Locating the $\gamma$-ray emission region of the flat spectrum radio quasar PKS 1510−089

Anthony M. Brown*

Department of Physics and Astronomy, University of Canterbury, Christchurch 8140, New Zealand

Accepted 2013 February 2. Received 2013 January 30; in original form 2012 November 30

ABSTRACT

I present a study of the high-energy $\gamma$-ray properties of the flat spectrum radio quasar, PKS 1510−089, based on 3.75 yr of observations with the Large Area Telescope detector on-board the Fermi $\gamma$-ray Space Telescope. Throughout the observing period, the $0.1 < E_{\gamma} < 300$ GeV $\gamma$-ray flux was highly variable, undergoing several flaring events where the daily flux exceeded $10^{-5}$ photons cm$^{-2}$ s$^{-1}$ on three separate occasions. The increased photon statistics of these large flares allowed the observations to be re-analysed in 6 and 3 h intervals, revealing flux doubling time-scales as small as $1.3 \pm 0.12$ h during the flare rise time, and flux halving time-scales of $1.21 \pm 0.15$ h during the flare decay. These are the smallest variability time-scales measured to date at MeV–GeV energies for the flat spectrum quasar class of active galactic nuclei.

The $> 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ flare events were also studied in more detail in an attempt to uncover evidence for the location of PKS 1510−089’s $\gamma$-ray emission region. In particular, two approaches were used: (i) searching for an energy dependence to the cooling time-scales, and (ii) searching for evidence of a spectral cut-off. The combined results of these two approaches, along with the confirmation of $\geq 20$ GeV photon flux from PKS 1510−089, suggest the presence of multiple $\gamma$-ray emission regions being located in both the broad line region and molecular torus region of PKS 1510−089.

An analysis of the highest photon events within the 3.75 yr data set finds PKS 1510−089 to be a source of $\geq 20$ GeV $\gamma$-rays at the 13.5$\sigma$ confidence level; a observational property which is difficult to explain in the traditional view that $\gamma$-ray emission from active galactic nuclei originates from the base of the relativistic jet. This gives further weight to the argument that there are multiple, simultaneously active $\gamma$-ray emission regions located along the relativistic jet of active galactic nuclei.

Key words: galaxies: active – galaxies: fundamental parameters – parameters quasars: individual: PKS 1510−089 – galaxies: jets – galaxies: nuclei – gamma-rays: galaxies.

1 INTRODUCTION

The successful launch of the Fermi $\gamma$-ray Space Telescope affords us an ideal opportunity to investigate the inner workings of active galactic nuclei (AGN). The ability of the Fermi-Large Area Telescope (LAT) detector to scan the entire $\gamma$-ray sky every 3 h allows us to study the $\gamma$-ray emission from AGN, unbiased by activity state or AGN subclass. This ability has revealed the blazar subclass of AGN to be the most numerous class of known $\gamma$-ray sources (Nolan et al. 2012), with approximately equal number of flat spectrum radio quasars (FSRQ) and BL Lac objects (Abdo et al. 2011b). Furthermore, not only do blazars dominated the extragalactic $\gamma$-ray sky, but during brief periods of intense flare activity, they can outshine galactic $\gamma$-ray sources as well (Abdo et al. 2011a).

Apart from the radio lobes of the nearby radio galaxy, Centarus A (Abdo et al. 2010a), the $\gamma$-ray emission region of AGN remains unresolved. As such, the origin of the $\gamma$-ray emission within blazars remains an open question. Answering this question is an active area of AGN research, with two main schools of thought: on the one hand, some believe the $\gamma$-ray emission originates from within the broad line region (BLR) of the AGN, while on the other hand, some believe the $\gamma$-ray originates further out from the central supermassive black hole (SMBH), within the molecular torus (MT) region of the AGN.

Traditionally the $\gamma$-ray emission has been assumed to be close to the base of the relativistic jet, within the BLR. The reasoning for this assumption is twofold: broad-band spectral energy distribution modelling and rapid $\gamma$-ray flux variability on small time-scales.

* E-mail: anthony.brown@canterbury.ac.nz

© 2013 The Author
Published by Oxford University Press on behalf of the Royal Astronomical Society
Multiwavelength (MWL) observations of FSRQs have found the broad-band spectral energy distribution to be adequately described by a leptonic model, with the emission region located within 300–1000 Schwarzschild radii from the central SMBH (e.g., see Ghisellini et al. 2010; Nalewajko et al. 2012). Likewise, the rapid flux variability implies a small emission region size. This is often interpreted as evidence of the emission region being located close to the base of the jet. This interpretation is based on the assumption that the full width of the relativistic jet is responsible for the observed γ-ray emission and that the size of the emission region, r, is simply related to the opening angle of the relativistic jet, ψ, and the distance from the SMBH, R, via r ≈ ψR (Dermer et al. 2009; Ghisellini & Tavecchio 2009).

More recently, the wealth of information afforded to us by the Fermi-LAT detector has found evidence of spectral breaks at GeV energies in the γ-ray spectrum of some AGN (Abdo et al. 2010c). These spectral breaks have been interpreted in the context of γ-ray absorption through photon–photon pair production with the He Lyman recombination continuum of the BLR (Poutanen & Stern 2010), thus pointing to a BLR origin of the observed γ-ray flux. It is worth noting though, that this interpretation has recently been brought into question (Harriss, Daniel & Chadwick 2012).

γ-ray emission from AGN has also been suggested to originate from the MT region of the jet, on the parsec-scale distance from the central SMBH. This suggestion is primarily based on the results of recent MWL observations which have found γ-ray flaring events to be accompanied by flare events at optical or radio wavelengths, with some of these radio flares being resolved on a parsec-scale distance from the SMBH (e.g., see Lahteenmaki & Valtaoka 2003; Marscher et al. 2010; Aguado et al. 2011; Orienti et al. 2013).

Further evidence for an MT origin of the γ-ray emission comes from the detection of very high energy (VHE) γ-ray emission from FSRQs. To date, three FSRQs have been detected at energies ≥100 GeV, of which PKS 1510–089 is one (Wagner 2010; Aleksic et al. 2011a,b). The photon-rich environment of the BLR of FSRQs is believed to severely attenuate any γ-ray emission through photon–photon pair production, resulting in a spectral cutoff above ≥20 GeV (e.g., see Donea & Protheroe 2003; Lui & Bai 2006). As such, the detection of VHE emission is difficult to explain with a pure BLR origin for the observed γ-ray.

One of the primary arguments against an MT origin for the γ-ray emission is that the further an emission region is from the central SMBH, the bigger it is through the combined effects of adiabatic expansion and the opening angle of the jet. However, this argument is only valid if the entire width of the relativistic jet is responsible for the observed γ-ray emission. What is more, this argument assumes that process of adiabatic expansion is dominant over any re-collimation process that occurs along the length of the jet. The latter assumption is not valid if the jet undergoes re-confinement (e.g., see Sokolov, Marscher & McHardy 2004). Furthermore, detailed computer simulations have found that jet instabilities can result in large overdensities in the matter distribution at large distances from the central SMBH (e.g., see Nishikawa et al. 2003; Perucho et al. 2006; Bromberg & Levinson 2009; Kohler, Begelman & Beckwith 2012).

