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Radio Band Observations of Blazar Variability

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Abstract. The properties of blazar variability in the radio band are studied using the unique combination of temporal resolution from single dish monitoring and spatial resolution from VLBA imaging. Such measurements now available in all four Stokes parameters, together with theoretical simulations, identify the origin of radio band variability and probe the characteristics of the radio jet where the broadband blazar emission originates. Outbursts in total flux density and linear polarization in the optical-to-radio bands are attributed to shocks propagating within the jet spine, in part, based on limited modelling invoking transverse shocks; new radiative transfer simulations allowing for shocks at arbitrary angle to the flow direction confirm this picture by reproducing the observed centimeter-band variations observed more generally, and are of current interest since these shocks may play a role in the γ-ray flaring detected by Fermi. Recent UMRAO multifrequency Stokes V studies of bright blazars identify the spectral variability properties of circular polarization for the first time and demonstrate that polarity flips are relatively common. All-Stokes data are consistent with the production of circular polarization by linear-to-circular mode conversion in a region that is at least partially self-absorbed. Detailed analysis of single-epoch, multifrequency, all-Stokes VLBA observations of 3C 279 support this physical picture and are best explained by emission from an electron-proton plasma.

Key words. Blazar variability—radio band—shocks—circular polarization.

1. Overview

In this review we discuss the properties of centimeter-to-millimeter band variability in Stokes I (total flux density), and compare the derived values to those determined in the Fermi γ-ray band. We summarize evidence for the shock-in-jet model invoked for explaining the optical-to-radio-band variations, and present new modelling results allowing oblique shocks. We show Stokes V (circular polarization) light curves illustrating the range of behaviour found, and illustrate how such measurements can be used in combination with all-Stokes, multifrequency imaging to place constraints on jet properties.

2. Total flux density: Stokes I

Single dish monitoring observations from Metsähovi, Michigan (hereafter UMRAO), and recently from the OVRO 15 GHz program, probe the properties of variability in the centimeter-to-millimeter bands on time scales of days to decades. In very active sources, e.g., see Fig. 1, the variability in Stokes I is continuous (no quiescent periods). Events do not repeat in either amplitude or spacing, and the amplitude changes by at most a factor of ∼8. In the spectral range 14.5–4.8 GHz observed by UMRAO, variations are highest at 14.5 GHz, and lowest and often delayed at 4.8 GHz. While the outbursts do not exhibit true periodicities, quasi-periodicities of the order of a few years have been identified in many sources; plausibly these correspond to the dynamical response time of the flow to perturbations. Doppler factors have been determined from fits to the fastest events, and values generally lie within the range $0 \leq D_{\mathrm{var}} \leq 35$ (e.g., Hovatta *et al.* 2009); however, as noted by Fan *et al.* (2009), there is considerable spread in the results obtained for a specific source when different analyses are compared. Structure functions have been used to identify both characteristic time scales and the noise process responsible for the variability; typically the time scales are two years with some spread, and the noise process is shot noise (Hughes *et al.* 1992). These radio band properties are characteristically different from those identified applying similar analysis procedures to Fermi monitoring

