# The Extreme Gamma-Ray-Emitting Blazar S5 0716+714: Jet Conditions from Radio-band Variability and Radiative Transfer Modeling

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## ABSTRACT

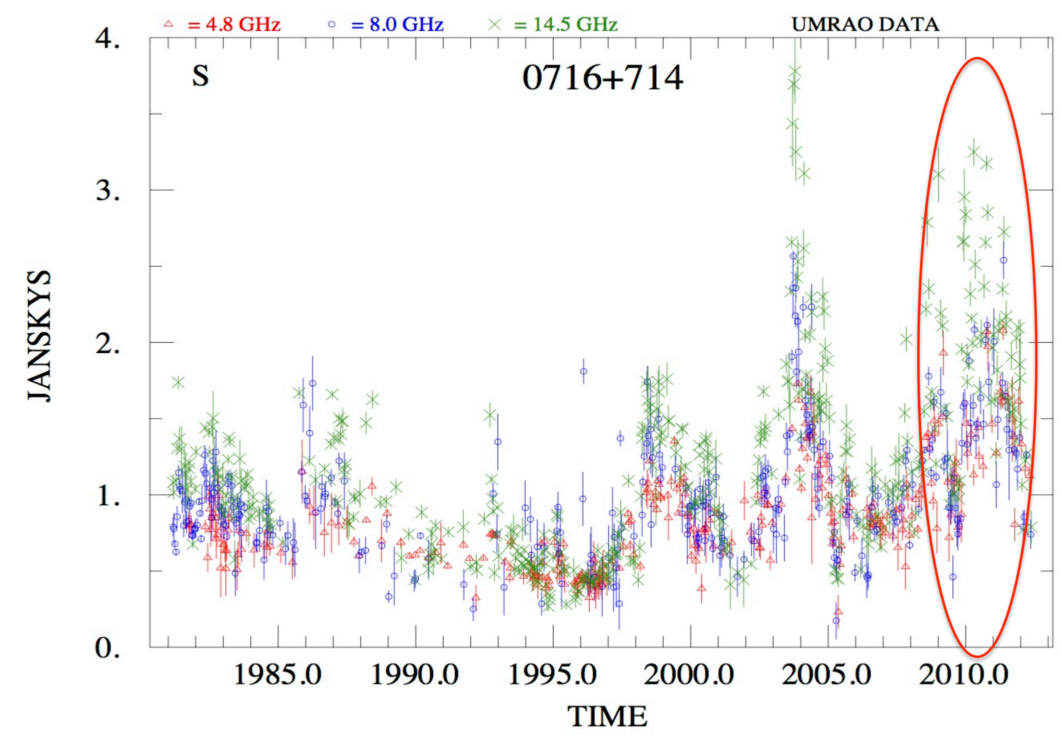
*As part of a study to identify the origin of the Fermi-detected emission from blazars in the GeV band, we present centimeter-band total flux density and linear polarization monitoring observations of the VHE blazar 0716+714 from the UMRAO program. These data, which show the signature of shocks during γ-ray flares, are used to constrain radiative transfer models in order to determine the shock and jet flow parameters. The modeling incorporates 8 forward-moving, transverse shocks. A rather wide 5° intrinsic opening angle for the radio jet, an unusually strong shock compression, and a very fast Lorentz factor of the shocks are identified.*

## Past Variability & Methodology

The emission properties of the ISP BL Lacertae object 0716+714 are distinguished from the general population of GeV blazars detected by Fermi: 1) The discovery of TeV emission by MAGIC in April 2008 requires particle acceleration to very high energies; while 2) the series of unusually-rapid, high-amplitude centimeter-band flares with steeply-inverted spectra apparent in the UMRAO data since 2002 (Figure 1 left) implies extreme flow conditions. Shocks have been proposed as a means to accelerate the particles to TeV energies, and the rapidity of the radio-band events qualitatively suggests strong compression of the emitting region within the shock-in-jet scenario (Hughes, Aller & Aller 2011). To test whether the observed radio-band flares in total flux density and linear polarization can be simulated by radiative transfer modeling incorporating propagating shocks, we analyzed a series of events since the launch of Fermi. Such modeling identifies the intrinsic jet flow properties and characterizes the shocks. Past work based on VLBA imaging has placed the GeV emission site at or near to the 43 GHz `core'; hence comparison of the 43 GHz and the UMRAO data (Figure 1: right) both aids in localizing the cm-band emission and provides information on the jet's opacity at parsec scales.

