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Gamma-ray flares from red giant/jet interactions in AGN

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We propose a new self-consistent hydrodynamical model for description of ultra-short flares of TeV blazars by compact magnetized condensations (blobs) produced when red giant stars cross the jet close to the central black hole. Our study includes a hydrodynamical treatment of evolution of the envelope lost by the star in the jet, and its high energy nonthermal emission through different leptonic and hadronic radiation mechanisms. We show that the fragmented envelope of the star can be accelerated to Lorentz factors up to 100 and radiate effectively the available energy in gamma-rays predominantly through proton synchrotron radiation. The model can readily explain the minute-scale TeV flares on top of longer (typical time-scales of days) gamma-ray variability as observed from the blazar PKS 2155−304, and constrain the key parameters of sources such as the mass of the central black hole $M_{\rm BH} \approx 10^8 M_\odot$, the total jet power $L_{\rm j} \approx 1.7 \times 10^{47}$ erg/s and the Doppler factor of the gamma-ray emitting blobs $\delta \geq 50$.

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1. Introduction

The flux variability of very high energy (VHE) gamma-rays on minute timescales detected from the BL Lac object PKS 2155−304 [1] challenges the standard scenarios suggested for explanation of nonthermal properties of TeV blazars [5, 10]. The extremely short duration of the flare imposes severe constrains on the size of the gamma-ray production region, $l' \leq c\tau' \simeq 3\times 10^{13}\tau'_3$ cm, where l' and $\tau'_3 = \tau'/10^3$s are the proper production size and the variability time scale in the frame of the jet, respectively; c is the light speed. The proper variability time-scale τ' is connected to the variability in the observer frame, τ, by the relation $\tau = \frac{\tau'}{\delta}$, where δ is the Doppler factor of the moving source (the blob): $\delta = \frac{1}{\Gamma(1-\beta\cos(\alpha))}$. Here the bulk Lorentz factor, Γ accounts for the relativistic transformation of time, and $(1-\beta\cos(\alpha))$ is responsible for the kinematic shrinking of duration of radiation.

While the inverse Compton (IC) models allow rather satisfactory explanations of the energy spectra and variability patterns of many blazars in general, the parameters used to fit some specific objects appear incompatible with the parameters defined from other observations [13, 14]. In this regard the models which invoke high energy protons for production of gamma-rays get certain advantages. The synchrotron radiation of protons, with a key assumption on the acceleration of particles with a rate close to $t^{-1} \sim eB/E$, where E is proton energy, coupled with a strong magnetic field between 10 to 100 Gauss, and large Doppler factor, $\delta \geq 10$, can provide relevant acceleration and radiation timescales, as well as can explain the extension of gamma-ray spectra to TeV energies [2].

2. Blobs in Relativistic Jets

Below we discuss the distinct features of interaction of red giants with AGN jets in the specific case of powerful blazars. Originally, the scenario of AGN jet – red giant (RG) interaction has been suggested by [3] for explanation of VHE observations of M87 - a nonblazar type nearby AGN with a large jet viewing angle $\geq 20^\circ$ and a modest jet power, $L_{\rm jet} \simeq 10^{44}$ erg/s. It was demonstrated that if a RG disturbed by tidal forces penetrates the jet, the ram pressure of the jet in M87 would be sufficient to remove the outer layer of the RG. This leads to formation of a dense cloud in the jet which, in combination of an effective particle acceleration, can trigger gamma-ray production through proton-proton interactions with required spectral and temporal properties. This model allows detectable gamma-ray fluxes because of the proximity of the source and non-relativistic speed of the blobs (otherwise the radiation from M87 would be de-boosted given the large aspect angle of the jet).

The AGN jet – red giant interaction (JRGI) gets very specific and important features in the case of powerful blazars [2]. High ram pressure can blow-up the outer layers of the star atmosphere even from a non-disturbed RG.