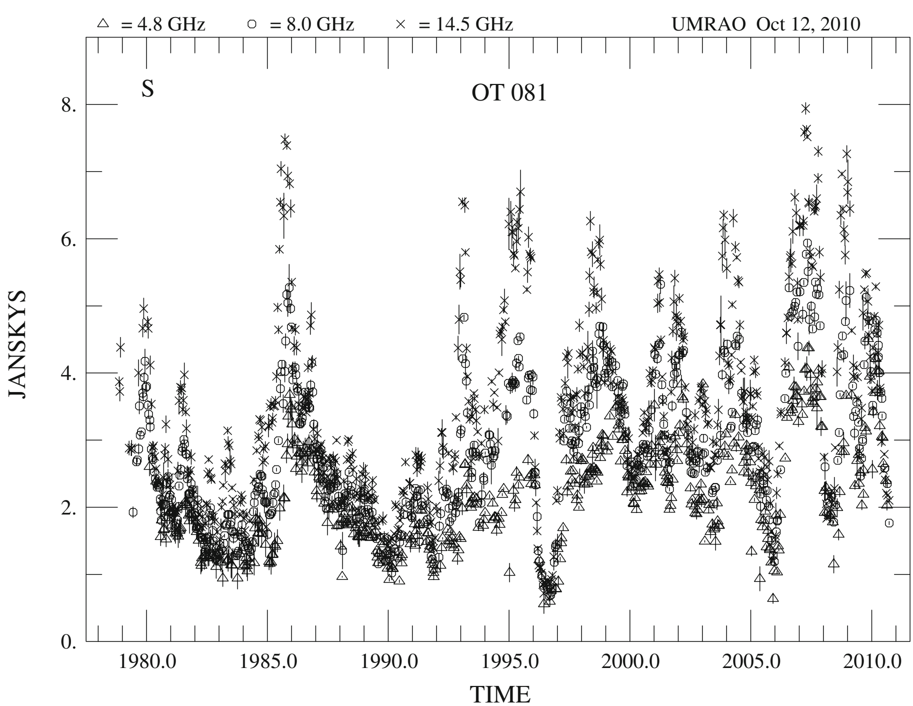

Figure 1. Two-week averages of total flux density observations over 3 decades illustrating the characteristic behaviour of radio band variability. Complementary 15 GHz MOJAVE VLBA imaging observations indicate a very compact source (e.g., Kovalev *et al.* 2005).

data; there the emission process is almost always flicker, the variability time scales are typically 4–12 weeks, and no periodicity is identified (Abdo *et al.* 2010).

3. Origin of the variability

The generally-accepted scenario for the production of the radio band variability is that shocks develop naturally within the relativistic jet flows (e.g., Hughes 2005). The magnetic field within the emitting region is turbulent. Supporting evidence comes from the low degrees of time-averaged linear polarization (see Fig. 2), which are much less than 60–70% expected for a canonical synchrotron source. The shock produces a compression as it passes through the emitting region yielding an increased degree of order. The event signature is a monotonic swing in the electric vector position angle (EVPA) and an increase in the fractional linear polarization. In our

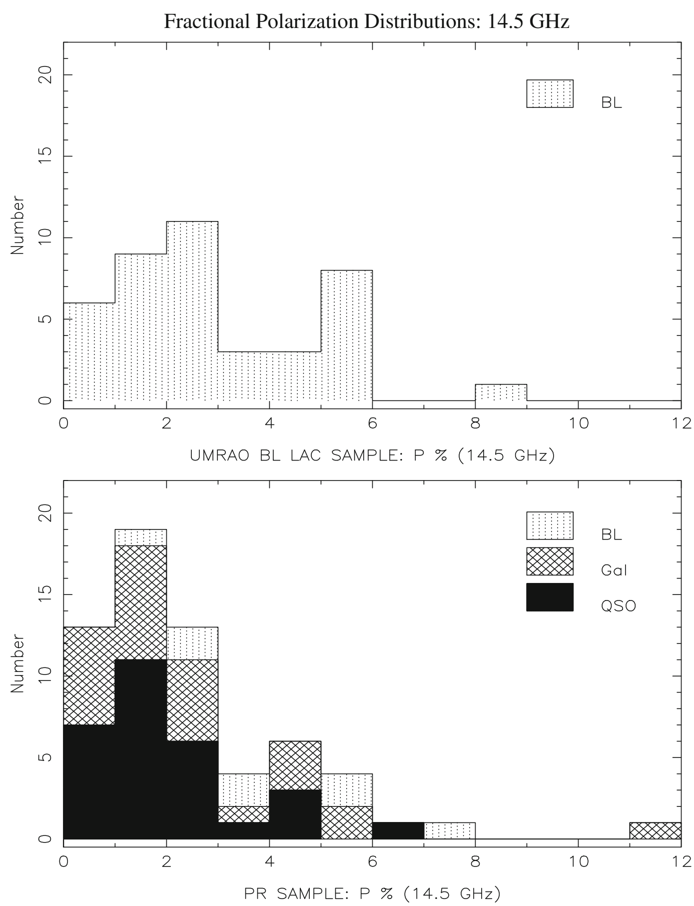

Figure 2. Histograms of fractional polarization determined from time-averaged long-term Q and U measurements for two flux-limited samples: the UMRAO BL Lac sample (1979–2005) and the Pearson–Readhead sample (1984–2005).

earlier work, the propagating shocks were assumed to compress transversely to the flow direction, and fits to events in three carefully-selected sources successfully reproduced the observed spectral evolution in both total flux density and linear polarization (e.g., Hughes *et al.* 1991). However, later events in these same sources could *not* be fit with the same source parameters, and the observed behaviour suggested that more generally, shocks are oriented at oblique angles to the flow direction.

