Non-thermal intracluster medium: a simultaneous interpretation of the central soft X-ray excess and WMAP’s detection of reduced Sunyaev-Zel’dovich Effect

Richard Lieu\textsuperscript{1} and John Quenby\textsuperscript{2}

\textsuperscript{1}Department of Physics, University of Alabama, Huntsville, AL 35899.
\textsuperscript{2}Blackett Laboratory, Imperial College, London, SW7 2BZ, U.K.

ABSTRACT

WMAP’s detection of the Sunyaev-Zel’dovich effect (SZE) at a much reduced level among several large samples of rich clusters is interpreted in terms of conventional physics. It is by now widely believed that the central soft X-ray and EUV excess found in some clusters cannot be of thermal origin, due to problems with rapid gas cooling and the persistent non-detection of the O VII line, but may arise from inverse-Compton scattering between intrachannel relativistic electrons and the cosmic microwave background (CMB). In fact, recently Chandra and XMM observations of the soft X-rays from Abell 3112 are well fitted by the sum of a power law and a thermal virialized gas component of comparable luminosities. Therefore the missing SZE flux could simply be due to an overestimate of the central density of virialized electrons which scatter the CMB. We also considered if higher energy electrons drawn from the same power-law population as those responsible for the soft excess may synchrotron radiate in the intrachannel magnetic field of strength $B \lesssim$ a few $\mu$G to produce cluster microwave emissions in the WMAP passbands that account for the missing SZE flux. Either explanation of the WMAP anomaly would bolster the current model of central cluster soft excesses, viz. non-thermal activities prevail in the core of at least some clusters. The energetic electrons may originate from AGN jet injection, then distributed cluster-wide with accompanying \textit{in situ} Fermi acceleration, by Alfvén waves. However the missing thermal electron explanation provides a less demanding model.

1. Introduction

In a recent paper, Lieu, Mittaz, Zhang 2006 (LMZ06) published the hitherto most comprehensive direct correlation of the \textit{Wilkinson Microwave Anisotropy Probe} first year
(WMAP1) data with the X-ray data of ROSAT and ASCA, in search for the SZE in the temperature of the cosmic microwave background (CMB) along the directions to 31 randomly chosen rich clusters located above the Galactic plane. The WMAP1 passbands being analyzed cover the frequency range of 41 – 94 GHz. This investigation led to the astonishing finding that on average the level of SZE detected by WMAP1 is no deeper than the intrinsic CMB primary anisotropy as seen by WMAP in directions of blank sky (i.e. away from rich clusters and groups), and in any case accounts only for 1/3 to 1/4 of the level expected from the X-ray measurements of the sample clusters. Moreover, LMZ06 explored and excluded a variety of possible reasons for the discrepancy, including emission by radio point sources in the clusters, which fail by a large margin to deliver sufficient flux to explain the apparent lack of SZE in the WMAP1 W-band of 94 GHz. The results of LMZ06 were corroborated recently by Bielby & Shanks 2007, which presented a similar correlation study between WMAP3 and X-ray observations by Chandra and ROSAT, and likewise reported a substantially less than expected SZE in the WMAP3 data for a much larger sample size than the 31 clusters of LMZ06. The additional information provided by Bielby & Shanks 2007 also included a ‘truncation test’ where the authors abruptly cut off the X-ray gas profiles of the Chandra cluster sample at a radius as small as 2 arcmin, and still found a SZE discrepancy of a factor of two along the central line-of-sight. Thus the anomaly is real and must be resolved.

A separate and superficially unrelated phenomenon of clusters is the discovery of excess EUV and soft X-ray emission in the energy range 0.1 – 1.0 keV which rises above the level expected from the spectrum of the hot virialized cluster gas. This property has been known for more than one decade to exist in some clusters (e.g. Lieu et al 1996, Kaastra et al 1999, Nevalainen et al 2003). In this paper we demonstrate that it is possible to connect the non-thermal inverse Compton interpretation of the cluster soft excess (Hwang 1997, Ensslin & Biermann 1998, Sarazin & Lieu 1998) with the SZE anomaly in WMAP by extending the dynamic range off this power-law distribution of electrons, so that the number density of electrons causing the SZE scattering is actually reduced. We also examine the viability of attributing any remaining SZE flux discrepancy (after the above effect is taken into account), to synchrotron radiation from an unmapped intracluster population of relativistic electrons.

