Swift/XRT view on S5 0716+714 during a flare

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ABSTRACT

The blazar S5 0716+714 has been monitored in its flaring state between 2015 January 19 and February 22 with Swift/XRT. During this period an exceptional flux level was observed in the X-ray range as well as in the other wavelengths, e.g. optical, near infrared and very high energy $\gamma$ rays. Here, we report X-ray observations of S5 0716+714 carried out during the outburst. The observed X-ray spectra, well described with broken power-law model, disentangle both synchrotron and inverse Compton components. The break energy shifts towards higher energies with increasing flux, revealing the dominance of synchrotron radiation in the X-ray spectrum observed. We also report spectrum softening with increasing flux. During the recent flare, significant temporal intranight variability is observed in the X-ray range.

Key words: galaxies: active – BL Lacertae objects: general, BL Lacertae objects: individual: S5 0716+714 – X-rays: general.

1 INTRODUCTION

Blazars are the most extreme Active Galactic Nuclei with non-thermal emission observed from the jet visible at small angle to the observer’s line of sight (e.g., Begelman et al. 1984). This group of sources includes BL Lacertae type objects as well as quasar-type blazars known as flat-spectrum radio quasars (FSRQs), high-polarization quasars (HPQs) or optically violent variables (OVVs), depending on the properties used for classification i.e.: radio spectral index, optical polarization or optical variability, respectively. Broad-band emission is observed from radio frequencies up to high energy or very high energy gamma rays (e.g., Wagner 2009; Vercellone et al. 2011; Abramowski et al. HESS Collaboration). The characteristic feature of blazars is their variability, manifested in all wavelengths, with different variability time scales down to hours or even minutes in the most extreme cases (e.g. Wagner & Witzel 1993; Aharonian et al. 2007; Gopal-Krishna et al. 2011; Saito et al. 2013; Liao & Bai 2015).

The spectral energy distribution (SED), in $\nu \nu F_\nu$ representation has a characteristic double-humped structure. This curvature of SED has been widely discussed in the literature, considering both leptonic and hadronic scenarios as a possible explanation (for review see e.g. Böttcher et al. 2013). In the most popular, so-called Synchrotron-self-Compton scenario, the first bump is attributed to the synchrotron radiation originating from relativistic electrons from the jet, while the second is produced in inverse Compton process, involving the same population of electrons and jet synchrotron photons. The location of peaks in SED allows to subdivide sources into high-energy, intermediate-energy and low-energy peaked objects: HBL, IBL and LBL, respectively (see, e.g., Abdo et al. 2010).

S5 0716+714 is a very bright (e.g. Aliu et al. 2012) IBL type blazar located at $z = 0.31$ (Donato et al. 2001). Several multi-frequency campaigns have targeted this source (e.g. Dai et al. 2013; Liao et al. 2014; Wu et al. 2014). The objects was also frequently monitored in X-ray range with different instruments reporting both spectral and temporal variability (e.g. Wagner 1992; Cappi et al. 1994; Liao et al. 2014). It is worth mentioning here that X-ray observations of S5 0716+714 revealed both synchrotron and inverse Compton components manifested in this domain (Cappi et al. 1994; Giommi et al. 1999; Tagliaferri et al. 2003; Donato et al. 2005; Ferrero et al. 2006).

2 OBSERVATIONS AND DATA ANALYSIS

The Swift mission (Gehrels et al. 2004) is a multi-wavelength space observatory equipped with following detectors: the Burst Alert Telescope (BAT, Barthelmy et al. 2005), X-ray Telescope (XRT, Burrows et al. 2005) and Ultraviolet/Optical Telescope (UVOT, Roming et al. 2005). Here, we study X-ray observations in the energy range of 0.3-10 keV obtained with Swift/XRT. Since April 2005 S5 0716+714 has been monitored in several pointed observations, both in photo-
ton counting (PC) and windowed timing (WT) modes. In this study, we focus on the flare observed during the period of 2015 January 19–February 22. The total exposure of the Swift/XRT observations studied (IDs 00035009146-00035009202) is 152 ks. Data were analysed using version 6.16 of the HEASOFT package with CALDB v.20140120 following the standard procedure *xrtpipeline*. Spectral analysis is performed in the energy range of 0.3-10 keV with the latest version of *xspec* package (version 12.8.2). All data are binned to have a minimum of 30 counts per bin. A single power-law model and also a broken power-law one are tested, both with hydrogen Galactic absorption $N_H = 3.22 \times 10^{20} \text{cm}^{-2}$ fixed as a frozen parameter.

