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LETTER

Letter to the Editor

On the nonthermal emission in active galactic nuclei

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Abstract. We consider the role of centrifugal force on the energetics of electrons moving along the magnetic field lines of spinning active galactic nuclei. We find the energy gained by charged particles against inverse Compton scattering and/ synchrotron radiation losses, become quite significant in the region close to the light cylinder. The particles accelerated by the centrifugal force become a part of the jet material. The scattering of UV–photons against the energetic electrons lead to the generation of X–ray and γ-ray photons within the light cylinder, and outside, they radiate the non–thermal optical radiation via the synchrotron emission.

Key words: Galaxis: active – nuclei – jets

1. Introduction

One of the most challenging problems in the area of active galactic nuclei (AGN) is the origin of nonthermal continuum emission (Ekers et al. 1996 and references therein). In the radio-loud AGN, the central engine has sufficient angular momentum and rotation energy to maintain jets and the non-thermal radiation. In-situ acceleration within jets is required to explain the existence of highly relativistic particles at radii where the light travel time from the nucleus is orders of magnitude larger than the radiative lifetime of the particles. In this paper, we consider the effect of AGN rotation on the charged particles moving along magnetic field lines. Both relativistic electrons and large scale magnetic fields are clearly shown to exist in AGN (e.g., Lovelace & Contopoulos 1991). The polarized continuum emission of the very centre directs towards a particle population at least at GeV level. On the other hand it has been shown that magnetic fields are involved in the driving mechanisms and collimation of jets (Camenzind 1996). The problem is, however, to couple the magnetohydrodynamical models with the observed relativistic particle population. It is the aim of our contribution to show that within a rotating magnetosphere which is at the foot points of a jet there exists a natural source for the relativistic particles. Injecting particles along the field lines and following them until the light cylinder (where the rotation speed reaches the velocity of light) we show that despite the intense UV-radiation field of the accretion disk, particles can reach high energies.

It is the aim of our contribution to present a possible connection of the MHD-scenarios for the jet production like the models developed by Camenzind (1996) and the acceleration of particles and accompanying radiation losses. In the next section we consider the acceleration of particles in a rotating magnetosphere. Section 3 contains the influence of inverse Compton scattering and synchrotron radiation on the particle acceleration. Finally, we present some conclusions.

2. Centrifugal acceleration of charged particles moving along rotating magnetic field lines

The idea that the magnetized winds emanating from rotating objects can extract angular momentum and energy, has been dealt in the variety of contexts, for example, the production of MHD-winds in AGN (Camenzind 1986), break down of solar rotation (Weber & Davis 1967; Mestel 1968; Michel 1969), and pulsar wind production (Goldreich & Julian 1970; Kennel et al. 1983; Gangadhara 1995, 1996). In what follows, we explore the possibility that rotational energy can be extracted from a rapidly rotating supermassive object by the magnetized plasma particles.

The polarization properties and spectra of AGN indicate the synchrotron radiation from relativistic electrons moving in the magnetic field at 1 parsec $\sim$ 1G. There are substantial evidences both from the theory as well as observations about the fact that magnetic fields play an important role in the production and collimation of jets (e.g., Lesch et al. 1989; Camenzind 1996; Blandford 1990; Wiita 1993).

Consider a typical galactic nucleus associated with the large scale magnetic field lines crossing the light cylinder. The radius of light cylinder in the case of AGN is $r_{\rm LC} = c/\Omega$, where Ω is the angular velocity of the field lines. If the field lines are rotating then the particles gain rotation energy when they move from slowly rotating region (central engine) to the fast rotating region (light cylinder). The equation of motion of a particle in the rotating frame is given by (Gangadhara 1996)

$$\frac{d}{dt}\left(m\frac{dr}{dt}\right)\hat{e}_{\rm r} = \boldsymbol{F}_{\rm B} + \boldsymbol{F}_{\rm c} + \boldsymbol{F}_{\rm cf}\,, \tag{1}$$

where

$$\begin{aligned} \boldsymbol{F}_{\rm B} &= \frac{q}{c}(\boldsymbol{v}_{\rm rel}\times\boldsymbol{B}) \text{ is the magnetic force}\,, \\ \boldsymbol{F}_{\rm c} &= \left[2m\frac{dr}{dt} + r\frac{dm}{dt}\right](\hat{e}_{\rm r}\times\boldsymbol{\Omega}) \text{ is the Coriolis force,} \\ \boldsymbol{F}_{\rm cf} &= m(\boldsymbol{\Omega}\times\boldsymbol{r})\times\boldsymbol{\Omega} \text{ is the centrifugal force}\,, \end{aligned}$$

