Variability of Blazars

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Abstract. This is an overview of variability properties of Blazars, focusing especially on fast flares. Blazars are the only class of sources detected in all wavebands of the electromagnetic spectrum that are accessible for astrophysical investigations. Their flux density is variable on a wide range of time-scales in all of these energy bands. It is shown that there still is significant variation on the shortest time-scales which can be probed at present. This suggests that we have not yet resolved the fastest events. The presence of rapid flares also limits our ability to derive meaningful correlations between changes observed in different energy bands.
Rapid flares have immediate consequences for the physical models of compact flat-spectrum sources. The short time-scales indicate that acceleration and radiative or Compton cooling occurs within small sub-volumes. Fast variations of polarisation characteristics suggest small-scale turbulence of the magnetic field configuration.
All gamma-bright source exhibit IDV at lower frequencies. Understanding IDV is hence mandatory for any self-consistent model of the radiation mechanisms in these objects.

Quasar variability is known almost since quasars were discovered as a specific class of objects. Right from the first days the short time-scales of variability had severe implications for physical models. The then-fastest variations over a few weeks or months immediately ruled out all models of generating the luminosity based on fusion-powered sources and led to black hole models. Variations have since been monitored in several long-term programs operating in the radio and optical bands. Several methods have been used to characterise variability with structure function analysis being used in most cases. The structure functions follow a power law over 3 orders of magnitude (weeks to decades) with a slope of about 1 (e.g. Hughes, et al., 1992). During the last decade studies in the X-ray and gamma-ray bands have become routine and even faster variations were found in all energy bands. It turns out the the structure functions become flatter on time-scales less than about one or a few days. The knee in the structure function causes variability of this temporal frequency to be especially prominent and led to the term "Intraday-Variability" (IDV, Wagner & Witzel, 1995).
These short time-scales allow indirect studies of AGN on spatial scales of the light travel time $c\Delta t$ corresponding to the flaring and decay times. The corresponding angular scales are several orders of magnitude smaller than any direct imaging experiment. The small volumes of the highly luminous cores immediately lead to very high brightness temperatures (10^{18} K) which call for very high Doppler factors ($\mathcal{D} \sim 100$). The ubiquity of highly relativistic particles makes these objects powerful emitters of high energy photons. It is hence no surprise that almost all IDV sources were found to be efficient gamma-ray emitters.

1 Variations from TeV to GHz

At the highest energy end of the electromagnetic spectrum accessible with current technology is the **TeV regime** which can be probed with ground-based Cherenkov telescopes. In addition to pulsars, a rapidly growing number of Cherenkov telescopes detected the active galaxies Mrk 421 (Schubnell et al., 1996), Mrk 501 (e.g. Bradbury, et al., 1997), and - at a lower level of significance - a few other AGN (e.g. Meyer & Westerhoff, 1996) of similar characteristics. In the two brighter objects variability was found on scales of about a year in between subsequent observing seasons, as well as within a specific campaign. The fastest flares reported so far lasted for a few hours in the case of Mrk 421 (Gaidos et al., 1996) down to less than an hour in Mrk 501 (Aharonian et al., 1997). There is some indication for spectral variations associated with these variations of TeV photon flux, but more detailed investigation with stereoscopic arrays are required.

The GeV energy regime was fully opened by EGRET on board CGRO. The third EGRET catalogue will contain more than 100 gamma-ray Blazars (Hartman et al., 1997), many of which had been observed ten to or more times during 1991-1997. As discussed by von Montigny (this meeting) all of the brighter sources are clearly variable from one observing epoch to the next (with typical observing times of 2 weeks and an average sampling of 0.15 month^{-1}). In addition, many of the brighter sources have been found to vary on time-scales of a few days, whenever they were bright enough to show variations directly (Wagner, 1997). Examples of gamma-ray IDV which can be studied directly are PKS 1622-297 (Mattox et al., 1997) and PKS 1406-076 (Wagner et al., 1995a).
We have used a statistical approach to investigate variability by taking one-day maps of the entire EGRET data set of a few, selected Blazars. An example light curve is the one shown in Fig. 1a for PKS 0528+134. This source was observed on more than 180 days during the first 5 years of EGRET operation. One can hence derive a reasonably well sampled structure function (Fig. 1b). Interestingly, this

