Multi-wavelength monitoring of the highly active blazar Mrk421
Investigating the high vs. low energy correlated variability

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Abstract. We present a long-term multi-wavelength monitoring of blazar Mrk421, obtained simultaneously with orbital and ground-based instruments. Daily optical observations from the University of Athens Observatory started as a follow-up monitoring of the major γ-ray flare of 12 April, 2013. This data set is compared with the γ-ray, X-ray and UV observations obtained with Fermi/LAT and SWIFT satellite telescopes respectively, as well as with the 95 GHz and 15 GHz data from the CARMA and OVRO 40-m radio telescope. We investigate the existence of correlated variations among the different wavebands using the discrete correlation function (DCF) technique.

Introduction

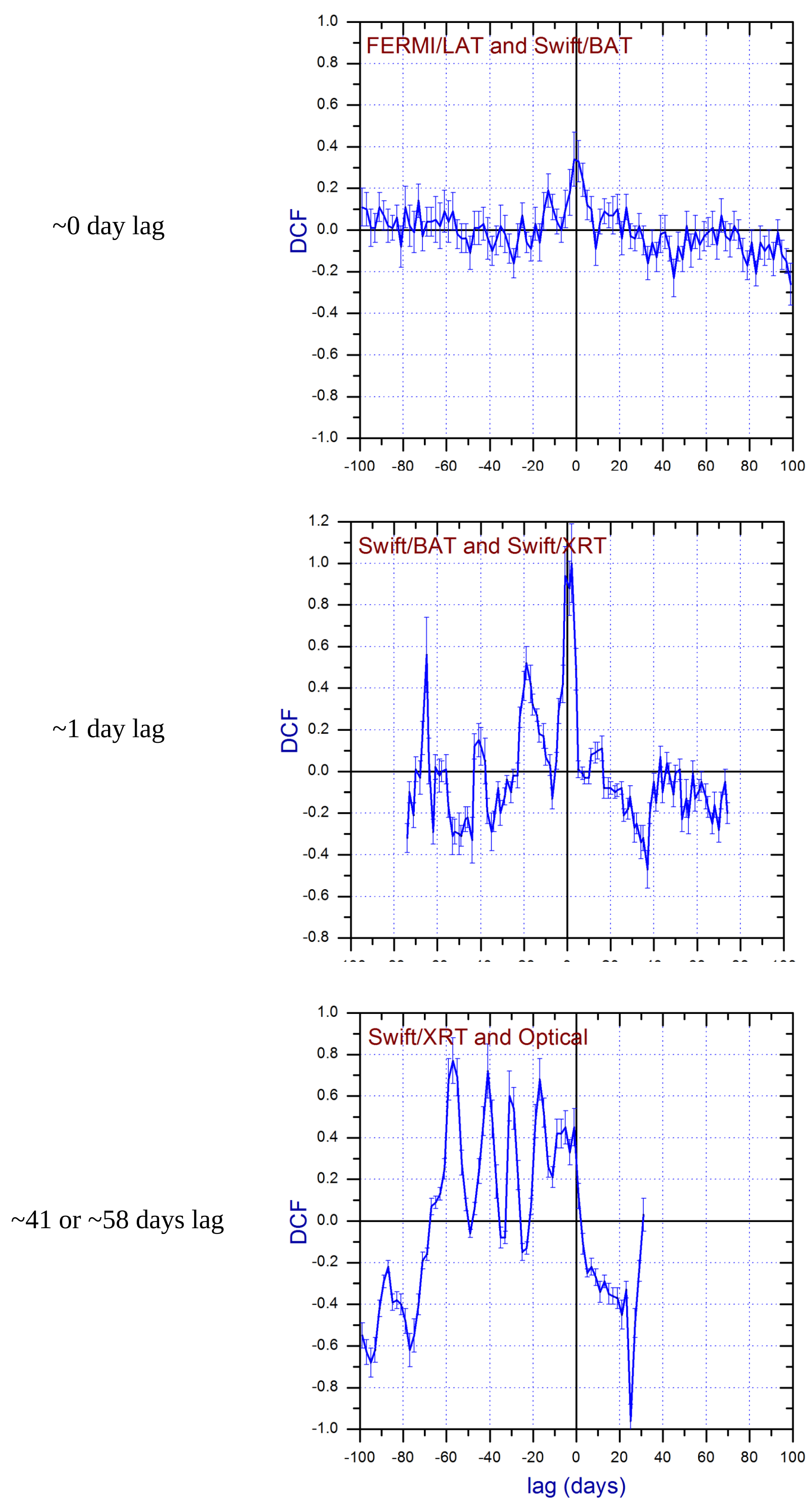
Mrk421 is one of the closest blazars to Earth (z=0.03) exhibiting large amplitude, rapid variations across the electromagnetic spectrum. It is extensively monitored in various wavelengths (e.g. Rebillot et al. 2006, Fossati et al. 2008, Gupta et al. 2008, Horan et al. 2009, Aleksić et al. 2012). Temporal correlations between two energy bands have been detected in the past (e.g., Giebels et al. 2007; Fossati et al. 2008, Hovatta et al. 2015). This behavior along with the fact that most campaigns with wide spectral coverage have shorter temporal coverage has motivated our long-term optical monitoring of Mrk 421.

