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DEGREE-SCALE GeV "JETS" FROM ACTIVE AND DEAD TeV BLAZARS

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ABSTRACT

We show that images of TeV blazars in the GeV energy band should contain, along with point-like sources, degree-scale jet-like extensions. These GeV extensions are the result of electromagnetic cascades initiated by TeV γ-rays interacting with extragalactic background light and the deflection of the cascade electrons/positrons in extragalactic magnetic fields (EGMFs). Using Monte Carlo simulations, we study the spectral and timing properties of the degree-scale extensions in simulated GeV band images of TeV blazars. We show that the brightness profile of such degree-scale extensions can be used to infer the light curve of the primary TeV γ-ray source over the past 10^7 yr, i.e., over a time scale comparable to the lifetime of the parent active galactic nucleus. This implies that the degree-scale jet-like GeV emission could be detected not only near known active TeV blazars, but also from "TeV blazar remnants," whose central engines were switched off up to 10 million years ago. Since the brightness profile of the GeV "jets" depends on the strength and the structure of the EGMF, their observation provides additional information about the EGMF.

Key words: galaxies: active – galaxies: jets – gamma rays: galaxies – methods: numerical

Online-only material: color figures

1. INTRODUCTION

Significant progress in understanding the activity of blazars, i.e., active galaxies with relativistic jets aligned with the line of sight (LOS), was achieved with the start of operation of the *Fermi* telescope. The combination of data from *Fermi* in the 0.1–10 GeV energy band and from ground-based γ-ray telescopes such as HESS, MAGIC, and VERITAS in the 100 GeV–10 TeV band provides detailed simultaneous spectral and timing information for the most extreme representatives of the blazar population (Abdo et al. 2009).

The TeV γ-ray flux from distant blazars is significantly attenuated by pair production on the infrared/optical extragalactic background light (EBL; Kneiske et al. 2004; Stecker et al. 2006; Franceschini et al. 2008; Primack et al. 2008). TeV γ-rays that are absorbed on the way from the primary γ-ray source initiate electromagnetic cascades in the intergalactic space. The charged component of the electromagnetic cascade is deflected by the extragalactic magnetic field (EGMF). Potentially observable effects of such electromagnetic cascades in the EGMF include the "echoes" of multi-TeV γ-ray flares (Plaga 1995; Murase et al. 2008) and the appearance of extended emission around initially point-like γ-ray sources (Aharonian et al. 1994; Neronov & Semikoz 2007; Dolag et al. 2009; Elyiv et al. 2009).

TeV γ-ray emission from blazars is believed to be relativistically beamed into a narrow cone (jet) with an opening angle $\Theta_{\rm jet} \sim \Gamma^{-1} \sim 5^\circ[\Gamma/10]$, where Γ is the bulk Lorentz factor of the γ-ray emitting plasma. Blazars are a special type of γ-ray emitting active galactic nuclei (AGNs) for which the angle between the LOS and the jet axis, $\theta_{\rm obs}$, is $\theta_{\rm obs} \lesssim \Theta_{\rm jet}$; see Figure 1 (Urry et al. 1991).

In general, the number of blazars with a given jet-LOS misalignment angle is expected to scale as $dN/d\theta_{\rm obs} \sim \theta_{\rm obs}$ in the range $0 < \theta_{\rm obs} \leqslant \Theta_{\rm jet}$. Thus most observed TeV blazars should have $\theta_{\rm obs} \sim \Theta_{\rm jet}$, rather than $\theta_{\rm obs} \simeq 0$. Consequently, the TeV γ-ray emission pattern is not symmetric with respect to the axis source observer. In sources with $\theta_{\rm obs} \sim \Theta_{\rm jet}$, most multi-TeV γ-rays are preferentially emitted on one side of the LOS, as is shown in Figure 1. As a result, the extended emission from the cascade initiated by the absorption of TeV γ-rays in interactions with EBL photons should appear as a one- or two-sided jet-like extension next to the primary point source (Aharonian 2004), rather than as a previously discussed extended axially symmetric halo (Aharonian et al. 1994; Neronov & Semikoz 2007, 2009; Dolag et al. 2009; Elyiv et al. 2009).

In what follows, we discuss the spectral and timing properties of such jet-like cascade extensions in the 0.1–1 GeV images of TeV blazars. Our study is based on two independent Monte Carlo codes for γ-ray induced electromagnetic cascades in the intergalactic space, introduced by Dolag et al. (2009) and Elyiv et al. (2009).