c is the velocity of light, q and m are the charge and the relativistic mass of particle, and $\boldsymbol{v}_{\rm rel}$ is the relative rotation velocity between particle and magnetic field lines. Hence an observer in the rotating frame declares that three forces are acting on a particle: (i) the force $\boldsymbol{F}_{\rm c}$ (Goldstein 1990) acts in the negative θ-direction, i.e., *opposite* to the direction of rotation, (ii) the force $\boldsymbol{F}_{\rm B}$ which initially acts in the direction of $\boldsymbol{v}_{\rm rel}\times\boldsymbol{B}$, and as particle moves it turns towards the positive θ–direction in the case of a positively charged particle, and (iii) the force $\boldsymbol{F}_{\rm cf}$ which acts radially *outward.*

The constraint forces $\boldsymbol{F}_{\rm c}$ and $\boldsymbol{F}_{\rm B}$ act in the direction perpendicular to the path of particle, and therefore, the work done by them is zero. They are so strong that they barely allow the particle to deviate even slightly from the prescribed path. The spiral motion of particle vanishes when $\boldsymbol{F}_{\rm c}$ and $\boldsymbol{F}_{\rm B}$ become equal and opposite.

The azimuthal–component of Eq. (1) gives

$$B = \frac{c\Omega}{qv_{\rm rel}}\left[2m\frac{dr}{dt} + r\frac{dm}{dt}\right]. \tag{2}$$

Similarly, the radial component gives

$$\frac{d}{dt}\left(m\frac{dr}{dt}\right) = m\Omega^2 r\,. \tag{3}$$

Equations (2) and (3) describe the constrained and accelerated motion of a particle, respectively. As the particle moves radially outward, the relative velocity between the particle and the magnetic field line increases with respect to r, and reaches maximum at the light cylinder. Since the particles gain rotation energy as they move from the central engine to light cylinder and centrifugal force acts along the field lines, a very strong magnetic field is not required to drag the particles with rotating AGN. The field required should be sufficient enough to balance the Coriolis force, as indicated by Eq. (2). Eventually the inertial forces overcome the tension in magnetic field lines, and hence the field lines are swept back in the direction opposite to the sense of rotation, hence the term toroidal twist. Beyond this point, the magnetic field is dominated by the toroidal component B_ϕ. In the limit of tightly wound field lines, the magnetic tension force tends to collimate the flow about the rotation axis (Begelman 1994).

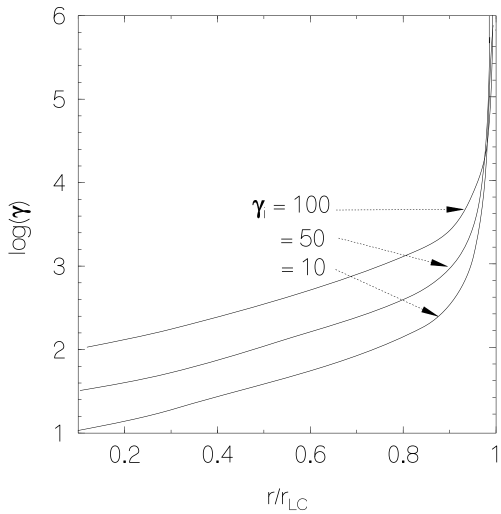

Fig. 1. The relativistic Lorentz factor γ as a function of r at different values of $\gamma_{\rm i}$ = 10, 50 and 100.

To find the relativistic momentum $\boldsymbol{p}$ of particle we solve Eq. (1) numerically. Assume that at the time t=0, an electron is introduced with an initial Lorentz factor γ_i at a distance $r = r_{\rm LC}/10$ from the rotation axis to move along the rotating magnetic field lines. The energy of the particle is obtained using $\varepsilon = \sqrt{p^2c^2 + m_0^2c^4}$ and the Lorentz factor from $\gamma = \varepsilon/m_{\rm e}c^2$.

