Probing an X-ray signature of multiple recollimation shocks in the blazar Mrk 421

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Abstract

Mrk 421, as most of the TeV high-frequency-peaked BL Lacs (HBLs), show stationary or slow motions of its VLBI radio-knots structure, in stark contrast with its known fast variability. This problem, known as "the bulk Lorentz factor crisis", can be resolved if we consider that these strings of knots are successive recollimation shocks in jets. Successive shocks predict that a unique pattern of the non-thermal emission variability should appear after each strong flare. Using the X-ray 13 years long dataset of the NASA space telescope Swift-XRT, we present the detection of such a distinct pattern at more than 3 sigma of significance against stochastic fluctuations.

I. Recollimation shocks

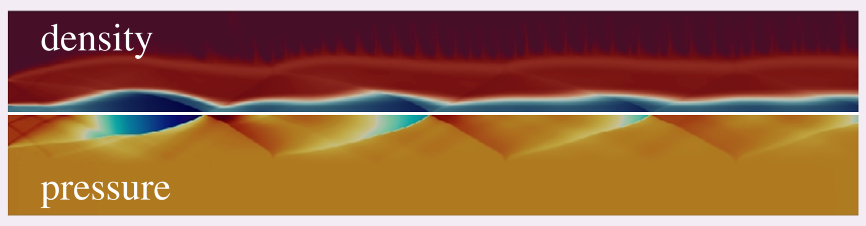


Figure 1: Hydrodynamic relativistic jet simulation displaying recollimation shocks [4].

Recollimation shocks are a phenomenon which naturally appears in jets as soon as they have a supersonic flow presenting a pressure mismatch with the external medium and a local severe pressure drop. The bouncing back and forth of the shocking waves, preceded by rarefaction waves, produces a string of standing conical shocks in jets. Such shocks are believed to be powerful particle accelerators [1].

II. VLBI radio jet of Mrk 421

Mrk 421 shows a steady VLBI jet structure of 4 quasi-stationary knots with 5 mas to the core over multiple years of observation.

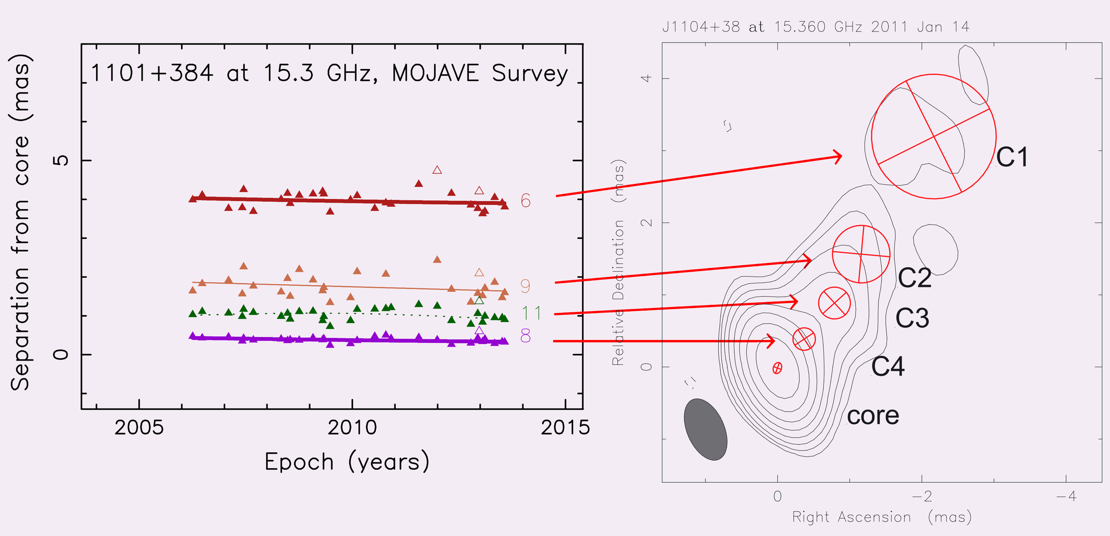


Figure 2: *Left:* Temporal evolution of 15.3 GHz knot-core distances of Mrk 421 observed by MOJAVE. *Right:* 2D Gaussian fit of these 15.3 GHz knots, observed 2011 Jan. 14 [5].

