X-ray Constraints on Cluster Magnetic Fields

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Lower limits to the intracluster magnetic field are derived from modeling broad band X-ray spectra of 6 galaxy clusters with radio halos (A401, A754, A1367, Coma (A1656), A2256, and A2319). The 0.7 - 10 keV spectra for all clusters were obtained with the Advanced Satellite for Cosmology and Astrophysics (ASCA) Gas Imaging Spectrometer (GIS). For A401, A754, A1367, and A1656, data from the HEAO1-A2 High Energy Detector (HED) (2-60 keV) was included in a joint fit to further constrain the allowed non-thermal component. Upperlimits to the non-thermal X-ray emission are a factor of \(~10\) improvement over previous values. Lower limits to the average magnetic field derived from these upperlimits and the radio spectral parameters range from 0.08 - 0.30\(\mu\)Gauss. A seed intracluster field amplified by turbulence from galaxy motion through the intracluster medium should have an average value in the range \(~0.1-0.2\) (Goldman & Rephaeli, 1991; De Young, 1992), thus the lack of any detections makes it unlikely that field amplification is due to galaxy wakes. In addition, all of these clusters have an asymmetric surface brightness distribution while several also have X-ray spectroscopic evidence of a merger. We suggest that cluster mergers rather than galaxy wakes are the source of the magnetic field amplification.
1. Introduction

The presence of a magnetic field and a population of relativistic electrons is inferred from modeling the radio halo in the Coma cluster (A1656) which is well described by a synchrotron spectrum over the approximate range, 10MHz - 3GHz (Giovanni et al. 1993). Other clusters of galaxies are also known to have diffuse radio halos: A401, A754, A1367, A2255, A2256, A2319 (references in Table 5). Non-thermal X-ray emission is expected from inverse Compton scattering of the cosmic microwave background photons off of the relativistic electrons. Detection of the predicted non-thermal component is complicated since X-ray observations of galaxy clusters are dominated by a hot intergalactic medium with continuum emission well described in the X-ray regime by thermal bremsstrahlung. Previous investigations have focused on energies above the exponential decay of the thermal spectrum, producing upper limits on non-thermal X-ray emission from some of the clusters known to have diffuse radio halos: A401, A2255, and A2256 (Rephaeli & Gruber 1988), A1367, A2319 (Rephaeli, Gruber, & Rothschild 1987) using HEAO1-A4 observations, and most recently for the Coma cluster, using the OSSE experiment on the Compton Gamma-ray Observatory (Rephaeli, Ulmer, & Gruber 1994). The upper limit on non-thermal X-ray emission together with the radio spectral parameters are used to place a lower limit on the average magnetic field, <B>. These papers have reported lower limits to <B> for the clusters as high as $\leq 0.15 \mu$G.

The origin and amplification mechanism of cluster magnetic fields is somewhat of a mystery. A primordial seed field amplified by gravitational collapse of a proto-cluster results in too weak of a field to give the observed Faraday Rotation measures (RM) (Ruzmaikin, Sokoloff, & Shukurov 1989). Evidence of metals in the intracluster medium out to $z \geq 0.3$ (Mushotzky and Loewenstein 1997) suggests that a seed field would originate in ejected galactic material. Turbulence from the motion of galaxies in the intracluster medium would
amplify the seed field to the observed RM levels (Ruzmaikin, Sokoloff, & Shukurov 1989). However, this mechanism can only produce an average field of $\sim 0.1-0.2 \mu$Gauss (Goldman & Rephaeli 1991; De Young 1992). If cluster magnetic fields are typically higher than $\sim 0.1-0.2$, then some other amplification mechanism would be needed. Previous upper limits to $<B>$ have been within this range or below and are thus inconclusive. Rotation Measures, though indicating a magnetic field in excess of this value, may be biased by local density peaks in a clumpy intracluster medium and may not give an accurate measure of the cluster magnetic field. Combined X-ray and radio measurements, such as we present in this paper, give a more robust measurement of the average cluster magnetic field.

