for systematic errors of background subtrac-
tion and the response matrices. With four in-
teresting parameters (kT, abundance, power-

law flux and index) 90% error bounds for the 
power-law flux, now given for the interval 0.8– 
40 keV, are $(2.5 - 19.1) \times 10^{-11}$ erg-cm$^{-2}$ s$^{-1}$. 
Best fit parameters and 90% confidence errors 
for the joint fits to the three spectral models 
are listed in Table 1. (For each combination 
of detectors the energy range for the power-

law flux has been chosen to provide parame-
ter and error estimates which are nearly inde-
pendent of the other parameters. This is ap-
proximately equal to the energy span of the 
joint data set.) In Figure 1, we show the spec-
trum of the best-fit isothermal plus power-law 
model (data and model components are dis-
played) in the upper panel, and residuals to 
the fit in the lower panel.

Most of the statistical weight in parame-
ter estimation comes from data at the lowest 
energies. Of special interest for the thermal 
plus power-law case is whether the HEXTE 
data favor the presence of a power-law com-
ponent. We tested the HEXTE data against 
a model in which the thermal parameters are 
set by the joint fit. With no second com-
ponent the HEXTE data give a marginally ac-
cetable ($P < 0.06$) $\chi^2$ of 27.1 for 19 dof. 
When the power-law flux is allowed to float 
to a best fit value the $\chi^2$ is dropped by 9.3 to
Allowing also the index to vary gives a best-fit value of 1.8, which – within errors – is consistent with the value of 2.2 obtained in the joint fit. For one interesting parameter, the error bounds on the 15–40 keV flux are $(1.2 - 4.3) \times 10^{-12} \text{ erg-cm}^{-2} \text{ s}^{-1}$.

The NT 20-80 keV flux (of interest for a direct comparison with the BeppoSAX results) computed from the best-fit parameters resulting from the full (ASCA, PCA, and HEXTE) dataset is $(0.7 - 8.6) \times 10^{-12} \text{ erg-cm}^{-2} \text{ s}^{-1}$, formally significant at the 2.9 $\sigma$ level. The significance of this flux is lower if HEXTE data are not included in the analysis. Note also that similar but less significant results are obtained when we first find the (poorly determined) best-fit isothermal to the PCA and ASCA data, and then determine a net high energy flux from the HEXTE data (a procedure adopted in the corresponding BeppoSAX MECS/PDS analysis). Doing so results in a 20-80 keV flux error bounds of $(0.2 - 8.0) \times 10^{-12} \text{ erg-cm}^{-2} \text{ s}^{-1}$, formally significant at 2.2 $\sigma$.

Fusco-Femiano et al. (2000), reporting results of A2256 measurements with the BeppoSAX satellite, have claimed detection of a 20-80 keV NT flux of $1.2 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$ at 4.6$\sigma$ significance. Assuming normal statistics we convert this to 90% error bounds of [0.74, 1.66] in the same units. Using the joint RXTE/ASCA dataset we obtain a comparable best-fit value for 20-80 keV flux of 0.26 and 90% confidence error bounds of [0.01, 0.79] in these units. Thus, while our best fit value is a factor of 4.6 smaller than that obtained by Fusco-Femiano et al. (2000), it is not in strong conflict. Fusco-Femiano have discussed the possibility that the radio and X-ray NT components are complex, with more than one index. In this case, our joint RXTE/ASCA NT flux may be sensitive largely to the steeper index visible to ASCA. Thus a better comparison may be with our HEXTE-only analysis. Indeed, this analysis corresponds rather closely to the approach adopted in the analysis of the BeppoSAX data. The HEXTE result gives a best-fit 20-80 keV flux of $4.3 \cdot 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$ and a 90% confidence error interval of $(0.3 - 10.0) \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$. While smaller than the reported BeppoSAX value by almost a factor of three, this result is not in a great conflict.