Apart from the three 1997-98 papers, there have been numerous suggestions of a general, non-thermal intracluster environment, an early example being Jaffe (1977) and, more recently, Quenby et al (1999). In particular, a model of the acceleration via Alfven waves driven by major cluster mergers is given by Brunetti et al (2004). Of further interest is the idea that relativistic jets carry a significant portion of the total energy output of radio galaxies, causing X-ray emission up to Mpc distance scales (Ghiellini & Celotti 2001). Celotti, Ghisellini, & Chiaberge (2001) provided an analysis of such a scenario for PKS 0637-752.
Unless a separate physical mechanism is proposed (and indeed there is at least one serious paper on the prospect of neutralino dark matter decay as a cluster’s non-thermal reservoir, see Colafrancesco, Profumo, & Ullio 2006), the possibility of cosmic rays as the key to solving the soft excess and S-Z puzzles hinges upon the manner in which energy from AGN is distributed widely throughout a cluster, and the speed in which re-acceleration can compensate for losses. It is well known that Böhm diffusion happens too slowly for this purpose (see section 3). Our model invokes Alfven waves as the spreading agent which is also responsible for rapid Fermi statistical acceleration.

2. Overall cluster non-thermal picture and energy budget

We assume a continuous non-thermal injection rate into the cluster environment of $10^{45}$ ergs s$^{-1}$ in both electron output and Poynting flux. This is based upon the analysis of observations by Ghisellini and Celotti (2001) and the the numbers arising from jet injection in the hydrodynamic models of Zanni et al (2005). The jet may be of cluster size in one dimension (Nulsen et al 2005). The cluster radius is assumed to be $\sim 1$ Mpc and the intrachannel magnetic field in the range 1 to 10 $\mu$G. (e.g. Govoni et al 2001; Medvedev, Silva, & Kamionkowski 2005). Ambient gas density is $\sim 10^{-4}$ to $10^{-3}$ cm$^{-3}$ (e.g. Brunetti et al 2004). We also took a typical cluster distance of 400 Mpc, an appropriate number for the clusters of the LMZ06 sample, since the mean redshift of the sample is $z = 0.1$, corresponding to a distance of 428.57 Mpc in a $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $h = 0.7$ cosmology (Bennett et al 2003, Spergel et al 2006).

While an energetic jet existing a reasonable fraction of the lifetime of a large, relaxed cluster can transport energy in one dimension on a cluster scale of 1.0 Mpc in $10^9$ year for a jet propagating at 1000 km s$^{-1}$, a more general three dimensional dispersion mechanism is necessary to account for the distributed acceleration required here. We adopt a $B=6$ $\mu$G magnetic field, tangled on a $\leq 1$ kpc scale over the central 0.5 Mpc region and a density of $10^{-3}$ cm$^{-3}$ (eg Coma cluster, Fretti et al., 1995) as representative parameters. Alfven waves then move with velocity $V_A = B/\sqrt{4\pi \rho} \approx 410$ km/s, allowing the transport of non-thermal energy over a cluster volume, radius 0.4 Mpc, in $10^9$ years. Instabilities within the jet and at the edges may produce the Alfven waves which continue to spread the energy after the bulk flow is dissipated. Rayleigh-Taylor and Kelvin-Helmholz instabilities in particular were mentioned by Zanni et al (2005). These authors show how the disturbance in density and entropy could have spread after the jet and shock were switched off, the computations being followed up to $10^9$ years.

Medvedev, Silva, & Kamionkowski (2005) computed a model of cluster-wide field am-
plification caused by the non-relativistic Weibel instability, although only 0.1% of the total energy ends up in the magnetic field. They claim that the short wavelength turbulence initially generated gives rise to much longer wavelengths on a cosmological time scale. Nishikawa et al, 2003, provide an example of this instability generating turbulence in a relativistic jet. Merger shocks and intense stellar winds are alternative sources of heat input to the cluster medium which may add to the wave energy. Fretti et al (2004) developed this idea and fitted synchrotron and inverse Compton models to observed spectra, based on giant radio halos.

