A BeppoSAX OBSERVATION OF THE IC 1262 GALAXY CLUSTER

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ABSTRACT

We present an analysis of BeppoSAX observations of the IC 1262 galaxy cluster and report the first temperature and abundance measurements, along with preliminary indications of diffuse, nonthermal emission. By fitting a 6' (~360 h_c/1 kpc) region with a single Mewe-Kaastra-Liedahl model with photoelectric absorption, we find a temperature of 2.1–2.3 keV and an abundance of 0.45–0.77 (both 90% confidence). We find that the addition of a power-law component provides a statistically significant improvement (F-test = 90%) to the fit. The addition of a second thermal component also improves the fit, but we argue that it is physically implausible. The power-law component has a photon index (Γ_X) of 0.4–2.8 and a nonthermal flux of (4.1–56.7) x 10^-5 photons cm^-2 s^-1 over the 1.5–10.5 keV range in the Medium Energy Concentrator Spectrometer detector. An unidentified X-ray source found in the ROSAT High Resolution Imager observation (~0′/9 from the center of the cluster) is a possible explanation for the nonthermal flux; however, additional evidence of diffuse, nonthermal emission comes from the NRAO VLA Sky Survey and the Westerbork Northern Sky Survey radio measurements, in which excess diffuse radio flux is observed after point-source subtraction. The radio excess can be fitted to a simple power law with a spectral index of ~1.8, which is consistent with the nonthermal X-ray emission spectral index. The steep spectrum is typical of diffuse emission, and the size of the radio source implies that it is larger than the cD galaxy and not due to a discreet source.

Subject headings: galaxies: clusters: individual (IC 1262) — radiation mechanisms: nonthermal — X-rays: galaxies

1. INTRODUCTION

Since the discovery of nonthermal emission in galaxy clusters in the form of a radio halo in Coma (Willson 1970), there has been a debate about the nature of its origin. Jaffe (1977) demonstrated that although active galactic nuclei (AGNs) in clusters could explain the numbers of relativistic electrons observed, this model could not explain the ability to diffuse through the entire cluster within their short (~10^8 yr) radiative lifetime. Holman, Ionson, & Scott (1979) proposed that primary electrons are able to diffuse at velocities greater than the Alfvén velocity and therefore could diffuse from point sources throughout the intracluster medium (ICM) within their radiative lifetime. There has also been some discussion that secondary electrons could explain the diffuse relativistic electron population. Secondary electrons are produced in proton-proton interactions from a population of relativistic protons (Dennison 1980), which have a relatively long radiative lifetime (~10^10 yr; Blasi 2001). The majority of authors, however, have looked to in situ reacceleration models from MHD turbulence or shocks (Eilek & Henriksen 1984, for example) to explain diffuse nonthermal emission from clusters. Mergers are the most popular theory for the origin of these shocks, since they provide the energy needed to produce a radio halo (Tribble 1993; Burns et al. 1994; Burns 1998) and are able to transport electrons via bulk flows (Roettiger, Burns, & Stone 1999).

Rephaeli (1979) correlated synchrotron emission to X-ray emission by demonstrating that cosmic microwave background photons inverse Compton scatter (ICS) off relativistic electrons and emerge in the X-ray regime. The relationship between the X-ray and radio flux is determined by the strength of the cluster magnetic field. With only ~30 clusters known to have radio halos (Giovannini & Feretti 2000 and references therein), three hot, rich clusters, Coma (Fusco-Femiano et al. 1999), A2256 (Fusco-Femiano et al. 2000), and A2199 (Kaastra et al. 1999), and one group, HCG 62 (Fukazawa et al. 2001), with detected nonthermal X-ray emission, it is difficult to constrain the current models. Detection of nonthermal emission in hot clusters is complicated because the X-ray emission is dominated by thermal emission in the 0.5–25 keV energy band, which is why the Phoswich Detection System (PDS) has been required to make nonthermal X-ray detections in hot clusters. In cool clusters, such as IC 1262 (kT ~ 2 keV), any nonthermal emission should be detectable in the 1.5–10.5 keV range and observable in the Medium Energy Concentrator Spectrometer (MECS), which unlike the PDS has spatial capabilities. Therefore, cool clusters provide an opportunity to add additional constraints, because the spatial information from the MECS can be used to constrain the regions of nonthermal emission and reduce the chances of contamination by AGNs.
The IC 1262 galaxy cluster (also ZwCl 1728.5+4353) is a poor cluster of galaxies at a redshift of $z = 0.0343$ (Colless et al. 2001), so that an angular distance of 1' corresponds to $60 \ h_{50}^{-1}$ kpc. The cluster is so named because it is dominated by the X-ray bright cD galaxy IC 1262 ($z = 0.0328$; Wegner et al. 1999). The cluster was observed by the HRI in 1997 March for $\sim 26$ ks and BeppoSAX in 1999 February for $\sim 100$ ks. Trinchieri & Pietsch (2000) analyzed the HRI data, mainly focusing on the cD galaxy.