4. Discussion

A2256 is the third cluster with extended regions of radio emission that has been observed by the RXTE for more than 100 ks. The results of the analysis reported here are qualitatively similar to those we have previously reported on Coma (Rephaeli, Gruber & Blanco 1999, Rephaeli & Gruber 2002) and A2319 (Gruber & Rephaeli 2002). In all three clusters the RXTE measurements yield evidence that the spectra in the combined PCA and HEXTE bands contain a secondary component which is either thermal or power-law. In the case of A2256 this evidence is much stronger when the ASCA data are included in the analysis. However, the spectral analysis alone does not yield sufficient statistical preference for the nature of the second component. We invoke other considerations in an attempt to determine the nature of this component.

Consider first thermal emission from IC gas at a lower temperature than that of the main emission component, as listed in Table 1. That deep observations over a wide spectral range require a more realistic emission model than a single temperature gas is, of
Table 1: Results of the spectral analysis

| Parameter                     | Single Thermal | Double Thermal | Thermal + Power-law |
|-------------------------------|----------------|----------------|---------------------|
| $kT_1$ (keV)                  | 7.66 ± 0.12    | 7.91^{+0.38}_{-0.20} | 7.67^{+0.28}_{-0.39} |
| $kT_2$ (keV)                  |                | 1.45^{+0.98}_{-0.35}    |                     |
| $\alpha$                      |                |                | 2.16^{+0.86}_{-0.30}    |
| Secondary flux fraction       |                |                |                     |
| 0.5-2 keV                     | 0.084^{+0.069}_{-0.035} |                |                     |
| 2-10 keV                      | 0.015^{+0.130}_{-0.060} |                |                     |
| 0.8-40 keV                    |                |                | 0.101^{+0.083}_{-0.077} |
| Abundance (solar)             | 0.194±0.018    | 0.208±0.028    | 0.218±0.030         |

All quoted errors are at the 90% confidence level.

course, not unexpected. Indeed, recent mapping of the temperature in the central $\sim 1/2$ Mpc ($H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$) radial region of A2256 by Chandra shows an emitting region (in the NE side of the cluster) with a fractional projected area of roughly $\sim 1/10$ where the gas temperature is $kT \sim 4$ keV. This value is still significantly higher than the value at the upper end of the 90% significance interval, $kT_2 \simeq 2.4$ keV. Emission at this temperature with a fractional 0.5-2 keV flux contribution of more than $\sim 5\%$ would have been measured, especially by ROSAT whose PSPC detector energy band matched this spectral range. Even so, we cannot formally rule out (also because of differences in collecting areas of the various detectors) the possibility that the second component is thermal at the above (relatively) low temperature. This is particularly so given the more realistic expectation that a two-temperature gas model is just a simplified representation of a more realistic continuous temperature distribution, as we have previously argued in the interpretation of RXTE measurements of Coma and A2319 (Rephaeli, Gruber & Blanco 1999, Gruber & Rephaeli 2002, Rephaeli & Gruber 2002).

