ANGULAR POWER SPECTRUM OF THE GALACTIC SYNCHROTRON RADIATION

XUELEI CHEN
The Kavli Institute for Theoretical Physics, UCSB, Santa Barbara, CA 93106, U.S.A.

ABSTRACT

We calculate the angular power spectrum of the galactic synchrotron radiation induced by the small scale fluctuations of the magnetic field and the cosmic ray electron density. Using the observed interstellar magnetic field spectrum, which is consistent with the Komolgorov turbulence model at the relevant scales, we find that $C_l \propto l^{-3.7}$. We estimate the cosmic ray electron density fluctuation spectrum with an injection-diffusion model, the shape of the angular power spectrum in this model depends on the correlations between the injection sources. For Poisson distribution of sources, $C_l \propto l^4$. We discuss the implications for the interpretation of cosmic microwave background (CMB) data and the impact on future 21 cm tomography experiments.

Subject headings: cosmic microwave background — radiation mechanism: non-thermal — radio continuum: galaxies — ISM: magnetic fields — cosmic rays

1. INTRODUCTION

The radio sky at $\nu < 1$ GHz is dominated by galactic synchrotron emission. It is believed to be produced by cosmic ray electrons propagating in the magnetic field of the Galaxy (Ginzburg & Syrovatski 1969). The galactic synchrotron emission is an important foreground for the cosmic microwave background (CMB) experiments (Smoot 1992). For the upcoming high redshift 21 cm tomography experiments (Madau, Meiksin, & Rees 1997; Tozzi et al. 2000; Chen 2004; Ciardi & Madau 2003; Gnedin & Shaver 2003; Furlanetto, Sokasian, & Hernquist 2004; Iliev et al. 2003; Loeb & Zaldarriaga 2004), as well as PAST (Pen et al. 2004), LOFAR$^1$, and SKA$^2$, it poses a major challenge.

The global galactic synchrotron emission spectrum from 0.3 MHz to 408 MHz can be fit with a two component disk model of the galaxy (Keshet, Waxman, & Loeb 2004a,b). Analysis of the existing radio surveys at 408 MHz, 1.42 GHz, and 2.326 GHz (Haslam et al. 1982; Reich 1983; Reich & Reich 1986; 1988; Jonas, Baart, & Nicolson 1998) shows that the synchrotron emission has a spectral index $\beta \approx 2.7$ (Platania et al. 2003), which is in general agreement with the CMB result (Bennett et al. 2003). The real space distribution of synchrotron emissivity over the galactic disk, taking into account spiral arms, were derived from the 408 MHz whole sky map using refolding techniques (Phillips et al. 1981a,b; Beuermann, Kanbach, & Bekhti 1985). In the Fourier space, the angular power spectrum of the galactic synchrotron radiation can be modeled reasonably well as a simple scaling relation: $C_l \propto l^{-\eta}$ (Tegmark & Efstathiou 1996; Tegmark, Eisenstein, de Oliveira-Costa, & Szalay 2002; Giardino et al. 2001, 2002), with $\eta = 2.4 - 3$ down to $l \sim 200$. Recently, the WMAP team obtained a shallower spectrum of $\eta \sim 2$ down to $l \sim 200$. These are extrapolated to higher $l$ in recent studies of the 21 cm foreground (Di Matteo, Ciardi, & Miniati 2004; Santos, Cooray, & Knox 2004).

In the present study we investigate the galactic synchrotron emission from a different perspective. We calculate the synchrotron angular power spectrum induced by the variation of the magnetic field and fluctuations in the cosmic ray electron density. Our primary objective is to achieve a physical understanding of the origin of the synchrotron emission anisotropy. In particular, we would like to ask which of these two mechanisms is responsible in producing the observed anisotropy? This will help us to assess the validity of the hypothesis adopted in the empirical analyses of CMB and 21 cm observation, e.g., will the power law form of the angular power spectrum hold down to small scales relevant for the pre-reionization 21 cm observation? At the same time, we may also gain useful knowledge about the galactic distribution of the cosmic ray electrons and the magnetic field. Similar physical modeling have been performed for a number of other foregrounds, e.g. free-free (Oh & Mack 2003; Cooray & Furlanetto 2004) and intergalactic shocks (Keshet et al. 2004a,b).

