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UV and X-ray Variability of Blazars

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Abstract. It is well established that the blazars show flux variations in the complete electromagnetic (EM) spectrum on all possible time scales ranging from a few tens of minutes to several years. Here we report the review of various UV and X-ray flux variability properties of blazars. Our analysis show that UV variability amplitude is smaller than X-rays, mostly soft X-rays hardness ratio show correlations with blazar luminosity and different modes of variability might be operating for different time scales and epochs. Quasi periodic oscillations are seen on a few occasions in blazars, higher fraction of high energy peaked blazars show intra day and short term variabilities in X-rays but variability duty cycle is much less in optical bands on intra day time scale compared to low energy peaked blazars. But these results are yet to be established.

Key words. Galaxies: active—galaxies: quasars—blazars—blazar: individual: PKS 2155–304.

1. Introduction

It has long been known that there are two major classes of luminous AGNs (i.e., quasars). Roughly 85−90% of these have very little radio emission ($S_{5\ \mathrm{GHz}}/S_B \leq 10$) and are therefore called radio-quiet quasars (RQQSOs). The remaining ∼10−15% of quasars are radio-loud quasars (RLQSOs), of which a small subset shows rapid variability at almost all wavelengths of the EM spectrum and also have strongly polarized emission. Such flat spectrum radio quasars (FSRQs) are now usually clubbed together with the intrinsically weaker, but highly variable BL Lacertae objects and are collectively known as blazars. Blazars have spectral energy distribution (SED) that show two peaks and this leads to two subclasses of blazars: LBL (red or low energy or radio selected) and HBL (blue or high energy or X-ray selected). The lower frequency SED component peaks at IR/optical in LBLs and at UV/X-ray in HBLs. The second component extends up to gamma-rays, usually peaking at GeV in LBLs and at TeV in HBLs. Blazar radiation at all wavelengths is predominantly nonthermal. The EM emission is dominated by a synchrotron component at low energy and at high energy probably by an inverse Compton component.

Blazar variability can be broadly divided into three classes. Significant variations in brightness may occur over the course of less than a day, often called microvariability, intra-night variability or intra-day variability (IDV) (Wagner & Witzel 1995). Short term variability (STV) can range from days to few months and long term variability (LTV) can have time scales of several months to several years (Gupta *et al.* 2004).

The real cause of blazar variability on diverse time scales is not yet well understood. In general, blazar variability is studied in its three phases which are: (1) outburst, (2) pre/post outburst, and (3) low-state. The outburst phase of a particular blazar has got maximum attention for simultaneous multi-wavelength observations and several such observational campaigns are organized till date (e.g., Urry *et al.* 1993, 1997; Brinkmann *et al.* 1994; Courvoisier *et al.* 1995; Edelson *et al.* 1995; Pesce *et al.* 1997; Pian *et al.* 1997; Ahronian *et al.* 2005, 2009; Foschini 2007 and references therein). These campaigns are very useful to understand the time lag and emission mechanism between different energy bands of the complete EM spectrum of a particular blazar. Generally, it is noticed that flares observed in the outburst or pre/post outburst state of a particular blazar at different epoch of observations, that each flare being thought of as a separate and independent event and different emission mechanisms are at work for different flares. Such observational evidence make blazar physics very complicated. Not much attention is given to understand blazar emission mechanism in their low-state. In low-state of blazars, they are mostly non-variable or if variability is seen, it is short lived and of low amplitude (Gupta *et al.* 2008).

In the present paper, we review the UV and X-ray variability studies done for the most studied, high energy peaked blazar PKS 2155–304 in UV/X-ray bands. We also mention some results based on other blazars.

The paper is structured as follows: in section 2, we report the important UV/X-ray variability results of the blazar. Section 3 presents some open questions on UV/X-ray variability of blazars and in section 4 we report the main conclusion of the present work.

