Two Blobs in a Jet Model for the $\gamma$-Ray Emission in Radio Galaxies

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Abstract

In the unified scheme, FR I type radio galaxies are identified with the blazar type active galaxies for which jets are aligned at large angles to the line of sight. A few radio galaxies of this type have been discovered to emit GeV–TeV gamma-rays. We consider a scenario that naturally explains the high energy gamma-ray emission at large angles to the jet axis. It is proposed that two emission regions are present in the jet at this same moment. The inner region (blob I) moves with the large Lorentz factor, producing radiation strongly collimated along the jet axis, as observed in BL Lac type blazars. The outer region (blob II), which moves with the mild Lorentz factor, contains isotropically distributed relativistic electrons in the blob reference frame. These electrons upscatter monodirectional soft radiation from blob I preferentially in the direction opposite to the jet motion. Therefore, gamma-rays, produced in blob II, can be emitted at relatively large angles to the jet axis in the observer’s reference frame. We analyze the basic emission features of such an external blob radiation model. The example modeling of the emission from the FR I type radio galaxy, NGC 1275, is presented.

Key words: galaxies: active – galaxies: individual (NGC 1275) – galaxies: jets – gamma rays: galaxies – radiation mechanisms: non-thermal

1. Introduction

According to the unification scheme, FR I type active galactic nuclei (AGNs) are interpreted as BL Lac type blazars viewed at large angles to the jet axis. Such an interpretation is supported by the observations of the inner radio jets in these sources, which are aligned at large angles to the line of sight, e.g., in Cen A ($i \sim (12–45)^\circ$ (Müller et al. 2014) and $i \sim (50–80)^\circ$ (Tingay et al. 2001), in NGC 1275 $i \sim (30–55)^\circ$ (Vermeulen et al. 1994; Walker et al. 1994) and $i \sim (65 \pm 16)^\circ$ (Fujita & Nagai 2017), and in M87 $i \sim (10–19)^\circ$ (Biretta et al. 1999). A few nearby FR I type radio galaxies, M87, Cen A, and NGC 1275, have been discovered to emit $\gamma$-rays extending up to TeV energies. In the case of M87, the differential TeV $\gamma$-ray spectrum is flat, which is well described by the power law with the index 2.2 ± 0.2 in the high state. It extends up to ~10 TeV (Aharonian et al. 2003; Albert et al. 2008; Acciari et al. 2009; Aliu et al. 2012). Moreover, the TeV emission is observed to vary on a timescale of a day. The spectrum in the Fermi-LAT energy range is complex showing hardening above ~10 GeV (Abdo et al. 2009a). The GeV emission below the break shows variability on a month timescale (Ait Benkhali et al. 2018) and a day to week timescale (Tanada et al. 2018). Such a short timescale variability of the low energy GeV component is also observed in the case of another radio galaxy Cen A (Sahakian et al. 2013; Brown et al. 2017). The TeV $\gamma$-ray emission from Cen A has been detected up to ~5 TeV, showing also a relatively flat spectrum (spectral index $\sim 2.7 \pm 0.5$, Aharonian et al. 2009). On the other hand, the $\gamma$-ray emission from NGC 1275 shows different behavior. It is observed only up to ~600 GeV with the steep spectrum, spectral index $\sim 4.1$ (Aleksić et al. 2012a, 2014a). The Fermi-LAT emission (discovered by Abdo et al. 2009b; Kataoka et al. 2010) shows strong variability up to an hour timescale (Brown & Adams 2011; Baghmanyan et al. 2017). The GeV emission has steadily increased over an 8 year time-span of the Fermi-LAT observations (Tanada et al. 2018). Recently, two very large flares from NGC 1275 have been observed in the GeV energies (Privato & Buson 2015; Lucarelli et al. 2017) and TeV energies (Mirzoyan 2017; Mukherjee & VERITAS Collaboration 2017; Ansoldi et al. 2018), with the flux increase of a factor of ~60.

The short timescale variability, of the order of days to hours observed at GeV–TeV energies, indicates that the emission in FR I type radio galaxies originates in the inner part of the jet or in the direct vicinity of the super-massive black hole (SMBH); for a review, see Rieger (2017). In the standard blob in a jet model the emission region should move in a rather mildly relativistic manner in order to produce $\gamma$-rays at angles of the order of ~40°–50° to the jet axis, as estimated in the case of Cen A and NGC 1275. Such emission might be explained in terms of the mildly relativistic homogeneous synchrotron self-Compton (SSC) model (e.g., Chiaberge et al. 2001) or in terms of more complicated structured jets (Tavecchio & Ghisellini 2008; Giannios et al. 2009). In fact, the high energy $\gamma$-ray emission at large angles to the jet axis is also expected from the region surrounding the inner jet in the inverse Compton (IC) $e^\pm$ pair cascade models (e.g., Sitarek & Bednarek 2010; Roustazadeh & Böttcher 2011). The emission, varying on a short timescale at a large angle to the jet axis, has also been expected in terms of the star/cloud–jet collision model in which the jet plasma interacts directly with the wind of the massive star (Bednarek & Protheroe 1997) or with the matter of the red giant (e.g., Barkov et al. 2010). The last class of models links large angle, variable $\gamma$-ray emission to the processes occurring in the magnetosphere of the rotating SMBH (e.g., Rieger & Mannheim 2002; Neronov & Aharonian 2007; Rieger & Aharonian 2008; Levinson & Rieger 2011; Aleksić et al. 2014b). It is not clear at present whether any of the abovementioned models can explain complex features of the $\gamma$-ray emission from radio galaxies.