### 3 SPECTRAL AND TEMPORAL VARIABILITY

The long-term light curve of S5 0716+714 and a zoom of the flare studied are presented in Fig. 1 and in the upper panel of Fig. 2 respectively. During the outburst, significant variability of the source is observed. The maximum flux during this flare is about 1.8 counts s$^{-1}$ km$^{-2}$ cm$^{-2}$. It is worth mentioning here that the flare reaches the highest flux level ever observed for S5 0716+714 with Swift/XRT and it is best sampled outburst for this source with this instrument. Data collected during the flare (separately in PC and WT mode) were fitted with single power-law and broken power-law models, in both cases with Galactic absorption. A comparison of the fit parameters for both models, as well as values of the $\chi^2$ statistic, is presented in Table 1. A single power-law model with a frozen value of $N_H$ yields worse fit to data.

Thus, the broken power-law model is the preferable description of the spectrum for S5 0716+714. The higher value of $\chi^2_{\text{red}}$ in WT mode was expected, since only the PC mode retains full imaging and spectroscopic resolution. In the spectra derived, in PC mode as well as in WT mode, an upturn for broken power-law model is revealed at about 4-5 keV. Fig. 3 shows an example of broken power-law fit to the data in the case of all observations of the recent flare in PC mode. The corresponding spectral energy distribution with an upturn point of 3.98 keV is presented in the bottom panel of Fig. 3.

In order to investigate spectral variability in greater detail, the single power-law and broken power-law models were also tested for four shorter intervals of observations, marked in Fig. 2 and defined in Table 2. The intervals were optimized to have good enough statistics and observed either in PC or WT mode. The fit parameters for models as well as values of $\chi^2$ statistics are collected in Table 1. For all the intervals both power-law as well as broken power-law models were tested using $F$-test (e.g. Bevington & Robinson 2003), resulting in probability value for predominance of power-law model of 6, 0.2, 6.6 and < 1 per cent for intervals (1), (2), (3) and (4), respectively. Hence, the favourable model of the spectra for these four intervals is a broken power-law with the upturn point of 3.98 keV is presented in the bottom panel of Fig. 3 and defined in Table 2. The intervals were optimized to have good enough statistics and observed either in PC or WT mode. The fit parameters for models as well as values of $\chi^2$ statistics are collected in Table 1. For all the intervals both power-law as well as broken power-law models were tested using $F$-test (e.g. Bevington & Robinson 2003), resulting in probability value for predominance of power-law model of 6, 0.2, 6.6 and < 1 per cent for intervals (1), (2), (3) and (4), respectively. Hence, the favourable model of the spectra for these four intervals is a broken power-law with the upturn point of 3.98 keV.

### Table 2. Selected intervals for detailed spectral studies. The following columns present: the number of the interval or information about data used; the observation ID – 00035009000; the total exposure; the observation mode.

| Interval | Observation IDs | Exposure [ks] | Mode |
|----------|----------------|---------------|------|
| (1)      | 147–153        | 11.1          | PC   |
| (2)      | 154–161        | 23.3          | PC   |
| (3)      | 169–173        | 19.3          | WT   |
| (4)      | 175–188        | 77.4          | WT   |
| all PC   | 147–202        | 102.9         | PC   |
| all WT   | 147–202        | 49.1          | WT   |

The recent intensive monitoring of S5 0716+714 results in eight nights during which the exposure of the observations is larger than 6 ks. For these nights, detailed light curves (with snapshot-wise bins) are presented in Fig. 3. The relatively high flux observed in each case gives a perfect possibility of studying intranight variability in the X-ray regime. In all the cases significant variability is detected, fitting with a constant to data points results in a value of $\chi^2_{\text{red}}$ of at least 2. The largest intranight variability is observed on MJD 57054 with $\chi^2_{\text{red}}$ equal to 16.

### 4 SUMMARY AND CONCLUSIONS

*Swift*/XRT observations of S5 0716+714 performed during the period of 2015 January 19–February 22 show significant brightness increase of the source. S5 0716+714 is known to
be a very variable object, and not only in the X-ray range (e.g. Wagner 1992; Cappi et al. 1994; Tagliaferri et al. 2003; Donato et al. 2005; Liao et al. 2014). The elevated flux of the source during the most recent flare was reported in different wavelengths e.g. optical (Bachev et al. 2015; Bachev & Strigachev 2015; Spiridonova et al. 2015), near-infrared (Carrasco et al. 2015), and very high energy gamma rays (Mirzoyan 2015). During the period observed, the flaring activity was not detected in GeV monitoring with Fermi Large Area Telescope[2].

Since the monitoring programmes mentioned do not provide publicly available light curves, we are not able to judge whether the shape of the flare is similar at other wavelengths or not. However, we note here, that the mentioned Astronomer’s Telegrams report an exceptional behaviour of S5 0716+714 starting from January 16. The Swift/XRT monitoring of the blazar started on January 19, but the highest flux level observed was detected in the X-ray regime a few days later.

