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ROSSI X-RAY TIMING EXPLORER OBSERVATIONS OF THE COMA CLUSTER

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ABSTRACT

The Coma Cluster was observed in 1996 for ≃90 ks by the PCA and HEXTE instruments aboard the *Rossi X-ray Timing Explorer* (*RXTE*) satellite—the first simultaneous, pointing measurement of Coma in the broad, 2–250 keV energy band. The high sensitivity achieved during this long observation allows precise determination of the spectrum. Our analysis of the measurements clearly indicates that in addition to the main thermal emission from hot intracluster gas at $kT \simeq 7.5$ keV, a second spectral component is required to best fit the data. If thermal, this component has a temperature ≃4.7 keV, and it contributes ≃20% of the total flux. Alternatively, the second component can be a power law, likely due to Compton scattering of relativistic electrons by the cosmic microwave background. This interpretation is based on the measurements of diffuse radio emission and the similar values of the radio and X-ray spectral indices. A Compton origin of the nonthermal component would imply that the volume-averaged magnetic field in the central region of Coma is $B \simeq 0.2$ μG, a value that is free of the usual assumption of energy equipartition. The energy density of the emitting electrons would then be $\sim 8 \times 10^{-14}$ ergs cm^{-3}. Barring the presence of unknown systematic errors in the *RXTE* source or background measurements, our spectral analysis yields considerable evidence for Compton X-ray emission in the Coma Cluster.

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (Coma) — galaxies: magnetic fields — radiation mechanisms: nonthermal

1. INTRODUCTION

Measurements of X-ray emission (at energies ≤20 keV) from a large number of clusters clearly show that the emission is predominantly thermal bremsstrahlung from hot ($kT = 3$–15 keV) intracluster (IC) gas. An isothermal gas distribution usually provides a good overall spectral fit to the continuum (and Fe Kα line, when measured), but large-scale temperature structure has been predicted and observed in some clusters (e.g., Markevitch 1996; Honda et al. 1996). Indeed, the gas distribution over typical radial regions of ≃2 Mpc is not expected to be isothermal (even excluding a small "cooling flow" region within the core). Sensitive spectral measurements are required to determine the temperature distribution well outside the central, largely isothermal region.

In addition to the more complex emission characteristics of nonisothermal gas, there could also be an appreciable additional nonthermal emission. Compton scattering of relativistic electrons by the cosmic microwave background (CMB) radiation is likely to be the leading nonthermal emission. When this emission is measured, we will have new information on magnetic fields (e.g., Tucker et al. 1973) and the energy spectrum of relativistic electrons in the IC space. The presence of these electrons is deduced from measurements of diffuse radio emission in the central regions of about a dozen clusters. Radio spectral indices and luminosities are in the ranges 1.2–1.8 and $\sim 10^{41}$–10^{42} ergs s^{-1} ($H_0 = 50$ km s^{-1} Mpc^{-1}), respectively. Implied electron energies are ∼1–100 GeV for magnetic field strengths 0.1–1 μG. Scattering of CMB photons by these electrons boosts photon energies to the wide range of ~ 1–10^4 keV (see, e.g., Rephaeli 1979).

Sensitive measurements of cluster spectra are therefore essential for the determination of the gas temperature distribution and nonthermal quantities in clusters. Knowledge of the temperature distribution is needed for understanding the gas thermal balance and is quite important in using the gas as a dynamical probe of the total mass distribution in clusters (e.g., Sarazin 1986). On the other hand, reasonably adequate knowledge of basic nonthermal quantities such as magnetic fields and the energy densities of electrons and protons is very desirable for a more complete understanding of the IC environment and plasma processes. Moreover, the possible dynamical role of magnetic fields (e.g., Loeb & Mao 1994; Makino 1997) and thermal heating by energetic particles (Rephaeli 1979; Rephaeli & Silk 1995) are but just two examples of practical ramifications of their presence in clusters. Of a more basic nature are issues such as the origin of diffuse IC radio emission and magnetic fields (Jaffe 1980; Ruzmaikin, Shukurov, & Sokoloff 1989; Goldman & Rephaeli 1991; Goldshmidt & Rephaeli 1993) and the propagation mode of cosmic rays in intergalactic space.