Interestingly, using the above arguments, evidence has been found for the γ-ray emission region of PKS 1510–089 to be located in both the BLR and the MT. From the first 11 months of Fermi-LAT operation, Abdo et al. concluded that the γ-ray emission originated from within the BLR (Abdo et al. 2010b); this conclusion primarily being driven by the presence of a cut-off in the γ-ray spectrum. However, both Marscher et al. and Orienti et al. have concluded from their respective MWL campaigns of PKS 1510–089 that the γ-ray originates from outside BLR region (Marscher et al. 2010; Orienti et al. 2013), with their conclusions primarily based on the flaring events being observed simultaneously at γ-ray, optical and radio wavelengths. It is important to note, however, that these three MWL studies focused on three separate flaring events.

This paper investigates the high-energy γ-ray flux and spectral properties of PKS 1510–089 during the first 3.75 yr of Fermi-LAT observations. In particular, the increased photon statistics associated with several large γ-ray flare events where the daily flux occasionally exceeds 10−5 photons cm−2 s−1, allow us to probe flux and spectral variability from PKS 1510–089 with unprecedented temporal resolution in the MeV–GeV energy range. In Section 2, I describe the Fermi-LAT observations and data analysis routines used in this study. The results on flux variability are shown in Section 3 with the in-depth flare analysis reported in Section 4. A brief discussion on a multi-zone model is given in Section 5 with the conclusions shown in Section 7.

2 FERMI-LAT OBSERVATIONS AND DATA REDUCTION

The LAT detector aboard Fermi, described in detail by Atwood et al. (2009), is a pair-conversion telescope, sensitive to a photon energy range from below 20 MeV to above 300 GeV. With a large field of view, ∼2.4 sr, improved angular resolution, ~0.8 at 1 GeV, and large effective area, ~8000 cm² on axis at 10 GeV, Fermi-LAT provides an order of magnitude improvement in performance compared to its Energetic Gamma-Ray Experiment Telescope (EGRET) predecessor.

Since 2008 August 4, the vast majority of data taken by Fermi has been performed in all-sky-survey mode, whereby the Fermi-LAT detector points away from the Earth and rocks north and south of its orbital plane. This rocking motion, coupled with Fermi-LAT’s large effective area, allows Fermi to scan the entire γ-ray sky every two orbits, or approximately every 3 h (Ritz 2007). This observational characteristic of the Fermi satellite affords us, for the first time, continuous monitoring of the high-energy γ-ray sky, allowing us to study the high-energy properties of AGN without suffering the biased of activity state often associated with pointed observations.

The data utilized in this study composed of all all-sky-survey observations taken during the first 3.75 yr of Fermi-LAT operation, from 2008 August 4 to 2012 May 4, equating to a mission elapsed time (MET) interval of 239557417 to 357818882. In accordance with the pass7 criteria, a zenith cut of 100° along with a rock angle cut of 52° was applied to the data to remove any cosmic-ray-induced γ-rays from the limb of the Earth’s atmosphere. All ‘source’ class events in a 15° radius of interest (ROI) centred on PKS 1510–089 were considered in the 0.1 < Eγ < 300 GeV energy range.

1 Below 10 GeV photon energy, the 68 per cent containment angle of the photon direction is approximately given by θ ~ 0.8 (Eγ/GeV)−0.3, with the 95 per cent containment angle being less than 1.6 times the angle for 68 per cent containment.

2 The Fermi-LAT database is accessible at http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi

3 ‘Source’ class events equates to event_class=2 in the pass7 data set.
Throughout this analysis, Fermi-LAT Science Tools version v9r27p1 were used in conjunction with instrument response functions (IRFs) v7SOURCE_v6. To investigate the γ-ray properties of PKS 1510−089, I utilized the unbinned maximum likelihood estimator of the Fermi-LAT Science Tools’ GTLIKE routine. GTLIKE allows us to fit the data with a series of both point and diffuse sources of γ-rays. The model used to calculate the likelihood of γ-ray emission from PKS 1510−089 was a combination of the most recent galactic, gal_2yep9v6_v0.fits, and extragalactic, iso_p7v6source.txt, diffuse models, and all point sources within a 15° Rol centred on PKS 1510−089. Each point source was modelled with a power-law spectrum of the form dN/dE = A(E/E_0)^{-Γ}. Both the photon index, Γ, and normalization, A, of point sources within 10° of PKS 1510−089 were free to vary during the model fitting, while, for sources greater than 10° from PKS 1510−089, both Γ and A were fixed to the values published in the Second Fermi Source Catalog (Nolan et al. 2012).

3 γ-RAY CHARACTERISTICS

3.1 Light curve

To investigate the temporal behaviour of the γ-ray flux, the 3.75 yr data set was binned into daily temporal bins, with the GTLIKE routine applied to each bin separately. Only time intervals where the corresponding test statistic,\(^4\) TS, was greater than 10 were considered, which equates to a significance of ≈3σ. The resultant light curve can be seen in Fig. 1, with statistical errors only.

Throughout the first 3.75 yr of operation, PKS 1510−089 was one of the brightest AGN detected by the Fermi-LAT. Because of these high flux levels, requiring TS ≥ 10 removes few daily bins from Fig. 1. The variable nature of PKS 1510−089’s γ-ray flux is clear to see, with the 3.75 yr light curve exhibiting short periods of flaring activity separated by extended periods of low fluxes on the order of (0.5−1) × 10^{-6} photons cm^{-2} s^{-1}. PKS 1510−089’s average daily γ-ray flux during the observing period is (1.39 ± 0.05) × 10^{-6} photons cm^{-2} s^{-1}, though on three separate days, the flux exceeded 10^{-5} photons cm^{-2} s^{-1} at the peak of the flare period. During these flares, the γ-ray flux was at historical maxima for PKS 1510−089.

To quantify the extent of the variability seen in Fig. 1, the duty cycle of the 0.1 < E_γ < 300 GeV γ-ray flux during the 3.75 yr observing period was derived. Defined as the fraction of time a source is at any given flux level, the duty cycle allows us to investigate if the observed flaring activity is typical or atypical for the source (e.g. Vercellone et al. 2004; Lott et al. 2012). Shown in Fig. 2, the duty cycle utilized all TS ≥ 10 flux measurements from the daily-binned light curve of Fig. 1. The duty cycle’s bins were defined by the minimum and maximum daily flux values observed, with a total of 100 bins within the flux range.

