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Implications of very rapid TeV variability in blazars

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ABSTRACT

We discuss the implications of rapid (few-minute) variability in the TeV flux of blazars, which has been observed recently with the HESS and MAGIC telescopes. The variability time-scales seen in PKS 2155−304 and Mrk 501 are much shorter than inferred light-crossing times at the black hole horizon, suggesting that the variability involves enhanced emission in a small region within an outflowing jet. The enhancement could be triggered by dissipation in part of the black hole magnetosphere at the base of the outflow, or else by instabilities in the jet itself. By considering the energetics of the observed flares, along with the requirement that TeV photons escape without producing pairs, we deduce that the bulk Lorentz factors in the jets must be $\gtrsim 50$. The distance of the emission region from the central black hole is less well-constrained. We discuss possible consequences for multi-wavelength observations.

Key words: accretion, accretion discs – galaxies: active – BL Lacertae objects: individual: PKS 2155−304 – BL Lacertae objects: individual: Mrk 501 – galaxies: jets – gamma-rays: observations.

1 INTRODUCTION

The discovery of variable GeV emission from blazars, by the *Compton Gamma-Ray Observatory* EGRET instrument (Hartman et al. 1992, 2001), opened up a new way to study the speed, composition and energetics of relativistic jets. The multi-day variability time-scales measured by EGRET fit comfortably within the prevailing paradigm that variability would be imprinted on the scale of the central black hole's horizon, and therefore $t_{\rm var} \sim r_{\rm g}/c = GM/c^3 = 1.4 m_9$ h, where $r_{\rm g}$ is the gravitational radius and $m_9 = M/10^9\,{\rm M}_\odot$ is the black hole mass in fiducial units. Disturbances created near the black hole could travel outward with a high Lorentz factor Γ (a combination of bulk and pattern speed), before radiating energy at a distance $\gtrsim \Gamma^2 r_{\rm g}$. According to this picture, gamma-rays would be produced at $\sim(10^2\text{–}10^4) r_{\rm g}$, i.e. in a region approaching the scales where most of the radio emission is produced. The required Lorentz factors, $\Gamma \lesssim 10$, are also consistent with the values inferred from radio measurements of superluminal motion and brightness temperatures. Moreover, placing the GeV emission region this far from the black hole greatly alleviates the problem of how the photons escape without producing pairs on the soft photon background.

This view has now been challenged by the results of TeV observations, which indicate strong variability in at least two blazars (PKS 2155−304: Aharonian et al. 2007; and Mrk 501: Albert et al. 2007b), on time-scales as short as a few minutes. Given the inferred black hole masses of $\sim 10^9\,{\rm M}_\odot$, these time-scales are one to two orders of magnitude shorter than the shortest time-scales expected. Although ultrarelativistic motion toward the observer can preserve a short variability time-scale even when the emission region is far from the black hole, it cannot shorten the variability time-scale imprinted by a source that is stationary in the observer's frame, without implausible fine-tuning. Therefore the TeV results indicate that the observed variability is imprinted either by a small fraction of the black hole's horizon, or by small-scale fluctuations intrinsic to the jet itself.

In this Letter we adopt the view that, irrespective of how the variability is triggered, it is the jet itself that is producing the TeV flares, and study the implications of short-time-scale variability. In Section 2 we present basic scaling relations that govern the size and energetics of the flaring regions, and we place these constraints in the context of possible emission mechanisms in Section 3. We show that the large apparent luminosity of the flares and their short time-scales constrain the energy content of the emitting regions. These constraints, and the requirements that the gamma-rays escape (Section 4), indicate that the flaring regions have bulk Lorentz factors $\gtrsim 50$, and most likely produce TeV gamma-rays via Comptonization of external radiation.