Attempts to detect nonthermal emission at energies ≥30 keV include the analysis of *HEAO 1* A-4 data from six Abell clusters (Rephaeli, Gruber, & Rothschild 1987; Rephaeli & Gruber 1988) and observation of the Coma Cluster with the *Compton Gamma Ray Observatory*/OSSE experiment (Rephaeli, Ulmer, & Gruber 1994). No significant nonthermal emission was detected, resulting in lower limits on the magnetic fields, which are typically ∼0.1 μG. It has recently been reported that nonthermal emission from Coma was detected with the PDS instrument aboard the *BeppoSAX* satellite (Fusco-Femiano et al. 1998). There have also been some attempts to measure nonthermal emission at lower energies, where the emission is predominately thermal. A combined analysis of *HEAO 1* A-2 and *ASCA* data on six clusters yielded only flux upper limits (Henriksen 1998). Detection of a power-law component in the *ROSAT* PSPC measurement of A85 has recently been reported by Bagchi, Pislar, & Lima Neto (1998). Finally, EUV observations of several clusters have reportedly led to the measurement of diffuse emission, which is possibly nonthermal (Sarazin & Lieu 1998; Bowyer & Berghofer 1998). However, the PSPC and EUV spectral bands are too narrow to allow proper,

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TABLE 1

RESULTS OF THE SPECTRAL ANALYSIS

Parameter	Single R-S	Two R-S	R-S + Power Law
kT_1 (keV)	7.47 ± 0.03	~8.2[a]	7.51 ± 0.18
Normalization[b]	0.352 ± 0.002	$0.26^{+0.06}_{-0.12}$	$0.328^{+0.013}_{-0.006}$
kT_2 (keV)	...	$4.7^{+1.6}_{-3.0}$	...
Normalization[b]	...	$0.06^{+0.15}_{-0.03}$	...
I_ϵ(5 keV) (cm^{-2} s^{-1})[c]	...	...	$(1.7 \pm 0.5) \times 10^{-3}$
Photon index	...	...	2.35 ± 0.45
Fe abundance[d]	0.166 ± 0.007	0.18 ± 0.01	0.19 ± 0.01
χ^2/dof	261.1/219	242.8/217	244.6/217

NOTE.—All quoted errors are at the 90% confidence level. R-S stands for "Raymond-Smith."

[a] Constrained to the interval [7, 10] while determining bounds to other parameters.

[b] Raymond-Smith emission measure in units of $10^{-14} \int N_e N_H dV/4\pi D^2$, where D is the luminosity distance and N_e, N_H are the total number of electrons and protons, respectively.

[c] 90% errors determined with photon index fixed at 2.35; allowing the index to vary increases the error to ±0.58.

[d] Abundance is expressed relative to solar values.

simultaneous fitting for the spectral parameters of both the thermal and nonthermal components.

Here we report the observation of the Coma Cluster with the Proportional Counter Array (PCA) and High-Energy X-ray Timing Experiment (HEXTE) experiments aboard the *Rossi X-ray Timing Explorer* (*RXTE*) satellite. Basic results of the wide-band spectral analysis are presented, along with an assessment of their implications.

2. OBSERVATIONS AND DATA REDUCTION

The Coma Cluster was observed by the PCA and the HEXTE on *RXTE* during 58 separate pointings totaling approximately 90 ks in 1996 June 10–22 and July 15. Spectra were accumulated by the PCA in "Standard 2" mode, which results in a 129 channel count spectrum from 2 to 60 keV. The HEXTE, which consists of two independent clusters of detectors, returned data in event-by-event mode; the data were subsequently accumulated into 256 channel spectra spanning 17–250 keV. To subtract the background, each HEXTE cluster was commanded to beam switch every 16 s between on-source and alternate off-source positions 1°.5 on either side.

Standard screening criteria were applied to the data segments (Earth elevation angle, spacecraft pointing, avoidance of the South Atlantic Anomaly), resulting in a net exposure time of 87,328 s (as measured by the PCA, which has negligible dead time). PCA detectors 0, 1, and 2 were on during all of this time; detectors 3 and 4 were enabled for only 50% of the observation. To form an internally consistent and continuous data set with long exposure, we therefore present results from PCA detectors 0, 1, and 2 only. Inclusion of the two remaining detectors does not change our results significantly. After correcting for dead-time effects, the corresponding on-source live-times for the HEXTE were 28,426 and 29,220 s for clusters A and B respectively, with off-source live-times nearly equal to 75% of these values.

The PCA background was estimated with the "L7/240" faint source model provided by the instrument team. This resulted in an insignificant net counting rate in the PCA in channels above 40 keV, to within ~1%. The HEXTE background was determined from the off-source pointings and also showed no problems.