The 3.75 yr duty cycle of PKS 1510−089 appears to have a well defined peak, where PKS 1510−089 spends the majority of time with a gradual decrease both above and below this peak value, and an excess of events at the highest flux levels associated with the 3 d were the flux was above 10^{-5} photons cm^{-2} s^{-1}. Tavecchio et al. (2010) constructed a Fermi-LAT duty cycle for PKS 1510−089 from 1.5 yr of LAT observations, finding that the source was at a high flux level for approximately 1 per cent of the total observing period, where ‘high flux level’ is defined as a flux that is a factor of 10 larger than the average flux level over the observing period. However, Tavecchio et al. noted that this percentage would most likely decrease over a larger observing period since they studied PKS 1510−089 specifically because it was in a high activity state during the observing period. This does indeed seem to be the case with the exceptional flare events observed during 55850 < MJD < 55880, which are ~10 times the 3.75 yr averaged flux, covering only ~0.2 per cent of the total observing period reported here.

3.2 Flux variability

To search for rapid flux variability on subday time-scales, the daily light curve shown in Fig. 1 was utilized to select periods of high flux

\(^4\) The test statistic, TS, is defined as twice the difference between the log-likelihood of two different models, 2[log L − log L_0], where L and L_0 are defined as the likelihood when the source is included or not, respectively (Mattos et al. 1996).
level. In particular, I concentrated on two flare periods which encompass the three days where the $\gamma$-ray flux from PKS 1510–089 was at historical maximum. The first period, ‘flare 1’, spanning the period $55850 < \text{MJD} < 55858$, saw the $0.1 < E_{\gamma} < 300$ GeV $\gamma$-ray flux from PKS 1510–089 peak at $(1.53 \pm 0.02) \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ on MJD = 55854. The second period, ‘flare 2’, spanned the period $55866 < \text{MJD} < 55876$, during which time, PKS 1510–089’s daily flux twice exceeded $10^{-5}$ photons cm$^{-2}$ s$^{-1}$: $(1.28 \pm 0.03) \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ on MJD = 55868 and $(1.23 \pm 0.08) \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ on MJD = 55873. These high flux levels allowed us to re-analyse the observations with GTLIKE, in 6 and 3 h bins and still satisfy the TS $\geq 10$ criteria for the majority of temporal bins. The resultant light curves can be seen in Fig. 3 for flare 1 and in Fig. 4 for flare 2.

As can be seen in both Figs 3 and 4, the 3 h binned light curve reveals a large amount of variability that was masked, or washed out, by the daily bins utilized in Fig. 1. Furthermore, the smaller temporal bins of Figs 3 and 4 reveal that the flux exceeded $10^{-5}$ photons cm$^{-2}$ s$^{-1}$ during 17 separate 3 h intervals, compared to three daily periods revealed in Fig. 1, with the $0.1 < E_{\gamma} < 300$ GeV $\gamma$-ray flux from PKS 1510–089 peaking at $(1.99 \pm 0.04) \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$, equating to $\sim 3 \times 10^{38}$ erg s$^{-1}$, on MJD = 55872.937 $\pm 0.063$.

To characterize the time-scales of the observed flux variability, the time taken for the flux to increase or decrease by a factor of 2 was evaluated. Referred to as the doubling/halving time-scale depending upon whether the flux is increasing or decreasing, this time-scale is defined by

$$F(t) = F(t_0) \times 2^{(t-t_0)/\tau},$$

(1)
variability time-scales that have a value which is greater than 5 standard deviations from zero were considered. A summary of intrinsic variability time-scales with $|\tau_{\text{int}}| < 3$ h, which have a significance of at least $5\sigma$, is given in Table 1.

This approach has two important caveats: first, for consecutive flux values where the difference is less than a factor of 2, the variability time-scale calculated is essentially how long it would take for a double or halving of flux to occur if the observed change in flux continued at its current rate. Secondly, the variability time-scales calculated assumes that the flux increase or decrease is constant throughout the 3 h bin, and as such, should be considered as an upper limit. Probing time-scales smaller than those observed is primarily limited by the 3 h period that Fermi-LAT takes to scan the entire sky and the amount of time a source is in the bore sight of the LAT instrument where the sensitivity is the greatest.

As one would expect, the 3 h binned light curves of Figs 3 and 4 reveal the most rapid variability. In particular, the shortest doubling rise time, $\tau_{\text{rise}}$, was found to be $1.30 \pm 0.12$ and $1.21 \pm 0.15$ h, respectively. Indeed, even requiring a $3\sigma$ difference in consecutive flux values to calculate the associated doubling/halving time-scale, result in the same time-scale for the quickest decay in flux, and only a slightly longer rise time of $1.36 \pm 0.13$ h. As such, the $1.21$ h decay-time and $1.3$ h rise-time time-scales observed in this study are the quickest flux variability observed from the FSRQ subclass of AGN in the MeV–GeV energy range. The implications for the origin of the non-thermal $\gamma$-ray emission are discussed in Section 4.

Table 1. Summary of quickest variability time-scales events of PKS 1510–089 during the 3.75 yr period, which are less than 3 h and have a significance of at least $5\sigma$. The times, $T_{\text{start}}$ and $T_{\text{stop}}$, are in MJD, with the fluxes in units of $10^{-6}$ photons cm$^{-2}$ s$^{-1}$.