Throughout this paper, we assume a Hubble constant of $H_0 = 50 \ h_{50}$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = \frac{1}{2}$. Quoted confidence intervals are at a 90% level, unless otherwise specified.

2. OBSERVATIONS AND METHODS

In order to produce a smoothed image from the MECS data, we first needed to create an exposure map. The SAX-DAS program EFFAREA uses a point-source ancillary response file (ARF) and a surface brightness profile (SBP) to produce an MECS ARF for a concentric, on-axis region of radially symmetric, extended emission. See Fiore, Guainazzi, & Grandi (1999) for details about this procedure. We obtained an on-axis point-source ARF from the Italian Space Agency (ASI) Web site and used the HRI data to create an SBP. Using EFFAREA, we created 12 ARFs for concentric regions with a width (inner to outer radius) of $0'5$ (approximately one-half of the 50% power radius [PR$_{50}$] of the MECS [1'2 at 6.4 keV; Fiore et al. 1999]). We assumed a linear response between channel number and energy bin and used the 12 concentric ARFs to create an exposure map for a circular region with a 6' radius. We wrote an algorithm based on the detector and sky pixels of the MECS2 source data to transform the MECS2 background events data from detector pixels to sky pixels. This algorithm produced an error of no more 3 pixel sky coordinates for the MECS2 source data, corresponding to an error of $\leq 0'4$, which is much smaller than the MECS PR$_{50}$ of 1'2 at 6.4 keV (Fiore et al. 1999). We created a smoothed X-ray flux map (Fig. 1) from the MECS2 events data (limited to the 1.5–10.5 keV range), using the corrected MECS2 background file (blank sky, taken at high Galactic latitude) and ARF-created exposure map. The 6' circular region contains the majority of cluster X-ray emission, while avoiding problems associated with the beryllium window support structure (Boella et al. 1997), and also limits the number of objects from the Faint Images of the Radio Sky at Twenty cm (FIRST) survey (White et al. 1997) in our extraction region to seven. Figure 1 also includes contours from the NRAO VLA Sky Survey (NVSS) data (Condon et al. 1998), which were smoothed with a Gaussian equal to the beamwidth of 45'', giving a resolution of $\sim 64''$, and the Digital Sky Survey (DSS) image of the cluster.

We obtained BeppoSAX Low Energy Concentrator Spectrometer (LECS), MECS2, and MECS3 cleaned event files from the ASI Web site and extracted spectral files from these source event files. We used the 6' on-axis spectral background files provided at the ASI Web site. Using the procedure described above, we created an MECS ARF for a 6' region of extended emission using EFFAREA. We used the on-axis redistribution matrix file (RMF) available for the MECS at the ASI Web site.

In the case of the LECS, we created an ARF and an RMF by considering our extended region to be numerous point sources and using a procedure similar to Ettori et al. (2000). The program LEMAT creates an ARF and an RMF for off-axis point-source observations of the LECS. We used LEMAT to create ARFs and RMFs for $\sim 45$ regions with

![Fig. 1.—DSS image of IC 1262 with MECS2 X-ray contours (blue lines), NVSS radio contours (red lines), and the 6' extraction region (black lines). Contour levels are 0.5, 1.0, 1.5, 2.0, 2.5, and $3.0 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$. Radio contours are 1.35, 2.70, 4.50, and 6.30 mJy beam$^{-1}$. Numbered crosses represent the seven reported FIRST sources in the 6' region.](image)
18 or more counts and then created a count-weighted ARF and RMF for the entire region.

