Multi-frequency Variability Study of Ton 599 during the High Activity of 2017

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Abstract

In this work, I have presented a multi-frequency variability and correlation study of the blazar Ton 599, which was observed for the first time in the flaring state at the end of 2017. Data from Fermi-LAT, Swift-XRT/UVOT, Steward observatory, and Owens Valley Radio Observatory(OVRO) (15 GHz) are used and it is found that the source is more variable in γ-rays and optical/UV than in X-rays and radio. Large variations in degree of polarization and position angle are observed during the flaring period. Maximum flux during the γ-ray flare is found to be $12.63 \times 10^{-7}$ at MJD 58057.5 from the 1 day bin light curve, which is the highest flux ever achieved by this source. It is further found that all the peaks of the flare are very symmetric, which suggests the cooling time of electrons is much smaller than the light-crossing time. Using 1 day as a fast variability time, the size of the γ-ray emission region is estimated as $1.88 \times 10^{16}$ cm. Two 42 GeV of photons are detected during the flare, which puts a constraint on the location of the emission region, and it is found that the γ-ray emitting blob is located at the outer edge or outside the broad-line region. The trend of increasing fractional variability toward higher energies is also seen. Strong correlations were seen between γ-ray, optical/UV, X-ray, and radio (15 GHz) emission. A small time lag between γ-rays and the optical/UV suggests their emission to be co-spatial, while the lag of 27 days between γ-rays and OVRO (15 GHz) suggests two different emission zones separated by a distance of ~5 pc.

Key words: galaxies: active – gamma rays: galaxies – quasars: individual (Ton 599)

1. Introduction

Blazars are thought to be radio-loud active galactic nuclei (AGNs) that have jets oriented close to the observer’s line of sight (Urry & Padovani 1995). They emit in all frequencies extending from the radio to very high-energy γ-rays. In general, blazars shows minute (Aharonian et al. 2007) to year (Raiteri & Villata 2013) scales of time variability across the entire electromagnetic spectrum. Their spectral energy distribution (SED) is characterized by two hump structures. The first one peaks in the low-energy band (IR to soft X-ray), which is well explained by synchrotron emission caused by relativistic electrons in the magnetic field of the jets and the second one peaks in the high-energy band (hard X-ray to γ-ray), which is thought to be the product of inverse Compton (IC) scattering of low-energy photons within the jets called synchrotron self-Compton (Konigl 1981; Marscher & Gear 1985; Ghisellini & Tavecchio 2009) or from outside the jets (external Compton; EC) with relativistic electrons. There is also an alternative way that can produce the high-energy hump through the hadronic process in which high-energy protons interact with low-energy protons and produce charge and neutral muons, and can decay into high-energy γ-rays and neutrinos. In leptonic scenarios, the external seed photons can come from direct disk emission, BLR, dusty or molecular torus (MT; Bottcher 2007).

Ton 599 is an FSRQ also known as 4C 29.45, and 3FGL J1159.5+2914 (Acero et al. 2015) with R.A. = 179.8826413 deg, decl. = 29.2455075 deg, and $z = 0.72449$. This is the first time the source has gone through a long flaring state across the entire electromagnetic spectrum. Many correlation studies have been done, between the optical, X-rays, and γ-rays, to discuss the connection between their emission regions, in FSRQ. Cohen et al. (2014) studied the correlation between the optical and γ-rays for 40 Blazars and they found that high-energy emission leads the low-energy emission by a time lag of 1–10 days. A correlation study of a sample of 183 blazars has also been done by Pushkarev et al. (2010) and they found that in most of the cases radio flare lags behind the gamma-ray flare. It is also true that, the time delay between flares of two bands depends on their separation (Fuhrmann et al. 2014). In blazars, the exact location of the gamma-ray emission region is not known because of the poor angular resolution at high energy. While on the radio emission region has been resolved in the jets of blazars with milliarcsecond resolutions of radio observations. Ramkrishnan et al. (2014) studied the correlation between γ-ray and radio emission for this source and found that γ-rays lag behind the radio with a time lag of 120 days, which constrains the gamma-ray emission region in the parsec-scale jet.

In this paper, I have studied the correlation between the optical, X-rays, and gamma-rays to understand the multiwaveband emission during the flare of 2017.