| $T_{\text{start}}$ | $T_{\text{stop}}$ | Flux start ($F_0$) | Flux stop ($F$) | $\tau_{\text{int}}$ (h) | Rise/Decay |
|-------------------|-------------------|-------------------|-----------------|----------------------|------------|
| 55850.312         | 55850.437         | 2.97 ± 1.15       | 5.00 ± 1.03     | 2.93 ± 0.41          | R          |
| 55850.812         | 55850.937         | 2.03 ± 0.91       | 4.30 ± 0.81     | 2.03 ± 0.39          | R          |
| 55851.062         | 55851.187         | 4.30 ± 0.81       | 9.46 ± 1.07     | 1.94 ± 0.22          | R          |
| 55851.937         | 55852.187         | 4.75 ± 1.87       | 9.48 ± 1.83     | 2.21 ± 0.39          | R          |
| 55852.187         | 55853.062         | 13.2 ± 0.97       | 3.71 ± 0.68     | 1.21 ± 0.15          | D          |
| 55853.062         | 55853.187         | 4.93 ± 0.45       | 15.2 ± 1.12     | 1.36 ± 0.13          | R          |
| 55853.187         | 55854.062         | 15.2 ± 1.12       | 4.84 ± 0.49     | 1.34 ± 0.13          | D          |
| 55854.062         | 55854.187         | 9.86 ± 1.73       | 5.45 ± 1.37     | 2.58 ± 0.32          | D          |
| 55856.062         | 55856.187         | 2.38 ± 0.19       | 5.23 ± 1.32     | 1.94 ± 0.17          | R          |
| 55856.187         | 55856.312         | 5.23 ± 1.32       | 2.79 ± 1.00     | 2.42 ± 0.47          | D          |
| 55866.312         | 55866.437         | 2.92 ± 0.38       | 5.41 ± 2.45     | 2.48 ± 0.28          | R          |
| 55867.437         | 55867.562         | 7.17 ± 0.64       | 3.96 ± 2.60     | 2.57 ± 0.20          | D          |
| 55868.812         | 55868.937         | 7.27 ± 1.98       | 12.29 ± 1.32    | 2.91 ± 0.22          | R          |
| 55869.062         | 55869.287         | 9.62 ± 0.34       | 3.27 ± 0.29     | 1.42 ± 0.07          | D          |
| 55869.187         | 55869.312         | 3.27 ± 0.29       | 8.50 ± 2.08     | 1.60 ± 0.19          | R          |
| 55869.687         | 55869.812         | 3.53 ± 0.80       | 6.65 ± 0.34     | 2.42 ± 0.11          | R          |
| 55870.187         | 55870.312         | 2.95 ± 1.12       | 5.82 ± 0.82     | 2.25 ± 0.30          | R          |
| 55870.437         | 55870.687         | 8.71 ± 1.80       | 3.95 ± 1.16     | 1.93 ± 0.38          | D          |
| 55872.062         | 55872.187         | 1.55 ± 0.47       | 4.39 ± 0.43     | 1.47 ± 0.21          | R          |
| 55872.562         | 55872.687         | 7.28 ± 1.58       | 14.17 ± 2.09    | 2.29 ± 0.27          | R          |
| 55873.437         | 55873.562         | 8.50 ± 1.02       | 4.71 ± 0.76     | 2.59 ± 0.22          | D          |
| 55873.687         | 55873.812         | 5.74 ± 0.61       | 3.10 ± 0.58     | 2.48 ± 0.21          | D          |
| 55874.687         | 55874.812         | 3.51 ± 1.35       | 6.67 ± 0.97     | 2.38 ± 0.31          | D          |
| 55875.062         | 55875.187         | 2.76 ± 1.20       | 4.74 ± 1.38     | 2.83 ± 0.54          | R          |
| 55875.437         | 55875.562         | 1.67 ± 0.85       | 5.41 ± 0.29     | 1.30 ± 0.12          | R          |
| 55875.812         | 55875.937         | 3.97 ± 0.66       | 9.87 ± 1.84     | 1.68 ± 0.28          | R          |

4 ORIGIN OF THE $\gamma$-RAY EMISSION

4.1 Variability time-scale

Taking the Doppler factor of the relativistic jet into consideration, causality implies that the size of an emission region, $R$, with a Doppler factor $\delta$, is related to the $\gamma$-ray variability time-scale, $\tau_{\text{var}}$, by

$$R \leq c\tau_{\text{var}}(1+z)^{-1},$$

where $\Gamma$ is the bulk Lorentz factor of the jet, $\beta = v/c$ and $\theta$ is the angle to the line of sight.
where \( z \) is the redshift of the source. For the intrinsic variability time-scales outlined in Table 1, the size of the \( \gamma \)-ray emission region for the observed flares can be constrained to be \( R^\gamma \lesssim (0.9–2.3) \times 10^{14} \) cm. For comparison, adopting a SMBH mass of \( 5.4 \times 10^8 \, M_\odot \) from Abdo et al. (2010b), the Schwarzschild radius \( \approx 1.6 \times 10^{14} \) cm.

Radio observations of PKS 1510–089 during 2010 February to June have shown that structures within its relativistic jet have Doppler factors of \( \delta = 47 \) (Kadota et al. 2012), while observations during 1998–2001 show similar values of \( \delta = 34–42 \) (Jorstad et al. 2005). If one assumes these rather extreme values for the Doppler factor are a good representation of the average velocity structure within PKS 1510–089’s relativistic jet, the emission regions of the flares reported here are found to be less than \( 3 \times 10^{-3} \) pc in size.

This suggests that only a very small portion of the relativistic jet is responsible for the observed \( \gamma \)-ray flares.

While these rapid variability time-scales allow us to gain insights into the physical properties of the \( \gamma \)-ray emission region, the extreme nature of the variability does little to constrain the location of the emission region. Small structure within the relativistic jet is not unique to just the inner regions of the AGN; small overdensities of plasma can occur in the jet at both the subparsec, BLR, and the parsec-scale, MT, region (Nishikawa et al. 2003; Peruch et al. 2006; Bromberg & Levinson 2009; Kohler et al. 2012).

External to the jet, however, the environment of the BLR and MT is significantly different, with the energy distribution of the BLR photon field peaking at ultraviolet energies, while in the MT it peaks at infrared energies. This difference in photon energies, and the subsequent cooling effect they have on the energy distribution of the particle population within the emission region, can be utilized to constrain the origin of the \( \gamma \)-rays.

Tavecchio et al. (2010) exploited this difference to constrain the cooling time-scales for a relativistic electron population located within the BLR and within the MT region. Utilizing equation (3) below, Tavecchio et al. calculated the cooling time-scale for an electron producing a 100 MeV \( \gamma \)-ray photon, through the inverse-Compton (IC) process, to be \( t_{\text{cool}} \approx 800 \) s in the BLR and \( t_{\text{cool}} \approx 12 000 \) s in the MT. Furthermore, for a 5 keV X-ray photon produced via the IC process, Tavecchio et al. calculated an electron cooling time-scale of \( t_{\text{cool}} \approx 31 \) h in the BLR and \( t_{\text{cool}} \approx 20 \) d in the MT.

\[
t_{\text{cool}} = \frac{3m_e c (1 + z)}{4\sigma_T U' \gamma \delta}.
\] (3)

The 3–6 h cooling time-scales that Tavecchio et al. observed did not allow them to distinguish between a BLR and a MT origin for the emission region. However utilizing the approach outlined in Tavecchio et al. (2010), the \( \tau_{\text{decay}} = 1.21 \pm 0.15 \) h cooling time-scale discovered in this study would suggest that the emission region, for the quickest flaring event, is located within the BLR.

It is important to highlight that this approach assumes that the IC interaction is occurring in the Thomson regime, which

\footnote{Given that X-ray cooling time-scales from blazars have been observed on the subhour time-scale (e.g. see Foschini et al. 2006 for FSRQs and Brown 2006 for BL Lac objects), the application of this approach to observed X-ray flux variability is questionable.}

\footnote{It should be noted that this conclusion does not apply to all variability time-scales reported in Table 1 since, for events with \( \tau_{\text{decay}} \geq 2.5 \) h, it is not possible to differentiate between the BLR and MT cooling time-scales of 800 and 12 000 s, respectively.}

4.2 Energy-dependent cooling time-scales

Tavecchio et al. assumed that the IC scattering was occurring in the Thomson regime, with \( \gamma e \ll 1 \) being true for all electron–photon interactions, where \( \gamma \) is the Lorentz factor for the electron and \( e \) is the energy of the photon. Dotson et al. (2012a,b) on the other hand found that the IC scattering occurred in the Klein–Nishina regime when the emission region was located in the BLR, while it occurred in the Thomson regime for emission regions located within the MT region of the AGN. This difference manifests itself as an energy-dependent cooling time-scale for emission regions embedded in the MT region and a (quasi-) energy independent cooling time-scale for emission regions embedded in the BLR. Specifically, utilizing the BLR and MT photon energy densities from Ghisellini & Tavecchio (2009), Dobson et al. calculated a \( < 1 \) h difference in the flux halving time-scale for 200 MeV photons and 20 GeV photons for an emission region located in the BLR, but a \( \sim 10 \) h difference in flux halving time-scales for the two photon energies from an emission region embedded in the MT region (Dotson et al. 2012a).

