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Multiwavelength study of the variability in blazars

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Abstract. Blazars are the radio-loud AGNs with polarized, highly luminous and rapidly variable non-thermal continuum emission ranging from radio to γ rays, from a relativistic jet. These features are interpreted in terms of the synchrotron radiation produced in the jet and beamed in the direction close to the line of sight ! Thus, the study of blazars provides an opportunity to understand the mechanism of energy extraction from the central black hole where jets are formed. A multi-wavelength study of variability is the only way to obtain information on the geometry of the jets and to constrain the parameters characterizing the spectral energy distribution (SED). Radio through γ-ray SED of blazars exhibits two broad humps-first at UV/optical and second one extending from X-ray to γ-rays whose origin is less understood.

Variability in blazars has been studied in a number of objects using satellite borne detectors in X, UV and γ-ray bands, sometimes co-ordinated with ground based observations in optical, IR and radio. The variability time scales obtained vary from minutes to years. Such studies wil be reviewed and the emerging scenario will be discussed.

Key words : AGN, blazars, multiwavelength, variability, synchrotron radiation, relativistic jet

1. Introduction

Blazars are a subclass of the Active Galactic Nuclei (AGNs), and are enigmatic objects producing very high luminosities in a very compact volume. The associated physical processes are still not known and are of nature other than those powering stars. Several decades of effort in understanding the energetics of blazars has not yielded the answers. On the contrary many questions relating to AGN physics have arisen. The study of variability in flux and degree of polarization in various frequency dominans is supposed to provide some clues in this direction.

Here an attempt is made to give a flavour of the multiwavelength variability in blazars.

2. Multiwavelength variability and blazars

All the AGN sources show large luminosity variations on time scales from minutes to several years. Variability studies have been important in understanding the physics of the central engine of AGN, which can not be spatially resolved by existing or planned interferometers. For many objects large international monitoring campaigns have been organised to achieve this goal.

Study of AGN, and Blazars in particular, requires observations in all spectral windows : Radio, mm/submm, IR, Optical, UV, X-ray and γ-rays. What is more important is the simultaneous multiwavelength studies of the variability of a number of objects with short sampling time. There are several excellent reviews available and some are : Wagner & Witzel (1995), Mcshotzky et al., (1993), Bregman (1990), Collin Soufrin & Lasola (1998), Saas-Fe lectures on AGN by Blandford, Woltzer & Netzer.

By studying the variability behaviour in a specific class of AGN, one can try to find the answer to a specific query. For example, vairability study of Radio-quiet AGN aims at finding the emission mechanism of the optical, UV and X-ray continuum and the kinematics of the gas which helps estimate the mass of the central black hole.

In case of blazars, which is the topic of discussion here, the objective behind studying variability is to try to understand the structure and physical state of the plasma in the jet, i.e. the geometry of the jet, acceleration and radiation processes.

3. What are blazars ?

The term 'Blazar' is not distinctly defined but includes BL Lac objects (featureless continuum) and Flat Spectrum Radio Quasars (FSRQ), which have emission lines with normal widths. These are usually distinguished from other types of AGNs if they have some of the following properties.

- They are strong and compact radio sources with flat spectra.
- They display strong and variable polarisation, especially in optical.
- They possess smooth power law continuum, connecting radio, IR, optical and UV emission, indicating radiation to be synchrotron and hence nonthermal.
- They exhibit rapid and high variability in intensity at all wavelengths.
- Most of these sources posses highly relativistic jets beamed into/close to line of sight.
- Many of these are detected to be γ-ray source as well.

This interpretation is strongly supported by direct VLBI observations of superluminal motion in radio cores. The fast variability indicates that the size of the emission regions must be small (~ 100 AU). From light travel time arguments, $R \leq c.\Delta_t$, where Δ_t is variability time scale in source frame.

4. Blazar continuum

Blazars are radio loud AGNs characterized by strongly polarized, highly luminous and rapidly variable non-thermal continuum ranging from radio to γ rays. The Compton Gamma Ray Observatory discovered that blazars are the most powerful extragalactic γ ray source up to

GeV/TeV energies. The extreme variability and relatively weak spectral features suggest that the *non-thermal* continuum is emitted by a relativistic jet close to the line of sight and hence the observed radiation is strongly amplified by relativistic beaming (Blandford & Rees 1978). This continuum steepens gradually towards shorter wavelength - from radio to UV (Impey & Neugebauer 1988).