3. SPECTRAL ANALYSIS

For each PCA detector, the net counting rate on-source was about 40 counts s^{-1}, compared to a background rate of 13 counts s^{-1}; thus, the Coma Cluster ($z = 0.02316$) was easily detected. Since we could find no evidence for temporal variability in the PCA source and background rates over the observation, we used the time-integrated PCA and HEXTE spectra to form the basic data set for spectral analysis.

Response matrices were generated with standard tools, and a small energy dependence for systematic errors (W. Heindl 1998, private communication), averaging about 0.5%, was applied to the PCA spectrum. Additionally, PCA spectral channels below 3 keV and above 30 keV were excluded because of severe sensitivity to artifacts in the background model and the small effective area of the PCA outside this range. The HEXTE data were restricted to the energy range 17–100 keV for similar reasons, resulting in source and background counting rates of 0.75 and 84.1 counts s^{-1}, respectively (cluster A) and 0.49 and 58.1 counts s^{-1} (cluster B). Finally, to account for any residual background subtraction errors, in all spectral fits we allowed PCA and HEXTE backgrounds to vary by a small factor; these corrections were of order 0.5%.

We first attempted fitting the data by a single-component Raymond-Smith thermal plasma model and then proceeded to fit the data with models containing additional components. In all three cases, the ~8 keV Raymond-Smith component accounts for the bulk of the observed flux. Best-fit parameters and 90% confidence intervals are listed in Table 1. All fits resulted in a dense pattern of point-to-point correlated positive and negative residuals between 5 and 20 keV at the ~1% level, about the accuracy of the response matrices. We could not correlate these residuals with any features of the background spectrum. Most of the observed emission is clearly thermal, so it is natural to determine first spectral parameters of a single, isothermal gas component. The best-fit temperature in this case is 7.47 ± 0.03 keV, in good agreement with the range determined from *ASCA* measurements (Honda et al. 1996). The observed Fe XXV Kα line yields an abundance of 0.17 ± 0.01 (in solar units), somewhat lower than previously determined values (≥0.2). No cold absorption was measurable, and given the 3 keV PCA threshold, none was expected.

The residuals from the best-fit isothermal model indicate, if anything, that an extra component is required. When a second thermal component is added, best-fit parameters are

$kT_1 \simeq 8.2$ and $kT_2 \simeq 4.7$ keV, with the second component accounting for a substantial fraction, ~20%, of the total flux. The value of χ^2 is lower by 16.7 than the value obtained in the single temperature model; the F-test probability of the second component is 0.9992 for 2 additional degrees of freedom.

An equally good fit ($\Delta\chi^2 = 16.7$) is obtained when the second component is a power law, with a photon index of 2.3 ± 0.45 (90% confidence). The PCA counting rate of this component is 5 counts s^{-1} compared to 88 counts s^{-1} for the thermal. The extrapolated power-law flux is too low to have been detected by the HEXTE given the ~29 ks live time. This component comprises most of the flux only at energies ≥60 keV. The iron abundance is now 0.19 ± 0.015, in better agreement with previous determined values. The count rate from the combined thermal and nonthermal emissions and that of just the power-law component are shown in Figure 1, together with the measurements.

4. DISCUSSION

The above spectral analysis points to the need for a second component in the Coma spectrum. In view of the simplified nature of a single-temperature IC gas and the mounting observational evidence for a possibly complex thermal distribution in clusters (e.g., Markevitch 1996; Honda et al. 1996), it is natural to consider first the likelihood that the additional emission is from a second gas component at a significantly different temperature than the primary component. The question is not merely the existence of a temperature gradient but also whether a lower temperature gas component emitting an appreciable fraction (~20%) of the total flux is consistent with previous observations and is theoretically viable. There does not seem to be any reported evidence for such a component in previous *ROSAT* or *ASCA* observations of Coma. Extensive *ASCA* observations covering a large part of the Coma Cluster region in 14 separate pointings do indicate a complex temperature structure (Honda et al. 1996). However, in the central region of interest to us here, only moderate temperature variation was detected, with an average value ~7.8 ± 0.3 keV (and a possible additional systematic uncertainty of 1.5 keV).

