Particle acceleration and high-frequency (X-ray and \(\gamma\)-ray) emission in the jets of active galactic nuclei

V.V. Usov and M.V. Smolsky

Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel

(Received ...... ; Accepted in final form ......)

Abstract. It is suggested that the outflowing plasma in the jets of active galactic nuclei (AGNs) is inhomogeneous and consists of separate clouds. These clouds are strongly magnetized and move away from the central engine at relativistic speeds. The clouds interact with an ambient medium which is assumed to be at rest. In the process of this interaction, particles of the ambient medium are accelerated to high energies at the cloud front and flow ahead of the front. It is shown that the radiation of the accelerated particles may be responsible for the X-ray and \(\gamma\)-ray emission from AGN jets. TeV \(\gamma\)-ray emission is generated in the inner parts of AGN jets where the Lorentz factor of the cloud fronts is \(\Gamma_0 \geq 30\), while GeV \(\gamma\)-ray emission emanates from the outer parts of AGN jets where \(\Gamma_0\) is \(\sim 10\).

Key words: acceleration of particles – galaxies: active – gamma-rays: theory

1. Introduction

At radio frequencies, where VLBI can resolve the emission regions at the milliarcsecond scale, many of radio-loud AGNs exhibit compact jets (e.g., Cawthorne, 1991). These jets are remarkably well collimated, with opening angles about a few degrees or even less. The radio emitting plasma of the jets moves at relativistic velocities. Lower limits to the bulk Lorentz factors of this plasma which are derived from the measured apparent transverse velocities of radio emitting blobs are between \(\sim 3\) and 10 (Impey, 1987).

The Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory (CGRO) has detected a few tens of extragalactic sources (Thompson et al., 1995), which are thought to be radio galaxies favorably oriented so that the axes of the radio jets are nearly aligned in our observing direction (e.g., Dermer, 1994). The \(\gamma\)-ray emission from these EGRET sources which are frequently called blazars is in the range from a few ten MeV to a few GeV. Besides, very hard \(\gamma\)-rays at TeV energies were detected from Mrk 421 and Mrk 501 with the ground-based telescopes (Punch, 1992; Quinn et al., 1996; Barrau et al., 1997). Hence, particles are accelerated in AGN jets at least up to the energies of \(\sim 10^9 - 10^{12}\) eV.
For the jets of AGNs, the typical size of the emission region in \( \gamma \)-rays is somewhere between \( \sim 0.01 \) pc and \( \sim 0.1 \) pc (e.g., Maraschi, Ghisellini and Celotti, 1992; Levinson, 1996) that is about one or two orders of magnitude smaller than the typical size of the radio emission region. Thus, the \( \gamma \)-ray emission most likely emanates from the inner parts of the jet. The bulk Lorentz factors of the inner \( \gamma \)-ray jets may be at least a few times more than the same of the radio jets because of deceleration of the jet plasma in the process of its interaction with an ambient medium (see below).

The variability of extragalactic compact jets in the radio and \( \gamma \)-ray emission is very high. Most probably, this variability at least on some time scales is due to strong nonstationarity of the plasma flow in AGN jets (Blandford and Königl, 1979; Romanova and Lovelace, 1997; Levinson and van Putten, 1997). In this paper, acceleration of particles and their emission in relativistic nonstationary jets are discussed.

2. Acceleration of particles

Let us consider the following model of the inner high-speed jets which are responsible for the \( \gamma \)-ray emission of AGNs. The outflowing plasma of such a jet is inhomogeneous and gathers into separate clouds along the jet axis. These clouds are strongly magnetized and move away from the central engine of AGN at relativistic speeds. The Lorentz factor of the cloud fronts is \( \Gamma_0 \geq 10 \). There is an ambient medium between the clouds which is more or less at rest in the frame of the AGN engine. This medium mainly consists of electrons and protons, and its magnetic field is negligible.

If the jet is free (confined solely by its own inertia), it resembles a conic section of a spherical wind. In this case, the components of the magnetic field parallel and transverse to the jet velocity are \( B_\parallel \propto r^{-2} \) and \( B_\perp \propto r^{-1} \), respectively, where \( r \) is the distance from the central engine. Therefore, at large distances from the engine the field of the plasma clouds is mainly across their velocity, \( B_\perp \gg B_\parallel \).