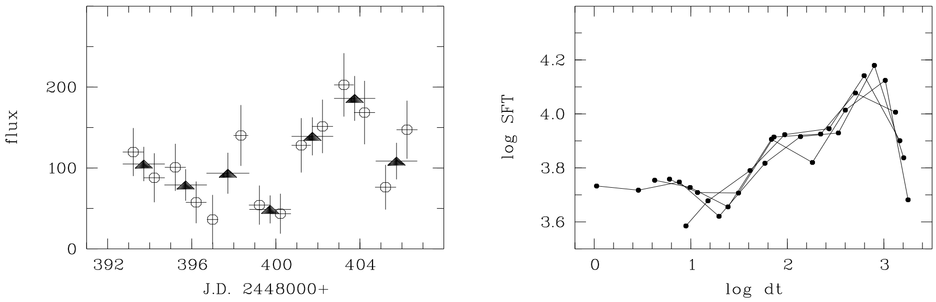

Fig. 1. Flux variations of PKS 0528+134 (left) measured with a sampling of one or two days (open circles and hatched triangles, respectively). Note that the latter is clearly under-sampled. The right panel gives the structure function derived for the entire data set of one day maps of PKS 0528+134 as discussed in Wagner et al., 1997.

also shows the phenomenon observed at lower photon energies that the slope of the structure function flattens towards shorter time-scales. This is statistical indication of the existence of gamma-ray IDV. Although a mere statistical study of IDV is of restricted value for a detailed physical analysis it is important to realize that GeV light curves are likely to be under-sampled. This needs to be taken into consideration in interpreting simultaneous multi-frequency campaigns.
We also note that the statistical investigations described above (Wagner, et al., 1997) give statistical evidence for detected gamma-ray flux in the brighter sources even during very faint states. The detection of a DC contribution to the gamma-ray emission facilitates the comparison of flare amplitudes throughout the electromagnetic spectrum.

The MeV regime has been studied by the COMPTEL telescope on board CGRO but only a small number of AGNs have been identified, almost all of them being EGRET Blazars. They tend to very in the MeV bands as well (Colmar, 1996) but the larger errors of the flux determinations do not allow any detailed studies of the variability properties.

In **the keV (X-ray) regime** fast variations down to time-scales of a few seconds have been observed in some brighter sources. Down to time-scales of a few hours changes in X-ray spectral indices have been found to accompany (and slightly lag behind) changes in total flux. These variations have been used successfully to derive quantitative SSC models (Takahashi et al., and Maraschi, this meeting).

At photon energies of a **few eV (optical emission)** flat-spectrum radio sources are known to vary on time-scales from decades (e.g. 3C 345, see Schramm et al., 1993) to seconds (Fig. 2). For the class of sources (but not for an individual object) variations have been investigated over seven orders of magnitude in time. Investigations of the fastest changes require large telescopes and modern detectors to push noise levels down. Although very fast flares as shown in Fig. 2 seem

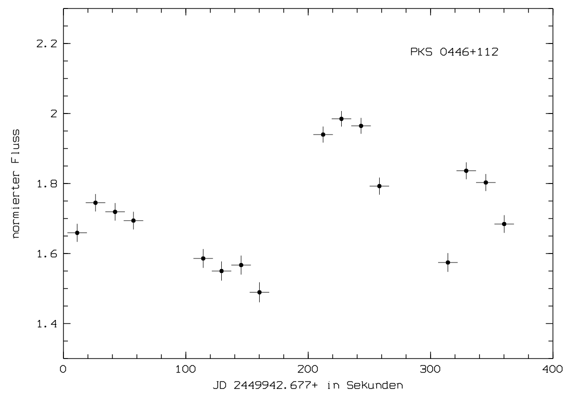

Fig. 2. Optical variability (normalised flux) on very short time-scales (t in seconds) in PKS 0446+112. Flares with amplitudes as large as 10 % occur during 100 seconds.