Since the MECS2 and MECS3 extraction regions are identical, we fitted them with all components tied. However, since they have different responses, we fitted them as separate files rather than merging them. Normalization cross-calibration between the MECS2 and MECS3 is generally good (~3%) according to the ASI Web site but varies between the LECS and MECS depending on the position of the centroid (Fiore et al. 1999). We therefore kept the normalizations between the LECS and MECS untied, even though the extraction regions were identical.

We used the HRI to determine the X-ray flux from the seven FIRST sources within our 6′ extraction region. Since we were looking for point sources in a region with extended X-ray emission, it was important to subtract both X-ray background and local diffuse emission. For our seven FIRST sources, we used 8″ regions to determine the source count rate. In order to determine the proper background plus diffuse emission, we extracted seven 8″ regions that were the same distance from the center of the diffuse emission as the source region. The one exception to this was the cD galaxy, which is very close to the center of the emission (~2″; see Fig. 1, FIRST source 1). In order to determine the background and diffuse emission in the vicinity of this source, we used six 8″ regions adjacent to the 8″ source region. Unfortunately, there are no detections above the 3σ level in the HRI for any of the FIRST sources, so the HRI cannot provide constraints on their X-ray flux.

We also used the HRI to identify possible X-ray sources that had not been detected in the current radio observations (i.e., radio-quiet AGNs). Using algorithms to determine point sources in diffuse regions can be problematic, because it is difficult to account for the diffuse emission. Since we are looking for significant fluctuations in a field that is ~10⁶ square pixels, significance means ≳1 in 10⁶, which is ~5σ. Therefore, we argue that any identifiable X-ray source should be visible above the X-ray background and diffuse emission. In fact, we identified the same three sources identified by Trinchieri & Pietsch (2000), only one of which (identified by Trinchieri & Pietsch 2000 as USNO-A1.0 source U1275-09534024) is in our 6′ extraction region. Since this source is close to the center of the diffuse emission (~0′9), we used six regions adjacent to our extraction region to determine the X-ray background plus local diffuse emission behind this source.

3. RESULTS AND ANALYSIS

We fitted the spectra with multiple-component models (Table 1). Figure 2 shows the plot of the single Mewe-Kaastra-Liedahl (MEKAL; Mewe, Gronenschild, & van den Oord 1985; Mewe, Lemen, & van den Oord 1986; Kaastra 1992; Liedahl, Osterheld, & Goldstein 1995) fit. Residuals are visible in the high end of the MECS data. Although a two-component MEKAL model gives the best fit to the data, the high-temperature component is unconstrained, and the two temperatures overlap within the 90% confidence range, meaning that at the 90% confidence level, this model is consistent with a single temperature. In addition, by examining the temperature-luminosity relationship found by Horner et al. (2000), we find that the high-temperature component produces a luminosity not consistent with its best-fit temperature. Our two-component MEKAL model gives a luminosity of (1.1—31.9) × 10³⁰ h₉⁵⁻² ergs s⁻¹ for the best-fit temperature of 2.88 keV, which is well below the luminosity of (1.6—2.0) × 10³⁰ h₀⁵⁻² ergs s⁻¹ predicted by Horner et al. (2000) for this temperature. Only the best-fit temperature is considered, rather than the 90% confidence range, because the 90% upper limit is unconstrained and the 90% confidence lower limit overlaps the low-temperature component.

| Model                        | kT₁ (keV) | Abundance | kT₂ (keV) | Γ_X | n_H (10²⁰ cm⁻²) | χ²/dof |
|------------------------------|----------|-----------|----------|-----|----------------|--------|
| MEKAL                        | 2.23±0.09 | 0.60±0.17 | ...      | ... | 4.1±14         | 239.6/188 |
| MEKAL + MEKAL                | 2.88±0.12 | 0.45±0.18 | 1.29±0.65 | ... | 4.7±13         | 230.9/185 |
| MEKAL + power law            | 1.94±0.15 | 0.69±0.22 | ...      | 1.7±11 | 4.4±15         | 231.5/185 |
| MEKAL + power law            | 2.23±0.12 | 0.75±0.29 | ...      | 2.8a | 4.0±14         | 233.2/186 |

