MAGNETIC SUNYAEV-ZEL’DOVICH EFFECT IN GALAXY CLUSTERS

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ABSTRACT

This Letter explores the influences of intracluster magnetic fields (\(\gtrsim 1\) \(\mu G\)) submerged in the hot electron gas on the classic Sunyaev-Zel’dovich effect (SZE) and on the thermal bremsstrahlung in X-ray emissions. As the Larmor frequency is much higher than all collision frequencies, the presence of a magnetic field may lead to an anisotropic velocity distribution of hot electrons. For the two-temperature relativistic Maxwell-Boltzmann distribution, we compute modifications to the classical thermal SZE. Intracluster magnetic fields tend to enhance the SZE with steeper radial variations, which bear important consequences for cluster-based estimates of cosmological parameters. By applying the magnetic SZE theory to spectral observations of SZE and Chandra X-ray emissions from the galaxy cluster A2163, a \(\sim 30–40\) \(\mu G\) central core magnetic field \(B_0\) is predicted. For the SZE and Chandra X-ray spectral observations of the Coma Cluster, our theoretical analysis is also consistent with an observationally inferred \(B_0 \lesssim 10\) \(\mu G\). As the magnetic SZE is redshift (\(z\)) independent, this mechanism might offer a potentially important and unique way of probing intracluster magnetic fields in the expanding universe.

Subject headings: cosmic microwave background — cosmology: theory — galaxies: clusters: general — magnetic fields — plasmas — radiation mechanisms: general

1. INTRODUCTION

The Sunyaev-Zel’dovich effect (SZE) in galaxy clusters offers a unique and powerful observational tool for cosmological studies. There has been persistent progress in detecting and imaging the SZE in clusters. In view of this rapid development in SZE observations, several important physical effects associated with the classical thermal and kinetic SZEs (Zel’dovich & Sunyaev 1969; Sunyaev & Zel’dovich 1980) have been further explored for their diagnostic potentials, such as relativistic effects (Rephaeli 1995), the shape and finite extension of a galaxy cluster with a polytropic temperature (Puy et al. 2000), halo rotation measures of polarized radio sources either within or behind clusters, and cluster cold fronts in X-ray images (Clarke, Kronberg, & Böhringer 2001; see Carilli & Taylor 2002 for a recent review). These observations reveal that most cluster atmospheres are substantially magnetized with typical field strengths of \(\gtrsim 1\) \(\mu G\) and with high areal filling factors out to megaparsec radii. In the cores of “cooling flow” clusters (Eilek & Owen 2002; Taylor, Fabian, & Allen 2002) and at cold fronts of merging clusters (Vikhlinin, Markevitch, & Murray 2001), magnetic fields may gain intensities of \(\sim 10–40\) \(\mu G\) and thus become dynamically important.

Magnetic fields in the intracluster gas allow for particle acceleration processes, which modify specific of heating processes, such that the electron energy distribution differs from the Maxwell-Boltzmann distribution. Such stochastic acceleration processes include shocks, magnetohydrodynamic (MHD) waves, etc. The bremsstrahlung from a modified Maxwell-Boltzmann electron gas might account for the observed X-ray spectra up to the highest energies of current X-ray observations (Ensslin, Lieu, & Biermann 1999; Blasi 2000). If energy injections by MHD waves are turned off, a galaxy cluster gradually thermalizes with electrons approaching a Maxwell-Boltzmann distribution on a rough timescale of \(\sim 10^7–10^8\) yr. As all collision frequencies (Nicholson 1983) are much lower than the electron Larmor frequency for the magnetized intracluster gas (Sarazin 1988), the electron velocity distribution is likely to be anisotropic as long as the parallel (relative to magnetic field \(B\)) pressure is not too much higher than the perpendicular pressure (Parker 1958; Hasegawa 1975).

We presume the result of a partial electron thermalization is a two-temperature relativistic Maxwell-Boltzmann distribution, i.e., an anisotropic velocity distribution. This two-temperature does not mean an electron gas having two components with different temperatures but refers to the same population with different average kinetic energies along and perpendicular to the local magnetic field. The main thrust of this Letter is to advance magnetic SZE theory in contexts of Chandra X-ray and radio SZE spectral observations for galaxy clusters.