More generally speaking, this difference would result in a time lag between the cooling of the MeV and GeV components of a \( \gamma \)-ray flare. Conversely, if present, a time lag can be used to constrain the energy density of the MT photon field (Dotson et al. 2012b).

To investigate the possibility of energy-dependent cooling time-scales, the daily light curve of Fig. 1, along with the 6 h binned light curves of Figs 3 and 4, was re-analysed as per the procedure outlined in Section 2, but for photons in two distinct energy groups: low energy, 0.1–1 GeV, and high energy, 1–300 GeV. Because of the limited number of events above 1 GeV and the requirement that each temporal bin has TS \( \geq 10 \), this re-analysis was not applied to the 3 h binned light curve. The resultant daily binned light curves for both low- and high-energy fluxes can be seen in Fig. 5. The low- and high-energy light curve, for both flare 1 and flare 2, binned in 6 h intervals, are shown in Figs 6 and 7, respectively.

Discrete correlation functions (DCF; Edelson & Krolik 1988) were applied to the low- and high-energy light curves of Figs 6 and 7 to search for the presence of a time lag in the flux level changes between the energy bands. An important characteristic of the DCF procedure is that it allows us to accommodate for differences in the sampling rates of the two light curves associated with the TS \( \geq 10 \) criterion. The DCFs represent a more robust approach to searching for energy (in)dependent cooling time-scales than simply applying equation (1) to the individual light curves since the latter is limited by the statistics and associated error of the high-energy light curve. Indeed, applying equation (1) to the daily binned light curves of Fig. 5 does not find any 1–300 GeV flux cooling time-scales at a \( \sigma \) level of confidence. Furthermore, if the application of equation (1) reveals the presence of significant variability time-scales in both the 0.1–1 and 1–300 GeV light curves, a priori knowledge of the magnitude of the time lag is needed to determine if the variability time-scales from the individual energy ranges are related.

The resultant DCFs for the flare 1 and flare 2 events are shown in Figs 8 and 9, respectively, binned in 6 h intervals. A positive time lag, \( t_{\text{lag}} \sim 10^3 \) h, between the two light curves implies...
that the 0.1–1 GeV flux is delayed with respect to the 1–300 GeV flux. However, it is important to note that this delay applies to both the flux increases and flux decreases. To interpret any observed lag in the DCF as evidence for energy-dependent cooling time-scales, one has to assume that there the flux increase in both energy bands occurs at the same time.

The DCF for the flare 2 event exhibits a clear peak. A Gaussian fit to this peak indicates that this temporal lag is $-6.13 \pm 2.83$ h.\(^8\)

\(^8\) It is worth noting that this peak feature is still present if the DCF is rebinned into 12 h intervals, while the 12 h binned DCF for flare 1 still has no well-defined peak, and large errors for negative time lags.
of the function fit was 55850, and 55853 was fitted with both a power law and a power-law description of PKS 1510−089's spectrum. Likewise, towards the end of the flare 1 event, there is also little difference in the TS values of the different spectral shapes. This variation in the TS value for the log-parabola description of the spectrum, relative to the power-law fit, suggests that throughout the flare 1 event, there is a change in the shape of the γ-ray spectrum. What is more, the preference of the log-parabola fit over the power-law fit implies the presence of a spectral cut-off does not automatically imply a BLR origin for the γ-ray flux; for example a cut-off in the γ-ray spectrum can also occur if there is a cut-off in the energy distribution of the particle population responsible for the γ-ray emission.

The daily differences in TS values during the flare 1 and flare 2 events can be seen in Figs 10 and 11, respectively. Flare 1 exhibits a large TS difference, ΔTS > 25, between a power law and a log-parabola description of PKS 1510−089's 0.1 < E < 300 GeV γ-ray spectrum during MJD = 55853, a day before flare 1's maximum flux. However, on MJD = 55850, at the start of flare 1, there is little difference in the TS value from either a power law or log-parabola description of PKS 1510−089's spectrum. Likewise, towards the end of the flare 1 event, there is also little difference in the TS values of the different spectral shapes. This variation in the TS value for the log-parabola description of the spectrum, relative to the power-law fit, suggests that throughout the flare 1 event, there is a change in the shape of the γ-ray spectrum. What is more, the preference of the log-parabola fit over the power-law fit implies the presence of a cut-off in the spectrum.

To investigate this spectral cut-off, the γ-ray spectrum during MJD = 55850 and 55853 was fitted with both a power law and log-parabola function, and the reduced χ² of the function fit was calculated. The spectra were obtained by applying GTLIKE separately to 10 logarithmic energy bins in the 100 MeV to 102.4 GeV energy range. Only energy bins with a GTLIKE TS value greater than 10 were considered in the function fit. The resultant spectrum power-law and

Figure 8. DCF (Edelson & Krolik 1988) calculated between the 0.1–1 GeV and the 1–300 GeV light curves of Fig. 6 for the flare 1 period, 55850 < MJD < 55858, binned in 6 h intervals. The shading indicates the error of the DCF. The DCF indicates that at a time lag of 0, this would suggest that there is no energy dependence to the cooling time-scale, and therefore point towards a BLR origin for the γ-ray emission. However, there is a large amount of uncertainty in the DCF for negative time lags, with additional peaks at ∼−2 and ∼−2.5, and thus it is not possible to draw strong conclusions about the DCF peak at 0 and the DCF for flare 1 in general. Furthermore, the DCF for the flare 2 event suggests that the DCF could be dominated by effects not related to the electron cooling time-scales. As such, this implies that for

Figure 9. DCF (Edelson & Krolik 1988) calculated between the 0.1–1 GeV and the 1–300 GeV light curves of Fig. 7 for the flare 2 period, 55866 < MJD < 55876, binned in 6 h intervals. The shading indicates the error of the DCF. A positive time lag implies that the 0.1–1 GeV flux is delayed with respect to the 1–300 GeV flux. A Gaussian fit to the DCF peak finds a time lag of −6.13 h to be present.