* Power law frozen at 2.8.
The addition of a power-law component to the data gives a similar improvement to the fit ($F$-test probability $= 90\%$ that a power law is needed; Fig. 3) and gives a thermal luminosity of $(2.2^{+51.6}_{-5}) \times 10^{42} \, h_{50}^{-2} \, \text{ergs s}^{-1}$ for the best-fit temperature of $1.95 \, \text{keV}$, which is consistent with the results of Horner et al. (2000) $[\sim (46-52) \times 10^{42} \, h_{50}^{-2} \, \text{ergs s}^{-1}]$. The best-fit temperature is used in comparing the two models (considering that a temperature range will only extend the error bars so that the two luminosities will still overlap). Our nonthermal detection in the MECS is at the 2.78 $\sigma$ level and gives $\Gamma_X = 0.4-2.8$ with a flux of $(3.4-25.7) \times 10^{-13} \, \text{ergs cm}^{-2} \, \text{s}^{-1}$ over 1.5–10.5 keV. The large range of flux is because of the large uncertainty in both $\Gamma_X$ and the normalization.

In order to confirm that the nonthermal emission is diffuse, we used the HRI observation to try to determine the X-ray flux from point sources in our 6$\arcmin$ extraction region. As discussed earlier, the seven FIRST sources were not detected in the HRI, so we have no constraint on their X-ray emission. U1275-09534024, however, was detected at the $\sim 5 \sigma$ level in the HRI, but the lack of spectral information in the HRI data precludes the analysis of U1275-09534024’s spectrum. We assumed a power law with $\Gamma_X$ equal to our best-fit value of 1.7, in order to see if it is a possible source of our nonthermal detection. Without an identification, the possibility exists that this source is variable in the X-ray. Since it is impossible to resolve it with the LECS or the MECS to determine its X-ray emission during the BeppoSAX observation, we can only assume that its X-ray flux does not vary above the 3 $\sigma$ level. We subtracted the X-ray background and diffuse emission from the HRI observation and determined that the flux from U1275-09534024 is $(0.1-10.2) \times 10^{-13} \, \text{ergs cm}^{-2} \, \text{s}^{-1}$ over 1.5–10.5 keV. Although this result falls within the 90% confidence range of the measured nonthermal emission, we point out that Trinchieri & Pietsch (2000) noted that U1275-09534024’s X-ray–to-optical flux ratio is only marginally consistent with an AGN and is more consistent with a star. Therefore, it may not be producing any nonthermal emission at all.

4. DIFFUSE NONTHERMAL EMISSION

Using the ROSAT HRI observation of IC 1262 and assuming our best-fit $\Gamma_X$ of 1.7, we determine that U1275-09534024 can account for the nonthermal emission we detected. However, there is additional evidence that there is diffuse nonthermal emission. By subtracting the point sources in NVSS and WENSS radio observations of our region, we find a radio excess of $154 \pm 7 \, \text{mJy}$ at 1.4 GHz and $2301 \pm 41 \, \text{mJy}$ at 0.33 GHz.

