Is very high energy emission from the BL Lac 1ES 0806+524 centrifugally driven?

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Abstract

We investigate the role of centrifugal acceleration of electrons in producing the very high energy (VHE) radiation from the BL Lac object 1ES 0806+524, recently detected by VERITAS. The efficiency of the inverse Compton scattering (ICS) of the accretion disk thermal photons against rotationally accelerated electrons is examined. By studying the dynamics of centrifugally induced outflows and by taking into account a cooling process due to the ICS, we estimate the maximum attainable Lorentz factors of particles and derive corresponding energetic characteristics of the emission. Examining physically reasonable parameters, by considering the narrow interval of inclination angles (0.7° – 0.95°) of magnetic field lines with respect to the rotation axis, it is shown that the centrifugally accelerated electrons may lead to the observational pattern of the VHE emission, if the density of electrons is in a certain interval.

Key words: Galaxies: active–BL Lacertae objects: individual (1ES0806 + 524)—acceleration of particles—radiation mechanisms: non-thermal.

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1. Introduction

In physics of active galactic nuclei (AGNs) one of the major problems is related to the understanding of origin of the high energy radiation. One prominent class of AGNs is the so-called BL Lac objects - supermassive black holes characterized by rapid and large amplitude flux variability. By using the radio observations from the Green Bank 91-m telescope [1], the AGN, 1ES 0806+524, was identified as a BL Lac object [2].

Recently, by VERITAS was found that the blazar, 1ES 0806+524 reveals VHE spectra in the TeV domain [3]. According to the standard model of BL Lacs, VHE radiation originates from the ISC of soft photons against ultra-relativistic electrons [4,5]. However, the origin of efficient acceleration of particles up to highly relativistic energies still remains uncertain and needs to be revealed. Proposed mechanisms based on the Fermi-type acceleration process [6] may be applied successfully for the TeV emission, only, if the initial Lorentz factors of electrons are considerably high (γ ≥ 10^2) [7].

It is clear that in the rotating magnetospheres (the innermost region of AGN jets and pulsar magnetospheres) the centrifugal effect should play a significant role in the overall dynamics of corresponding plasmas. For example, the rotationally driven parametric plasma instabilities have been studied for pulsars [8,9] and AGNs [10,11], respectively, and was shown, that under certain conditions, the relativistic effects of rotation may efficiently induce plasma instabilities, parametrically pumping the rotational energy directly into the plasma waves. The centrifugally induced outflows have been discussed in a series of works. Blandford & Payne in the pioneering paper [12] considered the angular momentum and energy pumping process from the accretion disk, emphasizing a special role of the centrifugal force in dynamical processes governing the acceleration of plasmas. It was shown that the outflows from accretion disks occurred if the magnetic field lines are inclined at a certain angle to the equatorial plane of the disk. In the context of studying the nonthermal radiation from pulsars, the centrifugal effect has been examined in [13,14,15], where the curvature emission of accelerated particles was studied. By applying the similar approach, Gangadhara & Lesch considered the role of centrifugal acceleration on the energetics of electrons moving along the magnetic field lines of spinning AGNs [16]. This work was reconsidered in a series of papers [17,18] and the method was applied to a special class of AGNs - TeV AGNs. It was shown that considera-
tion of straight field lines is a good approximation and was found that the centrifugal force may accelerate electrons up to very high Lorentz factors ($\sim 10^8$) providing the TeV energy emission via the ICS.

In the present paper we investigate a role of rotational effects in the VHE flare from the blazar 1ES 0806+524, by applying the method of centrifugal outflows, developed in [17,19]. We show that, for a certain set of parameters, due to the ICS in the Thomson regime, photons, when up-scattered against centrifugally accelerated ultra-relativistic electrons, produce the VHE radiation in the TeV domain. We show that a resulting luminosity output is in a good agreement with the observed data.

The paper is arranged as follows. In [2] we consider our model and derive expressions of the luminosity output and the energy of photons respectively. In [4] we present the results for the blazar 1ES 0806+524 and in [4] we summarize our results.