3. Cluster soft excess and power law component

3.1. Soft excess

A non-thermal component to the electron spectrum is indicated by measurements of a cluster soft excess from regions where thermal gas at a temperature considerably lower than virial is not likely to exist. Sarazin and Lieu (1998) estimated the intracluster cosmic ray electron energy necessary to account for the observed EUV luminosity of some clusters as due to inverse Compton (IC) interaction between the electrons and the CMB. The IC radiation power is predominantly in the EUV and soft X-rays waveband, when the CMB scatters off lower energy (300 ≲ γ ≲ 1,000) electrons. They quoted

\[ L_{\text{IC}} = \frac{4}{3} \frac{\sigma T}{m_e c^2} \bar{\gamma} U_{\text{CMB}} E_{\text{CR}} \]  

and demanded

\[ E_{\text{CR}} \sim 2.4 \times 10^{62} \left( \frac{L_{\text{EUV}}}{10^{45} \text{ ergs s}^{-1}} \right) \left( \frac{\bar{\gamma}}{300} \right)^{-1} \text{ ergs} \]  

For A1795 \( L_{\text{EUV}} \) may be as high as \( 10^{45} \text{ ergs s}^{-1} \) (Mittaz, Lieu, and Lockman 1998), while for the Coma cluster it is \( \sim \) a few \( \times 10^{42} \text{ ergs s}^{-1} \) (Lieu et al 1999). Thus \( E_{\text{CR}} \) ranges from \( 10^{59} \) to \( 10^{62} \text{ ergs s}^{-1} \). We will take the larger of the two values of cosmic ray energy content, viz. \( 10^{62} \text{ erg} \), as requiring explanation. Further, we map the IC output photons to electrons in the energy range just above 100 MeV, and assume that the electron spectrum cuts off at energies much below this value.

Recently, the report of strong soft X-ray excess in the cores of the clusters AS1101 (Werner et al 2007) and A3112 (Bonamente et al 2007) bolsters the non-thermal interpretation of the soft excess from cluster centers. The alternative model which invokes a warm thermal component to account for the excess must explain how this component can co-exist with the hot virialized cluster medium without being clumped into rapidly cooling high density clouds. Moreover, stringent upper limits on the amount of intracluster O VII were
derived from these observations, due to the absence of detectable signatures of O VII emission, the most sensitive tracer of warm gas hitherto available (see also Lieu & Mittaz 2005). The 2-7 keV luminosity of the power-law population of emitted photons required to fit the soft excess data is an appreciable fraction of the total X-ray luminosity in this passband, reaching 30% in the case of A3112 (Bonamente et al 2007).

3.2. Power law and hard excess

To understand how the presence of non-thermal electrons could mean a significant reduction in the total density of electrons in the region of concern of a cluster, let us compare the radiative losses of a single electron by thermal bremsstrahlung and inverse Compton scattering. In an electron-proton plasma, the thermal loss at energy $E$ and velocity $\beta c$ is

$$P_{\text{thermal}} = \frac{dE}{dt} = -\frac{\alpha r_e^2}{\beta^2} e \beta c n \bar{g} E$$

for plasma density $n$, Gaunt factor $\bar{g} \approx 1$, electron radius $r_e$ and fine structure constant $\alpha$. For inverse Compton losses at electron Lorentz factor $\gamma$,

$$P_{\text{non-thermal}} = \frac{dE}{dt} = -\frac{32}{9} \pi r_e^2 cn_{ph} \hbar \nu \gamma^2$$

where $n_{ph} \hbar \nu$ is the CMB energy density. Hence the ratio of thermal to non-thermal power is

$$\frac{P_{\text{thermal}}}{P_{\text{non-thermal}}} = \frac{0.67 \bar{g}}{\gamma^2}$$

at a virialized gas temperature of $kT = 9.5$ keV. Hence the required number density of $\gamma = 300$ electrons is down by a factor $\sim 10^5$ relative to the number density of 10 keV electrons.

