

Multiwavelength Cross-Correlation Using Millimeter AGN Light Curves from the Atacama Cosmology Telescope

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Abstract.

We present a pilot multiwavelength cross-correlation analysis of the blazar PKS 0208-512 between 2018 and 2023 using millimeter data from the Atacama Cosmology Telescope (ACT) and the Atacama Large Millimeter Array, optical data from the All-Sky Automated Survey for Supernovae, and γ -ray data from the *Fermi* Large Area Telescope. We report a near-zero time-lag between the optical and γ -ray bands, consistent with leptonic emission models, while the millimeter emission lags by a few weeks, suggesting millimeter emission originates from farther downstream in the jet. With the upcoming release of an ACT catalogue containing over 200 blazar light curves, these results highlight the potential of these light curves for time-domain active galactic nuclei studies and provide a foundation for extending this analysis to a larger blazar sample.

1 Introduction

The Atacama Cosmology Telescope (ACT) was a ground-based Cosmic Microwave Background (CMB) experiment in Chile that operated from 2007 to 2022 [1]. Observing at 30–220 GHz, ACT mapped 45% of the sky at \sim arcminute resolution, enabling both high-resolution (small-scale) CMB studies [2] and investigations of compact sources such as active galactic nuclei (AGN).

Blazars, a category of radio-loud AGN with jets oriented close to our line of sight, are Doppler boosted and variable across the electromagnetic spectrum. Their spectral energy distribution (SED) has two components: a low-energy bump (radio to optical/UV) from synchrotron emission, and a high-energy bump (X-ray to γ -ray) attributed to either leptonic or hadronic processes. In leptonic models, γ -rays arise from inverse Compton scattering of a seed photon population, synchrotron photons [3] or external photon fields [4–6], by relativistic electron in the jet, predicting correlated variability between the synchrotron and high-energy emission. Hadronic models attribute γ -ray emission to proton synchrotron radiation [7] or photo-pion production, leading to secondary particles, neutrinos, and γ -rays. Such processes are not necessarily tightly correlated with the electron synchrotron emission and can thus occasionally produce “orphan” flares, which involve variability in one band without counterparts in others [8]. Neutrinos are a “smoking gun” for the hadronic process and many studies today look to correlate AGN flares with neutrino events [e.g. 9].

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Both models have been supported by observations, sometimes even within the same source. Millimeter emission traces synchrotron processes; however correlations with optical emission are not always observed. For example, in the study of the blazar PKS 2326-502, Ref. [10] reported correlations between mm and γ -ray, and between optical and γ -ray, but not between mm and optical, suggesting synchrotron emission may be more complex than a simple single-zone model.

Here we present a pilot study of the flat-spectrum radio quasar PKS 0208-512. We cross-correlate its millimeter light curve from ACT with optical data from the All-Sky Automated Survey for Supernovae [ASAS-SN; 11, 12] and γ -ray data from the *Fermi* Large Area Telescope [*Fermi*-LAT; 13]. While many multiwavelength studies of blazars focus on γ -ray, X-ray, optical, infrared, and radio emission, variability in the millimeter remains comparatively poorly explored. This analysis provides an initial test of our pipeline, with the goal of applying it to a larger subset of the ACT AGN sample. By measuring time lags between bands, we aim to provide constraints on emission mechanisms and probe the structure of relativistic jets.

2 Data

In this paper we focus on the flat-spectrum radio quasar PKS 0208-512. The flux for the ACT millimeter light curve was extracted from daily maps created with nighttime data obtained from 2013 to 2020 in the 95 GHz band. Since ACT was a ground-based telescope, measurements were sensitive to weather conditions and only night time data were included, which caused significant gaps in the data ranging from weeks to months. A paper describing the initial set of ACT AGN light curves is in preparation. The light curve obtained with ACT was supplemented with datapoints from the Atacama Large Millimeter Array [ALMA; 14] calibrator catalogue [15], using measurements collected after 2015. The γ -ray light curve was obtained from the *Fermi*-LAT Light Curve Repository [16], a public database containing light curves for 1525 variable sources in the 4FGL-DR2 catalog [17]. The optical light curve was obtained from ASAS-SN Sky Patrol [18], a database of V-band photometry for ~ 111 million targets observed in the ASAS-SN survey as well as sources from numerous external catalogues. The light curves used in this analysis are plotted in Figure 1. In our analysis we use data between 2018-09-01 and 2023-01-01, a period covering a large flaring event during which all three bands are generally well sampled.

