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The Effect of a Non-Thermal tail on the Sunyaev-Zel'dovich Effect in Clusters of Galaxies

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Abstract

We study the spectral distortions of the cosmic microwave background radiation induced by the Sunyaev-Zel'dovich (SZ) effect in clusters of galaxies when the target electrons have a modified Maxwell-Boltzmann distribution with a high-energy non-thermal tail. Bremsstrahlung radiation from this type of electron distribution may explain the supra-thermal X-ray emission observed in some clusters such as the Coma cluster and A2199 and serve as an alternative to the classical but problematic inverse Compton scattering interpretation. We show that the SZ effect can be used as a powerful tool to probe the electron distribution in clusters of galaxies and discriminate among these different interpretations of the X-ray excess. The existence of a non-thermal tail can have important consequences for cluster based estimators of cosmological parameters.

Clusters of galaxies are powerful laboratories for measuring cosmological parameters and for testing cosmological models of the formation of structure in the Universe. These associations of large numbers of galaxies are confined by a much greater mass of dark matter, which also confines a somewhat smaller mass in very hot gas. The galaxies and the gas are in rough virial equilibrium with the dark matter potential well. While initially clusters

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were investigated through the observed dynamics of the galaxies they contain, in recent decades much information has been gathered from studies of the gas, primarily via X-ray observations of bremsstrahlung emission but also through the Sunyaev-Zel'dovich (SZ) effect [1]. Interpreting these observations requires a detailed understanding of the thermodynamic state of the gas. With increasingly more sensitive measurements, the gas dynamics should become clearer which would allow for a better understanding of the structure and dynamics of clusters as well as their effectiveness as tests of cosmological models.

Both the X-ray emission and the SZ effect are sensitive to the energy distribution of the electrons. It is usually assumed that in the intracluster gas the electron energy distribution is described by a thermal (transrelativistic Maxwell-Boltzmann) distribution function. The typical equilibration time for the bulk of this hot and rarefied electron gas is of order $\sim 10^5$ years and is mainly determined by electron-electron Coulomb scattering (electron-proton collisions are much less efficient). This time rapidly increases when the electron energy becomes appreciably larger than the thermal average, so that thermalization takes longer for higher energy electrons. In the absence of processes other than Coulomb scatterings, the electron distribution rapidly converges to a Maxwell-Boltzmann distribution. However, the fact that the intracluster gas may be (and actually is often observed to be) magnetized, can change this simple scenario: for instance, cluster mergers can modify the electron distribution either by producing shocks that diffusively accelerate part of the thermal gas, or by inducing the propagation of MHD waves that stochastically accelerate part of the electrons and heat most of the gas [2]. Although the bulk of the electron distribution is likely to maintain its thermal energy distribution, higher energy electrons, more weakly coupled to the thermal bath, may acquire a significantly non-thermal spectrum [2].

Until recently, X-ray observations could only probe energies below ~ 10 keV, where the observed radiation is consistent with bremsstrahlung emission from the intracluster plasma with a thermal electron distribution with temperatures in the $1 - 20$ keV range. The recent detection of a hard X-ray component in excess of the thermal spectrum of the Coma cluster [3] may be the first indication that the particle distribution in (some) clusters of galaxies

contains a significant non-thermal component. Observations of Abell 2199 [4] show a similar excess while no excess has been detected in Abell 2319 [5], thus, the source of this effect may not be universal.

As argued above, the presence of magnetic fields in the intracluster gas allows for acceleration processes that can modify the details of the heating processes, so that the electron energy distribution may differ from a Maxwell-Boltzmann. In this case, the bremsstrahlung emission from a modified Maxwell-Boltzmann electron gas can account for the observed X-ray spectra, up to the highest energies accessible to current X-ray observations [6,2]. This model works as an alternative to the more traditional interpretation based on the inverse Compton scattering (ICS) emission from a population of shock accelerated ultra-relativistic electrons [7]. The ICS model has many difficulties such as the requirement that the cosmic ray energy density be comparable to the thermal energy in the gas [6,8]. This unreasonably large cosmic ray energy density is hard to reconcile with the nature of cosmic ray sources in clusters [9] and with gamma ray observations [10]. Moreover, the combination of X-ray and radio observations within the ICS model strongly indicates a very low magnetic field, $B \sim 0.1\mu G$, much lower than the values derived from Faraday rotation measurements [11,12].

