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Multiwavelength spectral and temporal analysis of VHE Blazar 1ES 1959 + 650: Tracing emission mechanisms across flux states

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ABSTRACT

The high-synchrotron-peaked BL Lac object 1ES 1959 + 650 exhibited pronounced activity between MJD 60310–60603, including a very high energy (VHE) detection reported by Large High Altitude Air Shower Observatory. To investigate the underlying emission mechanisms, we performed a comprehensive temporal and spectral analysis using multiwavelength data from *Swift*-XRT/UVOT and *Fermi*-LAT, covering the optical/UV to GeV γ-ray bands. The source shows strong energy-dependent variability, with the largest fractional variability in γ-rays, followed by X-rays and UV/optical, consistent with leptonic emission scenarios. Based on the variability patterns, we identified distinct flux states (F1, F2, F3, F4, F5, VHE-FX1, and VHE-FX2). The X-ray spectra exhibit a clear 'harder-when-brighter' trend across these states. We modelled the broad-band spectral energy distributions (SEDs) using a one-zone model incorporating synchrotron and synchrotron self-Compton (SSC) emission, implemented in XSPEC using χ^2 minimization. During the VHE detection, the corresponding X-ray/optical emission likely resembled the F2 state. Modelling the VHE SED using F1-state data led to an SSC overprediction of the VHE flux, whereas all other states were well described within the one-zone framework. Systematic trends in physical parameters are observed across flux states, including spectral hardening, increasing break energy, rising bulk Lorentz factor, and decreasing magnetic field with increasing flux. These results suggest that enhanced particle acceleration efficiency and stronger Doppler boosting drive the observed flaring activity, while the decrease in magnetic field indicates conversion of magnetic energy into particle kinetic energy, consistent with shock-driven scenarios.

Key words: galaxies: active – (galaxies:) BL Lacertae objects: individual: 1ES 1959 + 650 – galaxies: jets – X-rays: galaxies.

1 INTRODUCTION

The extra-galactic γ-ray space is dominated by blazars (C. D. Dermer & B. Giebels 2016), a peculiar class of radio-loud active galactic nuclei powered by central supermassive black hole. Blazars consist of strong relativistic jet pointing close to the line of sight of an observer (C. M. Urry & P. Padovani 1995). Due to the small inclination angle, the jet emission is relativistically amplified. The non-thermal emission from blazars spans throughout the electromagnetic spectrum and exhibits a very fast variability, down to the time-scale of minutes in very high energy (VHE; $E_\gamma \geq 100$ GeV) regime (J. A. Gaidos et al. 1996; M.-H. Ulrich, L. Maraschi & C. M. Urry 1997; J. Albert et al. 2007; F. Aharonian et al. 2009; A. U. Abeysekara et al. 2020). Blazars come in two flavours: Flat Spectrum Radio Quasars, showing strong emission/absorption line features in their optical spectra, and BL Lacertae objects (BL Lacs), which show weak or no emission/absorption line features in their optical spectra (M. J. M. Marcha et al. 1996; P. Padovani et al. 2007; V. Beckmann & C. R. Shrader 2012).

The broadband spectral energy distribution (SED) of blazars comprises of two peaks in $\nu - \nu F_\nu$ space (G. Fossati et al. 1998; A. A. Abdo et al. 2010), the low-energy peak is in infrared to X-ray range, while the high-energy peak is in γ-ray band, ranging from MeV–GeV. The low-energy peak is well understood by the synchrotron radiation of the relativistic electrons in the jet (R. D. Blandford & M. J. Rees 1978; L. Maraschi, G. Ghisellini & A. Celotti 1992a; G. Ghisellini et al. 1993). The origin of the second peak is less clear and two scenarios have been put forth to explain it. Under leptonic scenario, the high-energy peak is either attributed to the inverse Compton (IC) up-scaterring of synchrotron photons by the relativistic electrons (synchrotron self-Compton, SSC) (A. Konigl 1981; G. Ghisellini & L. Maraschi 1989; L. Maraschi, G. Ghisellini & A. Celotti 1992b; M. Böttcher & J. Chiang 2002) or up-scattering of photons external to the jet (External Compton; EC) (M. C. Begelman & M. Sikora 1987). These external photons can be from accretion disc (C. D. Dermer & R. Schlickeiser 1993; M. Boettcher, H. Mause & R. Schlickeiser 1997), the broad-line region (M. Sikora, M. C. Begelman & M. J. Rees 1994; G. Ghisellini & P. Madau 1996), and the torus (M. Błażejowski et al. 2000; G. Ghisellini & F. Tavecchio 2008). The broad-band SED of blazars is generally

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