III. Theoretical lightcurve signature of recollimation shocks

We aim to probe flares associated with the flow passing through the knots, assuming they are stationary shocks. For a given apparent speed β_{app}, the time delay of the secondary flares can be set knowing the radio knot positions, as shown in Figure 3.

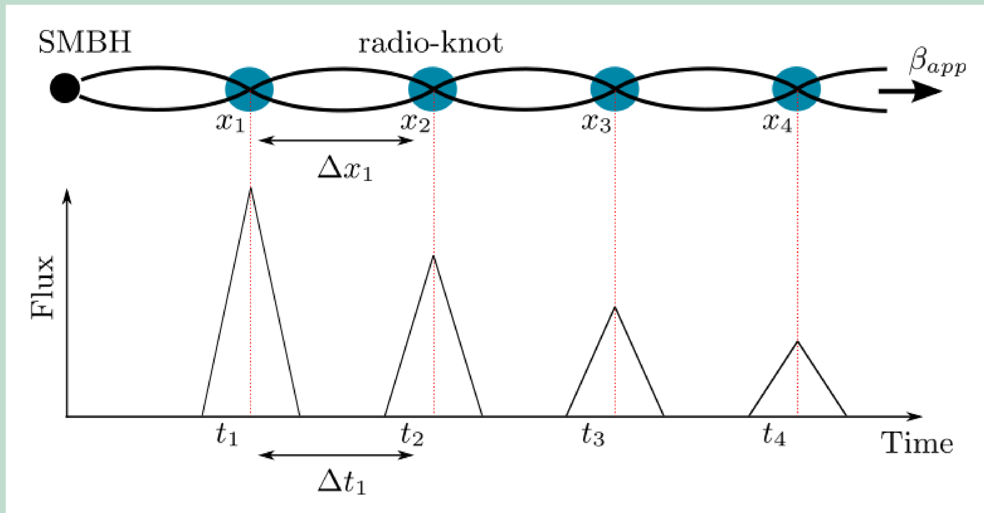


Figure 3: Simplified scheme of the expected lightcurve signature of a perturbation crossing the knots x_i with an apparent speed β_{app} linking the inter-knot distance Δx_1 with the delay between two consecutive flares Δt_1.

Considering a constant speed of the flow through a straight jet, the time gap Δt between each successive flare in the lightcurve should be directly proportional to the observed inter-knot gap Δx. We have the relation $\Delta t_i = (1+z)\Delta x_i/(c\beta_{app})$.

The multi-Gaussian model is defined as follow:

- The time gap between each peak is scaled to the inter-knot gap considering a constant flow speed.
- The width of each Gaussian is scaled to the width of each corresponding knot.
- The amplitude of each Gaussian is inversely scaled to the volume of corresponding knot.

The full theoretical model, including the baseline is given by

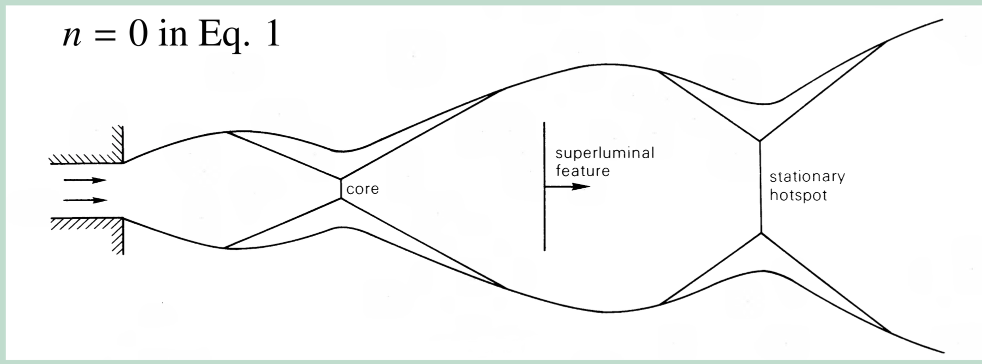
$$G_m(t) = \sum_{i=n}^{5} [A_i P_i(t)] + B(t), \tag{1}$$

with A_i and $P_i(t)$ the amplitude and Gaussian shape of each flare, and $B(t)$ a linear flux baseline.