The best way to resolve the question of whether the observed hard X-rays are due to ICS or are the first evidence for a modified thermal electron distribution in clusters is to probe directly such a distribution. We propose that this probe can be achieved by detailed observations of the SZ effect, which is the change in brightness temperature of the cosmic microwave background (CMB) photons when they traverse a hot electron gas such as the gas in clusters. In the following, we calculate the SZ effect for a modified electron distribution, including a high energy tail. We follow the procedure outlined in [13].

Photons of the CMB propagating in a gas of electrons are Compton scattered and their energy spectrum is modified. As long as the center-of-mass energy of the collision is less than $m_e c^2$, the scattering is accurately described by the Thomson differential cross-section. For CMB photons at low redshift this only requires that the electron energy in the cosmic

rest-frame be less than $\sim 1\,\mathrm{TeV}$. For scattering of a photon with initial frequency ν_i, off an isotropic distribution of electrons each with speed v, the probability distribution of the scattered photon having frequency $\nu_\mathrm{i}(1 + \Delta)$ is [14]

$$P(\Delta, \beta)\, d\Delta = \frac{\overline{F}(\Delta, \beta\,\mathrm{sgn}(\Delta))}{(1 + \Delta)^3}\, d\Delta \;, \qquad \Delta \in \left[-\frac{2\beta}{1 + \beta}, \frac{2\beta}{1 - \beta}\right] \tag{1}$$

where $\beta = \frac{v}{c}$ and

$$\overline{F}(\Delta, b) = \left| \frac{3(1 - b^2)^2(3 - b^2)(2 + \Delta)}{16 b^6} \ln \frac{(1 - b)(1 + \Delta)}{1 + b} + \frac{3(1 - b^2)(2b - (1 - b)\Delta)}{32 b^6 (1 + \Delta)} \right.$$
$$\left. \times \left(4(3 - 3b^2 + b^4) + 2(6 + b - 6b^2 - b^3 + 2b^4)\Delta + (1 - b^2)(1 + b)\Delta^2\right) \right| . \tag{2}$$

If instead of a fixed speed, we consider the scattering off electrons with a distribution of speeds, $\mathrm{p}(\beta)\, d\beta$, the distribution of Δ after one scattering is

$$P_1(\Delta) = \int_{|\Delta|/(2+\Delta)}^{1} d\beta\, \mathrm{p}(\beta)\, P(\Delta, \beta) \;. \tag{3}$$

This expression can be easily applied to determine the change in the spectrum of the CMB as seen through the hot gas in a cluster of galaxies. Since clusters have a small optical depth to Compton scattering ($\sim 10^{-2}$), the fraction of photons which are scattered is given by the optical depth, $\tau_\mathrm{e} = \sigma_\mathrm{T} N_\mathrm{e}$, where N_e is the projected surface density of free electrons. The change in brightness of the CMB at frequency ν due to the SZ effect is then given by

$$\Delta I(\nu) = \frac{2h\,\nu^3}{c^2}\tau_e \int_{-1}^{+\infty} d\Delta\, P_1(\Delta) \left[\frac{(1 + \Delta)^3}{e^{(1+\Delta)\,x} - 1} - \frac{1}{e^x - 1}\right], \tag{4}$$

where $x \equiv \frac{h\nu}{k_\mathrm{B} T_\mathrm{CMB}}$, T_CMB is the CMB temperature at the present epoch, and k_B is Boltzmann's constant. It is conventional in CMB studies to use the change in the thermodynamic brightness temperature rather than the change in brightness, the former being given by

$$\frac{\Delta T}{T_\mathrm{CMB}} = \frac{(e^x - 1)^2}{x^4\, e^x} \frac{\Delta I}{I_0} \tag{5}$$

where $I_0 \equiv \frac{2(k_B T_\mathrm{CMB})^3}{(hc)^2}$.