The overall radio to γ-ray spectral energy distributions (SEDs) of blazars exhibit a broad two hump structure as shown in Figure 1 (Fassati et al. 1998). The first peak occurrs either in the IR/optical (low energy blazars) or in the UV/X-ray region (high energy peaked blazars). These are also called red or RBL and Blue or XBL, respectively, based upon peaking energy or detection criteria. This long wavelength component in both types of blazars is synchrotron emission from relativistic electrons in the jet (Ulrich, Maraschi & Urry 1997), as evidenced by its high & variable polarization and flux from radio-to optical/UV.

The second spectral component extends from X-ray to γ-ray (GeV/TeV), and its origin is less understood but considered to be inverse Compton (IC) scattering of low energy photons. Origin of these photons is not very clear- they can be internal (synchrotron self Compton, SSC) or external (External Compton, EC-Bottcher 1999) to the jet. A detailed study of the blazar flux variation may provide considerable information on the emitting region dynamics.

The most striking difference between the blue & red blazars is that Blue blazars (XBLs) have significantly lower apparent radio luminosity while both have *similar* apparent X-ray luminosity. These also have typically lower optical polarization and variability amplitudes as compared to red blazars and are seen at large angles to LOS. The RBLs show larger near-IR colours. We see that the spectra of LBL fall off rapidly at wavelengths shorter than the synchrotron peak i.e. in optical-UV region, whereas spectra of HBL in the same bands are flatter. LBLs have been monitored extensively in optical, while HBL mostly in UV and X-ray bands.

5. Observed variation in different wave-bands

Variability of substantial amplitudes is detected throughout the entire electromagnetic spectrum and at all time scales which have been probed.

1. **GHz radio region :** Variability in GHz radio range is an interesting aspect of intra-day variability. Krauss et al. (1997) and Kedziora-Chudcer et al, (1997) find changing flux densities in 2 hour duration with flare amplitude changing by 20%. They also report polarization and spectral indices changing equally fast. Gabuzda et al (1989) report a drop by 40% in the polarized flux density of the core during 24 hours in 0735 + 178 blazar (Review by Saikia and Salter 1988). In general polarization variations were found correlated with those of total intensity at all wavelengths. However, anti-correlation was also noticed in some ! Bregman (1990) reports variations with timescale at different wavelengths : 0.1 - 1 GHz (Years), 1 - 10 GHz (Months to years), 10 - 100 GHz (weeks to months).

2. **Milli-eV (~ 230 GHz) :** These are the lowest frequencies still unaffected by scattering of electromagnetic waves in interstellar plasma. Therefore this wavelength region is important for variability study. But difficulty here is the strong background and atmospheric fluctuations to get enough accuracy for short time variations. Another problem is non-availability of sensitive detectors. Wagner (1997) reports significant intraday variation in PKS 0405-385.

