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Stochastic Particle Acceleration in Blazar Jets

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Abstract The bulk kinetic energy of jets can be dissipated via generating turbulent plasma waves. We examine stochastic particle acceleration in blazar jets to explain the emissions of all blazars. We show that acceleration of electrons by plasma turbulence waves with a spectrum $W(k) \sim k^{-4/3}$ produces a nonthermal population of relativistic electrons whose peak frequency of synchrotron emission can fit the observational trends in the spectral energy distribution of all blazars. The plasma nonlinear processes responsible for the formation of turbulent spectrum are investigated. Increases in the interaction time of turbulent waves can produce a flatter spectrum leading to efficient particle acceleration.

Key words: acceleration of particles – blazars: theory – plasma: turbulence – radiation mechanism: nonthermal

1 INTRODUCTION

Blazars are radio-loud AGNs characterized by emissions of strong and rapidly variable nonthermal radiation over the entire electromagnetic spectrum. Synchrotron emission followed by inverse Compton scattering in a relativistic jet and beamed into one direction is generally thought to be the mechanism powering these objects (Kollgaard 1994; Urry & Padovani 1995). All blazars have a spectral energy distribution (SED) with two peaks in a νF_ν representation (von Montigny et al. 1995; Sambruna, Maraschi & Urry 1996; Fossati et al. 1998), the low frequency peak (between the far IR and X-ray band) is thought to be due to synchrotron radiation from high energy electrons in the jet, while the high energy peak (between the MeV and TeV band) is due to the inverse Compton radiation from the same electrons. As the bolometric luminosity increases, both peaks shift to lower frequencies, and the high energy emission increases its dominance in the total output (Fossati et al. 1998). By fitting the SED of blazars with a synchrotron-self Compton model which includes the possible contribution of radiation produced outside the jet, Ghisellini et al. (1998) found that the energy $\gamma_{\rm peak} m_e c^2$ of the electrons emitting at the peaks of the spectrum strongly correlates with the amount of

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energy density U (both radiative and magnetic), the total intrinsic power and the amount of Compton dominance.

A correlation between $\gamma_{\rm peak}$ and U, $\gamma_{\rm peak} \propto U^{-0.6}$ is measured in the comoving frame. There is growing evidence that the overall blazar emission comprises a component that is changing only on long timescales (Pian et al. 1998, 1999; Fossati et al. 2000). The short-timescale, large-amplitude variability events, could be attributed to the development of new individual flaring components (Fossati et al. 2000). It seems to reveal that a particle suffers from continuous and instantaneous acceleration. It is widely believed that the radiation in the jet comes from the transformation of kinetic energy of the bulk motion and then goes into random energy. Here we suggest that the energy conversion occurs due to internal processes such as plasma turbulence formation and dissipation in the jet. The plasma turbulence is described as an ensemble of linear and nonlinear structures, such as shocks, discontinuities, and high-amplitude waves, which are typically observed in compressible plasma (Tsurutani et al. 1994, 1996). The kinetic energy of the bulk motion in the jet does not go directly into heating of the plasma or acceleration of the particles but into generation of plasma turbulent waves or shock waves which in turn can accelerate particles. The jet may have strong turbulent dissipation in the propagation phase. Therefore the steady component of blazar emission could be related to the particle acceleration of plasma turbulent waves, while the flaring component arises from shock processes in the jet. In this paper, we examine the stochastic acceleration of the particle by plasma turbulence to explain the characteristics of the SED of blazars.

2 PARTICLE ACCELERATION

Various mechanisms have been proposed and are being investigated for the acceleration of particles. These include direct acceleration by static electric fields (e.g. resulting from magnetic reconnection), shock acceleration, and stochastic acceleration by turbulence. Shocks are the most commonly considered mechanism of acceleration because they can quickly accelerate particle to very high energies. However this requires the existence of some scattering agent to force repeated passage of the particles cross the shock. The most likely agent for scattering is plasma turbulence. The rate of energy gain is governed by the scattering rate which is proportional to the pitch angle diffusion coefficient. However, the turbulence required for the scattering can also accelerate particles stochastically through resonant interactions. Stochastic acceleration has been successfully applied to ion and electron energizations in solar flares (Miller & Ramaty 1989; Miller, Lorosa & Moore 1996; Schlickeiser & Miller 1998) and is capable of accounting for a wide range of particle emissions (Hamilton & Petrosan 1992; Dung & Petrosian 1994; Pryadko & Petrosian 1997, 1999). Stochastic acceleration has also been applied to diffusive shock acceleration and cosmic rays (Schlickeiser 1994), lobes of radio galaxies (Lacome 1977; Achterberg 1979; Eilek & Henrikson 1984), and recently, the central region of AGNs (Dermer, Miller & Li 1996), Galactic black hole candidates (Li, Kusunose & Liang 1996), and AGN jets (Li, Miller & Colgate 1997).

