PROCEEDINGS OF SCIENCE

Blazar Variability and Time Lags at Millimetre Wavelengths: Insights from Metsähovi and ALMA Monitoring

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Blazars, a subclass of active galactic nuclei (AGN) with relativistic jets directed close to our line of sight, dominate the extragalactic gamma-ray sky and are characterised by strong variability across the electromagnetic spectrum. Millimetre observations are particularly valuable because they probe emission regions near the jet base, where high-energy flares are likely produced. In this study, we investigate the variability of the blazar 3C 279 using long-term light curves from Metsähovi (37 GHz) and ALMA Bands 3, 6, and 7 (84–345 GHz). Multiple time-series methods including the Interpolated Cross-Correlation Function (ICCF), Z-transformed Discrete Correlation Function (ZDCF), JAVELIN, and PyROA, were applied to search for inter-band time lags. In most cases, higher-frequency emission was found to lead lower-frequency variations, consistent with opacity-driven delays in the jet. However, certain deviations from this pattern suggest a more complex emission geometry or the influence of additional variability processes. We also quantified variability amplitudes using the fractional variability parameter ($F_{\rm var}$), which increases systematically from $\approx$ 0.29 at 37 GHz to $\approx$ 0.38 at 345 GHz, consistent with more compact and energetic emission regions at higher frequencies. These findings underscore the importance of coordinated, multi-frequency millimetre monitoring in constraining the connection between jet dynamics and high-energy emission, and they highlight the potential role of the Africa Millimetre Telescope (AMT) in future long-term blazar monitoring from the southern hemisphere.

High Energy Astrophysics in Southern Africa (HEASA2025)
16-20 September, 2025
University of Johannesburg, South Africa

*Speaker

PoS(HEASA2025)030

1. Introduction

Blazars, a class of active galactic nuclei (AGN) with relativistic jets oriented close to our line of sight, are among the most powerful and rapidly changing cosmic sources [1]. Their radiation spans the full electromagnetic spectrum, from radio waves to gamma-rays, and varies on timescales between minutes and years [2]. These extreme properties arise from non-thermal processes within their jets, where relativistic particles are accelerated and interact with magnetic fields [3]. Among blazars, 3C 279, a flat-spectrum radio quasar (FSRQ) at redshift $z \approx 0.536$, is one of the most studied due to its large-amplitude, rapid variability, superluminal jet motion, and intense flaring activity [4].

This study examines the opacity-driven delay hypothesis in 3C 279 using extended light curves from Metsähovi (37 GHz) and Atacama Large Millimeter Array(ALMA) (84–345 GHz). Multiple time-series techniques are applied to measure variability amplitudes and inter-band lags, with cross-validation ensuring reliable results.

2. Materials and Methods

The analysis uses four millimetre light curves of 3C 279. The 37 GHz data are provided by the Metsähovi Radio Observatory, which operates a 13.7-m Cassegrain radio telescope dedicated to long-term AGN monitoring. The programme has delivered uniformly calibrated flux-density measurements since 1979, with a typical sampling cadence of a few days.

The higher-frequency light curves are drawn from the ALMA calibrator monitoring programme. The sampling cadence is frequency dependent: Band 3 (84–116 GHz) is sampled every few days to ~1 week, Band 6 (211–275 GHz) typically every 1 to 4 weeks, and Band 7 (275–373 GHz) at intervals of several days to a few weeks. To ensure uniformity, the light curves were trimmed to overlapping ranges and cleaned of missing data, then analysed for variability and inter-band delays using four complementary methods.

2.1 Variability Quantification

The fractional variability amplitude $F_{\rm var}$ isolates intrinsic variability from measurement noise [5] and is defined as $F_{\rm var} = \sqrt{(S^2 - \sigma_{\rm err}^2)/\bar{x}^2}$, where S^2 is the sample variance, $\sigma_{\rm err}^2$ the mean squared error, and $\bar{x}$ the mean flux density. Uncertainties on $F_{\rm var}$ were computed following the analytic error propagation in [5], accounting for both measurement noise and the finite number of data points.

2.2 Time-Lag Estimation

Four complementary lag–estimation techniques were applied, each implemented through established software packages widely used in AGN reverberation studies (e.g. Python Cross-Correlation Function (PyCCF) [6], Z-transformed Discrete Correlation Function (ZDCF) codes [7], Just Another Vehicle for Estimating Lags In Nuclei (JAVELIN) [8], and Python Reverberation- mapping of Active galactic nuclei (PyROA) [9]):

1. **ICCF:** Implemented via `PyCCF` [6], which performs linear interpolation of light curves and uses FR/RSS bootstrapping [10] to estimate lag uncertainties. The lag is taken as the centroid of the upper 80% of the CCF.