The energetic, cosmic ray electrons in the cluster should not exceed equipartition with the magnetic field. To see that there is no danger here, take an X-ray luminosity of $5 \times 10^{44}$ ergs s$^{-1}$ for the central 0.5 Mpc cluster region and, using the IC loss rate of

$$\frac{dE}{dt} = 2.6 \times 10^{-14} \gamma^2 U_{\text{CMB}} = 1.04 \times 10^{-26} \gamma^2 \text{ ergs s}^{-1}.$$ 

one obtains a cosmic ray number density of $2 \times 10^{-8}$ cm$^{-3}$ and an energy density $5 \times 10^{-12}$ ergs cm$^{-3}$; this is to be compared with an equivalent equipartition field, which is as high as $10\mu$ G.

Evidence for cross-check the determination of a cluster’s mass by attributing all its X-ray luminosity to a hot virialized gas came from weak gravitational lensing. Smail et
al. (1997) find a 75% efficiency correction is needed to the lens shear strengths to bring X-ray determined masses into agreement. A lower X-ray cluster mass resulting from some of the emitted X-rays being of non-thermal origin would imply a higher efficiency of shear measurement, i.e. the correction factor of 75% may not be necessary. Adoption of the reduced number density in the thermal electron cluster component will also lead to an increase in the heavy element abundances inferred from line intensities because the continuum levels are reduced.

4. The balance between acceleration and loss

It is not useful to invoke diffusive shock acceleration as the distributed cosmic ray electron source since the Larmor radius, \( r_L = \gamma m_e c / (eB) \), even at \( 10^{13} \) eV electron energy is only \( \sim 0.1 \) pc in a \( 1 \mu G \) field, i.e. diffusive propagation over cluster scales is impossible (see also the second half of this section). Instead we appeal to a general Fermi acceleration phenomenon throughout the medium. However, the existence of shock accelerated cosmic rays at the boundaries of the large scale AGN jet driving the additional cluster heating is important for the generation of the necessary Alfven wave spectrum.

The model assumes a continuous injection of energy into at least short wavelength Alfven waves from the AGN injection, continuing to take place well after switch off of the jet as the large scale pressure wave spreads. As the Alfven wave front propagates across the cluster, the broad spectrum cosmic ray population streams ahead into a low scattering medium. Quasi-linear theory predicts a diffusive scattering coefficient (Bell 1978),

\[
\kappa_{\parallel} = \frac{4\pi r_L v B^2}{3E_w 8\pi} \tag{7}
\]

where \( E_w(x, p) \) is the energy density of the waves in resonance with particles of momentum \( p \) per unit logarithmic bandwidth. Scattering and hence acceleration and wave growth depends on the relation

\[
k = \frac{2\pi}{\lambda_{\text{wave}}} = \frac{v_\perp}{v_{||} r_L} \tag{8}
\]

between wave number and Larmor radius. Bell (1987) shows also that an approximation to quasi-linear theory for the growth rate of waves due to streaming is

\[
\sigma = \frac{4\pi V_A}{3 E_w p^4 v} \frac{\partial f}{\partial x} \tag{9}
\]

\( f(p) \) is the particle distribution function. The quantity \( (4\pi/3)p^4 v f(p) \) is the pressure per unit logarithmic bandwidth of particles of momentum \( p \). Assuming equipartition between
particle and wave energy at resonance in each energy band within the turbulent Alfven wave front driven by the region of shock acceleration, the growth rate in the region originally of lower scattering power is simply \( \sigma = V_A/\delta x \) where \( \delta x \) is the scale size for the gradient in \( f(p) \). A \( \delta x \leq 26 \) pc produces \( \sigma^{-1} \geq 6 \times 10^4 \) years, the time constant we will show is needed for acceleration of \( 2 \times 10^{13} \) eV electrons, the energy obtained in the most extreme version of the model developed. This may be compared with a minimum structural size determined by the Larmor radius at this energy when the jet is far out of \( 1 \times 10^{16} \) cm.

The strong turbulence resulting from the streaming instability allows a diffusion mean free path within an order of magnitude of the B"ohm limit throughout the accelerated particle energy range (Zank et al 2000). This treatment of scattering is in contrast to that of Brunetti et. al. (2004) who used an assumed initial Kolmogorov or Kraichman turbulence spectrum determined by a minimum k value to specify the quasilinear diffusion coefficient and then allow the wave particle interactions to cause decay of the wave’s spectral intensity.