In § 2, we calculate the X-ray emission and SZE spectra using the two-temperature relativistic Maxwell-Boltzmann distribution for electron velocity. Based on both Chandra X-ray and SZE spectral observations, we offer a specific prediction for the galaxy cluster A2163. Finally, we discuss cosmological implications of our magnetic SZE theory in § 3.

2. MAGNETIC SUNYAEV-ZEL’DOVICH EFFECT

Both X-ray emission and SZE spectra are sensitive to the hot electron energy distribution. By the presence of \(B \gtrsim 1\) \(\mu G\), electrons thermalize their parallel and perpendicular (relative to \(B\)) kinetic energies separately with a resulting two-temperature Maxwell-Boltzmann distribution on timescales of \(\sim 10^7–10^8\) yr.
We adopt a two-temperature thermal relativistic Maxwellian electron velocity distribution \( p_i(\beta_1, \beta_2) \), namely,

\[
p_i(\beta_1, \beta_2) d\beta_1 d\beta_2 \propto \gamma^3 \beta_2 \exp \left( -\frac{\gamma_1}{\Theta_1} - \frac{\gamma_2}{\Theta_2} \right) d\beta_1 d\beta_2,
\]

where \( \Theta_i = k_B T_i / (m_e c^2) \), \( \Theta_i \equiv k_B T_i / (m_e c^2) \), \( k_B = 1.38 \times 10^{-16} \text{ ergs K}^{-1} \) is the Boltzmann constant, \( c \) is the speed of light, and \( m_e \) is the electron mass; \( T_i \) and \( T_i \) are parallel and perpendicular temperatures, respectively; \( \beta_1 \equiv v_i / c \), \( \beta_2 = v_i / c \), \( \beta^2 = \beta_1^2 + \beta_2^2 \), \( \gamma = (1 - \beta^2)^{-1/2} \), and \( \gamma_1 = (1 - \beta_1^2)^{-1/2} \) for \( i = 1, 2 \), with \( v_i \) and \( v_i \) being parallel and perpendicular velocities, respectively. We assume \( B \) to be random over the entire galaxy cluster on scales larger than a typical coherence length of \( \sim 1-10 \text{ kpc} \). Thus, microscopically anisotropic electrons are macroscopically isotropic, analogous to a magnetized ferromagnet. Integrating in all directions, the electron speed or energy distribution becomes

\[
p_i(\beta) d\beta = N \gamma^3 \beta d\beta \int_0^\beta \exp \left( -\frac{\gamma_1}{\Theta_1} - \frac{\gamma_2}{\Theta_2} \right) d\beta_1,
\]

where \( N \) is a normalization factor computed numerically.

The firehose stability (Parker 1958; Hasegawa 1975) for velocity anisotropy requires

\[
B^2 / 2 \pi \equiv n_e (\langle m^2 e^2 \rangle - \langle m e^2 \rangle) > 0,
\]

where \( n_e \) is the electron number density, \( m \equiv \gamma m_e \). Angled brackets indicate averages over \( p_i(\beta) \), and the mean temperature \( T \) is defined by \( 3 k_B T / 2 \equiv (2 \langle m^2 e^2 \rangle + \langle m e^2 \rangle) / 2 \). It then follows that

\[
k_B T_i \equiv \langle m^2 e^2 \rangle = k_B T + B^2 / (2 \pi n_e),
\]

\[
k_B T_i \equiv \langle m e^2 \rangle = k_B T - B^2 / (6 \pi n_e),
\]

with \( B^2 / (2 \pi n_e k_B) \) being the upper bound for the temperature difference \( T_i - T_i \). For an observed X-ray energy spectrum and an empirically inferred \( B \) distribution in a cluster, one may estimate \( T_i \) and \( T_i \) by fitting the spectral data. By correlations between X-ray surface brightness and Faraday rotation measure (Dolag et al. 2001), a power law \( B \propto \left[ n_e(r) \right]^{0.71} \) was inferred with an exponent \( \alpha \) estimated from the slope of the ln \( B \) versus ln \( n_e \) relation. For example, one finds \( \alpha \sim 0.9 \) for the galaxy cluster A119 and \( \alpha \sim 0.5 \) for the galaxy cluster 3C 129, with a larger uncertainty in the latter. For \( \alpha = 0.5 \), \( T_i \) and \( T_i \) can remain constant in a magnetized galaxy cluster.

