ON THE SIMULTANEOUS GENERATION OF HIGH-ENERGY EMISSION AND SUBMILLIMETER/INFRARED RADIATION FROM ACTIVE GALACTIC NUCLEI

Z. Osmanov
Centre for Theoretical Astrophysics, ITP, Ilia State University, Kazbegi Str. 2a, 0160 Tbilisi, Georgia; z.osmanov@iliauni.edu.ge

Received 2010 May 27; accepted 2010 July 13; published 2010 August 27

ABSTRACT

For active galactic nuclei (AGNs), we study the role of the mechanism of quasi-linear diffusion (QLD) in producing the high-energy emission in the MeV–GeV domains strongly connected with the submillimeter/infrared radiation. Considering the kinetic equation governing the stationary regime of the QLD, we investigate the feedback of the diffusion on electrons. We show that this process leads to the distribution of particles by pitch angles, implying that the synchrotron mechanism is no longer prevented by energy losses. Examining a reasonable interval of physical parameters, we show that it is possible to produce MeV–GeV γ-rays that are strongly correlated with submillimeter/infrared bands.

Key words: galaxies: active – gamma rays: galaxies – infrared: galaxies – submillimeter: galaxies

1. INTRODUCTION

According to the model of active galactic nuclei (AGNs), cold material close to the central black hole forms an accretion disk, matter inside which, due to the dissipative forces, is transported inward causing the accretion disk to heat up. Such a hot material in turn can inverse Compton scatter photons up to X-ray energies (Blandford et al. 1990). From high-energy astronomical sources, blazar-type AGNs are objects of special interest, the standard model of which implies the presence of a supermassive black hole surrounded by the accretion disk and ejecting twin relativistic jets. The observationally evident broadband emission in the γ-ray domain attributed to the synchrotron relativistic jets. The observationally evident broadband emission spectrum of blazars is made of two components: the low-energy (from radio to optical) domain attributed to the synchrotron emission and the high-energy (from X-rays to γ-rays) part formed by either the inverse Compton mechanism (Blandford et al. 1990) or the curvature radiation (Gangadhara 1996; Thomas & Gangadhara 2005). A recent investigation of the parsec scale jets is very important. Giroletti et al. (2010) argued that the high-energy and radio emissions are strongly correlated. Our model on the other hand, as we will see, automatically provides a connection of radiation in high-energy and radio domains. Magnetospheres of AGNs have strong magnetic fields; therefore, synchrotron cooling timescales are relatively short, leading to efficient energy losses. This in turn creates appropriate conditions for particles to transit to their ground Landau state. When this happens, relativistic electrons will move only along magnetic field lines without emitting in the synchrotron regime.

Despite the very strong magnetic field, which prevents a continuous process of the synchrotron emission, there is a possibility to overcome the dissipative factors and maintain the cyclotron instability mechanism. Machabeli & Usov (1979) have studied the cyclotron instability of a two-component electron–positron plasma for the pulsar NP 0532. It was found that the instability arises near the light cylinder surface (a hypothetical zone, where the linear velocity of rigid rotation equals exactly the speed of light), leading to a certain distribution of particles by pitch angles and the consequent synchrotron radiation. Lominadze et al. (1979) considered the magnetospheres of the pulsar NP 0532 and the Crab nebula, studying the generation of waves from optical to gamma-ray domains. A similar approach was presented by Malov & Machabeli (2001) where the quasi-linear diffusion (QLD) was applied to the radio pulsars. The authors found that the transverse momenta of relativistic particles induced by the cyclotron instability caused the stable non-zero pitch angle distribution maintained by means of the QLD. Analyzing the data obtained from the MAGIC Cherenkov telescope between 2007 October and 2008 February (Aliu et al. 2008), we found that the observed coincidence of signals in the optical and γ-ray domains is easily explained by the QLD process, which leads to the increase of the pitch angles, making the synchrotron process feasible (Machabeli & Osmanov 2009, 2010).