2. Results

PKS 2155–304 ($\alpha_{2000.0}$=21 h 58 m 52.1 s and $\delta_{2000.0}=-30°13'31''.1$, $z = 0.116\pm 0.002$) was first identified as a BL Lac object by Schwartz *et al.* (1979) and Hewitt & Burbidge (1980). It is the brightest blazar in UV/X-ray energies in the southern hemisphere. It was discovered as a X-ray source by HEAO-1 (High-Energy Astronomy Observatory 1) satellite (Griffiths *et al.* 1979; Schwartz *et al.* 1979). Since 1970s, it has been observed on diverse time scales by several ground- and space-based telescopes in the complete EM bands simultaneously as well as in isolation (e.g., Carini & Miller 1992; Urry *et al.* 1993, 1997; Brinkmann *et al.* 1994; Courvoisier *et al.* 1995; Edelson *et al.* 1995; Pesce *et al.* 1997; Pian *et al.* 1997; Marshall *et al.* 2001; Aharonian *et al.* 2005, 2009; Dominici *et al.* 2006; Dolcini *et al.* 2007; Foschini *et al.* 2007; Piner *et al.* 2008; Sakamoto *et al.* 2008 and references therein). PKS 2155–304 was classified as a TeV blazar by the detection of VHE (very high energy) gamma-rays by the Durham Mark 6 telescopes (Chadwick *et al.* 1999). It was confirmed as a high energy gamma-ray emitter by high energy stereoscopic system (HESS) at a 45σ significance level (Aharonian *et al.* 2005) and it is so bright that IDV is also detectable in the VHE gamma-rays.

2.1 *UV/X-ray variability*

UV/X-ray flux variability is reported in the source in all possible time scales. The fastest X-ray variation with a factor of 4 increase in 4 hours observations by

European space agency's X-ray observatory (EXOSAT) was reported by Morini *et al.* (1986). The shortest time scale in UV is ∼10 days in which the blazar flux was decreased by 10% (Urry *et al.* 1986). The overall UV variation of a factor of 2 in 7 years (Urry *et al.* 1988) and the X-ray variation of a factor of 10 in the same period was noticed (Urry *et al.* 1986). In 20 days long extreme ultaviolet explorer (EUVE) monitoring campaign of the source in June–July 1993, the blazar has shown the brightness increase by a factor of 2 (Marshall *et al.* 2001). In a 5-day monitoring campaign in May 1994 of the source, it was noticed that there were comparable variations in UV and hard X-ray (Urry *et al.* 1997). In another 10 days continuous international ultraviolet explorer (IUE) and EUVE observations in May 1994, a rapid flare was detected on IDV time scale (Pian *et al.* 1997). In a two-day long monitoring campaign of the blazar in May 1994, a large flare, in which 1.5–7.5 keV flux changed by a factor of 2 on a time scale of 30 ks (Kataoka *et al.* 2000). The source was monitored in X-ray bands in May 1996 and in November 1996. The observed flux variations are a factor of 2 in May 1996 and ∼20% in November 1996 (Brinkmann *et al.* 2000). Over several years of observations of the blazar PKS 2155–304 show that the amplitude of variability is ∼4.5. PKS 2155–304 varies nearly as much over shorter periods which implies that dominant time scales in this blazar are truly quite short.

Structure function (SF) analysis of the X-ray light curve of the blazar in 2.5–20 keV shows that the variability time scale is ∼4 days (Kataoka *et al.* 2001). In a detailed search of intra-day variability time scales in 0.3–10 keV data of the blazar, it was noticed that the source varies on different time scales on different occasions, and the variability time scales are in the range of 15.7–41.4 ks (Gaur *et al.* 2010). Power spectral density (PSD) study of the source was done on various occasions. In May 1996 observations of the blazar, Kataoka *et al.* (2001) found that the normalized PSD power-law index is 2.23 with break frequency at $(1.2\pm0.4)\times10^{-5}$ Hz. On other occasions the PSD results are as follows:

(a) In 1 day EXOSAT data, PSD power-law index was -2.5 ± 0.2 (Tagliaferri *et al.* 1991);
(b) PSD power-law index of GINGA observations was -2.83 ± 0.3 (Hayashida *et al.* 1998);
(c) XMM–Newton data of 15 light curves of the blazar showed that the PSD power-law index is in the range of -3.52 to -1.68 (Gaur *et al.* 2010).

