Evidence for the Importance of Shocks in the Production of Radio-band and GeV Jet Emission in Blazars

M. F. Aller, P. A. Hughes, H. D. Aller (U. Michigan); T. Hovatta, V. Ramakrishnan (Aalto University Metsähovi Radio Observatory); S. G. Jorstad, A. P. Marscher, V. Bala (Boston U.)

Overview

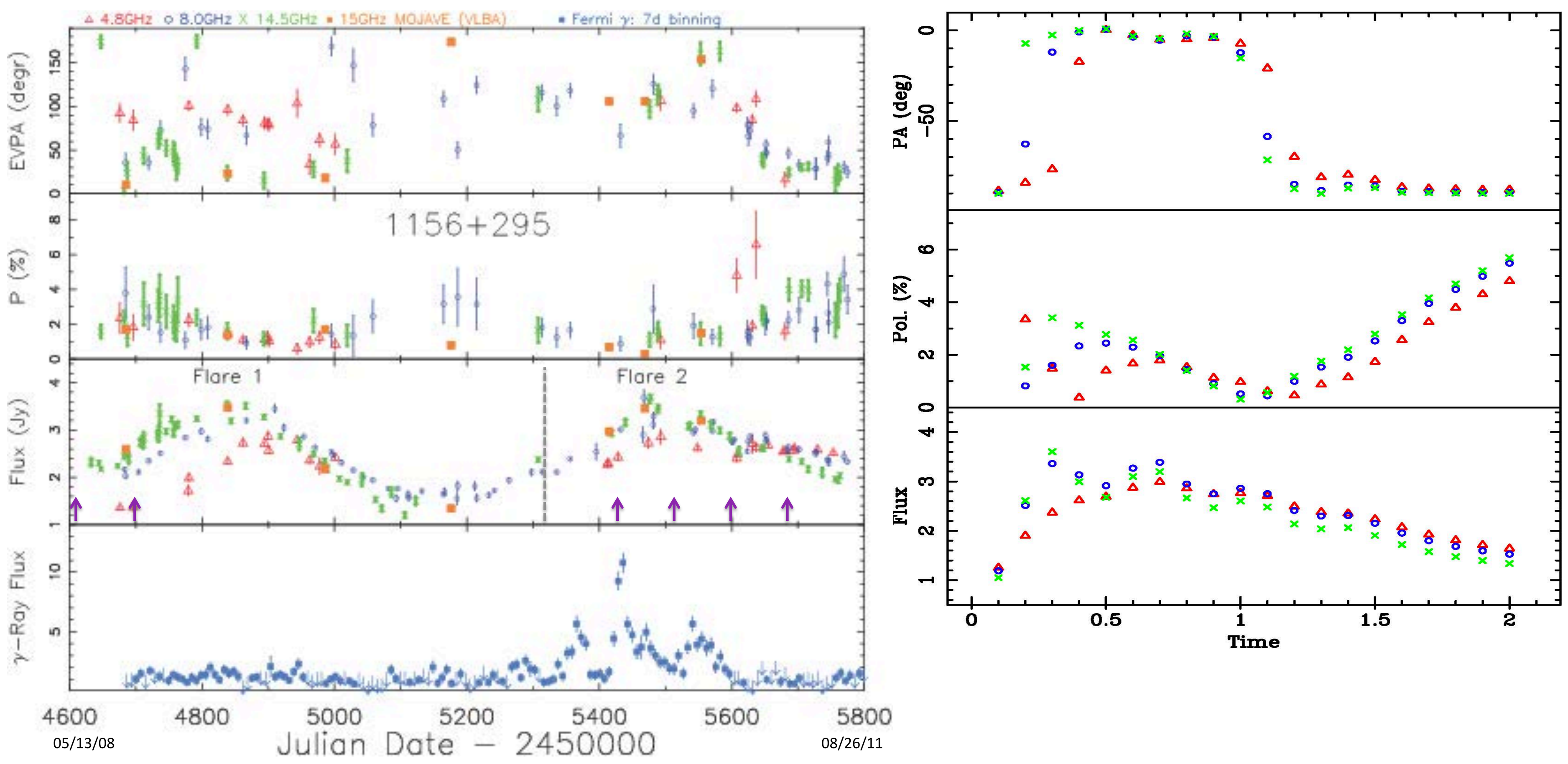
To identify jet conditions during GeV flaring, we use 3-frequency, centimeter-band linear polarization and total flux density monitoring data to constrain radiative transfer models incorporating propagating shocks at arbitrary angle to the flow. We demonstrate that the simulations successfully reproduce the main features of the spectral evolution in 4 blazars with diverse properties.