In the magnetospheres of AGNs, the magnetic fields are of the order of 10^6 G (Thorne et al. 1988) close to the supermassive black hole, and 100 G–300 G close to the light cylinder surface. Therefore, the aforementioned QLD mechanism could be of great importance for AGNs as well. For this purpose, by considering the cyclotron instability excited in the radio domain, in Osmanov & Machabeli (2010) we studied the quasi-linear interaction of the proper modes of AGN magnetospheric plasma with resonant plasma particles, investigating the QLD in the context of producing the soft and hard X-ray emission from AGNs. Under favorable conditions this mechanism could also be efficient for explaining the MeV–GeV energy synchrotron emission, strongly connected either with the submillimeter radio band or with the infrared emission induced by the cyclotron instability. This will be the subject of the present paper, which is organized as follows. In Section 2 we describe our model, in Section 3 we apply the mechanism of QLD to AGNs, and in Section 4 we summarize our results.

2. MAIN CONSIDERATION

In general, AGN magnetospheres consist of relatively low energy particles and very high energy particles (electrons). Therefore, in the framework of the model we consider, the plasma is composed of two components: (1) the so-called plasma component with the Lorentz factor, γp, and (2) the beam component with the Lorentz factor, γb (γb ≫ γp). Such a system, as was shown by Kazbegi et al. (1992), undergoes the cyclotron instability induced by the Doppler effect with the following resonance condition:

$$\omega - k_i V_i - k_i u_e \pm \frac{\omega B}{\gamma_b} = 0,$$

(1)
where \( k \) is the longitudinal (parallel to the background magnetic field) component of the wave vector, \( k_r \) is the component along the drift, \( V_\parallel \) is the longitudinal component of plasma flow velocity, \( u_\parallel \equiv eV_\parallel \gamma_b / \rho \omega_B \) is the drift velocity of particles, \( e \) is the speed of light, \( \rho \) is the field lines’ curvature radius, \( \omega_B \equiv eB / mc \) is the cyclotron frequency, \( B \) is the magnetic induction, and \( e \) and \( m \) are the electron’s charge and the rest mass, respectively. The positive sign corresponds to the damping of the excited modes, whereas the negative sign relates to the unstable mode. One can show that, when the aforementioned resonance takes place, the transverse waves with the dispersion relation

\[
\omega \approx k c (1 - \delta), \quad \delta = \frac{\omega_p^2}{4\sqrt{\rho} \gamma_b^3}
\]

are induced. \( k \) is the modulus of the wave vector, \( \omega_p \equiv \sqrt{4\pi n_p e^2 / m} \) is the plasma frequency, and \( n_p \) is the plasma density. From Equations (1) and (2), it is clear that the excited cyclotron frequency is given by (Malov & Machabeli 2001)

\[
\omega \approx \frac{\omega_B}{\delta \gamma_b}.
\]

In spite of the resonant character of the cyclotron modes, the corresponding frequency is not well peaked, because \( \omega_p \) also depends on the Lorentz factors of the resonant (beam) particles that do not have narrow energy spectra. It is worth noting that unlike the synchrotron mechanism (\( \lambda < n_p^{-1/3}; \lambda \) is the wavelength), where the radiation process can be described by a single particle approach, the excitation of the aforementioned waves is a collective phenomenon (\( \lambda > n_p^{-1/3} \)), which in turn is a direct consequence of the one dimensionality of the distribution function. On the other hand, such a behavior of this function is guaranteed by the strong magnetic field that forces particles to move along the field lines.

In general, two dissipative factors lead to a decrease of the pitch angle. The force that provides the conservation of the adiabatic invariant \( I = 3 c p_{\parallel}^2 / 2 e B \) in a non-uniform magnetic field (Landau & Lifshitz 1971; see also Osmanov & Machabeli 2010) is

\[
G_\perp = -\frac{m c^2 \gamma_b}{\rho} \psi, \quad G_\parallel = \frac{m c^2 \gamma_b}{\rho} \psi^2
\]

and the radiation reaction force (Landau & Lifshitz 1971) is

\[
F_\perp = -\alpha \psi (1 + \gamma_b^2 \psi^2), \quad F_\parallel = -\alpha \gamma_b^2 \psi^2,
\]

where \( \alpha = 2 e^2 \omega_B^2 / (3 c^2) \) and \( \psi \) is the pitch angle. Only under the action of these forces does the pitch angles tend to decrease, inevitably killing the synchrotron emission. In reality, the situation is principally different because the excited relatively low frequency waves (in our case submillimeter/infrared) by means of cyclotron resonance lead to QLD. Unlike the dissipative effects of \( (F, G) \), diffusion creates a non-zero distribution function with respect to pitch angles and supports the synchrotron emission. It is clear that under favorable conditions the effect of QLD may balance the dissipation; therefore, our objective is to find the distribution of particles by pitch angles, estimate their mean value, and analyze the corresponding synchrotron emission energy. On the other hand, since the QLD results from the feedback of the cyclotron modes, apart from the high-energy emission, the system will also be characterized by low-energy radiation.