The plasma clouds in the process of their motion interact with the ambient medium at the cloud fronts. For consideration of this interaction, it is convenient to switch to the frame of the cloud front. In this frame, the problem of the relativistic magnetized cloud – ambient medium interaction is identical to the problem of collision between a wide relativistic beam of cold plasma and a region with a strong magnetic field which is called a magnetic barrier. Recently, such a collision was studied numerically (Smolsky and Usov, 1996; Usov and Smolsky,
1998), and it was shown that when the energy densities of the plasma beam and the magnetic field are comparable,

\[ \alpha = 4\pi n_0 m_p c^2 (\Gamma_0 - 1)/B_0^2 \sim 1, \]

the process of the beam – barrier interaction is strongly nonstationary, and electrons are accelerated up to the mean energy of protons, i.e. up to the energy of \( \sim m_p c^2 \Gamma_0 \) (see Fig. 1), where \( n_0 \) is the density of protons and \( m_p \) is the proton mass, \( B_0 \) is the field strength. Both \( n_0 \) and \( B_0 \) are taken in the frame of the magnetic barrier. Besides, strong nonstationarity of the beam – barrier interaction results in generation of low-frequency electromagnetic waves in the front vicinity. The frequency of these waves is about the gyrofrequency of protons, \( \omega \simeq e B_0 / m_p c \Gamma_0 \), and their typical amplitude is \( \sim (0.2 - 0.3) B_0 \).

At \( \alpha \sim 1 \), in the frame of the ambient medium, the mean Lorentz factor of high-energy electrons which are accelerated at the cloud front and flow ahead of the front is (Usov and Smolsky, 1998)

\[ \langle \Gamma_e \rangle \simeq 0.1 (m_p/m_e) \Gamma_0^2 \]

within a factor of 2 or so, where \( m_e \) is the electron mass. The maximum Lorentz factor of accelerated electrons is about an order of magnitude more than their mean Lorentz factor:

\[ \Gamma_e^{\text{max}} \simeq 10 \langle \Gamma_e \rangle \simeq (m_p/m_e) \Gamma_0^2. \]
Equations (2) and (3) are valid only if the cloud front velocity is ultra-relativistic, $\Gamma_0 \geq 10$.

The energy spectra of accelerated electrons in the range from $\sim \langle \Gamma_e \rangle$ to $\Gamma_{e \mathrm{max}}$ depend on the value of $\alpha$, and at $0.5 \leq \alpha \leq 2$ they may be fitted by a power law distribution, $dn_e/d\Gamma_e \propto \Gamma_e^{-\beta}$, with the spectral index $\beta \simeq 2.4 - 2.8$.

At $\alpha \sim 1$, the kinetic energy that is lost by the clouds in the process of their interaction with the ambient medium is distributed in the following way (for details, see Smolsky and Usov, 1996; Usov and Smolsky, 1998). About 50% - 60% of this energy is in ultrarelativistic protons that are reflected from the cloud front. The rest of the kinetic-energy losses is distributed more or less evenly between high-energy electrons and low-frequency electromagnetic waves that are generated in the front vicinity due to nonstationarity of the interaction between the relativistic magnetized clouds and the ambient medium. Figure 2 shows the energy distribution for reflected protons in the frame of the cloud front. In this frame, the mean Lorentz factor of reflected protons is about $0.5 \Gamma_0$, while in the frame of the ambient medium it increases by the factor of $\sim 2 \Gamma_0$ and is $\langle \Gamma_p \rangle \simeq \Gamma_0^2$. 

Figure 2. Energy spectrum of protons which are reflected from the cloud front at $\alpha = 2/3$ in the frame of the front.
3. High-frequency radiation from AGN jets

3.1. Gamma-ray emission

The GeV and TeV $\gamma$-ray emission from AGN jets is usually interpreted as being produced by inverse Compton scattering of high-energy electrons on an external radiation which is either the thermal UV radiation of the accretion disk around a supermassive black hole (e.g., Dermer & Schlickeiser 1993) or the optical and UV emission of warm gas from the broad emission-line region around the AGN (e.g., Sikora, Begelman and Rees, 1994; Blandford and Levinson, 1995; Sikora et al., 1996).