to be very rare events, they demonstrate that substantial fractions of the total (beamed) emission from such Blazars may be emitted from volumes as small as d = $\mathcal{D} \cdot c \cdot 100s$, i.e. a few AU. They also indicate that very dense sampling is required to fully cover the behaviour of the most rapid sources. Although the characteristics of the fast flares have not been explored in sufficient detail, it is plausible to associate the characteristic time-scales with the acceleration of the radiating particles rather than some radiative time-scale (see e.g. Kirk, this meeting). The change in the structure functions at about one day separates two regimes, which can now be probed over a comparable dynamic range.
The flares of total flux are accompanied by dramatic variations of the degree of polarisation as well as position angle (Wagner, 1997). There are no trivial correlations of polarisation characteristics with total flux in any band. This is likely to be caused by the superposition of different, polarised components. This is especially important in the optically thin regime (i.e. optical emission) where several components along a single line-of-sight overlap. This number of regions with different polarisation characteristics cannot be very large, however, in order to avoid the individual contributions to be blended with a resulting low total polarisation and very small amplitudes of the polarisation light curves. 'Christmas-tree' models are limited to a rather small number of components. It is interesting to note that the polarisation changes only a little bit faster than the total flux (although not related). This suggests that the configuration of the magnetic field (i.e. its projected orientation) changes on spatial scales which are comparable to those of the emitting region.
The spectral indices change on similar time-scales as well. In general the source follow the common trend of becoming harder during brighter stages.

Another three orders of magnitude down in energy, in **the meV regime (about 230 GHz)**, radio variability is studied. This energy band is important because these are the lowest frequencies which are still unaffected by scattering of electromagnetic waves in the interstellar plasma. Although plagued by technical difficulties due to the enormously strong background and atmospheric fluctuations, it has become possible in the last years to get sufficient accuracy to investigate variations on short time-scales. In at least one source (PKS 0405-385) significant variations have been observed (Wagner, 1997).

Radio variability in **the GHz range** is the most amazing aspect of IDV. It is now obvious that even in the cm range sources may vary fast. Kraus et al. (1997) and Kedziora-Chudcer et al. (1997) find changing flux densities within two hours. While most sources seem to have very low amplitudes in the studies of Kraus et al., Kedziora-Chudcer reported flares with amplitudes up to 20 %. Both studies find polarisation and spectral indices to change equally fast.

Variability of substantial amplitudes is detected throughout the entire electromagnetic spectrum on all time-scales which have up to now been probed. There is no indication that structure functions cut off in the high frequency limit where the experiments are hampered by low photon fluxes and measurement errors. The wide extent in photon energy calls for studies of correlated variations.

2 Correlations

Although a very recent partner in multifrequency investigations it was already demonstrated, that variations of the TeV flux density are correlated with those at lower photon energies. Wagner (1996) and Takahashi et al. (1996) reported changes of the flux-density in the optical and X-ray regimes during a TeV campaign on Mrk 421. Cross-correlations of the three bands show a clear signal with a small, frequency-dependent lag. The broad-band energy spectrum suggests that both the X-rays and the TeV gamma-rays represent variations in a regime close to the high-energy cut-off of the electron population. The synchrotron emission extends into the X-ray regime, implying high Lorenz-factors. Inverse Compton scattering of these synchrotron photons produces TeV gamma-rays. The amplitudes in the two energy bands can hence be used to derive the magnetic field energy, if other reprocessing- or radiation mechanisms for the TeV emission can be excluded. In such a scenario the optical emission is clearly indicative of variation below the break-energy of the synchrotron emission (with the synchrotron peak occuring at 10^{16} Hz). The variation below the peak has lower amplitudes and is further diluted by the strong contribution of the host galaxy. The relation between X-rays and TeV emission in this source corresponds to the relation between optical and GeV emission in the case of radio-selected Blazars. The small amplitude optical variations in Mrk 421 are comparable to radio-IDV in radio selected sources. The comptonised optical radiation is observed in the GeV range, were the small amplitude variations cannot be investigated directly.