Because of the rapid scattering by waves, the electrons trapped in this region will have a near isotropic distribution. For simplicity, we assume isotropy of the pith angle distribution and evaluate the electron spectrum integrated through the finite acceleration site. The turbulence is confined to a region with size $c\Delta t$ outside the electron-ion or pair photosphere where particles undergo scattering and acceleration, but eventually escape within a certain time. We use the steady state solution of the kinetic equation for relativistic electrons to describe the spectral behavior of the steady components.

The kinetic equation describing the spectrum of the electrons in the emitting region according to Petrisian (1994) is

$$\frac{\partial^2}{\partial E^2}[D(E)f(E)] - \frac{\partial}{\partial E}[(A(E) + \dot{E}_L)f(E)] - \frac{f(E)}{T(E)} + Q(E) = 0, \tag{1}$$

where $f(E,t)dE$ is the number of electrons per unit volume in the interval dE, $E = \gamma - 1$ is the kinetic energy in units of $m_e c^2$, $D(E)$ is the diffusion rate, $A(E)$ the systematic acceleration rate, $\dot{E}_L$ the energy loss rate, $T(E)$ the mean escape time of electrons out of the emitting region, and $Q(E)$ an electron source term.

The energy loss term $\dot{E}_L$ includes both synchrotron and inverse Compton radiation losses and is given by

$$\dot{E}_L = -\frac{4\sigma_T}{3m_e c}(W_B + W_{\rm ph})(\gamma\beta)^2, \tag{2}$$

where $W_B = \frac{B^2}{8\pi}$, $W_{\rm ph}$, βc, and γ are the energy density of magnetic fields, ambient photon fields, electron velocity and Lorentz factor, respectively. The coefficient $T(E)$ is related to the average pith angle diffusion coefficient, $\langle D_{\mu\mu}\rangle$, via the mean free path $l \sim \beta c/\langle D_{\mu\mu}\rangle$. For a region with size $L = c\Delta t$, the escape time $T(p) = L^2/l\beta c$, and so

$$T(E) = \langle D_{\mu\mu}\rangle \frac{(\Delta t)^2}{\beta^2}. \tag{3}$$

The terms $A(E)$ and $D(E)$ are related to the average momentum diffusion coefficient $\langle D_{pp}\rangle$, we have

$$D(E) = \langle D_{pp}\rangle, \tag{4}$$

$$A(E) = \frac{1}{p^2}\frac{\partial}{\partial p}[\beta p^2 D(E)], \tag{5}$$

where $p \equiv |\mathbf{p}|/m_e c = \beta\gamma = \sqrt{E(E+2)}$.

Determination of the diffusion coefficients depends on the wave turbulent spectrum. The spectrum and level of turbulence are not known, therefore assumptions about their properties must be made. The turbulent waves are usually described by a spectral density $W(\mathbf{k})$ in wavevector space. For isotropic wave distributions, the nonlinear cascade of spectral energy usually leads to an inertial range spectral density $W(k) \propto k^{-q}$ (Zhou & Matthaeus 1990), where $k = |\mathbf{k}|$ and the spectral index q is between 1 and 2. A value of $q = 1$ over all wave numbers would imply infinite energy content; conversely, $q = 2$ is characteristic of a medium dominated by discontinuities, and corresponds to the case of diffusive shock waves. While fully developed homogeneous and isotropic fluid turbulence was known to have the value $q = 5/3$, Kraichnan's (1965) generalization to MHD suggested a value of $q = 3/2$. Here we will concentrate on the turbulent wave spectrum to demonstrate particle acceleration and to explain the SED of blazars.