4.3 Photon–photon pair production

Another important difference between the two possible locations for the γ-ray emission regions is the role that photon–photon pair production (γγ → e⁺e⁻) plays in attenuating the emitted γ-ray flux and the subsequently imprint that the process leaves on the observed γ-ray spectrum (Donea & Protheroe 2003; Lui & Bai 2006). Simply put, as a result of photon–photon pair production, the BLR of FSRQs is opaque to γ-rays above ∼20 GeV in energy, while the MT region is not. As a result, if the γ-ray region is located in the BLR, one would expect to see a cut-off in the γ-ray spectrum attributed to pair production, while a γ-ray spectrum originating from the MT would not have such a feature.

To search for a spectral cut-off feature, the flare 1 and flare 2 light curves were again re-analysed in daily bins, with PKS 1510−089 modelled by three additional models to the power law used originally in Section 2. To improve statistics, especially at the high-energy tail of the spectrum, the observations were re-analysed in daily intervals. The additional models utilized were a broken power law, a broken power law with an exponential cut-off and a log-parabola. All other point and diffuse sources in the RoI were modelled as before (see Section 2). The TS value for each model, in each daily bin, was compared to that of a simply power law to investigate if there is a significant deviation from a power-law spectrum during the flaring event. The difference in TS is defined as TSx − TSpower law, where x is the TS value for either the broken power law, broken power law with an exponential cut-off or log-parabola fits. A large positive difference in TS values indicates that the γ-ray spectrum is better described by a function with a cut-off feature then a simple power-law distribution, and as such, suggests the presence of a spectral cut-off. An important caveat of this approach is that the presence of a spectral cut-off does not automatically imply a BLR origin for the γ-ray flux; for example a cut-off in the γ-ray spectrum can also occur if there is a cut-off in the energy distribution of the particle population responsible for the γ-ray emission.
The difference in TS values, defined as $TS_x - TS_{\text{power law}}$, where $x$ is the TS value for either the broken power law, a broken power law with an exponential cut-off or a log-parabola fits, throughout the ‘flare 1’ period. To improve statistics, especially at the high-energy tail of the spectrum, the difference in model TS values was calculated on daily intervals of observations. There is a $TS > 25$ difference between a power law and a log-parabola description of PKS 1510–089 during MJD = 55853.

The spectra of PKS 1510–089 during MJD = 55850 and 55853 can be seen in Figs 12 and 13, respectively. From Fig. 12, it can be seen that at the start of the flare 1 event, when there is no difference in the TS values, the spectrum is well described by a power law, with no indication of a spectral cut-off present. However, the $\gamma$-ray spectrum during MJD = 55853, seen in Fig. 13, exhibits a clear deviation from a simple power-law distribution at the high-energy tail of the spectrum. The deficiency of the power law is confirmed by the reduced $\chi^2$ of the power-law fit, which is 1.885, while the reduced $\chi^2$ of the log-parabola fit is 0.282.

Figure 10. The difference in TS values, defined as $TS_x - TS_{\text{power law}}$, where $x$ is the TS value for either the broken power law, a broken power law with an exponential cut-off or a log-parabola fits, throughout the ‘flare 1’ period. To improve statistics, especially at the high-energy tail of the spectrum, the difference in model TS values was calculated on daily intervals of observations. There is a $TS > 25$ difference between a power law and a log-parabola description of PKS 1510–089 during MJD = 55853.

Figure 11. The difference in TS values, defined as $TS_x - TS_{\text{power law}}$, where $x$ is the TS value for either the broken power law, a broken power law with an exponential cut-off or a log-parabola fits, throughout the ‘flare 2’ period. To improve statistics, especially at the high-energy tail of the spectrum, the difference in model TS values was calculated on daily intervals of observations. No significant difference in TS value is seen throughout the second flare.

log-parabola fits for MJD = 55850 and 55853 can be seen in Figs 12 and 13, respectively. From Fig. 12, it can be seen that at the start of the flare 1 event, when there is no difference in the TS values, the spectrum is well described by a power law, with no indication of a spectral cut-off present. However, the $\gamma$-ray spectrum during MJD = 55853, seen in Fig. 13, exhibits a clear deviation from a simple power-law distribution at the high-energy tail of the spectrum. The deficiency of the power law is confirmed by the reduced $\chi^2$ of the power-law fit, which is 1.885, while the reduced $\chi^2$ of the log-parabola fit is 0.282.

For flare 2, on the other hand, Fig. 11 indicates that there is no significant deviation from a power-law description throughout the flare event, with the greatest difference in TS values being $\sim 10$. What is more, for a large number of days, the TS value for the power-law fit is greater than that of the spectral models with cut-offs. As such, the lack of a spectral cut-off suggests an MT origin for the $\gamma$-ray emission.

Figure 12. The spectrum of PKS 1510–089 during MJD = 55850. The solid green line indicates the best power-law fit to the spectrum, while the dash red line indicates the best log-parabola fit to the spectrum. The reduced $\chi^2$ of the power-law fit is 0.112, while the reduced $\chi^2$ of the log-parabola fit is 0.155. The $\text{GTLIKE}$ fit to the 3.2–6.4 GeV energy band has a TS value less than 10, and as such, was replaced by a 95 per cent confidence upper limit, however, this limit was not included in the reduced $\chi^2$ calculation for the function fit.

Figure 13. The spectrum of PKS 1510–089 during MJD = 55853. The solid green line indicates the best power-law fit to the spectrum, while the dash red line indicates the best log-parabola fit to the spectrum. The reduced $\chi^2$ of the power-law fit is 1.885, while the reduced $\chi^2$ of the log-parabola fit is 0.282.
5 MULTIPLE EMISSION REGIONS

Takens in isolation, the presence or lack of a spectral cut-off or temporal lag in the DCFs does not provide any strong evidence as to the location of the emission region. However, the combination of the two properties allows for a stronger argument as to the possible location.

Flare 1. At its peak flux, the 0.1–300 GeV spectrum of flare 1 (55850 < MJD < 55858) showed significant deviation, greater than TS > 25, from a power-law description, indicating the presence of a spectral cut-off. The presence of this cut-off was confirmed by the reduced $\chi^2$ values for the power-law and log-parabola fits to the 0.1–300 GeV spectrum on MJD = 55853, with the power-law fit having a reduced $\chi^2 = 1.885$ and the log-parabola fits having a reduced $\chi^2 = 0.282$. Because of photon–photon pair production, the spectral cut-off suggests that the $\gamma$-ray emission region associated with this flare is located within the BLR, on the subparsec scale from the central SMBH. While a peak at a time lag of 0 in the 0.1–1 GeV versus 1–300 GeV DCF for flare 1 would suggest that there is no energy dependence to the cooling time-scale, and thus a BLR origin for the $\gamma$-ray emission, the uncertainty in the DCF for negative time lags is too large to draw strong conclusions. Furthermore, the DCF for the flare 2 event suggests that the DCF is dominated by effects not related to the electron cooling time-scales and as such, implies that little is gained from the DCF approach outlined here with regards to determining the location of the $\gamma$-ray emission region.

