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The optical-gamma correlation in BL Lacertae

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Abstract. We present multifrequency light curves of BL Lacertae from February 2008 to October 2012. Low-energy data (optical and millimetre) were acquired in the framework of a GASP-WEBT project. High-energy data (ultraviolet, X-ray, and γ-ray) come from observations of the *Swift*, *RXTE*, and *Fermi* satellites. After a period of moderate activity, in May 2011 the source suddenly started to flare at γ and optical-UV frequencies. Activity at millimetre wavelengths and X rays began 3-4 months later. This behaviour offered a good opportunity to study the correlation among flux variability in different bands, in particular between the best-sampled optical and γ-ray light curves. However, even in this fortuitous case, we can only define a general correlation with likely no time lag, but with a lag uncertainty of ±1 day. Indeed, the data reveal a complex relationship between the γ and optical fluxes, which cannot be unveiled because of the small gaps in the sampling of this extremely variable source.

1 Introduction

The GLAST-AGILE Support Program (GASP) of the Whole Earth Blazar Telescope[1](WEBT) collaboration was started in 2007. The aim was to perform continuous monitoring of selected blazars at optical, near-infrared and radio frequencies, to compare with the high-energy observations of γ-ray satellites. BL Lacertae, the prototype of one of the two blazar classes, that of the "BL Lac" objects[2], is one of the sources followed by the GASP. It is hosted by a giant elliptical galaxy with $R = 15.5$ [1] at redshift $z = 0.069$ [2], and its flux is heavily absorbed by the Milky Way (Galactic extinction towards BL Lacertae is about 0.88 mag in the R band). A continuous γ-ray light curve of BL Lacertae has been provided by *Fermi* since its launch, in 2008. From that time, the source has been moderately active at γ rays as well as at optical frequencies until May 2011, when it started a series of strong flares in both bands lasting about 18 months. This flaring activity provided a good opportunity to study the optical-γ correlation and relationship with the flux behaviour at other frequencies.

1. http ://www.oato.inaf.it/blazars/webt/
2. Flat spectrum radio quasars (FSRQ) form the other blazar class.

2 Multifrequency light curves

Figure 1 shows the multifrequency behaviour of the BL Lacertae flux from February 2008 to October 2012. From top to bottom we see :

- The weekly-binned γ-ray flux in the 0.1-100 GeV energy range from the LAT detector onboard *Fermi*.
- The X-ray light curve from *Swift*-XRT (flux density at 1 keV) and *RXTE*-PCA (cts/s in the 2-10 keV range, properly rescaled).
- The UV flux densities in the *Swift*-UVOT $w1$ band, after correction for the Galactic extinction and subtraction of the host galaxy contribution.
- The R-band flux densities, after correction for the Galactic extinction and subtraction of the host galaxy contribution.
- The millimetre (230 GHz) light curve built with data acquired with the SubMillimeter Array (SMA) and IRAM 30 m telescope[3].

3. IRAM 30 m data were acquired as part of the POLAMI (Polarimetric AGN Monitoring with the IRAM-30 m-Telescope) and MAPI (Monitoring AGN with Polarimetry at the IRAM-30m- Telescope) programmes.