If strong magnetic fields are present in galaxy clusters, they are expected to impact a number of other research areas, such as the relationship of gas mixing (Valinia et al. 1996) during cluster evolution to the distribution of metals in the intracluster medium as well as cluster mass measurements derived from the radial gas pressure distribution (Makino 1997). In particular, it has been suggested that the presence of an equipartition magnetic field in the A2218 cluster might reconcile the apparent discrepancy between the total cluster mass inferred from gravitational lensing and that inferred from the X-ray emitting intracluster medium (Loeb & Mao 1994; Ensslin et al. 1997).

In this paper, we present new upper limits on the non-thermal X-ray component in six clusters of galaxies with diffuse radio halos using ASCA GIS and $HEAO1-A2$ HED spectra (Section 2). In Section 3, the procedure is given for calculation of the average magnetic field from the X-ray and radio parameters. In Section 4, we discuss the impact of the average magnetic field lower limits on theories of magnetic field amplification. We assume a value $H_0 = 50 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ in all of the calculations.
2. X-ray Spectral Observations

The significant limits these data place on the non-thermal X-ray component are a result of utilizing observations made with the *ASCA* (Tanaka, Inoue, & Holt 1994) GIS (Ohashi et al. 1996; Makishima et al. 1996) and to the technique of fitting multiple data sets to expand the energy band. In a joint fit, the *ASCA* and *HEAO1-A2* data provide broad band spectral coverage $\sim (0.7 - 60 \text{ keV})$. The GIS tightly constrains the gas temperature and also limits the allowable contribution of the power law component to the 0.7 - 10 keV spectrum. The HED data provides modest sensitivity in the hard X-ray regime, extending the spectrum out to 50 - 60 keV. The HED exposure times and count rates are given in Table 1. The HED has a field of view of 3$^\circ$x3$^\circ$ and an energy resolution of $\sim$20% at 6 keV. The HED has an effective area of 429 cm$^2$ and very accurate background subtraction utilizing offset pointings. The cluster with the highest signal-to-noise data, the Coma cluster, has $> 2\%$ random statistical error in the channel with the highest signal-to-noise. The systematic error in the energy calibration is $< 1\%$ and is not included in the spectral modeling because it is negligible compared to the statistical error. The characteristics of the *HEAO-1 A2* data are more fully described in Henriksen & White (1996) and references therein.

The GIS2 event files, undergone filtering using REV2 standards, were used with the latest (v4.0) response matrices. The v4.0 response matrices provide improved modeling of the low energy pulse height distribution. The high energy response calibration is dominated by statistical errors for sources of several counts sec$^{-1}$ or less (GIS News No. 2, 1995). Table 1 shows that the GIS count rates for the clusters, which range from 0.8 - 5.25 counts sec$^{-1}$, are relatively low and should be dominated by statistical errors at high energy. Comparison of the spectral parameters measured independently by the HED and GIS show good agreement (see Table 2) also indicating that it is unlikely that systematic errors in the GIS calibration dominate at high energies.
Blank sky GIS images were used for background subtraction since the cluster emission may cover the entire detector, thus precluding use of a source free region of the detector for background. The same image region on the GIS detector is used to extract the background region as is used to extract the source spectrum. Spectra were modeled using XSPEC version 9.0 (Arnaud 1996). The model used to fit the data consists of a Raymond and Smith plasma code (1977) with absorption cross sections (Morrison & McCammon 1983), solar abundance ratios (Anders & Grevesse 1989), and a power law component. The normalization on the thermal component is proportional to the emission integral which will vary with the size of the region modeled. For this reason, the HED and GIS normalization on the thermal component are not tied. The derived 90% confidence range on the thermal normalizations are given in Table 3 for the joint fit. They are generally in agreement except in the case of A1367. A1367 has a very irregular morphology with a broad surface brightness distribution compared to the other clusters. It is clearly bimodal. It is also, along with Coma, the closest. Thus, the thermal normalization, which is proportional to the emission integral, is quite different in each data set because of the diffuse emission outside of the GIS FOV. Other free parameters are the temperature, abundance, and column density. The abundance, temperature, and column density are tied, meaning the HED and GIS data are required to have the same value of these parameters. The power law photon spectral index ($\alpha_r + 1$) is fixed at the value calculated from the radio energy spectral index ($\alpha_r$)(see Table 5). Only data above 0.7 keV is used and the data is grouped to contain at least twenty counts in each bin to increase the reliability of the results obtained from a $\chi^2$ fit (Nousek & Shue 1989). The GIS spectrum is obtained from a region of radius 18 arcmin, which is chosen to enclose the reported radio halo, radius of 5 - 15 arc min (see Table 5), for every cluster. Since both data sets contain the non-thermal component, we tied these two normalizations. This is justified because, as we show below, the absolute photometric calibration of two spectra differ by less than 6-7%. 
Our method for constraining the NT component differs from earlier studies in the following. Earlier studies have fixed the thermal component at the emission weighted value and looked for residuals at higher energy. Our method provides better modeling of the thermal component by allowing it to vary rather than be fixed at a single value. This also makes it possible to use ASCA data above 0.7 keV, the highest signal-to-noise spectral data available for galaxy clusters, to help constrain both the thermal and power law component. Also, if multiple temperature components are present, then the GIS, with greater sensitivity at higher energy than other available data (e.g., the ASCA SIS or ROSAT PSPC) will most accurately model the hottest gas component and therefore provide the most accurate separation of the thermal and non-thermal (NT) components. The 90% confidence upper limit is measured by stepping the normalization of the NT component through a range of values while minimizing chi-square ($\chi^2$).