The mean energy of photons after scattering is (e.g., Blumenthal and Tucker, 1974)

$$\langle \varepsilon_\gamma \rangle \approx \varepsilon_0 \sin \langle \vartheta \rangle \Gamma_e^2,$$

where $\varepsilon_0$ is the typical energy of external photons that are scattered by high-energy electrons with the Lorentz factor $\Gamma_e$, $\langle \vartheta \rangle$ is the mean angle between the wave vector of external photons and the velocity of high-energy electrons. Roughly, we have $\varepsilon_0 \approx 1 - 10$ eV and $\sin \langle \vartheta \rangle \approx 1$ for scattering of electrons on the radiation of warm gas from the broad emission-line region and $\varepsilon_0 \approx 10^2 - 10^3$ eV and $\sin \langle \vartheta \rangle \approx \langle \vartheta \rangle \approx 10^{-2} (M_{\text{BH}}/10^8 M_\odot) (r/0.01 \text{ pc})^{-1}$ for scattering of electrons on the thermal radiation of the accretion disk, where $r_g$ is the gravitational radius of the putative black hole at the center of AGNs, $M_{\text{BH}}$ is the mass of the black hole which is conventionally about $10^8 M_\odot$. We can see that the value of $\varepsilon_0 \sin \langle \vartheta \rangle$ is more or less the same for the both kinds of external radiation, $\varepsilon_0 \sin \langle \vartheta \rangle \approx 1 - 10$ eV. From this equation and Equation (4), we have

$$\langle \varepsilon_\gamma \rangle \approx (1 - 10) \Gamma_e^2 \text{ eV}. \quad (5)$$

For $\Gamma_0 \approx 10$, which is the typical Lorentz factor of radio emitting blobs of AGN jets, Equation (3) yields the mean Lorentz factor of accelerated electrons $\langle \Gamma_e \rangle \approx 10^4$. Substituting $\langle \Gamma_e \rangle \approx 10^4$ for $\Gamma_e$ into Equation (5), we have the mean energy of photons after scattering $\langle \varepsilon_\gamma \rangle \approx 0.1 - 1$ GeV.

Using Equations (3) and (5), the maximum energy of photons after scattering is

$$\varepsilon_\gamma^{\text{max}} \approx \min \left[ m_e c^2 \Gamma_e^{\text{max}}, 10 (\Gamma_e^{\text{max}})^2 \text{ eV} \right] \approx 10^{11} \text{ eV}. \quad (6)$$

In Equation (3), $\Gamma_0 = 10$ is used to get the last equality. We can see that for $\Gamma_0 \approx 10$ the expected values of both $\langle \varepsilon_\gamma \rangle$ and $\varepsilon_\gamma^{\text{max}}$ are consistent with the EGRET data on the GeV $\gamma$-ray emission from AGNs.
As to the TeV $\gamma$-ray emission which was observed from Mrk 421 and Mrk 501 (Punch, et al., 1992; Quinn et al., 1996; Barrau et al., 1997), it may be explained by inverse Compton scattering of high-energy electrons which are accelerated at the front of a relativistic magnetized cloud only if $\varepsilon_{\gamma}^{\text{max}} \geq 10^{12}$ eV. From this condition and Equations (3) and (6), we have the lower limit on the Lorentz factor of the cloud fronts, $\Gamma_0 \geq 30$. The inverse Compton scattering producing the TeV $\gamma$-ray emission from both Mrk 421 and Mrk 501 will be in the Klein-Nishina limit where the scattered photon energy is comparable to the electron energy. In this case, the differential spectral index of photons after scattering coincides with the differential spectral index of high-energy electrons. The spectra of Mrk 421 and Mrk 501 in TeV $\gamma$-rays are not significantly different, and their differential spectral indexes are $\sim 2.5$ (e.g., McEnery et al., 1997, Quinn et al., 1997; Zweerink et al., 1997) that is consistent with the differential spectral index of high-energy electrons accelerated in the cloud front vicinity (see Section 2).

The high-energy protons which are accelerated in the process of their reflection from the cloud front may be a powerful source of TeV $\gamma$-rays too (cf. Mannheim and Biermann, 1992; Dar and Laor, 1997; Bednarek and Protheroe, 1997). TeV $\gamma$-rays may be produced efficiently by the interaction of the high-energy protons in the AGN jet with the protons of the ambient medium via, for example, $pp \rightarrow \pi^0 X; \pi^0 \rightarrow 2\gamma$ (Dar and Laor, 1997). In this case, the mean energy of generated $\gamma$-rays is

$$\langle \varepsilon_{\gamma} \rangle \simeq 70\langle \Gamma_p \rangle \text{ MeV.} \quad (7)$$

Taking into account that the mean Lorentz factor of protons reflected from the wind front is $\langle \Gamma_p \rangle \simeq \Gamma_0^2$, from Equation (8) it follows that the bulk photons is in the TeV range, $\langle \varepsilon_{\gamma} \rangle \geq 10^{12}$ eV, only if the Lorentz factor of the cloud front is extremely high, $\Gamma_0 \geq 10^2$.

