NONTHERMAL ORIGIN OF THE EUV AND SOFT X-RAYS FROM THE COMA CLUSTER: COSMIC RAYS IN EQUIPARTITION WITH THE THERMAL MEDIUM

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ABSTRACT

The role of cosmic rays (CRs) in the formation and evolution of clusters of galaxies has been much debated. It may well be related to other fundamental questions, such as the mechanism that heats and virializes the intracluster medium (ICM) and the frequency at which the ICM is shocked. There is now compelling evidence, both from the cluster soft excess (CSE) and the “hard-tail” emissions at energies above 10 keV, that many clusters are luminous sources of inverse Compton (IC) emission. This is the first direct measurement of cluster CRs: the technique is free from our uncertainties in the ICM magnetic field and is not limited to the small subset of clusters that exhibit radio halos. The CSE-emitting electrons fall within a crucial decade of energy where they have the least spectral evolution and where most of the CR pressure resides. However, their survival times do not date them back to the relic CR population. By using the CSE data of the Coma Cluster, we demonstrate that the CRs are energetically as important as the thermal ICM: the two components are in pressure equiparition. Thus, contrary to previous expectations, CRs are a dominant component of the ICM, and their origin and effects should be explored. The best-fit CR spectral index is in agreement with the Galactic value.

Subject headings: cosmic rays — galaxies: clusters: general — intergalactic medium — radiation mechanisms: nonthermal — ultraviolet: general — X-rays: general

Recent research on clusters of galaxies unveiled a number of independent and contemporaneous indications that nonthermal activities in the intracluster medium (ICM) are at a much higher level than previously thought. First came the Extreme Ultraviolet Explorer discovery of 69–190 eV radiation in excess of that expected from the thermal ICM, confirmed by the ROSAT and BeppoSAX detections of similar soft X-ray (0.1–0.4 keV) excesses (Lieu et al. 1996a, 1996b; Bowyer, Lampton, & Lieu 1996; Fabian 1996; Mittaz, Lieu, & Lockman 1998; Bowyer, Lieu, & Mittaz 1998; Kaastra 1998). Details of the cluster soft excess (CSE) data suggest that the phenomenon is very plausibly due to inverse Compton (IC) emission by cosmic-ray (CR) electrons scattering off the cosmic microwave background (Ensslin & Biermann 1998; Haw 1997; Sarazin & Lieu 1998), with the original thermal scenario being eventually rejected because it requires an unrealistically large amount of rapidly cooling gas (Mittaz et al. 1998). Since clusters are rarely diffuse radio sources (Hansich 1982), the operation of IC scattering is not restricted in the most general approach (Sarazin & Lieu 1998) to the population of radio synchrotron electrons only. Second, the BeppoSAX discovery of hard X-ray tails in the spectra of several essentially randomly selected clusters (Kaastra 1998; Fusco-Femiano et al. 1998) again reveals that an active nonthermal ICM is commonplace. In this Letter, we focus on the Coma Cluster, which does possess a radio halo. We shall demonstrate for the first time that the energetics of CRs in this cluster are very important, but the facts come from the latest data which are not related to the radio properties of clusters. Our conclusion regarding the significance of CRs is therefore quite general.

We summarize how evidence of varying degrees of strength is now accumulating to form a compelling case that Coma’s CSE is indicative of intense nonthermal activity: (1) there is close resemblance in spatial morphology between the EUV emission and the radio halo, which is not shared by the thermal X-ray emission (Bowyer & Berghöfer 1998), (2) the CSE data are modeled to the same satisfaction with fewer parameters and components by a nonthermal spectrum (see below), (3) extrapolation of the best-fit CSE power-law model to hard X-ray energies leads to a predicted flux that agrees very well with the BeppoSAX detected hard-tail flux from this cluster (Fusco-Femiano et al. 1998, again see below); this greatly consolidates the IC interpretation.

The EUV and soft X-ray data of Coma (Lieu et al. 1996a) are modeled here with a power-law plus thermal spectrum to respectively describe the CSE and the X-ray emission. The best parameters are shown in Table 1, where it can be seen that reasonable goodness-of-fit is achieved using 2 fewer degrees of freedom than pure thermal models with gas at warm and hot temperatures (Lieu et al. 1996a). A stringent test of the correctness of this model is afforded by extrapolating the power law to the 20–80 keV passband and comparing the total predicted flux with the cluster hard X-ray excess flux measured by BeppoSAX (Fusco-Femiano et al. 1998). The agreement is within a factor of 2.

