Perplexing correlations between Gamma-ray emission and parsec-scale jet orientation variations in the BL Lac object S5 0716+714

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The analysis of γ-ray flux variability along with the parsec-scale jet kinematics suggests that the high-energy radiation in the BL Lac object S5 0716+714 has a significant correlation with the mm-VLBI core flux density and with the local orientation of the inner jet flow. For the first time in any blazar, we report a significant correlation between the γ-ray flux variations and the variations in the local orientation of the jet outflow (position angle). We find that the γ-ray flux variations lead the 7 mm VLBI core flux variations by 82$\pm$32 days, which suggests that the high-energy emission in S5 0716+714 is coming from a region located 3.8$\pm$1.9 parsecs closer to the central black hole than the "core" seen on the mm-VLBI images. The results imply a strong physical and casual connection between γ-ray emission and the inner jet morphology in the source.

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1. Introduction

The tendency for the parsec-scale jets to change their orientation with time has been well established via long term VLBI studies on several AGN. Jet orientation variations – non-radial motion, helical paths of the jet features, curved jet structures, and variations in the direction of the inner jet flow, i.e. position angle or jet wobbling – on sub-parsec to parsec scales are frequently observed in blazars [1; 2; 3]. The exact origin of these variations is not yet clear, although accretion disk precession, orbital motion of the accretion system, or instabilities (Magnetohydrodynamic (MHD), and/or Kelvin-Helmholtz (KH)) in the jet flow have all been suggested. In some cases the inner jet position angle (PA) variations were found to correlate with the flux density variations at radio frequencies [1; 4]. However, a correlation between γ-ray flux and PA variations has not been reported so far. Here we report the observed correlation of γ-ray flux variations with the VLBI core flux density and the direction of the inner jet outflow in S5 0716+714.
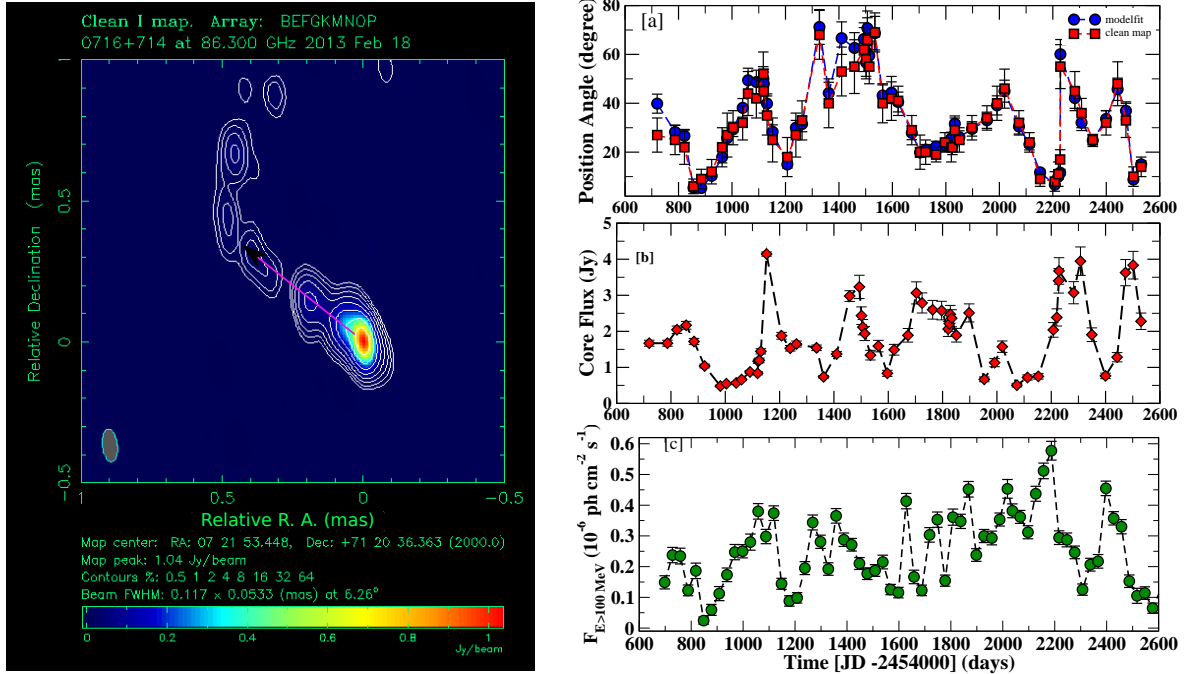

Figure 1: Left: Example of a 86 GHz VLBI image of S5 0716+714 observed on February 18, 2013. The arrow marks the orientation of inner jet outflow. Right: (a) Inner jet orientation (position angle) variations in the inner jet region (≤0.2 mas), (b) the 7 mm VLBI core flux density variations, and (c) monthly averaged γ-ray flux light curve.