In Osmanov & Machabeli (2010), we studied the role of the QLD in producing the X-ray emission by means of ultrarelativistic electrons in AGN magnetospheric flows. It was shown that the cyclotron resonance provides emission in a low-energy domain—the radio band. Unlike the physical conditions \((|G_\perp| \gg |F_\perp| \text{ and } |G_\parallel| \ll |F_\parallel|)\) considered in Osmanov & Machabeli (2010), in the present paper we examine a physically different regime, \(|G_\perp| \ll |F_\perp| \text{ and } |G_\parallel| \ll |F_\parallel| \), which reduces the stationary kinetic equation governing the QLD to (Malov & Machabeli 2001)

\[
\frac{\partial}{\partial \psi} (\psi F, f) = \frac{1}{mc \gamma_b} \frac{\partial}{\partial \psi} \left( \psi D_{\perp} \frac{\partial f}{\partial \psi} \right),
\]

where \( f = f(\psi) \) is the distribution function of particles and

\[
D_{\perp} \approx \frac{\pi^2 e^2}{m c^2} \frac{\delta}{\gamma_b^2} |E_k|^2
\]

is the diffusion coefficient. \(|E_k|^2 \) is the energy density per unit wavelength, and therefore the energy density of the cyclotron waves is of the order of \(|E_k|^2 \kappa \). If we assume that \( \sim 50\% \) of the resonant plasma energy, \( mc^2 n_b \gamma_b \), is converted to waves (Osmanov & Machabeli 2010), then for \(|E_k|^2 \) one obtains (Malov & Machabeli 2001)

\[
|E_k|^2 = \frac{m c^3 n_b \gamma_b}{2 \omega}.
\]

The distribution function obtained from Equation (7) is given by

\[
f(\psi) = C e^{-A \psi^4},
\]

where

\[
A \equiv \frac{\alpha mc \gamma_b^3}{4 D_{\perp}}, \quad C = \text{const}.
\]

Unlike the work presented in Osmanov & Machabeli (2010), due to the different regime, \( f(\psi) \) behaves as \( e^{-A \psi^4} \) instead of as \( e^{-A_1 \psi^2} \) (see Equation (11) in Osmanov & Machabeli 2010).

As we can see, particles are distributed by the pitch angles; therefore, the electrons will emit via the synchrotron process without damping.

3. DISCUSSION

In this section, we apply the model of the QLD to the light cylinder lengthscales of typical AGNs.

To explain high-energy radiation, it is strongly believed that AGN magnetospheres consist of highly relativistic electrons. This fact leads to another problem—how are these particles accelerated to such high energies? In general, there are several mechanisms that may account for the efficient acceleration of electrons. Indeed, as shown in a series of papers, the Fermi-type acceleration process (Catanese & Weeks 1999), the re-acceleration of electron–positron pairs as a feedback mechanism (Ghisellini et al. 1993), and centrifugal acceleration (Machabeli & Rogava 1994; Osmanov et al. 2007; Rieger & Aharonian 2008; Osmanov 2010) may provide very high Lorentz factors of the order of \( \gamma_b \sim 10^7–10^9 \). Therefore, in the framework of the paper the existence of such particles is assumed to be a given fact. If we suppose an isotropic distribution of relativistic
electrons, one can estimate the synchrotron cooling timescale (Osmanov & Machabeli 2010) as

\[ t_{\text{cool}} \approx 5 \times 10^{-3} \times \left( \frac{10^2 G}{B} \right)^2 \times \left( \frac{10^8}{\gamma} \right) \, \text{s}. \]  \hspace{1cm} (11)