2 SIZE AND ENERGETICS OF FLARING REGIONS

We assume that each flaring region, which has a size ℓ' in the jet comoving frame, is causally connected during the flare (of comoving

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★E-mail: mitch@jila.colorado.edu (MCB); acf@ast.cam.ac.uk (ACF); mjr@ast.cam.ac.uk (MJR) duration $\Delta t'$), implying $\ell' < c\Delta t'$. In the laboratory frame the time-scale is dilated to $\Gamma\Delta t'$, but from the observer's point of view the duration of the flare is compressed by a factor $(1 - \beta\cos\theta)^{-1}$, where $\beta = v/c$ is the dimensionless speed and θ is the angle of motion with respect to the line of sight. In the limit $\beta \approx 1$ and $\theta \lesssim \Gamma^{-1}$, the compression factor approaches $2\Gamma^2$. There is a strong observational selection effect that favours this limit for the fastest and most luminous flares, and we will assume that it holds in the following analysis. Thus an observed variability time-scale $t_{\rm var}$ implies

$$\ell' < t_{\rm var} c\Gamma. \tag{1}$$

In the laboratory frame, the total energy content of the flaring region is related to the comoving energy density ε' by $E \sim \varepsilon'\ell'^3\Gamma$. If a fraction f of this energy is radiated during the flare, the observed power is $P_{\rm obs} \sim fE/t_{\rm var}$ and the observer deduces an equivalent *isotropic* luminosity (i.e. luminosity inferred from the observed flux without accounting for intrinsic anisotropy or beaming effects) of

$$L_{\rm iso} \sim 4P_{\rm obs}\Gamma^2 < 4f\varepsilon' t_{\rm var}^2 c^3\Gamma^6. \tag{2}$$

The factor of Γ^2 in the first relation comes from the fact that the power is beamed in the direction of the observer. Measured values of $L_{\rm iso}$ can be quite large: for example, $L_{\rm iso} > 10^{46}$ erg s^{-1} for the bright TeV flares observed in PKS 2155−304 (Aharonian et al. 2007). We will therefore normalize $L_{\rm iso}$ to 10^{46} erg s^{-1}. However, the observed TeV spectra are quite steep (typical photon spectral indices ∼2.5–3.5), while EGRET data suggest that blazar spectra often peak in the 10–100 GeV band. Therefore, if the GeV emission flares as rapidly as the TeV emission, $L_{\rm iso}$ could well be larger than our fiducial value.

The shortest variability time-scales that have been measured to date in PKS 2155−304 (Aharonian et al. 2007) and Mrk 501 (Albert et al. 2007b) are 3–5 min, so we set $t_{\rm var} = 300t_5$ s. We then obtain a lower limit to the internal (comoving) energy density in the flaring region,

$$\varepsilon' > 10^9 f^{-1} L_{46} t_5^{-2}\Gamma^{-6}\ {\rm erg\ cm^{-3}} \sim f^{-1}U'_{\rm r}, \tag{3}$$

where $U'_{\rm r}$ is the comoving radiation energy density associated with the flare. Note that $U_{\rm r}{}'$ is smaller than the internal energy density.

We can assess whether the inferred internal energy density is reasonable by comparing it to the energy density associated with the jet flow,

$$\varepsilon'_{\rm j} \sim \frac{L_{\rm j}}{c\Gamma^2 r^2\Omega} \gtrsim \varepsilon', \tag{4}$$

where $L_{\rm j}$ is the jet power, r is the distance from the black hole and Ω is the solid angle subtended by the jet at r. Given the large values of Γ that we will deduce for the flaring regions, we anticipate that jet opening angles may have to be be much larger than $\sim\Gamma^{-1}$, in order to explain the statistics of observable sources. We therefore normalize Ω to 0.1 sr. Setting $x \equiv r/r_{\rm g}$, we obtain

$$\Gamma > 1.4\left(\frac{L_{\rm iso}}{L_{\rm j}}\right)^{1/4}\left(\frac{\Omega_{0.1}}{f}\right)^{1/4}\left(\frac{x_{\rm fl}m_9}{t_5}\right)^{1/2}, \tag{5}$$

where $x_{\rm fl}$ denotes the location of the flare. This relation places a significant constraint on Γ only if the rapid flares are produced at radii $\gtrsim(10^3\text{–}\ 10^4)r_{\rm g}$.

