KNOT IN CENTAURUS A: A STOCHASTIC MAGNETIC FIELD FOR DIFFUSIVE SYNCHROTRON RADIATION?

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ABSTRACT

The emission of relativistic electrons moving in the random and small-scale magnetic field is presented by diffusive synchrotron radiation (DSR). In this Letter, we revisit the perturbative treatment of DSR. We propose that a random and small-scale magnetic field might be generated by the turbulence. As an example, multiband radiation of the knot in Cen A comes from the electrons with energy $\gamma_e \sim 10^3$–$10^4$ in the magnetic field of $10^{-3}$ G. The multiband spectrum of DSR is well determined by the feature of a stochastic magnetic field. These results put strong constraints on the models of particle acceleration.

Subject headings: galaxies: active — galaxies: individual (Centaurus A) — galaxies: jets — radiation mechanisms: nonthermal — turbulence

1. INTRODUCTION

A popular explanation of nonthermal emission from objects such as gamma-ray bursts (GRBs) and jets in active galactic nuclei is synchrotron radiation. The relativistic electrons are buried in the external, homogenous, and steady magnetic field. However, this large-scale magnetic field is a priori and the origin of it in GRBs and jets is under debate. Alternatively, the perturbative and more general nonperturbative treatments of diffusive synchrotron radiation (DSR) have been proposed (Toptygin & Fleishman 1987; Fleishman 2006a); the so-called jitter radiation is a specific limiting one-dimensional case within the general perturbative DSR theory. DSR is the emission of relativistic electrons in the local and random magnetic field. The magnetic field might be produced by the following process: the anisotropic-distributed plasma can be disturbed by relativistic collisionless shocks; hence, the initial magnetic field is produced by the perturbation. The induced currents from the magnetic field amplify the original magnetic field, and thus Weibel instability occurs (Weibel 1959; Medvedev & Loeb 1999; Frederiksen et al. 2004; Hededal & Nishikawa 2005). Due to the lack of the external magnetic field, the particle acceleration cannot be treated by Fermi acceleration (Hededal et al. 2004, Nishikawa et al. 2006), as is the usual way. The DSR and jitter radiation have been selected to predict the spectrum of the GRB/afterglow (Fleishman 2006a; Medvedev 2006; Medvedev et al. 2007; Workman et al. 2007) and the knot in the jet (Fleishman 2006b). These analytical results are also identified with numerical simulations (e.g., Hededal & Nordlund 2005).

There are still some problems that should be concentrated on. For instance, the plasma frequency $\omega_p = (4\pi n e^2/m_e)^{1/2}$, as a function of the electron density $n$ in the plasma, is introduced; thus, the radiation properties are strongly affected by the local environment. Medvedev et al. (2005) played with the model by merging current filaments to generate the magnetic field, while in principle the generation of the magnetic field should be linked with the perturbation of the fluid field. Besides this filament merging effect, there could be other ways to produce a random magnetic field.

In this Letter, following the previous work of Fleishman (2006a) and Medvedev (2006), we put forward the case of emission by relativistic electrons moving in a stochastic magnetic field. In § 2, we review the perturbative DSR and focus on the origin of the magnetic field. The local and random magnetic field may be produced by turbulence but not Weibel instability. In § 3, we compare our results to the multiband spectrum of the knot in Centaurus A (hereafter Cen A). Finally, the discussion and future expectations are given in § 4.

2. RADIATION REVISITED AND STOCHASTIC MAGNETIC FIELD

The emission of a single relativistic particle in the small-scale magnetic field was first introduced by Landau & Lifshitz (1971). Here we follow the developed formula to calculate the radiation intensity, which is the energy per unit frequency per unit time (Fleishman 2006a):

$$I_\omega = \frac{e^4}{m^2 c^3 \gamma^2} \int_{1/2\gamma^2}^{\infty} d\omega \left( \frac{\omega}{\omega'} \right)^2 \left( 1 - \frac{\omega}{\omega' \gamma_r^*} + \frac{\omega^2}{2 \omega'^2 \gamma_r'^*} \right) \times \int dq \, dq d\Delta (\omega - q + qv) K(q) \delta[q_0 - q_0(q)],$$

where $\omega' = (\omega/2)(\gamma^2 - \theta^2 + \gamma_{\perp}^2/\omega^2)$, $\theta$ is the angle between the electron velocity and the radiation direction, $q$ and $q_0$ are the wavenumber and frequency of the disturbed field, respectively, $\gamma_r'^* = \gamma^* + \omega_{\perp}^2/\omega^2$, $\gamma$ is the electron energy, and $K(q)$ is the term for the random magnetic field.