So, PSD power-law index is almost constant in nearly two decades of observations of the blazar.

2.2 *Correlation in flux and hardness ratio*

During the multi-wavelength campaign of the blazar PKS 2155–304 in May 1994, it was noticed that the hardness ratio is steeper in flaring compared to the non-variable state of the source (Kataoka *et al.* 2000). On November 22–24, 1997, the blazar was continuously observed in multi-band X-rays. The 2−4 keV/0.1−2 keV hardness ratio shows a clear correlation with the source intensity (Chiappetti *et al.* 1999). During November 22–24, 1997 observations from Beppo SAX, the 1.5–3.5 keV/0.1–1.5 keV hardness ratio shows a clear correlation with the source intensity (Zhang *et al.* 1999). In two days earlier observations duration November 20–22, 1997 from

Beppo SAX, the 1.5–3.5 keV/0.1–1.5 keV hardness ratio shows a weak correlation with the source intensity (Zhang *et al.* 1999). In May 1994 campaign of the blazar observations show, during the flare, the hard X-ray flux proceeded the soft X-ray spectral evolution tracking a clockwise loop in photon index *vs.* flux plot, and hardness ratio is steeper in flaring compared to non-variable state (Kataoka *et al.* 2000). XMM–Newton observations of the same source during May 30–31, 2001 showed that the hardness ratio in UV and X-ray bands are correlated with X-ray flux (Zhang *et al.* 2006a, 2006b). It has been suggested that the synchrotron emission of PKS 2155–304 tends to peak in the UV-EUV rather than in the X-rays (Zhang 2008).

2.3 *Cross-correlation in different energy bands*

From simultaneous ROSAT and IUE observations of the blazar PKS 2155–304 in 1991, it was reported that the UV flux was lagging X-ray by $\sim$2 hours (Edelson *et al.* 1995). On other occasions, the simultaneous observations of the blazar from IUE, EUVE, ASCA and ROSAT for 10 days in May 1994, it was reported that UV lags EUV by $\sim$1 day and EUV lags X-ray by $\sim$1 day (Urry *et al.* 1997). On November 30, 2001 simultaneous XMM–Newton and optical observations of the blazar showed a major decline in the blazar flux in X-ray band but there is no significant variation in optical band (Zhang *et al.* 2006b). Using XMM–Newton observations from EPIC pn data, temporal cross-correlations between bands were computed and discussed by Zhang *et al.* (2006b) who found that the variations between bands were more strongly correlated during flares.

2.4 *Quasi periodic oscillations (QPOs) in blazars*

The presence of quasi-periodic oscillations (QPOs) is fairly common in both black hole (BH) and neutron star binaries in our galaxy and nearby galaxies (e.g., Remillard & McClintock 2006). Observations in the UV by IUE of PKS 2155–304 seemed to show a short-lived quasi-period of $\sim$0.7 day, but only a few cycles were present, so it was not a firm detection (Urry *et al.* 1993). Claims of detection of such QPOs in few other active galactic nuclei (AGNs) were made based on early X-ray observations (Fiore *et al.* 1989; Papadakis & Lawrence 1993; Iwasawa *et al.* 1998). However, all of those claimed QPO detections in AGNs were not found to be statistically significant (Tagliaferri *et al.* 1996; Benlloch *et al.* 2001; Vaughan 2005; Vaughan & Uttley 2006). Recently there have been a few stronger claims of QPO detection on diverse time scales ranging from a few tens of minutes to hours to days and even years using X-ray and optical data of various classes of AGNs (Espaillat *et al.* 2008; Gierliński *et al.* 2008; Gupta *et al.* 2009; Lachowicz *et al.* 2009; Rani *et al.* 2009, 2010).