If the flaring regions are indeed moving outward with the bulk Lorentz factor of the flow, then

$$x_{\rm fl} > \frac{c^3 t_{\rm var}}{GM}\Gamma^2 = 6\times10^{-2} m_9^{-1} t_5\Gamma^2. \tag{6}$$

For the values of Γ estimated below ($\Gamma \gtrsim 50$), this would imply $x_{\rm fl} \gtrsim 100$. However, it is also possible that the flaring regions are patterns that are fixed relative to the laboratory frame (e.g. associated with some external disturbance such as the funnel of the accretion flow), in which case the emitting gas could be located closer to the black hole. If the flares are moving outward, we can combine equations (5) and (6) to place a lower limit on the jet power, which is independent of the flare time-scale:

$$L_{\rm j} > 1.4L_{\rm iso}\left(\frac{\Omega_{0.1}}{f}\right). \tag{7}$$

3 RADIATION MECHANISMS

The double-humped spectral energy distributions (SEDs) of blazars are generally attributed to the superposition of a synchrotron spectrum – peaking in the infrared–optical or ultraviolet–X-ray for ‘low-peaked blazars’ (LBLs) and ‘high-peaked blazars’ (HBLs), respectively – and an inverse Compton spectrum (peaking at gamma-ray energies) produced by the same population of electrons. Both PKS 2155−304 and Mrk 501 are HBLs, as indeed are all but one of the blazars detected at TeV energies, to date.

The seed photons for Comptonization are provided primarily by either the synchrotron photons themselves [the synchrotron self-Compton (SSC) mechanism (Maraschi, Ghisellini & Celotti 1992; Bloom & Marscher 1996)] or a radiation field impinging on the jet from outside [the external radiation Compton (ERC) mechanism (Begelman & Sikora 1987; Melia & Königl 1989; Dermer & Schlickeiser 1994; Sikora, Begelman & Rees 1994)]. Since the flare radiation density in the comoving frame, $U'_{\rm r}$ (equation 3), includes both the synchrotron and Compton components, the dominance of the Compton (gamma-ray) hump strongly favours the ERC mechanism over the SSC mechanism. On the other hand, one cannot make such a strong statement if the synchrotron peak dominates; in this case, either mechanism is viable. The SEDs of the two highly variable TeV sources do not exhibit a trend: in Mrk 501 the synchrotron peak appears to dominate (Albert et al. 2007b), while the Compton component dominates the SED of PKS 2155−304 in data presented by Foschini et al. (2007) [but not in the (non-simultaneous) data quoted by Ghisellini et al. (1998)].

The fact that the spectra are quite flat (or even inverted) longward of each peak, and quite steep shortward, suggests that most of the energy in the accelerated electrons is contained in particles with high random Lorentz factors, radiating close to the peak. This view contrasts with earlier assertions that the peak is associated with cooling of the electrons (Sikora et al. 1994; Ghisellini et al. 1998), and could mean that the acceleration mechanism is ‘particle-starved’, in the sense that the Poynting flux exceeds the kinetic energy flux in the flaring region (Sikora et al. 2005). If particle acceleration is efficient in these flares (i.e. if f is not too small and most electrons are accelerated), then we may assume that the intrinsic energy density is primarily magnetic, $\varepsilon \sim B'^2/8\pi$, with

$$B' > 2\times10^5 f^{-1/2} L_{46}^{1/2} t_5^{-1}\Gamma^{-3}\ {\rm G}. \tag{8}$$

According to this emission model, the intrinsic synchrotron emissivity of PKS 2155−304 peaks at $\nu_{\rm syn} \sim 10^{16}\nu_{16}/\Gamma$Hz, which requires the random Lorentz factors of electrons contributing to the peak to satisfy

$$\gamma_{\rm peak} < 250\nu_{16}^{1/2} f^{1/4} L_{46}^{-1/4} t_5^{1/2}\Gamma. \tag{9}$$

If the intrinsic gamma-ray spectrum, peaking at $\sim10^{24}/\Gamma$Hz, is produced by Comptonization of the synchrotron spectrum, then $\gamma_{\rm peak} \sim 10^4$ and $\Gamma \gtrsim 50$. In this picture, scattering in the Klein–Nishina regime could contribute to the steepness of the TeV spectrum.

Although large values of Γ may be needed to produce rapidly fluctuating gamma-rays, they can also inhibit efficient synchrotron cooling of the flare plasma (Begelman, Rees & Sikora 1994). We have implicitly assumed that all of the dissipated energy is radiated away during the flare. This implies that the cooling time-scale in the comoving frame is shorter than $\Gamma\ t_{\rm var}$ – if this were not the case then our energetic requirements would have to increase. If cooling is dominated by synchrotron losses, then a sufficient condition to ensure efficient cooling is

$$\gamma > 10^{-4} f L_{46}^{-1} t_5 \Gamma^5. \tag{10}$$

To ensure that all electrons with $\gamma > \gamma_{\rm peak}$ are able to cool, we require

$$\Gamma < 40 \nu_{16}^{1/8} f^{-3/16} L_{46}^{3/16} t_5^{-1/8}. \tag{11}$$

Thus an SSC model for rapid flares from PKS 2155−304 can barely satisfy the condition for efficient cooling above $\gamma_{\rm peak}$, given our deduction that $\Gamma \gtrsim 50$; this constraint will become tighter once we consider the opacity due to pair production.