The differential photon number index is $\alpha \sim 1.75$ for all of the annular regions, which transforms to a similar index for the emitting electrons of $\mu \sim 2.5$, consistent with the index of $\mu = 2.7$ for Galactic CRs given the errors in $\alpha$ (Table 1). This, together with the fact that the acceleration (viz., diffusive shock acceleration; Axford, Leer, & Skadron 1977; Bell 1978a, 1978b; Blandford & Ostriker 1978; Krymsky 1977) and subsequent evolution (Ip & Axford 1985) of CRs involve the same physics at work in the ICM as those in the interstellar medium, strongly suggests that when investigating nonthermal processes in clusters our understanding of Galactic CRs cannot be ignored. In particular, limits on the total CR pressure may be inferred from the CSE data. Note that we will not involve the hard X-ray and radio data, since the pressure of these electrons is much lower.

Our ensuing conclusions regarding CR pressure may be changed if the electrons do not belong to the shock-accelerated

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CR population within Coma’s ICM. An alternative means of generating such highly relativistic electrons is by the jets (especially $e^+e^-$ pair jets) emanating from active galactic nuclei (AGNs). This mechanism cannot account for the data because the long diffusion time of electrons in the ICM (Völk, Aharonian, & Breitschwerdt 1996) renders it difficult for AGN outflows to form a large-scale diffuse population of radiating electrons. One would require a widespread distribution of AGNs, but the radio luminosity function of clusters reveals too few energetic AGNs to generate the CSE electrons. The electrons will have to be relic ones, injected at much earlier epochs when clusters had a larger number of AGNs. However, as demonstrated below, such electrons would not have survived the severe interim losses.

In Figure 1, we show the time evolution of CR spectra in the environment of the central region of Coma. The initial spectra follow those of Galactic CRs at the time of production (which for our purpose may be assumed instantaneous). In momentum space, both protons and electrons have a $p^{\alpha}$ power law. In energy space, this transforms to $E^{\alpha}$ at relativistic energies but flattens transrelativistically, eventually to $E^{-n/2}$ at low energies. Since the “flattening” occurs earlier for protons, for
equal numbers of both species injected to the shock at low energies, the protons will outnumber the electrons by a factor that is \( \gg 1 \) at energies \( \geq 0.1 \) GeV (a phenomenon quantitatively confirmed by observations; Webber 1983) and that increases with \( \mu \) along with the total pressure ratio of protons to electrons. Note especially that for an initial spectrum in the 0.1–1 GeV range relevant to the CSE, where the electrons are relativistic and the protons are transrelativistic, and the proton pressure per decade of energy is maximized, this pressure is already higher than that of the electrons by a factor of \( \sim 20 \).

As time progresses, the CRs will suffer losses. Escape is negligible for the energy range of interest (Völk et al. 1996), but particles smaller than 1 GeV will lose energy by Coulomb collisions with the hot ICM (Sarazin & Lieu 1998). More energetic protons are preserved because their principal loss mechanisms (knock-on collisions, neutron \( \beta \)-decay, and pion production) have interaction timescales (Marscher & Brown 1978) longer than a Hubble time. However, energetic electrons will be removed rapidly by IC and synchrotron losses (Sarazin & Lieu 1998), resulting in abrupt spectral cutoffs (Fig. 1). The total pressure ratio, which already has a large initial value, will therefore increase with time.

A parameter that places the present data in context is the ratio of the total proton pressure to the pressure of CSE-emitting electrons, with the latter defined as electrons having Lorentz factors between \( \gamma_{\text{min}} = 300 \) and \( \gamma_{\text{max}} = 775 \), since they can undergo IC scattering to produce photons within the CSE energy range of 0.069–0.4 keV according to the formula \( \gamma = 300(h \nu_{\text{CSE}}/75 \text{ eV})^{1/2} \). To begin with, \( r \) decreases slightly with time and reaches a broad minimum between 0.5 and 2 Gyr (1 Gyr = \( 10^8 \) yr); after that it rises sharply (see Fig. 2). The minimum exists because after creation the total proton pressure is rapidly reduced by the removal of low-energy protons, whereas the CSE electrons, which straddle between the regime of Coulomb and radiative losses, are in a band where the spectral evolution is minimized. Nonetheless, for evolutionary timescales in excess of 2 Gyr, no significant number of CSE electrons is expected, and the spectral slope is far steeper than our observed value. This places a severe limit on the age of the CRs and rules out the possibility of the CRs belonging to a relic population injected during the supernova “bright phase” of \( z \sim 2 \).

