PROCEEDINGS OF SCIENCE

The FSRQ PKS 1510-089: The Gamma-ray–Synchrotron Connection

Felix Jankowsky[*,a] **Stefan J. Wagner,**[a] **Omar Kurtanidze**[b] **and Michael Zacharias**[c]
[a]*Landessternwarte, Universität Heidelberg, Königstuhl, 69117 Heidelberg, Germany*
[b]*Abastumani Observatory, Mt. Kanobili, 0301 Abastumani, Georgia*
[c]*Centre for Space Research, North-West University, Potchefstroom 2520, South Africa*
E-mail: f.jankowsky@lsw.uni-heidelberg.de, swagner@lsw.uni-heidelberg.de, o.kurtanidze@lsw.uni-heidelberg.de, mzacharias.phys@gmail.com

The flat spectrum radio quasar (FSRQ) PKS 1510-089 (z=0.361) is known for its complex multi-wavelength behaviour. Since 2015, it has been very active across the entire electromagnetic spectrum. This has lead to joint observation campaigns including Fermi-LAT, Cherenkov telescopes and several instrument covering the synchrotron branch. Observations resulted in a range of remarkable measurements, including rapid flares above 200 GeV with peak-fluxes exceeding the long-term average by up to a factor of 30 and unprecedented optical flares peaking in R-band at 13.6 magnitudes. The comparison of the various multi-wavelength light-curves also show that different events follow different spectral evolution within the gamma-ray band and display different relationships to the synchrotron emission. We discuss different selection effects as well as the effect of pair-absorption on flares originating at different distances from the core and conclude that absorption in the BLR is not the sole reason for the broad-band diversity. This diversity of multi-frequency correlations during different flares also reflects a diversity in physical properties of the emission regions and – possibly – even different dominating radiation mechanisms. This has implications for interpretations of orphan flares and searches for potential correlations to neutrino emission in AGN.

7th Fermi Symposium 2017
15-20 October 2017
Garmisch-Partenkirchen, Germany

[*]Speaker.

PoS(IFS2017)034

1. Introduction

Flat-spectrum radio quasars (FSRQ) are blazars, hosting jets which are closely aligned with the line of sight, resulting in strongly beamed radiation in the observer's frame. Furthermore, they show broad emission lines in the optical spectrum. This means that the nuclear region surrounding the black hole and the jet-launching site contains the so-called broad-line region (BLR) – hot material emitting Doppler broadened lines.

PKS 1510-089 (redshift $z = 0.36$) is a particularly active source and is monitored in several energy bands. These observations reveal a complex multi-wavelength behaviour [1, 2] with changing correlation patterns between different wavelengths. This has lead to different interpretations, such as the requirement of at least two radiative emission components [3], or two spatially distinct emission zones [4].

In the past, the source has been extensively studied in X-ray [5, 6, 7], optical [8] and radio bands. VLBA observations point at very strong Doppler boosting in its jet [9, 10]. The source exhibits an FSRQ-typical spectral energy distribution (SED) dominated by two components. According to leptonic models, these are attributed to electron-synchrotron radiation peaking in the infrared regime and inverse Compton scattering of ambient soft photon fields peaking in gamma-rays [8].

More recently, it came into focus of very-high energy (VHE, $E > 100\,\mathrm{GeV}$) instruments [11] in order to further understand the inner workings of relativistic jets – efforts which have been accompanied by optical coverage. In this work, observations with ATOM and Fermi-LAT as well as H.E.S.S. and MAGIC [12, 13] from 2015 and 2016 are discussed.

2. Data analysis

2.1 Fermi-LAT

An analysis of the publicly available Fermi-LAT Pass 8 SOURCE class events above an energy of 100 MeV was performed for a Region of Interest (RoI) of 15° radius centred at the position of PKS 1510-089 in the time frame 2015 to 2016. All sources within the RoI (and 7° beyond) pertaining to the 3FGL catalogue have been accounted for in the likelihood analysis. In order to reduce contamination from the Earth Limb, a zenith angle cut of < 90° was applied. The analysis was performed with ScienceTools software package version `v10r0p5` using the `P8R2_SOURCE_V61` instrument response function and the `GLL_IEM_V06` and `ISO_P8R2_SOURCE_V6_V06` models for the Galactic and isotropic diffuse emission, respectively. In order to produce a finely binned (24h bins) lightcurve, a power-law model for the spectrum was assumed with the parameters left free to vary from bin to bin. The binning is centred on midnight UTC in order to synchronise it with night-time observations in Namibia. However, this does not eliminate the caveat that daily binned lightcurves of optical, Fermi-LAT and VHE data sample each 24h bin differently. Any comparison of these binned light-curves might therefore be affected by intra-day (less than 24h) variations.