2. BASIC FORMULAE

Before presenting our numerical results, we discuss the basic physics of the phenomenon in a simplified picture. In particular, we assume that the electromagnetic cascade consists of two steps only and replace probability distributions by their means. Then the mean free path of very high energy γ-rays through the EBL can be approximated by $D_\gamma(E_{\gamma_0}) = \kappa[E_{\gamma_0}/1\ \mathrm{TeV}]^{-1}$ Gpc, where the numerical factor $\kappa = \kappa(E_{\gamma_0}, z) \sim \mathcal{O}(1)$ includes the uncertainties of the EBL modeling. Pair production on EBL reduces the flux of γ-rays from the source by a factor $\exp[-\tau(E_{\gamma_0})]$, where $\tau \simeq D/D_\gamma$ is the optical depth with respect to pair production and D is the distance to the source.

Electron–positron pairs created in interactions of multi-TeV γ-rays with EBL photons produce secondary γ-rays via inverse Compton (IC) scattering on cosmic microwave background

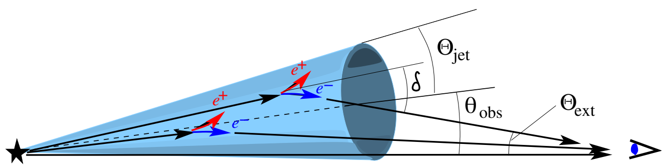

Figure 1. Geometry of the propagation of direct and cascade γ-rays from the source (on the left) to the observer (on the right).

(A color version of this figure is available in the online journal.)

(CMB) photons. Typical energies of the IC photons reaching the Earth are $E_\gamma = (4/3)\epsilon_{\rm CMB} E_e^2/m_e^2 \simeq 0.8[E_{\gamma_0}/1\text{ TeV}]^2$ GeV, where $\epsilon_{\rm CMB} = 6 \times 10^{-4}$ eV is the typical energy of CMB photons.

Deflections of e^+e^- pairs produced by the γ-rays, which were initially emitted away from the observer, can redirect secondary photons toward the observer. This effect leads to the appearance of extended emission around an initially point source of γ-rays (Neronov & Semikoz 2007; Dolag et al. 2009; Elyiv et al. 2009).

In the absence of perfect alignment of the jet axis with the LOS, the extended cascade emission might be strongly asymmetric. It might appear as a jet-like feature next to the primary γ-ray source. The maximal angular size of this jet-like feature can be estimated as the size of the projected γ-ray mean free path as $\Theta_{\rm ext,max} \simeq D_\gamma\theta_{\rm obs}/(D - D_\gamma)$, if $D_\gamma < D$ (i.e., $\tau > 1$). If $\tau(E_{\gamma_0}) < 1$, the cascade emission from the TeV γ-ray beam can extend to very large angles $\Theta_{\rm ext,max} \sim \pi/2$.

The jet-like extended emission can be observed only if deflections of the cascade e^+e^- pairs are sufficiently large to redirect the cascade emission toward the observer. If the correlation length of the EGMF is larger than the electron cooling distance $D_e = 3m_e^2c^3/(4\sigma_T U_{\rm CMB} E_e) \simeq 0.7[E_e/0.5\text{ TeV}]^{-1}$ Mpc, where σ_T denotes the Thomson cross section and $U_{\rm CMB}$ the energy density of the CMB photons, then the deflection angle can be estimated as (Neronov & Semikoz 2009) $\delta = D_e/R_L \simeq 3^\circ[B/10^{-17}\text{ G}][E_e/0.5\text{ TeV}]^{-2}$ with R_L being the Larmor radius of electrons and positrons.

If the correlation length λ_B of the EGMF is much smaller than the electron cooling distance D_e, the deflection angle can be estimated using the diffusion approximation as $\delta = \sqrt{D_e\lambda_B}/R_L \simeq 3^\circ[E_e/0.5\text{ TeV}]^{-3/2}[B/10^{-17}\text{ G}][\lambda_B/0.7\text{ Mpc}]^{1/2}$. If the EGMF is weak, electron/positron trajectories are not strongly deflected during one cooling time, and thus secondary cascade γ-rays are emitted within a cone with an opening angle of order $\mathcal{O}(\delta)$. In this case, only a part of the cascade emission could be observed. If the mean free path of the primary γ-rays is much shorter than the distance to the source, the angular extension could be estimated from the simple geometrical consideration of Figure 1 as $\sin(\Theta_{\rm ext}(B)) = (D_\gamma/D)\sin\delta$. Otherwise, the angular size of the source is found from the sum of the angles of triangle with vertices at the source, at the pair production point and at the position of the observer (see Figure 1) as $\Theta_{\rm ext}(B) = \delta - \theta_{\rm obs}$.