The main motivation for selecting A2256 for the long RXTE observation is, of course, the presence of extended regions of radio emission in the cluster. We first note that since significant emission from an AGN in the FOV is unlikely – emission from QSO 4C +79, near the edge of the RXTE FOV, was estimated to be negligible (Fusco-Femiano 2000) – and given no evidence for flux variability, we naturally associate the emission with the cluster. As is well known (e.g., Rephaeli 1977), Compton scattering of the radio producing relativistic electrons off the cosmic microwave background boosts photon energies to the X-ray region. From the measured radio and X-ray fluxes the magnetic field can then be inferred. However, in the case of A2256 this is not straightforward because of the complex structure of the radio emission which is dominated by a few extended sources with spectral (energy) indices in the wide range, $\sim 0.3-1.1,$
with substantial errors. Given no clear expectation on the predicted spectral index of the NT X-ray emission – and the complex spatial morphology of the radio emission – we use the measured total flux at 1.4 GHz, 397 mJy (Giovannini et al. 1999), and the deduced range of the X-ray power-law index to compute an effective value of the magnetic field across the large field of view of the RXTE, which includes all the dominant radio sources. Doing so, we determine the relatively wide 90% confidence range for the mean, volume-averaged field, $B_{rx} \simeq 0.2^{+1.0}_{-0.1} \mu G$. (The very high value at the upper end of this interval results from our conservatively estimated lower limit on the flux.) We emphasize that this value has only limited meaning: Since there is no spatial information on the power-law X-ray emission, the implicit assumption made here – and in all similar analyses of cluster magnetic fields from radio and X-ray measurements – is that these emissions occur over the same volume. If so, we can also estimate the mean relativistic energy density within the emitting region, radius $R$, by integrating the electron energy distribution over energies in the observed radio and X-ray bands. Doing so, we obtain $\rho_e \simeq 5^{+1.0}_{-1} \times 10^{-14} (R/1 \text{Mpc})^{-3}$ erg cm$^{-3}$.

Although the estimated mean field has limited meaning, it is comparable to the values we deduced for the mean field in Coma (Rephaeli & Gruber 2002) and A2319 (Gruber & Rephaeli 2002). Values of the field deduced from radio and X-ray measurements, $B_{rx}$, are generally much lower than those obtained from Faraday rotation measurements (e.g., Clarke, Kronberg, and Böhringer 2001, and the review by Carilli & Taylor 2002) of background radio sources seen through clusters, $B_{fr}$. The mean strength of IC fields has direct implications on the range of electron energies that are deduced from radio measurements, and therefore on the electron (Compton-synchrotron) loss time. The higher the electron energy, the shorter is the energy loss time; a short loss time would have immediate consequences on relativistic electron models (e.g., Rephaeli 1979, Sarazin 1999, Ensslin et al. 1999, Brüggen et al. 2001, Petrosian 2001). Reliable estimates of the field are therefore quite essential.

Differences between $B_{rx}$ and $B_{fr}$ could, however, be due to the fact that the former is a volume-weighted measure of the field, whereas the latter is an average along the line of sight, weighted by the electron density. In addition, the field and relativistic electron density would generally have different spatial profiles that could lead to very different spatial averages (Goldshmidt & Rephaeli 1993). Various statistical and physical uncertainties in the Faraday rotation measurements, and their impact on deduced values of IC fields, were investigated recently by Newman, Newman & Rephaeli (2002); their work strengthens the conclusion that a simple comparison of values of $B_{rx}$ and $B_{fr}$ is meaningless. More importantly, Rudnick & Blundell (2003) have recently shown very clearly that the estimation of cluster fields from Faraday rotation measurements is very uncertain due to the inclusion in the sample of cluster radio sources whose large contributions to the rotation measures originate from their intrinsic fields, not the cluster-wide fields that they were presumed to sample.

RXTE and BeppoSAX measurements yielded evidence for NT X-ray emission in 5 clusters. It is important to continue the search for NT emission in other clusters with extended regions of radio emission. In particular, it is
essential to obtain spatial information on this emission. This will likely be done for the first time by the IBIS instrument on the INTEGRAL satellite during a planned 500 ks observation of the Coma cluster. With the moderate $\sim 12'$ spatial resolution of IBIS, it should be feasible to determine the location of the region where the secondary emission is produced in this cluster.

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Fig. 1.— Joint RXTE-ASCA (photon) spectrum of the A2256 with folded Raymond-Smith ($kT \approx 7.7$) and power-law (index = 2.2) models. ASCA data are shown in green and blue circles; crosses are PCA data, and HEXTE data points are marked with red circles (with 68% error bars). The total fitted spectrum is shown with a histogram, while the lower histogram shows the power-law portion of the best fit. The quality of the fit is demonstrated in the lower panel, which displays the observed difference normalized to the standard error of the data point.