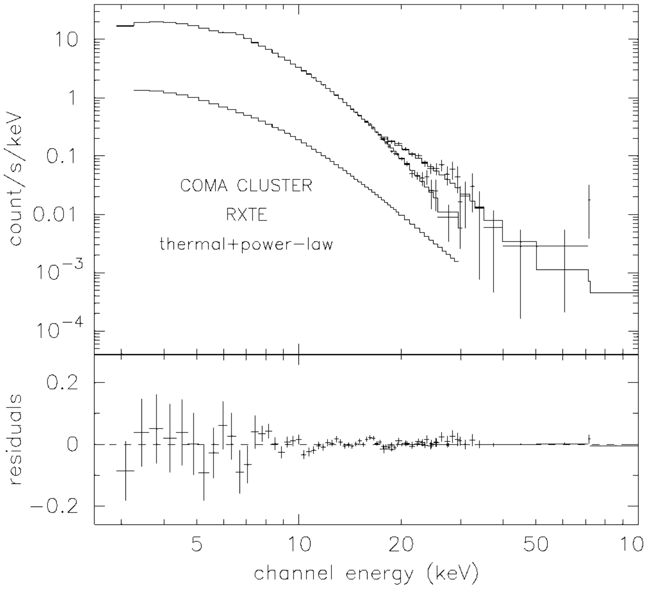

FIG. 1.—*RXTE* data and folded Raymond-Smith ($kT \simeq 7.51$) and power-law (index = 2.34) models; the latter component is also shown separately in the lower line.

To assess the theoretical viability of a continuous temperature distribution as an interpretation of the two thermal components, we consider a polytropic gas model, characterized by the index γ, the ratio of the gas specific heats. Formally, γ can assume only the discrete values 1, 4/3, and 5/3, corresponding to isothermal, relativistic, and adiabatic gas, respectively. By construction, $T(r)$ [$\propto n(r)^{\gamma-1}$] is a decreasing function of r which assumes the form $(1 + r^2/r_c^2)^{-3\beta(\gamma-1)/2}$ if the familiar isothermal density (n) profile is adopted. The gas core radius r_c and β were determined from the *ROSAT* image of Coma, $r_c \simeq 10.5' \pm 0.6'$, and $\beta \simeq 0.75 \pm 0.03$ (Briel, Henry, & Bohringer 1992). We have calculated the integrated flux from a polytropic gas, the mean emissivity-weighted temperatures in the regions $[0, r]$ and $[r, R_0]$, convolved over the triangular response of the PCA with $R_0 \simeq 58'$, all as functions of γ, β, and r. For the above values of γ, $0.6 \leq \beta \leq 0.8$, and the best-fit values of the normalization factors in Table 1, we find that the main spectral component originates from the inner $\leq 2r_c$ region, with the second component produced over the remaining (~40′) region within the PCA field of view. The ratio of the mean gas temperatures in these two regions is roughly comparable to the deduced value of ~0.6 only for $\gamma \sim 4/3$, a value appropriate in a relativistic gas. (This ratio is much smaller, ~0.35, for $\gamma = 5/3$.) But even if γ is viewed strictly as a free parameter, the mean temperatures are somewhat higher than found. Even for $\gamma \simeq 4/3$, these are ~9.3 and 5.4 keV, as compared with the most probable values of ~8.2 and ~4.7 keV found in the spectral analysis.

If a simple polytropic temperature distribution does not seem to be fully consistent with the parameters of the two-temperature fit, can these spectral components be explained as emission from $kT \sim 4.7$ keV gas clumps surrounded by hotter diffuse gas? The possibility that IC gas may be appreciably clumped, to the extent that its emission characteristics differ in a measurable way from those of uniformly distributed gas, was previously investigated in the context of an isobaric equilibrium model for the two components. Various considerations lead to the conclusion (e.g., Rephaeli & Wandel 1984; Holzapfel et al. 1997) that only a very small fraction of the gas can survive in small clumps over relevant cluster timescales (greater than 10^9 yr). It therefore seems that even though IC gas may not be fully isothermal, the deduced level of additional thermal emission (at a temperature significantly lower than ~8 keV) required to fit the *RXTE* data is higher than can be readily explained by either polytropic or clumpy gas distributions.

Perhaps a more viable and interesting possibility is that the additional spectral component is nonthermal. Consider, first, the possibility that the emission is from bright sources in the *RXTE* field of view. Of these, the brightest known background source is the Seyfert 1 galaxy X Comae. This active galactic nucleus has a redshift $z = 0.092$ and is located ~30′ northeast of the Coma center. Low-energy emission from X Comae was measured by *ROSAT*; the emission in the PSPC band (0.4–2.4) is best fit by a power law with a photon index 2.5 ± 0.16 and a luminosity of 1.4×10^{44} ergs s^{-1} in this band (Dow & White 1995). The extrapolated flux of this source at 10 keV is only ~3% of the flux in the second component deduced here. The few other known background sources contribute even less to the measured flux.