Two scenarios probed:

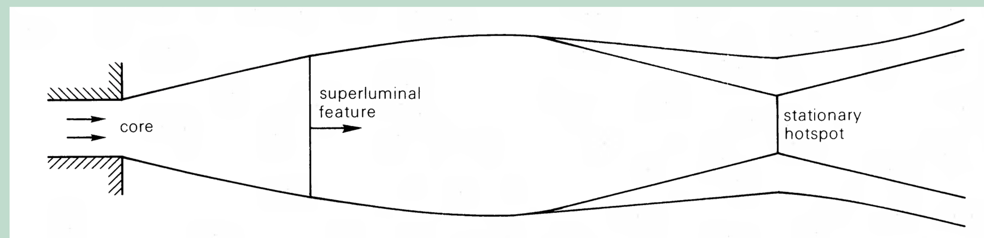
A) The core is a strong shock

$n = 0$ in Eq. 1



B) The core is only the expanding funnel

$n = 1$ in Eq. 1



Given the uncertainty on the nature of the radio core of Mrk 421 we probe the two proposed scenarios. In the case of a shock associated to the core we expect 5 successive flares, while if the core if only the jet expanding funnel we expect 4 successive flares with the first flare of a serie associated to the most upstream radio knot. The two presented figures are taken from [3].

IV. *Swift*-XRT lightcurve analysis

Swift-XRT [2] is sensitive in the soft X-ray energy range (0.3 -10 keV), which is excellent for measuring flux at the synchrotron peak energy for HBLs such as Mrk 421. We produced the 1 day binned lightcurve of Mrk 421 for the 13 years of observations by *Swift*-XRT. The most powerful flares with a temporal accuracy of about a day are then automatically selected, extracted within the time range $[t_{flare} - 40, t_{flare} + 600]$ days, and stacked together (see Figure 5). This stacking process has the advantage to reduce the intrinsic stochastic fluctuations of the source and make appear a possible regular flaring pattern. As seen in Figure 5 , two excesses at 11 and 23 days after the main flares, and a possible one around 64 days, suggest such a regular pattern. The flux excess around 600 days is intriguing and could be associated to long term quasi-periodic fluctuations.