Constraints on radiative efficiency are relaxed considerably if the gamma-rays are produced by the ERC mechanism. In order for ERC to dominate over SSC, the ambient radiation energy density must exceed the synchrotron energy density as measured in the comoving frame. The external radiation density in the laboratory frame must then satisfy

$$U_{\rm ext} > 10^9 L_{46} t_5^{-2} \Gamma^{-8}\ {\rm erg\ cm^{-3}}, \tag{12}$$

if the intensity at $x_{\rm fl}$ is approximately isotropic, corresponding to a luminosity $L_{\rm ext} \sim 2 \times 10^{35} (\Gamma/50)^{-8} m_9^2 x_{\rm fl}^2$ erg s^{-1}. Henceforth we normalize Γ to 50 because both energetic and transparency constraints will demand such values. If the external radiation illuminates the flaring region from behind, subtending a small solid angle $\Omega_{\rm ext}$ (with $\Gamma^{-2} \ll \Omega_{\rm ext}/2\pi \ll 1$) in the laboratory frame, then the required energy density and luminosity are increased by a factor $(\Omega_{\rm ext}/2\pi)^{-2}$. For radiation emitted at $r_{\rm ext} \ll r_{\rm fl}$ – from the central region of an accretion disc, for example – this factor is $\sim(r_{\rm fl}/r_{\rm ext})^4$, much steeper than the expected variation of emissivity with radius in most accretion scenarios. Therefore it seems most likely that the external radiation responsible for Comptonization is emitted at radii comparable to $x_{\rm fl}$ (Dermer, Schlickeiser & Mastichiadis 1992; Dermer & Schlickeiser 1993).

If the ($\sim$ isotropic) external radiation field peaks at a frequency $\nu_{\rm ext}$, then the condition for producing the gamma-ray peak at $\nu_\gamma \sim 10^{24}$ Hz is

$$\frac{\nu_\gamma}{\nu_{\rm ext}} \sim \Gamma^2 \gamma_{\rm peak}^2. \tag{13}$$

Combining this condition with equation (9), we obtain

$$\nu_{\rm ext} > 2 \times 10^{12} \nu_{16}^{-1} f^{-1/2} L_{46}^{1/2} t_5^{-1} \left(\frac{\Gamma}{50}\right)^{-4}\ {\rm Hz}. \tag{14}$$

Thus an ERC model for rapidly varying TeV flares would require an external radiation source in the submillimetre band, if the external radiation is diffuse, and a factor $\sim (\Omega_{\rm ext}/2\pi)^{-1}$ higher frequency if it comes from behind.

In contrast to the SSC mechanism, the cooling of relativistic electrons in the ERC model becomes more efficient with increasing Γ, with the least efficient cooling occurring when the two mechanisms are comparable. For electrons near $\gamma_{\rm peak}$ the ratio of cooling time to variability time is sensitive to Γ, varying $\propto \Gamma^4$ when SSC dominates and $\propto \Gamma^{-4}$ when external radiation controls energy loss.

4 ESCAPE OF RADIATION

The most stringent conditions on our flare model are set by the requirement that the gamma-rays escape without being absorbed in γ–γ pair production. In blazar models there are two possible targets for pair production: the synchrotron radiation intrinsic to the jet and the external ambient radiation. In the case of interactions with jet radiation, optimal conditions for escape occur if a TeV photon encounters radiation only within the flaring region in which it was produced. If the TeV photon has to pass through other radiating regions, this will decrease its escape probability; but given the amplitude of observed flares it is plausible that the escape constraint is set locally.[1] In considering pair production on ambient radiation, on the other hand, one must integrate over a path length of order r.