For very non-relativistic electrons, $P_1(\Delta)$ is narrowly peaked and can be accurately estimated via a 1st order Fokker-Planck approximation. This gives the classical formula [1]

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$$\frac{\Delta T}{T_{\mathrm{CMB}}} = y \left(x \frac{e^x + 1}{e^x - 1} - 4 \right) , \qquad (6)$$

where $y = \frac{1}{3}\tau_{\mathrm{e}} \langle \beta^2 \rangle$. In this limit the shape of the spectral distortion yields no useful information, only the amplitude, y, is interesting but it depends only on the 2nd moment of $\mathrm{p}(\beta)$. Fortunately the gas in rich clusters is hot enough for relativistic corrections to become important, leading to deviations from this classical formula at the $\sim 10\%$ level [13–17]. Through these relativistic corrections, changes in the electron energy distribution can be measured by the modified shape of the SZ spectrum, hence the shape of the SZ effect can be used to differentiate between thermal and non-thermal models. Even without spectral information, non-thermality can be inferred by the comparison of the X-ray flux and temperature with the amplitude of ΔT_{SZ}, however this requires a detailed model of the density structure of the cluster since the SZ effect and bremsstrahlung emission scale differently with density.

The SZ effect is usually computed assuming a thermal $\mathrm{p}(\beta)$, but here we include the effect of a non-thermal tail. We adopt the model for the distribution function used in [6] which fits both the non-thermal hard X-ray data and the thermal soft X-ray data. In particular, a thermal distribution for momenta smaller than p^* $(\equiv m_e c \beta^* \gamma^*)$ is matched to a power law distribution in momentum above p^*, and cutoff at momentum $p_{\max}$ $(\equiv m_e c \beta_{\max} \gamma_{\max})$ i.e.

$$\mathrm{p}(\beta) = \frac{C \gamma^5 \beta^2}{\Theta\, K_2(\frac{1}{\Theta})} \times \begin{cases} \exp(-\frac{\gamma}{\Theta}) & \beta \in [0, \beta^*] \\ \exp(-\frac{\gamma^*}{\Theta}) \left(\frac{\beta^* \gamma^*}{\beta \gamma}\right)^{\alpha+2} & \beta \in [\beta^*, \beta_{\max}] \\ 0 & \beta \in [\beta_{\max}, 1) \end{cases} . \qquad (7)$$

where $\gamma = \frac{1}{\sqrt{1-\beta^2}}$, $\gamma^* = \frac{1}{\sqrt{1-\beta^{*2}}}$, $\Theta = \frac{kT}{m_e c^2}$ gives the temperature of the low energy thermal distribution, and C (≈ 1) normalizes the function to unit total probability. For instance, in the model proposed in [2], a cutoff at $\beta_{\max}\gamma_{\max} \sim 1000$ arises naturally and insures that the electrons in the tail do not affect the synchrotron radio emission, but has little effect on the SZ spectrum. For $\gamma_* \gg 1$ one finds $C = 0.982$, indicating that only 1.8% of the electrons are in the non-thermal tail, however the electron kinetic energy is increased by 73% and the electron pressure by 48%, so the hydrodynamical properties of the gas can be greatly influenced by the non-thermal component.

The bremsstrahlung emissivity is given by

$$q_{brem}(k_\gamma) = n_{gas} \int dp \ n_e(p) \ v(p) \ \sigma_B(p, k_\gamma),$$ (8)

where n_{gas} is the gas density in the cluster, $v(p)$ is the velocity of an electron with momentum p and k_γ is the photon momentum. The bremsstrahlung cross section, σ_B, is taken from [18]. In deriving eq. (8), we assumed for simplicity that the cluster has constant density and temperature, but our results can be easily generalized to the more realistic spatially varying case.

As shown in [6], there is a wide region in the p^*-α parameter space that matches the observations. We choose the values $\beta^*\gamma^* = 0.5$ and $\alpha = 2.5$ that provide a good fit to the overall X-ray data, as shown in Fig. 1, where the thermal component has a temperature $T = 8.21$ KeV. The data points are from BeppoSAX [19] observations, while the thick curve is the result of our calculations for a suitable choice of the emission volume.