To assess the validity of our approach to modeling the non-thermal emission, we performed several consistency checks regarding the calibration of the HEAO1-A2 HED and ASCA GIS detectors. To compare the calibration of the data, a Raymond and Smith model was fit both independently and simultaneously to both data sets. The independent fit tests whether or not the spectra are the same shape while the simultaneous fit, with a subsequent calculation of the flux measured independently by each detector, tests the absolute photometric cross-calibration of the two data sets. Table 2 gives the results of independent fits, including the 90% limits on the cluster column density, temperature, and abundance. Comparison of the GIS and HED measurements show that the fit parameters are consistent. The best test of consistency is the Coma cluster where the HED signal-to-noise is highest and the parameters are well constrained by each data set. The parameters measured by the GIS and HED for Coma are in excellent agreement. To evaluate the relative photometric calibration of the two data sets, a single thermal component was fit to the A401 data sets simultaneously and the normalization of each data set allowed to vary (as was done when
a powerlaw was also included). A401 was chosen since it is the most distant, \( z = 0.0748 \), and the nominal extent of cluster X-ray emission, \( \sim 3 \text{ Mpc} \) is within the GIS field-of-view. The flux in the 2-10 keV band, the overlapping energy of the two data sets, is: \( 1.10 \times 10^{-2} \) photons cm\(^{-2}\) sec\(^{-1}\) in the GIS and \( 1.03 \times 10^{-2} \) photons cm\(^{-2}\) sec\(^{-1}\) in the HED. The flux scales as the normalizations and 90% confidence limits on the normalizations overlap. Thus, the HED and GIS, for our purposes, are well calibrated, to \( \sim 6-7\% \), and in excellent agreement.

Table 2 gives the results of the joint fit. No NT emission is required to obtain a good fit. Figures 1 - 6 show \( \chi^2 \) vs. energy for the best fit thermal spectrum with the upperlimit to the NT component added. Also shown are the model components, both individually and separate. In general, the entire thermal spectrum is distorted when a powerlaw is added. For a low temperature cluster such as A1367, the powerlaw becomes dominant in the spectrum above 20 keV. The 0.7 - 2 keV part of the spectrum also constrains the powerlaw.

