PROCEEDINGS OF SCIENCE

Long-term observation of Markarian 501 by LHAASO-WCDA

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Based on 42 months of observations by the Large High Altitude Air Shower Observatory (LHAASO), we report on the active behavior of the blazar Mrk 501, which exhibited several high states during this period. The most dramatic flare occurred between MJD 59334 and MJD 59348, reaching 62% of the Crab Nebula flux (> 1 TeV). The global spectral energy distribution (SED) of Mrk 501 above 1 TeV is well described by a power-law model with an exponential cutoff, yielding a power-law index of $\alpha = 2.18 \pm 0.04$ and a cutoff energy of $E_{\rm cut} = 9.51 \pm 1.44$ TeV. Ongoing studies focus on multi-wavelength correlations and broadband spectral modeling to further understand the underlying physical mechanisms driving these phenomena. LHAASO's all-weather capability and high duty cycle provide critical continuous data for such investigations.

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1. Introduction

Blazars constitute a type of Active Galactic Nuclei (AGN) characterized by relativistic jets oriented along our line of sight. Markarian 501 (Mrk 501), classified as a BL Lacertae blazars, is a powerful extragalactic source of Very High Energy (VHE) gamma rays, first detected by the Whipple (10-meter gamma-ray) telescope [1]. Notably, Mrk 501 exhibits significant variability across multiple energy bands. In 1997, the source entered an exceptionally high state, reaching a luminosity approximately six times that of the Crab Nebula, accompanied by a hard spectral index of 2.46 [2]. This dramatic flaring activity was not only observed in the VHE gamma-ray band but also prominently detected in X-rays. Observations from the *Rossi X-Ray Timing Explorer* (RXTE) [3] revealed that the X-ray emission during this event displayed highly variable behavior, with the synchrotron component extending up to energies of 100 keV. According to Synchrotron Self-Compton (SSC) models, gamma-ray emission originating from leptonic processes is expected to exhibit a strong correlation with X-ray emission. Consequently, long-term, unbiased multi-wavelength observations are essential for understanding the underlying physical mechanisms. The Large High Altitude Air Shower Observatory (LHAASO), with its high sensitivity and high duty cycle, is uniquely positioned to provide critical insights into the VHE gamma-ray behavior of such sources.

2. Experiment

The Large High Altitude Air Shower Observatory (LHAASO), situated at Haizi Mountain (29°21′27.56″N, 100°08′19.66″E, 4410 meters above sea level) in Sichuan Province, China, is a hybrid Extensive Air Shower (EAS) detector array. It comprises three main components: a 1.3 km^2 array (KM2A), a water Cherenkov detector array (WCDA), and a wide field-of-view air Cherenkov telescope array (WFCTA).

The WCDA consists of three water ponds covering a total area of 78,000 m^2 and is equipped with 3,120 water Cherenkov detectors (WCDs). Each detector is fitted with photomultiplier tubes (PMTs) of two sizes: 8-inch and 1.5-inch PMTs for the first pond, and 20-inch and 3-inch PMTs for the other two ponds. Simulations indicate that the energy threshold of the WCDA reaches 100 GeV. Further details have been published in [4–6]. The WCDA is characterized by its all-weather detection capability, wide field-of-view, and high sensitivity, achieving a duty cycle exceeding 98% and monitoring approximately 1/7 of the sky daily through transit observations. Consequently, the WCDA provides unbiased and continuous data without interruption.

The KM2A array is composed of 5,195 electromagnetic detectors (EDs) and 1,188 muon detectors (MDs), deployed over an area of 1.3 km^2. The EDs are spaced at intervals of 15 m, while the MDs are spaced at intervals of 30 m. A typical ED has a detection efficiency of approximately 98% and a time resolution of about 2 ns. The MDs are pure water Cherenkov detectors, shielded by 2.5 meters of soil. A typical MD has a detection efficiency exceeding 95% and a time resolution of about 10 ns. Additional details have been published in [5, 7, 8].

