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Reacceleration of Relativistic Electrons by Turbulent Alfvén Waves in Radio Jets

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Abstract.
Relativistic electrons may be effectively accelerated by turbulent Alfvén waves in radio jets. The acceleration spectrum is a power law with the electron energy as high as $\gamma \sim 10^6$, but the spectrum index is ~ 1.2 in the condition of diffusion approximation, which is less than the observation value.

The relativistic electrons in radio jets must be reaccelerated in situ according to the following facts. First of all, the brightness of radio jets should be weakened by adiabatic cooling and radiation loss, and the radiation spectrum index should decrease, too, if there is no occurrence of a reacceleration process. However, the surface brightness of radio jets decreases very slowly on a large scale (about a few Mpc). Second, the synchrotron-radiation half-lifetime of relativistic electrons in the magnetic field is too short for them to move the long distances to radio knots or lobes (Achterberg 1986).

In general, there are two kinds of acceleration mechanisms: the shock acceleration, and the stochastic acceleration caused by magnetized plasma turbulence. We consider a relativistic electron beam that moves along a uniform magnetic field $B = B_0\mathbf{e}_z$. In this case, the Alfvén waves should grow rapidly (Ma, Wang, & Huang 1995), and the plasma turbulence results from input at large eddies cascading down to smaller wavelengths by nonlinear effects or some instabilities. The resonant condition of wave-particle interaction is $\omega - n\Omega_e/\gamma - k_{\|}v_{\|} = 0$. The frequencies ω of the Alfvén waves are much less than the electron gyrofrequency Ω_e, and stochastic acceleration is possible in radio jets for the electrons with energy larger than $\sim 10\,\text{Mev}$.

A diffusion equation for relativistic electrons can be given as

$$\begin{aligned}\frac{\partial f}{\partial t} - S(p,t) \quad &= \quad \frac{\partial}{\partial \mu} D_{\mu\mu}\frac{\partial f}{\partial \mu} + \frac{\partial}{\partial \mu} D_{\mu p}\frac{\partial f}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}p^2 D_{p\mu}\frac{\partial f}{\partial \mu} + \\ &\quad + \frac{1}{p^2}\frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial f}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}p^2 A_L(p,\mu) f, \qquad (1)\end{aligned}$$

where $S(p,t)$ represents an additional source function and $A_L(p,\mu)$ describes the energy losses by radiation and collision. The diffusion coefficients D depend on the turbulence spectra of the Alfvén waves. According to observations in the interplanetary medium, the turbulence spectrum of Alfvén waves can be written as:

$$I(k_{\|}) = \begin{cases} I_0 k_{\|}^{-q}, & \text{if } k_{min} \le k \le \infty; \\ 0, & \text{otherwise.} \end{cases} \qquad (2)$$

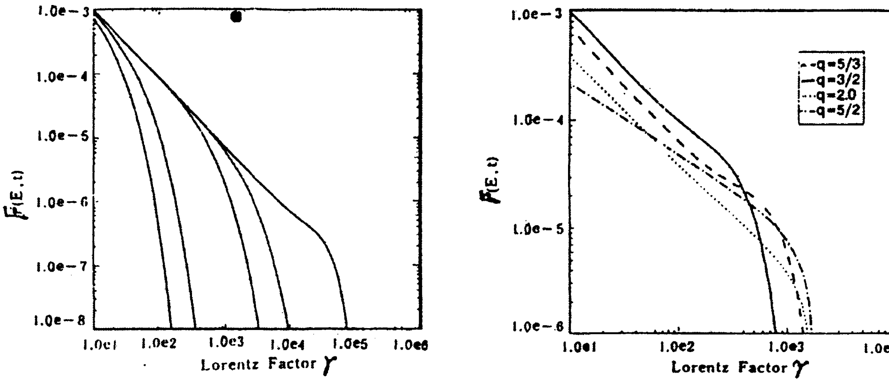

Figure 1. Left: The acceleration electron energy distribution for energy loss $A_L/A_0 = 10^{-6}$ at times $D_0t = 5$, 10, 50, 100, and 500. Right: The acceleration electron distribution for different Alfvén-turbulence spectral indices $q = 3/2$, $5/3$, 2, and $5/2$.