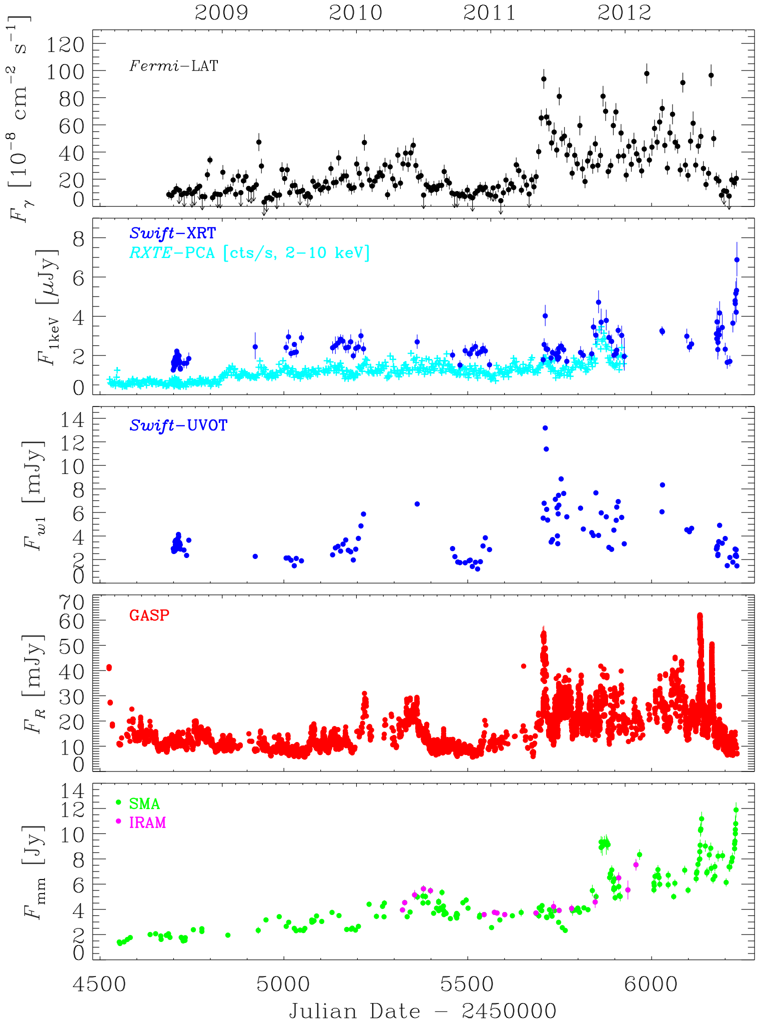

Figure 1. Multifrequency flux behaviour of BL Lacertae from February 2008 to October 2012. See text for details.

The *R*-band light curve in figure 1 was obtained by carefully assembling data from the following observatories participating to this GASP project : Abastumani, AstroCamp, Belogradchik, Calar Alto [4], Crimean, Galaxy View, Kitt Peak (MDM), Lowell (Perkins), Lulin, Mt. Maidanak, New Mexico Skies, ROVOR, Roque de los Muchachos (KVA and Liverpool), Rozhen, Sabadell, San Pedro Martir, Skinakas, St. Petersburg, Steward [5] (Bok and Kuiper), Talmassons, Teide (IAC80), and Tijarafe. It includes 10103 data points.

The figure shows a general correlation between the γ-ray and optical (and UV) fluxes ; in particular, they both increased suddenly in May 2011, introducing a long period of intense activity lasted until October 2012. This suggests that the γ-ray and optical radiations are produced in the same jet region and that γ photons are obtained by inverse-Compton scattering of soft photons off the same relativistic electrons that emit the optical photons through a synchrotron process.

4. Calar Alto data was acquired as part of the MAPCAT project : http ://www.iaa.es/~iagudo/research/MAPCAT

5. `http://james.as.arizona.edu/~psmith/Fermi`

A growth of activity was also observed in the millimetre band, but with a delay of 4-5 months, which may indicate that the millimetre emitting zone is located downstream in the jet from the γ/optical region. The X-ray light curve is not well sampled during the outburst, but the X-ray flux seems to correlate with the millimetre flux. If this is the case, the X-ray radiation would likely come from inverse Comptonisation occurring in the millimetre zone.

3 Spectral energy distribution

We selected six periods where there was enough statistics to perform a spectral analysis of the γ-ray flux. Period 1 goes from 2011 May 15 to June 11 ; Period 2 from 2011 July 3 to 9 ; Period 3 from 2011 October 30 to November 12 ; Period 4 from 2012 February 26 to March 3 ; Period 5 from 2012 April 1 to 14 ; Period 6 from 2012 August 19 to 31. The γ-ray spectra were fitted with a log parabola $dN/dE \propto (E/E_0)^{-\alpha-\beta \log(E/E_0)}$, with the reference energy E_0 fixed to 388.5 MeV as in the 2FGL catalogue [3]. Figure 2 shows the spectral energy distribution of BL Lacertae in these periods built with simultaneous data. The dispersion of the γ spectra reflects the uncertainties on the fits.