Studies in the TeV regime were preceded by investigations of correlations between GeV gamma-ray emission and radiation at lower frequencies. Several such campaigns have been carried out in a number of sources (e.g. 3C 279: Hartman et al., 1996, Wherle et al., in preparation, Maraschi, this meeting). As discussed by Maraschi (this meeting) the X-ray emission observed from XTE is due to synchrotron radiation. There is a close correlation between the high energy end of the synchrotron emission and the GeV radiation. In this high-luminosity object the UV and optical emission are not as closely correlated with the GeV radiation as the X-rays. A different situation was observed in PKS 1406-076 (Wagner et al., 1995a) with a close correlation between optical and GeV emission. Unlike 3C 279 the two light curves are not exactly coincidental. The GeV emission lags behind the optical flare by about one day. Less densely sampled simultaneous investigations of vast variability were reported in PKS 0420-014 (Wagner et al., 1995b), PKS 0528+134 (Mukherjee et al., 1996), and S5 0836+71 (von Linde et al., 1993). In none of these cases the sampling (at best about one measurement per day) was sufficient in view of the very fast changes (hours) which have been seen in some of these sources (see Section 1). It is unclear, therefore, whether less well sampled cases may be confused by relating long-lasting flares in one band to rapid flicker in another band. This is especially important when lags between different bands are compared.

In the X-ray band both, the high-energy tail of the synchrotron emission, as well as the onset of Compton-scattered radiation contribute. It is of special interest to study correlations with lower energy bands. One of the best studied objects, PKS 2155-304 had very different behaviour in two subsequent campaigns (Brinkmann et al., 1994, Urry et al., 1997). As illustrated by Georganopoulos & Marscher (this meeting) it is possible to understand this in terms of different states with different high-energy synchrotron cut-offs. This underlines the necessity of repeated campaigns to explore the range of physical parameters which can prevail within a single object.

The broad-band energy distribution of radio-selected BL Lac objects suggest that the peak of the synchrotron emission of these sources lies in the optical range. Correlations of optical light curves with variability at longer wavelengths can hence be used to probe variations of the electron population responsible for the emission in the range 10^9 to 10^{15} Hz. A close correlation has been found both in long-term studies (e.g. 3C 345, Schramm et al., 1993) as well as in studies of IDV (0716+714, Quirrenbach et al., 1991, 0954+65, Wagner et al., 1993). The close correlation confirms that the radio variability is not dominated by interstellar scattering and hence leads to very high apparent brightness temperatures of radio-IDV. Spectral changes which are associated with flux-density variability cause the formal lag (which is no longer than about one day) to depend on the observing frequency (Wagner et al., 1996). Changes in the break frequency can hence not only change the lags but also the characteristics of variability (as mentioned above for the case of the UV/X-ray variations of the X-ray selected BL Lac PKS 2155-304). The amplitudes are larger at higher photon energies. This again points to the similarity between the optical/radio correlations in the radio selected sources and the X-ray/optical correlations as seen in the X-ray selected TeV source Mrk 421.