Most of the known TeV blazars have moderate distances so that $\tau(E_{\gamma_0} = 1\text{ TeV}) \leqslant 1$. In this case, $\Theta_{\rm ext,max} \sim \pi/2$ and $\Theta_{\rm ext}(B) = \delta - \theta_{\rm obs}$. A measurement of $\Theta_{\rm ext} \ll \Theta_{\rm ext,max}$ thus provides a measurement of δ and, in this way, gives a constraint on the parameters of the EGMF, i.e., B and λ_B.

The difference in the path length between the direct and cascade γ-rays leads to a significant time delay of the cascade emission signal. For a given jet misalignment angle $\theta_{\rm obs}$, the time delay of emission coming from the direction θ away from the source is $T_{\rm delay} \sim \frac{D}{c}\left(\frac{\sin\theta+\sin(\theta_{\rm obs}+\Theta_{\rm jet})}{\sin(\theta+\theta_{\rm obs}+\Theta_{\rm jet})} - 1\right) \simeq \frac{D\theta(\theta_{\rm obs}+\Theta_{\rm jet})}{2c} \simeq 3 \times 10^6\left[\frac{(\theta_{\rm obs}+\Theta_{\rm jet})}{5^\circ}\right]\left[\frac{\theta}{5^\circ}\right]$ yr. Comparing this time scale with the typical time scale of AGN activity, $T_{\rm AGN} \sim 10^7$ yr, one sees that degree-scale extended emission in the GeV energy range depends on the TeV γ-ray luminosity of the blazar integrated over its lifetime.

3. RESULTS OF NUMERICAL MODELING

To model the asymmetric extended emission from the γ-ray-initiated electromagnetic cascade in intergalactic space, we have extended our two Monte Carlo codes such that they now follow the three-dimensional trajectories of individual cascade particles moving through the EGMF. The turbulent component of the EGMF has been calculated following the algorithm of Giacalone & Jokipii (1994).

To produce an image of the γ-ray-induced electromagnetic cascade, as it would be detected by a γ-ray telescope, we use the algorithm described by Elyiv et al. (2009). We have verified that the results obtained using the two different codes are compatible with each other.

We record positions and directions of all secondary γ-rays that cross a sphere of the radius $R = D$ around the source. We choose the directions of primary γ-rays to be distributed within a cone with an opening angle $\Theta_{\rm jet}$. We consider a primary γ-ray beam with a Gaussian profile, so that the probability for a primary γ-ray to have a direction misaligned by an angle Θ with respect to the jet axis is $p(\Theta) \sim \exp(-\Theta^2/\Theta_{\rm jet}^2)$.

For simplicity, we consider a monochromatic primary γ-ray beam with all the primary γ-rays having the same energy $E_{\gamma_0} = 1$ TeV. This is sufficient to demonstrate the existence of the effect discussed here for the first time, namely, degree-scale jet-like extensions in *Fermi* images of TeV blazars. The EBL background is taken from the calculations of Kneiske et al. (2004). We fix the distance to the source as $D = 400$ Mpc, so that $\tau(E_{\gamma_0}) \sim 1$. The EGMF is chosen to have a correlation length of the order of several Mpc, with its power spectrum sharply peaked at the wavenumber $k \simeq 1\text{ Mpc}^{-1}$. Our results could be generalized in a straightforward way to the case of an arbitrary primary γ-ray spectrum, arbitrary distance to the source and different EBL models, when considering extended emission from particular TeV blazars with known TeV band spectra and known redshift.

Figure 2 shows the effect of the misalignment of the primary γ-ray beam with the LOS on the morphology of the extended emission. The left panel of the figure corresponds to the situation $\theta_{\rm obs} = 0$, which is equivalent to the axially symmetric case considered by Dolag et al. (2009) and Elyiv et al. (2009). An axially symmetric extended "halo" around the primary point source is clearly visible. The other panels of the figure show the cases of a jet with an opening angle $\Theta_{\rm jet} = 3^\circ$ misaligned by angles $\theta_{\rm obs} = 3^\circ$, 6°, and 9°, respectively. It is clear that the misalignment of the jet axis with the LOS leads to the appearance of an extended jet-like feature on one side of the source. The ratio of the point source flux to the flux of the extension grows with the increase of the misalignment angle $\theta_{\rm obs}$.

