Variability Models of Gamma-Ray Blazars

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1. General remarks

Much observational efforts have been devoted in recent years to study blazar variability across the electromagnetic spectrum (for a recent review see e.g., Ulrich, et al. 1997). In addition to spectral and polarization information, variability data can provide stringent constraints on the radiation mechanisms, the geometry of the emission regions, beaming factors, formation and dynamics of shocks, and perhaps the jet’s content.

In most models the variability pattern is governed by the following timescales: i) the light travel time across the source, ii) the cooling time, iii) the acceleration or injection time of radiating particles, and iv) the dynamical time, which equals roughly the light crossing time in the case of a relativistically expanding source. It is conceivable, however, that the temporal structure observed involves additional, distinct timescales that are associated with completely different physical process, as demonstrated by other transient systems, e.g., radio pulsars, GRB; the overall pulse duration and the duty cycle in the former system reflect the rotation of a neutron star, whereas the temporal substructure (sub-pulses, polarization swings, etc.) is presumably connected with the emission mechanism. A plausible variability scenario for blazars is the formation of a train of shocks during a period of enhanced activity that might be associated with accretion instabilities or with the process responsible for the ejection of the jet. Such a possibility seems to be suggested by some recent observations which reveal, what appears to be rapid flaring during the occurrence of a much longer outburst (Wagner 1998).

In models whereby the emission originates from deep inside the jet, the size of the source is limited by optical depth effects. The gamma-spheres in the powerful sources and the photospheres of the IR-to X-ray emission lie in the range between $10^{-3}$ to about 1 pc (Blandford & Levinson 1995, and Levinson 1996). The corresponding light travel times, as measured by a distant observer at small viewing angles, then range from a few minutes to several weeks, assuming that the emitting plasma moves with Lorentz factor $\Gamma \approx 10$. The radio-spheres are typically located at much larger radii. This range of time scales is in accord with the rapid variability frequently observed in blazars (IDV has been observed in many bands, with changes on time scales as short as a few minutes in the optical and X-ray bands and a few hours in gamma-rays; Wagner 1997 and references therein). It also illustrates the temporal resolution and sampling rates required for testing predicted correlations or other model features.

Correlations between optical and gamma-ray emission in flat spectrum radio quasars, and between X-ray and TeV emission in BL Lac objects appears to
be another characteristic of blazar variability. The time lags between different bands and the relative amplitudes are important diagnostics of the radiation mechanisms and the structure of the emission region. They may also be influenced by geometrical and orientation effects (see below). Unfortunately, it seems that the sensitivity available, particularly in the gamma-ray band, is insufficient to provide good enough time resolution to test relevant model predictions. Another caveat is that the time separation between subsequent observations in recent multiwavelength campaigns (e.g., the high and low states in the 1994 campaign on 3C279; Maraschi et al. 1994, or the pre-flare and high state in the 1996 campaign; Wehrle et al. 1998) is very long compared with the variability time anticipated. Therefore, conclusions regarding the radiation mechanism for instance, which are drawn based on data taken at say two epochs in some individual source can be misleading. A better strategy might be to look for systematic trends (e.g., delays between gamma-ray and radio outbursts, as predicted by inhomogeneous models, or changes of cutoff energies) in a sample of sources. It is hoped that the next generation gamma-ray telescope and forthcoming campaigns will help elucidating the relation between the emission in different bands, and discriminating between models.

2. Models of blazar variability

Several types of variability models have been discussed in the literature. In one class of models, some of the source parameters (e.g., magnetic field, density) and/or particle acceleration rate are assumed to have explicitly time dependence. Such models may represent a physical situation in which sudden changes of the outflow parameters and/or particle acceleration rate result from e.g., magnetic reconnection episodes, as in the case of solar flares, encounter of a strong shock with a region of enhanced density or magnetic field, or various types of instabilities. The time dependent SSC model by Mastichiadis & Kirk (1997) and Kirk, Rieger & Mastichiadis (1998), who applied it to the TeV BL Lac objects, is an example. In ERC models the variability can be produced also by changes of the ambient radiation intensity. Geometrical effects may also have important implications for the observed variability. In particular, rapid variations of the observed flux in any band can be produced without straining the parameters of the emission region too far (Salvati, et al. 1998). Such effects may provide an explanation for the radio IDV which is problematic for other models (Wagner 1998). Another class of models associates the temporal behavior of blazars with the dynamics of shocks or blobs (e.g., Dermer & Chiang 1998; Levinson 1998a). Here the variability is produced by implicit time changes of the blob or front parameters that are associated with the inhomogeneity of the source. In the following we discuss a particular model of this type in some greater detail.

In the radiative front model (Romanova & Lovelace, 1997; Levinson 1998a) the variable emission seen originates inside dissipative fronts that are produced by overtaking collisions of highly magnetized, relativistic outflows, and consist of a pair of shocks and a contact discontinuity. In the regime where the ERC process dominates the production of the high-energy emission, the shape and timescale of the flare depend on the ratio of the thickness of expelled fluid slab and the gradient length scale of background radiation intensity; when this
ratio exceeds unity then the shape of the light curve is determined by the radial
variation of ambient radiation intensity, and is typically asymmetric with a rapid
rise and a longer decay. When it is much smaller than unity, the flare duration
is determined by the shock travel times across the fluid slabs (the cooling time
is typically shorter). In this case the decay is comparable to or shorter than
the rise. Since the ERC emission is anisotropic in the front frame it gives rise
to a radiative drag and consequent deceleration of the front during the rise of
the radiated flux. This renders the amplitude of variations and the high-energy
cutoff of the emitted spectrum sensitive to the Thomson opacity. Depending
upon the conditions in the source, pair production effects can lead to either, a
high-energy cutoff in the emitted spectrum or a propagating flare with longer
delays, longer durations and smaller amplitudes for higher energy gamma-rays.
In view of the relatively short timescales involved (see §1) and the decrease in
amplitude with increasing gamma-ray energy, the detection of such delays in the
gamma-ray band requires good sensitivity, typically much better than provided
by EGRET, and should be one of the prospects of future gamma-ray missions.
Since the synchrotron flux at low frequencies is self-absorbed at radius of peak
emission, radio outbursts lag gamma-ray flares in this model. Such delays have
been observed in several cases (e.g., Wehrle et al. 1998; Otterbein et al. 1998).
Detailed account of the correlations predicted for the angle averaged flux will
be given elsewhere (Levinson, in prep.). The radiative feedback should also give
rise to a dependence of the variability on the orientation of the source (Levinson,
1998b). Apart from changing the shape of the light curves, it can significantly
affect the predicted correlations. For example, the radio flux is emitted after the
front re-accelerates to its initial velocity and is, therefore, more beamed than
the flux emitted during the peak (at higher energies). Consequently, if viewed at
angles larger than the beaming cone of the radio emission but smaller than that
of the gamma-ray emission, a source may exhibit events whereby high-energy
outbursts are followed by a small or no change of the radio flux. There is some
observational evidence for such events (Mattox, priv. communication).

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