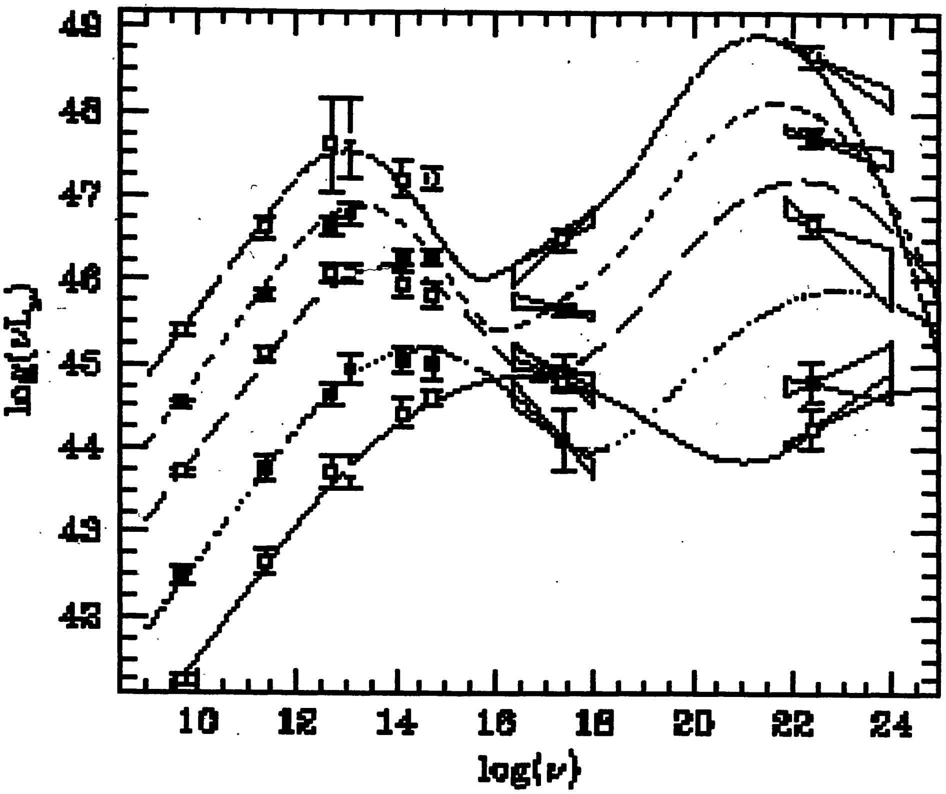

Figure 1. Two humped spectra of Blazars. The low-energy component peaks in IR for "red" (low energy blazars), and at UV/X-ray for "blue" (high-energy blazars). The location of synchrotron peak varies with luminosity-more luminous blazars peaking at low frequencies.

3. **Infrared :** Contrary to non-blazar AGNs, blazars have mostly non-thermal IR emission. Energy budget of blazars is dominated by IR in the 1 to 100μm region. For LBLs, a large fraction of bolometric luminosity is radiated in mid-IR (Impey & Neugebauer 1988). They showed that in this window blazars vary by half the amplitude of optical variation. Also rapid variation with timescale of weeks and a large (factor of 2) amplitude for IR variability are common (Observation of 3C 345 - Bregman et al., 1986). Edelson and Malkan (1987), in IRAS pointed observations, found two blazars to vary by a factor of two on timescale of few months. Optical and N-IR are found to vary together while Optical and far-IR have delay of weeks.

4. **Optical/UV :** The optical fluxes of blazars can change over several magnitudes on time scales of month to years (Webb et al. 1988). Microvariability (small amplitude variability, e.g. 0.1 magnitude changes in hours time), has also been confirmed (Miller, Carini & Goodrich 1989). The group at PRL detected 25 minutes variability in OJ 287 (Kulshrestha et al. 1984). In general, long term trends have typical time scales of several years in the rest frame (Smith et al. 1993, Smith & Nair 1995). Intra-night small amplitude blazar variability has also been observed (Jang & Muller 1995). Blazars also show significant variability in UV amplitude (8-80% variation) which is correlated with degree of optical polarization and goes against the disk model (Edelson 1992). Rapid variability on timescales of days is

common. SSC model is favoured over accretion disk ones. The UV radiation, like radio, appears to be beamed towards observer. *The most variable objects are interpreted as most beamed.* At times it is difficult to analyse time series as data on all epoches are not available.

5. **X-rays :** One major problem in the high energy region is that the number of photons collected is small. In case of HBL, medium energy X-ray emission (26 keV) is steep, extrapolating smoothly from UV, comprising part of the downward curving synchrotron spectrum. In LBL sources, synchrotron component curves down below X-ray band. In HBL, rapid large amplitude X-ray variability is seen with flux doubling in time scale of hours. Spectra harden with increasing intensity (Urry et al., 1986, Giommi et al., 1990). Looking at UV and X-ray variability of HBL one finds that both spectral changes and variability amplitudes were larger beyond synchrotron peak (in soft X-rays here). ROSAT survey of radio selected BL Lacs (red blazars) suggests flattened spectra than that of HBLs.