A potential effect on \( r \) concerns replenishment by secondary electrons as the pions decay. Protons with energies \( \geq 1 \) GeV, which encompass \( \sim 25\% \) of the initial CR pressure (Fig. 1), can interact with the hot ICM to produce pions, with the CSE-emitting electrons resulting from the subsequent pion decay carrying \( \sim 1\% \) of the pressure of the \( \geq 1 \) GeV protons (Marscher & Brown 1978). Thus, \( \sim 0.16\% \) of the CR pressure goes to creating CSE electrons within the pion loss \( e \)-folding time of 150 Gyr (Dennison 1980). Given that synchrotron and IC losses remove the initial \( r \sim 1\% \) electrons in \( \sim 3 \) Gyr, evidently the pion decay process played a negligible role in the evolution of the CSE electrons. Similar calculations reveal that replenishment is unimportant for electrons at all energies. However, the decay of neutral pions does result in a gamma-ray flux \( \sim 10 \) times below the current EGRET upper limit (Sreekumar et al. 1996), the detection of which would offer direct confirmation of the existence of energetic protons at CR proportions.

An estimate of the total CR pressure in Coma is available from our knowledge of \( r \) developed above and from the pressure \( P_r \) of the CSE electrons as determined observationally via the equation \( P_r = E_r \text{CSE}/3V \), with \( V \) being the volume of a cluster region and \( E_r \text{CSE} \) related to the deprojected CSE power-law luminosity \( L'_{r \text{CSE}} \) by

\[
E_r \text{CSE} = 8 \times 10^{41} L'_{42} \frac{3 - \mu}{2 - \mu} \frac{\gamma_{\text{max}}^2 - \gamma_{\text{min}}^2}{\gamma_{\text{max}}^2 - \gamma_{\text{min}}^2} \times L'_{\text{CSE}} \text{ergs,} \quad (1)
\]

where \( L'_{42} \) is \( L'_{r \text{CSE}} \) in units of \( 10^{42} \text{ ergs s}^{-1} \). The deprojection was performed by noting that the ratio \( L'_{r \text{CSE}}/L'_{\text{CSE}} \) of observed (i.e., projected) luminosities does not exhibit much variation with radius (see Table 1) and has an average value of 0.127, implying that a similar ratio of deprojected luminosities should also remain constant at this value. The ratio, coupled with the dependence of \( L'_{\text{CSE}} \) on radius as obtained from the \( \beta \) model (Briel, Henry, & Böhringer 1992), allows us to compute \( L'_{r \text{CSE}} \) and hence \( P_r \text{CSE} \).

The pressure ratio of thermal gas to CSE electrons is shown in Table 1, with the former obtained directly from the \( \beta \) model. The ratio varies from \( \sim 200 \) at the cluster center to \( \sim 700 \) at an angular radius of 16.5, with an overall value of \( \sim 250 \) for the entire sphere of radius 18'. Now from Figure 2 the total CR pressure is determined from \( P_r \text{CSE} \) via the value of \( r \) at a given age of the CRs, except this age is unknown because the epoch for the injection of such a vast amount of CRs remains to be explored (indeed, this epoch may not be unique). Nonetheless, as a conservative estimate of the CR pressure, we adopt the minimum value of \( r \), which is \( \sim 150 \) for \( \sim 1 \) Gyr of evolution.

Thus, within the entire 18' radius, the overall CR-to-gas pressure ratio is \( \sim 0.6 \), meaning that the two ICM components are already in approximate equipartition.

Can this profound consequence be avoided by varying certain aspects of the CR model used here? The electron spectral index is consistent with that of Galactic primary CRs and is constrained by the CSE data unless one assumes that the protons, which we do not measure, have a different index from the emitting electrons. However, theoretically the energetic protons are expected to have a smaller value of \( \mu \) since, unlike Galactic ones, cluster protons cannot escape (Völk et al. 1996), so if their spectrum differs from Galactic it should actually be closer to the \( \mu = 2.2 \) index at the acceleration source (i.e., strong shocks). Clearly a flatter proton index will increase the CR pressure further, so that the current estimate is in fact a lower limit.