The cloud will continue to remain in the jet if it would be accelerated along the jet axis. Thus, the confinement condition has the following form: $v_z = a_z t_{\rm jc} > V_{\rm orb}/\theta$, where $a_z = P_{\rm ram}\pi r_{\rm c}^2/M_{\rm c}$. One can obtains the cloud capture condition: $M_{\rm c,jc} \lesssim 3\times 10^{31} L_{\rm j,46} r_{\rm c,15}^2 M_{\rm BH,8}^{-1}$ g , where $r_{\rm c,15} = r_{\rm c}/10^{15}$cm is the size of the cloud after the hydrodynamical expansion. Thus, even if the stellar

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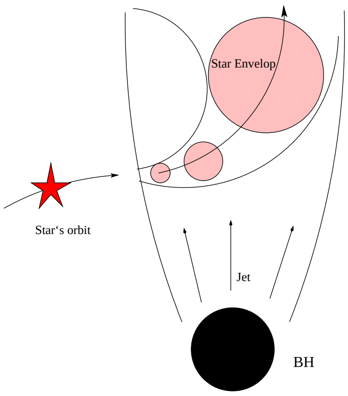

Figure 1: Schematic illustration of the scenario. When a star crosses the AGN jet, the outer layers of its atmosphere are ablated due to the high jet ram pressure; During the interaction with the jet the cloud gets expanded and involved to the jet motion.

matter is not broken into small blobs when the jet hits the RG, but instead forms a heavy cloud, this cloud will be trapped in the jet and accelerated up to sub-relativistic velocities (i.e. $\sim 0.1c$). In fact, independently on the initial conditions, during the acceleration phase the cloud is expected to be crushed in hundreds of small blobs [16]. Obviously, these blobs can be easier picked up by the jet flow.

At the relativistic stage, the dynamics of the cloud is described by the following equation:

$$\frac{d\Gamma_{\rm c}}{dt} = \left(\frac{1}{\Gamma_{\rm c}^2} - \frac{\Gamma_{\rm c}^2}{\Gamma_{\rm j}^4}\right)\frac{L_{\rm j} r_{\rm c}^2}{4\omega^2 c^2 M_{\rm c}}\,, \tag{2.1}$$

where $\Gamma_{\rm c}$ is the Lorentz factor of the cloud, $\omega \approx z\theta$ is cylindrical radius of the jet. The derivation of this equation is done in [2]. Let us introduce the following notations $g \equiv \Gamma_c/\Gamma_j$ and $y \equiv z/z_0$ (and $dy \approx c/z_0 dt$), here z_0 is the distance from SMBH to the point in the jet crossed by RG, i.e. we adapt the initial condition $g \ll 1$ at $z = z_0$. Several simplifications, in particular, assuming that $\Gamma_{\rm j} = $ const at the cloud acceleration scale, and $dt = z_0/cdy$, allow presentation of Eq.(2.1) in the form: $\frac{dg}{dy} = \left(\frac{1}{g^2} - g^2\right)\frac{D}{y^2}$, where $D \equiv \frac{L_{\rm j} r_{\rm c}^2}{4\theta^2 \Gamma_{\rm j}^3 z_0 c^3 M_{\rm c}}$. This equation allows an analytical solution, which defines y as a function of g and D.

In this paper we do not specify the origin of relativistic particles in the cloud. However, assuming that particle acceleration is a result of strong interaction between the cloud and the jet, we may conclude that high Lorentz factors do not support the production of non-thermal radiation. Indeed, the cloud-jet interaction intensity drops with the cloud's acceleration, The apparent intensity of the non-thermal phenomena can be roughly described by the luminosity correction function F_e, which accounts both for the Doppler boosting, i.e. $F_e \propto \Gamma_{\rm c}^4$, and for the interaction intensity, i.e. $F_{\rm e} \propto \left(\frac{1}{\Gamma_{\rm c}^2} - \frac{\Gamma_{\rm c}^2}{\Gamma_{\rm j}^4}\right)/z^2$. For the sake of clearness, we consider the correction function in dimensionless form $F_e = g^4(1/g^2 - g^2)/y^2$. Since the solution of Eq.(2.1) relates g and y, F_e is, in fact, a function of one variable. In Fig.2, we show it as a function of g (left panel) and as a function of the variable $\tau = y/\left(c\Gamma_{\rm j}^2\right)$ (right panel) corresponding roughly to the observer time. The values of the parameter $D = 0.1$, 1, 10 and 100 are used in both panels of Fig.2. It can be seen that in the case of

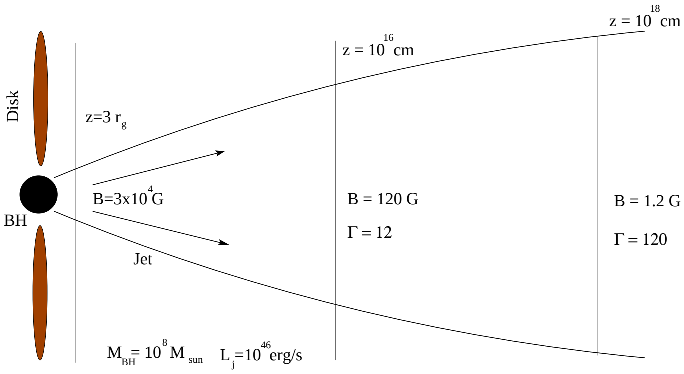

Figure 2: Sketch of the jet with characteristic magnetic field strength and bulk Lorentz factors at typical distances from a BH with mass $M_{BH} = 10^8 M_\odot$. The BH dimensionless parameter of rotation is assumed to be $a \approx 1$. We assume that initially the jet is magnetically dominated with the magnetization parameter $\sigma \gtrsim 100$.