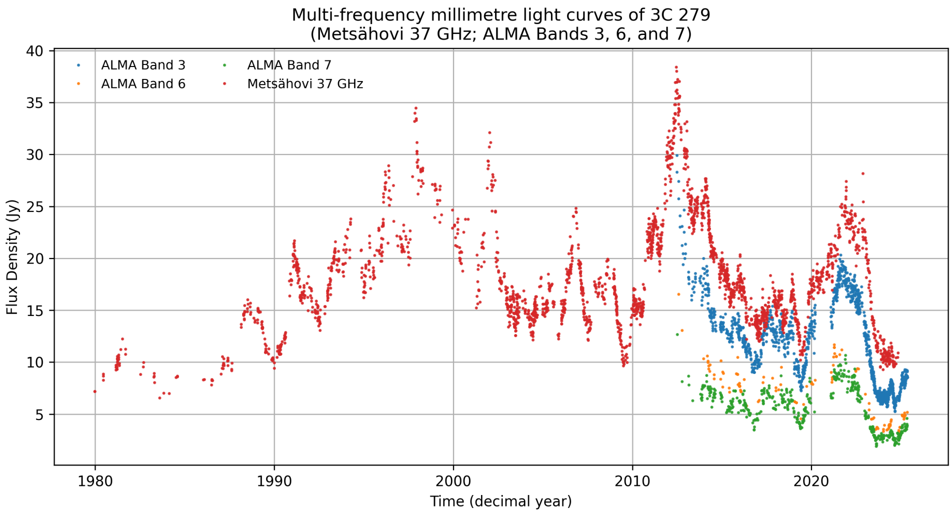

Figure 1: Flux variability over time for ALMA Bands 3, 6, 7, and Metsähovi 37 GHz.

2. **ZDCF:** The Z-transformed Discrete Correlation Function, using the modern Python/Fortran implementations applied in recent 3C 279 studies [7]. The method employs equal-population binning and Fisher's z-transform [11] to obtain robust correlations for irregularly sampled data.

3. **JAVELIN:** Models light curves as damped random walks convolved with a top-hat transfer function to infer lags; our analysis used the JAVELIN code [8], described in [12].

4. **PyROA:** A Bayesian approach treating the driving continuum as a Gaussian process, with each light curve modeled as a time-shifted convolution [13] [14].

3. Results

The multi-frequency light curves of 3C 279 reveal strong, correlated variability across all bands, clarifying the jet's emission structure and opacity effects.

3.1 Multi-frequency Variability

Light curves from Metsähovi (37 GHz) and ALMA Bands 3, 6, and 7 show pronounced, correlated flaring (Figure 1), indicating that the emission regions are physically linked and originate from a disturbance propagating downstream in the jet [3].

3.2 Fractional Variability Amplitude

F_{var} increases monotonically with frequency (Figure 2): from ≈ 0.28 at 37 GHz to ≈ 0.35 at 345 GHz, implying that higher-frequency emission arises from more compact, energetic zones.

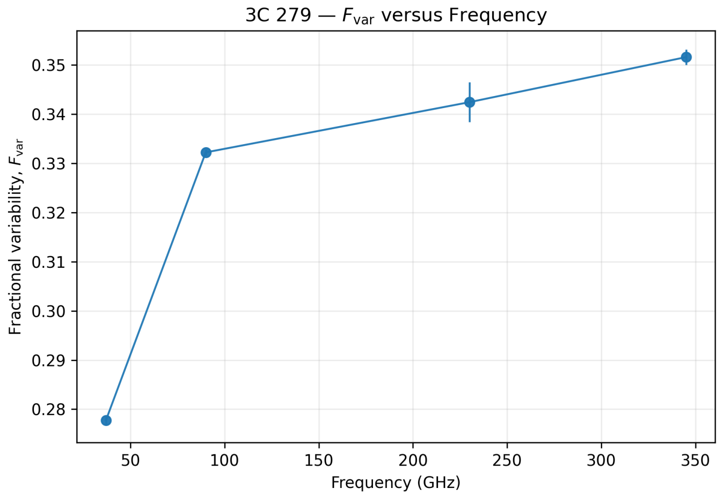

Figure 2: Fractional variability (F_{var}) versus frequency for 3C 279.

3.3 Inter-band Time Lags

Four independent methods (ICCF, ZDCF, JAVELIN, PyROA) were applied to quantify temporal relationships between frequencies. Lag uncertainties reflect the statistical sampling of each method: ICCF uses FR/RSS bootstrapping, ZDCF derives confidence intervals from Fisher-z bins, JAVELIN provides MCMC posteriors, and PyROA yields Bayesian posteriors. The reported errors correspond to the central credible intervals of these distributions.

Lag results (Table 1) show that lower frequencies systematically lag higher ones by ~30–40 days (ALMA pairs) and up to ~100 days (37–345 GHz), consistent with opacity-driven stratification in a relativistic jet [18]. A slight negative lag between 230 GHz and 345 GHz (-4.6 ± 0.7 days) suggests nearly co-spatial regions or additional physical processes [19]. The lag–frequency relation (Figure 3) follows a smooth trend consistent with an opacity-like power-law fit, providing an illustrative scaling for estimating lags at intermediate frequencies.