We are led to consider the possibility that the deduced spectral component is nonthermal emission resulting from Compton scattering of the radio-producing electrons by the CMB. Diffuse radio emission from the Coma Cluster was detected by many observers (e.g., Kim et al. 1990). The mean spectral flux from 21 measurements is

$$F_r \simeq (8.3 \pm 1.5) \times 10^{-12} \nu^{-1.34 \pm 0.06} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \quad (1)$$

in the frequency range 10–1420 MHz. While the power-law index varies across the cluster (Giovannini et al. 1993), the above value is an approximate average across the radio emitting region. These measurements imply the presence of electrons with energies in the (approximate) range 1–100 GeV. Scattering of these electrons by the CMB results in radiation in the range of 3 keV–30 MeV. The differential spectral photon flux at energy ϵ (in keV) depends strongly on the value of the mean, volume-averaged magnetic field B and is given in (Rephaeli 1979)

$$f_C \simeq (3.4 \pm 0.6) \times 10^{-18} B^{-2.34} \epsilon^{-2.34} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}. \quad (2)$$

The deduced nonthermal excess, $(1.9 \pm 0.4) \times 10^{-2} \epsilon^{-2.34}$ cm^{-2} s^{-1} keV^{-1}, yields $B \simeq (1.8 \pm 0.3) \times 10^{-7}$ G (90% confidence errors). With B determined, the flux is fully specified and can be easily integrated to obtain the estimated nonthermal X-ray luminosity in some energy band. Even though the exact value of the nonthermal luminosity is substantially uncertain given the errors in the power-law index and the electron energy range, it is clear that this luminosity is much higher than the radio luminosity. This follows from the fact that Compton energy losses of electrons are higher than their synchrotron losses by the ratio $8\pi\rho_0/B^2 \sim 316$, where ρ_0 is the CMB energy density.

While the mean value of the magnetic field is independent of the source size and distance (when it is assumed that the radio and nonthermal X-ray sources have the same size), the relativistic electron energy density ρ_e does depend on these quantities and the range of electron energies. Scaling to the observed radius of the diffuse radio emission, $R \sim 20'$, and integrating the electron energy distribution over energies in the observed radio and X-ray bands, we obtain $\rho_e \simeq 7.8 \times 10^{-14} (R/20')^{-3}$ ergs cm^{-3}, taking a distance of 139 Mpc (with $H_0 = 50$ km s^{-1} Mpc^{-1}). If the Galactic relation between the cosmic-ray proton and electron energy densities holds also in clusters, then the proton energy density can be as much as 100 times higher. This would imply that the cosmic-ray energy density in Coma is comparable to that in the Galaxy.

The flux in the nonthermal component reported here is only a factor of ∼4 lower than the upper limit obtained from the OSSE observation of Coma (Rephaeli et al. 1994). Archival *ASCA* measurements of the central region of Coma are best fit by a single-temperature Raymond-Smith model. Fitting these measurements with combined Raymond-Smith and power-law models hardly improves the fit (D. Marsden 1998, private communication), in marked contrast to the significantly better fit we obtain with the *RXTE* data. This simply reflects the far higher quality of the PCA measurements.

Diffuse EUV emission from the Coma Cluster was detected by the Deep Survey Telescope aboard the *Extreme Ultraviolet Explorer* (Bowyer & Berghofer 1998). The count rate is in excess of what is expected from the main X-ray–emitting gas and presumably cannot be explained simply by invoking a second, colder, $T \sim 10^6$ K, gas component. This, and a general similarity between the size and shape of the low-frequency radio and EUV emissions, led Bowyer & Berghofer (1998) to the conclusion that the excess EUV emission is largely nonthermal, resulting from Compton scattering of the CMB by a population of low-energy electrons. They adopt a value for the power-law index that is somewhat lower than the value used here, but also deduce $B \sim 0.2$ μG.

More directly relevant to the *RXTE* observations are similar observations of Coma with the Medium-Energy Concentrator/Spectrometer (MECS) and PDS instruments aboard the *BeppoSAX* satellite (Fusco-Femiano et al. 1998). These authors report the detection of a nonthermal component in the PDS data at energies 25–80 keV and find that $B \sim 0.16$ μG. Note that unlike the case with the *RXTE* measurements, an accurate spectral analysis of the combined MECS and PDS data was not possible because of the very different fields of view of these experiments. Also, because Fusco-Femiano et al. base their analysis only on the measurement of excess emission at energies greater than 30 keV, they obtain a very high value (greater than 40 keV) for the temperature of a second, thermal component. A more comprehensive discussion of all aspects of this work and a comparison between the *RXTE*, *BeppoSAX*, and EUV measurements will be given in a forthcoming paper.

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