The X-ray emission rate per unit volume per unit energy interval is given by

\[
j_X(E_X) = n_e^2 c \int d\beta p_i(\beta) \sigma_0(\beta, E_X),
\]

where \( \sigma_0(\beta, E_X) \) is the differential cross section (Haug 1997) for the bremsstrahlung of an X-ray photon with energy \( E_X \) from an electron of speed \( c \beta \). Given a central \( B_0 \), we fit an observed X-ray energy spectrum with the electron distribution (2) and \( T_i - T_i \) constrained by the marginal firehose stability (Parker 1958; Hasegawa 1975).

To scatter a cosmic microwave background (CMB) photon (Birkinshaw 1999) of frequency \( \nu \) off an isotropic distribution of thermal electrons with speed \( c \beta \), the probability for the scattered photon of frequency \( \nu(1 + s) \) is

\[
P(s, \beta) = \frac{3}{16 \gamma^3 \beta} \int_{\beta_1}^{\beta_2} \left[ 1 + \beta \mu^2 \right] \times \left[ 1 + \mu^2 \gamma^2 + (1 - \mu^2)(1 - \mu^2) / 2 \right] d\mu,
\]

where \( \mu = [(1 + s)(1 - \beta \mu) - 1] / \beta \), where \( \mu_1 = (s - \beta) / [(1 + s) \beta] \) and \( \mu_2 = 1 \) for \( s \geq 0 \) and \( \mu_1 = -1 \) and \( \mu_2 = (s + \beta) / [(1 + s) \beta] \) for \( s < 0 \). As the intracluster electron gas is macroscopically isotropic and has a thin optical depth \( \tau \sim 10^{-2} \), integral (5) is applicable to the magnetic SZE analysis. For photons scattered by an electron distribution of expression (2), the resulting distribution in the fractional frequency shift \( s \) is

\[
P_i(s) = \int_{(1+2/s)}^{(1)} \frac{d\beta}{\beta} p_i(\beta) P(s, \beta).
\]

For CMB photons scattered by a hot intracluster electron gas, the change in the CMB spectrum at frequency \( \nu \) caused by the magnetic SZE is

\[
\Delta \nu(\nu) = \frac{2 h \nu^3}{c^2} \tau \int_{\lambda - 4}^{\lambda + 4} ds \left[ \frac{P(s)(1 + s)^3}{e^{(s+1) - 1} - 1} - \frac{P(s)}{e^s - 1} \right],
\]

where \( \lambda = \nu h (k_B T_{\text{CMB}}) \), \( h = 6.63 \times 10^{-27} \text{ ergs} \) is the Planck constant, \( T_{\text{CMB}} \) is the present-day CMB temperature, and \( \tau = \sigma_T N_e \), with \( \sigma_T = 6.65 \times 10^{-25} \text{ cm}^2 \) being the electron Thomson cross section (e.g., Rybicki & Lightman 1979) and \( N_e \) being the column density of free electrons along the line of sight.

In the extensively used \( \beta \)-model for intracluster hot electron gas (Sarazin 1988; Fabian 1994), the empirical radial distribution of \( n_e(\rho) \) is

\[
n_e(\rho) = n_{e0}[1 + (r/r_c)^2]^{-1/2},
\]

where \( r_c \) is the core radius and \( n_{e0} \) is the central electron number density. It follows that \( \tau_c \), at radius \( r \) is given by

\[
\tau_c(r) = \tau_{e0}[1 + (r/r_c)^2]^{-1/2},
\]

where \( \tau_{e0} = n_{e0} \sigma_T \rho / 2 \pi \Gamma(3/2 - \frac{1}{2})(\Gamma(3/2)) \) and \( \Gamma(3/2) \) is the gamma function.

4 We use equations (2), (5), (6), and (9) in integral (7) to compute the magnetic SZE spectrum at \( r \).

For spectral observations of A2163, we estimate the lower limit of intracluster \( B \) from the data using our magnetic SZE theory. The thermal electron gas trapped in A2163 (redshift \( z \approx 0.203 \)), one of the hottest clusters, has a mean temperature \( k_B T_i = 12.4 \pm 0.5 \text{ keV} \) and a central density \( n_{e0} = 6.82 \times 10^{-3} \text{ cm}^{-3} \) with a core radius \( r_c = 0.269 \pm 0.025 \text{ Mpc} \), with a central Compton parameter \( \gamma_{\text{com}} = 3.21 \times 10^{-4} \).

