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Long-Term Multi-Band and Polarimetric View of Mkn 421: Motivations for an Integrated Open-Data Platform for Blazar Optical Polarimetry

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Abstract: In this work, by making use of the large software and database resources made available through online facilities such as the ASI Science Data Center (ASDC), we present a novel approach to the modelling of blazar emission whereby the multi-epoch SED for Mkn 421 is modelled considering, in a self-consistent way, the temporal lags between bands (both in short and long-timescales). These are obtained via a detailed cross-correlation analysis, spanning data from radio to VHE gamma-rays from 2008 to 2015. In addition to that, long-term optical polarisation data is used to aid and complement our physical interpretation of the state and evolution of the source. Blazar studies constitute a clear example that astrophysics is becoming increasingly dominated by "big data". Specific questions, such as the interpretation of polarimetric information—namely the evolution of the polarisation degree (PD) and specially the polarisation angle (PA) of a source—are very sensitive to the density of data coverage. Improving data accessibility and integration, in order to respond to these necessities, is thus extremely important and has a potentially large impact for blazar science. For this reason, we present also the project to create an open-access database for optical polarimetry, aiming to circumvent the issues raised above, by integrating long-term optical polarisation information on a number sources from several observatories and data providers in a consistent way. The platform, to be launched by the end of 2017 is built as part of the Brazilian Science Data Center (BSDC), a project hosted at CBPF, in Rio de Janeiro, and developed with the support of the Italian Space Agency (ASI) and ICRANet. The BSDC is Virtual Observatory-compliant and is built in line with "Open Universe", a global space science open-data initiative to be launched in November under the auspices of the United Nations.

Keywords: blazars; optical polarimetry; SED modelling; astronomical databases

1. Introduction

Blazars are a small sub-set of AGNs, distinguished by extreme observational properties, such as the presence of superluminal motion in high-resolution radio maps, and highly variable non-thermal emission over the entire spectrum. In blazars, such properties result from the fact that the plasma jets are pointing at a direction close to our line of sight, which amplifies the emission's relativistic effects [1]. Multi-frequency observations of blazars provide, therefore, a clear view of the physics and evolution of relativistic particles accelerated by the AGN.

The spectral energy distribution (SED) of blazars displays two broad humps. Radiation associated to the low-frequency part of the SED is firmly established as synchrotron emission from relativistic electrons interacting with the jet's magnetic field. The nature of the high-energy hump, peaking in the range from X- to gamma-rays, is attributed to two intrinsically different mechanisms: In a purely leptonic scenario, emission is due to inverse-Compton scattering of soft photons by the energetic electrons [2]; whereas in lepto-hadronic models a component from proton-synchrotron radiation [3] or photo-hadronic interaction [4] may be present.

The fact that a same population of relativistic particles is responsible for emission in the low and high-energy humps means that the entire SED of blazars may be correlated, requiring joint multi-instrument data to be studied, over 20 orders of magnitude in energy. In order to attain these goals, multifrequency observation campaigns have been done for some blazars, usually following a very bright flaring period: for example 3C454.3 [5], PKS2155-304 [6] and Mkn421 [7]. The kpc-scale sizes of the sources, contrasted with particle acceleration and cooling timescales as short as few hours or less, means that temporal analysis should span four orders of magnitude, from sub-hour to several years.

It is well known that this multi-band emission from blazars presents sizeable temporal lags in their correlated variability, spanning timescales which vary by orders of magnitude in range, depending on source state. Despite that, studies concerned with a detailed SED modelling usually neglect these properties, likely due to the difficulty in collecting good-coverage long-term data throughout the spectrum. As a consequence, SED models and the study of the temporal evolution of source parameters are usually based on time-averaged spectral information or considering strictly simultaneous multi-band snapshots of the source, neglecting correlation lags.