The angular extension of the cascade emission depends on the strength of the EGMF as long as the trajectories of e^+e^- pairs are not completely randomized. The morphological properties of the jet-like emission are practically independent from the properties of the EGMF, when the EGMF strength is such that the deflection angle $\delta \geqslant 2\pi$. Figure 3 shows the growth of the source extension with the increase of the EGMF strength.

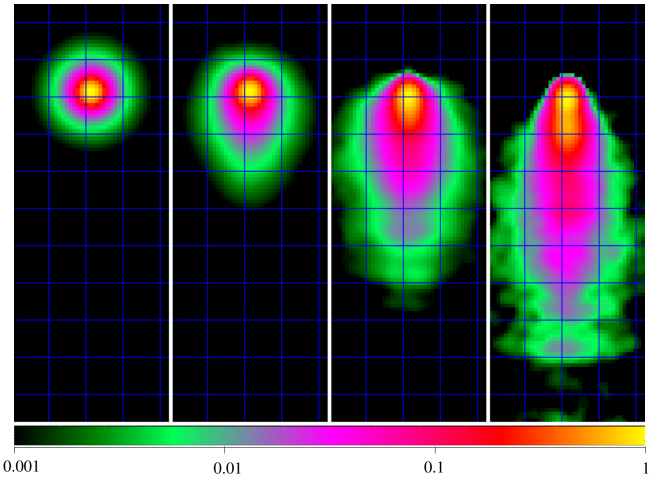

Figure 2. $E > 1$ GeV band images of the sky region around TeV blazars with jets inclined at $\theta_{\rm obs} = 0°$, $\theta_{\rm obs} = 3°$, $\theta_{\rm obs} = 6°$, and $\theta_{\rm obs} = 9°$ (left to right). The jet opening angle is $\Theta_{\rm jet} = 3°$ and the EGMF strength is $B = 10^{-16}$ G. The spacing of the coordinate grid is 2°; the color scale is logarithmic in surface brightness: yellow corresponds to the maximal surface brightness and black corresponds to the surface brightness less than 10^{-3} of the maximal value.

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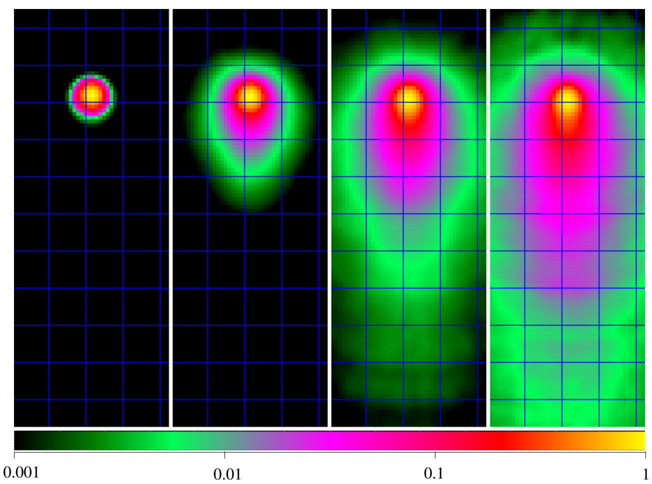

Figure 3. $E > 1$ GeV band images of the sky region around TeV blazars with $\Theta_{\rm jet} = \theta_{\rm obs} = 3°$ for different values of the EGMF strength. From left to right: 10^{-17} G, 10^{-16} G, 10^{-15} G, 10^{-14} G.

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For magnetic fields stronger than $B \sim 10^{-15}$ G, the size of the extended source reaches ten(s) of degrees. In this case, the extended source could significantly contribute to the diffuse γ-ray background.

Cascade emission coming from regions with angular distance $\theta \geqslant 1°$ to the primary source is delayed by $T_{\rm delay} \sim 10^5$–10^7 yr compared to the direct emission from the source. This means that "echoes" from periods of enhanced activity of the source (e.g., an enhanced accretion rate following major merger episodes), which happened all along the lifetime of an AGN some time T ago, could enhance the flux at the distance $\theta \simeq 1.^{\circ}7[T/10^6\ {\rm yr}][(\theta_{\rm obs} + \Theta_{\rm jet})/5°]$ from the source.

Figure 4 shows a time sequence of $E > 1$ GeV band images of the sky region around a TeV source at different times after a short episode of TeV γ-ray emission. One can clearly see that the emission at large angular distances is delayed by up to 10^7 yr.