The possibility that the effect of additional absorption beyond that accounted for by galactic neutral hydrogen affects the fit was also investigated. Table 3 contains the 90% confidence range on column density measured by the GIS as well as the Galactic \( n_H \) column density (Stark 1992). For all of the clusters, the agreement is excellent. This is also consistent with White et al. (1991) who found, using the Einstein Solid State Spectrometer, that of these 6 clusters, only A401 may show any evidence of additional absorption. These clusters also show substructure and are likely merging systems. Mergers anti-correlate with the presence of a cooling flow (which strongly correlate with absorption intrinsic to the cluster).

No NT components were detected, consistent with past analysis, however, a factor of \( \sim 10 \) more sensitive lower limits to the average cluster field were derived for 5 clusters: A401, A1367, A1656, A2256, and A2319. For A754, this is the first measured NT upperlimit.
The upper limits to the NT X-ray flux are given in Table 4 along with the column density, temperature, and abundance. The monochromatic X-ray flux is calculated in photons cm$^{-2}$ sec$^{-1}$ keV$^{-1}$ from the NT normalizations given in Table 2 and compared to previous upper limits in Section 4. All values are reported with 90% confidence.

3. Magnetic Field Calculation

In this section, we begin with basic equations which describe the radio and NT X-ray emission mechanisms and show how they are combined to constrain the average magnetic field using observables. The radio halo spectra are described by a power law function of the form,

$$S(\nu) = A\nu^{-\alpha_r},$$  \hspace{1cm} (1)

Where S is the radio flux and $\alpha_r$ is the energy spectral index. Values of $A$ are given in Table 5. The synchrotron power per volume per frequency ($P_s$) is given by equation 6.36 in Rybicki and Lightman (1979) which is rewritten here in terms of frequency ($\nu$) as,

$$P_s(\nu) = K_1C <B_P >^{\frac{p+1}{2}} \nu^\frac{p}{2},$$  \hspace{1cm} (2)

where

$$K_1 = \frac{\sqrt{3}q^3}{mc^2(p+1)}\Gamma\left(p\frac{4}{4} + \frac{19}{12}\right)\Gamma\left(p\frac{4}{4} - \frac{1}{12}\right)\left[\frac{2\pi mc}{3q}\right]^{-\frac{(p-1)}{2}}.$$  \hspace{1cm} (3)

The relativistic electron distribution, $N(\gamma) = C\gamma^{-p}$, specifies C where p is the electron spectral index and $\gamma$ is Lorentz factor. P is calculated from $\alpha_r$, $p = 2\alpha_r + 1$. $B_P$ is the magnetic field component which is perpendicular to the line of sight. In equation (3), q is the electron charge, c is the speed of light, m is the rest mass of the electron, and $\Gamma$ is the Gamma function.

The expression for the inverse Compton emission ($P_c$) from cosmic microwave background radiation (CMBR) scattering off of the relativistic electrons is given by equation
7.31 in Rybicki and Lightman (1979),

\[ P_c(\epsilon) = K_2 C(kT) \frac{p+5}{2} \epsilon^{\frac{1-p}{2}}, \]  

(4)

where T is the temperature of the CMBR, \( \epsilon \) is the photon energy, and

\[ K_2 = \frac{8\pi^2 r_0^2 D(p)}{h^3 c^2}. \]  

(5)

In this equation, \( r_0 \) is the classical electron radius and \( h \) is Planck’s constant,

\[ D(p) = J(p) \Gamma[\frac{p+5}{2}] \psi[\frac{p+5}{2}], \]  

(6)

\[ \psi(s) = \sum_{n=1}^{\infty} n^{-s}, \]  

(7)

\[ J(p) = 2^{p+3} \left( \frac{p^2 + 4p + 11}{(p+3)^2(p+5)(p+1)} \right). \]  

(8)

An expression for the NT X-ray flux \( (F_c) \) is derived in terms of observable quantities from equation (4) by eliminating \( C \) using equation (2). \( P_s \) and \( P_c \) are integrated over volume, and divided by \( 4\pi D^2 \), where \( D \) is the distance to the cluster.

\[ F_c = \frac{K_2}{K_1} (kT)^{\frac{p+5}{2}} < B_p >^{-\frac{p+1}{2}} A \int \epsilon^{-\frac{p+1}{2}} d\epsilon. \]  