The value of the magnetic induction is given by (Osmanov & Machabeli 2010)

\[ B_{lc} \approx 260 \times \left( \frac{L}{10^{45} \, \text{erg s}^{-1}} \right)^{1/2} \times \left( \frac{\Omega}{3 \times 10^{-5} \, \text{s}^{-1}} \right) \, \text{G}, \]  \hspace{1cm} (12)

where \( L \) is the bolometric luminosity of the AGN and \( r_{lc} = c/\Omega \) is the light cylinder radius (a hypothetical zone, where the linear velocity of rigid rotation exactly equals the speed of light). \( \Omega \) is the magnetic field lines’ angular velocity of rotation, normalized to the value \( 3 \times 10^{-5} \, \text{s}^{-1} \) (Belvedere et al. 1989). Throughout the paper, we assume that the magnetic field is robust enough to maintain the frozen-in condition in the magnetosphere of the AGN. Indeed, as one can see, for the typical magnetospheric parameters, \( \gamma_b \approx 10^8 \) and \( n_b \approx 10 \, \text{cm}^{-3} \), the condition \( B_{lc}^2/8\pi \geq \gamma_b n_b c^2 e^2 \) is satisfied, which means that the plasma particles will be forced to follow the rigidly rotating field lines. During such a motion, especially on the light cylinder length-scales, the electrons will experience a centrifugal force accelerating them to very high Lorentz factors \( \sim 10^8 \) to \( 10^9 \) (Osmanov et al. 2007; Rieger & Aharonian 2008).

It is clear from Equation (11) that for a certain class of physical parameters the synchrotron cooling timescale is of the order of \( 5 \times 10^{-4} \, \text{s} \). On the other hand, the kinematic timescale of the system, \( \tau_{\text{kin}} \sim r_{lc}/c \approx 3 \times 10^3 \, \text{s} \), is many orders of magnitude bigger than \( t_{\text{cool}} \), which in turn means that without the QLD, particles would stop emitting in the synchrotron regime very soon after transiting to their ground Landau level.

Kazbegi et al. (1992) showed that the anomalous Doppler effect generates the cyclotron waves with the frequency (Osmanov & Machabeli 2010)

\[ \omega \approx 6.8 \times 10^9 \times \left( \frac{\gamma_b}{100} \right)^4 \times \left( \frac{10^8}{\gamma_b} \right)^2 \times \left( \frac{B}{100 \, \text{G}} \right)^3 \times \left( \frac{10 \, \text{cm}^{-3}}{n_b} \right) \, \text{Hz}, \]  \hspace{1cm} (13)

leading to the process of the QLD, which, despite the efficient dissipative factors, creates the pitch angles.

To demonstrate the present model, we consider an AGN with the bolometric luminosity \( L = 10^{45} \, \text{erg s}^{-1} \). Let us examine the following parameters: \( \Omega = 3 \times 10^{-5} \, \text{rad s}^{-1} \), \( \gamma_p = 10^8 \), and \( n_b = 10 \, \text{cm}^{-3} \). Since the particles are distributed by their pitch angles (see Equation (9)), to analyze the synchrotron emission it is reasonable to estimate a mean value for \( \psi \),

\[ \bar{\psi} = \frac{\int_{0}^{\infty} f(\psi) d\psi}{\int_{0}^{\infty} f(\psi) d\psi} \approx 0.5 \sqrt{A}. \]  \hspace{1cm} (14)

Then one can show from Equation (14) that for the aforementioned parameters the pitch angle is of the order of \( 8 \times 10^{-3} \, \text{rad} \), and therefore relativistic electrons will inevitably emit photons with energies (Rybicki & Lightman 1979)

\[ \epsilon_{\gamma\nu} \approx 1.2 \times 10^{-8} B \gamma^2 \sin \psi. \]  \hspace{1cm} (15)

After substituting the value of \( \bar{\psi} \) into Equation (15), we see that the synchrotron emission generates radiation in the MeV–GeV domain.