To estimate the pair production opacity internal to the flare region, we use the estimate of radiation density $U'_{\rm r}$ from equation (3). We assume that this energy density is dominated by synchrotron radiation peaking at a frequency $10^{16} \nu_{16}/\Gamma$Hz, which therefore has a number density

$$\nu_{\rm peak} n'_\nu(\nu_{\rm peak}) \sim 6 \times 10^{19} \nu_{16}^{-1} L_{46} t_5^{-2} \Gamma^{-5}\ {\rm photon\ cm^{-3}}. \tag{15}$$

The cross-section for pair production peaks at $\sigma_{\gamma\gamma} \sim \sigma_{\rm T}/5$ close to threshold, where $\sigma_{\rm T}$ is the Thomson cross-section, and declines at higher energies. Blazar spectra tend to be quite flat longward of the synchrotron peak, with an energy spectral index $\alpha \sim 0.3$–0.5 (where the flux is $F_\nu \propto \nu^{-\alpha}$). Shortward of the peak they decline somewhat more steeply than ν^{-1}. Under these circumstances, the most probable pair-producing reactions are those close to threshold. The likely targets for photons with energy 1 TeV/Γ (i.e. the photons with observed energy $\sim$1 TeV) have frequencies $\nu_{\rm target} \sim 4 \times 10^{13}\ \Gamma$ Hz. We therefore need to correct $\nu_{\rm peak}\ n'_\nu(\nu_{\rm peak})$ by a factor $(\nu_{\rm peak}/\nu_{\rm target})^\alpha$ to account for the ratio of target photons to photons near the spectral peak. Anticipating that the minimum Γ for PKS 2155−304 will be large enough that $\nu_{\rm target} > \nu_{\rm peak}$, we adopt $\alpha = 1$. The correction factor is then $\sim 160 \nu_{16} \Gamma^{-2}$. Multiplying by a path length $\ell' = c t_{\rm var} \Gamma$ and the threshold cross-section, we obtain the optical depth to pair production,

$$\tau_{\gamma\gamma} \sim 2 \times 10^{10} L_{46} t_5^{-1} \Gamma^{-6}. \tag{16}$$

The condition $\tau_{\gamma\gamma} \lesssim 1$ then implies

$$\Gamma > 50 L_{46}^{1/6} t_5^{-1/6} \tag{17}$$

(Celotti, Fabian & Rees 1998). Thus the escape of TeV photons from the site of a rapid flare requires $\Gamma \gtrsim 50$, provided that the observed synchrotron emission comes from the same site. This result is independent of the distance of the flaring region from the black hole.

In the presence of diffuse external radiation, the threshold target frequency for pair production by a 1-TeV photon is $\sim 6 \times 10^{13}$ Hz, or about an order of magnitude higher than $\nu_{\rm ext}$ given by equation (14), if $\Gamma \sim 50$. Using equation (12) to estimate the external radiation density, and conservatively assuming a flat spectral index ($\alpha = 0$), we estimate a target photon number density $\nu_{\rm ext}\ n_\nu(\nu_{\rm ext}) \sim 3 \times 10^8\ L_{46}\ t_5^{-2}\ (\Gamma/50)^{-8}$ photon cm^{-3}. To obtain the pair production optical depth we multiply by the threshold cross-section and a path length $\sim r = 1.5 \times 10^{14}\ m_9\ x$:

$$\tau_{\gamma\gamma,{\rm ext}} \sim 6 \times 10^{-3} L_{46} t_5^{-2} \left(\frac{\Gamma}{50}\right)^{-8} m_9 x_{\rm fl}. \tag{18}$$

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[1] Note, however, that in the Sikora et al. (1994) ERC model for 3C 279, the pair production constraint due to internal synchrotron radiation is much less severe than that due to external diffuse radiation.

This relation implies that the rapid TeV variability could also be produced by Comptonization of diffuse external radiation, but only out to a radius of several hundred r_g for $\Gamma \sim 50$. Higher values of Γ would allow the flare to occur at larger radii.

If the external radiation came from behind the jet, this constraint would not be much changed. In a typical pair-producing collision, the angle between a TeV photon and the soft target would be small, $\sim (\Omega_{\rm ext}/2\pi)^{1/2}$, but because the incident soft photons must be more energetic by a factor $(\Omega_{\rm ext}/2\pi)^{-1}$, the pair production threshold is still about an order of magnitude above $\nu_{\rm ext}$. The ambient radiation density required by the ERC model is larger by a factor $(\Omega_{\rm ext}/2\pi)^{-2}$, but this increase is compensated for by the decrease in target photon number and collision rate per target photon, each of which scales as $\Omega_{\rm ext}/2\pi$. Thus the optical depth for pair production is not much changed, assuming that the ERC mechanism produces the TeV flares. If the SSC mechanism dominates, so that the external radiation supply is weaker, then the pair production constraint will be correspondingly relaxed.