(9)

The energy band of the observed flux determines the integration limits. Here, the limits were chosen to be 2-10 keV when the ASCA data is used alone (A2256, A2319) and 20-60 keV when HEAO1-A2 data is also fit. The flux is given in Table 4 in these energy bands. The spectral fit utilizes the full range of the data sets, 0.7 keV - 60 keV, so that 2-10 keV and 20-60 keV are nominal energy ranges for calculation of the hard X-ray fluxes. These energy bands are chosen to facilitate comparison with earlier measurements such as those referenced in Section 1. The temperature of the CMBR is taken as 2.7 K. This calculation is independent of the specific cosmic-ray electron distribution, size of the emitting region, or distance to the cluster. Using the radio data alone to determine \( < B_p > \), (i.e., equation (2)) would additionally require constraining \( C \) explicitly as well as the distance to the cluster and the size of the emitting region. The calculated \( < B_p > \) is given in Table 4 and ranges from 0.08 (A401) - 0.30 (A2256) \( \mu \text{Gauss} \).
4. The Amplification of Cluster Magnetic Fields

Using archival data, we have failed to detect non-thermal X-ray emission in the broad 0.7 - 60 keV band formed by ASCA and HEAO-1 A2 observations of clusters with radio halos. The upper limits on non-thermal X-ray emission derived from fitting these data were used with the radio parameters to obtain lower limits on the average magnetic field.

The method presented, modeling non-thermal emission as inverse Compton scattering of CMBR photons off of relativistic electrons, has been used to successfully detect high energy emission in sources other than clusters with radio halos: for example, the radio lobes of Fornax A (Kaneda et al. 1995; Feigelson et al. 1995) and possibly several galaxy clusters. Fornax A, located in the outer regions of a galaxy cluster, has a value of 2-3 $\mu$Gauss for the magnetic field associated with the radio lobes. Sarazin and Lieu (1998) suggest that the emission detected from several galaxy clusters using the Extreme Ultraviolet Explorer (EUV) (Lieu et al. 1996) may be also be non-thermal emission. The relativistic electrons which give the EUVE emission in galaxy clusters are of lower energy than those that produce the radio halos and their radio emission should be unobservable from Earth (Sarazin and Lieu 1998) as a radio halo. The EUVE emission may involve the low energy tail of the same population of relativistic electrons which produce the radio halos providing important information on the spatial distribution of the magnetic field and population of relativistic electrons.

Lower limits to the average cluster magnetic field values reported here are higher than earlier measurements for most of the clusters (A754 was not measured earlier). Though the HEAO1-A4 data used in these studies has the advantage of covering a higher energy band, 13 - 125 keV, the detectors have an effective area 5 - 10 times lower than the HEAO1-A2 HED. They also did not model the thermal spectrum. The ASCA data not only models the thermal spectrum well, it provides a tight constraint on the overall shape of the
spectrum, thus providing important limits on the flux of any additional NT component. For comparison, the upper limits on the NT flux at 30 keV are given for the 5 clusters in common in units of $10^{-6}$ photons cm$^{-2}$ sec$^{-1}$ keV$^{-1}$ as (A2,A4): A401 (2.2,19.0), A1367 (1.8,21.0), A1656 (1.9, 24.0), A2256 (0.37, 5.), and A2319 (2.1, 22.). For comparison, the lower limits to the average magnetic field are given for the 5 clusters in common as (A2,A4): A401 (0.08,0.04), A1367 (0.19,0.056), A1656 (0.26, 0.11), A2256 (0.30, 0.15), and A2319 (0.23, 0.11). Our results indicate that average cluster fields are typically at least $0.2 \mu$Gauss and several are in excess of this value.