Here we consider the standard blob in a jet scenario for the variable, high energy emission from the inner jet in radio galaxies. However, it is assumed that two emission regions are present within the jet at this same moment. The inner region (called blob I) moves fast and emits highly collimated radiation toward the outer, slowly moving region (called blob II). Isotropically distributed relativistic electrons, in the blob II...
reference frame, upscatter collimated radiation from the inner blob I, preferentially in the direction opposite to the jet propagation. Therefore, γ-rays produced in blob II are emitted at larger angles to the observer’s line of sight than expected in the case of the isotropic emission region. On the other hand, radiation produced in blob I is highly collimated along the jet axis. This emission is characteristic for the BL Lac type objects observed at small viewing angles. We discuss the basic emission features of such an external blob radiation model. We argue that the model can describe the high energy emission from radio galaxies viewed at large angles. Note that our model differs essentially from that proposed by Georganopoulos et al. (2005) in which radiation from the slow blob II is upscattered by the relativistic electrons in the fast blob I. That model seems to be more suitable for the AGNs observed at small inclination angles, i.e., BL Lacs. On the other hand, our scenario shows similarities to the external Compton disk model (Dermer et al. 1992) in which the accretion disk radiation is scattered by electrons in the blob moving relativistically along the jet. This model has been studied in more detail in Dermer & Schlickeiser (1993) and Dermer et al. (1997).

2. External Blob Radiation Model

Jets in active galaxies are expected to have complex structure. Their inner parts, close to the jet base, are composed of plasma that moves with large Lorentz factors. The emission from this region is relativistically boosted along the jet axis. The plasma in the outer parts, farther from the jet base, is decelerated as a result of interaction with the matter within the jet. We consider two separated regions in the jet, called blob I and blob II. Both blobs contain relativistic electrons and emit radiation in the synchrotron and the IC processes. In terms of such a two-blob scenario, the emission from the BL Lac type blazars is identified with the emission from the inner blob I. In fact, the TeV γ-ray emission from two extreme BL Lac type objects, Mrk 501 and PKS 2155-304 is strongly variable on a timescale down to a few minutes (Aharonian et al. 2007; Albert et al. 2007). Such short variability requires the presence of the emission region in the jet, which moves with the Lorentz factor over 50 (Begelman et al. 2008). On the other hand, observations of the superluminal motion of radio emitting regions in the parsec-scale jets suggest much lower values of the jet Lorentz factors. It is clear that the jet has to decelerate at some distance after initial propagation with the large Lorentz factor. If this deceleration occurs already in the inner jet, then this region will produce radiation at a relatively large angle to the jet axis. We show that the large angle emission can be significantly enhanced if the relativistic electrons in the blob II IC upscatter monodirectional soft radiation produced in blob I (see the geometrical situation presented in Figure 1). Therefore, the existence of these two regions in the jet, either well localized or quite extended, seems to provide a natural mechanism for the γ-ray emission observed from radio galaxies. Such geometrical structure of the jet, the inner fast blob, and the outer slow blob, creates the baseline for the model discussed here. Note that such general structure of the jet has already been discussed by Georganopoulos et al. (2005). However, in their model, the high energy emission is produced in blob I as a result of upscattering of the soft radiation produced in blob II. We consider the opposite scenario in which the high energy emission is produced in blob II as a result of upscattering the monodirectional radiation arriving from blob I. Due to the geometrical effects of the IC scattering process of the monodirectional radiation (from blob I) by isotropic relativistic electrons, which are isotropic in the blob II reference frame, the γ-ray emission from blob II can be produced at large angles to the jet axis. We argue that the emission from blob II is responsible for the γ-ray emission observed from FR I type radio galaxies observed at the angle of a few tens of degrees to the jet axis.

In the considered two-blobs-in-a-jet scenario, both blobs can in fact follow this same pattern during the propagation in the jet. The initially very relativistic jet can significantly decelerate as a result of the interaction with the matter surrounding the SMBH. Then, the Lorentz factor of the jet drops with the propagation distance according to the prescription expected in the case of the relativistic jets in gamma-ray bursts, i.e., \( \Gamma(z) \propto \Gamma_{0,1} (z_0/z)^{-3/2} \) (see Blandford & McKee 1976 and Sari 1997), where \( z \) is the distance measured from the base of the jet and \( \Gamma_{0,1} \) is the Lorentz factor of the jet at the distance \( z_0 \) from its base. The jet plasma with the initial Lorentz factor of the order of \( \Gamma_{0,1} = 100 \), e.g., at the distance \( z_0 = 3 \times 10^{16} \) cm from the base of the jet, can decelerate to the Lorentz factor of the order of \( \sim 3 \) at the propagation distance of \( \sim 10 \) \( R_0 = 3 \times 10^{15} \) cm. The abovementioned example parameters postulate that the acceleration of the blobs in the jet already occurs within a few tens of the Schwarzschild radii of an SMBH with the mass of the order of \( 3 \times 10^6 \) \( M_\odot \).

In order to perform the calculations of the γ-ray spectra produced in such an external blob radiation model, we have to determine the soft radiation field produced in blob I. Note that the radiation from blob I is strongly collimated along the jet axis, so it cannot be observed directly in the case of a specific FR I type radio galaxy that is observed at a large angle to the jet axis. Therefore, for the purpose of these studies, we apply the results of observations of the soft emission typical for the classical BL Lacs, which are viewed at small angles, e.g., Mrk 501. As an example, we assume that the flux of soft radiation, produced in blob I but observed at the distance to the Earth, is approximated by a simple power-law function,

\[
F(\varepsilon) = B \varepsilon^{-\alpha} \text{ ph. cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1},
\]

below the maximum energy \( \varepsilon_{\text{max}} \) and “\( B \)” is the normalization constant. Then, the density of photons from blob I, which is measured in the blob II reference frame, is

\[
\nu(\varepsilon) = F(\varepsilon) d_\text{ll}^2 D_{\text{ll}}^2 / (\varepsilon^2 \gamma^2) \text{ ph. cm}^{-3} \text{ MeV}^{-1},
\]

where \( d_\text{ll} \) is the luminosity distance to the specific BL Lac, and \( D_{\text{ll}} = (\Gamma_\text{ll}(1 + \beta_\text{ll}))^{-1} \) is the Doppler factor of blob II applied for the transformation of the soft radiation field from the observer’s

Figure 1. Schematic representation of the jet in a radio galaxy with two blobs (marked by “blob I” and “blob II”) moving with the Lorentz factors of \( \Gamma_1 \) and \( \Gamma_\text{ll} \). Blob I (closer to the jet base) emits strong soft radiation, \( \gamma \), which is Doppler boosted toward blob II (at a larger distance from the jet base). The relativistic electrons, in blob II, Comptonize the soft photons from blob I to the γ-ray energy range. Blob I moves with the large Lorentz factor and blob II moves with a relatively small Lorentz factor. Therefore, IC γ-rays (\( \gamma \)) are produced at a relatively large angle, \( \theta' \), to the jet axis measured in the blob reference frame.
reference frame to the blob II reference frame, $\Gamma_{\text{II}}$ is the Lorentz factor of blob II, its velocity $\beta_{\text{II}} = (\Gamma_{\text{II}} - 1)^{0.5}/\Gamma_{\text{II}}$, and $c$ is the speed of light. Note that radiation produced in blob I approaches from behind blob II (see Figure 1). The radiation field defined above can be seen only by the observer located at the jet axis, i.e., such a source belongs to the class of the BL Lac type according to the classification scheme. Therefore, in order to perform some realistic example calculations, the parameters of the emission stage observed in the case of a typical BL Lac type source such as Mrk 501, should be used (see Pian et al. 1998, and also Equation (2) in Bednarek & Protheroe 1999).