The fluctuation power spectrum of the galactic magnetic field has been measured (Minter & Spangler 1996; Han, Ferriere, & Manchester 2004), and is consistent with being produced by a turbulent interstellar medium (ISM) described by the Komolgorov scaling model (Komolgorov 1941; Elmegreen & Scalo 2004). With this we can calculate directly the anisotropy power spectrum induced by the magnetic field variation. The distribution of the cosmic ray electrons is less well known, but there is a broadly accepted picture of the cosmic electrons being produced in supernovae remnants (SNR), which then diffuses through the whole galaxy and be confined in a volume greater than the galactic disk (Ginzburg & Syrovatski 1964). We can calculate the cosmic ray density distribution with this model.

2. MODELS

Let us consider the angular power spectrum obtained over a small patch of “blank” sky field at high galactic latitude. In the optically thin case, the observed radiation intensity is simply an integral of the emissivity along the line of sight. At very low frequencies, synchrotron self-absorption and plasma absorption are important. For $70\, \text{MHz} < \nu < 200\, \text{MHz}$, corresponding to the redshift range of $6 - 20$ which is of interest to the study of the reionization process, these can be neglected,

$$I(\hat{n}, \nu) = \int d\tau \, \varepsilon(\hat{n}, r, \nu),$$

where $\varepsilon$ is the volume emissivity. The emissivity may have both spatial and frequency variations. If the two are separate,
we may write

\[ \varepsilon_\nu(x) = g(\nu)\psi(x), \quad \tilde{\varepsilon}_\nu(k) = g(\nu)\tilde{\psi}(k); \]  

where the tilde denotes Fourier transform, \( \psi(x) = \int \frac{d^3k}{(2\pi)^3} e^{ikx}\tilde{\psi}(k) \). The emissivity power spectrum is then

\[ P_\varepsilon(\nu_1, \nu_2, k) = g(\nu_1)g(\nu_2)P_\psi(k), \]  

Let us consider the case \( \nu_1 = \nu_2 = \nu \). At small scale, using the Limber approximation [Kaiser 1992, Zaldarriaga et al. 2004], the angular power spectrum is given by

\[ C^\gamma_l(\nu) = \frac{C^\psi}{4\pi k^2} \int \frac{dr}{r^2} P_\psi(l/r). \]  

If the emissivity has a power law spectrum, \( P_\psi(k) \propto k^n \), then \( C^\psi \propto l^n \). The integral is up to some cutoff point, at which the emissivity drops to 0.

We now consider the emissivity of synchrotron radiation. If the energy distribution of cosmic ray electrons \( f(E) \) at each point is approximated as a simple power law with \( f(E) = CE^{-\alpha} \), then

\[ \varepsilon(\nu) = \frac{3\nu^3}{m_e c^2 CB_\perp} \alpha_{\text{syn}}(p) \left( \frac{2\pi m_e c^4}{3eB_p} \right)^{-(p-1)/2} \]  

where \( \alpha_{\text{syn}}(p) = \frac{1}{p+1} \Gamma\left[ \frac{3p+1}{2} \right] \Gamma\left[ \frac{3p+9}{2} \right] \). We see that for power law distribution with \( f(E) \propto E^{-\alpha} \), \( I(\nu) \propto \nu^\alpha \), and \( T(\nu) \propto \nu^\beta \), where \( \alpha = -(p-1)/2 \), and \( \beta = -2 \). A power law is actually a good approximation to the real distribution function of cosmic ray electrons. In this approximation, variation of emissivity can be induced by varying the magnetic field \( B \), spectral index \( p \), and cosmic ray electron density normalization \( C \). Here we shall fix \( p \) and consider the variation of \( B \) and \( C \).

