Continuous optical monitoring of the highly active blazar Mrk421

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Abstract. We present the recent photometric monitoring of blazar Mrk421, obtained from the Gerostathopouleio Observatory at University of Athens. Follow-up observations have been performed on this source after a highly energetic flare which occurred on 12 April, 2013. The flare was observed in X- rays by Nustar & Swift and in GeV - TeV gamma-rays by the Fermi satellite and MAGIC/VERITAS telescopes respectively. Continuous photometric monitoring in the optical BVRI bands during 3 months after the flaring activity reveals a quasi-periodic light variation. This is one of the few times that Mrk421 was observed for such a long period without large observational gaps in four different filters. We find a strong correlation between the different optical bands. Although we did not detect any signs of intra-day variability, the optical flux is variable in longer time scales (days/weeks) with the relative amplitude of variations being approximately the same in all four bands.

Observations or Mrk 421

Mrk 421 is one of the closest to earth blazars at redshift z=0.031 (Punch et al. 1992) and it is classified as a high-peaked BL Lac object since the low-energy bump peaks in the UV/soft X-rays energy band. It has been detected in all energies of the electromagnetic spectrum, i.e. from radio wavelengths (e.g. Rebillot et al. 2006) up to Very High Energy (VHE) gamma-rays (Punch et al. 1992) and it has been a target of simultaneous multi-wavelength (MW) observing campaigns, e.g. Takahashi et al. 2000, Gupta et al. 2008, Fossati et al. 2008.

Photometric observations were obtained with the 0.40 m f/8 Cassegrain reflector at the University of Athens Observatory (located in Athens, Greece), and a SBIG ST-10 XME CCD camera, equipped with a set of U, B, V, R, I (Bessell) filters. The data span over a period of 135 days between March – July 2013, covering the variability in all optical bands. During this period Mrk 421 exhibited bright flaring activity in the X-rays up to the VHE gamma-rays, which motivated our long-term optical monitoring of the blazar. Our optical data set is one of the longest optical photometric observing run obtained for Mrk421, resulting in a dense and homogeneous data sample, since only one telescope was used.

Differential aperture photometry was performed on all images, using the AIP4WIN software (Berry & Burnell, 2000). The comparison and check stars were chosen according to Villata et al. (1998). However, since these stars are quite faint in comparison to the high optical emission of Mrk421 during this period, the stars GSC 3010:0688 and GSC 3010:0762 were used as comparison and check stars respectively.

Photometric uncertainty was typically 0.03 mag in all filters. The light contribution from the nearby host galaxy was excluded from the overall magnitude estimation, since the photometric aperture was chosen to be as small as 8 arcsec in radius, while the host galaxy is 10 arcsec away from Mrk421. The resulting photometric light curves, which are shown in Fig. 1, have been obtained after calibration to the standard system and converted into flux units (erg $cm^{-1}sec^{-1}Hz^{-1}$).