We calculate the $\gamma$-ray spectra produced by isotropic electrons with the equilibrium spectrum, $dN_e/dE_e$, which scatter mono-directional soft radiation with the spectrum, $n(\varepsilon)$, in the blob II reference frame, by integration of the following formula,

$$\frac{dN}{d\varepsilon, d\varepsilon', d\Omega'} = \int_{E_L}^{E_{\text{cut}}} dE_{\varepsilon'} \int_0^{\infty} dE_\varepsilon \int_{\varepsilon_{\text{min}}}^{\varepsilon_{\text{max}}} d\varepsilon \left[ \frac{d\varepsilon}{d\varepsilon'} \right] \left[ \frac{n(\varepsilon', \varepsilon, E_\varepsilon)}{d\varepsilon, d\varepsilon', d\Omega'} \right] d\varepsilon dE_e, \quad (3)$$

where $dN(\varepsilon', \varepsilon, E_\varepsilon)/(d\varepsilon, d\varepsilon', d\Omega')$ is the $\gamma$-ray spectrum produced by the mono-energetic electrons by scattering soft photons with energy $\varepsilon$. It is expressed by the convenient formulas obtained by Aharonian & Atoyan (1981). These spectra depend on the angle, $\theta'$, which is the angle between the directions of the soft photon and the $\gamma$-ray as measured in the blob II reference frame. In our geometrical case, this angle is measured from the jet axis (see Figure 1). In order to produce $\gamma$-ray photons with energy, $\varepsilon_{\gamma}$, the electron, soft photon, and $\gamma$-ray has to fulfill the following minimum kinetic condition given by, $\varepsilon_{\text{min}} = 0.5 \varepsilon_{\gamma} m_e c^2/[(1 - \cos \theta) E_\varepsilon^2 (1 - \varepsilon_{\gamma}/E_\varepsilon)]$ (see Appendix A in Moderski et al. 2005). If $\varepsilon_{\text{min}}$ is greater than the lower range of the soft photon spectrum, $\varepsilon_L$, the integration is performed only over the energy range of soft photons above $\varepsilon_{\text{min}}$. $\varepsilon_{\text{L}}$ is the upper energy range of the soft radiation. We assume that electrons in the blob have the energies in the range $E_{\text{min}} < E < E_{\text{max}}$. The lower limit on the energy of the electron, $E_{\text{L}}$, which is able to produce $\gamma$-ray with energy, $\varepsilon_{\gamma}$, is also obtained from the above kinetic condition by introducing in the above formula $\varepsilon = \varepsilon_{\gamma}$. This lower limit has to be below the maximum energy of available electrons in the blob, $E_{\text{max}}$. If $E_{\text{L}}$ is above $E_{\text{min}}$, then we integrate the electron spectrum only from $E_{\text{L}}$.

The angle $\theta'$ is related to the observation angle of the jet in the observer’s reference frame by the following transformation formula, $\cos \theta' = (\cos \theta - \beta_{\text{II}})/(1 - \beta_{\text{II}} \cos \theta)$, where $\theta$ is the observation angle in the observer’s reference frame. The $\gamma$-ray spectra are transformed from the blob II reference frame to the observer’s reference frame according to $E_{\gamma}'^2 dN'/d(E_{\gamma}', d\varepsilon', d\Omega') = D_{\text{II obs}}^2 \beta_{\text{II}}^2 dN/(d\varepsilon, d\varepsilon', d\Omega')$, where the Doppler factor is $D_{\text{II obs}} = [\Gamma_{\text{II}}(1 - \beta_{\text{II}} \cos \theta)]^{-1}$ and $E_{\gamma} = D_{\text{II obs}} \varepsilon_{\gamma}$. Note that in the case of radio galaxies, such as Cen A and NGC 1275, which are viewed at the range of the angles between 30° and 60°, the Doppler factor is at most of the order of $\sim 2$ (for 30° and $\Gamma_{\text{II}} = 3$) or $\sim 1.15$ (for 60° and $\Gamma_{\text{II}} = 1.12$), see Figure 2 for the dependence of the Doppler factor on the Lorentz factor of blob II for selected values of the observed angles. The radiation, produced within blob II, is in fact Doppler weakened for the Lorentz factors larger than $\sim 7$ in the case of the observation angle 30° and $\sim 1.7$ for the angle 60°. Therefore, the emission region in the jet (blob II), responsible for the high energy emission from radio galaxies, which are viewed at large angles $> 30^\circ$, has to move relatively slowly.

We assume that electrons in both blobs have the equilibrium spectra well described by the power-law function, i.e.,

$$dN_e/dE_e = A E_{\gamma}^{-\beta}, \quad (4)$$

where $A$ is the normalization coefficient. The spectral index, $\beta$, is linked to the spectral index of the synchrotron radiation produced in blob I by the well known relation $\beta = 2\alpha - 1$. So then, we assume that the spectral index of electrons does not change for blobs at different locations in the jet. In fact, this does not need to be the case. In the general case, different spectral indexes for the electron spectrum in blob I and blob II can be investigated as well.

