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Multiwavelength variability of the blazar Ton 599

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Abstract. We present a study of the multiwavelength variability of the blazar Ton 599 based on the radio-to-γ-ray data covering the period of 1997–2024. The data are represented by the 1–22 GHz measurements from the SAO RAS RATAN-600 radio telescope, the 5 and 8 GHz data from the IAA RAS RT-32 telescopes, and the 37 GHz data from the RT-22 telescope of CrAO RAS. The optical measurements in the R-band were collected with the SAO RAS 1-m Zeiss-1000 and 0.5-m AS-500/2, SPbSU 0.4-m LX-200, and CrAO RAS 0.7-m AZT-8 telescopes. We also used the archive data at 230 GHz from the Submillimeter Array (SMA) and the γ-ray data in the 0.1–100 GeV band from the Fermi-LAT point source catalogue 4FGL-DR2. The blazar exhibits extreme variability properties with a variability index varying from 0.47 to 0.98. A characteristic feature of the light curves is the presence of double and triple flares with different spectral properties. A significant correlation ($\geq 2\sigma$) between the radio, optical, and γ-ray bands is found with time delays from 0 to 365 days. The L–S periodograms show the significant peaks ($> 3\sigma$) related to periods of 2.4–3.9 years, which coincides with global oscillations obtained earlier on the time scale of 1987–2010.

Keywords: galaxies: active; quasars: individual (Ton 599); radiation mechanisms: non-thermal; methods: data analysis, statistical

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1 Introduction

The bright blazar Ton 599 at redshift $z = 0.725$ (Hewett & Wild 2010) is classified as a flat-spectrum radio quasar (FSRQ). The blazar belongs to the family of TeV sources detected with ground-based Cherenkov telescopes (Mukherjee & VERITAS Collaboration 2017). Ton 599 demonstrates a flaring activity with complex structure of flares in the γ-ray, optical, and high-frequency radio bands. This source had the strongest flares in 2017 and 2021–2023 (e.g., Prince 2019; Patel & Chitnis 2020; Manzoor et al. 2024). Quasi-periodical behaviour of the Ton 599 radio light curves in the centimeter range was reported earlier by Wang et al. (2014); Liu & Liu (2014). The investigation of the long-term light curves provides an opportunity to obtain constraints on the structure and physical conditions of the AGN central engine; the flare characteristics allow us to track dynamical processes in the central parts of AGNs. To this end, we constructed and investigated a set of multi-wavelength (MW) long-term light curves of Ton 599 from γ-ray to radio bands covering a period of several decades.

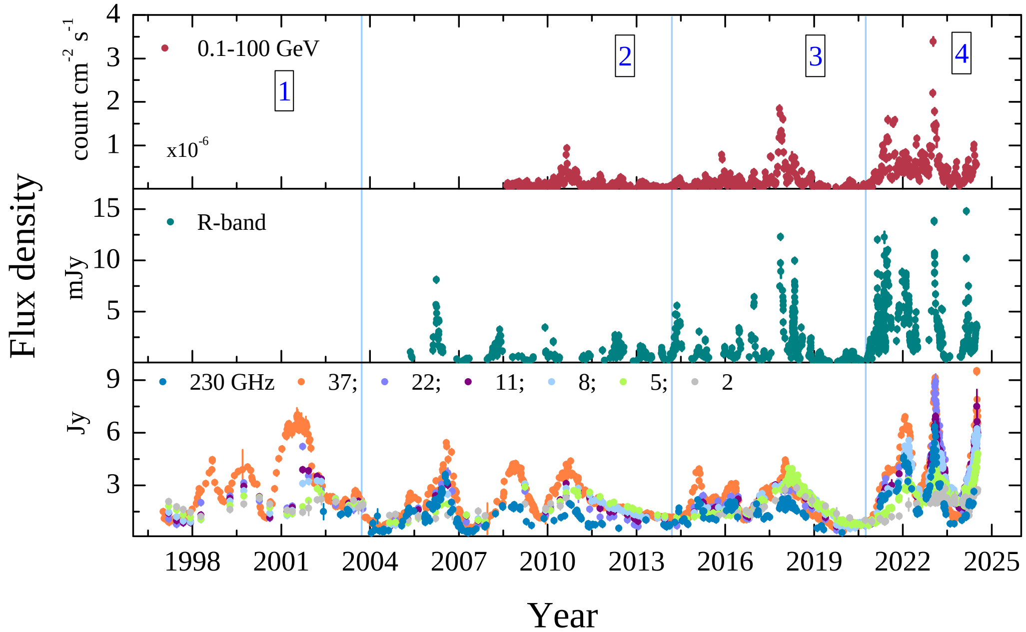

Fig. 1. Multiband light curves of Ton 599 in 1997–2024. The four epochs chosen for analysis are depicted by straight vertical lines.