We use the pith-angle-averaged angle and momentum diffusion coefficients for electrons resonating with turbulent waves given by (Dermer, Miller & Li 1996)

$$\langle D_{pp}\rangle = \frac{\pi}{2}\left[\frac{q-1}{q(q+2)}\right]\beta_g^2\zeta(ck_{\rm min})(r_L k_{\rm min})^{q-2}\frac{p^q}{\beta}, \tag{6}$$

$$\langle D_{\mu\mu}\rangle = \frac{\pi}{2}\left[\frac{q-1}{q(q+2)}\right]\zeta(ck_{\rm min})(r_{\rm L} k_{\rm min})^{q-2}\beta p^{q-2}. \tag{7}$$

We find that the three momentum-dependent coefficients are

$$A(E) = \frac{\pi}{2}\left(\frac{q-1}{q}\right)\beta_{\rm g}^2\zeta(ck_{\rm min})(r_{\rm L}k_{\rm min})^{q-2}p^{q-1}, \quad (8)$$

$$D(E) = \frac{\pi}{2}\left[\frac{q-1}{q(q+2)}\right]\beta_{\rm g}^2\zeta(ck_{\rm min})(r_{\rm L}k_{\rm min})^{q-2}\frac{p^q}{\beta}, \quad (9)$$

$$T(E) = \frac{\pi}{2}\left[\frac{q-1}{q(q+2)}\right]\zeta(ck_{\rm min})(r_{\rm L}k_{\rm min})^{q-2}p^{q-2}\frac{(\Delta t)^2}{\beta}, \quad (10)$$

where $r_{\rm L} \equiv m_e c^2/eB$ is the nonrelativistic Larmor radius of the electron and $c\beta_{\rm g}$ is the group velocity of the resonant wave. The quantity ζ is the normalized energy in turbulent waves, such that $\zeta \equiv W_{\rm tot}/W_B$, where $W_{\rm tot}$ is the total energy density of turbulence with wavenumber greater than $k_{\rm min}$. We assume that the turbulence is produced at scales approximately equal to the size of the emitting region, and take the term $k_{\rm min}$ to be $k_{\rm min} = (c\Delta t)^{-1}$. Using the accelerating rate $A(E)$ and the radiative cooling rate $\dot{E}_L$, we find that the peak energy $\gamma_{\rm peak}$ is given by

$$\gamma_{\rm peak} = (9.44\times10^3)^{\frac{1}{3-q}}(6.59\times10^{-13})^{\frac{q-2}{3-q}}\left(\frac{q-1}{q}\right)^{\frac{1}{3-q}}\beta_{\rm g}^{\frac{2}{3-q}}\zeta^{\frac{1}{3-q}}B^{-\frac{q}{3-q}}\left(1+\frac{W_{\rm ph}}{W_B}\right)^{-\frac{1}{3-q}}\left(\frac{\Delta t}{\rm day}\right)^{\frac{1-q}{3-q}}. \quad (11)$$

In order to obtain an explicit value $\gamma_{\rm peak}$, an estimate of the magnetic field of emitting region in the jet is required. Most of the power transported by the jet must reach the radio lobes, therefore only a small fraction can be radiatively dissipated. Ghisellini et al. (1998) computed the bulk Lorentz factor, dimension of the emitting region, value of the magnetic field and the particle density for all the 51 blazars detected by EGRET for which both the redshift and the γ-ray spectral shape were known at the time, and determined three powers,

$$L_{\rm p} = \pi R^2\Gamma^2\beta c n'_{\rm p} m_{\rm p} c^2, \qquad L_{\rm e} = \pi R^2\Gamma^2\beta c n'_{\rm e}\langle\gamma\rangle m_{\rm e} c^2, \qquad L_B = \pi R^2\Gamma^2\beta c\frac{B^2}{8\pi}, \quad (12)$$

where $n'_{\rm p}$ and $n'_{\rm e}$ are the comoving proton and lepton densities, R is the cross section radius of the jet, which is assumed to be $c\Delta t$, $\langle\gamma\rangle m_{\rm e}c^2$ is the average lepton energy, and Γ the bulk Lorentz factor of the jet. Ghisellini (2000) compared these powers with the radiated power, and found that the bulk kinetic power of the jet formed by normal plasma agrees with the energy requirements of the radio lobes. This power is about 100 times larger than the power in the magnetic field. In fact, in the comoving frame, the quantity $\frac{L_B}{L_{\rm p}}$ is equal to $\frac{1}{2}\beta_{\rm A}^2$, where $\beta_{\rm A}$ is the Alfvén velocity in units of c. It is shown that the Alfvén velocity in the emitting region is about ten percent of light velocity. From the bulk kinetic power of the jet $L_{\rm p}$, we can estimate the magnetic field to be