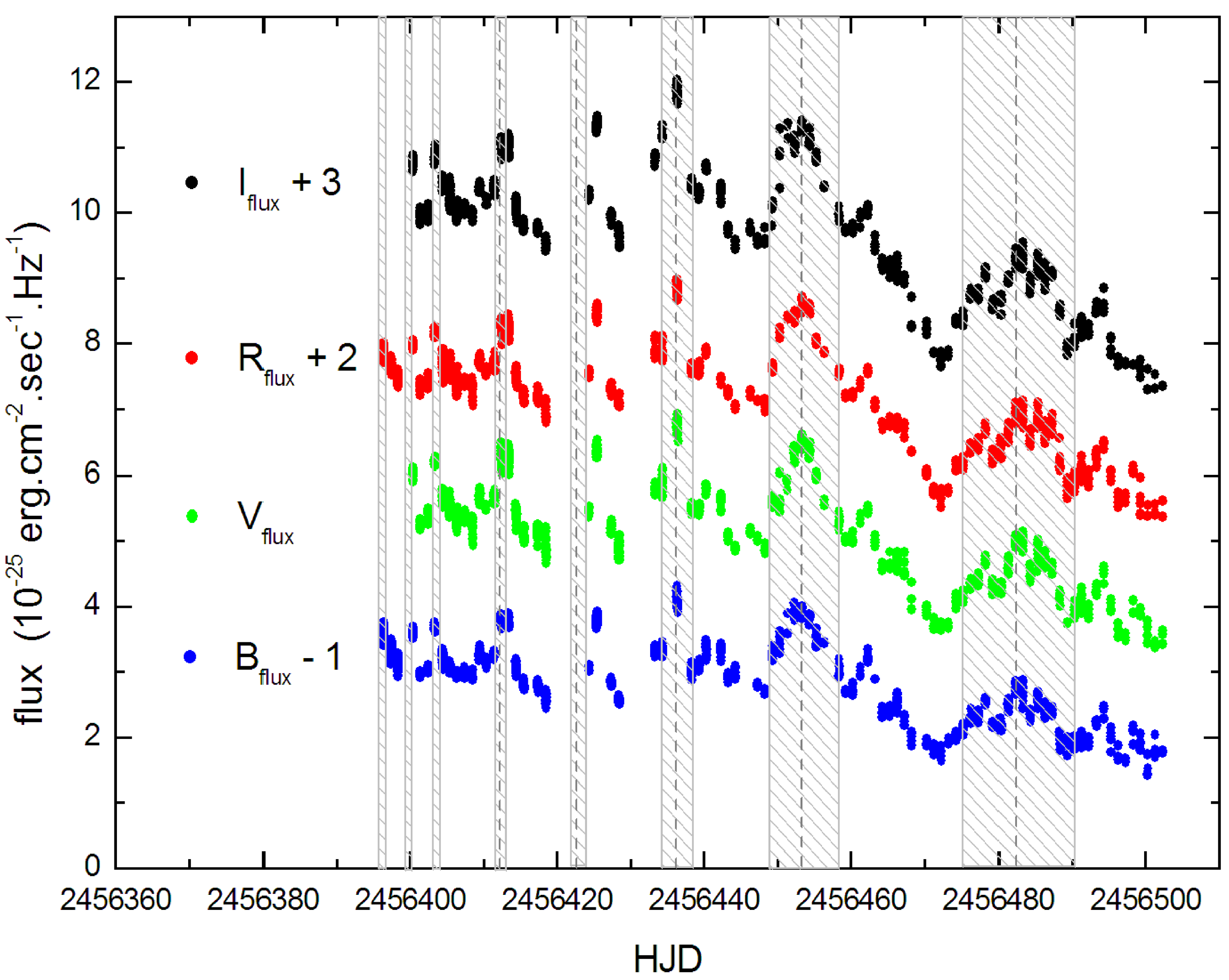

Figure 1: The photometric light curves in all optical bands. Gray areas mark the periods of brightness peak, while the width of each box represents the duration of each peak and the dashed line the day of maximum brightness. Note that the (assumed) peak at HJD=2456423.0 is absent, due to bad weather conditions. The observed maximum at HJD=2456425.5 seems to be the secondary peak, following the non-observed one.

Optical Flux Variability

Blazar variability timescales are often divided into three categories: the intra-day variability (IDV) which ranges between a few minutes up to one day (Wagner & Witzel 1995), the short-term variability (STV) which ranges between a few days to a few months and the long-term variability (LTV), which covers all variations longer than a few months, up to several years (Gupta et al. 2004). With the data spanning over 3 months and with a high-density coverage, IDV and STV can be studied in detail, in comparison to the flare activity in X-ray and γ-ray region.

Fig. 1 clearly show STV with a strong correlation between all four optical bands. The data do not show a clear IDV. A very weak IDV of 0.008 mag might be a weak indication of possible short-scale flare events. On the other hand, STV is much more obvious. Several flares with amplitude of ~0.3 mag (even 0.5 mag in some cases) are resolved during the entire observing period. These flares are visible in all filter bands. Among the most prominent features, the most important are the following:

1) all four optical bands are highly correlated with each other
2) the overall brightness is getting lower with time (LTV)
3) no IDV is observed within a 2-3 hour run, or it is very weak
4) time interval between peaks is getting progressively longer, and each peak lasts longer than the previous one
5) each individual peak is followed by a secondary one of lower amplitude and shorter duration

Another feature of the presented light curves, which cannot be directly deduced from Fig.1, is the achromaticity of the flux variability, i.e. the amplitude of variations relative to the average flux does not differ among the optical filters. This is in contrast to previous works, where the amplitude of variations increases with decreasing wavelength (e.g. Horan et al. 2009).