The timescale of the $\gamma$-ray emission from blob II is determined by the variability timescale of the soft emission produced in blob I and by the dimensions of blob II. The first timescale is expected to be short since blob I is moving with the large Lorentz factor, i.e., $T_I \approx R_I/(cD_I) \approx 100 R_{14.5}/D_{4.5} \text{s}$, where the radius of the inner blob is $R_I = 3 \times 10^{13} R_{14.5} \text{cm}$, the Doppler factor of blob I is $D_I = [\Gamma_I(1 - \beta_I)]^{-1} = 100 D_{100}$, and $\Gamma_I$ and $\beta_I$ are the Lorentz factor and the velocity of blob I. The radius of the blob is determined by its distance from the base of the jet. For the jet opening angle equal to 0.1 rad, the blob radius is an order of magnitude smaller than its distance from the jet base. The above estimated timescale variability is of the order of that observed in the BL Lacs such as Mrk 501 and PKS 2155-304. The second timescale depends on the Doppler factor of blob II, $D_{\text{II obs}}$. Its value, in the case of jets inclined at the angles above 30°, is not far from unity for mildly relativistic jets. The variability timescale of the $\gamma$-ray emission from blob II is of the order of the light crossing time through the dimensions of blob II, i.e., $T_{\text{II}} \sim R_I/(cD_{\text{II obs}})$. Therefore, blob II has to have rather small dimensions. In the case of NGC 1275, the GeV $\gamma$-ray emission has been observed to vary on the e-folding rise time 8.03 ± 0.24 hr and on the decay time of 1.21 ± 0.22 hr (Baghmamyan et al. 2017). This few-hours timescale variability corresponds to the dimensions of blob II, $R_{\text{II}} \sim (1.3-8.6) \times 10^4 D_{\text{II obs}} \text{cm}$, which is very close to the jet base, i.e., within 100 Schwarzschild radii of the SMBH for the jet with the opening angle of the order of degrees, or the GeV $\gamma$-ray emission comes from a different region in the jet, e.g., from blob I. However, the above estimates are...
becoming less extreme if the new measurements of the black hole mass in NGC 1275, \( \sim 3 \times 10^7 M_\odot \), are more realistic (Onori et al. 2017). Another solution of this variability crisis is the assumption of a much smaller inclination angle of the observer to the jet axis than that derived in the case of the parsec-scale jet in NGC 1275. Note, however, that such a short timescale variability has not been reported during the period of MAGIC observations at sub-TeV \( \gamma \)-ray energies (and also in the analysis of the simultaneous data from the Fermi-LAT instrument) when only a hint of variability is observed on a monthly timescale (Aleksić et al. 2014a). This longer timescale variability corresponds to the size of the stationary emission region of the order of \( R \sim 8 \times 10^{16} \) cm.

### 3. \( \gamma \)-Ray Spectra from Blob II

In the considered scenario, the fast inner blob I produces radiation collimated along the jet axis. The soft energy part of this beamed radiation from blob I (the synchrotron part) is Comptonized by electrons in blob II. At first, we investigate the angular dependence of the IC \( \gamma \)-ray emission from blob II. It is expected that the essential part of this radiation is emitted at large angles with respect to the jet axis due to the geometry of the IC process occurring in blob II (the isotropically distributed relativistic electrons and the monodirectional soft radiation arriving from blob I, see details of the IC scattering process for such a scattering geometry considered by Aharonian & Atoyan 1981). The spectrum of soft photons is assumed to be of the power-law type with the spectral index \( \alpha \) and arbitrary normalization. As an example, we show the distribution of \( \gamma \)-rays with energy of 1 TeV, produced by electrons with the mono-energetic spectrum at energy equal to 10 TeV, in the blob II reference frame (see Figure 3(a)). These calculations have been performed by integrating Equation (3) with the electron spectrum given by the Dirac delta function. As expected, there is a clear deficit of \( \gamma \)-ray emission in the direction along the jet since soft photons arrive to blob II exactly from this direction (see Figure 1). This deficit is larger for the soft radiation with the flatter spectrum; see the results for \( \alpha = 1.3 \) (dashed curve) and 1.8 (solid). After transformation to the observer’s reference frame, the \( \gamma \)-ray emission shows the maximum at a specific angle that depends on the Lorentz factor of the blob II. It is close to \( \sim 11^\circ \) for \( \Gamma_II = 3 \). It moves to \( \sim 18^\circ \) for \( \Gamma_II = 2 \), and to \( \sim 57^\circ \) for \( \Gamma_II = 1.1 \) for \( \alpha = 1.3 \) (Figure 3(b)). These optimal angles are shifted to \( 13^\circ , 21^\circ , 5, \) and \( 70^\circ \) for \( \alpha = 1.8 \), respectively (Figure 3(c)). Note that the highest level of the \( \gamma \)-ray emission in the range of the observation angles between \( 30^\circ \) and \( 60^\circ \), i.e., the range of angles derived for the radio galaxies Cen A and NGC 1275, is observed for the Lorentz factor of blob II close to \( \Gamma_II = 2 \). Therefore, the \( \gamma \)-ray emission observed in these radio galaxies has to originate in relatively slowly moving emission regions. For the comparison, we also show the angular distribution of the \( \gamma \)-ray emission in the observer’s reference frame in the case of the isotropic soft radiation field and relativistic electrons in blob II (see the thin curves in Figures 3(b) and (c)). These two distributions are normalized at the angle \( \theta = 10^\circ \), which is considered as the transition angle for which the AGN is classified either as the BL Lac type or the radio galaxy. Note the clear differences in the angular distribution of the \( \gamma \)-ray emission between the anisotropic model considered here (thick curves) and the fully isotropic IC model (thin curves). External blob radiation model produces \( \gamma \)-rays, which are clearly more preferentially emitted at large angles to the jet axis.