The Fermi acceleration time constant is

\[
\tau_F = \frac{\lambda v}{3V_A^2},
\]

where \( v \) is the particle velocity, and \( \lambda \) is the diffusion mean free path. Experience in measuring \( \lambda \) in the turbulent interplanetary medium suggests \( \lambda \sim 30r_L \), rather than the B"ohm value.

The lifetime of an electron of energy \( \gamma m_e c^2 \) against inverse Compton interactions (losses) on the cosmic microwave background (CMB) of energy density \( U_{\text{CMB}} \), is

\[
\tau_{\text{IC}} = \frac{\gamma m_e c^2}{3\sigma_T c \gamma^2 U_{\text{CMB}}} = 2.31 \times 10^{12}\gamma^{-1} \text{ years, for } \gamma \gg 1.
\]

By equating inverse Compton and Fermi time constants after applying our adopted parameters, we obtain a maximum permitted electron energy of \( 1.9 \times 10^{13} \) eV, and a life of \( 6.1 \times 10^4 \) years. This limit is important to our ensuing calculation of a possible upper limit to the electron spectrum. With negligible reacceleration, the loss time at \( \gamma = 300 \) is \( 7.7 \times 10^9 \) years.

V"olk, Aharonian and Breitschwerdt (1996) reviewed the non-thermal energy content of galaxies and discussed the contribution of shocks to the cosmic ray content. We may consider two alternatives to the Alfvenic heating model for the supply of high energy electrons. The first employs shocks at collisions between clusters and hence parameters for the medium inside clusters, so \( V_{sh} = 10^7 \) cm/s and \( B = 6 \times 10^{-6} \) G. If the model to explain the SZE anomaly requires distributed synchrotron radiation at 41 GHz, the electron \( \gamma \) given by \( \nu = 4.3 \times 10^6\gamma^2 B \) needs to reach \( \gamma = 4.0 \times 10^4 \), where the IC loss time is \( 5.8 \times 10^7 \) years. Now using as the approximate shock acceleration time

\[
\tau_{ac} = \frac{3\kappa_{||}}{V_{sh}^2}
\]
where
\[ \kappa_{||} = \frac{1}{3} \lambda v \]  
(13)
is the diffusion coefficient, one finds that \( \tau_{ac} \approx 10^4 \) years. However, the time to diffuse over a cluster scale of \( R = 400 \) kpc,
\[ \tau_{\text{diffusion}} \sim \frac{R^2}{\kappa_{||}} \]  
(14)
is \( 10^{15} \) years. The second alternative concerns relativistic AGN jets near their source. We take \( V_{sh} \sim c \) and \( B = 6 \times 10^{-6} \) G. These parameters yield \( \tau_{ac} \sim 10^{-3} \) year. The timescales relating to shock acceleration indicate that there should be no lack of localised sources of relativistic electrons, especially in an AGN environment where a relativistic jet of Lorentz factor \( \Gamma \) produces the \( \Gamma^2 \) factor increase of acceleration first noted Quenby and Lieu (1989). However, the long diffusion timescale spells the impossible task of filling the entire cluster with a non-thermal population using isolated diffusive shock acceleration sources as input, i.e. the energetic particles so produced are expected to emit synchrotron radiation only locally. Völk et al had similarly found extremely long times for the escape of particles from clusters.

5. Possible Cluster 50 GHz Emission

5.1. Synchrotron Emission

As an alternative, or even an addition to the model explaining of the SZE, the extension of the cluster non-thermal population to energies sufficient to provide synchrotron radiation in the WAMP response range is explored. Without a detailed, non-linear model of the cosmic ray cluster electron spectrum, which is beyond the scope of this work, we cannot predict the overall spectral shape. Models without particle-wave back reaction and relying only on synchrotron loss produce a pile up at high energies before a cutoff (Borovsky and Eilek, 1986). A typical model where turbulent driving of waves occurs, in this case from eddies inherent in jet turbulence radiating waves, is studied by Eilek and Henriksen (1984). They find a power law electron and synchrotron spectrum can arise. Here we will assume a power law, but only need it to relate low energy electrons yielding Inverse Compton photons and high energy electrons yielding synchrotron photons without need of detailed knowledge of the shape in between. Take the intracluster cosmic ray electron spectrum as
\[ \frac{dn(\gamma)}{d\gamma} = \frac{N}{4\pi} \gamma^{-s} \text{ cm}^{-3} \text{ sr}^{-1}. \]  
(15)
The power output is
\[
\frac{d^2P}{dV d\nu} = 1.7 \times 10^{-21} NB^{\frac{s+1}{2}} \left( \frac{4.3 \times 10^6}{\nu} \right)^{\frac{s}{2}} \text{ergs cm}^{-3} \text{Hz}^{-1}.
\] (16)