3.2. X-RAY EMISSION

High-energy electrons which are accelerated at the cloud front and move ahead of the front interact not only with high-frequency (optical, UV and X-ray) photons, but with the low-frequency electromagnetic waves too (about these waves, see Section 2). The motion of electrons and their radiation in the fields of electromagnetic waves is characterized by the following dimensionless Lorentz-invariant parameter (e.g., Blumenthal and Tucker, 1974):

$$\eta = \frac{e\bar{B}}{m c \omega}, \quad (8)$$
where $\tilde{B}$ is the wave amplitude and $\omega$ is the wave frequency. At $\eta \ll 1$, electrons radiate via Compton scattering. In this case, the energy spectrum of photons after scattering does not depend on the wave amplitude (see Equation (3)). Radiation of electrons in the fields of strong electromagnetic waves, $\eta \gg 1$, is called as Compton-synchrotron radiation. This radiation closely resembles synchrotron radiation. Indeed, it is well known that electromagnetic radiation of relativistic electrons is concentrated in the direction of the particle’s velocity within a narrow cone of angle $\Delta \varphi \simeq 1/\Gamma_e \ll 1$, and this radiation may be observed only if the observer is inside of the cone (e.g., Rybicki and Lightman, 1979). The formation length of radiation of relativistic electrons in a magnetic field $B$ is about $\Delta l \simeq 2R_B \Delta \varphi \simeq 2c/\omega_B = 2m_ec^2/eB$, where $R_B = (c/\omega_B)\Gamma_e$ is the electron gyroradius and $\omega_B = eB/m_ec$ is the electron gyrofrequency. For the Compton-synchrotron radiation, $\eta \gg 1$, the formation length is much smaller than the wave-length, $\lambda$, of the strong electromagnetic waves, $\Delta l \simeq (\omega/\pi \omega_B)\lambda = \lambda/\pi \eta \ll \lambda$, and the electromagnetic fields of the strong waves may be considered as infinite and static, where $\lambda = 2\pi c/\omega$. Therefore, the Compton-synchrotron radiation is like the synchrotron radiation in the magnetic field which is equal to the local magnetic field of the waves. For example, the mean energy of photons which are generated via the Compton-synchrotron radiation is $\nu_{sc} \simeq (\omega_B/2\pi)\Gamma_e^2$ that coincides with the mean energy of synchrotron photons and qualitatively differs from the mean energy of photons after Compton scattering (cf. Equation (4)). [For details on Compton-synchrotron radiation see (Gunn and Ostriker, 1971; Blumenthal and Tucker, 1974).] To avoid a misunderstanding, it is worth noting that the so-called synchrotron-self-Compton (SSC) models are frequently discussed for blazars (e.g., Maraschi et al., 1992). In these models, the soft photons are arised from the synchrotron emission, and then, $\gamma$-rays are generated via Compton scattering of these soft photons.

For the low-frequency waves with $\tilde{B} = \tilde{B}_{LF} \simeq (0.2 - 0.3)B$ and $\omega = \omega_{LF} \simeq eB/m_pc\Gamma_0$ which are generated at the cloud front, we have

$$\eta \simeq \frac{\tilde{B}_{LF} m_p \Gamma_0}{B m_e} \gg 1,$$

where $B \simeq \Gamma_0 B_0$ is the magnetic field of the cloud in the frame of the ambient medium, i.e. in the frame of the central engine of AGN. In this case, the typical frequency of Compton-synchrotron radiation of high-energy electrons is (e.g., Blumenthal and Tucker, 1974)

$$\nu_{sc} \simeq \frac{e(\tilde{B}_{LF})\Gamma_e^2}{2\pi mc} \simeq 3 \times 10^6 (\tilde{B}_{LF})\Gamma_e^2 \text{ Hz},$$

$$\eta \ll 1,$$

$$\omega \ll \omega_B.$$
where $\langle \tilde{B}_{LF} \rangle \simeq \frac{1}{2} \tilde{B}_{LF} \simeq 0.1B$ is the mean field value of strong low-frequency waves.