The \( \gamma \)-ray spectra produced in blob II are investigated more systematically in the blob II reference frame in Figure 4. We show how the \( \gamma \)-ray spectra depend on different parameters describing this model such as the maximum energies of electrons injected with the power-law spectrum (Figure 4(a)), spectral index of electrons (Figure 4(b)), different low energy cutoffs in the soft synchrotron spectrum arriving at blob II from blob I (Figure 4(c)), and different emission angles in the blob II reference frame (Figure 4(d)). In these calculations, we assume that electrons are accelerated with the power-law spectrum. Their spectral index, \( \beta \), is related to the spectral index of the soft synchrotron radiation, \( \alpha \), according to \( \beta = 2\alpha - 1 \). The spectra of soft photons are normalized to 1 MeV cm\(^{-3}\) (Equation (2)) and the spectra of relativistic electrons to the energy of 1 MeV. The dependence of the \( \gamma \)-ray spectra on the maximum electron energy and on the spectral indexes of soft photons and electrons look quite straightforward. Note that the low energy cutoff in the soft photon spectrum has a strong influence on the break in the \( \gamma \)-ray spectrum (Figure 4(c)). If the low energy soft photons are not present, then even energetic electrons cannot produce the high energy \( \gamma \)-rays due to
The spectrum of the monodirectional soft radiation from the inner blob II. The soft radiation has the simple power-law spectrum with spectral index $\alpha$ between $E_{\text{min}}$ and $E_{\text{max}}$. Normalized to 1 MeV. We assume that soft photons are produced by electrons in the synchrotron process. Electrons in both blobs are accelerated in a similar way. (a) SED as a function of the maximum energy of relativistic electrons, $E_{\text{max}} = 10^3$ MeV (solid), $10^5$ MeV (dashed), $10^6$ MeV (dotted–dashed), $10^7$ MeV (dotted), (b) for different spectral indexes of soft photons, $\alpha = 2.5$ (solid), 2.01 (dashed), 1.5 (dotted–dashed), and 1 (dotted), (c) for different low energy cutoffs in synchrotron spectrum, $E_{\text{min}} = 10^{-1.5}$ MeV (solid), $10^{-10}$ MeV (dashed), $10^{-8}$ MeV (dotted–dashed), $10^{-6}$ MeV (dotted), $10^{-4}$ MeV (dotted–dashed), and (d) for different emission angles of the $\gamma$-ray photons in the blob II reference frame, $\theta = 180^\circ$ (solid), $90^\circ$ (dashed), $45^\circ$ (dotted–dashed), $20^\circ$ (dotted–dashed), and $10^\circ$ (dotted). Unless specified differently, the other parameters of the model are $\alpha = 1.75$, $\beta = 90^\circ$, $E_{\text{min}} = 10$ MeV, $E_{\text{max}} = 3 \times 10^7$ MeV, $\varepsilon_{\text{min}} = 10^{-10}$ MeV, and $\varepsilon_{\text{max}} = 0.01$ MeV. The spectrum of the monodirectional soft radiation is defined by Equations (1) and (2) with the photon flux at the observer normalized to 1 MeV cm$^{-2}$.

In order to perform more realistic calculations of the $\gamma$-ray spectra expected in such a model, we fix the spectrum of the soft emission from blob I. It is assumed to be similar to that observed in classical BL Lacs. As an example, we apply the level of the synchrotron spectrum observed during one of the flares in Mrk 501, i.e., its isotropic equivalent soft radiation luminosity is $10^{45}$ erg s$^{-1}$ and the spectrum is described by Equations (1) and (2). The spectral index of this emission is approximated by $\alpha = 1.6$. The spectral index, $\beta$, of the power-law spectrum of isotropic electrons is assumed to be linked to the spectrum of soft photons as expected in the synchrotron process, i.e., $\beta = 2\alpha - 1$. The example calculations of the $\gamma$-ray spectra produced in blob II are shown in Figure 5. In general, the SED of produced $\gamma$-rays is shaped by the three competing effects. First, the soft radiation field produced in blob I and detected in the case of the observer located on the jet axis (the BL Lac type emission), is reduced by the Doppler factor $D_{\text{II,obs}} = \left[\Gamma_\text{II}(1 - \beta_\text{II} \cos\theta)\right]^{-1}$ since this monodirectional radiation approaches blob II from behind, i.e., from the base of the jet. Second, the upscattering of the monodirectional soft photons by the isotropic relativistic electrons in the blob II reference frame occurs strongly anisotropically, i.e., preferentially in the direction of upcoming soft photons consistent with the direction of propagation of blob I. This effect is responsible for the emission of $\gamma$-rays preferentially in the opposite direction to that of the motion of blob II. Third, the $\gamma$-rays from blob II are Doppler boosted with the Doppler factor $D_{\text{II,obs}} = \left[\Gamma_\text{II}(1 - \beta_\text{II} \cos\theta)\right]^{-1}$. This effect can either enhance the $\gamma$-ray fluxes in the observer’s reference frame or significantly reduce them, depending on the value of the observation angle, $\theta$, in the observer’s reference frame. The
combination of these three effects is responsible for the features of the γ-ray SED shown in Figure 5.

Note the interesting dependence of the spectra on the observation angle, θ, in the observer’s reference frame. In contrast to the homogeneous SSC (HSSC) model, the γ-ray spectra, produced in terms of our model, do not show maximum fluxes for the angle θ = 0° but for the specific range of angles, which is characteristic for the radio type galaxies (see spectra for the range of angles θ = 15°–30° in Figure 5(a)). Therefore, we conclude that such a model can explain more naturally the appearance of the high energy γ-ray emission from the radio galaxies that are viewed at relatively large angles. The γ-ray spectra produced in our model do not behave systematically also on the change of the Lorentz factor of blob II (see Figure 5(d)). The largest γ-ray fluxes are expected for the intermediate values of the Lorentz factors of the emission region (blob II) of the order of ΓII = 2–3. Therefore, the optimal conditions for the γ-ray emission at large angles are provided by the blobs moving with the intermediate Lorentz factors. Then, the Doppler factors characterizing such blobs obtain the optimal values as already discussed above (see Figure 2). On the other hand, dependence of the γ-ray SED on other parameters is more systematic. For example, the spectra show simple dependence on the spectral index of the soft radiation and the relativistic electrons (see Figure 5(b)) and on the maximum energy in the spectrum of relativistic electrons (see Figure 5(c)).