Table 1: Inter-band lags (days). Positive values indicate that the lower-frequency band lags the higher-frequency band.

Pair	ICCF	ZDCF	JAVELIN	PyROA
37–90	63.3 ± 5.2	62.0 ± 0.5	53.4 ± 7.8	62.4 ± 14.4
37–230	99.1 ± 14.0	98.1 ± 1.4	99.2 ± 23.5	99.1 ± 25.0
37–345	97.8 ± 7.9	108.1 ± 6.6	105.1 ± 7.6	99.6 ± 28.5
90–230	41.6 ± 11.8	40.7 ± 0.4	28.0 ± 1.9	39.3 ± 7.3
90–345	35.8 ± 5.5	34.6 ± 0.3	28.4 ± 7.1	31.7 ± 6.2
230–345	−8.3 ± 13.8	−6.8 ± 1.1	−2.4 ± 0.9	−8.8 ± 2.3

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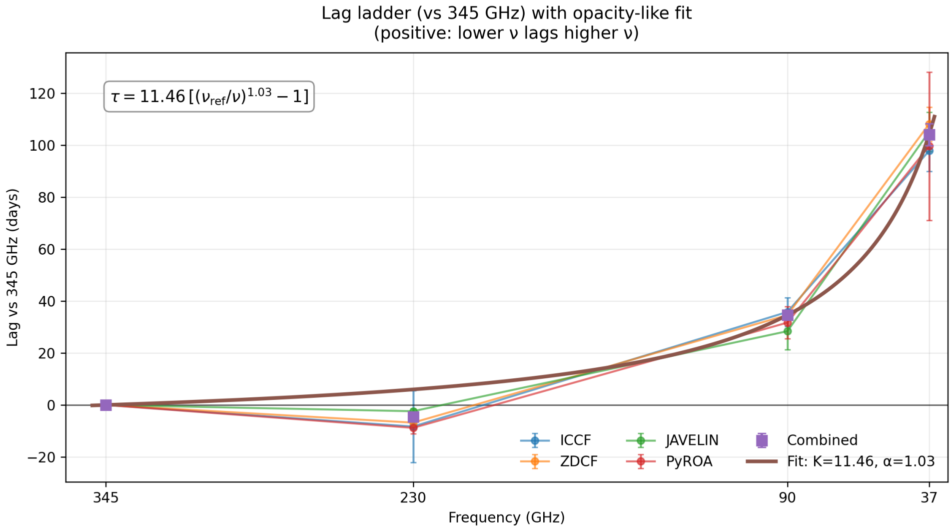

Figure 3: Average lag as a function of frequency, showing higher-frequency emission leading lower bands. The brown curve shows an illustrative power-law fit ($\tau = K[(\nu_{\rm ref}/\nu)^{\alpha} - 1]$) consistent with opacity-driven delays.

4. Discussion

The frequency-dependent variability and inter-band delays in 3C 279 constrain the mechanisms driving blazar jets. The monotonic rise in $F_{\rm var}$ supports models where higher-frequency emission arises from compact zones with stronger magnetic fields and higher particle densities [15]. This aligns with stratified-jet expectations, where higher frequencies probe smaller regions with shorter cooling timescales [16]. The slightly steeper 230–345 GHz slope hints at added processes, perhaps magnetic reconnection or local shocks [17].

Our lag analysis confirms a systematic trend where higher frequencies lead lower ones, consistent with opacity-driven stratification [18]. This behaviour is also broadly consistent with recent multi-band radio/mm analyses of 3C 279, such as [7], who similarly found progressively increasing delays toward lower frequencies. Their lags between 230 GHz and ~47 GHz (of order 130 days) are comparable in magnitude to our 230–37 GHz result (~99 days), reinforcing the interpretation of a smooth, frequency-dependent propagation of variability along the jet. The near-linear lag–frequency increase (Figure 3) fits a power-law relation, supporting a gradient in jet conditions as predicted by shock-propagation models [20]. The negative 230–345 GHz delay likely traces co-spatial emission zones or complex variability components [19].

5. Conclusion

This study confirms opacity-driven delays in 3C 279, with higher-frequency emission leading lower-frequency variations and a steadily rising $F_{\rm var}$. The magnitude and ordering of the lags are broadly consistent with earlier radio/mm studies of the source, including the frequency-dependent delays reported by [7], reinforcing the picture of a stratified, optically thick jet in which disturbances propagate downstream. Minor deviations at the highest ALMA bands suggest additional fast processes acting near the jet base. Overall, these results support a layered jet structure and illustrate the value of multi-method lag analysis for probing emission geometry in blazars.

Acknowledgements

We acknowledge the Metsähovi Radio Observatory for providing the 37 GHz AGN monitoring data used in this study, with Merja Tornikoski and Anne Lähteenmäki responsible for the Metsähovi AGN monitoring program. This work has been partially supported by the ERC Synergy Grant ERC-2022-SYG project 101071643 *BlackHolistic*.

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