Multi-wavelength sample

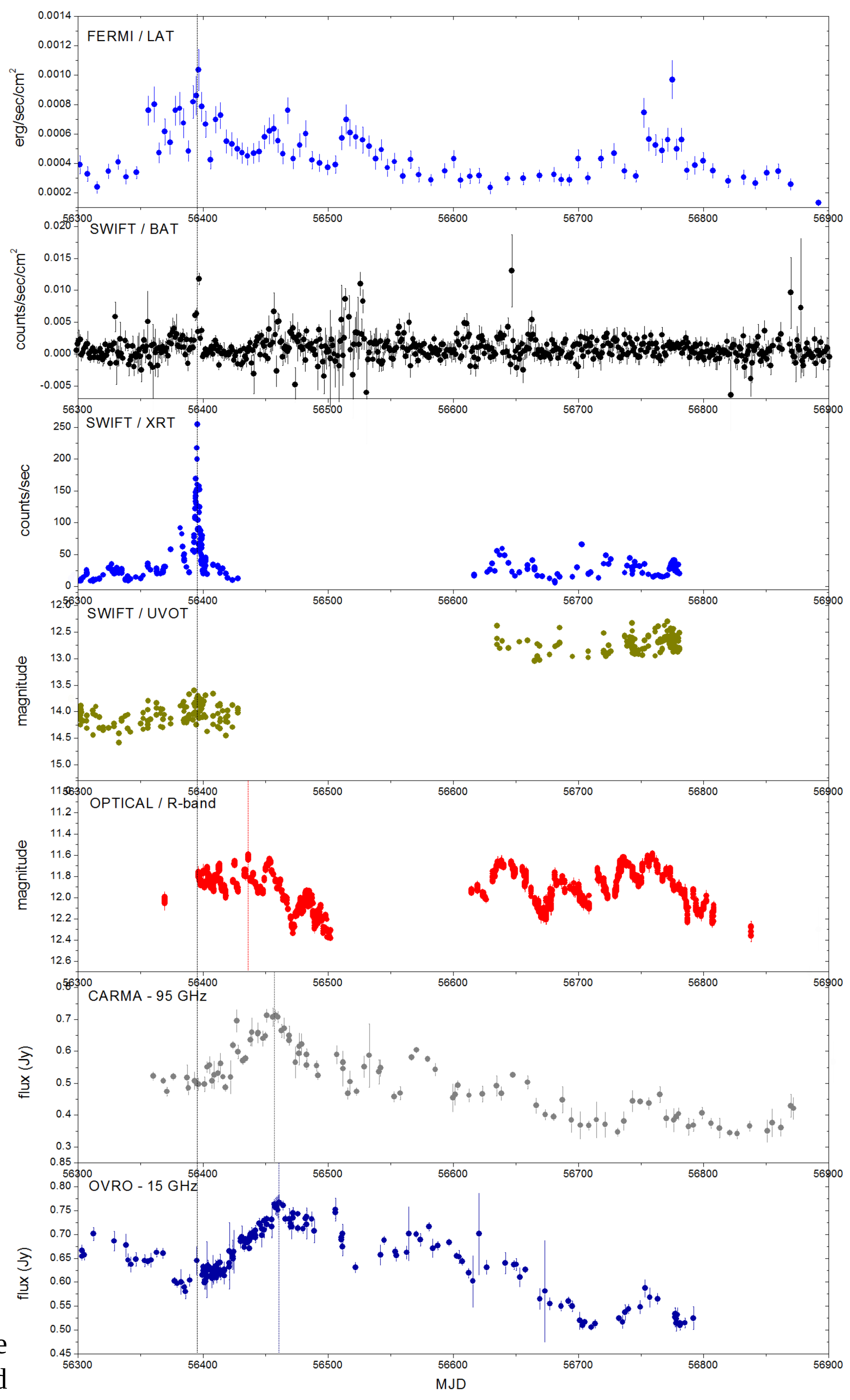
Our sample consists of contemporary data in seven different energy bands: γ-rays (FERMI/LAT), hard X-rays (Swift/BAT), soft X-rays (Swift/XRT), UV (Swift/UVOT), optical (UoA), millimeter (CARMA) and radio (OVRO) wavelengths. The data sets extend over the period of about 600 days (MJD 56300-56900). The optical observations (R-band) were performed from the University of Athens Observatory in a daily basis. It is one of the most comprehensive optical observing campaigns, in terms of duration (temporal coverage), density of data (most observations were obtained on a daily basis) and homogeneity (data have been obtained with a single instrument). The CARMA 95 GHz data were obtained as part of the *Monitoring of γ-ray Active galactic nuclei with Radio, Millimeter and Optical Telescopes (MARMOT)* program (http://www.astro.caltech.edu/marmot/), while the OVRO 40-m 15 GHz data were obtained as part of an on-going blazar monitoring program where ~1800 blazars are observed with twice per week cadence (Richards et al. 2011).