We note that the number of point sources detected in the Westerbork Northern Sky Survey (WENSS; 0.33 GHz) is different from the number in the NVSS (1.4 GHz); however, this may be due to AGN self-absorption at low frequencies. Considering a simple power-law fit to the radio excess, we find an energy index $\alpha_r \sim 1.8$, which is consistent within 90% confidence with the result found with the X-ray observation ($\Gamma_X = 2.8$). Examining the contour plot of $\Gamma_X$ versus normalization (Fig. 4), we note that the normalization is much larger for steeper photon indexes. In fact, if the photon index is frozen at 2.8, the best-fit model predicts a flux of
Examining each of the nonthermal models more closely, we note that the temperature decreases with the addition of a free power law (see Table 1) and remains constant for a power law with a photon index constrained to the implied radio value ($\Gamma_X = 2.8$). For a power law with a free spectral index, the high-energy photons are fitted with the power law, which causes a reduction in the temperature. When the photon index is frozen at the radio implied value ($\Gamma_X = 2.8$), the power law provides a significant number of photons at low energies (in the MECS), preventing a decrease in the temperature. By freezing the power law at $\Gamma_X = 2.8$ and its normalization to the 90% confidence lower limit, the best-fit temperature remains 2.23 keV. In this case, the power-law fit simply provides photons for the high-energy band of the spectrum. If instead the power-law normalization is frozen at its 90% confidence upper limit, the steep power law dominates at low energies, forcing the best-fit temperature up to 2.27 keV. As with the other power-law models, the thermal model falls off at the high energy, at which the power law begins to dominate again. The 90% confidence upper limit for the normalization, with $\Gamma_X = 2.8$, seems physically implausible for several reasons: the implied B field is less than 0.1 $\mu$G (see § 5 below), the MECS spectrum is dominated by the power law and not the thermal component, the best-fit abundance is very high ($\sim 0.95$), and a steep power law with a relatively high flux should also be visible in the LECS. This implies that as with hot, rich clusters (such as Coma), a simple power law is probably not the best model for the nonthermal spectrum, but without more data, it is the only model we can construct.

5. IC 1262’s RADIO HALO

The strongest evidence of diffuse, nonthermal, radio emission comes from the excess radio emission found after subtracting point sources from the NVSS and WENSS observations. The 3 $\sigma$ radio contour for the NVSS data in Figure 1 implies that the halo extends a distance of $\sim 6'$, which corresponds to a distance of about 360 $h_{50}^{-1}$ kpc (radius of $\sim 180 h_{50}^{-1}$ kpc). Although relativistic electrons from the cD galaxy (FIRST source 1 in Fig. 1) could be leaking out, traveling at their Alfvén velocity, they could reach a distance of only less than 8.0 $h_{50}^{-1}$ kpc within their radiative lifetime ($\sim 10^8$ yr), implying that cosmic-ray acceleration must occur in the ICM.

Radio halos are usually on the order of $0.8–1.2 h_{50}^{-1}$ Mpc (Feretti & Giovannini 1996). The so-called minihalos, which are similar in size to IC 1262’s radio halo ($\sim 200$ kpc; Gitti et al. 2003), are observed in cooling-flow clusters dominated by cD galaxies (Gitti et al. 2003). Since cooling flows can be seen as an excess in surface brightness over the diffuse emission in the center of a cluster, we fitted the radial profile (from the HRI data) of IC 1262 to a $\beta$-model. Although a central excess was not explicitly visible in our fit to the surface brightness profile, a single $\beta$-model did not adequately fit the data. Adding a second component to the $\beta$-model reduces $\chi^2$ by 30 for a reduction of 2 degrees of freedom. This model (see Fig. 5) gives an inner core radius of $31^{\prime\prime} – 35^{\prime\prime}$ ($31–35 h_{50}^{\prime\prime}$ kpc) with $\beta = 0.48–0.52$, and an outer core radius of $213^{\prime\prime} – 252^{\prime\prime}$ (213–252 $h_{50}^{-1}$ kpc) with $\beta = 0.30–0.76$. The 90% confidence upper limit for the normalization, with $\Gamma_X = 2.8$, implies that the best-fit temperature remains 2.23 keV. In this case, the power-law fit simply provides photons for the high-energy band of the spectrum. If instead the power-law normalization is frozen at its 90% confidence upper limit, the steep power law dominates at low energies, forcing the best-fit temperature up to 2.27 keV. As with the other power-law models, the thermal model falls off at the high energy, at which the power law begins to dominate again.

Examining Figure 5, we see a central excess above the diffuse emission out to $\sim 100 h_{50}^{-1}$ kpc, suggesting that a cooling flow or cD galaxy dominates within this region. Since the central excess is approximately one-half the size of the radio halo, we conclude that the radio halo associated with IC 1262 is not a minihalo.