In order to quantify the variability amplitude in different wavelengths we calculated the fractional rms flux variability (***f_{rms}***), which is defined as:

$$f_{rms} = \sqrt{\frac{S^2 - \overline{\sigma^2}}{\overline{F}^2}} \quad \text{where} \quad \overline{F} = \frac{1}{N}\sum_{i=1}^{N} F_i \quad \text{and} \quad S^2 = \frac{1}{N-1}\sum_{i=1}^{N}(F_i - \overline{F})^2$$

are the average flux and the variance of our sample light curve. Finally, $\overline{\sigma^2} = \frac{1}{N}\sum_{i=1}^{N}\sigma_i^2$ is the mean error squared with σ_i^2 being the errors associated with each flux measurement. Our results show that the ***f_{rms}*** for each filter band is: B=0.136, V=0.139, R=0.131, I=0.137.

Data analysis

The almost uninterrupted photometric monitoring in the optical BVRI bands during 3.5 months after the flaring activity in mid-April 2013 reveals a quasi-periodic light variation, gradually fading down towards the nominal optical flux of Mrk421.

Due to the tight correlation between different filters, in what follows, we will restrict our analysis on the B-filter:

- **Autocorrelation function (ACF):** The autocorrelation coefficients as a function of the lag are shown in Fig. 2. Their slow decrease implies that the optical light curve is non-stationary and there is an underlying trend in the time-series.
- **Lag-Plot:** If ***X(t)*** denotes B-mag at time ***t***, then the lag-plot is simply a graph of ***X(t)*** vs ***X(t-1)*** (see Fig. 3). Our data points are clustered along the diagonal (red line), i.e. the value at time ***t*** can be predicted if a value at the previous time is known. Thus, our optical data are highly auto-correlated.
- **Autoregressive modeling (AR):** Due to the high degree of autocorrelation we assume that the optical light curve is described by an 2nd order AR process, which is best described by:

  $X_t = a_0 + a_1 X_{t-1} + a_2 X_{t-2} + \varepsilon_t$ where a_0=12.615±0.056, a_1=0.750±0.029, a_2=0.230±0.029

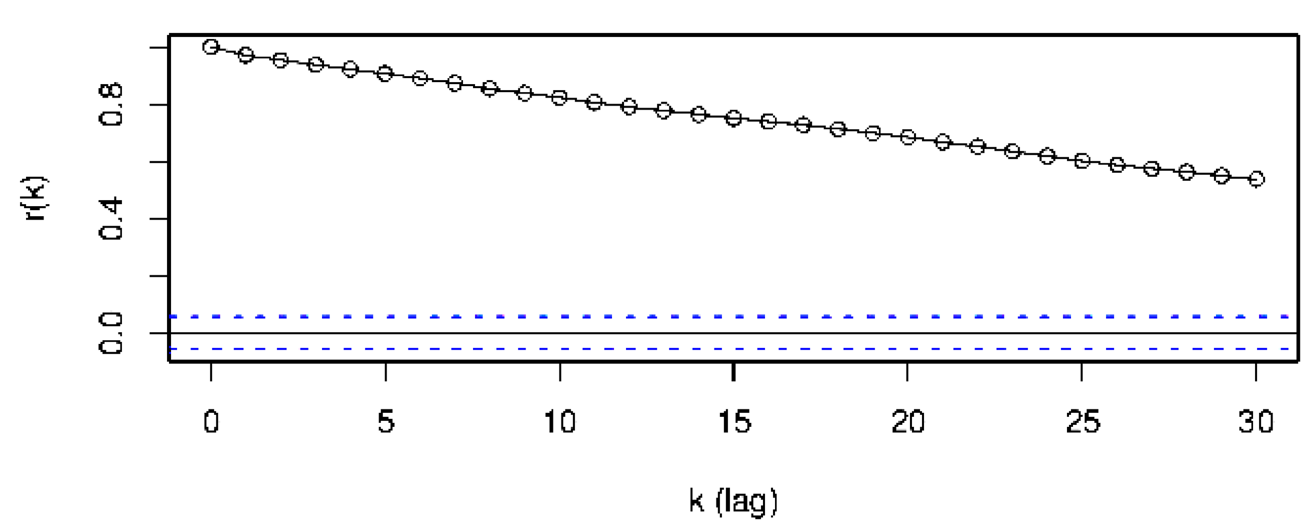

Fig. 2: Autocorrelation coefficients r(k) as a function of the time lag k of the corresponding time-series in B filter.