The QLD works if the cyclotron modes are excited; therefore, it is essential to estimate the timescale of the corresponding instability (\( t_{\text{ins}} \)) and compare it with the kinematic timescale of the system. According to the work of Kazbegi et al. (1992), the growth rate of the instability is given by

\[ \Gamma = \frac{\pi \omega_b^2}{\omega \gamma_p} \quad \text{if} \quad \frac{1}{2} \frac{u_e^2}{c^2} \ll \delta \]  \hspace{1cm} (16)

and

\[ \Gamma = \frac{\pi \omega_b^2}{2 \omega \gamma_p} \frac{u_e^2}{\delta \cdot c^2} \quad \text{if} \quad \frac{1}{2} \frac{u_e^2}{c^2} \gg \delta, \]  \hspace{1cm} (17)

where \( \omega_b \equiv 4\pi n_b e^2/m \) is the plasma frequency of beam electrons. It is easy to show that for \( n_b = 10 \, \text{cm}^{-3} \), \( \gamma_p = 200 \) (see Figure 1), \( V_b \sim c \), and \( \rho \sim R_g \), one obtains \( u_e^2/(2c^2) \ll 1 \), implying that the increment of the instability is given by Equation (16). The cyclotron resonance makes sense if \( \tau_{\text{ins}}/\tau_{\text{kin}} < 1 \); then, by taking into account the definition of the kinematic timescale, \( r_{lc}/c \), and the instability timescale, \( 1/\Gamma \), one can show that the aforementioned condition reduces to

\[ 3.5 \times 10^{-3} \times \left( \frac{\gamma_p}{100} \right)^5 \times \left( \frac{10^8}{\gamma_b} \right)^2 \times \left( \frac{10 \, \text{cm}^{-3}}{n_b} \right)^2 < 1. \]  \hspace{1cm} (18)

As is clear from Equation (18), the condition is very sensitive to the Lorentz factor of the plasma components, and for relatively higher values of \( \gamma_p \), the condition will be violated. The upper limit of \( \gamma_p \), when the condition is still valid, is of the order of 300 for \( \gamma_b \sim 10^8 \) and \( n_b \sim 10 \, \text{cm}^{-3} \). To study the efficiency of the QLD, we examine the following set of parameters: \( L = 10^{45} \, \text{erg s}^{-1}, \Omega = 3 \times 10^{-5} \, \text{rad s}^{-1}, \gamma_p = 200 \), and \( n_b = (5; 10; 15) \, \text{cm}^{-3} \); the results are demonstrated in Figure 1 where we show the behavior of \( \epsilon_{\gamma\nu} \) versus \( \gamma_b \). From the plots, it is clear that \( \epsilon_{\gamma\nu} \) is a continuously increasing function of the beam’s Lorentz factor, which is a natural result of the fact that
more energetic particles produce more energetic photons. The behavior of $\epsilon_{\gamma \nu}$ versus $n_b$ is different, as denser beam electrons produce photons with lower energies. This can be seen from Equations (10) and (14): $\bar{\psi} \sim \sqrt{D_{\perp \perp}}$, which by combining with $D_{\perp \perp} \sim n_b^3$ (see Equations (7) and (8)) confirms the dependence $\epsilon_{\gamma \nu}(n_b)$. According to the results demonstrated in the figure, relativistic electrons with Lorentz factors $\gamma_p = (1-2) \times 10^8$ may provide the high-energy radiation in the MeV–GeV domain.

Since the generation of the synchrotron emission strongly depends on the cyclotron waves, we also investigate the behavior of $\epsilon_{\gamma \nu}$ versus $\omega$. Figure 2 shows the function $\epsilon_{\gamma \nu}(\omega)$ for several values of $n_b$. The set of parameters is the same as in the previous figure. As is clear from the plots, the 200–1200 MeV radiation is strongly connected with the submillimeter ($\sim (0.3-3) \times 10^{12}$ Hz) and low infrared ($\sim (3-3.8) \times 10^{12}$ Hz) emission.

Another important parameter the physical system depends on is the Lorentz factor of the plasma component. Therefore, it is reasonable to demonstrate the function $\epsilon_{\gamma \nu}(\omega)$ for different values of $\gamma_p$. These results are shown in Figure 3, where the set of parameters is $L = 10^{45}$ erg s$^{-1}$, $\Omega = 3 \times 10^{-5}$ rad s$^{-1}$, $\gamma_p = 200$, and $n_b = (5; 10; 15) \text{cm}^{-3}$. As seen from the figure, higher values of $\gamma_p$ correspond to lower synchrotron energies. Indeed, by taking into account the relation $\bar{\psi} \sim \sqrt{D_{\perp \perp}}$ combined with Equations (7) and (8) one can see that $\bar{\psi} \sim 1/\gamma_p^2$.