These results are consistent with the ERC model of Sikora et al. (1994), which focused on the low-peaked blazar 3C 279. In that case, the synchrotron peak was at lower frequencies, $\nu_{16} \sim 0.1$, while the variability time-scale was taken to be 1 d ($t_5 \sim 300$) with $\Gamma \sim 5$. These numbers give an external radiation peak frequency in the ultraviolet, $\nu_{\rm ext} \sim 10^{16}$ Hz, and an optical depth for pair production $\tau_{\gamma\gamma,\rm ext} \sim 7 \times 10^{-4} m_9 x$. Thus flares located at about $r \sim 10^{18}$ cm are marginally optically thin to pair production.

5 DISCUSSION

We have analysed the requirements for producing rapid (few-minute), high-amplitude TeV variability in relativistic blazar jets. Our model is based on the two standard models for gamma-ray emission from blazars, in which the two spectral 'humps' correspond to synchrotron radiation and inverse Compton scattering, respectively. As in the standard models, we show that the flaring gamma-rays could be produced either by Comptonizing the synchrotron photons (SSC model) or by Comptonizing a diffuse background source of submillimetre radiation (ERC model). Since the flaring regions must be quite small to satisfy causality constraints, they must have large bulk Lorentz factors, $\Gamma \gtrsim 50$, in order for the TeV radiation to avoid pair production against the synchrotron photons. Very long baseline interferometry measurements of superluminal motion in PKS 2155−304 (Piner & Edwards 2004) and Mrk 501 (Giroletti et al. 2004) suggest lower values of Γ in these objects, but we stress that the regions producing radio emission and gamma-ray flares may have very different properties.

Although both SSC and ERC mechanisms appear capable of explaining the rapid TeV variability, ERC seems more likely to dominate. Whereas SSC models are tightly constrained (or possibly excluded) between upper limits on Γ imposed by radiative efficiency and lower limits imposed by transparency and Comptonization constraints, ERC models merely have to satisfy a lower limit on Γ (since the radiative efficiency of ERC increases with Γ). The radiation energy densities required by ERC are modest, and would be hard to avoid, even in the presence of a radiatively inefficient accretion flow of the sort likely to be found in BL Lac objects. Moreover, the dominance of the Compton peak over the synchrotron peak, which characterizes the SED of at least one of the highly variable TeV sources (PKS 2155−304: Foschini et al. 2007), is strong, direct evidence for the ERC process.

ERC flares could be produced close to the $\gamma-\gamma$ photosphere, along the lines suggested by Blandford & Levinson (1995). Setting $\tau_{\gamma\gamma,\rm ext} \sim 1$ in equation (18) and using equation (12) to estimate the external radiation density, we obtain an external luminosity of $L_{\rm ext} \sim 3 \times 10^{40} L_{46}^{-2} t_5^{4} (\Gamma/50)^8$ erg s^{-1}. This does not represent the entire unbeamed luminosity of the blazar, but merely the portion produced at radii $\gtrsim x_{\rm fl}$. If the flare occurs at radii $x_{\rm fl} \sim 10^2$– 10^3, as seems likely, then such low luminosities could be fully compatible with standard accretion models. In particular, the external submillimetre radiation could be non-thermal emission produced by a radiatively inefficient accretion flow, or thermal emission produced by the outer, cool parts of an accretion disc. Alternatively, it could be produced by relativistic electrons in a shear layer surrounding the jet. The effective external luminosity would vary with radius, depending on the geometry of the source and the run of $\Gamma(r)$. If these behaviours were known, one could calculate a relationship between the isotropic luminosity of a flare and its duration. The measured power density spectrum $\propto$ frequency^{-2} of PKS 2155−304 (Aharonian et al. 2007) implies $L_{\rm iso} \propto t_{\rm var}$.