$D \gtrsim 1$ the solution weakly depends on the parameter D, and the non-thermal activity of the blob is expected to have a narrow peak of duration $t_0 \approx \frac{z_0}{c}\frac{1}{D}\frac{1}{2\Gamma_{\rm j}^2}$. The maximum of the correction function occurs at $g_{\rm max} \approx 0.8$.

In the case of $D \ll 1$ the situation is quite different. Namely, the expected nonthermal activity has no pronounced peak, thus such a blob cannot produce a high-amplitude flare. In this regard, we can formulate the condition $D \gtrsim 1$ as a requirement for a sharp flare of the blob. This condition can be reformulated as a upper limit on the cloud mass: $M_{\rm c,rc} \lesssim \frac{L_{\rm j} r_{\rm c}^2}{4\theta^2 c^3 z \Gamma_{\rm j}^3}$. The above relation depends not only on properties of the cloud (its size and mass) but also on the jet power and Lorentz factor. Thus, for quantitative calculations one needs detailed information about the dynamics and properties of blazar jet.

Although, the process of the jet formation is not fully understood, the recent hydrodynamical studies of different scientific groups show that the Blandford-Znajeck [9] process may be at work in AGN and suggests a concept of magnetically accelerated jets. Thus, the jet base is expected to be strongly magnetized and likely magnetically dominated at $z \leq 1$pc [11, 4, 6]. This immediately gives the magnetic field strength of the jet in laboratory frame $B_{\rm j} \approx \left(\frac{4L_{\rm j}}{cz^2\theta^2}\right)^{1/2} \approx 120\, L_{\rm j,46}^{1/2} z_{17}^{-1}\, \theta_{-1}^{-1}\, {\rm G}$. During the jet propagation, the magnetic field energy can be transformed to the bulk kinetic energy. At the linear stage a simple relation defines the bulk Lorentz factor [7] $\Gamma_j \approx \frac{\omega}{4r_g}$. Finally, the opening angle of the jet is expected to be $\theta \approx 1/\Gamma_j$ [12]. Now we can estimate the magnetic field in the jet comoving frame,

$$B_{\rm c} \approx \frac{2}{z}\left(\frac{L_j}{c}\right)^{1/2} \approx 12 z_{17}^{-1} L_{j,46}^{1/2}\, {\rm G}\,. \tag{2.2}$$

Fig.2 illustrating the typical magnetic fields and the bulk Lorentz factors of the jet at three different distances from BH. These values are in a good agreement with observed values of magnetic field on parsec scales in the AGNs [13].

One can present $M_{\rm c,rc}$ in the form $M_{\rm c,rc} \lesssim 0.5 \times 10^{26} L_{\rm j,46} r_{\rm c,15}^2 \Gamma_{j,1.5}^{-3} M_{\rm BH,8}^{-1}\,{\rm g}$. Note that at this late stage the cloud can be already significantly expanded with a radius $r_{\rm c,15} \gg 1$.

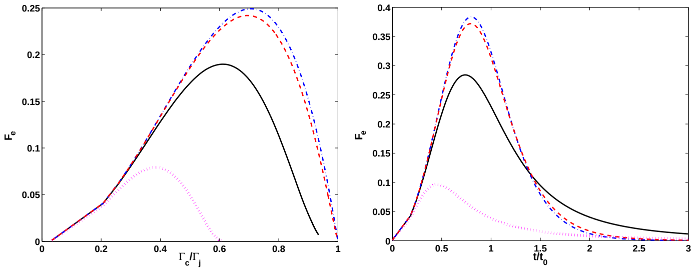

Figure 3: Solutions of Eq.(2.1) shown as F_e vs Lorentz factor of the cloud (left panel) and as F_e vs the observer's time ($t_0 = z_0/2D\Gamma_j^2 c$) (right panel). The Lorentz factor of the jet is assumed to be $\Gamma_j = 30$. The following values of the D-parameter were used: $D = 100$ (dot-dashed lines), $D = 10$ (dashed line), $D = 1$ (solid line) and $D = 0.1$ (dotted line).