For a Poynting flux-dominated jet, the strength of the cloud magnetic field at the distance $r$ from the central engine is

$$B \simeq 10^2 \left( \frac{L}{10^{47} \text{ ergs s}^{-1}} \right)^{1/2} \left( \frac{r}{0.01 \text{ pc}} \right)^{-1} \text{ G}, \quad (11)$$

where $L = 4\pi r^2 c (B^2/8\pi)$ is the total luminosity for a spherical Poynting flux-dominated wind. Such a jet may be roughly considered as a conic section of this wind.

From Equations (4), (10) and (11), the ratio of the mean energy of Compton-synchrotron photons and the mean energy of $\gamma$-rays is

$$\frac{\langle \varepsilon_{sc} \rangle}{\langle \varepsilon_\gamma \rangle} \simeq 2 \times 10^{-8} \left( \frac{\varepsilon_0 \sin \langle \vartheta \rangle}{1 \text{ eV}} \right)^{-1} \left( \frac{L}{10^{47} \text{ ergs s}^{-1}} \right)^{1/2} \left( \frac{r}{0.01 \text{ pc}} \right)^{-1}. \quad (12)$$

In the case of Mrk 421 for its typical parameters, $L \sim 10^{47} \text{ ergs s}^{-1}$, $r \sim 0.01 \text{ pc}$, $\varepsilon_0 \sin \langle \vartheta \rangle \sim 3 \text{ eV}$ and $\langle \varepsilon_\gamma \rangle \sim 10^{12} \text{ eV}$, Equation (12) yields $\langle \varepsilon_{sc} \rangle \sim 10 \text{ keV}$ that is consistent with the multifrequency observations of Mrk 421 (Macomb et al., 1995; Schubnell et al., 1997; Zweerink et al., 1997). Fits of X-ray and $\gamma$-ray spectra of Mrk 421 and another extragalactic sources in the frame of presented model are under way.

4. Conclusion and discussion

We have considered in this paper the generation of X-ray and $\gamma$-ray emission from the AGN jets. High-energy electrons which are responsible for this emission are accelerated inside the jets in the process of interaction between relativistic magnetized clouds and an ambient medium which is assumed to be nearly at rest. For a powerful extragalactic source of TeV $\gamma$-rays like Mrk 421, the Lorentz factor of these clouds is $\Gamma_0 \geq 30$. Recently, it was shown (Renaud and Henri, 1997) that in the case of supermassive black holes relevant to AGNs the terminal Lorentz factor of the jet plasma may be as high as 60 that is more than the lower limit on $\Gamma_0$.

For high-energy electrons which are accelerated at the cloud front, the characteristic time of their energy losses is

$$\tau_{\text{loss}} \simeq \frac{5 \times 10^8}{(\langle \tilde{B}_{LF}^2 \rangle + 4\pi u_{ph}) \Gamma_e} \text{ s}, \quad (13)$$

where $u_{ph}$ is the photon energy.
where \( u_{ph} \) is the energy density of soft photons in ergs cm\(^{-3} \) and \( \langle \tilde{B}_{LF}^2 \rangle \) in G\(^2 \). For typical parameters, \( \langle \tilde{B}_{LF}^2 \rangle \simeq 4\pi u_{ph} \simeq 10 \), from Equations (2) and (13) we have \( \tau_{\text{loss}} \) is \( \sim 2 \times 10^3 \) s at \( \Gamma_0 = 10 \) and \( \sim 2 \times 10^2 \) s at \( \Gamma_0 = 30 \). We can see that the value of \( c\tau_{\text{loss}} \) is much smaller than the typical size of the emission region in \( \gamma \)-rays which is \( \sim 10^{17} \) cm (Maraschi et al., 1992; Levinson, 1996). Therefore, high-energy electrons do not propagate far from the barrier front because of their energy losses. As to propagation of the high-energy protons through the ambient medium, it depends essentially on the magnetic field of the ambient medium. Consideration of interaction between the protons which are reflected from the cloud front and the ambient medium with taking into account development of two-stream instability is under way and will be addressed elsewhere.

It is worth noting that the Compton scattering of photons which are generated via the Compton-synchrotron emission may be a powerful source of \( \gamma \)-rays from the AGN jets as well. However, we did not consider this process because, in fact, it is a version of the synchrotron-self-Compton models in which the Compton-synchrotron radiation is used instead of the synchrotron radiation.