As is clear from the results, the QLD together with the cyclotron instability may guarantee the production of high-energy radiation in the MeV–GeV domains strongly connected with submillimeter/infrared emission. The major difference in results from our previous work is that in Osmanov & Machabeli (2010) we studied the physical conditions leading to the excitation of X-rays connected with the relatively low frequency radio band (KHz–MHz), whereas in the present paper both energies (produced by synchrotron and cyclotron mechanisms, respectively) are much higher. This investigation sets another problem: since the QLD is a feasible mechanism providing the aforementioned high energies, one of the important next steps could be the testing of MeV–GeV AGNs exhibiting an efficient submillimeter/infrared radiation and seeing if the strong correlation is observationally evident. This in turn could be a certain test for estimating the AGN magnetospheric parameters, such as the density and the Lorentz factors of the plasma component and beam electrons. A particular future objective is to theoretically investigate the radiative signatures of both high-and low-energy emissions, respectively. This will be the subject of a future paper.

4. SUMMARY

The main aspects of the present work can be summarized as follows.

1. Mechanisms producing strongly connected high- and low-energy radiations were studied by taking into account the QLD in the AGN magnetospheres. Considering a physical regime different from that of Osmanov & Machabeli (2010), we investigate the efficiency of the QLD in a region close to the light cylinder surface.

2. For the considered physical parameters, it has been shown that the cyclotron instability appears at a relatively low frequency range, producing radiation in the submillimeter/infrared domains. On the other hand, despite the short cooling timescales, the effect of diffusion on particles recreates the pitch angles and produces the high-energy radiation in the MeV–GeV bands.

3. The problem was studied in terms of three major magnetospheric parameters: the beam, the plasma component’s Lorentz factors, and the beam electrons’ density. It was shown that the photon energy, $\epsilon_{\gamma \nu}$, is a continuously increasing function of the beam’s Lorentz factor and the beam density. Contrary to this, by increasing the plasma component’s Lorentz factor, the corresponding photon energy decreases.

The research was supported by the Georgian National Science Foundation grant GNSF/ST06/4-193.

REFERENCES

Aliu, E., et al. 2008, ApJ, 674, 1037A
Belvedere, G., Paternó, L., & Pidatella, R. M. 1989, MNRAS, 237, 827
Blandford, R. D., Netzer, H., & Woltjer, L. 1990, Active Galactic Nuclei (Springer: Berlin)
Catanese, M., & Weeks, T. C. 1999, PASP, 111, 1193
Gangadhara, R. T. 1996, A&A, 314, 853
Ghisselli, G., Haardt, F., & Fabian, A. C. 1993, MNRAS, 263, L9
Giroletti, M., Reimer, A., Fuhrmann, L., Pavlidou, V., & Richards, J. L. 2010, (arXiv:1001.5123)
Kazbegi, A. Z., Machabeli, G. Z., & Melikidze, G. I. 1992, MNRAS, 253, 377
Landau, L. D., & Lifshitz, E. M. 1971, Classical Theory of Fields (London: Pergamon)
Lominadze, J. G., Machabeli, G. Z., & Mikhailovsky, A. B. 1979, J. Phys. Colloq., 40, 713
Machabeli, G., & Osmanov, Z. 2009, ApJ, 700, L114
Machabeli, G., & Osmanov, Z. 2010, ApJ, 709, 547
Machabeli, G. Z., & Rogava, A. D. 1994, Phys. Rev. A, 50, 98
Machabeli, G. Z., & Usov, V. V. 1979, AZhZh Pis’ma, 5, 238
Malov, I. F., & Machabeli, G. Z. 2001, ApJ, 554, 587
Osmanov, Z. 2010, New Astron., 15, 351
Osmanov, Z., & Machabeli, G. 2010, A&A, 516, A12
Osmanov, Z., Rogava, A. S., & Bodo, G. 2007, A&A, 470, 395
Rieger, F. M., & Aharonian, F. A. 2008, A&A, 479, L5
Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: Wiley)
Thomas, R. M. C., & Gangadhara, R. T. 2005, A&A, 437, 537
Thorne, K. S., Price, R. H., & Macdonald, D. A. 1988, Black Holes: The Membrane Paradigm (New Haven, CT: Yale Univ. Press)