The intrinsic steepness of the TeV spectrum in the rapidly varying sources is unlikely to arise from cooling, since the spectrum appears to be considerably steeper than the hard tail of the synchrotron hump. Klein–Nishina effects could contribute to the steepness, as could 'self-absorption' due to pair production. The latter effect can occur when the TeV photons pair-produce against synchrotron photons shortward of the peak. Ignoring Klein–Nishina effects, the emissivity for TeV gamma-rays has the same slope as the high-energy synchrotron photons (say, $j_\nu \propto \nu^{-\alpha}$, where $\alpha \sim 1$). Since the absorption coefficient scales with TeV frequency as $\alpha_\nu \propto \nu^{\alpha}$, however, higher energy TeV photons find more targets for pair production. Therefore, if the source is self-absorbed, the TeV energy spectral index is $2\,\alpha$. This would tend to decrease the TeV variability relative to the synchrotron photons, if SSC dominates, and might cancel the non-linearity expected from the SSC mechanism.

Our analysis implies some significant differences between LBLs and HBLs that may explain why only the latter have exhibited rapid variability at TeV energies [and, with the exception of a detection of weak emission from BL Lac (Albert et al. 2007a), why only HBLs have been detected in the TeV band]. Since LBLs have $\nu_{16} \sim 10^{-4}$–10^{-2}, equation (9) implies that $\gamma_{\rm peak}$ would have to be lower by a factor of 0.01–0.1 if these objects were to produce very rapid flares via the dissipation of magnetic energy. In this case, gamma-rays could not be produced by SSC; ERC would have to dominate, with the characteristic frequency of the external radiation $\nu_{\rm ext}$ in the ultraviolet. Such an external radiation source is probably not found in BL Lac objects, but might be present in optically violently variable (OVV) quasars. In the quasar case, however, both the radial scale of the external radiation and its luminosity are expected to be quite large, implying that the pair photosphere will be located at $\gtrsim 10^4 r_g$. At these radii the jet is likely to be so expanded that the energy density will be insufficient to create an intense, rapid flare (cf. equation 5); moreover, the conversion of Poynting flux to kinetic energy (or its loss to radiation) may have largely taken place by this radius, further hampering the production of flares. Therefore we might not expect such a system to produce very rapid flares with high luminosities. LBL BL Lac objects may have trouble producing rapid flares even at GeV energies, since they lack a strong source of ultraviolet radiation; to produce such flares in these objects would require the slow dissipation of relatively weak magnetic fields, according to equations (8) and (9); thus we would expect $t_5 \gg 1$. These arguments also suggest a reason for the relative weakness of TeV emission, compared with GeV emission, in those LBLs that have been detected in gamma-rays. In LBLs, the external Comptonization required to produce TeV photons probably extends further into the Klein–Nishina regime, since the photon energy in the electron rest frame is roughly the geometric mean between the seed photon energy and the TeV final energy. This will compound the spectral steepening caused by effects like self-absorption due to pair production, creating a much weaker TeV signal.

Our model does not make strong predictions about the distance from the black hole at which the flares are produced. The main constraint is that the flow must have accelerated to $\Gamma \gtrsim 50$ before reaching the flare zone. It is well known that relativistic jets, subject to magnetohydrodynamical or fluid forms of pressure, tend to accelerate rather slowly. In a ballistic, ultrarelativistic flow Γ increases roughly linearly with radius, suggesting that the jet should reach at least $100r_{\mathrm{g}}$ before producing the observed flares. If the jet is collimated, e.g. by magnetic stresses, the acceleration could be slower still. However, if the jet is extremely ‘particle-starved’ – as we suggested based on evidence that the mean random Lorentz factor of electrons in the flare zone could be as large as $\sim 10^4$ – then it may undergo a very rapid episode of acceleration close to the black hole. By analogy with pulsar winds, magnetocentrifugal stresses can accelerate the wind to Lorentz factors $\sim \sigma^{1/3}$ close to the light cylinder, where σ is the ratio of energy density to rest mass density and the light cylinder would generally be expected to lie at a few r_{g} (Michel 1969; Begelman & Li 1994). If this ratio could be as large as 10^6 for blazar jets, then these jets would probably accelerate to $\Gamma \sim 100$ almost immediately. The remaining energy density would be just enough for the electrons to be accelerated to an average Lorentz factor of $\sim 10^4$.

The detection of large-amplitude variability on time-scales shorter than r_{g}/c is important and surprising. We can already infer higher Lorentz factors than have generally been contemplated for blazars, and that the phenomenon is triggered by processes that involve extreme relativistic plasmas, perhaps in a black hole magnetosphere. These possibilities lend added motivation to future observations – and especially to simultaneous multi-band observations that could discriminate among the options.

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