Not any kind of the ambient medium is suitable for strong acceleration of electrons at the cloud front. For example, if the ambient medium consists of \( e^+e^- \) pairs, the discussed mechanism of electron acceleration does not work, and Equations (4) and (3) are out of their applicability (Smolsky and Usov, 1996).

As noted above, electrons of the ambient medium may be strongly accelerated in the cloud front vicinity only if \( \alpha \) is \( \sim 1 \) (Usov and Smolsky, 1998). At \( \alpha \sim 1 \), from Equation (1) the density of the ambient medium in its frame is of the order of

\[
 n_1 = \frac{B^2}{4\pi \Gamma_0^4 m_p c^2}.
\]

For \( r \simeq 0.01 \) pc, \( L \simeq 10^{47} \) ergs s\(^{-1} \) and \( \Gamma_0 \simeq 30 \), from Equations (11) and (14) we have \( B \simeq 10^2 \) G and \( n_1 \simeq 1 \) cm\(^{-3} \).

There are a few reasonable sources of the ambient medium in the AGN jets. They are compact clouds of warm gas, stellar winds or a trail of plasma which is left after ejection of a relativistic magnetized cloud (on interaction between the AGN jets and compact clouds of warm gas, see Higgins, O’Brein and Dunlop, 1995; Bicknell, Dopita and O’Dea, 1997). It is difficult to say now about what is the main source of the ambient medium. All these sources are able, in principle, to be responsible for the ambient medium with such a low density as
At the central regions of AGNs, where the γ-ray emission is generated, the density of stars is very high, and the mean stellar density may be as high as \( \sim 10^8 \, M_\odot \, pc^{-3} \) or even more (e.g., Lauer et al., 1992). Massive OB stars, \( M_{OB} \sim 10 M_\odot \), contain a substantial part of the mass of the stellar clusters at the AGN center. Therefore, it is natural to expect that there is at least a few such massive stars at the distance \( r \leq 0.01 \, pc \) from the AGN engine.

Massive stars are characterized by intense winds (e.g., Garmany and Conti, 1984; Leitherer, 1988). For a typical massive OB star, the mass-loss rate is \( \dot{M}_{OB} \sim 10^{-7} - 10^{-6} M_\odot \, yr^{-1} \), and the terminal velocity of the matter outflow is \( v_\infty \approx (1 - 3) \times 10^8 \, cm \, s^{-1} \).

The wind density at the distance \( r_w \) from the OB star is

\[
n_w \approx \frac{\dot{M}_{OB}}{4\pi r_w^2 v_\infty m_p}.
\]

For \( \dot{M}_{OB} \approx 10^{-7} M_\odot \, yr^{-1}, \, v_\infty \approx 2 \times 10^8 \, cm \, s^{-1}, \, r_w \approx 0.01 \, pc \), from Equation (15) we have \( n_w \approx 1 \, cm^{-3} \). Hence, the stellar winds from massive stars may be one of the reasonable sources of the ambient plasma with the density \( n_w \approx n_1 \) which is favorable for strong acceleration of electrons in the AGN jets.

A remarkable change in the TeV γ-ray emission of Mrk 501 was seen in 1997: the flux of TeV γ-rays increased dramatically from previous seasons (e.g., Quinn et al., 1997). In April and May, 1997, Mrk 501 at times was the brightest TeV source in the sky. The average emission level has increased by a factor of more than 16 since its discovery as a TeV γ-ray source in 1995. Maybe, this long-time variability of Mrk 501 in TeV γ-rays results from the orbital motion of a OB star around the putative supermassive black hole at the center of Mrk 501. Indeed, in the process of orbital motion of a massive OB star around the black hole the ambient-plasma density in the jet may vary with the orbital period, \( P \), of the star:

\[
P \approx 10 \left( \frac{M_{BH}}{10^8 M_\odot} \right)^{-1/2} \left( \frac{r}{0.01 \, pc} \right)^{3/2} \, yr,
\]

and the most favorable condition, \( \alpha \approx 1 \) or \( n_w \approx n_1 \), for acceleration of electrons in the AGN jet may occur at times. As it is mentioned in Section 2, in this case, when \( \alpha \) is \( \sim 1 \), the luminosity of the jet in γ-rays is extremely high. Maybe, such a brightening of Mrk 501 in TeV γ-rays was observed in 1997. If this suggestion is right, it is expected that the TeV γ-ray emission of Mrk 501 is modulated with the period \( P \approx 10 \)
yr, and the duration of the stage with a strong TeV γ-ray emission is about an order of magnitude smaller than $P$.