A conspicuous SZE spectrum has been observed in A2163 at four frequencies by the BIMA array at 30 GHz (LaRoque et al. 2002), by DIABOLO at 140 GHz (Desert et al. 1998), and...
and by SuZIE at 140, 218, and 270 GHz (Holzapfel et al. 1997) with Galactic dust corrections (LaRoque et al. 2002). These data were previously fitted with a Compton parameter $\gamma_{\text{th}} = 3.56^{+0.41+0.19}_{-0.41-0.19}$ for a thermal SZE together with a kinetic SZE for a positive peculiar velocity $V_p = 415^{+1030+460}_{-450-440}$ km s$^{-1}$ (68% confidence level [CL]; Carlstrom, Holder, & Reese 2002).

A positive-velocity kinetic SZE leads to an overall downward shift of the thermal SZE spectrum, especially around the zero point ($\sim 218$ GHz) of the SZE.

We fit the observed X-ray spectrum of Figure 2 for a mean temperature $T \approx 12.4$ keV by equations (2) and (4) with different $B$ strengths and infer relations among $B$, $T_p$, and $T_i$. Here we take $\alpha = 0.5$, with $T_p$ and $T_i$ being constants (see parameters of Figure 1). Inserting these relations into equations (2), (6), and (7), we obtain the spectra of the magnetic SZE. Figure 1 shows SZE spectra computed for A2163 with different parameters in comparison with the observed SZE spectrum. The model without a magnetic field (solid line for $T = 12.4$ keV) underestimates signals of the SZE (especially at $v = 140$ GHz) with $\chi^2 = 3.82$ in a $\chi^2$ fit. An intracluster magnetic field tends to enhance signals of the SZE, and the best fit is $B_0 = 36 \mu G$ with $\chi^2 = 0.78$. As the marginal firehose stability (Parker 1958) is used here, the fitting estimate represents the lower limit of $B_0 = 36 \mu G$ for A2163. A magnetic field also increases the null frequency of the pure thermal SZE, similar to the kinetic SZE with a positive velocity. This degeneracy can be removed by SZE signals at other frequencies (e.g., 100 and 400 GHz, etc.). The SZE spectrum data can be fitted with $T = 14.4$ keV (Fig. 1, gray line) and $B_0 = 0$, but the thermal spectrum data do not fit well with $T = 14.4$ keV (Fig. 2, dashed line). Figure 3 shows computed radial SZE features of thermal ($B = 0$) and magnetic ($\alpha \neq 0$) SZE for cluster A2163 at 30 GHz. With a smaller exponent $\alpha$, SZE signals steepen from the central to peripheral parts of a cluster. This can be utilized to determine macroscopic mean $B$ structures by obtaining spatially resolved magnetic SZE intensity maps (Carlstrom et al. 2002). Note that 30 GHz of Figure 3 is just an illustrating example.

3. DISCUSSION

Contrary to recent results (Koch et al. 2003; Zhang 2004), we find that the anisotropic velocity distribution of electrons caused by magnetic field $B$ enhances the SZE. Our model results of Figures 1–3 can be critically tested against more precise spectral SZE measurements of A2163 in the frequency bands of $\sim 50$–130 GHz and $\sim 300$–600 GHz by MAX, MSAM, and SuZIE types of experiments in the frequency passbands of 90–670 GHz and by AMiBA in the band 84–104 GHz, Nobeyama at 21 and 43 GHz, the James Clerk Maxwell Telescope at 350 and 650 GHz, SZA in the bands of 26–36 and 85–115 GHz, the BIMA array and the Owens Valley Radio Observatory in the band of 26–36 GHz, MINT at 150 GHz, and ACT at 150, 220, and 270 GHz. Multifrequency projects such as the upgraded MITO (LaRoque et al. 2002; De Petris et al. 2002) and

Fig. 1.—SZE spectrum of A2163 (triangles with error bars are data points). The heavy solid line ($T = 12.4$ keV) is the thermal SZE with parameters determined from X-ray observations with $B_0 = 0$. The dashed, dotted, and dash-dotted lines represent the magnetic SZE with different central magnetic field strengths $B_0$ and with other cluster parameters being the same. We take $\alpha = 0.5$, so that $T_p$ and $T_i$ remain constant in the galaxy cluster. The gray line ($T = 14.4$ keV, $B_0 = 0$) coincides with the dash-dotted line.