2. Main consideration

Let us consider the typical parameters of 1ES 0806+524: the black hole mass, $M_{BH} \approx 5 \times 10^8 M_\odot$ [21], ($M_\odot$ is the solar mass) and the bolometric luminosity, $L \approx 7 \times 10^{44} \text{erg/s}$ [22]. We examine particles originating from the accretion disc at the distance $\sim 10 \times R_g$ from the central object, where $R_g \equiv 2GM_{BH}/c^2$ is the gravitational radius of the black hole. Then, by taking the value of the equipartition magnetic field,

$$B \approx \sqrt{\frac{2L}{r_c^2 c}},$$

into account, one can show that for typical parameters, $r \approx 10 \times R_g$, $n \in (0.0001 - 1) \text{cm}^{-3}$, $\gamma_0 \approx 1$, the value of the ratio, $B^2/\gamma_0 m_n c^2$, is in the following interval $\sim 10^9 - 10^{13}$ ($\gamma_0$, $n$ and $m_n$ are electrons’ initial Lorentz factor, the density and the rest mass respectively). Therefore, the magnetic field energy density exceeds the plasma energy density by many orders of magnitude, which indicates that the plasma co-rotates with the angular velocity,

$$\omega = \sqrt{\frac{GM_{BH}}{r_0^3}},$$

(2)

corresponding to the Keplerian motion at $r_0 \approx 10 \times R_g$.

We see that due to the frozen-in condition the particles follow the co-rotating magnetic field lines and accelerate centrifugally. Therefore, it is reasonable to consider dynamics of the electron, sliding along the rotating magnetic field lines. We apply the method developed for AGNs in [17,18] and assume that the straight field lines co-rotate. Then, if we take an angle $\alpha$ between the magnetic field, $\vec{B}$, and the angular velocity of rotation, $\vec{\omega}$, into account, after the transformation of coordinates: $x = r \sin \alpha \cos \omega t$, $y = r \sin \alpha \sin \omega t$ and $z = r \cos \alpha$ of the Minkowskian metric, $d\tau^2 = \eta_{\mu\nu}dx^\mu dx^\nu$, where $\eta_{\mu\nu} = \text{diag}\{-1, +1, +1, +1\}$ and $x^\mu = (ct; x, y, z)$, the metric in the co-moving frame of reference is given by [17,19]

$$ds^2 = -c^2 \left(1 - \frac{\omega^2 r^2 \sin^2 \theta}{c^2}\right) dt^2 + dr^2.$$  

(3)

For the equation of motion we get:

$$\frac{d}{d\chi} \left( \frac{\partial \mathcal{L}}{\partial (\dot{\vec{x}}_\mu)} \right) = \frac{\partial \mathcal{L}}{\partial x_\mu}.$$  

(4)

$$\mathcal{L} = -\frac{1}{2} mc^2 \tilde{g}_{\mu\nu} \frac{d\vec{x}^\mu}{d\chi} \frac{d\vec{x}^\nu}{d\chi},$$

(5)

$$\tilde{g}_{\mu\nu} \equiv \text{diag}\left\{-\left(1 - \frac{\Omega^2 r^2}{c^2}\right)^{-1}, 1\right\},$$

(6)

where $\Omega = \omega \sin \alpha$, $\vec{x}$. 

Then, by taking the four velocity identity, $\tilde{g}_{\alpha\beta} \frac{dz^\alpha}{d\chi} \frac{dz^\beta}{d\chi} = -1$, into account, one can derive from Eq. (4) the radial equation of motion [19]:

$$\frac{d^2 r}{d\tau^2} = \frac{-\omega^2}{1 - \frac{\omega^2 r^2}{c^2}} \left[1 - \frac{\omega^2 r^2}{c^2} - 2 \left(\frac{dr}{dt}\right)^2\right].$$

(7)

Solving Eq. (7), it is straightforward to show that the Lorentz factor of the particle changes radially as [4]:

$$\gamma = \frac{1}{\sqrt{\bar{m} \left(1 - \frac{v^2}{R_{lc}^2}\right)}},$$

(8)

where

$$\bar{m} = \frac{1 - \frac{r_0^2}{R_{lc}^2} - \frac{v_0^2}{c^2}}{(1 - \frac{r_0^2}{R_{lc}^2})^2}, R_{lc} \equiv c/\omega.$$  

$r_0$ and $v_0$ are the initial position and the initial radial velocity of the particle, respectively and $R_{lc}$ is the radius of the light cylinder - a hypothetical zone, where the linear velocity of rigid rotation exactly equals the speed of light, $c$.