6. **High Energy - γ-rays :** These have no direct detection from ground and also have only couple of dozens of photons per day. One of the most important results with the CGRO-EGRET instrument is detection of more than 60 blazars. These emit enormous power in γ-rays from 100 MeV to GeV. Practically all EGRET blazars are strongly variable on time scales of months and days (3C 279: Kniffen et al. 1993; Miller et al. 1996). Most extreme case, PKS 1622-297, brightened by factor of 10 in two days (Mattox et al 1995; Miller et al., 1996). Optical monitoring registered a comparable flare preceeding γ-rays by 22 Hrs (Wagner et al. 1995). It was also seen for PKS 0420-014 that epochs of γ-ray detection coincided with outbursts in optical emission observed in 5-year monitoring. Using Cerenkov radiation technique, high energy (TeV) γ-rays were detected. Mrk 421 was detected at Whipple Observatory - energy varying by factor 10 (Punch et al., 1992). TeV power dominates the bolometric luminosity in Mrk 421. Observation of short time scale explorations are diffcult due to low count rate. Mrk 501 has also been detected at TeV (Quinn et al. 1996). A likely origin of the γ-ray emission is Compton scattering of lower energy photons by the same relativistic electrons producing the low frequency component. The correlation of variability at high and low frequncies is a crucial test for this model.

6. Correlations

The key to understanding radiation mechanism and geometry of the jet is to study the correlations among the variations in different wavelength regimes. If the variation in one wavelength are correlated without lag to the other wavelength then one can say that the emissions are from the same region and that the mechanisms could also be the same. On the other hand, if a lag is found, that one can infer that radiation progresses from one region to other. Correlations between different wavelength regions are noticed as we see in the following :

Radio and optical correlation. On time scales of years - optical emission from blazars are seen to be weakly correlated with radio - with lead time of about 1 year (Hufnagel & Bregman 1992). Stronger correlation is noticed in the optical and 37 GHz or higher radio, with lead time of months (Tornikoski et al., 1994). Not every optical flare has a radio counterpart. At higher frequencies flares are faster (1-2 months) and if sampling is not adequate, it may appear simultaneous. Although particles radiating IR, optical and submm to centimeter wavelength are physically related, most likely by a shock, they occupy distinct spatial regions and hence may not correlate. Systematic long term monitoring of a number of objects from mm to IR indicate that *flares usualy propogate from short to long wavelengths.* On very short (intraday) time scales, radio and optical variability seem to be correlated with no lag (Wagner & Witzel 1995).

mm-X-ray correlation. 3C 279 light curves in radio, mm, optical, UV, X-ray and γ-ray confirm that on time scales of months to years X-ray correlates with high frequency radio flux (mm region), while optical- UV correlate with γ-ray flux (Grandi et al. 1994).

Optical - γ-ray correlation. It is difficult to organize simultaneous coverage due to involvement of ground observatories and space facilities. In case of PKS 1406-076, optical flux rises by 60% while γ-ray flux increased by a factor of 3 - optical leads γ-ray by a day ! (Wagner et al. 1995). Also, in PKS 0420-014, γ-ray high state corresponds to optical flare (Wagner et al. 1995). We have made observations in optical (linear polarization) region in co-ordination with γ-ray (TeV) observation by BARC group (Bhat et al. 1997), both using facilities at Mt. Abu. An enhanced degree of polarization was noticed during a high γ-ray activity (Joshi et al 2000). It hints at possible origin of these emissions from a common region with polarised radiation produced in synchrotron process and TeV emission as inverse Compton upscattered low energy photons.

In a multiwavelength campaign on Mrk 421, Takahashi et al. (2000) report observations made with ASCA, EUVE, SAX, CAT, HEGRA, Whipple and other optical telescopes, During last week of April 1998, large flares were detected superposed on already higher state flux of Mrk421. Figure 3 shows 2-10 KeV (ASCA) flux to increase by factor of 4. EUVE noticed a series of flares correlated with X-ray flares. Optical data also shows a variation of 0.1 mag at 12.6 mag in R. However, radio does not show any enhancement. A comparison shows X-ray & TeV-γ-rays correlated with hours time scale. Soft to hard X-ray lags is 2000 seconds. A systematic longer time monitoring is required as energy dependence is more complex than thought. Origin of flares appear to be due to blobs of plasma passing through a region where shock fronts are formed and electrons are accelerated.

Now let us look at what variability of Blazar tells us.