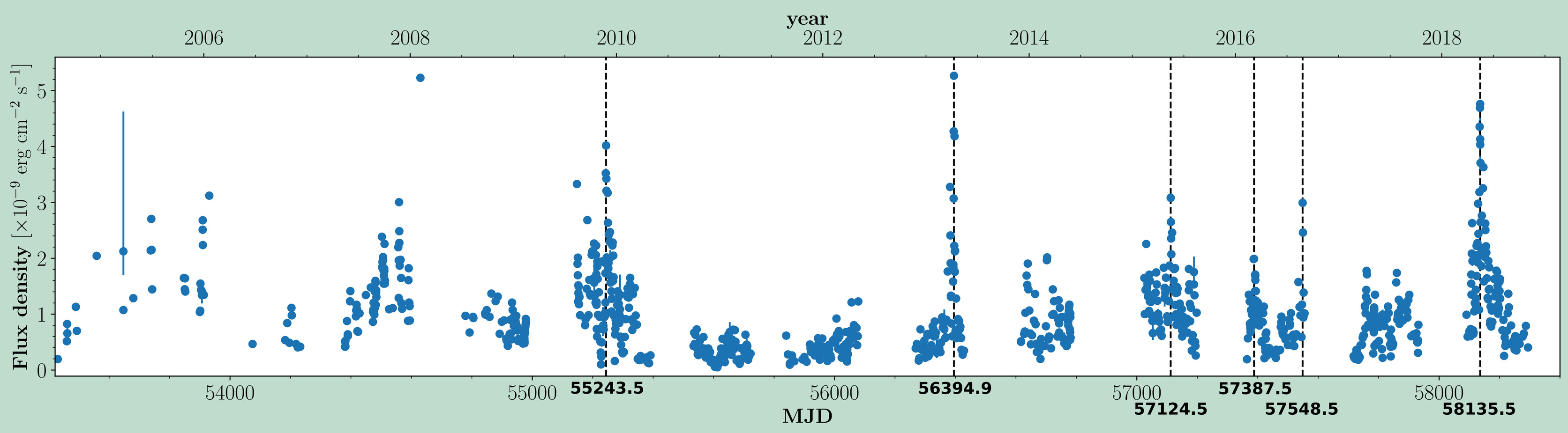


Figure 4: *Swift*-XRT lightcurve from March 2005 to May 2018. Vertical dashed lines represent the selected flares.

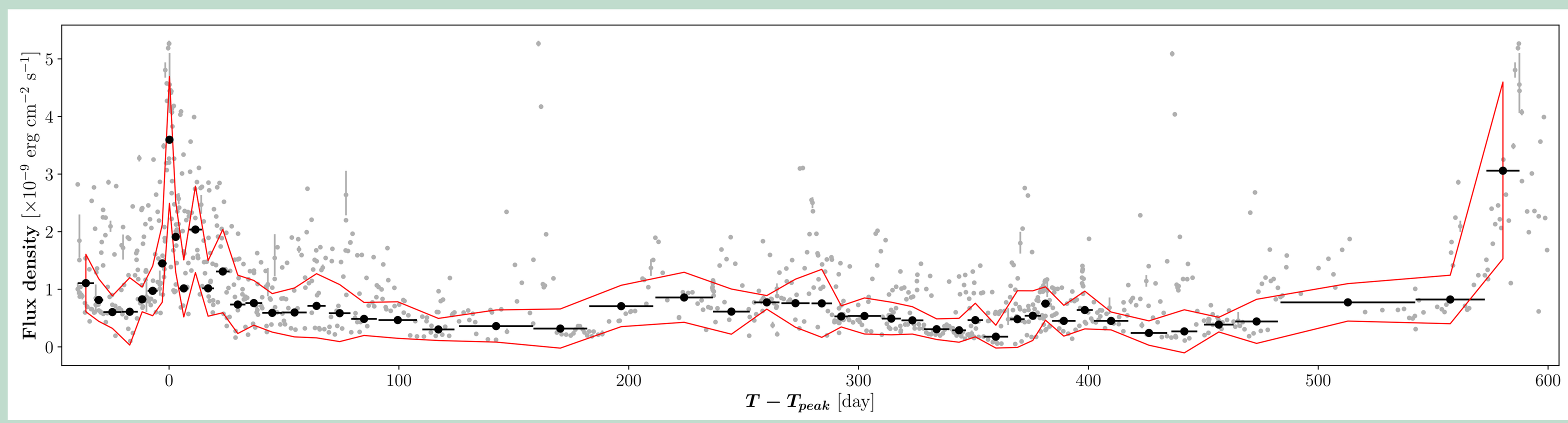


Figure 5: Flare-stacked lightcurve used to probe a post-flare variability pattern. For clarity we show a binned dataset, with 18 data points per bin. The red lines picture the RMS range associated with the flux dispersion of stacked lightcurves.

VI. Results and interpretation

We identify a regular flaring pattern associated to the radio knots in the Mrk 421 jet. The scenario of a main flaring zone in the most upstream radio knot is favored (see Figure 6) at a significance level above 3.2 σ against stochastic fluctuations produced by several millions of realistic lightcurves simulations. Such a pattern is consistent with a flow apparent speed of 45^{+4}_{-2} c and allows us to constrain the jet beaming parameters as shown in Figure 7.