These values for the average magnetic field in the intracluster medium begin to constrain theories for their origin. It has been hypothesized that a seed field is supplied through gas loss by galaxies and is then amplified by the turbulent motion of galaxy wakes. Estimates of the mean field achievable by this amplification process range from $\sim 2\mu$G (Ruzmaikan et al. 1989) to 0.1 - 0.2 $\mu$G (Goldman and Rephaeli 1991). Amplification of seed fields has also been considered by De Young (1992) using time-dependent evolution of magneto-hydrodynamic turbulence from galaxy wakes. He found that it is very difficult to produce $\mu$Gauss fields with this mechanism and that radio halos must result from extreme conditions in this scenario. Goldman and Rephaeli (1991) use a lower, more realistic value for the efficiency of conversion of kinetic energy into magnetic field energy thus getting ambient fields in the range of 0.1 - 0.2. Their work suggested that the magnetic fields amplified by galaxy wakes should be confined to this range and should have been detectable. Our lack of detections begin to question galaxy wakes as a source of the magnetic field energy since they cannot amplify the magnetic fields to the observed lower limits. Larger fields require a greater source of kinetic energy.

Part of the legacy of the ROSAT observatory is the discovery that X-ray substructure in galaxy clusters is prevalent. All of the clusters have asymmetric X-ray morphology
similar to that seen in hydrodynamical simulations of cluster mergers (Roettiger, Loken, and Burns 1997). At least three of the clusters, A754 (Henriksen and Markevitch 1996), Coma (Honda et al. 1996), and A1367 (Donnelly et al. 1998) have spectral evidence of a merger as well. Some of the other clusters also show additional evidence of a merger: A401 (Fujita et al. 1996; Fabian, Peres, and White 1997), A2256 (Miyaji et al. 1993; Briel and Henry 1994; Roettiger, Burns, and Pinkney 1995), and A2319 (Markevitch 1996). The similarity between the direction of the elongation in the radio and X-ray maps of the Coma cluster also suggests a connection between the merger and the radio halo (Deiss et al. 1997). Burns et al. (1994) found that the energy from the merger of the NGC 4389 group is sufficient to power the radio halo. Bohringer et al. (1992) also found that the available energy specifically from the accretion of groups near the core may be enough to reaccelerate cosmic ray electrons and amplify the magnetic field to maintain the halo. The energy associated with subcluster merger will amplify the magnetic field and accelerate the relativistic electrons to produce the observed level of synchrotron emission. Okoye and Onuora (1996) found that only a small amount of boosting is necessary to explain the observed radio luminosity of the Coma C source (radio halo). Similar conclusions have been found for the A2319 cluster (Feretti, Giovanni, Bohringer 1997). It is also important to note that amplification by subcluster merger is fundamentally different than from galaxy wakes since galaxy motions are continual and subcluster mergers are isolated in time. That the merger will have a lifetime much less than the cluster lifetime means that if the merger accelerates the cosmic-ray electrons, then the radio halo will also have a lifetime less than the cluster. An explanation for merging clusters with no radio halo may be related to the large amount kinetic energy available in a major merger. The turbulent motions in major mergers may amplify the seed field to a strong enough level so that the synchrotron cooling time is substantially less than the merger lifetime. In this scenario, we would only see those radio halos from select mergers: those that are strong enough to make radio halos yet weak
enough so that synchrotron lifetime is long enough for the radio halo to be observable.

5. Conclusions and Future Prospects

Calculation of the average magnetic field in galaxy clusters with radio halos, as outlined in this paper, is straight-forward and depends on observable radio and X-ray parameters. Lower limits to the average magnetic field range from 0.08 - 0.30 $\mu$G. They are higher than previous measurements due to our fitting a combination of the ASCA GIS and HEAO1-A2 HED which make a broad band, 0.7 - 60 keV spectrum. The highest values, $\sim$0.30 $\mu$G, are higher than the range, 0.1 - 0.2 $\mu$G, believed to be amplified by galaxy wakes; several others are in the range of 0.1 - 0.2 $\mu$G, yet are undetected. If future observations of these clusters show that typical average cluster magnetic fields are $> 0.2 \mu$G then amplification by subcluster merger rather than galaxy wakes may be more plausible. The higher magnetic field created by a major merger also results in a shorter synchrotron cooling time for the cosmic-ray electrons and therefore a shorter lifetime for the radio halo. This would account for the fact that radio halos are rare while clusters with substructure are common.