Polarimetry data on the jet's emission is another important ingredient in the study of blazars, and coordinated optical polarimetry observations are becoming increasingly common as part of large multi-wavelength campaigns for the study of blazars. The interpretation of polarimetry data is nevertheless complex. The analysis of the evolution of the polarisation position angle (PA) is specially delicate, due to its 180 degrees ambiguity in the measurements [8] , and density of data coverage can become an important issue in some cases.

Such observational characteristics clearly demonstrate the convenience of large integrated databases to provide the required data services which are beyond any individual group's capabilities to coordinate, acquire and analyse—see the example of the SEDBuilder tool from ASDC, in Figure 1. More recently, not only EM information, but also multi-messenger data, is becoming increasingly relevant in the field of blazar astrophysics, demanding, for example, software tools and data-services for cross-matching blazar catalogues and high-energy neutrinos and cosmic ray sky maps [4].

Mkn 421 was the first extragalactic TeV object detected [9] and remains one of the brightest and most studied gamma-ray blazars to date. It has been intensely monitored by several instruments in different frequencies and for a long period; thus, the amount of data available is quite large and with overlapping periods on several wavelengths, as apparent from the multi-band light-curve in Figure 2. This makes Mkn421 a good source for a comprehensive study of the multi-band correlations and consequently the time evolution of the emission.

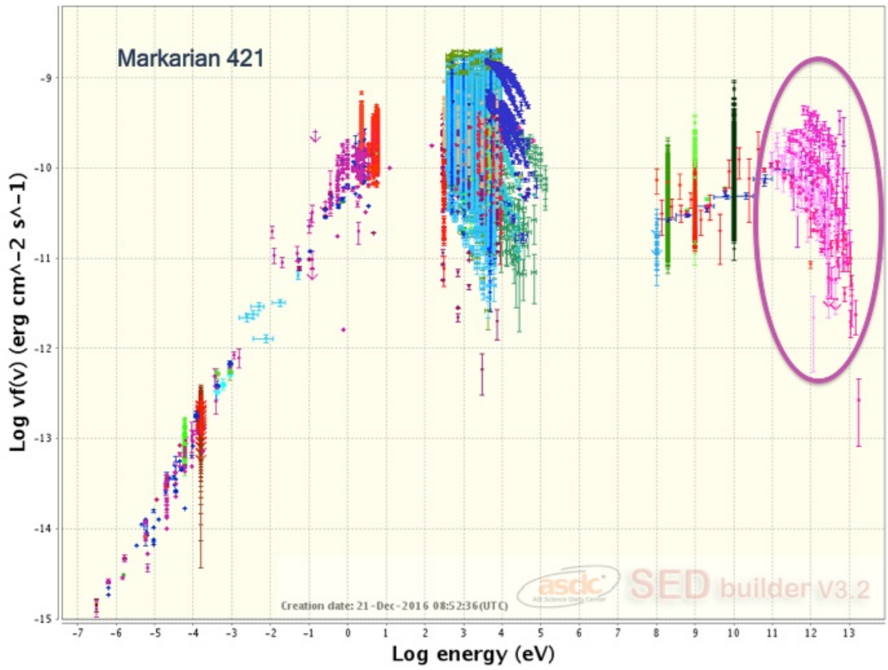

Figure 1. The multi-wavelength blazar spectral energy distribution (SED) of Mkn421. The marked VHE gamma-ray points are provided by the Brazilian Science Data Center (BSDC) database. The plot is made collecting data from a dozen catalogues spanning more than 30 years, collected by over 10 different instruments. They come from a number of catalogues which are integrated and made available online via Italian Space Agency (ASI) Science Data Center (ASDC).The plots are produced with SEDBuilder [10].