The galactic magnetic field is typically a few \( \mu \text{G} \), for this magnetic field the emission at 70 – 200 MHz is produced primarily by cosmic electrons with \( E \sim 0.1 \text{ GeV} \). The local cosmic ray electron density can be measured directly. There is some uncertainty in the normalization, and corrections have to be made for solar modulation. A recent compilation of measurements yields [Casadeli & Bindi 2004], in our units, \( C = 1.7 \times 10^{-11} \text{ cm}^3 \text{ GeV}^{-1} \), and \( p = 3.44 \), at the energy of a few GeV. The spectral index \( p = 3.4 \) yields \( \alpha = -1.2 \), and \( \beta = -3.2 \). For comparison, the WMAP measurement [Bennett et al. 2003] indicates that towards star forming regions, \( \beta = -2.5 \), and towards the halo, \( \beta = -3.0 \). Radiative loss of electron energy provides a natural explanation to the steeping of the electron spectrum away from star-forming region. Below 3 GeV, the electron spectrum becomes flatter, probably because the primary energy loss mechanism changes from radiation to ionization. The locally measured electron density may not represent the average, nevertheless we will use it as a trial value. We will take \( p = 3 \), which gives a slightly better fit to the radio data than the steep \( p = 3.4 \) value. We also assume a disk scale height of 1 kpc (corresponding to the thick disk in the Keshet et al. 2004 model), and a smooth magnetic field of 4 \( \mu \text{G} \). With this set of parameters, the integrated sky brightness temperature at 408 MHz is 20 K, which reproduces the observed value at high galactic latitude [Haslam et al. 1982].

Let us consider first the magnetic field with \( C \) fixed. Now

\[ \psi = b(x) = B_\perp^{(p+1)/2}(x). \]  

\[ \text{FIG. 1.} \quad \text{The magnetic field energy spectrum as extrapolated from Minter & Spangler} \ (1992) \text{and Han} \ (2004). \text{The dotted part is interpolation.} \]

\[ \text{If there is a large smooth global magnetic field component which varies only on large scale and fluctuations around it are small, then we can write } B = B_0 + \delta B(x), \text{ and} \]

\[ B_\perp^{(p+1)/2} = B_0^{(p+1)/2} \left( 1 + \frac{p+1}{2} \frac{\delta B_\perp(x)}{B_0} + \ldots \right) \]

then

\[ P_\psi(k) = \frac{(p+1)^2}{6} C^2 B_0^{p+1} P_{\delta B}(k). \]  

The interstellar medium turbulent [Elmegreen & Scalo 2004]. Komolgorov derived a scaling relation for scale-invariant turbulence [Komolgorov 1941], with a power spectrum of the form \( k^{-11/3} \). The magnetic field fluctuation spectrum can be determined by energy equipartition. The predicted magnetic field fluctuation spectrum is confirmed on the scales of 0.01 pc – 100 pc by observation of the Faraday rotation of extragalactic sources [Minter & Spangler 1996]. At larger scales and on the galactic disk, the magnetic field spectrum is flatter, probably because at these scales the motion is dominated by two-dimensional structure (vortices). If we join the small scale and the large scale observations [Han et al. 2004], we obtain

\[ E(k) = \left\{ \begin{array}{ll} 2.03 \times 10^{-11} k_{\text{pc}^{-1}}^{5/3} \text{ erg cm}^{-3} \text{ kpc}, & k_{\text{pc}^{-1}} > 1.57 \times 10^3 \\ 1.34 \times 10^{-12} k_{\text{pc}^{-1}}^{5/3} \text{ erg cm}^{-3} \text{ kpc}, & k_{\text{pc}^{-1}} < 6.28 \end{array} \right. \]

This is plotted in Fig. 1 (Note that our definition of \( k \) differs from Han et al. 2004 by a factor of \( 2\pi \)). The energy is related to the power spectrum by

\[ P_{\delta B}(k) = 2E_B(k)/k^2. \]  

Other scaling models have also been suggested. For example, some MHD turbulence have \( E \sim k^{-5/3} \) instead of \( k^{-11/3} \) [Kraichnan 1965]. However, this would produce an angular power spectrum not very different from the Komolgorov one.

We can then carry out the calculation, with the magnetic field spectrum given in Eq. (3) and the locally measured electron density. However, even though we keep \( C \) fixed to investigate the variation induced by the magnetic field, in reality
it must decrease as we move away from the galactic disk. We can approximate this effect by taking the power spectrum $P_p(k)$ also as an explicit function of $r$, i.e. $P_p(k,r) \sim P(k)e^{-2r/r_0}$, where $r_0$ is the scale height of the halo in which the cosmic ray electrons are confined. It turns out that this damping factor only changes the result by a small factor, because the large $r$ contribution is already suppressed by the $P \sim (1/r)^{5/3}$ factor. For the small scale that we are mostly interested in, Komolgorov spectrum applies, $P_p(k) \sim k^{-11/3}$, and $C_l \sim l^{-3.7}$.