As is clear from Eq. (8), in due course of time the Lorentz factors of electrons become very high in the vicinity of the light cylinder ($r \sim R_{lc}$). On the other hand, it is clear that acceleration lasts until the electron encounters a photon, which in turn inevitably limits the Lorentz factor of the particle. During the ICS an electron will lose energy, whereas a photon will gain energy. This mechanism is characterized by the so-called cooling timescale [20]

$$t_{cool} = 3 \times \frac{\gamma}{(\gamma^2 - 1)U_{rad}} \text{[s]},$$

(9)

where $U_{rad} = L/4\pi c^2 r^2$ is the energy density of the radiation. The acceleration process is characterized by the acceleration timescale, $t_{acc} = \gamma/(d\gamma/dt)$, which after applying Eq. (8) can be presented by

$$t_{acc} = \frac{c}{2\Omega^2 \sqrt{1 - \bar{m}} \left(1 - \frac{\Omega^2 r^2}{c^2}\right)}.$$  

(10)
Generally speaking, initially the electrons accelerate, but in due course of time the role of the inverse Compton losses increase and the acceleration becomes less efficient. The maximum energy attainable by electrons is achieved at a moment when the energy gain is balanced by the energy losses due to ICS. Mathematically this means that the following condition \( t_{\text{acc}} \approx t_{\text{cool}} \) has to be satisfied. After applying Eqs. (11) the aforementioned condition leads to the expression of the maximum Lorentz factor \( \gamma_{\text{max}} \)
\[
\gamma_{\text{max}} \approx 10^{14} \sqrt{m} \left[ \frac{6 \Omega}{U_{\text{rad}}(R_L)} \right]^{\frac{2}{3}},
\]
where \( R_t \approx R_{lc}/\sin \alpha \). If electrons with such high kinetic energies encounter soft photons having energy, \( \epsilon_s \), then, photons’ energy after scattering is given by
\[
\epsilon = \gamma_{\text{max}}^2 \epsilon_s.
\]
As we have already mentioned, the particles reach maximum kinetic energy almost on the LC surface. Let us assume that a layer where the ICS takes place and the high energy photons are produced has a thickness, \( \Delta r \). Then, for the corresponding infinitesimal volume of a cylindrical layer we get:
\[
\begin{aligned}
\frac{dV}{\sin \alpha} & \approx \pi R_t(2R_t + \Delta r) \Delta r \sin \alpha, \\
\end{aligned}
\]
If we take a single particle Thomson power
\[
P_{IC} \approx \sigma_T c^2 U_{\text{rad}},
\]
into account, then the total power emitted from the radiation zone can be expressed as follows
\[
L_{IC} = \int nP_{IC}(\alpha) dV = \int \sigma_T c n R_t(2R_t + \Delta r) \Delta r \frac{\gamma_{\text{max}}^2(\alpha) U_{\text{rad}}(\alpha)}{\sin \alpha} d \alpha,
\]
where \( \sigma_T \approx 6.65 \times 10^{-25} \text{cm}^2 \) is the Thomson cross-section.

3. Discussion

According to the observations of VERITAS, performed from November 2006 to April 2008, the blazar 1ES0806+524, has the VHE emission with the intrinsic photon spectrum, \( \Gamma_i = (2.8 \pm 0.5) \), and the intrinsic integral flux, \( F_{\gamma > 3\text{TeV}} = (4.4 \pm 1.1) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1} \) [8]. Then the intrinsic differential photon spectrum can be easily restored by the integral flux
\[
\frac{dN_i}{d\epsilon} = \left( \frac{3}{4} \right)^{\Gamma_i} \Gamma_i - 1 \times F_{\gamma > 3\text{TeV}} \times \left( \frac{\epsilon}{0.4\text{TeV}} \right)^{-\Gamma_i} = \frac{F_0}{0.4\text{TeV}} \times \left( \frac{\epsilon}{0.4\text{TeV}} \right)^{-\Gamma_i},
\]
where \( F_0 \approx (11.8 \pm 2.9) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1} \).