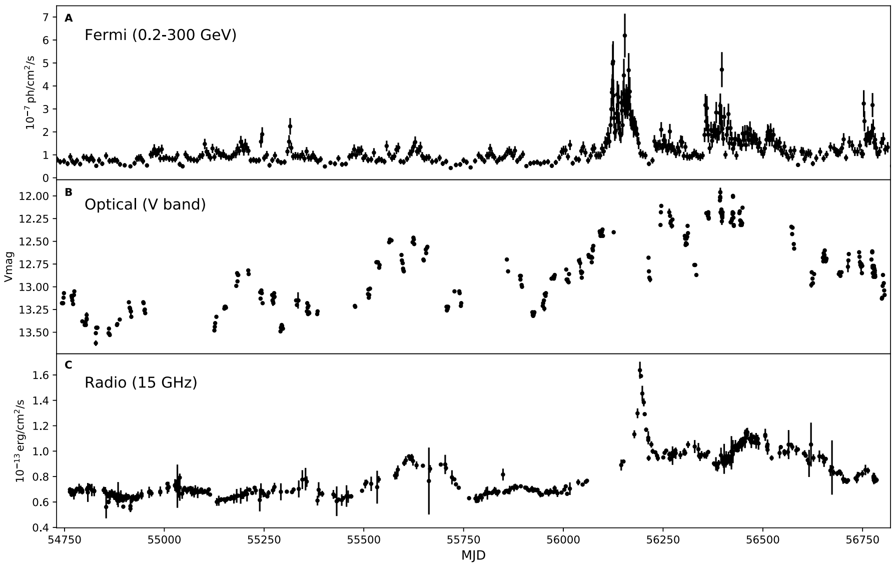

Figure 2. A long-term, multi-wavelength light-curve of Mkn421, showing 6 years of continuous coverage, from 2008 to 2014. The presence of intense variability in all timescales, from years to days, is apparent. The OVRO data was collected using the online database provided by ASDC [10]; the Fermi gamma-ray data, which was analysed by us using an adaptive binning algorithm; the Steward Observatory optical data was directly obtained from the observatory's online database.

2. The Dataset

We obtained long term multi-wavelength light-curves for Mkn421 for a period of 6 years, from 2008 to 2014. The only continuous observations were done by the OVRO observatory (at 15 GHz), the Steward observatory (V band) and the Fermi satellite. X-ray and UV data are also available from Swift but with long gaps (of approximately six months) due to the source proximity to the sun. We obtained the radio light curve from the ASDC SED tool [1], while the optical data was taken directly from the observatory and checked for galaxy contamination. The Fermi light curve for the period was calculated using an adaptive binning method, where the size of the bins is flexible and chosen to produce constant flux uncertainties, so that they are narrower at higher states [11]. In this way rapid changes of flux can be found. In Figure 2 we show the three long term light curves; it is interesting to note that both in the gamma-ray and the radio light curve the source appears to undergo a change of state sometime before MJD 56000 (beginning of 2012). While before there were only small flares, after 2012 it underwent a series of intense ones and the continuum emission increased. Due to this change of behaviour, we consider both periods separately (before and after 2012 – corresponding to MJD 56000) in calculating the cross-correlation functions.

3. Analysis

3.1. Time Lags

Since AGN light curves are very often unevenly sampled, we used the Z-transformed discrete correlation function (ZDCF [12]) to calculate the cross-correlation functions. Simulations show that the use of Fischer's Z transform improve the performance in sparse light curves over the traditionally used discrete correlation function (DCF [13]). We calculated the cross-correlation functions between all three light-curves shown in Figure 2, before and after 2012. By using a maximum likelihood analysis [14], we could find the maximum of the correlation function and the fiducial interval. For the period from 2008 to 2012, the only indication of a correlation is between optical and radio:

$$\tau_{o-r} = -35.8^{+9.91}_{-20.5}\ \text{days}, \tag{1}$$

whereas for the period after 2012 (MJD 56000), we have: $\tau_{r-o} = -48.5^{+9.70}_{-20.2}$ days, $\tau_{r-g} = -45.3^{+7.00}_{-20.7}$ days, and $\tau_{o-g} = -5.6^{+10.7}_{-8.69}$ days.