4. Interpretation of NGC 1275

NGC 1275 is the radio galaxy in the Perseus cluster, which hosts an SMBH with the mass of ~(3.4–8) × 10⁸ M☉ (Wilman et al. 2005; Scharwächter et al. 2013). The observed isotropic equivalent luminosity in the soft radiation observed from NGC 1275 is of the order of 4πd²_{L} F(ε) = 1.5 × 10^{44} erg s⁻¹, where the luminosity distance to NGC 1275 is assumed to be 70 Mpc for the redshift z = 0.017559 (see NED: http://ned.ipac.caltech.edu/ and Figure 6 on the left). However, this emission is emitted at a relatively large angle to the jet axis, i.e., θ = 30°–50°. Due to the beaming effects, the synchrotron emission from the inner blob I is expected to be larger in the direction along the jet axis, i.e., comparable to that observed in BL Lac type AGNs observed along the jet. According to our model, this soft photon emission along the jet axis serves as a target for the relativistic electrons in the outer blob II. As an example, we perform the calculations of the γ-ray emission from blob II, assuming that the isotropic equivalent power in the soft radiation field, as observed along the jet axis, is in the range of 3 × 10^{55}–10^{56} erg s⁻¹. For this power, we obtain the density of the soft photons in blob II by using Equation (2) and assuming that blob II is at a distance of 3 × 10^{16} cm or 3 × 10^{17} cm from the base of the jet. The spectral index of this soft radiation has been fixed on α = 2 between ε_{min} = 10^{-8} MeV and ε_{max} = 10^{-5} MeV in order to be consistent with the observations of NGC 1275 (see NED: http://ned.ipac.caltech.edu/). Note that the soft synchrotron spectrum in NGC 1275 also extends outside the energy range determined by ε_{min} and ε_{max} (although with different spectral indexes). We have checked that the scattering of the soft radiation field outside the energy range ε_{min} and ε_{max} by relativistic electrons has only a minor effect on the γ-ray spectrum. We perform the example calculations of the γ-ray spectra assuming two limiting values for the observation angles of the jet in NGC 1275, i.e., θ = 30° and 50°.

These γ-rays have to propagate through the synchrotron radiation field produced by electrons within blob II. In order to find out whether their absorption is important, we calculate the optical depths for the γ-rays in the radiation field of the homogeneous blob II. Unfortunately, the low energy bump in the NGC 1275 spectrum is poorly constrained by the observations. We apply the Planck data, the optical KVA, and Chandra observations, which are nearly simultaneous with the MAGIC and Fermi-LAT observations as reported in Figure 10 in Aleksić et al. (2014a). The optical depths are calculated following the procedure and the standard formula shown in Section 2.2 in Bednarek & Protheroe (1999), see also Dondi & Ghisellini (1995). They are shown in Figure 6 for the radius of blob II equal to 3 × 10^{15} cm, and two values of the the Doppler factor of blob II equal to D_{ blobs} = 2 and 1.3. We also show the soft radiation field produced within blob II for which these optical depths have been obtained. It is clear that the absorption effects in the soft radiation field of blob II has to be taken into account for the case of blob II with the radius equal to 3 × 10^{15} cm. Note that the optical depth is inversely proportional to the radius of the blob. Therefore, for blob II with the radius 3 × 10^{16} cm, the absorption effects become much smaller. We include the absorption effects on the γ-ray spectra,
produced in the homogeneous blob II, by introducing the reduction factor equal to \( R(E_{\gamma}) = \{1 - \exp[-\tau(E_{\gamma})]\}/\tau(E_{\gamma}) \).

In fact, produced \( \gamma \)-rays might also be absorbed in the soft radiation field from blob I. It is expected that this absorption plays a minor role in the absorption process of \( \gamma \)-rays due to the geometry of this radiation, i.e., monodirectional distribution approaching from the direction behind blob II. The threshold condition for the \( \gamma-\gamma \) absorption is clearly larger, i.e., \( \varepsilon > 2m_e^2c^4/E_{\gamma}/(1 - \cos \theta_{\text{abs}}) \), where \( m_e \) is the electron rest energy. For the observation angle \( \theta_{\text{obs}} = 30^\circ \), the threshold is 7.5 larger and results in the reduced density of soft photons from blob I by a factor of \( \sim(7.5)^2 \sim 55 \), assuming the soft differential power-law spectrum with the index \( -2 \). Correspondingly, for the angle \( \theta_{\text{obs}} = 50^\circ \), this factor becomes \( \sim(2.8)^2 \sim 7.8 \). Therefore, we conclude that the absorption effects of \( \gamma \)-rays in the soft radiation from blob I should usually be less important than the absorption of \( \gamma \)-rays in the soft radiation produced within blob II.

The \( \gamma \)-ray spectra, produced in the case of small \( R = 3 \times 10^{15} \text{ cm} \) and \( z = 3 \times 10^{16} \text{ cm} \) and large \( R = 3 \times 10^{16} \text{ cm} \) and \( z = 3 \times 10^{17} \text{ cm} \) blob II are shown in Figure 7. A good description of the NGC 1275 \( \gamma \)-ray spectrum is obtained in the case of a small blob II for the observation angles closer to \( \theta \sim 30^\circ \) provided that the total energy in the relativistic electrons in blob II is of the order of a few \( 10^{47} \text{ erg} \) (see Figure 6 on the left and Table 1). This total energy is obtained from the formula

\[
U_{\gamma} = \int_{E_{\gamma_{\text{min}}}^{E_{\gamma}}} dN_\gamma \frac{dE_\gamma}{dE_\gamma} E_\gamma dE_\gamma,
\]

where the normalization constant \( A \) obtained from the comparison of the observed \( \gamma \)-ray spectrum from NGC 1275 with the spectrum calculated in terms of our model for the normalization of the constant \( A \) equal to unity, and \( E_{\gamma_{\text{min}}} \) and \( E_{\gamma_{\text{max}}} \) are the applied minimum and maximum energies of relativistic electrons. The electron spectrum is assumed to be well described by a single power law up to TeV energies. The change in the observed sub-TeV \( \gamma \)-ray spectrum is due to the absorption in the soft radiation from blob II. The spectral index of the electron spectrum is related to the spectral index of the soft synchrotron radiation \( \beta = 2\alpha - 1 = 3 \). However, the absorption effects in the \( \gamma \)-ray spectrum calculated for the small blob II and the observation angle \( \theta \sim 30^\circ \) are too strong to describe the \( \gamma \)-ray spectrum from NGC 1275 (Figure 7). In the case of the large blob II, located at a larger distance from the base of the jet, the absorption effects are too low to explain the change of the spectral behavior in the GeV–TeV energy range. Therefore, we consider the scenario in which the spectral change in the \( \gamma \)-ray spectrum is due to the acceleration of