3 Methods

All light curves were binned in 3-day intervals to reduce short-timescale noise and to better match the longer sampling cadence of the millimeter light curve. This binning also helps to mitigate the effects of irregular sampling on the cross-correlation analysis, which benefits from more uniformly distributed data points. We employed the discrete correlation function (DCF), as described in [19] to measure correlations between each pair of light curves. The DCF is well suited for irregularly sampled data and provides an estimate of the correlation as a function of time lag by averaging the products of flux deviations for all pairs of points within each time-lag bin. The time-lag bins were constructed to contain 300 point pairs each, leading to non-uniform bin widths that increase at larger time lags. This insured the DCF has consistent statistical significance across time lag bins. To evaluate the significance of the DCF peaks, we generated 5,000 uncorrelated simulated light curves with the `lcsim` Python package [20] and computed their DCFs. This package uses the algorithm introduced in Ref. [21] to generate Gaussian noise following a specified power spectral density (PSD).

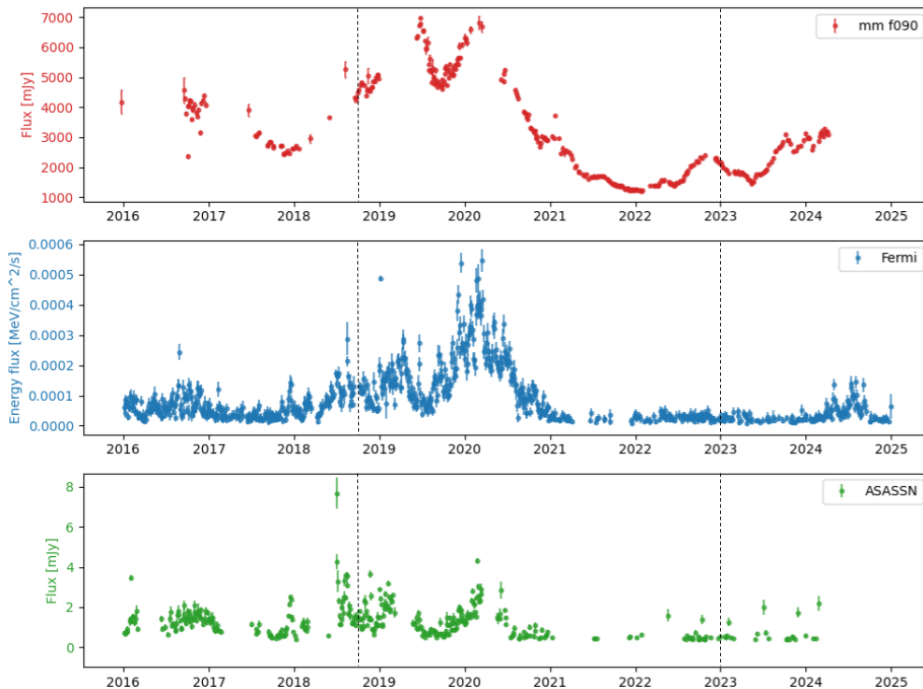


Figure 1. All light curves for PKS 0208-512. *Top:* millimeter light curve from ACT and ALMA. *Middle:* γ -ray light curve from *Fermi*-LAT. *Bottom:* Optical light curve from ASASS-SN. We use the data between 2018-09-01 and 2023-01-01, delimited by dotted lines in the plots.

To first order, the PSD of a blazar can be described as a power-law [22]. The power-law spectral indices for each of the light curves were obtained by calculating the continuous wavelet transforms of the light curves and fitting a power law to the global wavelet spectrum, which provides a stable estimate of the PSD slope for non-stationary AGN variability and is less affected by uneven sampling than Fourier-based methods. We used spectral indices of 2 (mm), 1.8 (optical), and 1.7 (γ -ray). Each simulated light curve was re-scaled and re-sampled to match the observational cadence and variance of the data. These served as a null distribution for assessing the statistical significance of the observed correlations.

4 Results and Discussion

The results of the cross-correlations are presented in Figure 2. The DCF shows peaks at the 2σ significance level for both the mm–optical and mm–gamma correlations. The mm–optical correlation peaks at a time lag of ~ 30 days, estimated by fitting a Gaussian to the DCF, while the mm–gamma correlation peaks at ~ 25 days, obtained by fitting a skew-normal distribution. For the optical–gamma correlation, the DCF reaches a higher significance of 3σ with a time lag of ~ 3 days, again estimated by Gaussian fitting. These lags are mutually consistent, which provides additional confidence to the results. The near-zero lag between the optical and γ -ray light curves agrees with leptonic emission models, in which high-energy γ -rays originate from inverse-Compton scattering of optical synchrotron photons within co-spatial regions of the jet. In contrast, the delayed millimeter emission most likely arises further down the jet,

where electrons have cooled enough to radiate at longer wavelengths. This spatial separation naturally explains the observed delays between the millimeter and optical/ γ -ray flares.