The basic question that we want to answer is whether the non-thermal tail in the electron distribution produces distortions in the CMB radiation that can be distinguished from the thermal SZ effect. To answer this question, we calculate the SZ spectrum using eq.s (4&5), plotting the results in Fig.s 2&3, for a thermal model and two non-thermal models, each based on Coma. There is an appreciable difference between the curves, as large as $\sim 60\%$ at high frequencies ($x > 5$), and at low frequencies ($x < 1.7$), the region currently probed by most SZ observations, the relative difference is at the level of $\sim 10 - 20\%$.

Of particular interest observationally is the frequency of the zero SZ spectral distortion, x_0, defined by $\Delta I(x_0) = \Delta T(x_0) = 0$. Measuring the difference in the CMB flux on and off the cluster near the zero allows the measurement of small deviations from eq. (6) with only moderate requirements on the calibration of the detector, and is very sensitive to the radial velocity of the cluster in the CMBR frame, v_c. For a thermal plasma [13]

$$x_0 = 3.830 \left(1 + 1.13 \Theta + 1.14 \frac{\beta_c}{\Theta}\right) + \mathcal{O}(\Theta^2, \beta_c^2)$$ (9)

where $\Theta = \frac{kT_e}{m_e c^2}$, $\beta_c = \frac{v_c}{c}$. Eq (9) is no longer valid for a non-thermal electron distribution. For our canonical parameters, no cutoff, and $v_c = 0$, we find that x_0 is shifted to 3.988, the

same as would be obtained for a thermal distribution with an unreasonably large temperature of $18.62\,\mathrm{keV}$, and $v_c = 0$, or with the "correct" temperature ($8.21\,\mathrm{keV}$) and $v_c = 111\,\mathrm{km/sec}$. Even with our non-thermal tail it is the velocity which mostly determines the value of x_0, although the non-thermal electrons can bias the v_c determinations by $\sim +10^2\,\mathrm{km/sec}$.

To conclude, we mention other important consequences of the existence of a non-thermal electron distribution. As noted above the non-thermal component might correspond to only a few percent in additional electrons which do not contribute significantly to the nearly thermal 1-10 keV X-ray emission, while at the same time the electron pressure may be increased by nearly a factor of two (we have no evidence whether there is similar increase in the ion pressure). Many cluster mass estimates which are based on X-ray observations, use the hydrostatic relation $M_c \propto \nabla p / \rho$, and if the pressure has been significantly under-estimated due to non-thermal electrons the cluster mass would also be underestimated. Cluster masses play an important role in normalizing the amplitude of inhomogeneities in cosmological models, and the non-thermal electron populations may lead to an underestimate in this cluster normalization. The baryon fraction in clusters have also been used as an indicator of the universal baryon-to-mass ratio, Ω_b / Ω_m. If a cluster mass is underestimated due to non-thermal electrons then the cluster baryon fraction will be overestimated. Note that the Coma cluster, which does have a non-thermal X-ray excess, has played a particularly important role in cluster Ω_b / Ω_m estimates.

Using a combination of X-ray and SZ measurements, clusters have been used to estimate Hubble's constant, $H_0 \propto I_X / (\Delta T_{SZ})^2$ [13]. We have shown that a non-thermal electron distribution generally increases ΔT_{SZ} for fixed τ_e and Θ, and therefore one should use a larger proportionality constant when non-thermal electrons are present. Therefore cluster estimates of H_0 without taking into account a non-thermal electron distribution would under-estimate H_0.

If our model of the non-thermal tail held universally then naive estimates of M_c, Ω_b / Ω_m, and H_0 should be respectively adjusted upward, downward, and upward by 10's of percent. However estimates of cosmological parameters using clusters generally make use of measure-

ments of an ensemble of clusters. Supra-thermal X-ray emission does appear in two of three clusters, but the statistics are not good enough for an accurate prediction of how frequently a non-thermal electron distribution might be present in a sample of clusters. Therefore the overall bias introduced in parameter estimates is necessarily uncertain. In any individual cluster the bias in a parameter estimator will depend on the spatial distribution of the non-thermal electrons, which is also uncertain and not well-constrained by present hard X-ray measurements. The important point is that the magnitude of cosmological parameter mis-estimation might be quite large.

Confirmation or refutation of the hypothesis that the X-ray excess is due to a non-thermal tail will have important consequences not only for the understanding of cluster structure but for cosmology as well. We argue that SZ measurements are the best way to test this hypothesis, and illustrate in figure 4 that this is within the capabilities of present technology.