The first significant X-ray QPO detection of $\sim$1 hour time scale in an AGN has been reported for a narrow line Seyfert 1 galaxy RE J1034+396 (Gierliński *et al.* 2008). Espaillat *et al.* (2008) have reported a likely X-ray QPO on the time scale of 3.3 ks in 3C 273, which is a FSRQ (flat spectrum radio quasar). Lachowicz *et al.* (2009) have reported a probable detection of an X-ray QPO in the BL Lac PKS 2155–304 on a time scale of $\sim$4.6 hours but again, as only $\sim$4 cycles of this fluctuation were seen during 18 hours of the observation, the QPO indication is not iron-clad. All three of these QPO detections on IDV time scales were based on observations made with XMM–Newton. On few occasions, optical QPOs on IDV time scales were recently claimed to be present in another BL Lac, S5 0716+714 (Gupta *et al.* 2009; Rani *et al.* 2010). By using All Sky Monitor (ASM) data from the Rossi X-ray Timing Explorer (RXTE), Rani *et al.* (2009) have reported a possible QPO from the BL Lac AO 0235+164 on a short term variability (STV) time scale of $\sim$18 days and a possible QPO from the BL Lac 1ES 2321+419 on a long term variability (LTV) time scale of $\sim$420 days.

3. Open questions on blazar variabilities

3.1 *Do higher fraction of HBLs show IDV in X-rays but not in optical?*

It is noticed that HBLs are mainly focused target of variabilities in high energy bands. To compare HBLs and LBLs optical IDV and STV, we observed three HBLs namely Mrk 421, 1ES 1959+650 and 1ES 2344+514 in about 50 nights. We noticed that Mrk 421 has shown IDV on a few occasions (duty cycle $\sim$10%) but there is no IDV detection in the blazars 1ES 1959+650 and 1ES 2344+514 (Gaur *et al.* 2011a, 2011b). But we have found STV in all these three HBLs. On the other hand, large fraction of HBLs X-ray light curves show IDV (Gaur *et al.* 2010; Mohan *et al.* 2011). STV is seen in all HBLs we studied in X-rays (Gaur *et al.* 2010; Mohan *et al.* 2011). Do these observational evidence show that jet irregularities which is a prime cause of IDV and STV vanish in HBLs after X-ray emitting region? To answer this, a detailed study of optical IDV and STV is required for a large sample of HBLs.

3.2 *In blazars, do more than one emission mechanism work at a time?*

In blazars, the radiation emitted by the plasma in jet, which has bulk relativistic motion and is oriented at small viewing angles, will be affected by relativistic beaming, which in turn implies a shortening of the observed time scales by a factor of δ^{-1}, where δ is the Doppler factor. A correlation between the average flux and the IDV time scales should be expected if the variability arises from changes in velocity of, and/or viewing angle to, the emitting region. In a recent study in optical band for the blazar S5 0716+714, Gupta *et al.* (2009) did not see such a correlation, which implies that optical emission from this blazar is not governed by a single mechanism and thus more than one source of the radiation is probably present at these times. To reach a firm conclusion, such study for a large number of blazars are required in different EM bands (e.g., X-rays and optical) and if the obtained results from other blazars also do not show any correlation in flux and variability time scales then it will imply that, in general, more than one emission mechanism are at work in blazars at a time.

4. Conclusion

- Blazars show UV variation on short and long time scales.
- Blazars show X-ray variations on intraday, short and long time scales.
- In general, UV variability amplitude is smaller than X-ray.
- In most cases, soft X-ray's hardness ratio show correlation with source luminosity.
- In blazars, different modes of variability might be operating for different time scales and epochs.

- What fraction of blazar light curves show intra-day variability is still not well known and need focused effort to work on a large data sample to reach a firm conclusion.
- Still there is a need to develop a more acceptable model which can nicely explain different behaviour of blazars light curves and QPOs especially on intra-day time scale.

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