2.2 ATOM

The Automatic Telescope for Optical Monitoring (ATOM) is a 75 cm telescope located at the H.E.S.S. site in Namibia. It monitors around 300 γ-ray emitters – most of which have been detected with Fermi-LAT – in R and B bands and provides Target-of-Opportunity triggers for H.E.S.S. as well as optical coverage for ongoing H.E.S.S. observations. It thus enables multi-wavelength comparisons for flaring events seen with H.E.S.S.

PKS 1510-089 has been monitored with ATOM since 2007. Following flares in 2015 and 2016 the coverage increased. The source flux is derived via differential photometry with 5 custom calibrated secondary standard stars in the same field of view.

3. Lightcurves and correlations

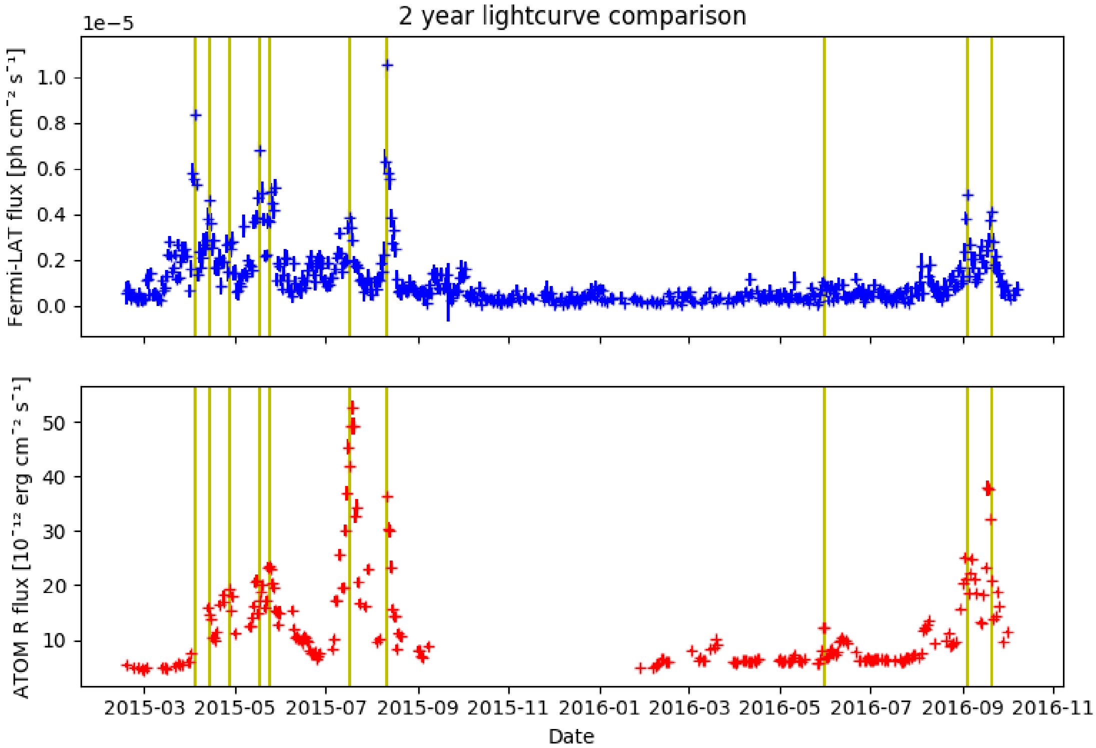

Figure 1: GeV (Fermi-LAT, top) and optical (ATOM, bottom) lightcurve of PKS 1509-089 during 2015 and 2016. Data are averaged in 24h bins with a common phase. The yellow lines mark pronounced flares in the optical, GeV, or TeV bands.

Flux variations during 2015 and 2016 are shown in figure 1. PKS 1510-089 has been very variable over the course of these two years and the flux ratio $\frac{F_\gamma}{F_{\text{optical}}}$ is clearly not constant between different flares.

For example, the two bright flares centred around 17 July 2015 and 11 August 2015 respectively display a marked difference. For the former the Fermi-LAT flux peaks at $(3.9 \pm 0.4) \times 10^{-6}\,\text{ph}/\text{cm}^2\text{s}$ while the ATOM flux peaks at $(54.2 \pm 1.7) \times 10^{-12}\,\text{erg}/\text{cm}^2\text{s}$. For the latter flare the flux derived with LAT is $(10.5 \pm 0.7) \times 10^{-6}\,\text{ph}/\text{cm}^2\text{s}$ compared to an optical flux of $(36.4 \pm 1.2) \times 10^{-12}\,\text{erg}/\text{cm}^2\text{s}$. This results in a GeV-$\gamma$/optical flux ratio which differs by more than a factor of four between the two events. The GeV-γ/optical flux ratios do not seem to cluster around discrete values but appear to be represented by a continuous distribution of γ/optical ratios.