2. Results

For the study presented here, we used the 7 mm and 3 mm VLBI data of the source observed between August 2008 and September 2013. The inner jet orientation variations were determined taking a flux density-weighted average of the clean delta components at 3 times above the image noise level. In an alternative approach, we measured the position angle of the innermost Gaussian model-fitting. As an example a 3 mm VLBI map of the source is shown Fig. 1 (left). In right panel,
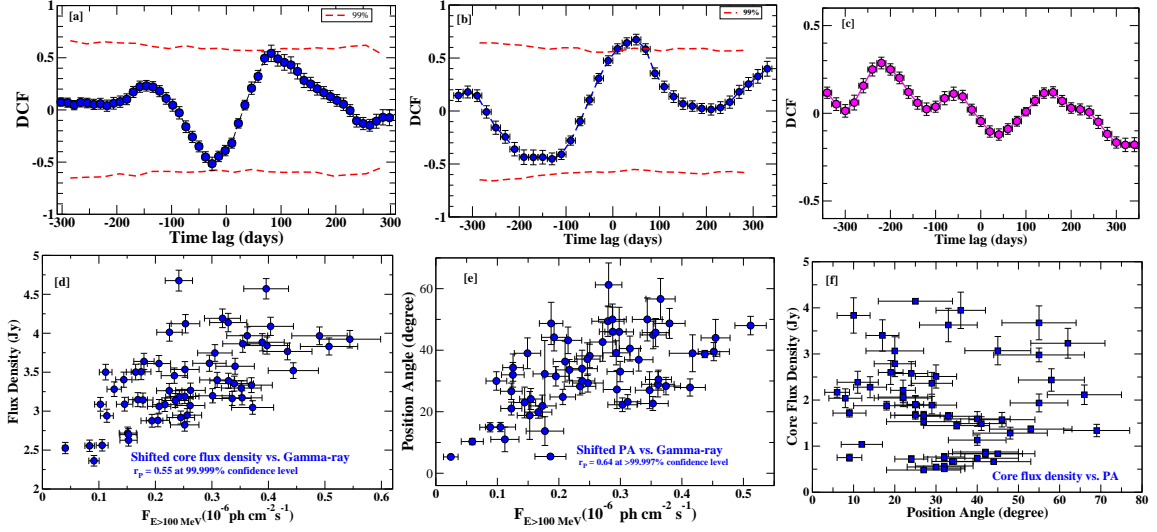
Figure 2: Top: Cross-correlation analysis curves – (a) gamma-ray vs. core flux density, (b) gamma-ray vs. position angle, and (c) core flux density vs. PA. The dashed lines show the 99% confidence levels. Bottom: (d) Shifted (by 80 days) core flux density plotted vs. γ-ray photon flux, (e) shifted (by 40 days) PA plotted vs. γ-ray photon flux, and (f) core flux density plotted vs. PA.

we plot the position angle (PA) variations in the central region of the jet (a), and the 7 mm VLBI core flux density variations (b). The γ-ray (0.1-300 GeV) data obtained by the *Fermi*-LAT (Large Area Telescope) were used to investigate the high-energy flux variations over the same time period. The details of observations and data reduction can be found in [3]. The monthly averaged γ-ray photon flux light curve is shown in Fig. 1 (c).

We used the discrete cross-correlation function (DCF)[5; 6] analysis method to investigate a possible correlation of γ-ray flux with core flux density and jet orientation variations; the results are presented in Fig. 2 (top). We found a significant correlation between γ-ray and core flux density variations with the former leading the latter by a time lag of 82 ± 39 days (Fig. 2 a). The observed time lag places the γ-ray emission region upstream of the mm-VLBI core by $\geq(3.8\pm1.9)$ parsec (deprojected using a viewing angle, $\theta \leq 4.9°$ and apparent jet speed $\beta_{apparent}=10$) [3]. In Fig. 2 (d), we show the time shifted (by the observed time lag) 7 mm VLBI core flux density plotted vs. the γ-ray photon flux. A clear correlation among the two can be seen, which is confirmed by a linear correlation analysis, yielding $r_P = 0.55$ and 99.999% confidence level, where r_P is the linear Pearson correlation coefficient. The DCF analysis also suggests that the γ-ray flux variations correlate significantly with the PA variations (Fig. 2 b), which is also confirmed by a linear correlation analysis with $r_P = 0.64$ at 99.997% confidence level. The shifted PA vs. γ-ray photon flux plot is shown in Fig. 2 (e). Since the γ-ray flux variations correlate with both the core flux density and PA variations, we would also expect a correlation between core flux density and PA variations. The formal DCF analysis however does not reveal a significant correlation between core flux density and the PA variations (see Fig. 2 c). We note that the absence of a significant correlation between the two does not rule out a weak correlation or much more complex behavior. A ring like pattern in the core flux density vs. PA plot (Fig. 2 f) could be a hint of such a more complex behavior.

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3. Summary and Conclusions

The observed correlations of the γ-ray photon flux variations with the inner jet orientation and the 7 mm core flux density variations can be interpreted as a moving shock propagating down a relativistic jet with non-axisymmetric pressure or density gradients/patterns, or a shock moving in a bent jet. Alternatively, instability patterns moving downstream and passing the two emission regions at different viewing angles, or even a rotation of the helical jet around its own z-axis, would cause very similar variations [3]. Correlated variations can be expected if the two emission regions share same boosting cone. A correlated variation between the core flux density and the inner jet orientation is expected in a simple geometrical interpretation. The absence of such a correlation suggests that there are some unknown factors (e.g. opacity) in addition to geometry which suppress the core flux density and jet orientation correlation. High-frequency VLBI monitoring with denser time sampling would be required to better understand the jet morphology and it's relation to the γ-ray emission.

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