The Hard X-ray Detector (HXD) (Takahashi et al. 1996) to be flown on ASTRO-E will have $\sim$10 times the effective area at 10 keV compared to the HEAO1-A2 and extend to higher energy. This will allow detection or much better limits on cluster magnetic fields to be set. These new limits to the cluster magnetic field will be able to determine the strength of cluster magnetic fields and severely constrain theories for their origin.

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| Cluster | HED Seconds | HED Counts sec\(^{-1}\) | GIS Seconds | GIS Counts sec\(^{-1}\) |
|---------|-------------|-----------------------|-------------|-----------------------|
| A401    | 3990        | 2.32±0.11             | 32322       | 1.39±0.0076           |
| A754    | 4957        | 1.43±0.050            | 19716       | 1.82±0.010            |
| A1367   | 4520        | 2.86±0.056            | 10646       | 0.84±0.0094           |
| Coma    | 4247        | 8.34±0.072            | 9440        | 5.25±0.024            |
| A2256   | -           | -                     | 34726       | 1.57±0.007            |
| A2319   | -           | -                     | 14336       | 2.41±0.013            |
Table 2. Comparison of Best Fit Parameters

| Cluster | Data Set | $n_H \times 10^{22}$cm$^{-2}$ | kT(keV)   | Abundance | NT Normalization<sup>a</sup> | $\chi^2$/dof |
|---------|----------|-------------------------------|-----------|-----------|-----------------------------|--------------|
| A401    | GIS      | 0.10 - 0.14                   | 7.67 - 8.71 | 0.21 - 0.31 | -                           | 563/609      |
|         | HED      | 0.0 - 2.76                    | 5.59 - 10.90 | 0.0 - 0.64 | -                           | 53.9/42      |
|         | Joint    | 0.10 - 0.14                   | 7.68 - 8.68 | 0.20 - 0.32 | < 0.0077                    | 617/655      |
| A754    | GIS      | 0.042 - 0.084                 | 9.50 - 11.22 | 0.16 - 0.30 | -                           | 539/528      |
|         | HED      | 0.0 - 0.51                    | 7.29 - 13.89 | 0.0 - 0.60 | -                           | 12.5/11      |
|         | Joint    | 0.041 - 0.081                 | 9.67 - 11.28 | 0.15 - 0.29 | < 0.0024                    | 552.1/542    |
| A1367   | GIS      | 0.0 - 0.023                   | 3.3 - 3.7   | 0.17 - 0.40 | -                           | 306.4/268    |
|         | HED      | 0.0 - 8.94                    | 3.17 - 3.83 | 0.10 - 0.23 | -                           | 66.5/47      |
|         | Joint    | 0.0 - 0.022                   | 3.4 - 3.7   | 0.14 - 0.25 | <0.00862                    | 374.9/318    |
| Coma    | GIS      | 0.0-0.015                     | 8.69 - 9.49 | 0.22 - 0.33 | -                           | 543.3/564    |
|         | HED      | 0.00 - 0.78                   | 7.92 - 8.70 | 0.14 - 0.27 | -                           | 50/52        |
|         | Joint    | 0.0 - 0.024                   | 8.42 - 9.03 | 0.21 - 0.29 | <0.0055                     | 600/619      |
| A2256   | GIS      | 0.029 - 0.063                 | 6.74 - 7.39 | 0.16 - 0.25 | <0.005                      | 682.9/605    |
| A2319   | GIS      | 0.065 - 0.11                  | 9.18 - 10.67 | 0.18 - 0.32 | <0.0075                     | 562.2/534    |