I. ACKNOWLEDGEMENTS

REFERENCES

[1] Y.B. Zel'dovich and R.A. Sunyaev, Ap. & Sp. Sci. **4**, 301 (1969).

[2] Blasi, P. 1999, To be published in Astrophys. J. Lett. (preprint astro-ph/0001344).

[3] R. Fusco-Femiano, D. Dal Fiume, L. Feretti, G. Giovannini, P. Grandi, G. Matt, S. Molendi, and A. Santangelo, Astrophys. J. Lett. **513**, L21 (1999)

[4] J.S. Kaastra, R. Lieu, J.P.D. Mittaz, J.A.M. Bleeker, R. Mewe, S. Colafrancesco and F.J. Lockman, preprint astro-ph/9905209.

[5] S. Molendi, S. De Grandi, R. Fusco-Femiano, S. Colafrancesco, F. Fiore, R. Nesci, and F. Tamurelli, Astrophys. J. Lett. **525**, L73 (1999).

[6] T.A. Enßlin, R. Lieu, and P.L. Biermann, preprint astro-ph/9808139.

[7] H.J. Volk, and A.M. Atoyan, preprint astro-ph/9812458.

[8] P. Blasi and S. Colafrancesco, Astropart. Phys., **12**, 169 (1999).

[9] V.S. Berezinsky, P. Blasi and V.S. Ptuskin, Astrophys. J. **487**, 529 (1997).

[10] P. Blasi, Astrophys. J. **524**, 603 (1999)

[11] K.-T. Kim, P. P. Kronberg, P.E. Dewdney and T.L. Landecker, Astrophys. J., **355**, 29 (1990).

[12] L. Feretti, D. Dallacasa, G. Giovannini and A. Taglianai, A&A **302**, 680 (1995).

[13] M. Birkinshaw, Phys. Rep. **310**, 97 (1999).

[14] A. Stebbins, in *The Cosmic Microwave Background* ed.s C.H. Lineweaver, J.G. Bartlett, A. Blanchard, M. Signore, & J. Silk (Dordrecht: Kluwer) pp 241-270 (1997).

[15] Y. Rephaeli, Astrophys. J. **445**, 33 (1995).

[16] A. Challinor and A. Lasenby, Astrophys. J. **499**, 1 (1998).

[17] N. Itoh, Y. Kohyama and S. Nozawa, Astrophys. J. **502**, 71 (1998).

[18] E. Haug, A&A **326**, 417 (1997).

[19] Courtesy of R. Fusco-Femiano.

Figure Captions:

Fig. 1

X-ray emission from the Coma cluster for the modified electron distribution adopted in our calculations. The solid line is for $\beta_{max}\gamma_{max} = \infty$ while the dashed line is for $\beta_{max}\gamma_{max} = 1$. The dotted line is the contribution expected from a purely thermal electron distribution.

Fig. 2

Fractional brightness change normalized to the opacity) as a function of the dimensionless frequency x. Lines are labelled as in Fig. 1.

Fig. 3

Fractional temperature change as defined in eq. (6). The lines are labelled as in Fig. 1.

Fig. 4

Here we more closely compares the difference between a thermal and non-thermal SZ spectrum using our model parameters for the Coma cluster. We plot the difference between ΔT and $\Delta T_{\text{fiducial}}$, where $\Delta T_{\text{fiducial}}$ is given by the classical formula, eq (6). We have adjusted an additive constant to each of the spectra, corresponding to the unknown contribution of the primordial anisotropies and the kinematic SZ effect, so that all the spectra match at $32\,\text{GHz}$ where the SZ effect has been measured in Coma, and at $218\,\text{GHz}$, near x_0. We have also adjusted the overall amplitude, set by τ_{e}, to match the the reported peak SZ decrement of $-505\,\mu K$. The gray curve gives this difference for a thermal spectrum with $T_{\text{e}} = 8.21\,\text{keV}$, which fits the 1-10 keV X-ray data, and the black curve gives this difference for our model non-thermal spectrum which fits all of the X-ray data. We see that over a broad range of frequencies one must measure ΔT with an accuracy of better than $10\,\mu\text{K}$ in order to distinguish the two models.