As part of an investigation of the role that shocks may play in the generation of γ-ray flaring observed by Fermi, we are intensively monitoring a core group of about two dozen γ-ray and radio bright blazars to determine whether the shock signature is present during flares detected by Fermi. We have identified several cases where this signature is present, and an example is shown in Fig. 3. Note that the EVPA exhibits a swing through about 40° rather than 90° as expected for a transverse shock. As part of this investigation, new radiative transfer models have been developed which allow for the propagation of shocks at arbitrary angle to the flow direction. The new models, built on our work carried and out in the mid 1980s, are determined primarily by two free parameters: the shock compression and the shock direction (forward

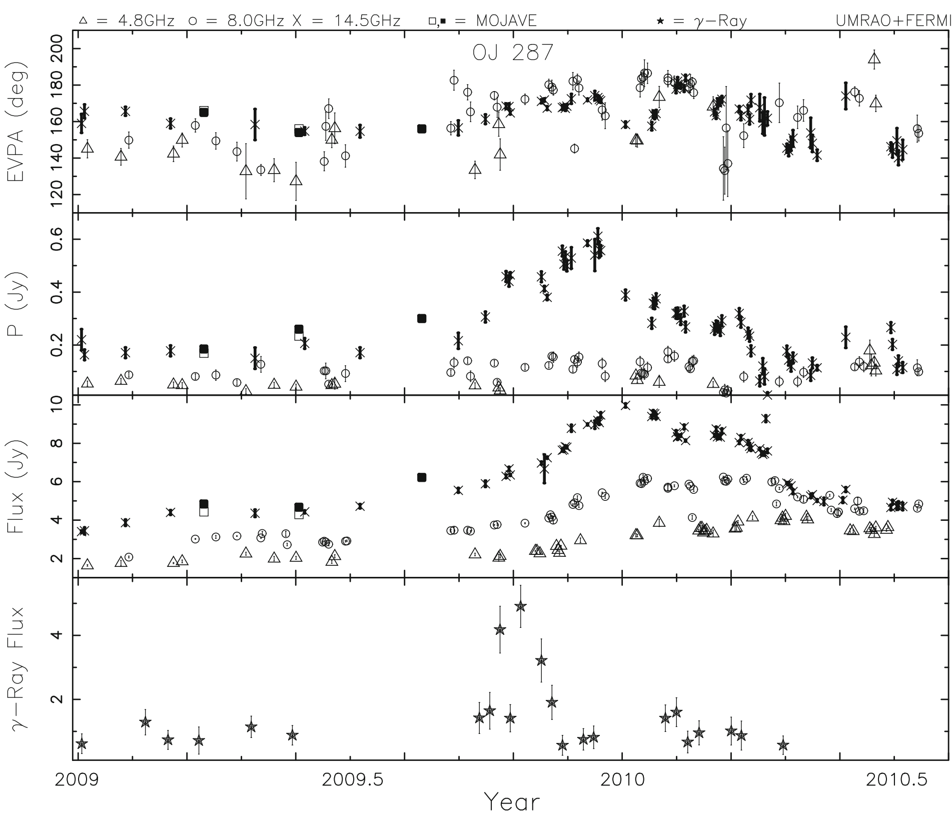

Figure 3. Example of a source exhibiting an oblique shock signature during a γ-ray flare. Linear polarization and total flux light curves are shown in panels 2–4. The lower panel gives the γ-ray light curve, kindly provided by S Jorstad (units: photons/s/cm^2 $\times$ 10^{-7}).

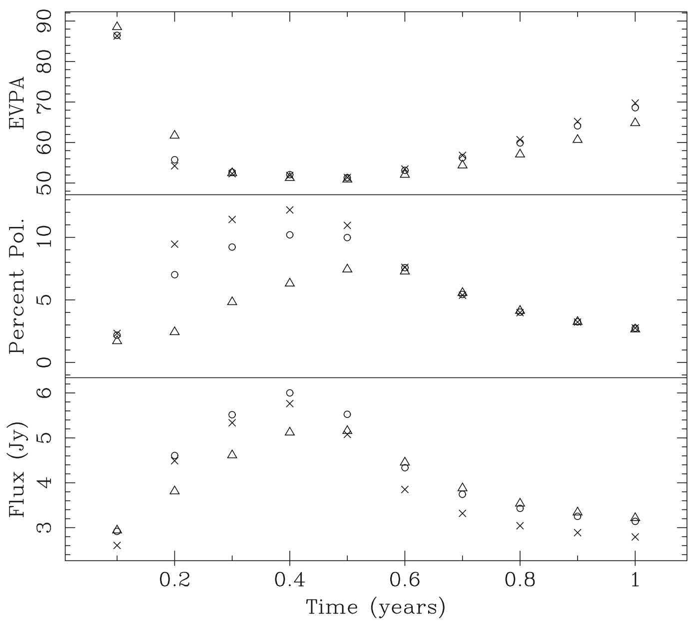

Figure 4. Simulated light curves at 3 frequencies assuming a forward moving shock oriented at an obliquity of 45°, and a shock compression of 0.7.

or reverse). In the example shown in Fig. 4 the viewing angle is 10°, the Lorentz factor of the flow is 2.5, and the Lorentz factor of the shock is 6.7. Comparison with Fig. 3 shows that the simulation successfully reproduces the main features of the data: a total flux outburst, an increase in linear polarization by up to 10%, a swing in EVPA through about 40°, and the spectral behaviour during outburst evolution.