2 Data

The MW light curves (Fig. 1) are constructed using the γ-ray data from Fermi-LAT in 2008–2024 (Abdollahi et al. 2023), the optical R-band measurements in 2005–2024 from the Zeiss-1000 and AS 500/2 (SAO RAS), LX-200 (SPbSU), and AZT-8 (CrAO RAS) telescopes, and the mm-band 230 GHz SMA measurements in 2002–2024[1] (SMA; Gurwell et al. 2007). The radio light curves are based on the monitoring in 1997–2024: at 37 GHz with the radio telescope RT-22 (CrAO RAS), at 1–22 GHz with RATAN-600 (SAO RAS), and at 5 and 8 GHz with the RT-32 (IAA RAS). To analyze certain flaring events, we divided the entire light curve into 4 epochs, as it is shown in Fig. 1.

3 The properties of MW variability

The blazar exhibits extreme emission variability in a wide wavelength range with a variability index V_S (Aller et al. 1992) varying from 0.47 to 0.98 on a time scale of 27 years. For example, the flux density changes from 0.4 to ∼9.5 Jy at 37 GHz. An interesting feature of the Ton 599 light curves is the presence of double and triple flares with different spectral properties (Fig. 1) as well as the presence of a possible periodicity of flux density at high radio frequencies of 22–230 GHz. Moreover, at 37 GHz a triple structure of active states is clearly visible over four epochs: 1997–2004, 2004–2013, 2013–2020, and 2020–2024+. The periods of the triple flares lasted 7–9 years at 37 GHz.

The variability properties were analysed using the standard methods: (i) the structure function to estimate the variation time scale, (ii) the discrete correlation function to search for correlation and time lags between the flares at different wavelengths, (iii) the Lomb–Scargle (L–S) periodogram to search for periodicities. The structure function analysis reveals variability time scales $t_{\rm var} = 100$–1000 days within the four activity epochs. Based on these values, the upper limit of the size of emitting regions R are 1.2–12.3 pc, assuming $R \leq c \cdot t_{\rm var} \cdot \delta/(1+z)$, where c is the speed of light and $\delta = 25$ (Kang et al. 2021) is the Doppler factor.

A cross-correlation analysis between MW light curves reveals that flares at lower frequencies follow flares at higher frequencies, with different time delays during individual epochs. The time lag decreases with frequency in the range from 0 to 120 days for epoch 2, from 0 to 145 days for epoch 3, and from 0 to 60 days for epoch 4. For epoch 1 the time lags vary from 0 to 365 days for the pair of frequencies 2–37 GHz. Based on the time lags $t_{\rm lag}$, we have estimated the distance D between the

[1] http://sma1.sma.hawaii.edu/callist/callist.html

emitting regions from the expression $D = \beta \cdot c \cdot t_{\rm lag}/[(1+z)\cdot \sin\theta]$, where $\beta \approx 7.4$ is the apparent jet speed and $\theta = 4.2^\circ$ is the viewing angle (Ramakrishnan et al. 2014). We have obtained $D \leq 5$ pc for epoch 2, $D \leq 6$ pc for epoch 3, and D up to 2.5 pc for epoch 4.

To find the long-term periodicity, we used the L–S periodograms (Lomb 1976; Scargle 1982), which are widely used in astronomy for unevenly sampled time series. The L–S periodograms show significant peaks (above 3σ) related to periods of 2.4–3.9 years for all the wavelength bands, this coincides with the second and third harmonic modes (2.4 and 3.4 yrs) obtained by Wang et al. (2014) at 4.8, 8, and 14.5 GHz on the time scale of 1987–2010. These periods can be attributed to the mean distance between individual peaks in the triple flares that are seen in our radio light curves, especially at frequencies of 37 and 22 GHz. If we apply the L–S method to search for periodicities in a wider range, the resulting periods appear in the range between 5.6 and 8.3 years, which reflects the distance between these triple flares.

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