The result of our calculation for $\nu = 150$ MHz (21 cm line at $z \sim 9$), and 23 GHz are plotted in Fig. 2 as solid lines, along with the WMAP K band data (centered at 23 GHz). Remarkably, at small $l$, the anisotropy power amplitude is of the same order of magnitude as the WMAP data (At such small $l$, the Limber approximation may not be very good, nevertheless the true result will be of the same order of magnitude). This means that the magnetic field fluctuation may play a role in the formation of the observed synchrotron anisotropy. However, it is clear that compared with the data $C_l$ drops too fast as $l$ increases.

If the smooth magnetic field component is absent and the fluctuating field dominates, then

$$P_p = \langle B^{\mu \nu}(k) \rangle = \langle B^{\mu \nu}(k)c(p) \rangle$$

where $c(p) = \frac{1}{2\pi} \int_0^\pi \sin^2 \theta \mathrm{d} \theta = \sqrt{\frac{2}{\pi}} \Gamma[(3+p)/2]/\Gamma[(2+p)/2]$. In this case, the result is uncertain, because it depends on the higher order correlation $\langle B^{\mu \nu}(k) \rangle$. If we make the gaussian-like ansatz $\langle B^{\mu \nu}(k) \rangle \sim \langle B^{2}(k) \rangle^{1/2}$, and $P_p(k) \sim k^{-7/3}$, then the result is $C_l \sim l^{-7/3}$. For the Komolgorov spectrum $\eta_B = -11/3$, $C_l \sim l^{-7.3}$, which is extremely steep and can be neglected entirely. However, this assumption may be incorrect.

Now we consider the variation of the cosmic ray electron density. This is not known from observation. To make an estimate of the fluctuation, we consider an injection-diffusion model (Ginzburg & Syrovatskii 1964), in which the cosmic ray electrons are produced (injected) in point sources, then diffuse out, until eventually losing all their energy or escaping the confinement volume. The density of electrons at a point in space is then dependent on the distance to nearby sources. Neglecting the momentum space diffusion, the density normalization constant at position $r$, time $t$ satisfies the diffusion equation

$$\frac{\partial C(r,t)}{\partial t} = D\nabla^2 C(r,t) + q(r,t) - \frac{C(r,t)}{\tau}$$

where $q(r,t)$ is the cosmic ray electron injection rate at $r$, and $D$ is the diffusion coefficient, which is constant below 5 GeV, and $D \approx 2 \times 10^{23}(E/5\text{GeV})^{0.6}$ at $E > 5\text{GeV}$ (Kobayashi et al. 2004). The last term in the equation represents loss of electrons by radiation, ionization, etc., or by escaping the confinement volume, with $\tau$ the loss time scale. For radiative losses (Casadei & Bind 2004),

$$\tau \approx 2.1 \times 10^7 (E/\text{TeV})^{-1}\text{yr.}$$

We note that in the injection-diffusion model, the scale height of the cosmic ray halo is a few times of $\sqrt{D\tau}$, with the above values we have $\sqrt{D\tau} \approx 0.3\text{kpc}$. Although very crude, our model is self-consistent. In Fourier space,

$$\frac{\partial \tilde{C}(k)}{\partial t} + (Dk^2 + \frac{1}{\tau})\tilde{C}(k) = \tilde{q}(k)$$

The steady state solution is

$$\tilde{C}(k) = \frac{\tilde{q}(k)}{(Dk^2 + \frac{1}{\tau})}.$$  

The power spectrum is then

$$P_C(k) = \frac{P_p(k)}{(Dk^2 + \frac{1}{\tau})}.$$  

Supernovae remnants are most likely the primary source for these cosmic ray electrons. The injection function is then $q = N_e \kappa_{SN}$, where $N_e$ is the number of cosmic ray electrons produced in one supernova, and $\kappa_{SN}$ is the number of supernovae explosions per unit volume per unit time. If the distribution of supernovae is Poisson, with $\langle \kappa_{SN} \rangle = 1/(Vt_{SN})$, where $V$ is the volume in which one supernova explode per average interval $t_{SN}$, then

$$P_C(k) = \frac{N_e^2 V}{(Dk^2 + \frac{1}{\tau})t_{SN}^2 V^2}.$$  

When $k \to 0$, we have $P_C(k) = C_0^2 V$, where $C_0$ is the average of $C$. From this we obtain

$$\frac{N_e}{V} = C_0 t_{SN}/\tau.$$  

As a reality check, we take $E \sim 1\text{GeV}$, a stellar disk with radius of 15 kpc, and a scale height of 300 pc, and also assume that in this volume the average interval of supernovae explosion is 50 years, then we find $N_e \sim 10^{48}$, which requires an energy of $10^{45}\text{erg}$, which is a small fraction of the total energy of a supernova, hence supernovae do have sufficient energy to generate these cosmic ray electrons.