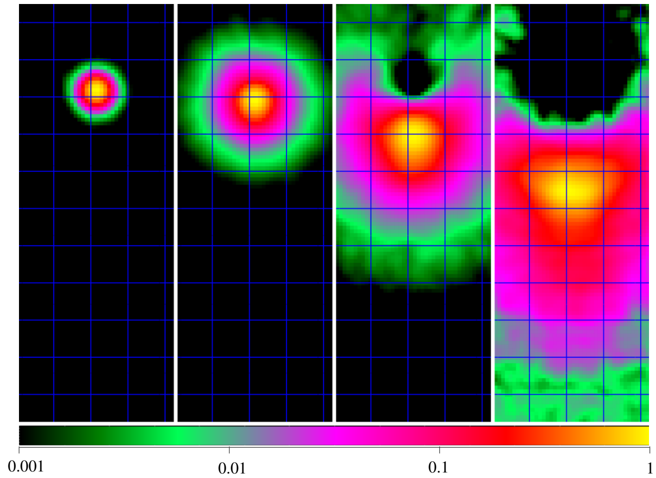

Figure 4. $E > 1$ GeV band images of the sky region around a TeV blazar with $\Theta_{\rm jet} = \theta_{\rm obs} = 3°$ at different times following instantaneous injection of 1 TeV γ-rays at the source. From left to right: images in time intervals $0 < T_{\rm delay} < 10^5$ yr, 10^5 yr $< T_{\rm delay} < 10^6$ yr, 10^6 yr $< T_{\rm delay} < 3 \times 10^6$ yr, and 3×10^6 yr $< T_{\rm delay} < 10^7$ yr after the outburst. $B = 10^{-16}$ G.

(A color version of this figure is available in the online journal.)

The flux coming from the region at an angular distance θ from the point source is proportional to the source flux averaged over the period $T_{\rm delay}$. Therefore, it is possible that GeV γ-rays are detectable today from an AGN which was active some 10^7 yr ago, but at present it is no longer active. In this case, a GeV source would be classified as "unidentified": the parent AGN (1) could not be identified as an AGN in the optical, X-ray, and TeV γ-ray bands or (2) the GeV source is displaced from the position of the parent AGN. The characteristic feature of such an unidentified "AGN remnant" is the absence of counterparts at lower energies: If the GeV γ-rays are produced by e^+e^- pairs deposited in the intergalactic medium by primary TeV γ-rays, the only energy loss mechanism for the pairs is IC scattering on CMB photons.

4. DISCUSSION

The presence of extended jet-like emission at degree scales should be a generic feature of GeV band images of TeV blazars. The total flux of the jet-like extended source is proportional to the source luminosity in the TeV energy band. Taking into account the fact that TeV blazars have hard γ-ray spectra, the primary source luminosity in the TeV band could be much larger than its GeV luminosity, so that the overall extended source luminosity could be higher than the primary source luminosity in the GeV band. This means that the best candidates for the search of extended emission are TeV blazars with hard intrinsic spectra.

This does not automatically mean that the extended emission should be readily detectable in *Fermi* images of TeV blazars. In spite of the larger luminosity, the extended source flux might be suppressed if the EGMF is strong enough to randomize the trajectories of e^+e^- pairs before they lose their energy to the GeV band via IC emission. The maximal possible suppression of the extended source flux is by a factor of $\Theta_{\rm jet}^{-2} \sim 100$.

Another potential problem for the detection of jet-like extended emission next to TeV blazars is that the extended source has to be identified on top of the diffuse γ-ray background. The minimal detectable flux for extended sources increases roughly as $\theta^{1/2}$, where θ is the angular length of the jet-like extended source. Thus, sources at larger distances, for which the jet-like extensions appear more compact, are better candidates for the search of extended emission in the *Fermi* energy band.

Finally, the detectability of extended emission close to TeV blazars strongly depends on the angular resolution of the Large Area Telescope (LAT). At low energies, $E_\gamma \sim 0.1$ GeV, the LAT angular resolution is relatively poor, $\theta_{\rm PSF} \simeq 10^\circ$. It is clear that only very large angular size jet-like extensions with an angular diameter $\theta \sim \theta_{\rm PSF}$ could be detected. However, the detectability of such large extended sources would be complicated by the high level of diffuse sky background within the $\sim 10^\circ$ region around the source. At the same time, the size of the point-spread function (PSF) decreases to $\theta_{\rm PSF} \leqslant 1^\circ$ above GeV energies. This dramatically improves the sensitivity of the telescope for the search of extended emission: extensions of much smaller angular size could be detected on top of a strongly reduced background. This favors the search of extended emission at energies above ~ 1 GeV.