Flare 2. During the flare 2 period (55866 < MJD < 55876) the daily flux twice exceeded $10^{-5}$ photons cm$^{-2}$ s$^{-1}$. However there was no significant deviation from a power-law distribution at any point during the flare event. As such, without invoking the presence of axion-like particles, the lack of spectral cut-off points towards a MT location for the $\gamma$-ray emission region associated with this flare. The 0.1–1 GeV versus 1–300 GeV DCF for flare 2 does not reveal any evidence for an energy dependence to the cooling time-scales, though this may to be due to the fact that the DCF is dominated by an apparent energy dependence in the flare rise time.

While there is ~8 d between the two flaring episodes, there is evidence indicating that the two flare events are spatially separated by >1 pc, with flare 1 being of BLR origin and flare 2 being of MT origin. Thus a natural conclusion to draw from these studies is that there are multiple, simultaneously active, $\gamma$-ray emission zones along the relativistic jet in both the BLR and MT, capable of emitting 0.1–300 GeV $\gamma$-rays.

Multizone emission models have often been used to explain the broad-band spectral energy distribution of blazars (e.g. see Brown 2006; Nalewajko et al. 2012), or to explain the $\gamma$-ray emission from misaligned AGN (Lenain et al. 2008). However, for these multizone models, the $\gamma$-ray emission origin is either in the BLR or the MT, never both.

From a MWL campaign of PKS 1510–089, during the first 11 months of Fermi-LAT operation, Abd et al. concluded that the $\gamma$-ray emission originated from within the BLR (Abdo et al. 2010b); this conclusion primarily being driven by the presence of a cut-off in the $\gamma$-ray spectrum. However, both Marscher et al. and Orienti et al. have concluded from their respective MWL campaigns of PKS 1510–089 that the $\gamma$-ray originates from outside BLR region (Marscher et al. 2010; Orienti et al. 2013), with their conclusions primarily based on the flaring events being observed simultaneously at $\gamma$-ray, optical and radio wavelengths. The presence of multiple $\gamma$-ray emission regions along the jet allows us to reconcile these seemingly contradictory conclusions, with PKS 1510–089 being able to produce $\gamma$-ray flares from regions both within the BLR and the MT regions of its relativistic jet.

6 VHE EMISSION

Finally I briefly turn my attention to emission of VHE $\gamma$-rays from PKS 1510–089. The detection of VHE $\gamma$-ray photons from FSRQs is difficult to accommodate in a pure BLR-origin model for the location of the $\gamma$-ray emission region. VHE $\gamma$-ray emission from PKS 1510–089 was originally detected by the High Energy Stereoscopic System (HES) telescope array in 2010 and has been recently confirmed by the Major Atmospheric Gamma-Ray Imaging Cherenkov (MAGIC) telescope array (Wagner 2010; Cortina 2012). A gtlike likelihood analysis of all >50 GeV photons from PKS 1510–089 detected by Fermi-LAT, utilizing the same point source and diffuse model as that of Section 2, finds PKS 1510–089 to be a source of VHE $\gamma$-rays at the ~4.6$\sigma$ confidence level. Furthermore, a gtlike likelihood analysis finds PKS 1510–089 to be a source of >20 GeV $\gamma$-rays at the ~13.5$\sigma$ confidence level.

A closer inspection of the individual photon events reveals that the highest energy photon detected from PKS 1510–089 has an energy of 70 GeV, with a total of 11 events above 20 GeV within 0.1 of PKS 1510–089. Kataoka et al. (2010) and Brown & Adams (2011) found that it is the GeV $\gamma$-ray flux and spectral shape that is important when triggering ground-based VHE $\gamma$-ray observations, with a higher GeV flux or, harder $\gamma$-ray spectrum, more likely to be associated with the emission of VHE $\gamma$-ray photons. To investigate if this applies to PKS 1510–089, the arrival times of the >20 GeV photons was compared to the hardness ratio of the light curves of Fig. 5. The hardness ratio was defined as the 1–300 GeV flux divided by the 0.1–1 GeV flux. The light curve of the hardness ratio, binned in daily intervals, along with the arrival times of the >20 GeV photons, can be seen in Fig. 14.

There is no evidence in Fig. 14 of a correlation between the arrival of >20 GeV photons and a spectral hardening as shown by a higher hardness ratio. Furthermore, there does not appear to be any obvious temporal clustering of >20 GeV photons and the hardness ratio only exceeds 0.2 on one occasion. Interestingly, there are no >20 GeV photons around the time where there is a spike in the hardness ratio of ~0.6.

The MAGIC detection of PKS 1510–089 resulted from 10 h of observations taken during the period 2012 February 3 to 2012 February 20 (55960 < MJD < 55980), either side of a full moon period (Cortina 2012). From Fig. 14 we see that there is no obvious increase in the hardness ratio during this period, and no >20 GeV photons were detected either. Likewise, during the HESS observations, 2010 March, only one >20 GeV photon was detected, and the hardness ratio exhibits a slight decreasing trend. As such, it would appear that for PKS 1510–089, there is no obvious 0.1–300 GeV flux trend that leads to the emission of VHE $\gamma$-rays. This can be interpreted as further evidence of multiple emission regions along the jet being simultaneously active, since such a scenario would lead to...
The black crosses represent hardness ratio, defined as the 1–10 GeV photons cm$^{-2}$ s$^{-1}$ flux divided by the 0.1–1 GeV flux, of PKS 1510–089 over the entire 3.75 yr period. The red filled triangles represent the arrival times of VHE emission occurring when the ≥GeV γ-ray flux increased by a factor of 10 over the 0.1–300 GeV flux, while those inside the BLR contributing to the 0.1–10 GeV flux. While this study has unveiled evidence that both the BLR and MT location models are correct, further studies are needed to see if this property is unique to PKS 1510–089 or a characteristic of FSRQs in general.

7 CONCLUSIONS

An in-depth study of the 0.1–300 GeV γ-ray properties of PKS 1510–089 utilizing Fermi-LAT observations from 2008 August to 2012 May has been reported. During this period, PKS 1510–089 has persistently been one of the brightest and most variable AGN observed by the LAT detector. Several large γ-ray flares were observed, where the daily 0.1–300 GeV γ-ray flux exceeded 10$^{-3}$ photons cm$^{-2}$ s$^{-1}$. The photon statistics associated with these large flares allowed the daily-binned light curve to be re-analysed in both 6 and 3 h intervals and still satisfy a TS ≥ 10 criteria for the vast majority of bins. The 3 h binned light curve revealed the presence of doubling/halving time-scales as small as $\tau_{\text{rise}} = 1.30 \pm 0.12$ h and $\tau_{\text{decay}} = 1.21 \pm 0.15$ h.