Equation (1) is the general expression for perturbative treatment. It is pointed out by Fleishman (2006a) that the rectilinear motion of electrons is valid for large frequencies; however, at low frequencies, the particle trajectory traverses several correlation lengths scattering by magnetic inhomogeneities, and thus the particle deflection angle accumulated along the coherence length exceeds the beaming angle (see Fig. 1 of Fleishman 2006a).

The dispersion relation $q_0 = q_0(q)$ of the nonrelativistic plasma was presented in Weibel (1959). The improved equations for the isotropic and relativistic plasma were given in detail by Mikhailovski (1980), while Yoon & Davidson (1987) built the analytical model for the relativistic plasma with a water bag distribution. More comprehensive works have been performed recently by Silva et al. (2002), Wiersma & Achterberg (2004), and Fiore et al. (2006). In this Letter, we choose the dispersion relation of relativistic collisionless shocks considered by Milosavljević et al. (2006).

Weibel instability is an efficient way to generate the random magnetic field in relativistic shocks (Silva et al. 2003; Schlick-
shown as the local turbulent spectrum does not show a straight power law. Therefore, we propose that the turbulent spectrum be described by the Kolmogorov form with the classical index 5/3. For the magnetic turbulence, the cascade delay time may enter the estimation of the energy transfer rate: the energy spectrum of Kraichnan has an index of −3/2. Although the situation we focus on has no external magnetic field, at small scales, the turbulence is still shown as the cascade properties. Self-excited Alfvén turbulence has also been found (Sokolov et al. 2006). Moreover, we note that the nonmagnetized and magnetized turbulence have a high degree of similarity (Cho et al. 2002; Lazarian & Beresnyak 2005). All these evidences indicate that a general form of fluid turbulence can also be valid for the study of random magnetic field generation. Furthermore, the index of the turbulence spectrum is not universal. Zhou & Matthaeus (1990) investigated local turbulent effects with transport models and other nonlinear terms. Using the scaling model (She & Leveque 1994), which presents the cascade as an infinitely divisible log-Poisson process (She & Waymire 1995), Boldyrev et al. (2002) derived a steeper spectrum compared to that of Kolmogorov. In fact, as estimated by Wang (2002), the index value of a turbulent spectrum has the range between −1 and −2. MacLow & Ossenkopf (2000) found that the local turbulent spectrum does not show a straight power law. Therefore, we propose that the turbulent spectrum be shown as

$$F(k) \propto k^{-a}f(k/k_*)$$

where $k_* < k < k_0$. $k_0$ corresponds to the viscous scale of the fluid, while $k_*$ is linked with the scale of the resistive cascade transfer. We choose $f(k/k_0)$ as an exponential-drop form.

The magnetic field amplified by the turbulence spectrum has been described by Niemiec & Ostrowski (2004, 2006). We obtain the amplified magnetic field as

$$\langle |B|^2(k) \rangle \propto \int_k^\infty F(k') dk'.$$

In general, equation (2) presented as a power law with a cutoff at high wavenumber is universal for the fluid dynamo turbulence, whatever the radiation field is. The $K(q)$ in equation (1) can be linked by the magnetic field as $K(q) = C_0\langle |B|^2(q) \rangle$, where $C_0$ is the normalization number. Therefore, this turbulent approach for obtaining a magnetic field is the development in the framework of current DSR theory.

3. THE CASE OF CEN A

Cen A, the nearest proto–FR I galaxy, was sketched from the observational view (Israel 1998). In particular, the knot in the jet has been detected in radio, X-ray (Hardcastle et al. 2003; Kraft et al. 2003; Kataoka et al. 2006), and infrared (Hardcastle et al. 2006) bands. With these observations, this object provides a multiband spectrum to constrain the radiation mechanisms and the models of particle acceleration.

The central density of the knot in Cen A is $n = 3.7 \times 10^{-3} \text{ cm}^{-3}$ (Kraft et al. 2003); the correlation length of the random magnetic field is estimated by $l_{corr} \sim (0.1–1)\mu l_{sk} \sim 10^{-3}–10^{-1} \text{ cm}$, where $l_{sk} = c/\nu_{esc}$ is the skin depth, while the size of the knot is less than 10 pc (Hardcastle et al. 2003). The flare points and complicated light curves (Hardcastle et al. 2006) indicate the disturbed effects of the irregular magnetic fields. These small-scale random inhomogeneities give us the opportunity to calculate the emission using perturbative DSR. We insert equation (2) into equation (1) and calculate numerically; we set the turbulent spectrum $\alpha = 1.45$. The electron energy distribution $dN/d\gamma \propto \gamma^{-s}$ is assumed to be $s = 3.3$. The bulk Lorenz factor is $\Gamma = 12$. The range of $k$ for turbulent spectrum calculation can be estimated by $k_* \sqrt{\gamma} = P^{1/2}$, where the Prandtl number is $Pr \sim 10^{-3} T^4 n \sim 10^{-14}$ for the warm medium in the knot of Cen A (Schekochihin & Cowley 2007). The final result in comparison to the observational data is shown in Figure 1. Thus, we use the single gross turbulent spectrum to reproduce the multiband emission, with its drop-off point properly shown in the X-band. From the data fitting, we find that the relativistic electrons with $1 \leq \gamma \leq 10^{-1}–10^3$ are enough for this multiband emission, while the turbulent magnetic field is strong, at least $10^{-3} \text{ G}$, which is larger than the equipartition value of 100 $\mu$G estimated by synchrotron radiation (Kataoka et al. 2006).