## Radiative Transfer Modeling

To test the shock-in-jet scenario, we modeled the radio-band outbursts shown in Figure 1 (red circled region at left and right plot) with radiative transfer calculations incorporating propagating shocks oriented at an arbitrary direction to the flow direction. The number of shocks (8) was set by the resolved structure in the radio-band linear polarization and total flux density light curves and the expected profile for a single shock. The modeling assumes a power law distribution of radiating particles and a passive, turbulent magnetic field before the passage of these shocks. Each shock is characterized by a compression factor κ, a length l, and the shock sense (F or R). Simulated light curves based on the shock parameters in Table 1 are shown in Figure 2 (right). The jet parameters given in Table 2 were obtained using an iterative procedure to reproduce the spectral evolution in the multi-frequency UMRAO light curves. See Aller, Hughes, Aller, Latimer, & Hovatta 2014 for details.



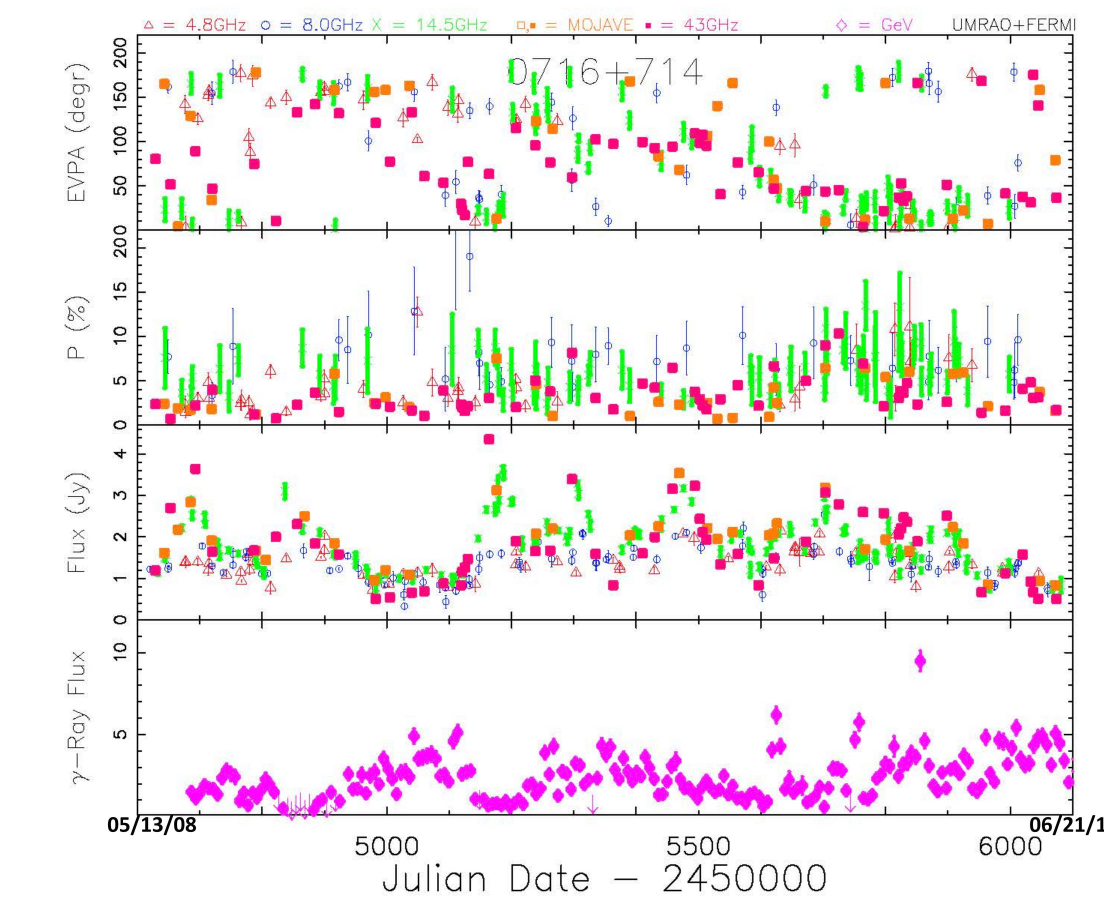
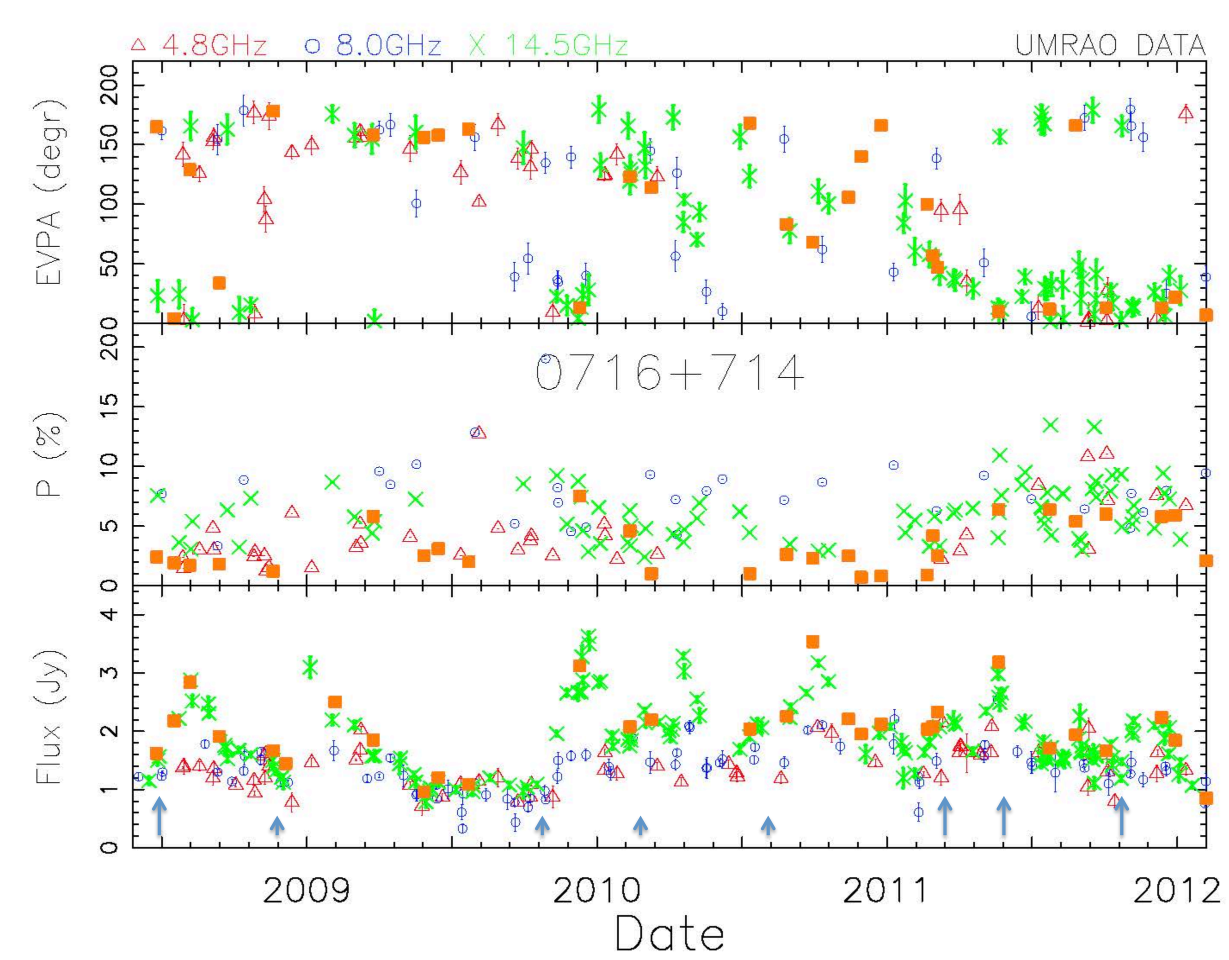