Figure 1 shows the variation of γ with respect to r for the particles with $\gamma_{\rm i}$ = 10, 50 & 100. The curves indicate increase of particles energy due to centrifugal force as they approach the light cylinder. If we include radiation losses, the steepness of the curves will be reduced.

Once the particles reach the light cylinder, they cannot return to the central engine along the same or other field lines, as they experience a decelerating force in their return path. Therefore, they must leave the AGN as a jet.

Using $m = \gamma m_{\rm e}$, Eq. (3) can be written as

$$\frac{d^2r}{dt^2} + \eta(t)\frac{dr}{dt} - \Omega^2 r = 0\,, \tag{4}$$

where m_e and γ are the rest–mass and the Lorentz factor of particle, and

$$\eta(t) = \frac{1}{\gamma}\frac{d\gamma}{dt} = \frac{d(\ln\gamma)}{dt} \tag{5}$$

is a slowly increasing function of time t for $r < r_{\rm LC}$. Since we are interested in the behaviour of particle trajectory and energy near light cylinder, we assume $\eta(t)$ to be approximately constant over a small interval of time. Then the Eq. (4) may be solved by assuming r(t) has the form $e^{\alpha t}$, where α is found from

$$\alpha^2 + \eta\alpha - \Omega^2 = 0\,, \tag{6}$$

which has the solution

$$\alpha = \sqrt{\frac{\eta^2}{4} + \Omega^2} - \frac{\eta}{2}. \tag{7}$$

Near the light cylinder, η takes the values much higher than Ω as the particles are strongly driven in the direction of rotation, therefore we find

$$\alpha \approx \frac{\eta}{2}\left[1+2\left(\frac{\Omega}{\eta}\right)^2\right] - \frac{\eta}{2} = \frac{\Omega^2}{\eta}. \quad (8)$$

Taking $r(0) = r_0$ as the initial condition at t=0, we obtain

$$r(t) = r_0 e^{\frac{\Omega^2}{\eta}t}. \quad (9)$$

Equation (9) describes the position of a particle over a small interval of time during which η can be treated as approximately constant.

In the rest frame of an observer, let $\boldsymbol{r}(t)$ make an angle Ωt with the x–axis. Then the co-ordinates of the position of a particle are

$$x(t) = r_0 e^{\frac{\Omega^2}{\eta}t}\cos(\Omega t), \qquad y(t) = r_0 e^{\frac{\Omega^2}{\eta}t}\sin(\Omega t). \quad (10)$$

Hence, the particle follows a curved trajectory as it moves along the rotating magnetic field lines. Let $\tan\delta = dy/dx$ and $ds = \sqrt{dx^2+dy^2}$ be the slope and arc-length of the trajectory at any time t. Then the radius of curvature of particle trajectory is

$$R = \frac{[1+(dy/dx)^2]^{3/2}}{|d^2y/dx^2|} = \sqrt{1+\left(\frac{\Omega}{\eta}\right)^2}\, r(t). \quad (11)$$

Consider a typical AGN with light cylinder radius $r_{\rm LC} = 5\cdot 10^{15}$ cm and magnetic field $B = 100$ G (Lesch et al. 1989). Using Eq. (2), we can estimate the maximum value of η in a magnetic field of given strength:

$$\eta = \frac{1}{r}\left(\frac{\omega_B}{\Omega}v_{\rm rel} - 2\frac{dr}{dt}\right), \quad (12)$$

where $\omega_B = qB/mc$.

Using $v_{\rm rel} = c/100$, $dr/dt \approx c$, $\gamma = 10^4$ and $r = r_{\rm LC}$, we find for an electron $\eta = 1.8\cdot 10^3$ s^{-1}, which is much higher than $\Omega = 6\cdot 10^{-6}$ rad s^{-1}. Therefore, Eq. (5) gives

$$\gamma(t) = \gamma_0 e^{1800\,t}, \quad (13)$$

where γ_0 is the value of γ at time $t = 0$. Hence in the region near light cylinder, the centrifugal acceleration becomes very large and it dominates over the radiation reaction exerted by the ambient radiation field.