However, the lack of a statistically significant mm–optical correlation warrants further investigation. The time lags should be interpreted with caution as the results may be sensitive to the time-lag binning, which varies across different time-lags. A more rigorous statistical framework will be required to properly quantify the uncertainties associated with the time-lag estimates.

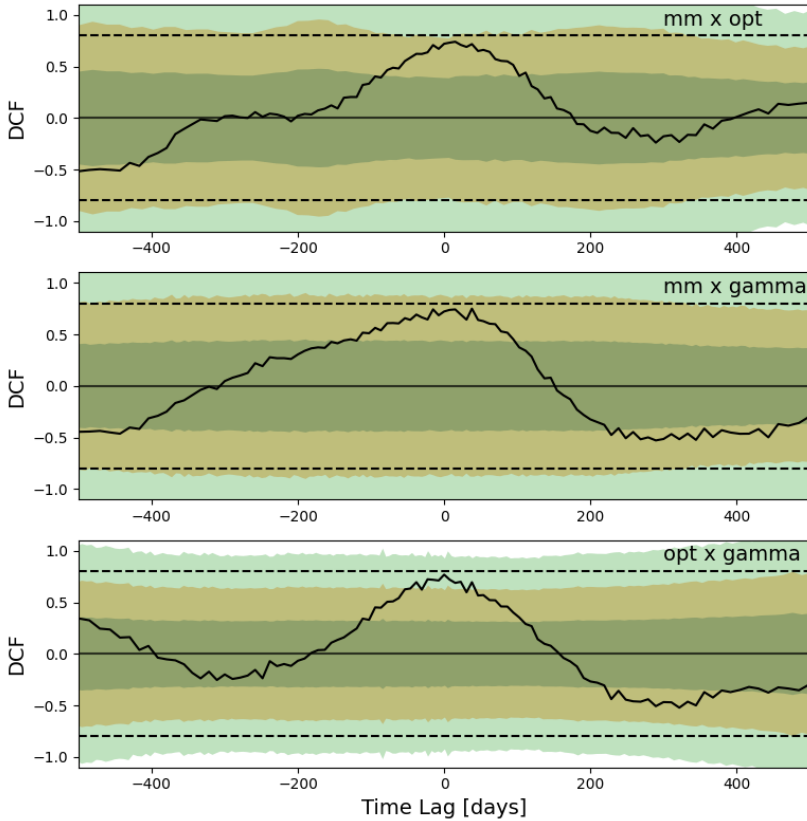


Figure 2. Results from cross-correlating the millimeter and optical light curves (*top*), the millimeter and γ -ray light curves (*middle*), and the optical and γ -ray light curves (*bottom*). The shaded regions represent the 1-, 2-, and 3- σ uncertainties obtained from cross-correlating the uncorrelated simulated light curves. The dotted line represents a DCF value of 0.8, included for visual aid.

5 Conclusion

We presented a first case study of multiwavelength variability in the blazar PKS 0208-512 using millimeter light curves from ACT and ALMA, combined with optical data from ASAS-SN and γ -ray data from *Fermi*-LAT. The cross-correlation revealed time lags that are broadly consistent with leptonic emission scenarios, with the optical and γ -ray light curves varying nearly simultaneously, while the millimeter emission is delayed by several weeks, likely originating further downstream in the jet.

These results highlight the power of time-domain multiwavelength studies for understanding emission processes in AGN jets. While the correlations observed here support leptonic models, the absence of a strong mm–optical correlation shows the complexity of synchrotron emission, and the limitations of single-zone emission models. A larger statistical sample will be required to assess if such lag patterns are common among blazars, and to constrain the relative importance of leptonic and hadronic contributions across different sources.

Future work will apply this pipeline to a larger set of ACT AGN light curves and include additional millimeter data from the South Pole Telescope. Extending this analysis to a population study will allow for more robust constraints on jet morphology and emission mechanisms. Furthermore, additional statistical tools must be explored to quantify uncertainties in measured time lags.

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