Discrete Correlation Function technique

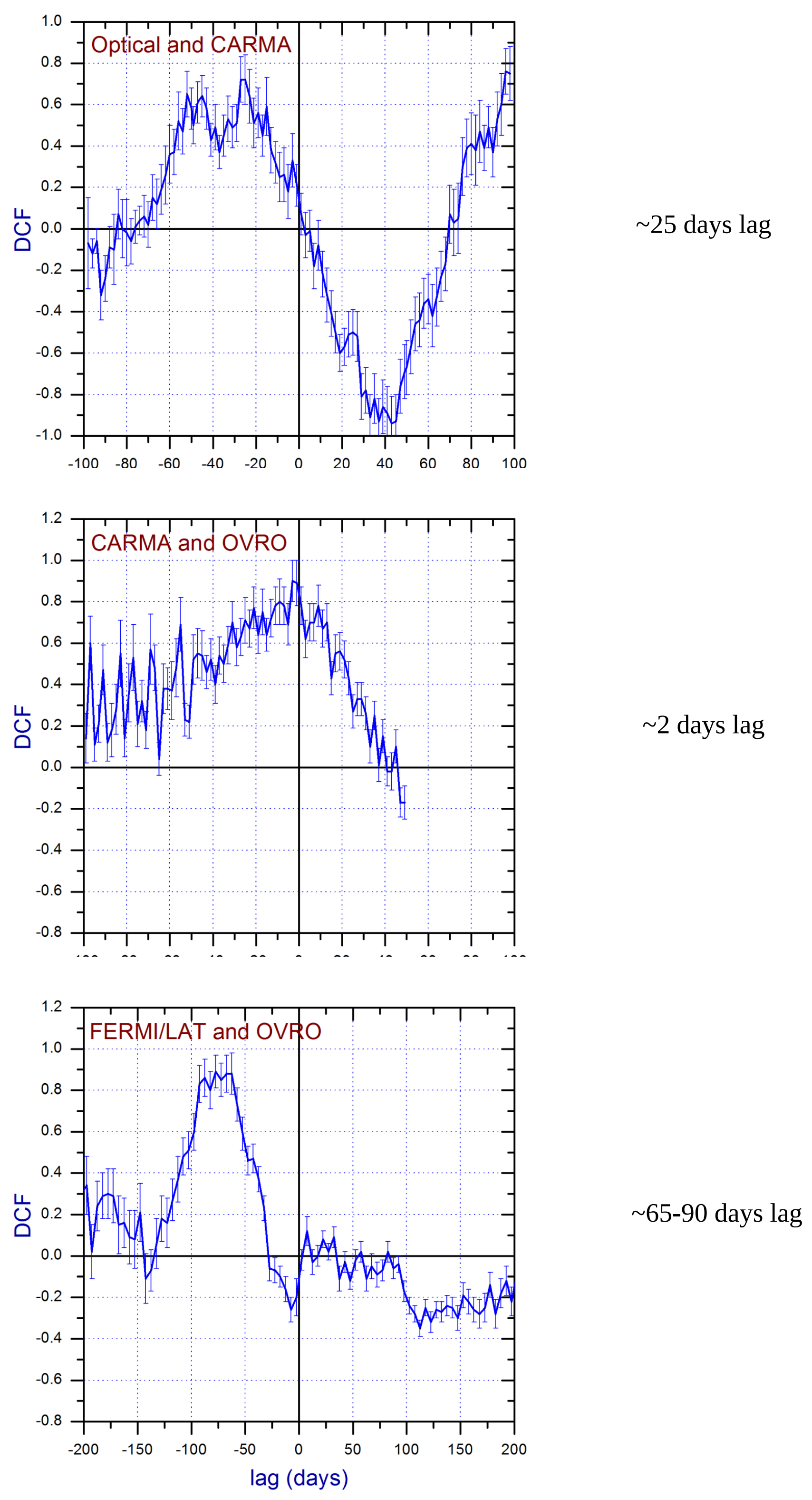
We estimate the DCF using the method described by Edelson & Krolik (1988). For every consecutive pair of data sets in our study, a DCF plot is created and shown in figures below. The minimum number of data points used in order to calculate the correlation at a given lag was limited to 10. The DCF is a mathematical measure of the correlation between data series and does not reveal the responsible physical mechanism. In this study we present the preliminary correlation results without taking into account the significance of the time lags found with the above technique.