Here, k_{min} is the minimum wavenumber of the Alfvén waves. These diffusion coefficients have been written by Schlickeiser (1989). The important energy-loss processes for relativistic electrons in a magnetized plasma are Coulomb collision (E_c), bremsstrahlung radiation (E_b), and synchrotron radiation (E_s). We find that the ratio of different radiation losses can be expressed as $E_c/E_s \sim \gamma^{-2}\beta_A^{-2}$ and $E_b/E_s \sim 10^{-4}\gamma^{-\frac{3}{2}}\beta_A^{-2}$, where $\beta_A = \frac{v_A}{c}$. For ultrarelativistic electrons in jet plasmas with $\gamma > \beta_A^{-1}$, the dominant energy-loss process is synchrotron radiation.

When the relativistic electrons are scattered by Alfvén turbulence, their relative change in pitch angle is much larger than their relative momentum change. As an estimation, the ratio between the relative variation of the pitch-angle cosine and the momentum can be written as $\frac{(\Delta\mu/\mu)}{(\Delta p/p)} \sim [\frac{p^2 D_{\mu\mu}}{\mu^2 D_{pp}}]^{\frac{1}{2}} \sim 1/\beta_A$. This value is much larger than 1. We take the diffusion approximation in Equation (1) and average over pitch angle. Finally, after taking the variable transform $p \to E$ and $F_E = 4\pi p^2 f(p)\mathrm{d}p/\mathrm{d}E$, we obtain the following equation.

$$\frac{\partial F_E}{\partial t} = \frac{\partial^2}{\partial E^2} D_0 E^q F_E - \frac{\partial}{\partial E}(A_0 E^{q-1} - A_L E^2) F_E + S(E,t), \qquad (3)$$

with $D(E) = c^2\langle D_{pp}\rangle = D_0 E^q$ and $A_L = \frac{4}{3} \times 10^{-9} B^2 + 10^{-13} E^{-2}$, where energy E is in units of $m_e c^2$, and magnetic field B is in gauss. Also, $A_0 = (q+2)D_0$ and $D_0 \simeq 10^{-7}$–10^{-10} when we take the parameters in jets as $B \simeq 10^{-3}$–10^{-6} gauss, $n_e \simeq 10^{-2}\,\mathrm{cm}^{-3}$, $R_A \simeq 10^{-2}$–10^{-4}, and $\beta_A \simeq 10^{-2}$.

The electron energy spectrum for energy loss $A_L/A_0 = 10^{-6}$ and the evolution with the time are shown in Figure 1. The ratio of the energy losses must be in the range of 10^{-6}–10^{-7} in order for the accelerated electron energy to come up to $\gamma \sim 10^6$. Figure 2 shows the time evolution of the electron distribution for different Alfvén-turbulence spectral indices q. We find that the spectral index δ of the accelerated electrons depends slightly on the spectral index q of the Alfvén turbulence. The electron-energy spectral index δ decreases as the wave index q increases. This means that the stochastic acceleration is more effective for larger wave indices and lower-frequency Alfvén waves.

In summary, the stochastic acceleration mechanism of Alfvén turbulence is effective for acceleration of ultrarelativistic electrons. The acceleration spectrum is a power-law spectrum with the electron energy as high as $\gamma \sim 10^6$ and the acceleration time-scale shorter than 10^{12} sec. These results are consistent with observations of radio jets. However, the spectral index of accelerated electrons is ~ 1.2, which is less than the observed values, ~ 2.0–2.8. This discrepancy may be caused by the diffusion approximation because the energy losses of synchrotron radiation are proportional to the pitch angle $(1-\mu^2)^{1/2}$. The ratio condition of different radiation losses will be unsatisfied for the ultrarelativistic electrons with small pitch angles. A direct solution of the stochastic acceleration (Equation [1]) is required.

References

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