Previous studies of the source in X-ray domain revealed both synchrotron and inverse Compton components in the X-ray range, with break energy in the range of 1.5-3.0 keV (Tagliaferri et al. 2003; Donato et al. 2005; Ferrero et al. 2006; Pochinski et al. 2006). We note here that observations mentioned were mostly performed in the quiescence state of the blazar. Ferrero et al. (2006) studied changes of the break energy in broken power-law spectral fit for different flux levels. The authors have shown that, during the elevated flux-level period, the crossing point is shifted to a higher energy of about 5 keV, while for the lower flux states the upturn occurs at about 2 keV.

In our studies, we found that the X-ray variable spectrum of S5 0716+714 is well described with broken power-law model. This description is consistent with synchrotron cooling processes associated with a single emitting component. The lack of any significant spectral variability also confirms that there is no need of any additional emitting component. The break energy in broken power-law description shifts to higher values with increasing flux level. We found that most of the X-ray emission is observed in the energy range of 0.3-5 keV. Furthermore, we found that source follows the softer-when-brighter trend typical for IBL-type objects (e.g. Ferrero et al. 2006).

The temporal variability studies of S5 0716+714 have revealed significant intranight variability in the X-ray regime. Previously, in this blazar, such feature has been observed mainly in the optical regime (e.g. Montagni et al. 2006; Bogdan et al. 2015).

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Table 1. The parameters for power-law and broken power-law fits to the data. The following columns give: the number of interval or information about data used; the normalization, the photon indices, the break energy and the reduced $\chi^2$ value for power-law fit; the normalization, the photon index and the reduced $\chi^2$ value for power-law fit. Normalizations $N_{br}$ and $N_{po}$ are given in $10^{-3}$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$, while break energy is expressed in keV.

| Interval | $N_{br}$ | $\gamma_1$ | $\gamma_2$ | $E_{br}$ | $\chi^2_{red,br}$(d.o.f.) | $N_{po}$ | $\gamma$ | $\chi^2_{red,po}$(d.o.f.) |
|----------|----------|------------|------------|----------|--------------------------|---------|---------|--------------------------|
| (1)      | 3.913±0.061 | 2.375±0.028 | 1.08±0.10  | 4.68±0.74 | 1.111(214)               | 3.927±0.061 | 2.353±0.025 | 1.130(216)               |
| (2)      | 6.466±0.061 | 2.541±0.015 | 0.20±0.80  | 5.75±0.50 | 0.957(288)               | 6.479±0.061 | 2.532±0.015 | 0.994(290)               |
| (3)      | 5.184±0.054 | 2.391±0.018 | 1.27±0.42  | 5.10±0.50 | 1.294(263)               | 5.187±0.054 | 2.380±0.018 | 1.311(265)               |
| (4)      | 7.657±0.029 | 2.663±0.068 | 0.10±0.10  | 5.10±0.50 | 2.473(268)               | 7.688±0.029 | 2.646±0.066 | 2.862(470)               |
| all PC   | 5.125±0.036 | 2.447±0.012 | 1.73±0.20  | 3.98±0.38 | 1.177(390)               | 5.150±0.035 | 2.425±0.011 | 1.237(392)               |
| all WT   | 7.050±0.025 | 2.622±0.062 | 0.10±0.10  | 5.20±0.40 | 2.663(514)               | 7.072±0.025 | 2.606±0.061 | 3.003(516)               |

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2 http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/
Figure 5. Intra-night variability visible during 8 selected nights of the recent flare. Observations taken in PC mode and WT mode are marked in red and blue, respectively. Modified Julian Date of each observation night is given in right top corner in each plot and the x-axis shows fractional part of the day.

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Figure 2. The light curve of S5 0716+714 presenting Swift/XRT observations taken during the recent flare. The following panels show light curve in the energy bands of: 0.3-10 keV, 0.3-5 keV, 5-10 keV, 0.3-1 keV, 1-10 keV and the corresponding hardness ratios. The intervals selected for spectral analysis discussed in Sec. are marked with grey areas. Observations taken in PC mode and WT mode are denoted in red and blue, respectively.

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Figure 3. The figure presents spectrum as well as spectral energy distribution of S5 0716+714 including all observations taken during the recent flare in the PC mode. The data are fitted with broken power-law model. The upper panel presents spectral points with fitted model, the middle one shows data and folded-model ratio, while in bottom one the spectral energy distribution is presented. The red line shows the fitted model.

Figure 4. The HR5 = F(5-10 keV)/F(0.3-5 keV) and HR1 = F(1-10 keV)/F(0.3-1 keV) hardness ratios of S5 0716+714 as a function of total source intensity. Observations taken in PC mode and WT mode are marked in red and blue, respectively. One point with large error bars is removed from the second panel for better visibility.