Now the peak frequency of the synchrotron spectrum is given by
\[
\nu \approx 4 \times 10^6 \gamma^2 B \text{ Hz}
\] (17)

If the lower limit to \( \gamma \) could correspond to \( \gamma \approx 200 \), or electron energy \( \approx 100 \text{ MeV} \), below the peak of the cosmic ray electron flux in our Galaxy, the minimum emitted frequency is \( \nu_{\text{min}} = 1.7 \times 10^5 \text{ Hz} \). The upper emitted frequency, corresponding to the electron cutoff energy of \( 1.9 \times 10^{13} \text{ eV} \) as explained after Eq. (11), is \( \nu_{\text{max}} = 3.4 \times 10^{16} \text{ Hz} \). The cluster volume assumed is \( V_{\text{vol}} = 1.4 \times 10^{73} \text{ cm}^3 \). To explain the anomalies in the S-Z observations, a synchrotron power output \( \approx 20,000 \) times less than that of the CMB (i.e. \( \approx 10^{-19} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1} \)) is required at 41 GHz. Thus the power at this frequency is defined for equation (16) and represents the measurement at one energy of the assumed cosmic ray electron spectrum.

The second measurement the electron spectrum is afforded by the cluster soft excess. More precisely, by taking \( 10^{62} \) ergs as the cosmic ray energy content and linking the IC photons to the electron energy range just above \( 100 \text{ MeV} \) for an electron spectrum that cuts off below this value, a second point on the electron spectrum is defined.

5.2. Electron spectrum required by the SZE anomaly and soft excess

The electron spectrum may be recast into a more recognizable form, as
\[
n(\gamma)d\gamma = \rho(E)dE = \rho_0 E^{-s}dE
\] (18)

where
\[
\rho_0 = \left( m_e c^2 \right)^{s-1} \frac{N}{4\pi}.
\] (19)

A typical set of spectral parameters satisfying both the SZE anomaly and the EUV excess are: \( s = 5.92 \), \( N = 4.13 \times 10^5 \text{ cm}^{-3} \text{ sr}^{-1} \) and \( \rho_0 = 4.0 \times 10^{32} \text{ cm}^{-3} \text{ eV}^{s-1} \), applicable to the energies between \( 100 \text{ MeV} \) and \( 2 \times 10^4 \text{ GeV} \), with an ensuing intracluster relativistic electron number density of \( \approx 2.0 \times 10^{-8} \text{ cm}^{-3} \). For comparison, our Galaxy contains a cosmic ray proton number density of \( 6 \times 10^{-8} \text{ cm}^{-3} \). There is thus no difference between the requirements on acceleration in the intracluster medium containing a central AGN and the cosmic ray flux in a normal galaxy.
To ensure that the model works self-consistently, we emphasize that the proposed intracluster non-thermal electrons will not by themselves produce any obvious SZE signal above the normal level from the intracluster hot gas. Moreover, their synchrotron radiation at radio frequencies is below normal radio astronomy sensitivity limits. A typical cluster observation has its lowest contour at 1 mJy over a 43 arcsec beam resolution. This corresponds to a background from the cluster of $10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Hz$^{-1}$. Thus, unless we contemplate a larger cosmic ray population than depicted by Eq. (16) using maximum associated parameters, it would require an exceptionally low noise observation to pick out the aspect of cosmic ray signal suggested here. There are indeed some large clusters where a radio halo appears. Giovannini et al (1999) found $\sim 5\%$ of a complete X-ray selected cluster sample to have diffuse radio emission. Synchrotron radial profiles more extended than that of X-rays can produce 2 – 2.5 Mpc source sizes, while mini-halos confined to central regions and radio relics on the cluster periphery were also reported (Brunetti 2004).

