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Multi-wavelength flares and magnetic field in blazars: a case study of IBL S5 0716+714

S. Chandra[1], K. P. Singh[1] and K. S. Baliyan[2]

[1]Tata Institute of Fundamental Research, Mumbai-400005, India
email: sunil.chandra@tifr.res.in

[2]Physical Research Laboratory, Ahmedabad, Gujarat - 380009

Abstract. We present a study performed to understand the role of magnetic field during a historical outburst of IBL S5 0716+714 witnessed in early 2015. The two month long profile of the outburst reveals several episodes of sub-flares superimposed over the diminishing trend of the peak-flux. The broadband X-ray spectrum from *Swift* + *Nustar* exhibits a break at $4.9^{+0.4}_{-0.5}$ keV which is consistent with the valley in the SED predicted by model. The spectral index variations, closely correlated to the flux variations during the first prominent sub-flare, indicate the alterations in the particle energy distribution coinciding the onset of the flare. The PA rotations approximately at the same epoch are used to constrain the field and its geometry.

Keywords. AGN, Blazar, Blazar-jet-magnetic fields, etc.

1. Introduction

The blazars are a subclass of Active Galactic Nuclei (AGN) seen at very small angles (<15°) to the relativistic jet emanated from very close to the central engine. The constraints on the role and morphologies of the magnetic fields in blazar jets are crucial ingredients for a complete understanding of the radiative processes. The presence of the magnetic field in blazars is supported by the detection of highly polarized emission in the optical and radio, parametrized by the degree of polarization (DP) and the position angle (PA). The DP has imprints of both, the particle energy distribution (PED) and the local magnetic field, whereas, the PA presents a non-contaminated representation of the morphology of the magnetic field. Therefore, PA and DP provide the most effective proxies for the jet magnetic field. The blazar emission is characterized by the strong variability comprising episodes of the multi-wavelength (MW) outbursts which may or may not be associated with the PA rotations. The formation of the shock in downstream jet and re-accelerations of the relativistic plasma is the most preferable scenario to explain the MW variability. The spectral energy distribution (SED) and the flux/polarization variability are used as a tool for the detailed understanding of the outbursts. The two kind of widely accepted models, leptonic and hadronic, corroborate the shock-in-jet framework, are employed to recreate the SEDs and lightcurves (see Böttcher *et al.* 2013 for the comparison of these two classes of models). The basic framework of both the classes rely on the synchrotron emission from ultra-relativistic leptons (e^-/e^+) to explain the low energy emission (radio- to X-rays). However, the ultra-fast variability is better explained by the leptonic approaches. The leptonic models induct the two emission scenarios for the high energy radiation (X-rays to TeV), namely SSC (Self Synchrotron Comptonization), and EC (External Comptonization), where they assume that the seed population for the Compton up-scattering comes from synchrotron photons or the photons external to the emission zone (disk, torus, BLR, CMBR etc), respectively. The complete understanding of the outbursts requires the simultaneous modeling of the the lightcurves, the DP & PA variability and SEDs. This requirement is primarily facilitated by two models, namely the Turbulent Extreme Multi-zone Model (TEMZ; Marscher 2014) and Helical Magnetic Field Model (HMFM; Zhang *et al.* 2015). Most importantly, these models use two different assumptions for the magnetic fields (small-scale turbulent-chaotic v/s large-scale ordered) and its morphology (straight v/s helical). The HMFM model is more favorable for the correlated PA rotations($> 180°$) during MW-flares and incorporates a self consistent tracing of the particle dynamics, radiation transfer and the polarization.

In the following sections we summarize the study of an outburst for the intermediate energy peaked BL Lac object (IBL) S5 0716+714 (z$\sim$0.31) during early 2015.

2. Data analysis

S5 0716+714 is one of the blazars being regularly monitored using Mt Abu Infrared observatory (MIRO), India, since late 2005. This source underwent a major outburst from 11 January 2015 to 28 February 2015. Being a very prominent flare (rising by 2.5 mag to reach 11.27 mag in NIR J band, between 01-11 January 2015; Carrasco *et al.* 2015), this outburst is followed by the facilities across the globe. We have performed the optical photometric and polarimetric observations using the facilities at MIRO during 16-30 January 2015.