$$B = 4.46\left(\frac{\beta_{\rm A}}{0.1}\right)\left(\frac{\Delta t}{\rm day}\right)^{-1}\left(\frac{\Gamma}{10}\right)^{-1}\left(\frac{L_{\rm p}}{10^{46}\,{\rm erg}^{-1}}\right)^{\frac{1}{2}}\ {\rm G}. \quad (13)$$

Assuming the acceleration of electrons is by Alfvén turbulence, the group velocity of the resonant wave $\beta_{\rm g}$ is equal to $\beta_{\rm A}$. For the case $q = 3/2$, we find that

$$\gamma_{\rm peak} = 5.54\times10^3\left(\frac{\zeta}{0.1}\right)^{\frac{2}{3}}\left(\frac{\beta_{\rm A}}{0.1}\right)^{\frac{1}{3}}\left(\frac{\Delta t}{\rm day}\right)^{\frac{2}{3}}\left(\frac{\Gamma}{10}\right)\left(\frac{L_{\rm p}}{10^{46}\,{\rm erg}^{-1}}\right)^{-\frac{1}{2}}\left(1+\frac{W_{\rm ph}}{W_B}\right)^{-\frac{2}{3}} \quad (14)$$

and the corresponding synchrotron peak frequency

$$\nu_{\rm p} = 5.88 \times 10^{14} \left(\frac{\zeta}{0.1}\right)^{\frac{4}{3}} \left(\frac{\beta_{\rm A}}{0.1}\right)^{\frac{5}{3}} \left(\frac{\Delta t}{\rm day}\right)^{\frac{1}{3}} \left(\frac{\Gamma}{10}\right) \left(\frac{L_{\rm p}}{10^{46}\,{\rm erg}^{-1}}\right)^{-\frac{1}{2}} \left(1+\frac{W_{\rm ph}}{W_B}\right)^{-\frac{4}{3}} {\rm Hz}\,. \quad (15)$$

When $q = 5/3$, we find

$$\gamma_{\rm peak} = 4.65 \times 10^{2} \left(\frac{\zeta}{0.1}\right)^{\frac{3}{4}} \left(\frac{\beta_{\rm A}}{0.1}\right)^{\frac{1}{4}} \left(\frac{\Delta t}{\rm day}\right)^{\frac{3}{4}} \left(\frac{\Gamma}{10}\right)^{\frac{5}{4}} \left(\frac{L_{\rm p}}{10^{46}\,{\rm erg}^{-1}}\right)^{-\frac{5}{8}} \left(1+\frac{W_{\rm ph}}{W_B}\right)^{-\frac{3}{4}} \quad (16)$$

and the peak frequency

$$\nu_{\rm p} = 4.13 \times 10^{12} \left(\frac{\zeta}{0.1}\right)^{\frac{3}{2}} \left(\frac{\beta_{\rm A}}{0.1}\right)^{\frac{3}{2}} \left(\frac{\Delta t}{\rm day}\right)^{\frac{1}{2}} \left(\frac{\Gamma}{10}\right)^{\frac{3}{2}} \left(\frac{L_{\rm p}}{10^{46}\,{\rm erg}^{-1}}\right)^{-\frac{3}{4}} \left(1+\frac{W_{\rm ph}}{W_B}\right)^{-\frac{3}{2}} {\rm Hz}\,. \quad (17)$$

From the above peak frequencies, we find that the plasma turbulence with Kolmogorov and Kraichnan spectra cannot accelerate efficiently relativistic electrons to very high energies to produce an SED typical of a high energy peaked BL Lacs (HBL). This does not show that stochastic particle acceleration is not efficient. In fact, the acceleration rate $A(E)$ strongly depends on the spectral index q of plasma turbulence with

$$A(E) = c(q)\beta_{\rm g}^2 \zeta p^{q-1} B^{q-2} \left(\frac{\Delta t}{\rm day}\right)^{1-q}, \quad (18)$$