As an example, we consider a blazar with the TeV band luminosity $L_0(E_{\gamma_0}) \sim 10^{43}$ erg s^{-1} beamed in a cone with an opening angle $\Theta_{\rm jet} = 3^\circ$, so that the equivalent isotropic luminosity of the source is $L_{\rm iso} \simeq 10^{45}$ erg s^{-1}. In the absence of absorption, the source would give a flux $F_{\rm iso,0} \simeq 10^{-10}[D/300 \text{ Mpc}]^{-2}$ erg (cm^2 s)$^{-1}$. At energies E_γ such that $\tau(E_{\gamma_0}) \geqslant 1$ the overall luminosity of the cascade emission is comparable to the primary source luminosity at energy E_{γ_0}, so that in the case of small EGMFs ($\delta \leqslant \Theta_{\rm jet}$), i.e., at the level of the lower bounds $B \sim 10^{-17}$–10^{-16} G derived from *Fermi* observations (Neronov & Vovk 2010; Tavecchio et al. 2010), the flux in the cascade is $F_{\rm cascade} \sim F_{\rm iso,0}$. In this case, the cascade emission is readily detectable in the GeV band by *Fermi*. In the opposite case, the cascade emission is completely isotropized and the cascade flux is suppressed by a factor of $1/\Theta_{\rm jet}^2 \sim 4 \times 10^2$, so that it is marginally below the minimal detectable flux for extragalactic *Fermi* point sources in the GeV band, $F_{\rm min} \sim 10^{-12}$ erg (cm^{2}s)$^{-1}$.

Thus, in the most pessimistic case jet-like extensions are detectable only for the brightest blazars with the observed steady-state flux at the level of $F_{\rm iso} \simeq \exp(-\tau)F_{\rm iso,0} \sim 3 \times 10^{-11}$ erg (cm^2 s)$^{-1}$ (assuming $\tau \simeq 1$). Only several extragalactic sources with sufficient steady-state flux are detected by *Fermi* above 100 GeV (Neronov et al. 2010a). Among these sources, 3C 66A, 1ES 0502+675, PG 1553+113, and, possibly, PKS 2155–304 are at sufficiently large redshifts for strong cascade emission in the GeV energy range. These sources should be considered as primary candidates for the search of the jet-like extended emission. By contrast, all sources with sufficiently high flux at few $\times$ 100 GeV (Neronov et al. 2010b) are viable candidates for the detection of the extended jet-like emission, if the EGMF is weak.

The number of detectable "blazar remnants" also strongly depends on the EGMF. If the EGMF is so weak that $T_{\rm delay} \ll T_{\rm AGN}$, blazar remnants would not exist, since cascade and direct emission would be observed together. If typical deflection angles of electrons emitting in the GeV band are several degrees ($B \sim 10^{-17}$ G for large λ_B), the number of blazar remnants observable in the GeV band should be comparable to the number of active TeV blazars, since $T_{\rm delay} \sim T_{\rm AGN}$. If the EGMF is much stronger, the number of potentially observable blazar remnants grows because the cascade emission is emitted in a wider cone than emission from the parent blazar. However, the typical flux of the blazar remnants decreases because of the same effect. Thus, for strong EGMFs, the number of blazar remnants above the *Fermi* sensitivity limit might be very small. The strong dependence of the observability of blazar remnants on the EGMF strength implies that constraints on the EGMF could be deduced from their source statistics.

To summarize, we have shown that GeV band images of TeV blazars should possess degree-scale jet-like extended features. These features trace the direction of the TeV γ-ray beam emitted by the blazar. They are produced as results of electromagnetic cascades initiated by TeV γ-rays interacting with EBL photons. We have performed Monte Carlo simulations of three-dimensional electromagnetic cascades developing in the EGMF. Using these Monte Carlo simulations, we have derived the properties of the GeV jet-like extended emission near TeV blazars. We have investigated the dependence of the characteristics of the jet-like extended sources (the angular size, the brightness profile) on the strength of the EGMFs and on the opening angle and orientation of the primary TeV γ-ray beam from the blazar. We have also demonstrated that the γ-ray signal in the jet-like extended emission is delayed up to 10^7 yr compared to the direct γ-ray signal from the primary point source. The very long time delay of the cascade emission means that the extended GeV source could be detected next to a blazar that is no longer active as a blazar.

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