Where the subscripts "r", "o" and "g" in the equations refer to "radio", "optical" and "gamma-ray" bands respectively. Here, a negative lag means that the lower energy band comes after the higher energy one. All these lags are consistent with each other and the gamma-optical lag is consistent with a zero day lag. In Figure 3 we show all the cross-correlation functions. The lag between Fermi and radio is especially evident considering the very intense flare present in both light curves. This is further corroborated by the series of smaller flares in gamma-rays starting in MJD 56400, corresponding to a small increase in radio flux also around 40 days later. The optical flux at this period is also high, and is nearly simultaneous with the gamma-rays.

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[1] tools.asi.asdc.it/SED/

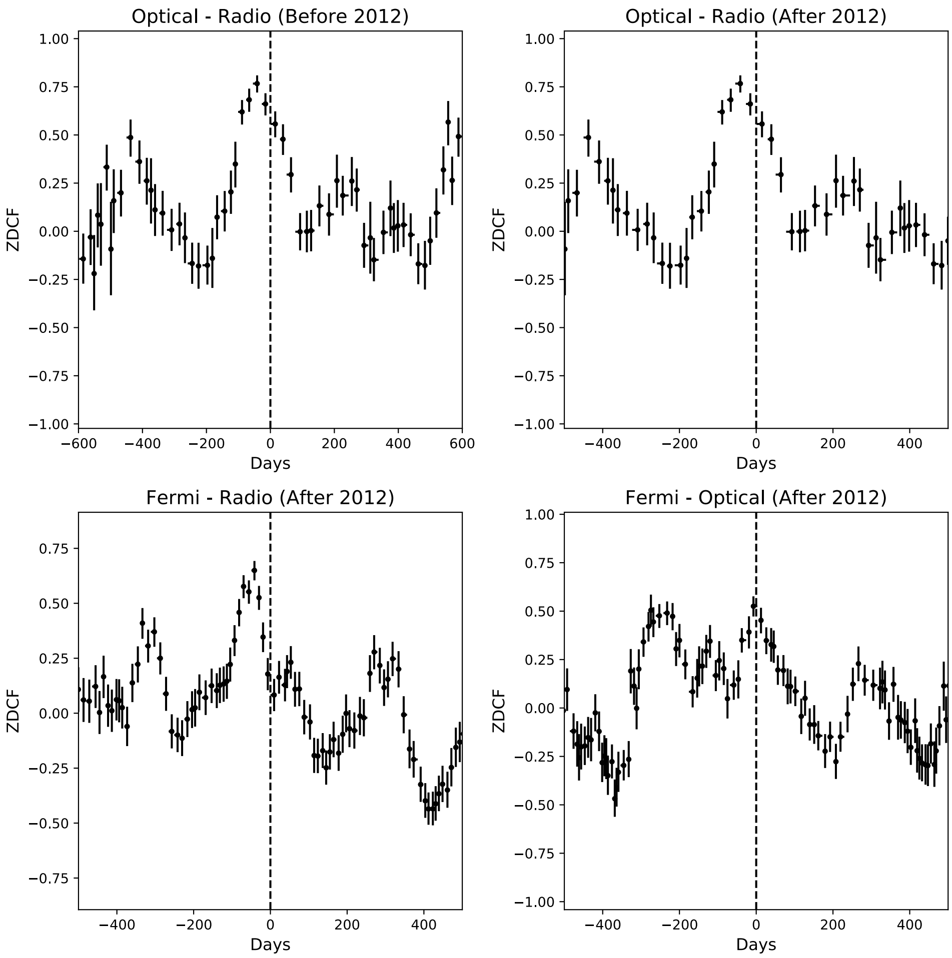

Figure 3. The significant correlation functions between all light curves. (**top left**) Optical-Radio before 2012; (**top right**) Optical-Radio after 2012; (**bottom left**) Fermi-Radio after 2012; (**bottom right**) Fermi-optical after 2012. A negative lag indicates that the lower energy band comes after.

3.2. SED Fitting

With the lags between different energy bands calculated, we proceeded to build the SEDs for each period. We shifted the Fermi and optical light curves by the values indicated above (considering a zero day lag between them). In addition to the data we had, we added also x-ray and UV data from Swift XRT and UVOT, respectively, taken from the ASDC website. The coverage from Swift is not continuous however; during the period our data covers, there are six windows of observation from Swift, which we divided in two each (for a total of 12) to constrain the variability and make the fitting procedure easier. We used a single-zone SSC model with the distribution of the electrons given by a power law with an exponential cut-off.