In conclusion, the IC interpretation of the CSE, considered
highly plausible because of its theoretical self-consistency, the lack of conflict with earlier data (especially measurements of cluster baryonic contents), and the ability to explain the many varying behavior shown by the recent data (soft excess and hard-tails), has significant implications on our understanding of clusters. In particular, in order to account for the observed CSE flux of Coma, equipartition between CRs and gas is unavoidable. This means the role of ICM CRs (e.g., Berezhzinsky, Blasi, & Ptuskin 1997) should be investigated in the light of the latest observations, since it has an impact on our understanding of cluster evolution—in particular, the gas heating process and the history of the level of shock acceleration activity necessary to produce such a vast amount of CRs. One question is whether mergers (Henry 1995) can shock the ICM frequently and violently enough. Further, more detailed modeling of an evolutionary process which involves interactions between CRs, gas, and magnetic field within the gravitational potential well of the dark matter is now necessary. Certainly the common expectation of the CR pressure being $\sim 1\% - 10\%$ of the gas pressure—an expectation based on the past supernova rate as inferred from the iron abundance in the hot ICM—severely falls short of the current observations, which represent the first direct measurement of cluster CRs.

The detection of nonthermal emission also causes a downward revision of the gas mass, since the X-rays no longer have a completely thermal origin. For the entire $18'$ radius of Coma, our best-fit parameters indicate that the nonthermal component accounts for $\sim 22\%$ of the emission measure required by a purely thermal origin of the X-rays, and its presence implies a reduction in the gas mass by $\sim 11\%$.

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REFERENCES

Axford, W. I., Leer, E., & Skadron, G. 1977, Proc. 15th Int. Cosmic-Ray Conf. (Plowdiv), 11, 132
Bell, A. R. 1978a, MNRAS, 182, 147
———, 1978b, MNRAS, 182, 443
Berezhzinsky, V. S., Blasi, P., & Ptuskin, V. S. 1997, ApJ, 487, 529
Blandford, R. D., & Ostriker, J. P. 1978, A&A, 221, L29
Bower, S., Lampton, M., & Lieu, R. 1996, Science, 274, 1338
Bower, S., Lieu, R., & Mittaz, J. P. D. 1998, IAU Symp. 188, The Hot Universe, ed. K. Koyama, S. Kitamoto, & M. Itoh (Dordrecht: Kluwer), 52
Bower, S., & Berghöfer, T. 1998, ApJ, 506, 502
Briel, U. G., Henry, J. P., & Böhringer, H. 1992, A&A, 259, L31
Dennison, B. 1980, ApJ, 239, L91
Ensslin, T. A., & Biermann, P. L. 1998, A&A, 330, 90
Fabian, A. C. 1996, Science, 271, 1244
Fusco-Femiano, R., Dal Fiume, D., Feretti, L., Giovannini, G., Matt, G., & Molendi, S. 1998, in Proc. 32nd COSPAR Scientific Assembly, in press (astro-ph/9808012)
Hanisch, R. J. 1982, A&A, 111, 97
Henry, J. P. 1995, Nature, 377, 13
Hwang, C.-Y. 1997, Science, 278, 1917
Ip, W.-H., & Axford, W. I. 1985, A&A, 149, 7
Kaastra, J. 1998, in Proc. 32nd COSPAR Scientific Assembly, in press (astro-ph/9808012)
Krymsky, G. F. 1977, Dokl. Acad. Nauk SSSR, 234, 1306
Lieu, R., Mittaz, J. P. D., Bower, S., Breen, J. O., Lockman, F. J., Murphy, E. M., & Hwang, C.-Y. 1998, Science, 274, 1335
Lieu, R., Mittaz, J. P. D., Bower, S., Lockman, F. J., Hwang, C.-Y., & Schmitt, J. H. M. M. 1996b, ApJ, 458, L5
Marscher, A. P., & Brown, R. L. 1978, ApJ, 221, 588
Mittaz, J. P. D., Lieu, R., & Lockman, F. J. 1998, ApJ, 498, L17
Sarazin, C. L., & Lieu, R. 1998, ApJ, 494, L177
Sreekumar, P., et al. 1996, ApJ, 464, 628
Völk, H. J., Aharonian, F. A., & Breitschwerdt, D. 1996, Space Sci. Rev., 75, 279
Webber, W. R. 1983, in Composition and Origin of Cosmic Rays, ed. M. M. Shapiro (Dordrecht: Reidel), 83

Note added in proof.—Our current efforts on the cluster Abell 2199 (J. Kaastra et al., in preparation [1998]) involve simultaneous modeling of EUVE, ROSAT, and BeppoSAX data and reveal a nonthermal component that rises in prominence with cluster radius, consistent with the spatial behavior of the CSE in this and two other regular clusters: A1795 and A4038 (e.g., see Mittaz et al. 1998). The presence of a dominant relativistic electron population in the great voids of cluster fringes poses a major puzzle, especially for the BeppoSAX hard-tail energies where the electrons are extremely short lived.