2. Multiwavelength Observations and Data Analysis

2.1. Fermi-LAT

Fermi-LAT is a pair conversion γ-ray telescope sensitive to photon energies between 20 MeV to higher than 500 GeV, with a field of view of about 2.4 sr (Atwood et al. 2009). The LAT’s field of view covers about 20% of the sky at any time, and it scans the whole sky every three hours. The instrument was launched by NASA in 2008 into a near-Earth orbit. Ton 599 has been continuously monitored by Fermi-LAT since 2008 August. The standard data reduction and analysis procedure1 has been followed. The other analysis procedure is the same as that given in Prince et al. (2018). I have analyzed the Fermi-LAT data from 2014 Jan to 2018 Jan and found that most of the time the source was in a quiescent state and started showing major activity at the end of 2017 (Figure 1). At the end of 2015,
the flux rises but that does not last for a long time, and the maximum flux was $\sim 4 \times 10^{-7}$ ph cm$^{-2}$ s$^{-1}$.

2.2. Swift-XRT/UVOT

Ton 599 was observed by Swift-XRT/UVOT during its flaring state. Details on the observations are presented in Table 1. Cleaned event files were obtained using the task “xrtpipeline” version 0.13.2. Latest calibration files (CALDB version 20160609) and standard screening criteria were used for reprocessing the raw data. Cleaned event files corresponding to the Photon Counting mode were considered. Circular regions of radius 20 arcsec centered at the source and slightly away from the source were chosen for the source and the background regions, respectively, while analyzing the XRT data. The X-ray spectra were extracted in xselect. The obtained spectra is fitted using simple power-law model with galactic absorption column density $N_H = 1.77 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005). The Swift Ultraviolet/Optical Telescope (UVOT, Roming et al. 2005) also observed Ton 599 in all six filters: U, V, B, W1, M2, and W2. The source image was extracted from a region of 5 arcsec centered at the source. The background region was chosen with a radius of 10 arcsec away from the source from a nearby source-free region. The "uvotsource" task has been used to extract the source magnitudes and fluxes. Magnitudes are corrected for galactic extinction (Schlafly & Finkbeiner 2011) and converted into flux using the zero-points (Breeveld et al. 2011) and conversion factors (Larionov et al. 2016).

2.3. Steward Optical Observatory

I have also used the archival data from the Steward Optical Observatory, Arizona (Smith et al. 2009). Ton 599 is being continuously monitored with the SPOL CCD Imaging/Spectrometer as a part of Fermi multiwavelength support program Optical V-band and R-band photometric data are used along with the polarimetric (degree of polarization (DoP) and position angle (PA)) data for the whole flaring period during the end of 2017.

2.4. Owens Valley Radio Observatory (OVRO) Data at 15 GHz

Ton 599 is also observed in the radio by OVRO (Richards et al. 2011) as a part of the Fermi monitoring program. I collected the radio data at 15 GHz during MJD 58040–58120.

3. Results and Discussions

I have analyzed the Fermi-LAT data from 2014 Jan to 2018 Jan (MJD 56751—MJD 58140). The light curve of the source, along with the photon index during these years, is shown in Figure 1. It is clear that most of the time a source is in the quiescence state where flux is very low (close to zero) and sometimes it shows a high flux state. The rise in the flux with spectral hardening was observed toward the end of 2015, with flux reaching the value $\sim 4 \times 10^{-7}$ ph cm$^{-2}$ s$^{-1}$. After 2015 Ton 599 was in more or less a quiescent state with some small fluctuations in 2016. In 2017 it started showing activity and at the end of 2017 the source underwent clear major flares. A zoomed-in view of the flare is shown in the right panel of Figure 1 and a period has been chosen just before the flare when the source is in quiescence and called it pre-flare. I studied this major flare, along with multiwavelength observations, and performed fractional variability and correlation.

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**Table 1**

| Observatory         | Obs-ID       | Exposure (ks) |
|---------------------|--------------|---------------|
| Swift-XRT/UVOT      | 00036381023  | 2.48          |
| Swift-XRT/UVOT      | 00036381024  | 2.53          |
| Swift-XRT/UVOT      | 00036381025  | 2.46          |
| Swift-XRT/UVOT      | 00036381026  | 2.47          |
| Swift-XRT/UVOT      | 00036381027  | 2.40          |
| Swift-XRT/UVOT      | 00036381028  | 1.61          |
| Swift-XRT/UVOT      | 00036381030  | 2.20          |
| Swift-XRT/UVOT      | 00036381031  | 2.27          |
| Swift-XRT/UVOT      | 00036381032  | 1.58          |
| Swift-XRT/UVOT      | 00036381033  | 1.65          |
| Swift-XRT/UVOT      | 00036381034  | 1.67          |
| Swift-XRT/UVOT      | 00036381035  | 1.99          |
| Swift-XRT/UVOT      | 00036381036  | 0.99          |
| Swift-XRT/UVOT      | 00036381037  | 1.94          |
| Swift-XRT/UVOT      | 00036381038  | 2.02          |
| Swift-XRT/UVOT      | 00036381040  | 1.92          |
| Swift-XRT/UVOT      | 00036381041  | 0.90          |
| Swift-XRT/UVOT      | 00036381042  | 0.87          |
| Swift-XRT/UVOT      | 00036381044  | 1.73          |
| Swift-XRT/UVOT      | 00036381046  | 1.84          |
| Swift-XRT/UVOT      | 00036381047  | 1.94          |
| Swift-XRT/UVOT      | 00036381048  | 1.93          |

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**Figure 1**

Left: light curve of Ton 599 from 2014 Jan to 2018 Jan. Right: zoomed-in view of the flare at the end of 2017 and a vertical green dashed line separating the two states of the source.