The corresponding luminosity above 0.3\( \text{TeV} \) up to 1\( \text{TeV} \) can be estimated as follows:
\[
L_{VHE} = \Delta S \int_{\epsilon_1}^{\epsilon_2} \frac{dN_i}{d\epsilon} d\epsilon,
\]
where \( \epsilon_1 = 0.3\text{TeV} \) and \( \epsilon_2 = 1\text{TeV} \). We assume that the high energy emission originates from the jet, having an opening angle, \( 2\alpha_m \) (where \( \alpha_m \geq \alpha_2 \)). \( \Delta S \approx \pi D^2 (\sin^2 \alpha_2 - \sin^2 \alpha_1) \) and \( D \approx 630\text{Mpc} \) is the distance to the blazar.

By taking the parameters into account, one can see from Eq. (17) that the luminosity in the energy interval (0.3 – 1)\( \text{TeV} \) is given by
\[
L_{VHE} \approx (3.7 \pm 1.3) \times 10^{43} (\sin^2 \alpha_2 - \sin^2 \alpha_1) \left( \frac{\text{erg}}{\text{s}} \right),
\]

According to the standard theory, it is well known that the accretion disks thermally radiate and the corresponding temperature is expressed as in the following way [24]:
\[
T \approx 3.1 \times 10^8 Q^{2/5} M_{8}^{-1/5} d^{-3/5} \left( 1 - d^{-1/2} \right)^{2/5} K,
\]
where
\[
Q \equiv \frac{\dot{M}}{3M_{8} \text{yr}^{-1}},
\]
is the dimensionless mass accretion rate, \( M_{8} \equiv M_{BH}/10^8 \text{M}_{\odot} \) and \( d \equiv r_*/3R_g \).

For the given luminosity, the mass accretion rate can be estimated as:
\[
\dot{M} \approx \frac{L}{0.1c^2},
\]
then, combining Eqs. (19,21) one can show that energy, \( \epsilon_s = kT' \), of accretion disc’s thermal photons emitted in the area from \( r' = 15 \times R_g \) to \( r' = R_{lc} \) is of order \( \sim 10\text{eV} \). Therefore, as we see from Eq. (12), for producing energies from thousands of \( \text{GeV} \) to \( \text{TeV} \) domain, one requires very high Lorentz factors \( (1 - 3) \times 10^5 \).

One can see that the aforementioned values of Lorentz factors are achieved for very low inclination angles. In Fig. 1 we show \( \gamma_{\text{max}} \) as a function of the inclination angle. The set of parameters is \( v_0 = 0.4c \), \( r_0 = 10 \times R_g \), \( \omega = 4.5 \times 10^{-6} \text{s}^{-1} \) and \( L = 7 \times 10^{44} \text{erg/s} \). As is clear from the figure, the electrons reach high values of the Lorentz factor for small angles, \( 0.7^\circ - 0.95^\circ \). This is a natural result because, one can straightforwardly show from Eq. (11), that \( \gamma_{\text{max}}(\alpha) \) behaves as \( 1/\sin^2 \alpha \) and therefore, provides higher kinetic energies for lower inclinations.