The Framework for the Model

Several lines of evidence suggest that GeV γ-ray flares are produced in the parsec-scale jets of blazars (e.g. Jorstad 2012). Hence modeling of temporally-associated radio-band flares can provide information on the physical conditions associated with γ-ray flaring. These properties include the energetics of the radiating particles, the viewing angle of the jet, and the degree of order of the magnetic field in the emitting region. We adopt a scenario where propagating shocks oriented at an arbitrary direction relative to the jet flow compress an emission region containing a passive, turbulent magnetic field; this compression produces an increased degree of order of the B field, an associated increase in the fractional linear polarization (P%) and an increase in the emissivity (a flare in total flux density). An additional ordered component of the B field is included as a free parameter. Each shock is assumed to span the cross section of the flow and to propagate at a constant rate. The number of shocks within an outburst is determined from the structure apparent in the light curves constructed from centimeter-band monitoring data obtained with the 26-meter University of Michigan Radio Astronomy (UMRAO) paraboloid, combined with the expected burst profile shape for a single shock (Hughes, Aller, & Aller 2011). All shocks occurring within an outburst envelope are assumed to have the same obliquity relative to the flow direction.

Radiative Transfer Modeling

The fundamental parameters defining a jet and shock system and their observational constraints are given in Table 1. These include the internal state of the quiescent flow, the flow's bulk dynamics and orientation, and the shock attributes. As illustrated in Hughes, Aller, & Aller (2015), where the effect of changing individual input parameters on the simulated light curves is shown, the free parameters are well-constrained by the UMRAO data. The modeling uses an iterative procedure outlined in Aller, Hughes, Aller, Latimer, & Hovatta (2014). To illustrate the range of variability properties and the ability of the shock-in-jet models to reproduce the primary features of the spectral variability including the amplitude range of the variations and the spectral behavior, we show the observed and simulated light curves in Figures 1 & 2 for outbursts in two blazars with diverse jet properties. VLBA imaging data at 43 GHz from the Boston U. program and at 15 GHz from MOJAVE provide independent constraints and checks on the radiative transfer modeling results.



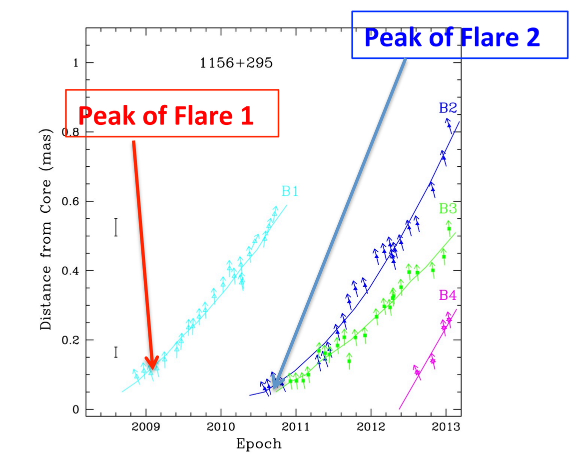


Figure 1b. 43 GHz structural changes upstream of the centimeter-band emission site. Complex structure in the imaging data combined with the larger number of shocks required to model Flare 2 are consistent with the notion that shock interactions play a role in producing Y-ray flares.