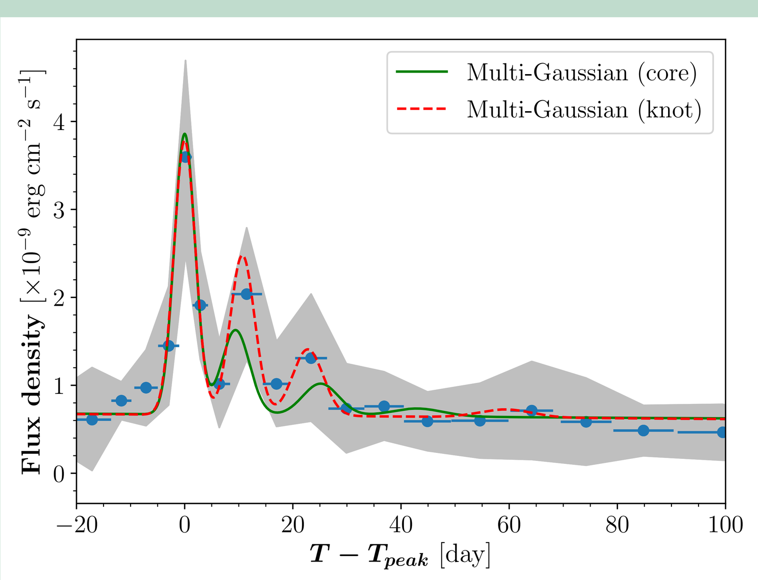


Figure 6: Comparison of the different models on top of the stacked lightcurves; a multi-Gaussian from a main flare in the radio core, and a multi-Gaussian from a main flare in the upstream radio knot.

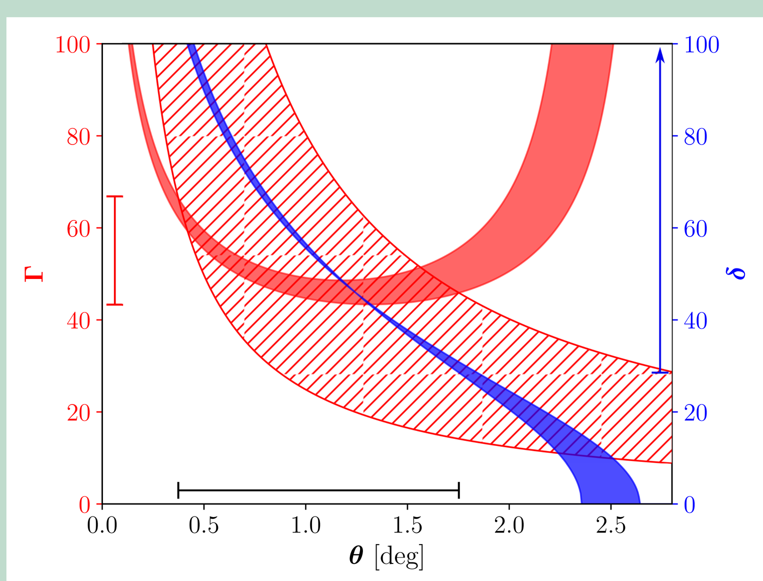


Figure 7: Lorentz factor (red) and Doppler factor (blue) as a function of the angle with the line of sight θ. The segments are showing the likely range for each parameter.

Acknowledgment:

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References

[1] G. Bodo and F. Tavecchio. A&A, 609:A122, 2018.
[2] D. N. Burrows, et al. *SSRv*, 120:165–195, 2005.
[3] R. A. Daly and A. P. Marscher. ApJ, 334:539–551, 1988.
[4] O. Hervet, et al. A&A, 606:A103, 2017.
[5] R. Lico, et al. A&A, 545:A117, 2012.
[6] M. L. Lister, et al. ApJS, 234:12, 2018.