Fig. 2.—Energy spectrum of the central $r \leq 5'$ region of A2163 by Chandra. The gray and dashed lines are the $T = 12.4$ and 14.4 keV thermal bremsstrahlung fits. The dotted line shows our magnetic model of essentially the same fit as $T = 12.4$ keV yet with different $B_0$, $T_p$, and $T_i$ from Fig. 1. The lower energy part ($\sim 2.1$ keV) is contaminated by the soft excess (Markevitch & Vikhlinin 2001). The spectral resolution for energy $\sim 5.0$ keV is not high enough and is blended with the Fe Kα line (peaked at 5.3 keV for $z = 0.203$). We fit the 2.1–5.0 keV band with an uncertainty in $T$ of 0.9 keV (90% CL).

Fig. 3.—Radial features of thermal and magnetic SZE modeled for A2163 at 30 GHz. The solid line is the thermal SZE; the dashed, dotted, and dash-dotted lines are models with the same central magnetic field strength $B_0 = 36 \mu G$ but different $\alpha$-values.
the OLIMPO (Masi et al. 2003) experiments are very promising to provide some valuable results for spectral SZE observations. A2163 may involve merger shocks that could amplify $B$ (e.g., Markevitch & Vikhlinin 2001). The spectral index maps of A2163 show a spectral steepening from the central to peripheral radio halo regions, implying a radial decrease of $B$ in reacceleration models (e.g., Feretti et al. 2003). Fitting the SZE spectrum of A2163 with a combination of thermal and nonthermal electrons was attempted (e.g., Colafrancesco, Marchegiani, & Palladino 2003), but no evidence was found for hard X-ray excess due to the prevalence of the magnetic SZE due to the prevalence of the magnetic field. Based on X-ray and SZE measurements, 41 galaxy clusters were used to independently estimate Hubble constant $h_{100} = 0.61 \pm 0.03 \pm 0.18$, where the uncertainties are statistical and systematic at 68% CL for an $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ cosmology (Carlstrom et al. 2002; Reese 2004). Our analysis of A2163 shows that an intracluster magnetic field induces microphysical anisotropies in electron velocity distribution to enhance the SZE. It appears that inferences from cluster models without a magnetic field would systematically underestimate $h_{100}$ as in the case of A2163, for which Holzapfel et al. (1997) inferred a lower $h_{100} = 0.60 \pm 0.04$ against the current Wilkinson Microwave Anisotropy Probe result of $h_{100} = 0.71 \pm 0.04$. As the cluster asphericity and orientation in the sky are random and the average cluster peculiar velocity is zero, these factors should contribute to the statistical uncertainty with the Hubble constant being unaltered. The underestimation of Hubble constant might be explained by the generic presence of a core magnetic field of $B_0 \sim 10^{-400} \mu$G in this sample of galaxy clusters.

Another important cosmological effect of the ubiquitous enhancement of magnetic SZE due to the prevalence of $\approx 1$ $\mu$G magnetic fields in galaxy clusters would be observable in the CMB angular spectrum, especially at high $l \approx 3000-4000$. This contribution to CMB fluctuations may be estimated and tested by CMB experiments such as ACT, Planck, SZA, etc. Details of these two cosmological effects will be pursued in forthcoming papers.

For X-ray (Arnaud et al. 2001) and SZE (De Petris et al. 2002) spectral observations of the Coma Cluster (A1656), our magnetic SZE analysis (Hu & Lou 2004) is consistent with the currently inferred $B_0 \approx 10$ $\mu$G (Carilli & Taylor 2002). Likewise, the magnetic SZE can be utilized in other galaxy clusters with high-resolution and high-sensitivity X-ray and SZE spectral observations to estimate the lower limit of $B_0$ as well as SZE spatial features. While it is necessary to estimate all possible corrections to the classic SZE in order to isolate the magnetic contribution, this may be a unique procedure to probe intracluster magnetic fields at high redshifts $z$, at least statistically. Finally, anisotropic distributions of nonthermal relativistic electrons should lead to a distinct magnetic SZE in radio lobes of grandiose extragalactic jets.

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