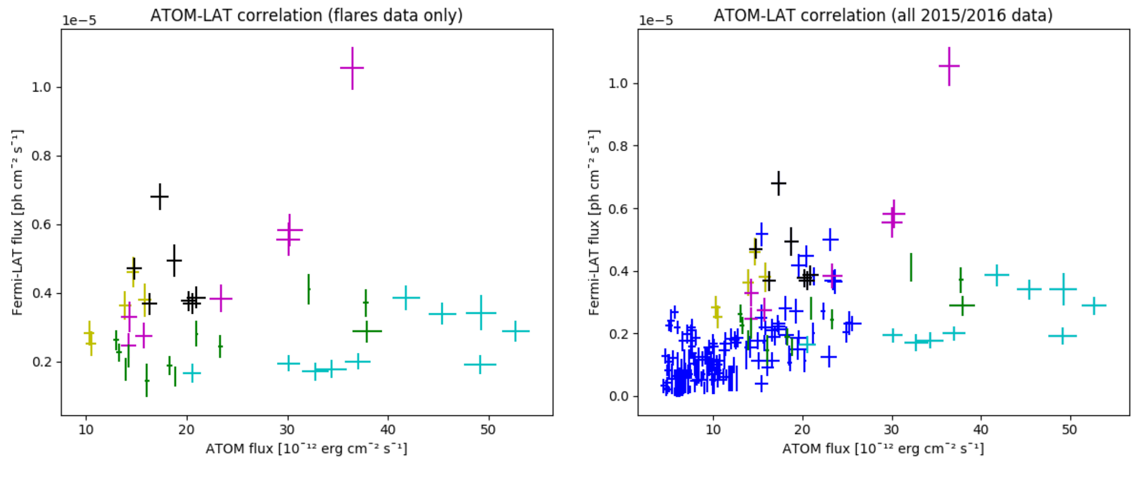

Figure 2: (a) ATOM/Fermi-LAT correlation for selected, well-resolved flares, sampled by several 24h bins. Each colour denotes a different flare. (b) Same, with data during quiescence' for 2015 and 2016 added in dark blue.

In order to study the evolution of the γ/optical flux ratio during individual flares that can be well-resolved in time, five isolated, well-sampled events are compared in figure 2. For any of the events a linear correlation between the GeV-γ-ray and optical flux is observed, but the slope of the relations during different events varies significantly. Including the full set of simultaneous measurements a correlation between optical and GeV γ-ray fluxes is only marginally significant and exhibits a scatter of up to a factor of five at fixed optical or gamma-ray fluxes.

Despite the poor correlation in the amplitudes of individual events, a highly significant cross-correlation of the light-curves without any significant lag is observed. This justifies the comparison of contemporaneous bins and excludes the possibility that the poor correlation of amplitudes is caused by temporal lags.

4. Discussion

As stated in the introduction, the SED of PKS 1510-089 is dominated by a synchrotron and an inverse Compton component. Significant spectral evolution during flares in either of the two components might result in the scatter observed for the variations in flux ratio between optical and gamma-ray seen in this source.

4.1 Optical spectral evolution

In order to examine possible spectral changes in the synchrotron emission, multi-band observations of August and September 2016 with ATOM are shown in figure 3. A significant correlation between R band flux and B – R colour is detected. A brightening of PKS 1510-089 corresponds to a change in colour to the red – which means that the observed optical spectrum becomes softer.

The flux measured in the optical band includes the contributions of synchrotron radiation peaking in the IR band, the photo-ionising continuum responsible for the BLR emission peaking in the