In passing, we note that although the best-fit $\beta$ for the outer core radius is 0.31, which is much flatter than expected for a cluster of galaxies and is consistent with results found by Helsdon & Ponman (2000) for loose groups of galaxies, within our 90% confidence range, $\beta$ is consistent with the value of $\sim 0.66$ associated with clusters of galaxies (Jones & Forman 1984). We also point out that IC 1262’s diffuse gas has a temperature of $\sim 2$ keV, which is hotter than for any known group ($\sim 0.3–1.8$ keV; Mulchaey 2000), and that the outer core radius of $\sim 250 h_{50}^{-1}$ kpc is typical for a cluster (Jones & Forman 1984).

Following the method outlined in Henriksen (1998) and assuming a simple ICS power-law model ($\Gamma_X = 1.7$), we determined the magnetic field for the $6'$ extraction region. Using the nonthermal, X-ray flux, radio excess, and best-fit photon index, we find an average cluster magnetic field of 0.01–0.87 $\mu$G for the NVSS and 0.04–1.0 $\mu$G for the WENSS. These magnetic fields are consistent with the typical range for an average cluster magnetic field (0.1–1.0 $\mu$G; Dolag et al. 2001), providing more evidence for the existence of diffuse emission. The fact that the lower limits are less than 0.1 $\mu$G implies that the nonthermal flux is probably less than the 90% confidence upper limit. Petrosian (2001), however, has demonstrated, using models other than simple power laws for the radio emission, that higher magnetic fields are possible in clusters such as Coma, even if the measured nonthermal X-ray flux is considered to be created via the ICS process.

6. DISCUSSION

IC 1262 is a poor, cool cluster that shows some evidence of nonthermal X-ray emission. While a similar claim can be made for another low-mass system, the compact group HCG 62, IC 1262 is distinguished in that it shows evidence...
for a radio halo, whereas HCG 62 does not (Fukazawa et al. 2001). Currently, cluster mergers are the most popular model for the cosmic-ray acceleration that leads to the production of diffuse nonthermal emission. IC 1262 shows no direct X-ray evidence of a merger, such as elongated X-ray emission (as in the case of A754) or bimodal X-ray morphology (as in the case of A1750). There is, however, optical evidence that the cluster may have undergone a merger. The cD galaxy has a redshift of $z = 0.0328$ (9858 km s$^{-1}$; Wegner et al. 1999) compared to a redshift of $z = 0.0343$ (10311 km s$^{-1}$; Wegner et al. 1999) for the cluster. This gives a peculiar velocity $\Delta v$ of 453 km s$^{-1}$, which is more than 3 $\sigma$ above the dispersion of peculiar velocities ($168\,^{+41}_{-14}$ km s$^{-1}$) of cD galaxies found by Oegerle & Hill (2001). A line-of-sight merger could be the explanation for this unusually high peculiar velocity. In addition, Trinchieri & Pietsch (2000) analyzed the ROSAT HRI observation of IC 1262 and found a bright arc near the cD galaxy, which may indicate dynamic evolution of the cD galaxy due to a merger.

Our analysis has suggested that diffuse, nonthermal emission is associated with IC 1262. We find a 2.78 $\sigma$ detection in the MECS but no detection in the LECS to be within 90% confidence. This lack of detection in the LECS is probably because it is not as sensitive to hard photons as the MECS. Although our 90% confidence in $\Gamma_X$ and normalization indicate that U1275-09534024 could be the reason for our non-thermal detection, the radio implies the existence of diffuse nonthermal emission. When the diffuse radio excess is fitted to a simple power law, it gives a spectral index $\alpha_r \approx 1.8$. When we use the radio to confine $\Gamma_X$ to 2.8, then the non-thermal X-ray emission cannot be accounted for with point sources. We also reiterate that U1275-09534024 may not even be emitting nonthermal X-ray emission. A deeper radio observation will be able to confirm the existence of a radio halo and provide a spectral index that can be used to constrain $\Gamma_X$. With a sensitivity up to $\sim 30$ keV, the Rossi X-Ray Timing Explorer Proportional Counter Array should be able to detect any diffuse nonthermal X-ray emission associated with IC 1262 and would also be able to determine the variability, if any, of U1275-09534024.

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