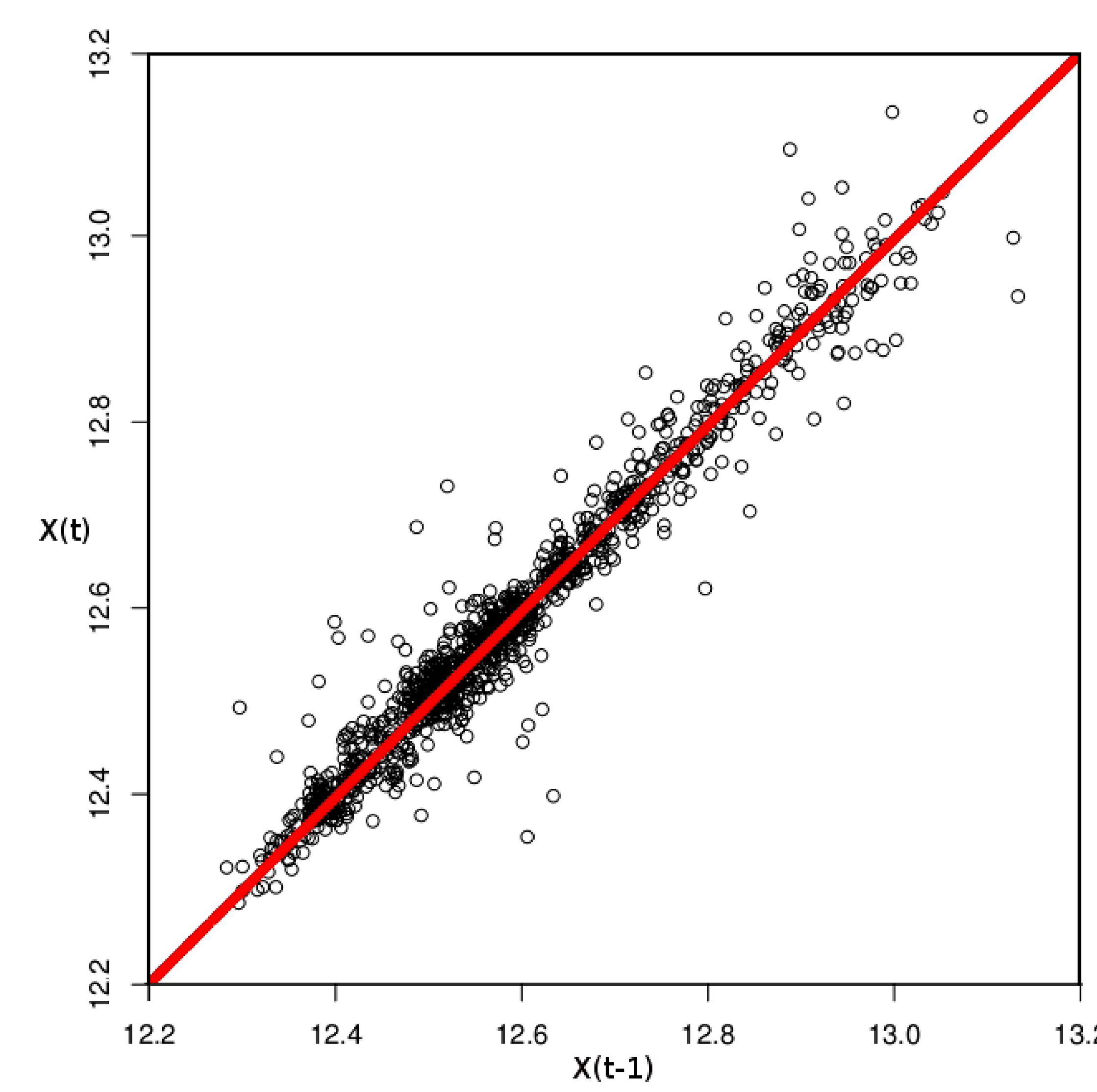

Fig. 3: Lag-plot for the optical (B-filter) light curve (points). Red line is plotted for guiding the eye.

Summary

- This study presents one of the most comprehensive observing campaign, in terms of duration (temporal coverage), temporal density (observations were obtained almost daily), wavelength range and consistency/homogeneity of data.
- The observing campaign was obtained with the opportunity of the very recent strong flare activity which occurred on 13 April 2013, in order to follow and study the optical behavior of Mrk421, as an active high-energy emitting source.
- No X-ray and VHE gamma-ray data were available for our observing period. Therefore, no direct link between optical and X-ray flux was found during these days. A similar result was also extracted by Rebillot et al. 2006.
- Time-series analysis revealed a high degree of auto-correlation in all optical filters. This means that flux measurements at a certain time strongly depend on their past values.

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