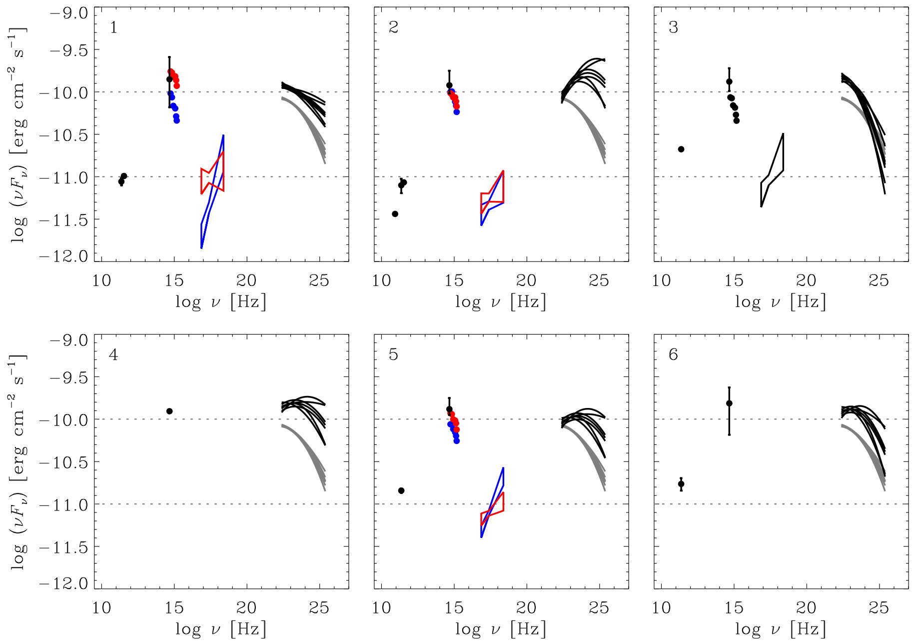

FIGURE 2. Spectral energy distribution of BL Lacertae from millimetre to γ-ray frequencies, during six periods of high γ-ray flux in 2011–2012.

The grey γ-ray spectrum is the result of considering the whole outburst, from 2011 May 1 to 2012 August 31. In case there were multiple *Swift* observations in the same period, we showed the brightest and faintest UV and X-ray states. Because of the dense *R*-band sampling, we plotted the whole variability range at this frequency. Millimetre observations were available for all epochs but one.

The γ-ray spectrum displays noticeable variability, suggesting that the peak of the inverse-Compton emission component moves from the MeV to the GeV range. In Period 1 the optical specral steepening in the low flux state corresponds to an X-ray spectral hardening.

4 Gamma-optical correlation

A cross-correlation analysis of the γ-ray and optical light curves by means of the Discrete Correlation Function (DCF) reveals a fair correlation between the γ and optical flux variations, with no time lag. Monte Carlo simulations allow us to define an uncertainty of ± 1 day on the time lag. This result reflects an average behaviour, suggesting co-spatiality of the γ-ray and optical emission regions, but a deeper analysis reveals a complex correlation, which is difficult to explain.

Figure 3 displays the γ-ray (top) and optical (bottom) light curves during the 2011–2012 outburst. Sub-daily binned γ-ray fluxes (green diamonds) are superposed to the daily-binned ones (blue crosses), while before and after the outburst the γ-ray fluxes are weekly binned (black dots). We notice that the strongest observed γ-ray flare at JD=2456084 does not correspond to the strongest observed optical flare, which instead peaked at JD=2456131–32. This in turn has just a modest counterpart at γ rays.

A zoom into the periods corresponding to the major optical flares, as displayed in figure 4, reveals that a better definition of the γ-optical correlation is hindered by the small gaps in the sampling, because of the extremely fast variability of the source. Indeed, around JD=2455710 there are many optical peaks either preceding or following the γ peaks, so it is difficult to establish correspondences. The γ-ray and optical events at JD=2456131–32 could be simultaneous, if we missed an optical maximum between the observed rising and falling stages. The γ-ray peak at JD=2456164 is preceded by two very fast optical flares, but we could have missed a contemporaneous optical event.

We finally notice that, in general, optical flares present more spikes than the γ-ray ones, which can only partly be justified by the different sampling. They also develop on longer time scales. It is possible that the optical emitting region in the jet is made up of substructures and that not all of them emit γ-ray photons.

A more detailed presentation of these data, together with an analysis of the BL Lacertae optical polarisation and interpretation of flux and polarisation variability, can be found in [4].

