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Spectral Hardening Revealed by Geometric De-boosting in the Masked Jet of PKS 2155-304

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Abstract

Blazar gamma-ray variability is predominantly stochastic and well described by red-noise processes. However, a subset of sources exhibits quasi-periodic oscillations (QPOs) on year-long timescales, whose physical origin remains debated. In high-synchrotron-peaked (HSP) blazars, departures from a single power-law gamma-ray spectrum, manifested as high-energy upturns in the GeV band, may probe emission mechanisms and the intrinsic duty cycle. We investigate the link between the 1.7 yr gamma-ray QPO in PKS 2155-304 and an exceptional spectral hardening event identified in the Fermi-LAT HSP blazar population. We analyze 18 years of Fermi-LAT data using 30-day binning, applying Singular Spectrum Analysis to mitigate red-noise effects and a Moving Block Bootstrap approach to quantify the correlation between photon flux and photon index. We find a statistically significant softer-when-brighter chromatic trend, supporting a geometric origin of the flux modulation. The spectral hardening event is phase-locked to the QPO trough, implying that the hardening signature is detectable only when geometrically boosted soft emission is suppressed at the flux minimum. We propose a Geometric Gate scenario in which jet geometry regulates the visibility of acceleration processes. These results favor a two-component jet structure and suggest that spectral hardening during low-flux states, even in non-periodic sources, may reveal jet physics otherwise obscured by relativistic amplification.

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