Figure 1a. Left: daily averages of the UMRAO monitoring data for the QSO 1156+295 showing the total flux density, fractional linear polarization, and electric vector position angle (EVPA: restricted to a range of 180°) at 14.5, 8.0, and 4.8 GHz in panels 2-4. The lower panel shows the weekly-averaged Fermi GeV light curve (units: 10^{-7} photons/cm²/sec). The vertical dashed line marks the start of the modeled time window shown (Flare 2). Upward purple arrows mark shock onsets. Source-integrated MOJAVE 15 GHz VLBA data are shown for comparison as gold squares. Right: the simulated radio-band light curves for Flare 2 based on the input parameters in Table 2. Flux is scaled to match the peak value at 14.5 GHz. The time units are arbitrary. Colors denote the three UMRAO frequencies.

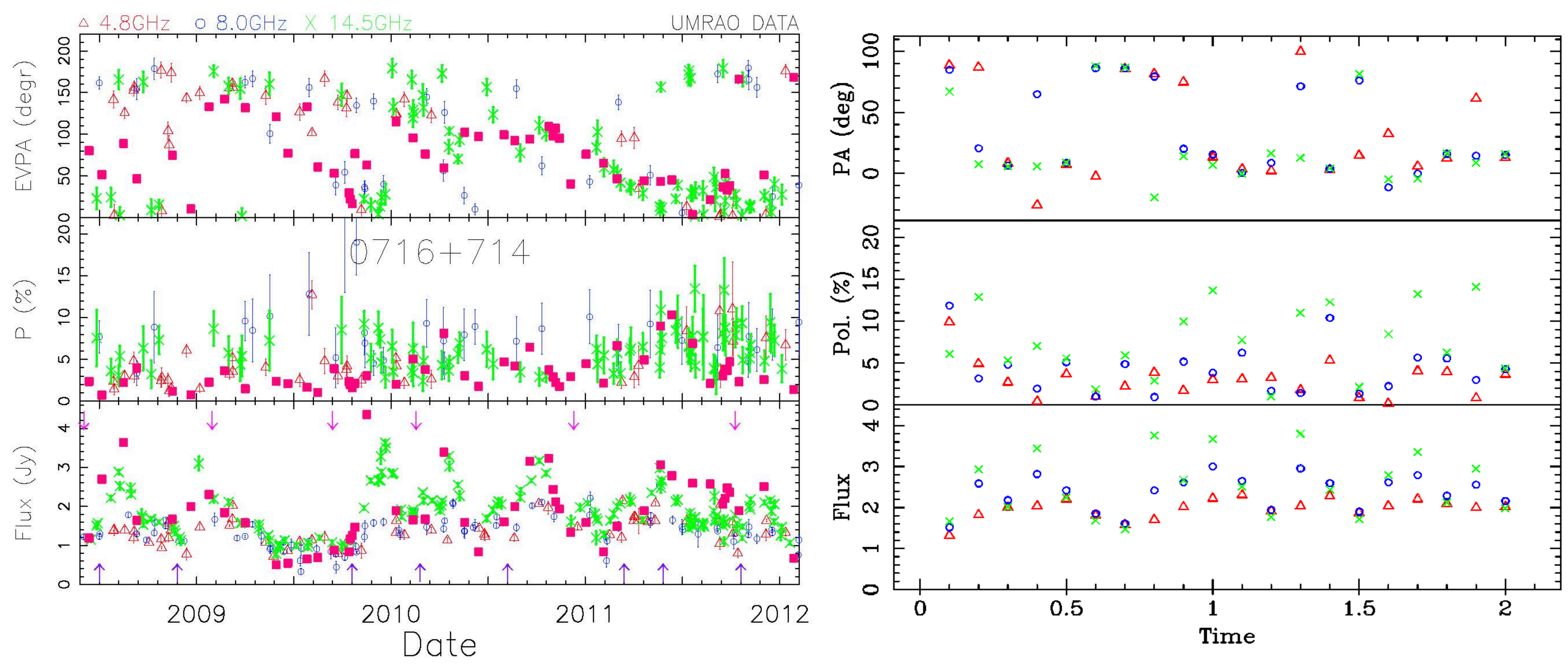


Figure 2. Left: Daily-averaged UMRAO data for the TeV-bright ISP BL Lacertae object 0716+714 which exhibited a series of GeV flares during this time period. Symbols are as in Figure 1. Comparison of the 15 GHz UMRAO data and the 43 GHz VLBA core fluxes and linear polarizations (magenta squares) shows that these generally track which is unusual. This suggests either that the emission regions are spatially close or that the 43-15 GHz emission region is transparent. Downward magenta arrows in panel 1 mark the times at which 43 GHz jet components separate from the core. Upward purple arrows mark the shock onsets. Right: Simulated light curves. Eight forward-moving, transverse shocks, with strong compressions in the range 0.18≤κ≤0.25, were included. The range in centimeter-band total flux density is similar to that in 1156+295, but P% is a factor of 3 higher.

Table 1. Free Parameters and Data Constraints

Parameter	Constraint
Low energy cutoff (γ_i)	EVPA spectral behavior
Axial B field (**B**z)	EVPA and P%
Bulk Lorentz Factor (γ_f)	P%
Viewing Angle (θ)	P%
Shock obliquity (η)	ΔEVPA
Shock sense (F or R)	Doppler Factor and β_{app}
Shock length (l)	duration of flare in S
Shock Compression (κ)	ΔS and P%
Shock onset (t_0)	start of flare in S or P

Table 2. Summary of Jet Parameters for Modeled Flares

Parameter	0420-014	0716+714	OJ 287	1156+295*
Spectral index (α)	0.25	0.25	0.25	0.25
Fiducial Lorentz factor	1000	1000	1000	1000