A simple estimate gives us an order of magnitude estimate of the maximum energy a particle can gain from the centrifugal acceleration. Close to the light cylinder ($v_{\rm rel} \sim c$; $\Omega \sim v_{\rm rel}/r$) the minimum time scale for acceleration is close to the inverse of the relativistic electron gyrofrequency ω_B,

$$t_{\rm acc} \simeq \eta^{-1} \simeq \omega_{\rm B}^{-1} = \frac{\gamma m_{\rm e} c}{eB}. \quad (14)$$

The loss time for inverse Compton scattering is given by (e.g., Longair 1992)

$$t_{\rm loss}^{\rm IC} \simeq \frac{3\cdot 10^7}{\gamma U_{\rm rad}}\ {\rm s} \quad (15)$$

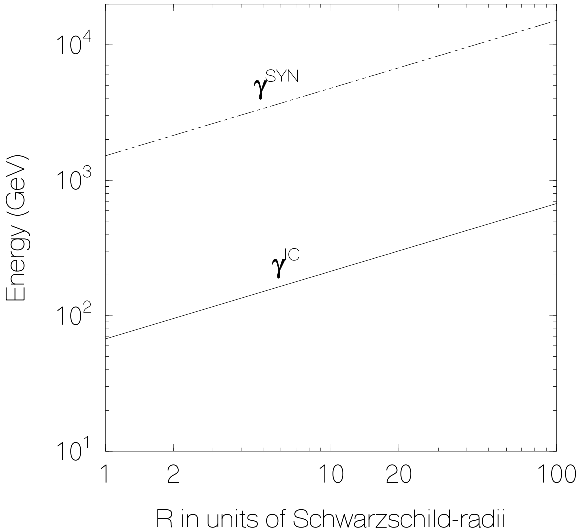

Fig. 2. The relativistic Lorentz factors $\gamma^{\rm IC}$ and $\gamma^{\rm SYN}$ as functions of R.

and for synchrotron losses

$$t_{\rm loss}^{\rm SYN} \simeq \frac{5\cdot 10^8}{\gamma B^2}\ {\rm s}, \quad (16)$$

where $U_{\rm rad}$ denotes the energy density of the incoming radiation. We can estimate $U_{\rm rad}$ of the central luminosity L at a distance R as $U_{\rm rad} \simeq L/4\pi R^2 c$. Using the definition of non-relativistic electron gyrofrequency $\omega_{\rm ce} = eB/m_{\rm e}c$, we obtain the expression for maximum Lorentz factor an electron can achieve via centrifugal acceleration, including inverse Compton scattering and/or synchrotron radiation,

$$\gamma_{\rm max}^{\rm IC} \simeq \sqrt{\frac{3\cdot 10^7\omega_{\rm ce}}{U_{\rm rad}}} \quad \text{and} \quad \gamma_{\rm max}^{\rm SYN} \simeq \sqrt{\frac{5\cdot 10^8\omega_{\rm ce}}{B^2}}. \quad (17)$$

The ratio of both is

$$\frac{\gamma_{\rm max}^{\rm SYN}}{\gamma_{\rm max}^{\rm IC}} = \sqrt{8\pi}\frac{\sqrt{U_{\rm rad}}}{B}. \quad (18)$$

Hence depending upon the radiation intensity and the field strength, one of the radiation mechanisms will limit the centrifugal acceleration.

Figure 2 shows both the Lorentz factors for a central luminosity of $L = 10^{46}$ erg s^{-1} over the central 100 Schwarzschild-radii of a black hole with $10^8\,M_\odot$. The toroidal component of magnetic field is assumed scale as $B(R) \propto B_0 R^{-1}$. With $B_0 = 1$ kG we still have $U_{\rm rad} > B(R)^2/8\pi$ (Fig. 3), which means inverse Compton scattering is faster than synchrotron radiation, and that is the reason why $\gamma_{\rm max}^{\rm SYN} \gg \gamma_{\rm max}^{\rm IC}$.

Our results imply that continuously a population of 10 GeV electrons escape from the central 10^{15} cm region (the light cylinder), in which they scatter the UV-photons to the X–ray and/ γ–ray ranges (von Montigny et al. 1995). Outside the light cylinder, the particles may encounter weaker magnetic fields (e.g.