| Model | Large Blob II | Small Blob II |
|-------|--------------|--------------|
| \( R \) | \( 3 \times 10^{16} \text{ cm} \) | \( 3 \times 10^{17} \text{ cm} \) |
| \( z \) | \( 3 \times 10^{16} \text{ cm} \) | \( 3 \times 10^{17} \text{ cm} \) |
| \( L_{\gamma} \) | \( 10^{46} \text{ erg s}^{-1} \) | \( 3 \times 10^{45} \text{ erg s}^{-1} \) |
| \( \theta = 30^\circ \) | \( 1.2 \times 10^{10} \text{ erg} \) | \( 4 \times 10^{10} \text{ erg} \) |
| \( B \) | \( 5 \text{ G} \) | \( 27 \text{ G} \) |
| \( \theta = 35^\circ \) | \( 10^{48} \text{ erg} \) | \( 17 \text{ G} \) |
| \( \theta = 50^\circ \) | \( 4.7 \times 10^{49} \text{ erg} \) | \( 2.5 \text{ G} \) |

Figure 7. Interpretation of the \( \gamma \)-ray SED observed from the radio galaxy NGC 1275 by the \( \gamma \)-ray spectra expected in terms of the small (right figure) and large (left figure) external blob radiation model. In the small blob model, the SED is described by the spectra calculated for the angle \( \theta = 35^\circ \), the Lorentz factor of blob I \( \Gamma_{\gamma} = 1.7 \), with the absorption effects included as described in the main text (thick solid curve). The spectrum before absorption in the blob II radiation is shown by the thin solid curve. The spectra obtained for the angles \( \theta = 30^\circ \) and \( 35^\circ \) (and \( \Gamma_{\gamma} = 2 \) and \( \Gamma_{\gamma} = 1.5 \)) are shown by the thin dotted and dashed curves, respectively. In the large blob II model, the SED is well described by the \( \gamma \)-ray spectra, including moderate absorption, for the range of the observation angles between \( \theta = 30^\circ \) and \( 50^\circ \) (thick solid and dashed curves). The unabsorbed spectra are shown by the thin solid and dashed curves. The Lorentz factor of blob II is equal to \( \Gamma_{\gamma} = 2 \) (for \( \theta = 30^\circ \)), \( \Gamma_{\gamma} = 2 \) (for \( \theta = 30^\circ \)), and 1.5 (for \( \theta = 50^\circ \)). The spectrum of the soft synchrotron radiation, emitted along the jet axis, is of the power-law type with the spectral index \( \alpha = 2 \) in the energy range \( E_{\gamma_{\text{min}}} = 10^{-8} \text{ MeV} \) and \( E_{\gamma_{\text{max}}} = 10^{-7} \text{ MeV} \). Its isotropic equivalent luminosity of the soft radiation is equal to \( 3 \times 10^{45} \text{ erg s}^{-1} \) for the small blob model and to \( 10^{48} \text{ erg s}^{-1} \) in the large blob model. The spectrum of electrons (in the blob frame) is also of the power-law type, with the spectral index linked to the spectral index of the soft radiation by \( \beta = 2\alpha - 1 \), above \( E_{\gamma_{\text{min}}} = 2 \text{ MeV} \). In the large blob model, the electron spectrum extends to \( E_{\gamma_{\text{max}}} = 300 \text{ GeV} \) and \( 500 \text{ GeV} \) for the angles \( \theta = 30^\circ \) and \( 50^\circ \) and in the small blob model up to \( E_{\gamma_{\text{max}}} = 10 \text{ TeV} \). The required energy in relativistic electrons is reported in Table 1.
electrons to only sub-TeV energies. With such an assumption, the γ-ray spectrum from NGC 1275 can be well explained for the range of the observation angles, $\theta = 30° - 50°$ (see Figure 7 on the left). However, the requirement on the energy in relativistic electrons, i.e., a few $10^{49}$ erg, is more restrictive (see Table 1). However, even such large total energy in electrons in blob II seems to be acceptable, keeping in mind that NGC 1275 emits $\sim 10^{44}$ erg s$^{-1}$ for the dynamical timescale of the emission in the jet of the order of $\sim z/c \sim 10^7$ s. Note that estimated total energy in relativistic electrons in blob II are anticorrelated with the assumed power in the soft synchrotron radiation and with the square distance of blob II from the base of the jet. We conclude that in the case of the large blob II the GeV–TeV γ-ray emission from the radio galaxy NGC 1275 can be well described by the external blob radiation model even if the jet is viewed by the observer at a relatively large angle to the jet axis.

We also calculate the magnetic field strength in terms of the considered models that is required in order to produce observable flux of the synchrotron bump. We apply the relativistic electrons with the total energy ($\gamma$) observable flux of the synchrotron bump. We apply the relativistic electrons with the total energy (and spectrum) reported in Table 1. The obtained values of the magnetic field strength are also reported in Table 1. For the considered models, the magnetic field strength should be in the range between $B = 2.5$ and 27 G. We conclude that in the case of the large blob II model, viewed at the angle of 50°, the energy density of the magnetic field is close to the equipartition to the energy density of relativistic electrons. In the case of other models, the energy density of the magnetic field dominates over the energy density of relativistic electrons. Therefore, magnetic energy can serve as a source of energy for the acceleration of electrons. Moreover, it is expected that the electrons are confined within the blob by the magnetic field.

The electrons in blob II should also produce γ-rays by Comptonizing soft radiation produced in blob II, i.e., in the synchrotron self-Compton (SSC) process. We calculate the γ-ray spectra produced in blob II in terms of the SSC model for these same parameters as considered in the case of the external blob radiation models with the small and large blob II. The example spectra are shown in Figure 7 for the small blob II observed at the angle $\theta = 35°$ (dotted–dashed curve) and for the large blob II at the angles $\theta = 30°$ (dotted–dashed) and $\theta = 50°$ (dotted–dashed). Our calculations show that the γ-ray spectra produced in terms of the external blob model clearly dominate over the γ-ray spectra produced within blob II in terms of the SSC model. This effect is due to the fact that the density of photons from blob I within blob II, calculated for the luminosity $3 \times 10^{45}$ and $10^{46}$ erg s$^{-1}$, is much stronger than the density of photons produced within blob II (the observed luminosity of the NGC 1275 $\sim 1.5 \times 10^{44}$ erg s$^{-1}$).