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3.1. Multiwavelength Light Curves

A multiwavelength light curve of Ton 599 during the flaring episode MJD 58040–MJD 58120 is shown in Figure 2. The first panel shows the 1 day binning of Fermi-LAT data. As we have seen in Figure 1 the source started showing the activity in the end of 2017. In Figure 2, the flux started rising after MJD 58040 and lasted for around 2.5 months and again got back to its quiescent state after MJD 58120. The flux started rising very slowly and it took around 20 days to become a full-fledged flare. The source showed a clear and major peak at MJD 58057.5 and the maximum flux attained is \( \sim 13 \times 10^{-7} \text{ ph cm}^{-2} \text{s}^{-1} \) from 1 day binning. After the major peak, the source was in a higher state for almost two months, with an average flux of \( 6.69 \times 10^{-9} \text{ ph cm}^{-2} \text{s}^{-1} \).

Swift-XRT/UVOT observations were carried out when the source was already in the flaring state. All the details of the observations are mentioned in Table 1. The XRT light curve for 2.0–10.0 keV are shown in the second panel of Figure 2. The source shows the higher state in X-rays and its first peak coincides with the \( \gamma \)-ray peak at MJD 58058 with a flux of \( 3.80 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1} \). The X-ray flux shows fluctuating behavior during the \( \gamma \)-ray flare and it settles down into its quiescent state as the \( \gamma \)-ray flare ends. The quiescent state flux is noted as \( 0.87 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1} \).

Ton 599 was also observed with UVOT in all six filters (\( U, B, V, W1, M2, W2 \)). The light curves for the optical (\( U, B, V \)) and UV (\( W1, M2, W2 \)) filters are shown in the third and fourth panels of Figure 2, respectively. Since Ton 599 was already flaring when \( \text{Swift} \) started looking at it, the optical and UV fluxes were already in the high state. It shows that the peak at MJD 58058 clearly coincides with the X-ray as well as the \( \gamma \)-ray first peak. At the peak optical the \( U, B, V \) fluxes are \( 5.92 \times 10^{-11}, 6.17 \times 10^{-11}, 5.81 \times 10^{-11} \), and the UV \( W1, M2, W2 \) fluxes are \( 6.19 \times 10^{-11}, 7.41 \times 10^{-11}, 6.54 \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1} \), respectively. In the light curve it is clearly seen that the source was very variable in both the optical and UV throughout the flaring period, similar to the behavior observed for the \( \gamma \)-rays. The optical and UV also follow the last peak of the \( \gamma \)-ray flare at MJD 58103. After two months of flaring, the optical and UV flux attained quiescent states with a flux close to zero at MJD 58118.

Steward V-band and R-band magnitudes are plotted in the fifth panel of Figure 2. It is found that Ton 599 is brighter in the R band than in the V band during the flare. The average magnitudes during the flare in the V and R bands are 14.9 and 14.5, respectively.

In the sixth panel of Figure 2, the radio light curve is shown at 15 GHz from OVRO. It can be clearly seen that the source is in the quiescent state in the radio, while it is flaring in the \( \gamma \)-rays and other wave bands. The radio flux started rising slowly at MJD 58060 and after almost 30 days it attained a maximum flux of 3.56 Jy at MJD 58089. The delay in the radio flare is investigated while studying the correlations among the different wave bands in Section 3.6.

DoP and PA are plotted in panels seven and eight of Figure 2. Huge variation is seen in DoP and PA during the flare. Over 10 days (MJD 58070–58080), DoP varies from 4% to 22% and PA varies from 30° to 175°. The variation in the DoP and PA can be explained by the shock-in-jet model (Marscher et al. 2008; Larionov et al. 2013; Casadio et al. 2015), in which a shock wave moving down the jet following magnetic field lines and covering only a portion of the jet’s cross section, can lead to this variation in DoP and PA during the flare.