Figure 1. Left: Long-term total flux density at centimeter-band from UMRAO monitoring showing the variability at 3 frequencies over the past 4 decades. The activity is continuous with no quiescent period, and the flares are unusually rapid. Right: Time window since the launch of Fermi showing from bottom to top weekly-binned Fermi photon fluxes (photons/s/cm$^2$ X $10^{-7}$), total flux density, and linear polarization (fractional polarization and electric vector position angle). For comparison source integrated VLBA data from MOJAVE at 15.4 GHz (orange) and core fluxes from the B.U. monitoring program at 43 GHz (magenta) are shown. EVPAs are restricted to a range of 180°, and no corrections are included for Faraday rotation since VLBA-determined rotation measures are low for the source (Hovatta et al. 2012). The 14.5 GHz and 43 GHz polarization and total flux densities characteristically track suggesting either that the emission region is optically thin or that the emission sites are spatially close. The source is highly core-dominated in the VLBI imaging data.



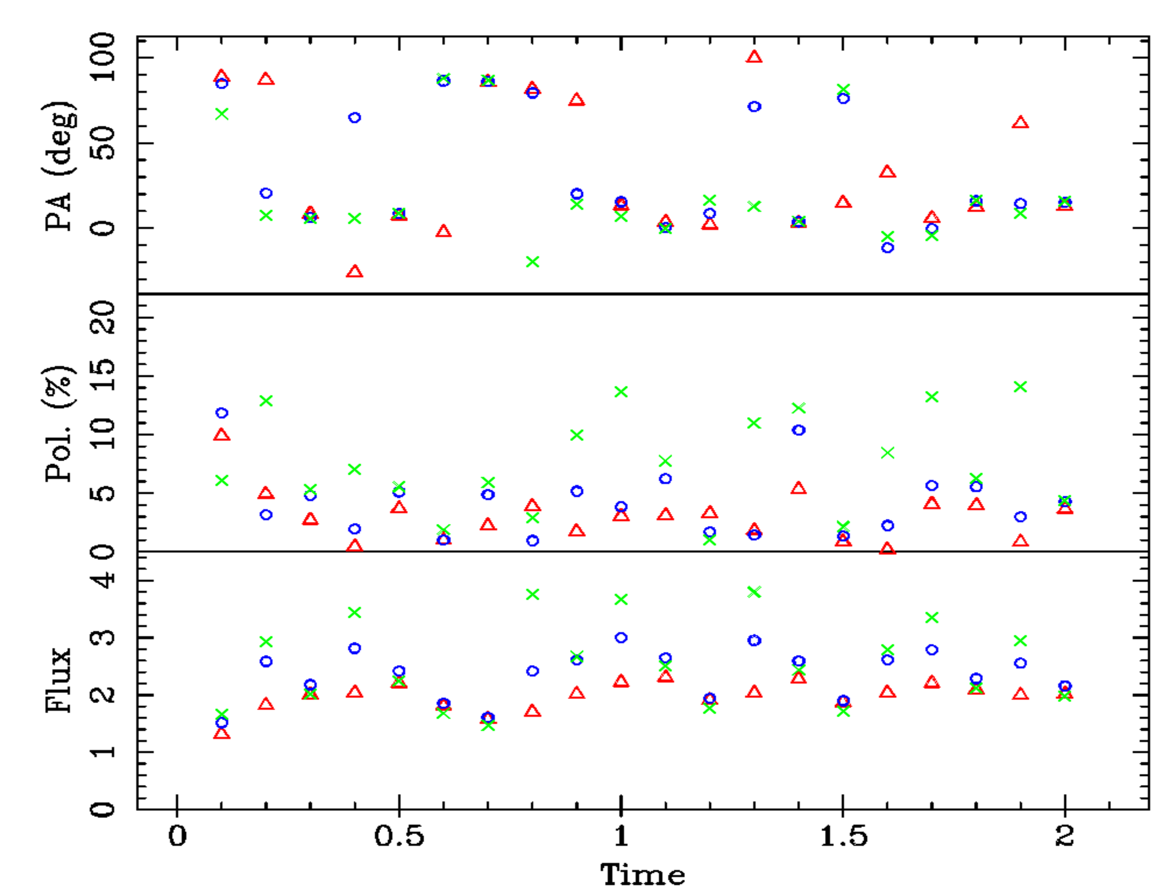




Figure 2. Left: the data for the time segment modeled with $\sigma_p$ omitted for clarity. Arrows mark shock To. Right: the simulation based on the parameters below. Flux is scaled to match the peak flux density at 14.5 GHz. Time is the fraction of the modeled time window. The simulation reproduces the general character of the spectral behavior and the amplitude of P%. However, not all details are matched, suggesting that a more complex model is required for this source.

**Table 1: Shock parameters**

| Shock | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| To-2000 | 08.5 | 08.9 | 09.8 | 10.15 | 10.6 | 11.2 | 11.4 | 11.8 |
| K | 0.18 | 0.18 | 0.18 | 0.2 | 0.17 | 0.2 | 0.27 | 0.25 |
| Length | 0.005 x the extent of the flow | | | | | | | |
| Sense | All shocks forward moving with respect to the flow | | | | | | | |

**Table 2: Jet parameters**

| PARAMETER | VALUE |
|---|---|
| Spectral index | 0.25 |
| Fiducial Lorentz factor | 1000 |
| Cutoff Lorentz factor | 50 |
| Bulk Lorentz factor (LF) | 20 |
| Jet opening angle | 5.2° |
| Viewing angle | 12.0° |
| Shock obliquity | 90° |
| LF of the shocks | 77 |
| Shock $\beta_{app}$ | 9.5c |
| Energy in Axial B field | 36% |

## Conclusions

Radiative transfer modeling of the UMRAO data, incorporating 8 forward-moving shocks, is able to reproduce the main features of the spectral variability. This modeling identifies a high bulk Lorentz factor, consistent with prior VLBI results, a rather wide (5.2°) intrinsic jet opening angle, and strong shock compressions. The apparent speeds of the emission pattern are high but less than the Lorentz factor (77) since the observer lies outside of the critical cone of the fast flow. The viewing angle, a parameter very well-constrained by both the polarization and total flux density data, is higher than found for 3 other γ-ray-bright blazars that we have modeled (Aller, Hughes, Aller et al. 2014). The modeling identifies that the emission originates in a partially optically-thick part of the jet, ruling out the optically-thin scenario, and supporting spatially-close emission sites.

*REFERENCES:*
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