The extreme value of $M_{\rm c,rc}$ can be achieved at $r_c \approx \omega$: $M_{\rm c,rc} \lesssim 2\times10^{26} L_{\rm j,46} M_{\rm BH,8} \Gamma_{j,1.5}^{-1}$ g. Note that this is the upper limit.

The radiation of blazars is probably strongly Doppler boosted-type sources. The parameter $\xi \ll 1$ accounts for the overall efficiency of transformation of the absorbed jet energy to nonthermal emission through acceleration and radiation of relativistic particles. For small angles, $\delta \approx 2\Gamma_{\rm c}$, thus we obtain the following simple relation $L_\gamma = 3\xi F_e L_{\rm j} \Gamma_j^2 \frac{r_{\rm c}^2}{\omega^2}$, which has a few interesting implications. In particular, one can estimate the size of the blob. Given that $\Gamma_{\rm j} \approx \omega/(4r_{\rm g})$ and $\max F_e \approx 0.4$, and using a few typical normalizations, we obtain $r_{\rm c} \geq 5\times10^{14} M_{\rm BH,8} L_{\gamma,47}^{1/2} L_{\rm j,46}^{-1/2} \xi_{-1}^{-1/2}$ cm, Here we use a quite high normalization for the efficiency, $\xi_{-1} = \xi/0.1$

Another important estimate can be obtained for the maximum apparent luminosity of the blob. It is achieved when the blob eclipse the whole jet, i.e. $r_{\rm c} \approx \omega$. In this case one obtains: $L_{\gamma\max} = 4\times 10^{47} \xi_{-1} L_{\rm j,46} \Gamma_{\rm j,1.5}^2\,{\rm erg\,s^{-1}}$. where $\Gamma_{\rm j,1.5} = \Gamma_j/10^{1.5}$. Note that the apparent nonthermal luminosity of the blob is proportional to $\Gamma_{\rm j}^2$. Remarkably, even for relativity modest values of the jet Lorentz factor, $\Gamma_{\rm j} \sim 10$, and the conversion efficiency, $\xi \sim 0.01$, L_γ is comparable to the jet power.

2.1 Time variability

The principal variability scale in the JRGI scenario is related to the duration of effective interaction of the cloud with the jet; it is determined by the function F_e. Since the model requires very effective acceleration of particles, with $\geq 10\%$ efficiency of energy transformation to nonthermal particles, the shape of function F_e (see Fig. 2) can be treated as the time profile of particle acceleration with the characteristic timescale $\Delta t \approx \frac{2z_0^2\theta^2}{r_{\rm c}^2} \frac{\Gamma_{\rm j} c^2 M_{\rm c}}{L_{\rm j}}$. Note that in the extreme case, when the blob eclipse the entire jet, $z_0^2\theta^2/r_{\rm c}^2 \sim 1$, thus Δt depends only on the jet Lorentz factor Γ_j and power L_j, as well as on the mass of the cloud M_c:

$$\Delta t \approx 60 \Gamma_{j,1.5} L_{\rm j,46}^{-1} M_{\rm c,25}\,{\rm s}\,, \tag{2.3}$$

The total energy of electromagnetic radiation which can be emitted by the cloud can be estimated as $E_{\rm tot} \approx 2.5\times10^{49} \xi_{-1} M_{\rm c,25} \Gamma_{j,1.5}^3$ erg. The blob-jet interaction can be quite brief - shorter than the detected variability of ultrafast flares of PKS 2155−304 and Mkn 501. Moreover, for small mass clouds, it can be as short as 1 sec, provided, of course, that this will be accompanied by fast radiative or adiabatic cooling of electrons or rapid changes of the Doppler factor of the blob.

Let us assume that we have strong turbulent chaotic motion of fragments (blobs) of the initial cloud with characteristic velocity of $v_{\rm s} \sim c/\sqrt{3}$. Due to interactions with each other, the blobs can change their speeds on timescales $t_{\rm s} \sim 2r_{\rm c}/v_{\rm s}$ leading to the variability on a timescale

$$\tau \approx t_{\rm s}/\delta \sim 5\times 10^{2} M_{\rm BH,8} L_{\gamma,47}^{1/2} L_{\rm j,46}^{-1/2} \xi_{-1}^{-1/2} \delta_{2}^{-1}\,{\rm s}, \tag{2.4}$$

where Doppler factor is determined as $\delta_2 = \delta/10^2$.