Using this relation we finally obtain

$$P_C = \frac{C_0^2}{(Dk^2 + \frac{1}{\tau})} V.$$  

Note that when written in this form, the result does not depend on $t_{SN}$. The resulting $C_l$ is plotted as dashed curves in
Fig. 2 At large angle, the predicted $C_l$ in this model is comparable to the case of magnetic field induced fluctuation, and agrees with what is observed at the order of the magnitude level. However, at large $l$, $C_l \sim l^{-4}$, again the spectrum is too steep compared with observation. Although the spectrum flattens at small $k$, this happened only at scales comparable to the disk scale height, thus affecting only large angle ($l \sim \text{a few}$).

In the above we have assumed a Poisson distribution of supernovae remnant. If they are correlated, with $P_{SN}(k) \propto k^3$, then $C_l \sim l^{-4}$. Supernovae may well be correlated, as their rate should be proportional to the star formation rate, which in turn depends on the density. However, the Komolgorov model of turbulence suggests $\gamma < 0$. The observation of fluorescent star light distribution in nearby spiral galaxies seem to confirm this expectation, which has a power law of $P_k \sim k^{-4}$ at the 100 pc scale (Elmegreen, Elmegreen, & Leitner 2003). If so, then the correlation of SNR may not help us. However, more observations are needed to address this issue.

3. CONCLUSION

We have calculated angular power spectrum of the galactic synchrotron radiation induced by the variation of the magnetic field and cosmic ray electron density. We found that at low $l$, the amplitudes of the anisotropy power produced by both mechanisms are comparable to the observed value. This indicates that these physical mechanisms are relevant to the production of the observed foreground anisotropy. However, neither of these two mechanisms can produce the $C_l \sim l^{-2}$ power spectrum observed by WMAP (Bennett et al. 2003), and are also steeper than the older value of $\eta \sim 2.4-3$. The magnetic field model induce power spectrum of the form $C_l \sim l^{-2}$, while for the electron density fluctuation it is $C_l \sim l^{\gamma}$ if the spatial distribution of the SNR is Poisson. This may be remedied if the spatial distribution of supernova remnants has the form $P_{SN}(k) \sim k^2$. However, observations seem to indicate $P_{SN}(k) \sim k^{-4}$. We made a number of simplifications in our calculation. We did not consider the detailed distribution of global magnetic field and cosmic ray sources in the Galaxy, nor do we consider accelerations outside SNR. It is unlikely that inclusion of any of these details would change our qualitative conclusion. Perhaps more important is our assumption of a universal energy spectrum of the electrons. In reality, the spectral index varies from place to place, and this may induce additional anisotropy. To model this, we need to include momentum space diffusion. We plan to address these issues in subsequent studies.

If the galactic synchrotron emission does have a steep angular power spectrum as suggested here, how could we reconcile this with the shallower power spectrum reported by the WMAP team? One intriguing possibility is that there may be another type of foreground, which has a frequency dependence similar to the synchrotron radiation at the relevant bands, and was mistaken as synchrotron radiation. Recently, several groups of researchers have suggested that some of the foreground identified as synchrotron by the WMAP team may actually be spinning dust (Lagache 2003; Finkbeiner 2003; de Oliveira-Costa et al. 2004). This has a peak at 10GHz–20GHz, which would not affect the 21 cm measurements. There might also be other foregrounds, e.g. of extragalactic origin, which contributes to the radio survey. Alternatively, there may be other unknown mechanisms which produce the small scale anisotropy in the galactic synchrotron radiation. Further investigations are needed to identify what is responsible for producing the small scale anisotropy power. For the two known physical mechanisms discussed here, the anisotropy power at small scales is much smaller than derived from simple extrapolation.

I thank J. L., Han, E. Scannapieco, S. Furlanetto, D. Casadei and S. P. Oh for suggestions and discussions. This work is supported by the NSF grant PHY99-07949.

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