where $c(q) = \frac{\pi}{2}\left(\frac{q-1}{q}\right)(1.16\times10^{-5})(6.59\times10^{-13})^{q-2}$. Comparing the statistical relation $\gamma_{\rm peak} \propto (W_B + W_{\rm ph})^{-0.6}$ found by Ghisellini (1998) with equation (11), we immediately obtain $q = 4/3$. The peak energy of relativistic electrons now is given by

$$\gamma_{\rm peak} = 3.78 \times 10^{4} \left(\frac{\zeta}{0.1}\right)^{\frac{3}{5}} \left(\frac{\beta_{\rm A}}{0.1}\right)^{\frac{1}{5}} \left(\frac{\Delta t}{\rm day}\right)^{\frac{3}{5}} \left(\frac{\Gamma}{10}\right)^{\frac{4}{5}} \left(\frac{L_{\rm p}}{10^{46}\,{\rm erg}^{-1}}\right)^{-\frac{2}{5}} \left(1+\frac{W_{\rm ph}}{W_B}\right)^{-\frac{3}{5}}. \quad (19)$$

The peak frequency is

$$\nu_{\rm p} = 2.73 \times 10^{16} \left(\frac{\zeta}{0.1}\right)^{\frac{6}{5}} \left(\frac{\beta_{\rm A}}{0.1}\right)^{\frac{9}{5}} \left(\frac{\Delta t}{\rm day}\right)^{\frac{1}{5}} \left(\frac{\Gamma}{10}\right)^{\frac{3}{5}} \left(\frac{L_{\rm p}}{10^{46}\,{\rm erg}^{-1}}\right)^{-\frac{3}{10}} \left(1+\frac{W_{\rm ph}}{W_B}\right)^{-\frac{6}{5}} {\rm Hz}, \quad (20)$$

which weakly depends on the size of the emitting region and the bulk kinetic power of the jet, and strongly depends on the turbulent level, the turbulent wave velocity, the rate of external photon density and magnetic field density in the emitting region.

The above peak frequency certainly explains the observed properties of the blazar SED. For the same properties of plasma turbulence for blazars, i.e., with $\beta_{\rm A}$ and ζ fixed, the peak frequency of synchrotron emission is determined by external photon fields. Therefore a well-defined sequence of the peak frequency in HBLs, LBLs and FSRQs (Ghisellini 1998) is caused by the increasing role of external photon fields (e.g. broad emission-line radiation).

3 WAVE TURBULENT SPECTRUM

The central issue of accelerating particles to high energy is the spectral index of plasma turbulence. The formation of the turbulent wave spectrum results from nonlinear interactions of waves. In fully developed fluid turbulence, neighboring wave numbers couple strongly to form a conservative transport of energy in wave-number space from their injection wavelength, through the inertial range, into the short-wavelength dissipation range. The Reynolds number R_e measures the relative strength of the nonlinear and viscous stresses at the scale of the correlation length of fluctuations. As R_e increases to form turbulence, the scale for dissipation decreases such that the rate of energy cascade through the inertial range equals the short-wavelength dissipation rate in steady state. If the cascade rate is independent of R_e, the cascade of spectral energy will yield a well-verified Kolmogoroff spectrum $W(k) \propto k^{-5/3}$ in the inertial range.

The nonlinear interactions of waves are more complex in plasma turbulence than in the fluid case because both the mean magnetic field and the cross helicity strongly affect the cascade rate (Zhou & Matthaeus 1990). If the Alfvén mode dominates plasma turbulence, a strong background magnetic field will lower the interaction time of the eddies to $\tau_{\rm A} = 1/(kV_{\rm A})$ (Kraichnan 1965). If $\tau_{\rm NL}$ denotes the characteristic time taken for the nonlinear term to change the velocity substantially in the absence of magnetic fields, it would take $\tau_{\rm NL}/\tau_{\rm A}$ coherent interactions, each of time $\tau_{\rm A}$, to produce the same change as $\tau_{\rm NL}$ without the field. Assume each individual interaction takes $(\tau_{\rm NL}/\tau_{\rm A})^2$ interactions. This means the time for spectral transfer will increase from $\tau_{\rm NL}$ to $\tau_{\rm s} \equiv (\tau_{\rm A})(\tau_{\rm NL}/\tau_{\rm A})^2 = \tau_{\rm NL}^2/\tau_{\rm A}$. For resonant wavenumber k, $(\delta B)^2 = kW(k)$, $\tau_{\rm NL} = [k^3W(k)]^{-\frac{1}{2}}$ and the dissipation rate is