The present work extends the studies by Chandra *et al.*(2015b), hereafter C15. The MW data from *Fermi*, *Swift* and MIRO for the durations of 01 January - 28 February 2015 are analyzed using the methods adopted by C15. The only available long *Nustar* observations of the source (ObsID: 90002003002; Date-Obs: 24 January 2015 & Exp. 18.5 ks) are analysed to understand the broader X-rays spectrum (0.3 - 80 keV), using standard prescriptions by *Nustar* team. The *Swift+Nustar* spectra are simultaneously fitted using absorbed broken-powerlaw model + a constant multiplicative factor to the *Nustar* spectrum to take care of variability introduced by ≈1-day difference in the observations. The intra-night R-band photometry data for 4 nights (23-26 January, 2015) are also analyzed using the methodologies adopted by Chandra *et al.* (2012) (see Fig. 1b for micro-variability on 23 January 2015).

3. Results

The multi-wavelength lightcurves shown in Fig. 1a & 1b clearly establish the MW-nature of 2015 outburst. The optical flux (V= 12.06 mag) communicated by Chandra *et al.* (2015a) corresponds to the historically highest flux value till date for this source. A significant micro-variability is witnessed on 23 January 2016, characterized by the timescale of $\sim$ 1.2 hrs. Rapid variations in the DP un-correlated with total flux and rotations in the PA by $>180°$ are observed during the onset of the first sub-flare. Fig. 1a depicts the lightcurves lasting for almost two months, covering the full outburst. As evident from Fig. 1a, the 2015 outburst consists of a number of small sub-flares superimposed over a longer trend. The peak of the first two X-ray flares are of similar level, whereas all the six sub-flares in UV/optical show a tendency of diminishing peak flux with time. A frequency dependent inter-night optical variations are also observed. The X-ray spectral indices, derived from XRT-data, show the flux dependent variations. The first sub-flare is accompanied with a correlated changes in the spectral index. Afterwards, it remained at same level ($\alpha \sim 2.6$) throughout the second sub-flare and ahead. The X-rays spectra, derived from the nearest possible observations by Swift & Nustar shows a satisfactory fit ($\chi_\nu \sim 1.2$, $\nu = 328$) with a break at $4.9^{+0.4}_{-0.5}$ keV. The spectral index before the break, derived from this combined fitting ($\alpha = 2.6{\pm}0.04$, $\beta = 1.8^{+0.06}_{-07}$) is in agreement with

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the estimates obtained from the XRT spectrum alone. A detailed qualitative analysis of the constraints on the spectral shape of S5 0716+714 using same dataset is presented by Wierzcholska & Siejkowski (2016). The Fig. 2a and Fig. 2b shows the simultaneous modeling of the polarization variations and the SED with HMFM model for the duration of MJD 57046 - 57048, the span of the first polarization swing (borrowed from C15). The SED is superimposed with *Swift+Nustar* spectrum showing the spectral break at 4.9 keV to be consistent with the model-predicted turn-over or the "valley" which is an estimate of the frequency corresponding to the equal cooling rates for the synchrotron and SSC processes.

4. Discussion

The 2015 outburst comprises a series of sub-flares associated with the major event and is seen at very broad spectrum. The flux variations in the optical bands are frequency dependent, making the shock driven processes more favourable over the geometry dependent models. The micro-variability seen during 23 January 2015, exhibiting sub-hour optical variations, may possibly be due to small fluctuations introduced in the shock front. The variations in the spectral indices closely following the flux variations in 0.3-10.0 keV band, during the first X-ray flare (MJD 57040-57054), can be explained in the following manner: The PED is forced to evolve during the interaction of the plasma with the shock which again tries to retain its initial configuration afterwards. The absence of similar correlations during the second X-ray sub-flare and ahead (MJD 57055-57075), indicate that the particle accelerations, here, somehow try to preserve the PED of the flaring state. The detailed modelling of the simultaneous MW-lightcurves, polarization and the SED, for a part of the data (MJD 57046-57053), shows the magnetic field alterations (poloidal$-$ $>$toroidal$-$ $>$poloidal) during the passage of the shock through the emission region (see Table 2 of C15 for the derived parameters). The second PA rotations and the corresponding flux variations indicate the possibilities of the magnetic-reconnection or the shock driven reconnection, inferred from the lowering in the synchrotron flux (optical) coinciding with the rise in the EC (γ-rays) flux, however, a detailed modelling lacks because of the large data gap. The similar argument can also be associated to the spectral index and flux variations, specially for the span of MJD 57046-57053. The multiple MW sub-flares associated with the major outbursts in blazars are becoming more evident because of the good cadence monitoring provided by the coordinated campaigns. Such patterns reflect the several episodes of particle energization before the major one diminishes. However, the proper constraints on the radiative processes are still limited because of the unavailability of strictly simultaneous data.