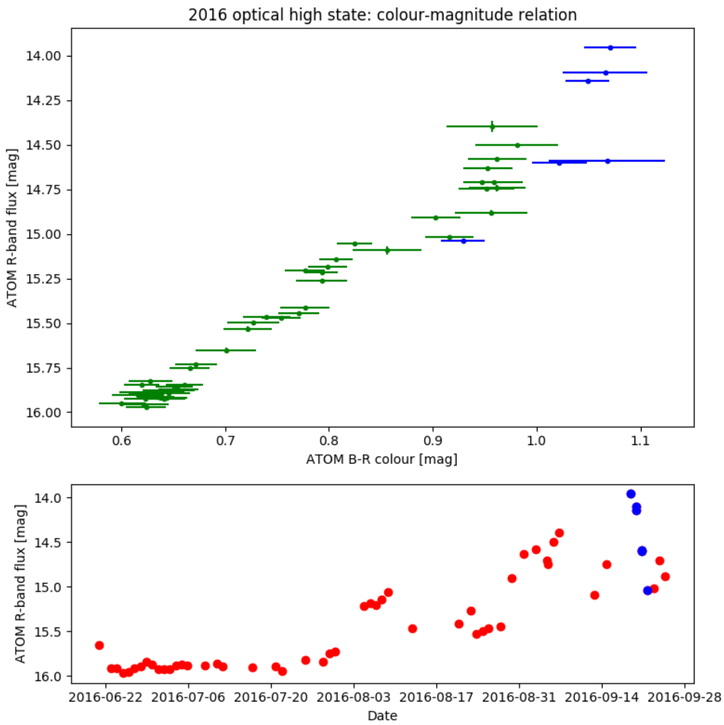

Figure 3: Colour-flux correlation of ATOM observations (top) and the corresponding R-band lightcurve (bottom). The blue data points in each plot correspond to each other.

UV and the host galaxy emission peaking in the visible spectrum [8]. A flux increase of the synchrotron component will reduce the relative contributions of the host galaxy and thermal AGN emission and result in an integrated colour that is closer to the intrinsic synchrotron emission.

A second argument against variability of thermal radiation is the short time scales of the changes. As is shown with the blue points in figure 3, the optical flux can change by roughly 1 mag over the course of three days. Such fast changes cannot be explained with changes in thermal emission originating in the BLR and the photo-ionizing accretion disk.

It can therefore be concluded that the poor γ/optical correlation is neither due to fast spectral variations in the synchrotron emission nor due to changes in the host or BLR contamination of the observed optical spectrum.

4.2 γ-ray spectral evolution

In inverse Compton radiation the optical band probes particle energies above the energy range of Fermi-LAT. Given the observed optical variability it is therefore beneficial to compare the fluxes in the GeV range with those in TeV, as different slopes in the inverse Compton spectrum could also be cause for the multi-wavelength behaviour of PKS 1510-089.

In 2015, the H.E.S.S. collaboration conducted a monitoring programme on this source and observed several of the flares during that time period. Comparison with Fermi-LAT data yields a poor correlation between the GeV and TeV bands [12]. The inner part of the jet of PKS 1509-089 is surrounded by a very luminous BLR, providing an intense radiation field which might contribute to the GeV gamma-ray emission by supplying seeds for external Compton scattering while at the same time absorbing TeV emission by photon-photon pair absorption. Different ratios of GeV and TeV flux may in principle be a result of different flares originating from regions that suffer different amounts of TeV absorption, i.e. originating at different distances from the black hole. This possibility can be tested by dense sampling of individual events across the entire SED.

4.3 The VHE flare in May 2016

In May 2016, a joint Target-of-Opportunity campaign with H.E.S.S., MAGIC and ATOM observed an extremely bright VHE flare including significant intra-night variation [13], accompanied by a flare with moderate amplitudes in the GeV and optical bands. While the integrated Fermi-LAT flux above 100 MeV did not show pronounced variability, a significant spectral hardening was detected. This indicates that while the overall, MeV dominated flux observed by Fermi-LAT remained low, the flare set in at energies in the GeV band.

The flux recorded with Fermi-LAT was too low to trace the spectral evolution in the GeV band but illustrates that the variations in the GeV-TeV ratio in this case constitutes a flare in only the high-energy part of the observed inverse Compton emission. This cannot be caused by variable BLR absorption or variations in the seed field for external Compton scattering.

5. Summary

The flaring characteristics of PKS 1510-089 reveal different flares exhibiting different scalings of $\frac{F_{\mathrm{optical}}}{F_{\mathrm{GeV}}}$ and $\frac{F_{\mathrm{GeV}}}{F_{\mathrm{TeV}}}$. However, by examining flares from a multi-wavelength perspective we can rule out potential biases. While the long integration time required for binning Fermi-LAT data affects conclusions on intra-day variability, binning and phasing of different data sets is not responsible for the lack of multi-wavelength correlation. The same is true for contamination of the optical information by host galaxy and BLR, as the short time-scales of variability during flares cannot be explained in that way. The very good correlation between optical spectrum and flux also disqualifies fast spectral variability in the electron-synchrotron emission. The occurrence of a one-night TeV flare without a MeV counterpart is a strong argument against pair absorption as the reason for spectral variability in the inverse Compton radiation.

This leaves flares by multiple components or due to different radiation mechanisms as the main candidates to explain the behaviour of PKS 1510-089.