Calculated DCF plots between FERMI/LAT, Swift/BAT, Swift/XRT and Optical (R-band) data sets.



The sample of all data sets used in this study, spreading over the entire electromagnetic spectrum from high energies (top: FERMI/LAT, GeV) to very low ones (bottom: OVRO,15 GHz).
Vertical dashed lines represents the moment when the high energy flare occurred on 12 April 2013 (MJD 56394±1) and the reciprocal signals detected a few days later in lower energies.



Calculated DCF plots between Optical (R-band), CARMA (95 GHz) and OVRO (15 GHz) data sets.

The observed time lags

- Setting the peak time of the γ-ray flare (MJD 56394) as zero time we detect corresponding flares in lower energies (optical, millimeter and radio) a few days later (see table below).

Brightness Peak	Energy band
MJD 56394±1	FERMI/LAT
MJD 56394±1	Swift/BAT
MJD 56395±1	Swift/XRT
MJD 56436±2 or 56453±2	Optical
MJD 56461±2	CARMA
MJD 56463±2	OVRO

- Subtracting the brightness peak time of each data set from the γ-ray flare time we get:

~0 day lag between FERMI/LAT and Swift/BAT (MJD 56394±1)
~1 day lag between Swift/BAT and Swift/XRT (MJD 56395±1)
~41-58 day lag between Swift/XRT and Optical (MJD 56435±2)
~25 day lag between Optical and CARMA (MJD 56460±2)
~2 day lag between CARMA and OVRO (MJD 56461±2)

As a consequence we see (also shown on last DCF plot):
~65-90 day lag between FERMI/LAT and OVRO.

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Results extracted from DCF plots

- We find essentially no lag between γ-rays and soft/hard X-rays, while there is a prominent lag between high-energies (γ-and X-rays) and low (UV to radio) energies. A negative lag means that the first dataset (higher energy) is leading the second one (lower energy) (see top-left of each plot).
- The R-band light curve shows a multi-peak behavior, which, in turn, gives several peaks in the corresponding DCF plot. Such features are not visible in the DCF plots between other data sets due to the less dense sampling in other energy bands.
- We find only 1-day lag between γ-rays and X-rays (FERMI/LAT and Swift/XRT). Fossati et al. (2008) also found a very tight correlation between TeV γ-rays and X-rays. This supports the idea that a single electron distribution in one physical region is responsible for the emission in both energy bands.
- We detect several small-scale flares in optical light curve. Their appearance frequency is ~ 20 - 40 days. The flares rise timescale is ~5-10 days, while their decay time is longer (~20-25 days). Preliminary calculations give a 1/e folding time of approximately 30 days and they show that all flares share the same decay rate (see similar results in Hovatta et al. 2015). Note that these small timescale flares cannot be detected when sampling is relatively sparse (data acquisition every 3 days).
- We find a time lag between high and low energies of the order of 65-90 days. A similar correlation was found by Hovatta et al. (2015) when radio, millimeter and γ-ray data sets of slightly longer duration were cross-correlated and it was found that a γ-ray flare was followed by a radio flare at 15 GHz after 40-70 days.