The present model is based on an assumption that maximum kinetic energy of particles is determined by the balance of energy gain due to the acceleration and energy losses due to the ICS. Generally speaking, this approach is valid only if the energy losses is dominated by the ICS. On the other hand, apart from the inverse Compton scattering, also the curvature radiation could impose significant limitations [25].
The centrifugal acceleration mainly happens close to the light cylinder, and since the power of a single particle curvature radiation behaves as \( \sim \gamma^4 \), one has to check the constraint imposed by this mechanism on relativistic particle dynamics. A total power radiated by a single particle is given by

\[
P_c = \frac{2e^2c}{3R_c^2}\gamma^4,
\]

where by \( R_c \) we denote the curvature radius. Then, the timescale of curvature emission can be defined by the following way:

\[
t_c = \frac{\gamma mc^2}{P_c}.
\]

To find the limitation imposed on the maximum Lorentz factor let us note that electrons initially accelerate efficiently, and this process lasts until the energy gain is balanced by the curvature losses. This happens when \( t_{\text{acc}} \approx t_c \). By taking Eqs. (10,23) into account and assuming \( R_c \sim R_{\text{lc}} \), it is straightforward to show

\[
\gamma_{\text{max}}^c \approx \left( \frac{3mc^3}{e^2\omega_0^{1/2}} \right)^{2/5} \approx \frac{3.5 \times 10^{11}}{\gamma_0^{1/5}}.
\]

From Eqs. (11,23) we see that for \( \gamma_0 \sim 1 \) one has the following inequality \( \gamma_{\text{max}}^c > \gamma_{\text{max}} \). This indicates that the curvature radiation does not impose a significant limitation on the maximum attainable Lorentz factors. Therefore we conclude that maximum attainable kinetic energies are determined only by the ICS.

As is clear from Eq. (12), the VHE emission \((0.3\text{TeV} - 1\text{TeV})\) detected by VERITAS can be achieved for the following interval of Lorentz factors \((1.5 - 2.8) \times 10^5\). Equation (11) shows that when the inclination angles are in the following range \( \alpha \in (0.7^\circ - 0.95^\circ) \), electrons attain Lorentz factors from the aforementioned region of values (see Fig. 1). \( \nu_0 = 0.4c, r_0 = 10 \times R_g, \omega = 4.5 \times 10^{-6}\text{s}^{-1} \) and \( L = 7 \times 10^{44}\text{erg/s} \).

In Fig. 2 we show the behavior of the emission energy versus the inclination angle. As is clear from the figure, acceleration of electrons inside the region, \( 0.7^\circ \leq \alpha \leq 0.95^\circ \), provides the photon energies from \( 0.3\text{TeV} \) up to \( 1\text{TeV} \).

For finding the luminosity output above \( 0.3\text{TeV} \), we have to integrate Eq. (12) from \( \alpha_1 \approx 0.7^\circ \) to \( \alpha_2 \approx 0.95^\circ \). Let us consider the following set of parameters: \( n = 1.1 \times 10^{-3}\text{cm}^{-3}, \nu_0 = 0.4c, r_0 = 10 \times R_g \) and \( \tau = 15 \times R_g \), then, the integration in Eq. (12) gets the VHE luminosity output of order \( 4.8 \times 10^{39}\text{erg/s} \). From Eq. (14) we see that for \( \alpha_1 \leq \alpha \leq \alpha_2 \), the observed VHE luminosity is in the range \( \sim (4.6 \pm 1.6) \times 10^{39}\text{erg/s} \), therefore, our results are in a good agreement with the observed data.

For plotting our graphs and getting the results we used the parameters with the best fitting, although the values from the following ranges are also applicable: \( r_0/R_g \in [10 - 20], \nu_0 \in [0 - 0.7c], n \in [0.7 - 1.4] \times 10^{-3}\text{cm}^{-3}, r^*/R_g \in [10 - 20] \).

On the other hand, the high energy photons may undergo the \( \gamma\gamma \) absorption. It is well known that gamma rays interact most effectively with the background photons of energy \( 26 \)

\[
\epsilon_b = 4 \frac{(mc^2)^2}{\epsilon} \approx 1 \text{TeV/}c\text{eV}
\]

and the corresponding cross section has a peak at \( \sigma_0 \approx \sigma_T/5 \). The optical depth of high energy photons, then becomes

\[
\tau \equiv \frac{R_{lc}}{\lambda} = n_{IR} \sigma_0 R_{lc},
\]