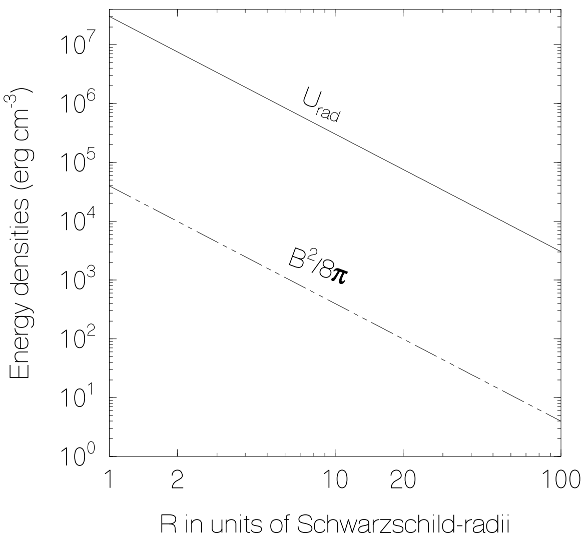

Fig. 3. The radiation energy density and magnetic energy density as functions of R.

Blandford 1990) along which they can easily generate the observed steady nonthermal optical emission of AGN via synchrotron radiation:

$$\nu \simeq 10^{14} Hz \left[\frac{\gamma}{5000}\right]^2 \left[\frac{B}{1G}\right] \tag{19}$$

3. Conclusion

A simple approximation to the plasma dynamics, is the study of motion of individual plasma particles, and it is a good approximation for the rarefied plasma. We consider a physical mechanism which relates the MHD-scenarios for the production of relativistic jets via rotating magnetospheres (e.g. Camenzind 1996) and particle acceleration, visible as continuous nonthermal radiation ranging from gamma-radiation down to optical and radio emission. The charged particles moving along the rotating magnetic field lines experience the centrifugal acceleration. Depending upon the stiffness of the magnetic field lines, this can become very strong compared to the inverse Compton scattering and synchrotron radiation losses. Our model provides a natural explanation for an efficient way of extracting the rotational energy from central engines and the continuous escape of the high energy electrons from AGN into the jet material. They scatter the UV–photons to the X–ray and γ–ray ranges at the light cylinder, and outside they generate the steady nonthermal optical emission of AGN via synchrotron radiation. It may even account for the continuous radio emission, taking into account that the particles loose energy (i.e. γ drops) and the magnetic field strengths decreases as well (Blandford 1990).

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References

Begelman M. C., 1994, The Nature of Compact Objects in Active Galactic Nuclei, eds: A. Robinson & T. Terelevich, Cambridge Univ. Press, New York, p. 361
Blandford R. D., 1990, Active Galactic Nuclei, Saas-Fee Advanced Course 20, eds. T. J. L. Courvosier & M. Mayor, Springer, Berlin, p. 161
Camenzind M., 1986, A&A, 156, 137
Camenzind M., 1996, Solar and Astrophysical Magnetohydrodynamical Flows, ed. K. Tsinganos, NATO ASI Series 481 Kluwer, Dordrecht, p. 699
Ekers R., Fanti C., Padrielli L., 1996 Extragalactic Radio Sources, IAU 175, Kluwer, Dordrecht
Gangadhara R. T., 1995, Ap&SS 232, 327
Gangadhara R. T., 1996, A&A, 314, 853
Goldreich P., Julian W. H., 1970, ApJ, 160, 971
Goldstein H., 1990, Classical Mechanics, Narosa Pub. House, New Delhi, p. 287
Kennel C. F., Fujimura F. S., Okamoto I., 1983, J. Ap. Geophys. Fluid Dyn., 26, 147
Longair M. S., 1992, High Energy Astrophysics, Cambridge Uni. Press, New York, vol. 1, p. 103
Lovelace R. V. E., Contopoulos J., 1991, Extragalactic Radio Sources– From Beams to Jets, eds: J. Roland, H. Sol & G. Pelletier, Cambridge Univ. Press, New York, p. 235
Lesch H., Appl S., Camenzind M., 1989, A&A, 225, 341
Mestel L., 1968, MNRAS, 138, 359
Michel F. C., 1969, ApJ, 158, 727
von Montigny C., et al., 1995, ApJ, 440, 525
Weber E. J., Davis L. Jr., 1967, ApJ, 148, 217
Wiita P. J., 1993, In Accretion and Jets in Astrophysics, Proc. Guo Shou Jing Workshop, ed. Q. B. Li, L. T. Yang, G. Z. Xie, P. B. Yang, Wuhan, China: Huazhong Normal Univ. Press, p. 1

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