5. Prospects of the blazars' study with AstroSat

AstroSat, the first Indian multi-wavelength observatory in space, launched on 28 October 2015, provides a strictly simultaneous coverage over a broad spectrum (550 nm 130 nm in optical/UV and 0.3-($>$)120 keV in X-rays, with unprecedented timing and spectral accuracies (ref. http://astrosat.iucaa.in). We refer to the Science Support Center† for in-orbit performances for various instruments and data policies. The blazars are one of the key science objects for the AstroSat. The consortium of HCT + MIRO + SAAO + AstroSat is prepared to organize the MW campaigns during ongoing and upcoming cycles, aiming to uncover the role of magnetic fields in the wake of the more sophisticated blazars' emission models, e.g. Zhang *et al.* (2016) and references therein.

† http://astrosat-ssc.iucaa.in/

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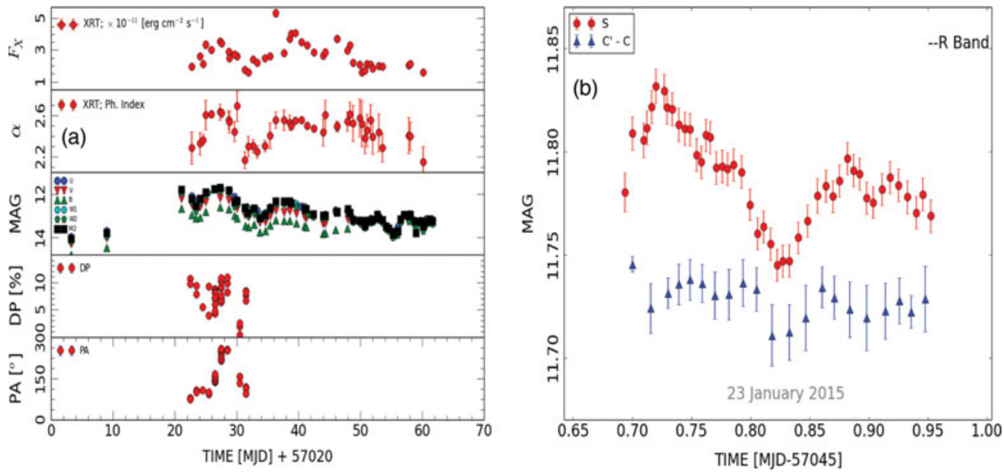

Figure 1. a: The MW lightcurves observed during 01 January-28 February 2015 with the top panel as X-ray lightcurve derived from spectral fitting. The next two panels represent the spectral indices & UV lightcurves, respectively. The last two panels highlight the DP variations and PA rotations during first sub-flare. **b:)** The intra-night R-band lightcurve from MIRO dated on 23 January 2015 with the source magnitudes (red) and differential magnitudes of the comparison and control star (blue).

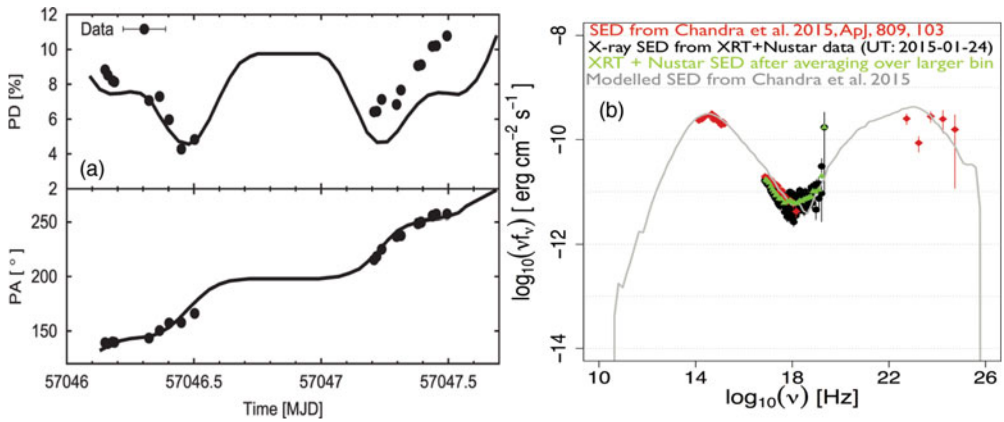

Figure 2. a): The HMFM model and the data for the DP and the PA variations (C15). **b):** The modeled broad-band SED of first sub-flare, borrowed from C15 with the *Swift+Nustar* SED over-plotted. Note that the SED shown in C15 is strictly simultaneous.

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