<sup>a</sup>Non-thermal upperlimit in photons cm$^{-2}$s$^{-1}$keV$^{-1}$ at 1 keV
Table 3. Data Comparisons

| Cluster | GIS $N_H$   | Galactic $N_H$ | GIS Normalization | a HED Normalization a |
|---------|-------------|----------------|-------------------|-----------------------|
| A401    | 0.10 - 0.14 | 0.105          | 0.080 - 0.083     | 0.067 - 0.078         |
| A754    | 0.042 - 0.070 | 0.045          | 0.099 - 0.10      | 0.055 - 0.062         |
| A1367   | 0.0 - 0.023  | 0.021          | 0.042 - 0.051     | 0.52 - 0.77           |
| Coma    | 0.0 - 0.015  | 0.009          | 0.28 - 0.29       | 0.26 - 0.28           |
| A2256   | 0.029 - 0.063 | 0.042          | -                 | -                     |
| A2319   | 0.065 - 0.11 | 0.083          | -                 | -                     |

aNormalization of thermal component
Table 4. X-ray Spectral Constraints

| Cluster | Compton Flux ($10^{-12}$ ergs cm$^{-2}$ sec$^{-1}$) | Average Magnetic Field (µGauss) |
|---------|---------------------------------------------------|--------------------------------|
| A401    | <3.3$^a$                                           | >0.08                          |
| A754    | <1.5$^a$                                           | >0.29                          |
| A1367   | <2.6$^a$                                           | >0.19                          |
| Coma    | <2.9$^a$                                           | >0.26                          |
| A2256   | <4.1$^b$                                           | >0.30                          |
| A2319   | <10.6$^b$                                          | >0.23                          |

$^a$HEAO1-A2 and ASCA data, 20-60 keV

$^b$ASCA data alone, 2-10 keV
Table 5. Radio Spectral Parameters

| Cluster  | Z\(^{a}\) | A(ergs cm\(^{-2}\) sec\(^{-1}\)Hz\(^{-1}\))\(^{b}\) | Energy Spectral Index (\(\alpha_r\)) | Halo Radius (arc min) |
|----------|-----------|---------------------------------|-----------------------------------|----------------------|
| A401\(^{c}\) | 0.0748    | 1.6\times10\(^{-12}\)          | 1.4                               | 15                   |
| A754\(^{d}\) | 0.0528    | 2.5\times10\(^{-12}\)          | 1.3                               | 12                   |
| A1367\(^{e}\) | 0.0213    | 5.5\times10\(^{-11}\)          | 1.5                               | 8                    |
| Coma\(^{f}\)  | 0.0235    | 8.3\times10\(^{-12}\)          | 1.34                              | 10                   |
| A2256\(^{g}\) | 0.0601    | 6.5\times10\(^{-9}\)           | 1.8\(^{i}\)                      | 5                    |
| A2319\(^{h}\) | 0.0529    | 2.0\times10\(^{-11}\)          | 1.4                               | 5                    |

\(^{a}\)Sarazin (1988)

\(^{b}\)S(\(\nu\))=A\(\nu^{-\alpha_r}\)

\(^{c}\)Roland et al. (1981): Flux of 0.080 Jy at 610 MHz

\(^{d}\)Andernach et al. (1988): 0.136 Jy at 2.7 GHz

\(^{e}\)Gavazzi (1978): 0.363 Jy at 610 MHz

\(^{f}\)Kim et al. (1990): 0.72 Jy at 1 GHz

\(^{g}\)Bridle and Fomalont (1976); Bridle et al. (1979): 0.1 Jy at 610 MHz.

\(^{i}\)Bridle et al. (1979) give a range of 1.2 < \(\alpha\) < 1.8

\(^{i}\)Harris and Miley (1978): 1 Jy at 610 MHz
Fig. 1.— In the upper panel, A401 GIS and HED data is shown with the best fit model. The model consists of a Raymond and Smith thermal component with the maximum allowable powerlaw added (90% confidence). The model components are shown separately and summed. In the lower panel $\chi^2$ vs. energy is shown.

Fig. 2.— Same as Figure 1 shown for A754.

Fig. 3.— Same as Figure 1 shown for A1367.

Fig. 4.— Same as Figure 1 shown for the Coma cluster.

Fig. 5.— Same as Figure 1 shown for A2256.

Fig. 6.— Same as Figure 1 shown for A2319.