3. Results

Figure 1 presents the 42-month multi-wavelength light curves spanning from March 2021 to July 2024. In the VHE regime, Mrk 501 exhibited significant variability, indicating active gamma-ray emission, while no substantial outbursts were observed in the 0.1 - 100 GeV and 15 - 50 keV bands. Several notable peaks and piled-up outbursts are evident. A particularly prominent burst occurred between MJD 59337 and MJD 59348, during which the flux rapidly increased. A similar structure was observed in both the LAT and XRT observations. Another distinctive feature was a long-term elevated state of Mrk 501, lasting from MJD 59400 to MJD 59800. This period began with an overall increase in flux, followed by several outbursts at the peak, and concluded with a gradual decline in flux, described as an "exhaustion" phase. This phenomenon is more pronounced in the XRT observations. Following the elevated state, Mrk 501 entered a quiescent phase, with the majority of data points clustering in the lower flux range, interspersed with occasional spikes.

3.1 Global Spectra of Energy Distribution

By accumulating data over extended periods, LHAASO can provide a comprehensive picture of Active Galactic Nuclei (AGN) behavior, including variations in luminosity and spectral characteristics. This continuous dataset enables the investigation of long-term evolution and facilitates studies based on uninterrupted, no-alarm data.

Given that LHAASO's measurements extend to several TeV, the attenuation due to pair production induced by the low-energy extragalactic background light (EBL) has a non-negligible effect on the observed flux. To derive the intrinsic spectral model of Mrk 501, we assumed both a power-law model and a power-law model with an exponential cutoff:

$$F = F_0 \left(\frac{E}{1\ \mathrm{TeV}} \right)^{-\alpha}, \tag{1}$$

$$F = F_0 \left(\frac{E}{1\ \mathrm{TeV}} \right)^{-\alpha} \exp\left(-\frac{E}{E_{\mathrm{cut}}} \right), \tag{2}$$

which were convolved with EBL models [15–17]. The corrected SEDs, along with the observed SED (without EBL correction), are shown in Figure 2. The intrinsic spectrum of Mrk 501 exhibits a curvature around 10 TeV, which cannot be adequately explained by a simple power-law model. Instead, a power-law model with an exponential cutoff is preferred. The best-fit parameters are $F_0 = 10.89 \pm 0.31 \times 10^{-12}\ \mathrm{TeV}^{-1} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, $\alpha = 2.18 \pm 0.04$, and $E_{\mathrm{cut}} = 9.51 \pm 1.44$ TeV, with minimal variation across the three EBL models considered.

we compare LHAASO's results to spectra measured by other instruments (MAGIC[18]; VERITAS [18]; HAWC[19]; ARGO-YBJ[20] and TACTIC[21]) in Figure 3.

3.2 Flaring Behavior

During the observation period, Mrk 501 exhibited several flaring, with the most dramatic flare occurring in the interval MJD 59334 and MJD 59348 (see Figure 4). To characterize the timescales of these flares, we employed an exponential function with asymmetric rise (T_r) and decay (T_d) timescales:

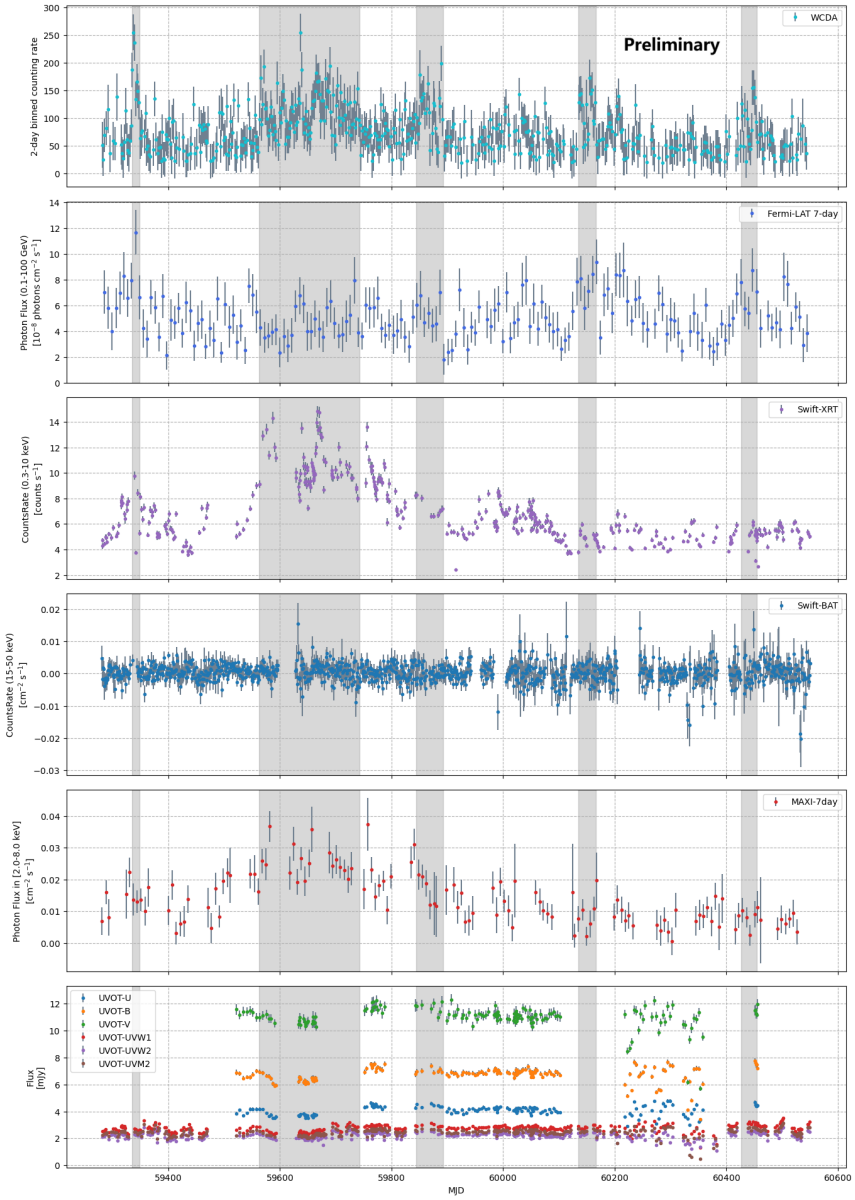

Figure 1: Long term Mrk501 multi-wavlength light curves spanning from 59281 until end of 60550. Top to bottom: WCDA 2-day binned counting rate for $N_{hit} > 60$; Fermi-LAT 3-day fluxes for energy $\in [0.1, 100]$ GeV from Fermi Light Curve Repository (LCR)[9, 10]; Swift-XRT X-ray counting rate for energy $\in [0.3, 10]$ keV from UK Swift Science Data Centre (UKSSDC)[11, 12]; Swift-BAT hard X-ray counting rate for energy $\in [15, 50]$ keV) from Swift/BAT Hard X-ray Transient Monitor[13]; MAXI X-ray 7-day binned counting rate for energy $\in [2, 8]$ keV from MAXI on-demand process[14] and Swift-UVOT fluxes of six filters from UKSSDC. Grey shadow regions denote the high states deponded on LHAASO-WCDA observation.

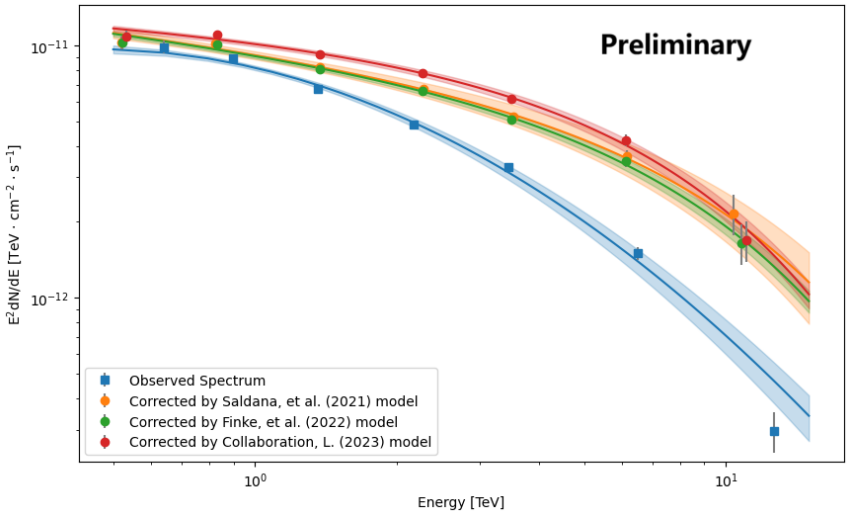

Figure 2: The spectral models after EBL correction. Colored shaded region means 1σ uncertainty of fitting.