4. Stokes V: Circular polarization

Surveys have shown that Stokes V emission from AGN is common, but it has not been observed routinely because of the difficulty in detecting such weak emissions. VLBA observations place the CP emission site at or near the radio core (e.g. Homan & Wardle 2004), the region believed to be the $\tau = 1$ surface or a standing shock. UMRAO monitoring observations of Stokes V were carried out for a few sources at 4.8 and 8 GHz during the late 1970s and early 1980s, but the program was subsequently dropped because it restricted the measurements to a few very bright AGN. However, in 2002 we resumed the program and added observations at 14.5 GHz in late 2003. Our specific observational goals are:

- to ascertain whether the polarity is stable to test the viability of models such as Ensslin's (2003) whereby the handedness (polarity) is an indicator of the direction of rotation of the quasar engine;
- to determine variability time scales; and
- to look for relations between the variations in all four Stokes parameters as tests of competing proposed emission mechanisms. We show example data in Fig. 5.

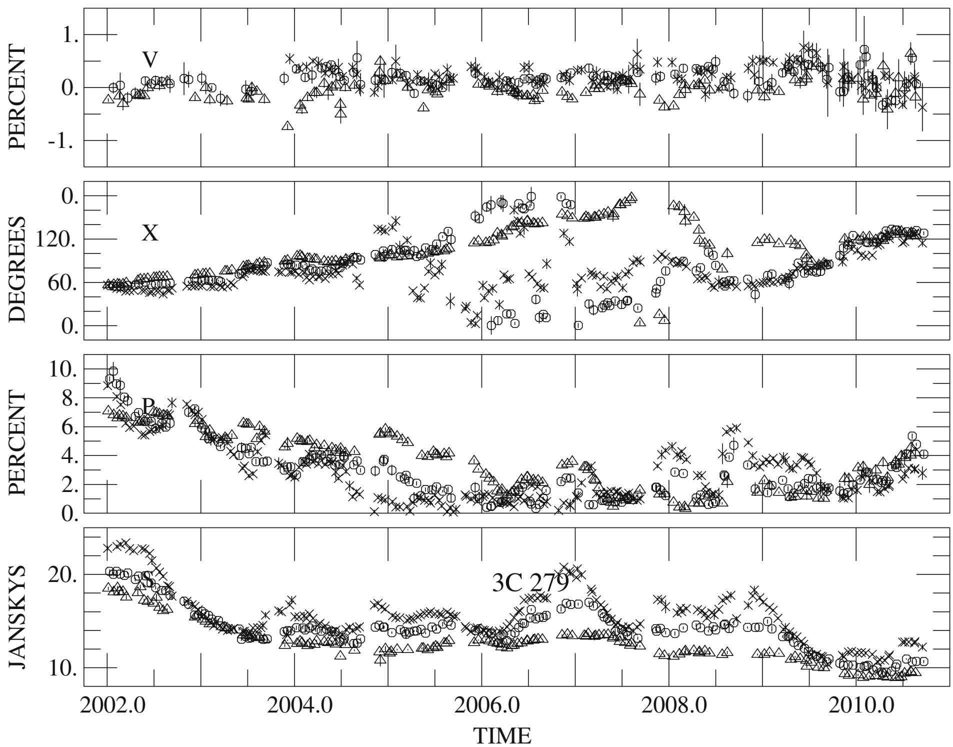

Figure 5. Two-week averages of total flux density, LP and CP since 2002 in 3C 279. This source has exhibited repeated polarity flips at 4.8 GHz, and polarity differences as a function of frequency at a single epoch, e.g., in 2004.

While we find preferred polarities in each source, there are also polarity flips at 4.8 and 8 GHz in many sources; these persist for a few months to a few years and commonly occur at times at which there is evidence for self-absorption in the Stokes I spectrum. Identification of variability on these long time scales requires a dedicated long-term program rather than ad hoc measurements. The data are overall consistent with linear-to-circular mode conversion.

As a next step in our work, we are collaborating with Homan, Wardle & Lister to obtain multifrequency, all-Stokes VLBA imaging data for a small group of sources. Stokes V spectra were presented for 3C 84, 3C 279 and 3C 380 in Homan *et al.* (2006), and a detailed analysis of the spectra of the three core components responsible for the CP emission in 3C 279 has been published (Homan *et al.* 2009). A self-consistent model was proposed which provided an estimate of the low energy cut-off of the particle energy distribution, suggested that a turbulent magnetic field and not a large scale helical field, plays the dominant role in the mode conversion process, and was consistent with the presence of a predominantly electron–proton plasma. Data from two additional observing epochs are not yet analyzed, and it will be very interesting to see whether the same generic picture is provided by these data.

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