The radiative cooling of synchrotron emission may be one of the reasons able to explain the deeper spectrum toward high-energy bands (Heavens & Meisenheimer 1987; Meisenheimer et al. 1989). The observation of M87 supports this traditional interpretation (Harris et al. 2006). And the synchrotron emission by two populations of electrons is needed (Sambruna et al. 2001) to explain the X-ray spectrum of 3C 273. But for the spectrum of the knot in Cen A, the difference of the spectral indexes between the flatter part and the deeper part is less than 0.5 (Hardcastle et al. 2006). This is contradictory to the prediction of typical synchrotron electron cooling. For another point of view, the relatively low number density of the knot can contribute just a small amount of absorption; thus, the strong decrease of flux in the X-ray band is not due to dust attenuation. Therefore, the drop-off point in the spectrum might present the behavior of the turbulence.

From another side, we may directly describe the magnetic...
field as $B^2(k) \propto k^{-n}$. For this point, we avoid the detailed treatments of any turbulence model. With the double power law as the form of the magnetic field to calculate DSR, we select $p_1 = 1.4$ and $p_2 = 1.7$, respectively, to get the result shown in Figure 2. But the bulk Lorenz factor is changed from $\Gamma_1 = 12$ to $\Gamma_2 = 2$. This result gives us an alternative clue to explain the multiband spectrum: the break point in the spectrum might indicate the bulk transition state of the shock from the extrarelativistic to the subrelativistic phase.

There are some knots in other objects observed by multiband telescopes. Different knots have different spectral slopes and different quantities of flux, indicating the nonuniform turbulent mode and different acceleration processes. In this Letter, we give the example of Cen A. However, whatever the spectral shape is, we see that the observational spectrum can be explained by perturbative DSR theory: the emission is dominated by the random magnetic field, which could be amplified by the turbulence. Thus, the spectral shape is uniquely determined by the random magnetic field from the radio to the X-ray band.

4. DISCUSSION

In this Letter, we use the turbulent spectrum to amplify the random magnetic field. We find that the spectrum shape of DSR is only dominated by the stochastic magnetic field. The existence of this kind of magnetic field has been confirmed by numerical simulations (Haugen et al. 2004a, 2004b; Schekochihin et al. 2004). Thus, the whole multiband radiation is produced originally from a relatively small region, about several parsecs, with a series of physical processes.

Furthermore, the light curves at the radio, infrared, and X-ray bands of the knots are more complicated. It seems that the emission is first seen in the X-ray band, followed by the infrared and radio bands (Hardcastle et al. 2006). We expect that the turbulent magnetic field could have time evolution during the cascade process with energy transfer. The final radiation spectrum may be a composite result from the multistucture of the turbulence spectra and is averaged by the time evolution. Deep research of the delicate structure in the turbulent magnetofluid is encouraged to explain the time-dependent features.

Three aspects are included in the whole scenario: turbulence, magnetic field, and particle acceleration. In our opinion, first, the fluid background is disturbed by the relativistic collisionless shock, and the perturbative dynamos are distributed as the turbulence spectrum; then, the initial magnetic elements are amplified by the turbulence, shown as the random and small-scale magnetic field; finally, the particles can be accelerated by relativistic shocks and/or turbulent flow to produce DSR as a first step, then continually accelerated to the higher energy part by other mechanisms that are related to the mature magnetic field. For simplicity, in this Letter, we assume that the electron injection is continuous so that the spectrum does not show energy loss by radiation.

The electron energy distribution $dN(\gamma)/dE \propto \gamma^{-p}$ has no universal index $s$ (Shen et al. 2006). This suggests that particle acceleration may also have multiple processes. There are at least two ways to accelerate electrons. Honda & Honda (2005) considered that the electrons are accelerated by the interaction with the local magnetic filaments; although our model prohibits an external magnetic field, since the Alfvén turbulence can be self-excited by the diffusive shocks (Sokolov et al. 2006), the popular Fermi and stochastic acceleration can also be accepted in the local region. Other models reveal that the index $s$ varies upstream and downstream of the shock (Keshet & Waxman 2005; Baring 2007). Recent research even finds that particle acceleration is affected by the equation of state (Morlino et al. 2007). Further investigation into the relationship of turbulence, magnetic field, and particle acceleration is expected.

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