5.3. Gamma-Ray Limits

There are some indications of non-thermal, hard X-ray cluster emission, but a typical EGRET gamma ray upper limit (on the Coma cluster, Sreekumar et al, 1996) is $3 \times 10^{-8}$ photon cm$^{-2}$ s$^{-1}$ at 100 MeV. The higher $\gamma$ end of our proposed electron power-law will produce gamma rays, also by the IC effect on the CMB. For a particular energy of the emerging photon the required electron $\gamma$ is given by

$$h\nu_{\text{IC}} = \frac{4}{3} \gamma^2 h\nu_{\text{CMB}},$$

and using the equation for the rate of IC energy loss for an electron, we find an electron density $4 \times 10^{-24}$ electrons cm$^{-3}$ above the recoil threshold for IC induced 100 MeV gamma emission. Assuming most of the emission is concentrated at around the threshold of $\gamma \sim 6 \times 10^5$, and a cluster distance of 100 Mpc, the flux at earth is $\sim 1 \times 10^{-11}$ photon cm$^{-2}$ s$^{-1}$, i.e. even under the scenario of maximal cosmic ray pressure the EGRET limit is not violated by our model.

6. Summary and conclusions

Although the basic ideas of utilizing AGN activity and Alfvenic heating as a prime energy source for the intrachuster medium have been proposed, we focussed upon a number of specific non-thermal cluster processes. Our model started with the limited spatial extent of the AGN related jet feeding. Alfven waves then distribute the energy within a cluster
time frame, resulting in a cluster-wide population of relativistic electrons with a power-law spectrum. The chief constraint on electron lifetime, and hence spectral hardness, is inverse Compton loss on the CMB. Provided a reasonable fraction of the observed cluster AGN power can spread outwards, there will be enough energy to explain the WMAP1 SZE anomaly of LMZ06 and the cluster soft excess phenomenon. The proposed mechanism is in-line with previous ideas in interpreting giant radio halos, although we treat the generation of the intracluster wave spectrum in a different manner.

Among the two models offered, the simplest explanation of the WMAP SZE anomaly is that the cluster electron population has hitherto been overestimated, because all the emitted X-rays from a cluster were attributed to the virialized hot thermal medium when as many as half of these thermal electrons should in fact be replaced by a much smaller population (in terms of number density) of cosmic ray electrons accelerated to modest Lorentz factors. After correcting for this effect, the result is a significant reduction of the predicted SZE. In the alternative (more indirect, and hence perhaps less likely) approach to solving the observational problems, we invoked synchrotron radiation in the microwave frequency range from the higher energy end of the same power-law distribution of cluster cosmic ray electrons as that responsible for the SZE anomaly. Such electrons can exist only if a continuous input from Alfvenic acceleration at high Lorentz factors (to combat IC losses) is available.

The salient features of our proposed model to reduce the thermal electron content of clusters are summarized as follows. (a) For non-thermally active clusters the WMAP SZE anomaly would not implicate negatively upon the cosmological origin of the CMB. Rather, it probes the properties of the intracluster medium, which (for some clusters at least) harbor a cosmic ray energy density approaching that of our own Galaxy. (b) Contribution to cluster mass from the thermal medium are significantly overestimated in clusters with anomalous SZE. Cosmic abundances may be underestimated. (c) Anomalous SZE could arise from clusters with one or more of the following special characteristics: powerful AGNs, cluster scale X-ray jets, long radio jets, radio ‘ridges’, radio halos, or other evidence for recent cluster merger. (d) Similarly, soft excess emissions are more likely where there is evidence of large-scale cluster turbulence, as above. (e) Extended cluster radio emission identified in some massive clusters could be explained by an enhanced version of the same Alfvenic heating and IC loss balance presented herein. (f) Relatively higher fluxes of non-thermal X-rays are emitted by clusters with anomalous SZE. (g) The full SZE is expected to be found in relaxed clusters that do not exhibit any of the characteristics outlined in section 3.
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