Several campaigns have been successful in demonstrating close correlations between different combinations of wavebands, in some cases bracketing 15 orders of magnitude in photon energy. Lags between the bands are very small, at least for IDV, indicating that this mechanism operates in the optical thin regime without major geometric dilutions. This strengthens the hope that IDV can indeed be used to probe small-scale structure within extragalactic jets. Many campaigns have not been successful in deriving correlations, giving rise to the worry that the successful examples are due to statistical coincidences. This is a major concern in radio/optical correlations (which imply very high brightness temperatures) or synchrotron/gamma-ray correlations (to study the mechanisms responsible for the high gamma-ray fluxes). Apart from technical reasons (unfavourable sampling, poor coverage, etc.) there are physical reasons not to expect close correlations in each campaign:

The close correlation of total flux in the optically thin part of the synchrotron regime (in the optical band) with spectral index in the radio band in 0716+714 (Wagner et al., 1996) together with much larger spectral changes on scales of weeks suggest that the source will exhibit different states at different epochs. This is similar to the range of variability patterns found in PKS 2155-304. Especially the high transparency required for radio IDV (Sikora et al., 1994) may not prevail completely undisturbed for a long time. The range in time-scales suggests that various modes of variability (flares and flicker) exist in a single source. These modes may be caused by changing Doppler factors (for inhomogeneous flows) or by different mechanisms (acceleration, radiative cooling) dominating different epochs. Correlations for the various modes may hence show different lags and amplitude scalings. In addition the large Doppler factors may cause a fixed observers' frequency to shift into different spectral branches in different campaigns on the same source. Although all of these considerations complicate the interpretation they also allow us to obtain a more complete picture of the potentially rich behaviour of a (set of) source(s).

3 Models

In addition to the variety of intrinsic variability characteristics, the observed flux may also be modulated by propagation induced effects. Although gravitational microlensing (an achromatic effect) has been suggested for BL Lac objects in general and in the case of a few selected objects in particular, various pieces of evidence exclude microlensing as being responsible for IDV of Blazars in general (Wagner & Witzel, 1995). At radio frequencies, the observed flux-density may also vary due to interstellar scintillation (ISS). Scintillation will certainly affect radio observations of compact sources. If the Blazars are as compact as implied by the short time-scales of variability they still have an angular diameter larger than galactic pulsars and will not show diffractive effects. They will be affected by refractive ISS however. The steep spectral dependence of ISS-induced variability allows two independent ways to study its role: Observations at very high radio frequencies (e.g. 230 GHz) are unaffected. The IDV of PKS 0405-385, mentioned above, can hence not be caused by IDV. It is well possible, however, that the same source is variable to to ISS at lower frequencies at the same time, as suggested by Kedziora-Chudcer et al., 1997. The role of ISS at lower frequencies can only be constrained from simultaneous observations in the radio and optical bands. Close correlations rule out a dominant contribution of ISS to the radio variability (at those epochs) and require the radio variations to be intrinsic.

Intrinsic variations imply very high brightness temperatures of up to 10^{19} K (Wagner & Witzel, 1995). Incoherent synchrotron emission cannot exceed the Compton limit on the brightness temperatures of 10^{12} K. The canonical suggestion to explain this contradiction is the assumption of a highly relativistic flow with beaming corrections (proportional to $\mathcal{D}^3$) and relativistic aberrations (Marscher, 1992). Sikora et al. (1994) point out that jets of low radiative efficiency may be as fast as $\mathcal{D} \sim 100$. The difficulties of these extreme values lie in the implication of a large unbeamed parent population and extremely low densities along the los.

The possibility that the emission is actually partly coherent would reduce the requirements for very high Doppler factors, since the Compton limit increases by about three orders of magnitude. Large degrees of circular polarisation are not an unavoidable consequence of coherent radiation. Small amounts of circular polarisation have been detected in 3C 279 (Wardle, private communication).

The coincidence of IDV and high gamma-ray luminosities call for a common explanation. The fastest flares have time-scales close to those predicted for particle acceleration. The shocks responsible for the acceleration are very thin along the line-of sight. Small-scale turbulence is of similar size. The polarisation is not totally washed out, which argues in favour of a small number of cells contributing to the total emission at any specific time. The magnetic field appears to be tangled on scales comparable to the emitting volumes. This argues in favour of very thin beams (possibly within wider jets) or jets with nearly perfect vacua.