(i) Blazar spectra are characterized by two broad spectral components - one with peak power at low frequency (IR to UV/X) called synchrotron SSC, and another with peak power at very high energies (GeV to TeV - γ rays) - probably Inverse Compton.

(ii) Variability in both components is much more pronounced above the corresponding peaks - variability amplitude increases with frequency - so that spectra hardens with increasing intensity.

(iii) Finite time lags estimated among flares in optical through X-rays light curves. Say, for PKS 2155-304 and Mrk 421, the soft X-ray photons lag hard X-ray by 1 hour. For Mrk 421, EUV and optical lag TeV by 1 day.

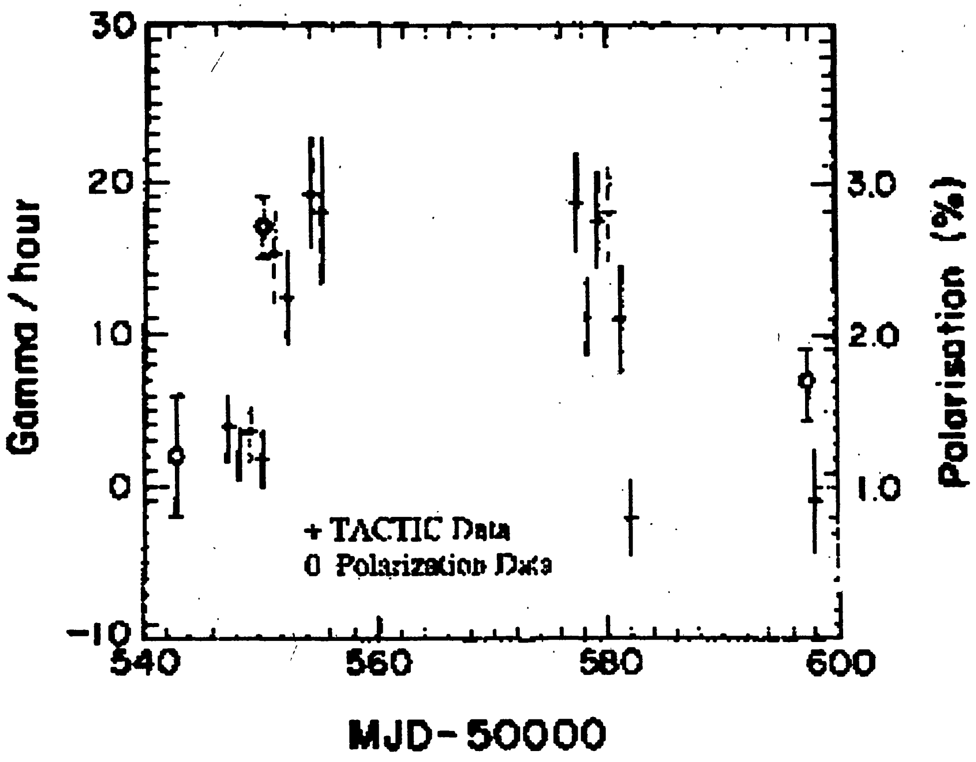

Figure 2. Variation in the γ-ray flux and the degree of linear polarization (optical) in Mrk 501 during April-May, 1997.

The observed multifrequency variation in blazars is complex. For the high energy synchrotron radiation, both soft and hard lags are seen in same object ! Soft lags can be explained by synchrotron cooling provided electron acceleration is rapid, while hard lags can be explained by slow acceleration.

Studying short time scale behaviour and looking for spectral changes while following complete outburst may be key to pin down the basic emission mechanism.

7. Summary

It is clear that blazars vary at all the frequencies with timescales varying from seconds to years. However, it is very difficult to have short timescale sampling, necessary for higher frequencies for obvious reasons. The variability provided some fundamental clues but many questions are still unanswered. Some of the highlights are :

- ★ For nonthermal activity of blazars, the basic model consists of a relativistic jet, closely aligned with line of sight. It is filled with energetic particles emitting synchrotron and Compton scattered radiation - radio through γ-rays.
- ★ The radiating particles have bulk motion - beaming the radiation towards us. Thus blazars appear more luminous and variable.