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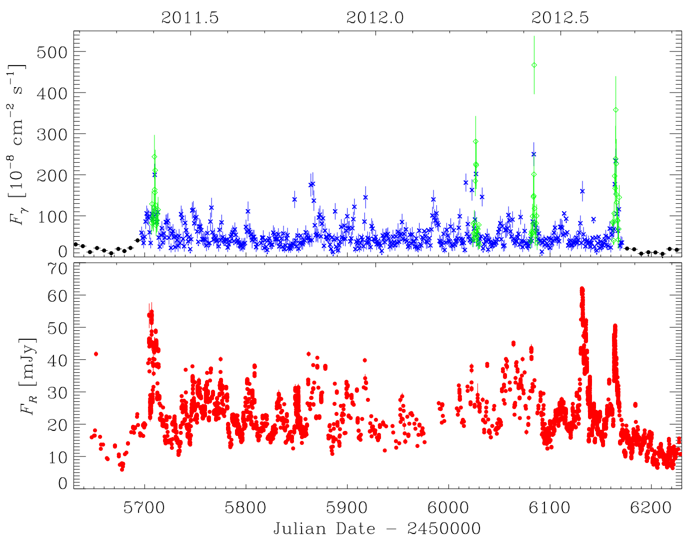

FIGURE 3. Top : weekly (black dots), daily (blue crosses), and sub-daily (green diamonds) binned γ-ray fluxes of BL Lacertae during the 2011–2012 outburst. Bottom : optical light curve in the same period.

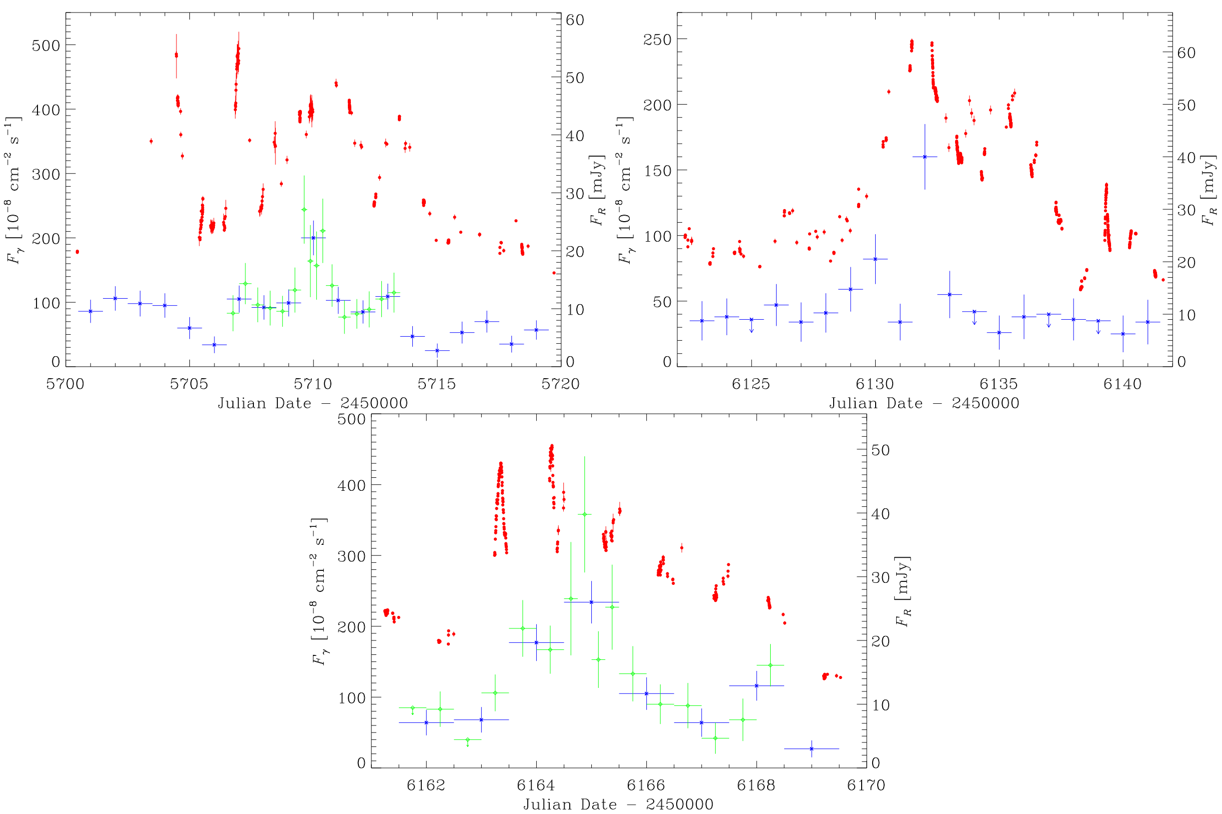

FIGURE 4. Comparison between the R-band flux densities (red dots) and γ-ray daily (blue crosses) and sub-daily (green diamonds) fluxes in 2011 May 18 – June 7 (upper left), 2012 July 13 – August 2 (upper right), and 2012 August 21–30 (bottom).

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