The fit was done numerically using a Markov-chain Monte-Carlo code, deriving the best-fit and uncertainty distributions of the parameters through a sampling of their likelihood functions. A detailed explanation of the method can be found at [11]. In Figure 4 we can see the evolution of the parameters for each period compared to the Radio light curve. It is interesting to notice that the strong increase of N_0 and the magnetic field correlates with the presence of a small flare.

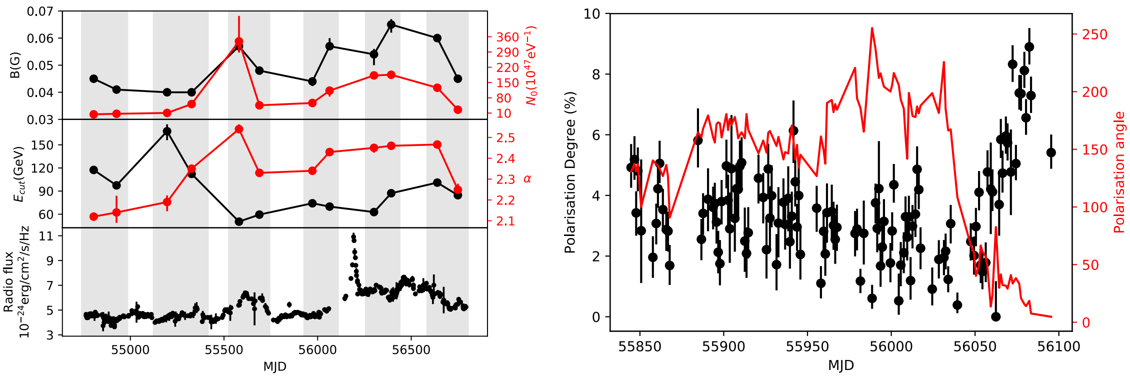

Figure 4. (**left**) The evolution of the parameters of the SED, with the periods chosen in gray, with the radio lightcurve on the bottom for comparison. (**right**) Polarisation angle and degree. The rotation of the angle can be seen around MJD 56040, right before the rise in the degree.

3.3. Polarisation Measurements

From 2008 to 2012, a large polarisation campaign was undertaken using the Liverpool Telescope and data from the Tuorla blazar monitoring program [15]. We present the data for MKN421 in Figure 4, right panel, with data from the end of 2011 to the middle of 2012. It can be seen that in the beginning of 2012, the degree of polarisation increases strongly (reaching an all-time maximum), while the polarisation angle rotates by 180 degrees; this change of behaviour is just before the intense flare in gamma-rays in 2012 (see Figure 2). Unfortunately, due to visibility, there is no optical data during the flare. However, this could be an indication that changes in the polarisation are related to flaring activity.

4. Discussion and Conclusions

We collected long term multi-band data for Mkn 421 in order to study the time evolution of the emission. We detected a change of state in gamma-rays in the beginning of 2012, from a more quiescent state to a series of intense flares and an overall increase in the continuum emission. We then calculated the cross-correlation function for each period (before and after the 2012 outbursts), between the three different long term light curves. We used this information to perform a fit of the SED for each period, already considering the time lags calculated before, with a single-zone SSC model.

We also obtained optical polarimetric data from the end of 2011 to the beginning of 2012. Mkn421 shows an all-time maximum of the polarisation degree, and a flip of the polarisation angle of 180 degrees; this comes just before the intense flare in γ-rays.

The multi-band data and study was aided by online tools for data querying and mining provided by the ASDC, which integrate information from a number of data providers. The VHE data was provided by the BSDC VO database. At BSDC, we are also developing an analogous tool for multi-provider integration and visualisation of optical polarimetry data for release this year.

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