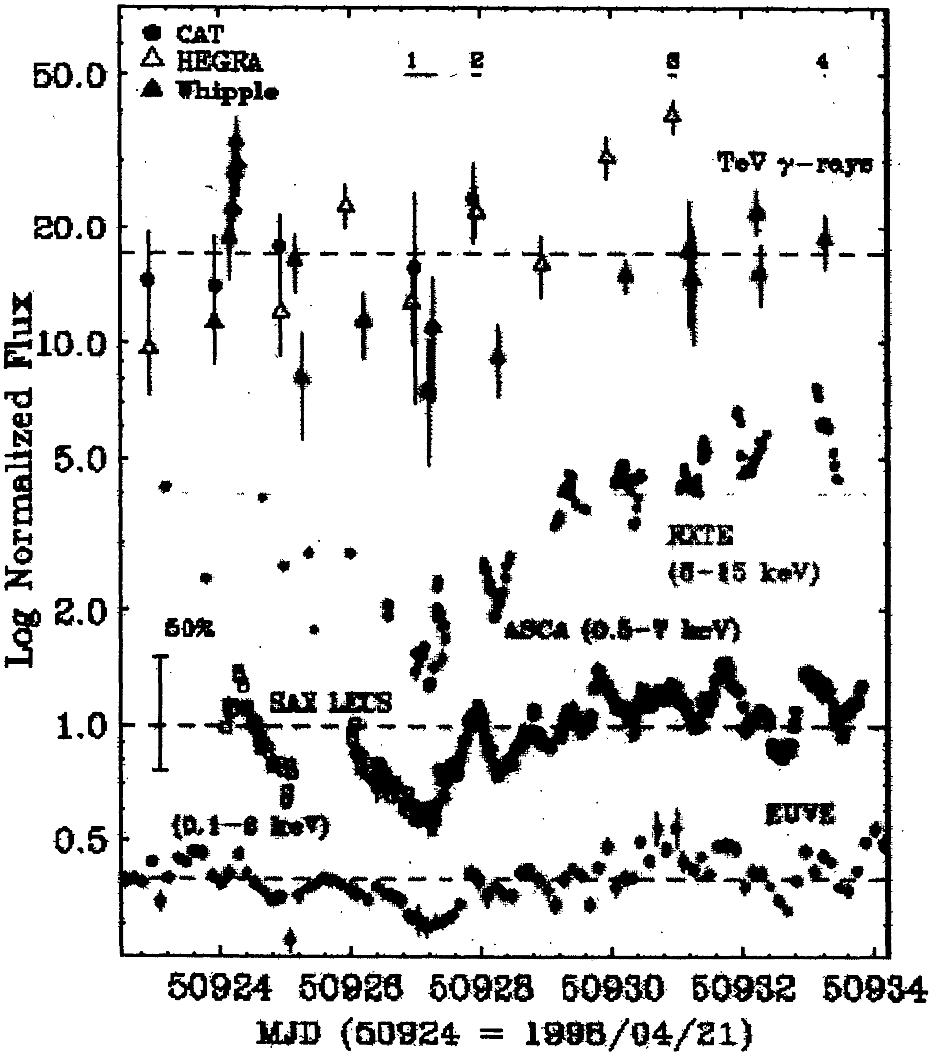

Figure 3. Multiwavelength campaign results for Mrk 421 (Takahashi et al. 2001).

- ★ Structure of the jet, nature of seed photons which are to be upscattered to γ-rays are NOT very clear.

- ★ Short lags in UV to X-ray range in Mrk 421 and PKS 2155-304 (HBL sources) indicate that energy injection in the jet occurs in top down fashion. Since LBL also have same variability, it is important to look for IR to UV lags in LBL using ground/space facilities. Comparison of flare evolution in blue and red blazars will give clues to the differences in jet.

- ★ Determination of the nature of seed photons is important. It will help determine the physical conditions in the jet and to understand how jets are influenced.

- ★ Multiwavelength campaigns, taking bright sources, are best means here too. One should look for short term variability over short time scales the external photon field is not expected to change.

- ★ Jet models imply that energy is transported in the jet in a dissipation-less way from small scales to relatively large distancess - a light day or more. Further work is needed here as it holds the key to understanding how energy is extracted from the central black hole.

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