References

Aharonian, F. et al., 1997. in *Fourth Compton Symposium*, C. Dermer & J. Kurfess (Eds.), AIP Press, in press.
Bradbury, S.M. et al., 1997. *A & A*, 320, L5.
Brinkmann, W., Maraschi, L., Treves, A., et al., 1994. *A & A*, 288, 433.
Colmar, W. 1996 in *Gamma-Ray Emitting AGN*, Heidelberg Workshop, http://www.lsw.uni-heidelberg.de/projects/extragalactic/gamma-ray.html
Gaidos, J.A. et al. 1996. *Nature*, 383, 319.
Hartman, R.C., Webb, J.R., Marscher, A.P., et al. 1996. *Ap.J.*, 461, 698.
Hartman, R.C. et al., 1997, in *Fourth Compton Symposium*, C. Dermer & J. Kurfess (Eds.), AIP Press, in press.
Hughes, P.A., Aller, H.D., & Aller, M.F., 1992. *Ap.J.*, 396, 469.
Kraus, A., Krichbaum, T.P., & Witzel, A. 1997, in *Radio Emission from Galactic and Extragalactic Compact Sources*, J. Wrobel & A. Zensus (Eds.), ASP, in press.
Marscher, A. 1992. in *Physics of AGN*, W. Duschl & S. Wagner (Eds.), p. 510.
Mattox, J.R., Wagner, S.J., Malkan, M., et al. 1997. *Ap.J.*, 476, 692.
Meyer, H. & Westerhoff, S. 1996 in *Gamma-Ray Emitting AGN*, Heidelberg Workshop, http://www.lsw.uni-heidelberg.de/projects/extragalactic/gamma-ray.html
Mukherjee, R., Dingus, B.L., Gear, W.K., et al. 1996. *Ap.J.*, 470, 831.
Quirrenbach, A., Witzel, A., Wagner, S., et al. 1991. *Ap.J.*, 372, L71.
Schramm, K.-J., Borgeest, U., Camenzind, M., et al. 1993. *A & A*, 278, 391.
Schubnell, M.S., et al. 1996. *Ap.J.*, 460, 644.
Sikora, M., Begelman. M.C., & Rees, M.J. 1994. *Ap.J.*, 421, 153.
Takahashi, T., Kataoka, J., Kii, T. et al. 1996, in: *Blazar Continuum Variability*, H.R. Miller, J.R. Webb, & J.C. Noble (Eds.), ASP Conf. Ser., Vol. 110, p. 311.
Urry, C.M. et al. 1997, *Ap.J.*, in press
von Linde, J., Borgeest, U., Schramm, K.-J., et al. 1993. *A & A*, 267, L23
Wagner, S.J. 1996. *A & A Suppl.*, 120, C495.
Wagner, 1997, in *Radio Emission from Galactic and Extragalactic Compact Sources*, J. Wrobel & A. Zensus (Eds.), ASP, in press.
Wagner, S.J. & Witzel, A. 1995. *Ann. Rev. Astron. Astrophys.*, 33, 163.
Wagner, S.J., Witzel, A., Krichbaum, T.P. et al. 1993. *A & A*, 271, 344.
Wagner, S.J., Mattox, J.R., Hopp, U., et al. 1995a. *Ap.J. Lett.*, 454, L97–L100.
Wagner, S.J., Camenzind, M., Dreissigacker, O., et al. 1995b. *A & A*, 298, 688.
Wagner, S.J., Heidt, J., Witzel, A., et al. 1996. *AJ*, 111, 2817.
Wagner, S.J., von Montigny, C., & Herter, M. 1997, in *Fourth Compton Symposium*, C. Dermer & J. Kurfess (Eds.), AIP Press, in press.