where \( \lambda \) is the mean-free path of infrared photons,

\[
n_{IR} = \frac{L(\epsilon_b)}{4\pi R_{lc}^2 c \epsilon_b}
\]
is the corresponding photon density and \( L(e_b) \) the infrared luminosity. After substituting Eq. (27) into Eq. (26), one can derive an expression of the optical depth of high energy photons \( \tau \):

\[
\tau = \frac{L(e_b)\sigma_T}{4\pi R^2c e^b} \approx 5 \times \frac{L(1\text{eV})}{10^{-6}L_{\text{Edd}}} \times \frac{10^5}{\gamma} \times \frac{\epsilon}{\text{TeV}},
\]

where \( L_{\text{Edd}} \approx 6.5 \times 10^{46} \text{erg/s} \) is the Eddington luminosity of 1ES 0806+524.

As we see from the figures, for producing radiation in the 1TeV domain, one has to accelerate the electrons up to \( \gamma \approx 2.8 \times 10^5 \). For 1ES 0806+524 no infrared data are published so far, on the other hand, since the TeV emission is detected, therefore the infrared luminosity of 1ES 0806+524 must be less than \( 5.6 \times 10^{-7}L_{\text{Edd}} \approx 3.6 \times 10^{40} \text{erg/s} \) (see Eq. (23)). One has to note that the centrifugal acceleration leads to the TeV variability timescale of the order \( \sim (1-2)\text{days} \) [13]. It is worth noting that TeV blazars exhibit the variability on hour to minute timescales, but this particular feature is not detected for 1ES 0806+524.

As our investigation shows, the centrifugally accelerated outflows may provide the detected VHE emission of 1ES 0806+524 via the ICS if the parameters are chosen appropriately. From the aforementioned set of parameters very important one is the density of relativistic electrons, which has to be in the following interval \([0.7-1.4] \times 10^{-3} \text{cm}^{-3}\) in order for the centrifugal acceleration to explain the detected high energy emission. This we consider as a certain test to check if the mentioned mechanism is feasible.

4. Summary

(i) For explaining the observed TeV energy radiation from 1ES 0806+624 detected by VERITAS, we have considered the inverse Compton scattering of disk thermal photons against centrifugally accelerated ultra-high energy electrons.

(ii) We have shown that due to very strong magnetic field, the electrons are in the frozen-in condition, which leads to the co-rotation of particles. Due to the co-rotation, electrons centrifugally accelerate almost up to the light cylinder surface, and in the nearby zone of it the electrons upscatter against soft thermal photons, causing the limitation of particles’ kinetic energy. We also have shown that the role of the curvature radiation in limiting the maximum kinetic energy is negligible with respect to the inverse Compton losses.

(iii) We considered the \( \gamma\gamma \) absorption of high energy photons in the background field of soft infrared photons. From the observationally evident fact that the TeV radiation escapes the central source, we estimated the maximum value of infrared luminosity which has not been detected so far.

(iv) We have found that for physically reasonable parameters the ICS occurs in the Thomson regime. It has been shown that for the following interval of inclination angles, \( 0.7^\circ - 0.95^\circ \), with the best fitting parameters the resulting emission energies, \( (0.3\text{TeV} - 1\text{TeV}) \) and the luminosity output, \( 10^{39} \text{erg/s} \) are in a good agreement with the observed data. On the other hand, if the parameters are chosen in certain physically reasonable intervals, the high energy emission is also possible. Therefore we offer the following test: if one indirectly measures the density of the relativistic electrons, and finds its value to be in the following range, \([0.7 - 1.4] \times 10^{-3} \text{cm}^{-3} \), then the centrifugal acceleration is a feasible mechanism in producing the TeV photons via the ICS.

In the paper we have done several approximations. The first limitation is that we studied the straight magnetic field lines, although, especially in the very vicinity of the light cylinder the curvature of field lines becomes significant. Therefore, the generalization of the present approach will be the next objective of our future work.

The next approximation concerns the fact that according to our model magnetic field is not influenced by plasma kinematics. On the other hand, for real astrophysical scenarios, it is obvious that plasmas may undergo the overall configuration of the magnetic field. For this reason, it is very important to generalize the approach presented here and see how the collective phenomena change the results.

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