Cutoff Lorentz Factor	50	50	20	50
Bulk Lorentz Factor	5	20	5	10
Viewing angle (degrees)	4	12	1.5	2
Axial magnetic field (units of energy density)	16%	36%	50%	50%
Number of Shocks	3	8	3	4
Shock obliquity (degrees)	90	90	30	90
Shock sense	F	F	F	F
β_{app} (units of c)	11	9.5	17	22

* Flare 2

The shock compressions for three blazars modeled are in the range 0.5≤κ≤0.8. However, stronger compressions are required for 0716+714 to fit the unusually-rapid rise times of the outbursts in total flux density. The shock modeling for this source identified that the source is partially optically-thick, ruling out an optically-thin scenario, and suggesting that the 14.5 GHz emission arises at or near to the 43 GHz core, an upstream region of the jet flow associated with a standing shock.

RESULTS

The main features of the centimeter-band spectral variability in both total flux density and linear polarization are well-produced adopting a scenario incorporated propagating shocks. The radio-band events modeled are temporally-associated with Y-ray flares, suggesting that these shocks contribute to the acceleration of particles to high energies. The interaction of shocks may also play a role in the generation of the high energy flares. The modeling identifies jet properties which are not directly observable, including the presence of fast flows and a range of viewing angle. While the magnetic field is predominantly turbulent in our model, to fit the UMRAO data requires an additional significant ordered component which could be either in the form of an axial field or a low pitch angle helical field.

REFERENCES:

Aller, M.F., Hughes, P.A., Aller, H.D., Latimer, G.E., & Hovatta, T., ApJ, 791, 53, 2014

Hughes, P. A., Aller, M. F., & Aller, H. D., ApJ, 735, 81, 2011

Hughes, P. A., Aller, M. F., & Aller, H. D., ApJ, 799, 207, 2015

Jorstad, S., http://fermi.gsfc.nasa.gov/science/mtgs/symposia/2012/program/c1 SJorstad.pdf, 2012

ACKNOWLEDGMENTS:

This work was funded in part by NASA/FERMI GI grants, NNX11AO13G, & NNX13AP18G (U. Michigan) and NNX08AV65G & NNX11AQ03G (BU); and an award from the Jenny & Antti Wihuri foundation & by the Academy of Finland project number 267324 (T.H). It has used data from the MOJAVE website which is maintained by the MOJAVE team.