$$\epsilon = \frac{(\delta B)^2}{\tau_{\rm s}} = kW(k)\frac{\tau_{\rm A}}{\tau_{\rm NL}^2} = V_{\rm A}[W(k)]^2k^3, \tag{21}$$

it implies that the steady state spectrum $W(k)$ is Kraichnan spectrum which is proportional to $k^{-3/2}$. If we suppose that each interaction is dependent of the others it will take more interactions. We assume that the turbulent waves take $(\tau_{\rm NL}/\tau_{\rm A})^\alpha$ interactions to transfer energy, the time for spectral transfer will increase from $\tau_{\rm NL}$ to $\tau_{\rm s} \equiv (\tau_{\rm A})(\tau_{\rm NL}/\tau_{\rm A})^\alpha = \tau_{\rm NL}^\alpha\tau_{\rm A}^{1-\alpha}$ and the dissipation rate will be

$$\epsilon = \frac{(\delta B)^2}{\tau_{\rm s}} = kW(k)\tau_{\rm NL}^{-\alpha}\tau_{\rm A}^{\alpha-1} = k^{\frac{\alpha}{2}+2}W(k)^{\frac{\alpha}{2}+1}V_{\rm A}^{1-\alpha}. \tag{22}$$

Therefore the steady state spectrum is given by

$$W(k) \propto \epsilon^{\frac{2}{\alpha+2}}k^{-\frac{\alpha+4}{\alpha+2}}. \tag{23}$$

The spectral index q is equal to $\frac{\alpha+4}{\alpha+2}$ and is between 1 and 2. A value of α representing the nonlinear interactions of the eddies determines the turbulent wave spectrum. The longer the time for spectral transfer, the flatter the turbulent spectrum. The case of $\alpha = 0$, $q = 2$ corresponds to diffusive shock wave acceleration, and is determined by the interaction time $\tau_{\rm A}$ of the turbulent wave mode. The case of $\alpha \to \infty$, $q = 1$ corresponds to a noise spectrum with infinite energy content, and is related to the infinite time of spectral transfer. The condition $\alpha = 4$ ($q = 4/3$) leads to the stochastic particle acceleration of blazar jets discussed in the above section. A more general case can be obtained by including a nonlinear time $\tau_{\rm NL}^\pm$ for each of the general wave modes $z^\pm = \delta v \pm \delta B$, where z^+ and z^- refer to waves propagating "outward" and "inward" with respect to the background magnetic field, and by replacing $\tau_{\rm A}$ with τ_3, the triple decorrelation time arrived at by taking the sum of the rates for nonlinear and Alfvénic processes (Zhou & Matthaeus 1990). Therefore $(\tau_3^\pm)^{-1} = \tau_{\rm A}^{-1} + (\tau_{\rm NL}^\pm)^{-1}$, $\tau_{\rm s}^\pm = \tau_3^\pm(\tau_{\rm NL}^\pm/\tau_3^\pm)^\alpha$ and dissipation rates $\epsilon^\pm = (z_k^\pm)^2(\tau_{\rm s}^\pm)^{-1}$. The cascade rates of z^+ and z^- are no longer equal. The steady state spectrum will be more complex.

4 CONCLUSIONS

We have examined stochastic particle acceleration by plasma wave turbulence in blazar jets. We find that in the case of turbulent spectrum, $W(k) \propto k^{-\frac{4}{3}}$, electrons can overcome both synchrotron and Compton losses and be accelerated to form a nonthermal population. Their synchrotron emission is in agreement with the SED properties of blazars. The synchrotron peak frequency $\nu_{\rm p}$ is determined by the balance between acceleration and cooling; it depends weakly on the size of the emitting region and the bulk kinetic power of the jet, and strongly on the turbulent level, the turbulent wave velocity and the rate of external photon density and magnetic field density in the emitting region. An increase of external photon density will cause a rapid decrease of $\nu_{\rm p}$. We simply investigated the plasma nonlinear processes responsible for the formation of turbulent spectrum. The turbulent spectrum depends on the nonlinear interactions of waves. An increase in the interaction time of turbulent waves can produce a flatter spectrum which leads to an efficient particle acceleration.

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