The 10$^{-3}$ photons cm$^{-2}$ s$^{-1}$ flare periods were studied in more detail in an attempt to find evidence for the location of PKS 1510–089’s γ-ray emission region. In particular, two approaches were used: (i) searching for an energy dependence to the cooling time-scales, and (ii) searching for evidence of a spectral cut-off.

The flare 1 event (55850 < MJD < 55858) possessed a spectral cut-off at its peak flux. However, the uncertainty in the DCF did not allow any clear conclusions on whether an energy dependency in the variability time-scales is present. While there is an apparent peak in the DCF for flare 1 at a time lag of 0, possibly hinting at a BLR origin for the flare, the large uncertainty in the DCF at negative time lag values does not allow for any strong conclusions to be drawn from the DCF with regards to the origin of the γ-ray emission.

The flare 2 event (55866 < MJD < 55876) showed no evidence for a spectral cut-off, possibly hinting at a MT origin of the γ-ray emission. If this is so, one would expect to see an energy dependency to the cooling time-scale. While no evidence for this could be seen in the DCF of the 0.1–1 and 1–300 GeV flux levels, this may be due to the fact that the DCF is dominated by an apparent energy dependence in the flare rise time.

These seemingly contradictory origins for the observed γ-ray flares can be reconciled if there are multiple, simultaneously active γ-ray emission zones along PKS 1510–089’s relativistic jet, capable of emitting 0.1–300 GeV γ-rays. Since the inner regions of FSRQs are opaque to γ-rays above 10–20 GeV in energy, this multizone model can explain the existence of VHE γ-rays for PKS 1510–089, with emission regions in the MT producing the observed VHE flux, while those inside the BLR contributing to the 0.1–10 GeV flux. While this study has unveiled evidence that both the BLR and MT location models are correct, further studies are needed to see if this property is unique to PKS 1510–089 or a characteristic of FSRQs in general.

ACKNOWLEDGEMENTS

I thank SEB for her helpful discussions and insights which have been invaluable to this paper. I also thank the referee for her/his comments and suggestions that improved the quality and clarity of this paper. This work is supported by the Marsden Fund Council from New Zealand Government funding, administered by the Royal Society of New Zealand. This work has made use of public Fermi data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA Goddard Space Flight Center. This work has also made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration.

REFERENCES

Abdo A. A. et al. (Fermi-LAT Collaboration), 2010a, ApJ, 719, 1433
Abdo A. A. et al. (Fermi-LAT Collaboration), 2010b, ApJ, 721, 1425
Abdo A. A. et al. (Fermi-LAT Collaboration), 2010c, ApJ, 722, 520
Abdo A. A. et al. (Fermi-LAT Collaboration), 2011a, ApJ, 733, L26
Abdo A. A. et al. (Fermi-LAT Collaboration), 2011b, ApJ, 743, 171
Agudo I. et al., 2011, ApJ, 726, L13
Aleksic J. et al. (MAGIC Collaboration), 2011a, A&A, 530, 4
Aleksic J. et al. (MAGIC Collaboration), 2011b, ApJ, 730, 8
Atwood W. B. et al., 2009, ApJ, 697, 1071
Bromberg O., Levinson A., 2009, ApJ, 699, 1274
Brown A. M., 2006, PhD thesis, Univ. Durham, UK
Brown A. M., Adams J., 2011, MNRAS, 413, 2785
Cortina J., 2012, Astron. Telegram, #3965
Dermer C. D., Finke J. D., Krug H., Bottcher M., 2009, ApJ, 692, 32
Donea A.-C., Protheroe R. J., 2003, Astropart. Phys., 18, 377
Dotson A., Georganopoulos M., Kazanas D., Perlman E. S., 2012a, ApJ, 758, 15
Dotson A., Georganopoulos M., Kazanas D., Perlman E. S., 2012b, in Fermi & Jansky Proc., preprint (arXiv:1206.0012)
Edelson R. A., Krolik J. H., 1988, ApJ, 333, 646
Foschini L. et al., 2006, A&A, 450, 77
Foschini L., Ghisellini G., Tavecchio F., Bonnoli G., Stamerra A., 2011, A&A, 530, 77
Ghisellini G., Tavecchio F., 2009, MNRAS, 397, 985
Ghisellini G., Tavecchio F., Ghirlanda G., Maraschi L., Celotti A., 2010, MNRAS, 402, 497
Harris J., Daniel M. K., Chadwick P. M., 2012, ApJ, 761, 2
Horns D., Maccione L., Meyer M., Mirizzi A., Montanino D., Roncadelli M., 2012, Phys. Rev. D, 86, 5024
Jorstad S. G. et al., 2005, AJ, 130, 1418
γ-ray properties of PKS 1510−089

Kadota A., Fujisawa K., Sawada-Satoh S., Wajima K., Doi A., 2012, PASJ, 64, 109
Kataoka J. et al., 2010, ApJ, 715, 554
Kohler S., Begelman M. C., Beckwith K., 2012, MNRAS, 422, 2282
Komatsu E. et al., 2009, ApJS, 180, 330
Lahteenmaki A., Valtaoja E., 2003, ApJ, 590, 95L
Lenain J.-P., Boisson C., Sol H., Katarzynski K., 2008, A&A, 478, 111
Lott B., Escande L., Larsson S., Ballet J., 2012, A&A, 544, A6
Lui H. T., Bai J. M., 2006, ApJ, 653, 1089
Marscher A. P. et al., 2010, ApJ, 710, 126
Mattox J. R. et al., 1996, ApJ, 461, 396
Nalewajko K., Sikora M., Madejski G. M., Exter K., Szostek A., Szczerba R., Kidger M. R., Lorente R., 2012, ApJ, 760, 69
Nishikawa K.-I., Hardee P., Richardson G., Preece R., Sol H., Fishman G. J., 2003, ApJ, 595, 555
Nolan P. L. et al., 2012, ApJS, 199, 31
Orienti M. et al., 2013, MNRAS, 428, 2418
Perucho M., Lobanov A. P., Martí J.-M., Hardee P. E., 2006, A&A, 456, 493
Poutanen J., Sterl B., 2010, ApJ, 717, L118
Ritz S., 2007, in Ritz S., Michelson P., Meegan C., eds, AIP Conf. Proc. Vol. 921, Overview of GLAST Mission and Opportunities. Am. Inst. Phys., New York, p. 3
Roncadelli M., De Angelis A., Galanti G., 2012, J. Phys. Conf. Ser., 375, 2029
Sokolov A., Marscher A. P., McHardy I. M., 2004, ApJ, 613, 725
Tavecchio F., Ghisellini G., Bonnoli G., Ghirlanda G., 2010, MNRAS, 405, 94
Tavecchio F., Roncadelli M., Galanti G., Bonnoli G., 2012, Phys. Rev. D, 86, 5024
Vercellone S., Soldi S., Chen A. W., Tavani M., 2004, MNRAS, 353, 890
Wagner S., 2010, HEAD Meeting, 11, 2706

This paper has been typeset from a \LaTeX file prepared by the author.