It is possible that some of the gamma-ray flares are dominated by leptonic processes while others have a hadronic origin. The diversity in multi-frequency behaviour may therefore also affect searches for potential correlations of AGN activity and neutrino emission.

The difference in scaling relations between different flares implies that some of the 'orphan' flares (flares recorded at gamma-ray energies that have not been recorded in contemporaneous monitoring of the synchrotron component) may result from selection effects.

PKS 1510-089 is an unusual gamma-bright FSRQ, exhibiting an unusually bright BLR, an unusually bright blue bump and unusually high Doppler boosting. It is unclear, whether these individual properties are responsible for the unusual multi-frequency behaviour, or whether its properties are shared among all blazars given proper sampling in different bands.

PoS(IFS2017)034

References

[1] A. M. Brown, *Locating the γ-ray emission region of the flat spectrum radio quasar PKS 1510-089*, MNRAS **431** (May, 2013) 824–835, [1301.7677].

[2] S. Saito, Ł. Stawarz, Y. T. Tanaka, T. Takahashi, M. Sikora and R. Moderski, *Time-dependent Modeling of Gamma-Ray Flares in Blazar PKS1510–089*, ApJ **809** (Aug., 2015) 171, [1507.02442].

[3] K. Nalewajko, M. Sikora, G. M. Madejski, K. Exter, A. Szostek, R. Szczerba et al., *Herschel PACS and SPIRE Observations of Blazar PKS 1510-089: A Case for Two Blazar Zones*, ApJ **760** (Nov., 2012) 69, [1210.4552].

[4] A. Barnacka, R. Moderski, B. Behera, P. Brun and S. Wagner, *PKS 1510-089: a rare example of a flat spectrum radio quasar with a very high-energy emission*, A&A **567** (July, 2014) A113, [1307.1779].

[5] K. P. Singh, C. R. Shrader and I. M. George, *X-Ray Spectrum of the High-Polarization Quasar PKS 1510-089*, ApJ **491** (Dec., 1997) 515–521, [astro-ph/9708073].

[6] F. Tavecchio, L. Maraschi, G. Ghisellini, A. Celotti, L. Chiappetti, A. Comastri et al., *Gamma-loud Quasars: A View with BeppoSAX*, ApJ **543** (Nov., 2000) 535–544, [astro-ph/0006443].

[7] J. K. Gambill, R. M. Sambruna, G. Chartas, C. C. Cheung, L. Maraschi, F. Tavecchio et al., *Chandra observations of nuclear X-ray emission from a sample of radio sources*, A&A **401** (Apr., 2003) 505–517, [astro-ph/0302265].

[8] J. Kataoka, G. Madejski, M. Sikora, P. Roming, M. M. Chester, D. Grupe et al., *Multiwavelength Observations of the Powerful Gamma-Ray Quasar PKS 1510-089: Clues on the Jet Composition*, ApJ **672** (Jan., 2008) 787–799, [0709.1528].

[9] J. F. C. Wardle, D. C. Homan, C. C. Cheung and D. H. Roberts, *The Ultra-Fast Quasar PKS 1510-089: Direct Evidence for a Changing Orientation of the Central Engine*, in *Future Directions in High Resolution Astronomy* (J. Romney and M. Reid, eds.), vol. 340 of *Astronomical Society of the Pacific Conference Series*, p. 67, Dec., 2005.

[10] S. G. Jorstad, A. P. Marscher, M. L. Lister, A. M. Stirling, T. V. Cawthorne, W. K. Gear et al., *Polarimetric Observations of 15 Active Galactic Nuclei at High Frequencies: Jet Kinematics from Bimonthly Monitoring with the Very Long Baseline Array*, AJ **130** (Oct., 2005) 1418–1465, [astro-ph/0502501].

[11] S. J. Wagner and H.E.S.S. Collaboration, *Detection of VHE Gamma-ray Emission from a Type 1 Quasar*, in *AAS/High Energy Astrophysics Division #11*, vol. 11 of *AAS/High Energy Astrophysics Division*, p. 27.06, Nov., 2010.

[12] M. Zacharias, F. Jankowsky, M. Mohamed, H. Prokoph, D. Sanchez, S. Wagner et al., *Monitoring of the FSRQ PKS 1510-089 with H.E.S.S*, *ArXiv e-prints* (Aug., 2017) , [1708.00623].

[13] M. Zacharias, J. Sitarek, D. Dominis Prester, F. Jankowsky, E. Lindfors, M. Mohamed et al., *The exceptional VHE gamma-ray outburst of PKS 1510-089 in May 2016*, *ArXiv e-prints* (Aug., 2017) , [1708.00653].