Acknowledgements

We thank M. Milgrom for helpful conversations. This research was supported in part by MINERVA Foundation, Munich / Germany.

References

Barrau, A. et al.: 1997, preprint astro-ph/9705249
Bednarek, W. and Protheroe, R.J.: 1997, Monthly Notices Roy. Astron. Soc. 287, L9
Bicknell, G.V., Dopita, M.A. and O'Dea, C.P.O.: 1997, Astrophys. J. 485, 112
Blandford, R.D. and Königl, A.: 1979, Astrophys. J. 232, 34
Blandford, R.D. and Levinson, A.: 1995, Astrophys. J. 441, 79
Blumenthal, G.R. and Tucker, W.H.: 1974, in: R. Giacconi and H. Gursky (eds.), 'X-Ray Astronomy', D. Reidel Publishing Company, Dordrecht, p. 99
Cawthorne, T.V.: 1991, in: P.A. Hughes (ed.), 'Beams and Jets in Astrophysics', Cambridge Univ. Press, Cambridge, p. 187
Dar, A. and Laor, A.: 1997, Astrophys. J. 478, L5
Dermer, C.D.: 1994, in: J. Tran Thanh Van, G. Fontaine and E. Hinds (eds.), 'Particle Astrophysics, Atomic Physics and Gravitation', Proc. XXIXth Rencontres de Moriond, Frontiers, Singapore, p. 47
Dermer, C.D. and Schlickeiser, R.: 1993, Astrophys. J. 416, 458
Gunn, J.E. and Ostriker, J.P.: 1971, Astrophys. J. 165, 523
Garmady, C.D. and Conti, P.S.: 1984, Astrophys. J. 284, 705
Higgins, S., O'Brein, T.J. and Duplop, J.: 1995, Astrophys. and Space Sci. 233, 311
Impey, C.D.: 1987, in: J.A. Zensus and T.J. Pearson (eds.), 'Superluminal Radio Sources', Cambridge University Press, New York, p. 233
Lauer, T.R. et al.: 1992, Astron. J. 104, 552
Leitherer, C.: 1988, Astrophys. J. 326, 356
Levinson, A.: 1996, Astrophys. J. 459, 520
Levinson, A. and van Putten, M.H.P.H.: 1997, Astrophys. J. 488, 69
Macomb, D.J. et al.: 1995, Astrophys. J. 449, L99
Mannheim, K. and Biermann, P.L.: 1992, Astron. Astrophys. 253, L21
Maraschi, L., Ghisellini, G. and Celotti, A.: 1992, Astrophys. J. 397, L5
McEnery, J.E. et al.: 1997, preprint astro-ph/9706125
Punch, M. et al.: 1992, Nature 358, 477
Quinn, J. et al.: 1996, Astrophys. J. 456, L83
Quinn, J. et al.: 1997, preprint astro-ph/9706142
Renaud, N. and Henri, G.: 1997, preprint astro-ph/9706154
Romanova, M.M. and Lovelace, R.V.E.: 1997, Astrophys. J. 475, 97
Rybicki, G.B. and Lightman, A.P.: 1979, Radiative Processes in Astrophysics, John Wiley and Sons, New York
Schubnell, M.S. et al.: 1997, in: C.D. Dermer, J.D. Kurfess and M.S. Strickman (eds.), 'Fourth Compton Symposium', AIP, New York (in press)
Sikora, M., Begelman, M.C. and Rees, M.J.: 1994, Astrophys. J. 421, 153
Sikora, M., Sol, H. and Begelman, M.C. and Madejski, G.M.: 1996, Monthly Notices Roy. Astron. Soc. 280, 781
Smolsky, M.V. and Uskov, V.V.: 1996, Astrophys. J. 461, 858
Thompson, D.J. et al.: 1995, *Astrophys. J. Suppl.* **101**, 259
Usov, V.V. and Smolsky, M.V.: 1998, *Phys. Rev. E* **57**, 2267
Zweerink, J.A. et al.: 1997, *Astrophys. J.* **490**, L141

*Address for correspondence:* Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel
\[ \frac{dn_e}{d\Gamma_e} \text{ [arb. units]} \]