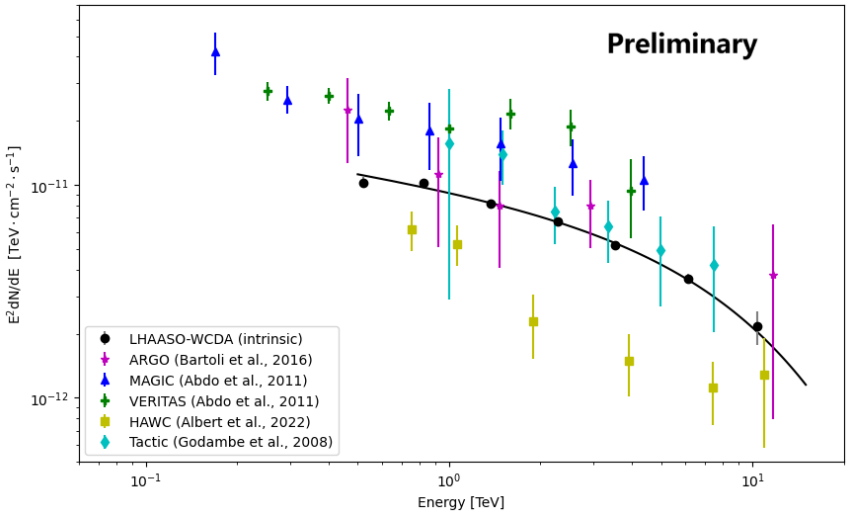

Figure 3: Comparison with previous results. MAGIC (16.2 hr) and VERITAS (9.7 hr) from [18], HAWC (1038 days) from [19], ARGO-YBJ experiment between 2007 and 2010 from [20] and TACTIC telescope (129.25 hr) from [21].

$$F(t) = 2F_v \left[\exp\left(\frac{t_0 - t}{T_r}\right) + \exp\left(\frac{t - t_0}{T_d}\right) \right]^{-1} + F_c \tag{3}$$

where t_0 represents the peak time, F_c is the constant baseline counting rate, and F_v is the flaring component superimposed on the baseline rate. The parameter T_r corresponds to the rise timescale and T_d to decay timescale.

During this flare, the brightness of Mrk 501 increased by a factor of 6 relative to its quiescent state within 2 days, rising from 9% to 62% of the Crab Nebula flux (> 1 TeV), and subsequently decayed over the course of 6 days. The asymmetric timescales of the flare, characterized by a shorter

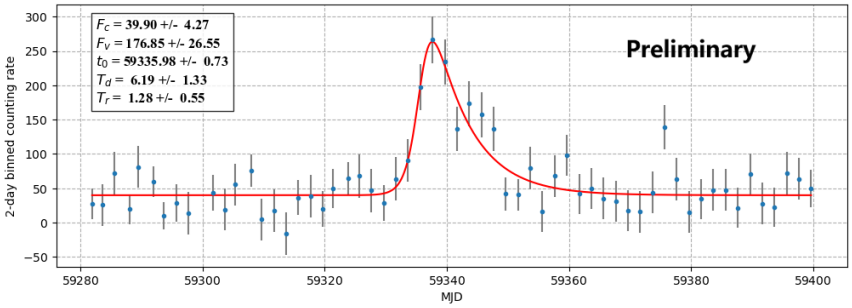

Figure 4: Detail light curve in the beginning and toward the end of the time range (MJD 59274 to MJD 59407). The blue data points represent the measured 2-day binned counting rate, with error bars indicating the uncertainties. A red line overlays the data, representing a fitted model.

rise time and a longer decay time, may indicate that the particle acceleration process occurs more rapidly than the cooling process. The underlying physical mechanisms driving this phenomenon remain under investigation.

4. Summary

Based on 42 months of observations conducted by LHAASO, we find that Mrk 501 exhibits relatively active behavior, experiencing several high states. The most dramatic flare occurred during MJD 59334 and MJD 59348, reaching 62% of the Crab Nebula flux (> 1 TeV). The global SED of Mrk 501 above 1 TeV is well described by a power-law model with an exponential cutoff, characterized by a power-law index of $\alpha = 2.18 \pm 0.04$ and a cutoff energy of $E_{\rm cut} = 9.51 \pm 1.44$ TeV. Studies on multi-wavelength correlations and broadband spectral modeling are currently ongoing.

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