Eq. (2.3) and (2.4) show that the JRGI model suggested in this paper, allows, at certain combination of several principal parameters characterizing the system, variability on timescales as short as 100 s. Obviously this can be realized in the case of effective acceleration of particles and their radiation In the following section we discuss the efficiency and features of major radiation mechanisms related to both protons and electrons. In this paper we do not discuss the specific mechanisms of particle acceleration, but simply assume that both electrons and protons are effectively accelerated during the interaction of the blob with the jet. Note that while the electrons (and positrons) have a "primary" origin, i.e. are initially contained in the jet, the protons can have only an external origin. In our model protons are supplied by red giants interacting with the jet.

3. Discussion

In the case of July 2006 flares of PKS 2155−304, the total energy of the nonthermal radiation detected during the burst was about $E_{\rm tot} \approx L_\gamma \Delta t \approx 10^{51}$erg. On the other hand, this value can be estimated through the duration of the shortest flaring episode of $\tau \approx 200$s. Namely, the total energy realized during the whole burst can be estimated as: $E_{\rm tot} \approx 3.8\times 10^{52} L_{\gamma,47} M_{BH,8}^{3} \tau_2^{-2}$ ergs. This yields the following lower limit on the mass of the central black hole $M_{BH} \gtrsim \frac{c^3(\Delta t \tau^2)^{1/3}}{3G} \approx 3.1\times 10^{7} \tau_2^{2/3} \Delta t_4^{1/3}\, M_\odot$.

In the case of strongly magnetized jets with the magnetic field of $B \sim 100$ G, the proton synchrotron radiation channel is a more natural mechanism for generation of short TeV flares. The only crucial condition for an effective realization of the proton synchrotron scenario is the particle acceleration with a rate close to the theoretical electrodynamic limit, i.e. $\eta \leq 10$. We note, that the escape of protons from the blob is not so crucial because the relativistic proton can radiate not only in the cloud but also in the jet, where magnetic field could be even larger than inside the blob. Substituting Eqs.(2.2,2.4) into the Larmor radius $r_{\rm L} \approx E\Gamma/eB_{\rm j}$ and taking into account that the gyroradius should be smaller than the size of the blob, one obtains $80 L_{\gamma,47} \Delta t_4^{7/6} L_{j,46}^{-7/4} \tau_2^{-2/3} \eta_1^{-1/2} \xi_{-1}^{-1} < 1$. This equation allows to constrain the luminosity of the jet

$$L_j \gtrsim 10^{47} \frac{L_{\gamma,47}^{4/7} \Delta t_4^{2/3}}{\tau_2^{8/21} \eta_1^{2/7} \xi_{-1}^{4/7}}\ {\rm erg\ s^{-1}} \tag{3.1}$$

and its Lorentz factor

$$\Gamma_c \gtrsim 25 L_{\gamma,47}^{3/14} \tau_2^{-1/7} \eta_1^{1/7}\,. \tag{3.2}$$

The corresponding Doppler factor can be as high as $\delta \gtrsim 50$. Thus, one should expect the maximum of the proton-synchrotron spectrum around $\approx 1.5\eta_1^{-1}$ TeV. The observed cut-off in the flare spectrum around 4 TeV requires the acceleration parameter of $\eta \leq 10$. This implies that we deal with an extreme accelerator.

An important question in the suggested scenario is the expected rate of the flaring events, which is related to the number of RGs at the relevant jet scales. The jet region suitable for production of the powerful flares (similar to the burst detected from PKS 2155−304) can be defined $z < 1$pc, thus the corresponding side cross section of the jet $S_e \approx z^2\theta \sim 10^{33}\theta_{-1}z_{17}^2\mathrm{cm}^2$. The Υ is number of flaring event per year which can be estimated as the following $\Upsilon \approx S_e V_{orb} n$. We can estimate the density of the RG required to produce Υ flaring event as the following: $n \sim 10^6 \Upsilon M_{\mathrm{BH},8}^{-1/2}\theta_{-1}^{-1}z_{17}^{3/2}\mathrm{pc}^{-3}$. Unfortunately, no direct information is available on the density of stars in the vicinity of the BH. Thus, depending on the assumed distribution law, the number of RGs in the vicinity of the BH may or may not be enough. However we note that studies of the possible stellar density profiles in the vicinity of the BH in AGN [8, 15] show that the densities similar to the required one ($\sim 10^6$ pc^{-3}) are rather feasible.

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