5. Conclusion

We propose an external blob radiation model for the high energy emission from the FR I radio galaxies, which are supposed to be viewed by the observer at a large angle with respect to the jet propagation. In this model, the isotropically distributed relativistic electrons in the outer blob II upscatter monodirectional soft radiation produced in the inner blob I. As a result of such specific scattering geometry (see for details Aharonian & Atoyan 1981), the angular distribution of the γ-ray photons does not peak at the jet axis. This is in contrast to the predictions of the HSSC single blob models in which case electrons and soft synchrotron photons are isotropic in the blob reference frame. In the HSSC model, the strongest radiation is emitted along the jet axis due to the dominant Doppler boosting effect. On the other hand, it is considered here that the geometric model predicts the strongest radiation at some angle to the jet axis that depends not only on the Doppler boosting effect but also on the angular distribution of high energy emission in the blob II reference frame (see Figures 3 and 4). We investigate the basic features of the high energy radiation as a function of the parameters describing the spectra of soft photons and relativistic electrons, the Lorentz factor of blob II, and the location of the external observer with respect to the jet (Figure 5). We conclude that the calculated γ-ray spectra depend in a systematic way on the parameters describing the spectra of soft radiation and relativistic electrons, but depend in a nonsystematic way on the observation angle of the jet and the Lorentz factor of blob II.

We show that such a model can naturally explain the high energy emission observed from radio galaxies, which are expected to be observed at large inclination angle to the jet axis. As an example, we interpret the emission from the FR I radio galaxy, NGC 1275, which is supposed to be viewed at the angle in the range of $\sim (30° - 50°)$ (Figure 6). We conclude that the spectrum observed simultaneously by the Fermi-LAT and the MAGIC telescopes, in the GeV–TeV energy range, can be well described for the reasonable power in the low energy soft photons emitted from blob I, equal to the isotropic equivalent synchrotron power of the order of a few $10^{45}$ erg s$^{-1}$. Such emission power is within the range of the powers (a few $\sim 10^{45}$–$10^{46}$ erg s$^{-1}$) observed from the BL Lac type objects, e.g., Mrk 501 (Ahnen et al. 2017), Mrk 421 (Aleksić et al. 2012b), or PKS 2155-304 (Aharonian et al. 2009; Abramowski et al. 2012). In the case of a relatively small optically thick blob ($R = 3 \times 10^{15}$ cm), the total energy in the relativistic electrons in blob II, able to explain the γ-ray emission from NGC 1275, should be equal to $\sim 10^{48}$ erg, for the viewing angles not far from $\sim 30°$. However, the absorption effects for the small blob II viewed at the angle of 50° are too strong to provide a correct description of the NGC 1275 spectrum. In the large blob II model, the absorption effects are small enough to provide a correct description of the observed spectrum for the whole range of the observation angles $30° - 50°$. However, in this case, the energy in relativistic electrons should be much larger, i.e., of the order of a few $10^{49}$ erg, which is still acceptable in the case of blobs in jets of AGNs.

Finally, we note that the model proposed here shows general similarities to the external disk model developed in Dermer et al. (1992) and Dermer & Schlickeiser (1993). In the Dermer and Collaborators model, the radiation from the accretion disk has to dominate over the radiation produced in the inner part of the jet (e.g., inner blob). Such a situation is expected in the case of OVV type blazars as seen out of the axis. Our model is more suitable for the radio galaxies in which case the disk emission is typically on a low level. Then, the scattering of radiation produced in the inner blob by electrons in the outer blob can likely dominate.

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References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009a, ApJ, 707, 55
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009b, ApJ, 699, 31
Abramowski, A., Acero, F., Aharonian, F., et al. 2012, A&A, 539, 149A
Acciari, V. A., Aliu, E., Arlen, T., et al. 2009, Sci, 325, 444
Aharonian, F. A., & Atoyan, A. M. 1981, Ap&SS, 79, 321
Aharonian, F., Akhperjanian, A., Beilicke, M., et al. 2003, A&A, 403, L1
Aharonian, F., Akhperjanian, A. G., Anton, G., et al. 2009, A&A, 502, 749
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2007, ApJL, 664, L71
Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al. 2017, A&A, 603, 31A
Ait Benkhali, F., Chakraborty, N., & Rieger, F. M. 2018, A&A, in press (arXiv:1802.03103)
Albert, J., Aliu, E., Anderhub, H., et al. 2007, ApJ, 669, 862
Albert, J., Aliu, E., Anderhub, H., et al. 2008, ApJL, 685, L23
Aleksić, J., Alvarez, E. A., Antonelli, L. A., et al. 2012a, A&A, 539, L2
Aleksić, J., Alvarez, E. A., Antonelli, L. A., et al. 2012b, A&A, 542, 100A
Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2014a, A&A, 564, A5
Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2014b, Sci, 346, 1080A
Aliu, E., Arlen, T., Aune, T., et al. 2012, ApJ, 746, 141
Ansoldi, S., Antonelli, L. A., Arcaro, C., et al. 2018, A&A, in press (arXiv:1806.01559)
Baghmanyan, V., Gasparian, S., & Sahakyan, N. 2017, ApJ, 848, 111
Barkov, M. V., Aharonian, F. A., & Bosch-Ramon, V. 2010, ApJ, 724, 1517
Bednarek, W., & Protheroe, R. J. 1997, MNRAS, 287, L9
Bednarek, W., & Protheroe, R. J. 1999, MNRAS, 310, 577
Begelman, M. C., Fabian, A. C., & Rees, M. J. 2008, MNRAS, 384, L19
Biretta, J. A., Parks, W. B. S., & Acchetto, F. M. 1999, ApJ, 520, 621
Blandford, R. D., & McKee, C. F. 1976, PhFl, 19, 1130
Brown, A. M., & Adams, J. 2011, MNRAS, 413, 755
Brown, A. M., BAhm, C., Graham, J., et al. 2017, PhRvD, 95, 063018

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