3.2. High-energy Photons and Temporal Evolution

High-energy photons are also detected by Fermi, using the “ULTRACLEAN” class of events and a 0.5° ROI. The results are plotted in Figure 3, which shows the photon energy on the \( \gamma \)-axis and their arrival times on the \( x \)-axis. Only photons with energy greater than 10 GeV and with a probability of being greater than 99.5%, are shown in Figure 3. It is found that most of the photons have energy below 20 GeV and only a few have been detected above 20 GeV. Two 42 GeV photons were detected during the flare with probabilities of 99.7% and 99.8% at MJD 58065.7 and 58100, respectively.

The temporal evolution of the flare has been studied here and I have fitted the first peak of the flare, shown in Figure 4, with a sum of exponentials that provide the rise and decay times of the peak. The functional form of the sum of exponentials is as follows:

\[
F(t) = 2F_0 \left[ \exp \left( \frac{t - t_0}{T_r} \right) + \exp \left( \frac{t - t_0}{T_d} \right) \right]^{-1},
\]

where \( F_0 \) = flare amplitude at time \( t_0 \), \( T_r \) = rise time, and \( T_d \) = decay time (Abdo et al. 2010b). The peak shown in Figure 4 is symmetric, with rise and decay times of \( 2.22 \pm 0.14 \) and \( 2.30 \pm 0.13 \) days, respectively. The temporal fitting is also applied for other peaks found during the flare, and most of them are found to be symmetric. The symmetric time profile is expected when the cooling time of electrons \( t_{\text{cool}} \) is much smaller than the light-crossing time \( R/c \) (Chabiéberge & Ghisellini 1999), where \( R \) is the size of the emission region.

In the lower panel of Figure 4, gamma-ray fluxes are plotted with respect to the photon spectral index and a clear brighter and harder spectral behavior is seen. During this high activity, the spectral index is harder than those reported in the 3FGL catalog by Agero et al. (2015) for this source.

3.3. \( \gamma \)-Ray Emission Region

The \( \gamma \)-ray flare and the photon spectral index are plotted separately in Figure 5. A clear variation in the spectral index is seen during the period (MJD 58040–MJD 58120). In the pre-flare state (Figure 1), between MJD 57980 and MJD 58040, the source is almost in quiescence, with an average flux of \( 9.35 \times 10^{-8} \text{ ph cm}^{-2} \text{s}^{-1} \) and an average photon index of 2.38. The source experiences a full-fledged flaring episode from MJD 58054 to 58110. The average photon flux rises to \( 6.94 \times 10^{-7} \text{ ph cm}^{-2} \text{s}^{-1} \), with an average spectral index of 1.96. The maximum flux attained during the flaring episode is \( 12.63 \times 10^{-7} \text{ ph cm}^{-2} \text{s}^{-1} \) at MJD 58057.5, with a photon index of 1.81 (Figure 5). The fastest variability time from the 1 day binning light curve (Figure 5) is estimated here using the studies among different wavelength during the flaring period (MJD 58040–MJD 58120).

Gamma-ray spectral analysis is also performed; the four spectral models mentioned in Prince et al. (2018) are used to fit the gamma-ray SEDs.
The following expression:

\[ F(t_2) = F(t_1) 2^{(t_2-t_1)/t_d} \]

where \( F(t_1) \) and \( F(t_2) \) are the fluxes measured at time \( t_1 \) and \( t_2 \), respectively, and \( t_d \) represents the doubling/halving timescale of flux. A range of variability times is found, from one day to a
few days. One day is used as the fastest variability time to estimate the size of the emission region, using the relation

\[ R \approx c \, t_{\text{var}} \, \delta \, (1 + z)^{-1}, \]

where \( z = 0.72 \) and \( \delta \) is the Doppler factor. The size of the emission region is found to be \( 1.88 \times 10^{16} \text{ cm} \), for \( \delta = 12.5 \) (Zhang et al. 2002; Liodakis et al. 2017), which is close to the value (\( \delta = 15 \)) estimated by Ghisellini et al. (1998).

Detection of high-energy photons (>20 GeV) during the flare of Ton 599 puts a constraint on the location of the \( \gamma \)-ray emission region. Liu & Bai (2006) estimated the optical depth for gamma-rays with energies 10–100 GeV produced within the BLR. They found that the BLR is opaque for above 20 GeV/(1 + z) gamma-ray photons. This means that the high-energy photons seen during the flare (Figure 3) must have been emitted outside or on the outer edge of the BLR. The distance (\( R \)) of the \( \gamma \)-ray emitting blob from the central super massive black hole is also estimated using the relation \( R \sim r / \psi \), where \( r \) is the size of the \( \gamma \)-ray emitting region and \( \psi \) is the semi-aperture angle of the jet (Foschini et al. 2011). In general, \( \psi \) lies between 0.10 and 0.25 (Dermer et al. 2009; Ghisellini & Tavecchio 2009).

Figure 3. Arrival times of photons with energy >10 GeV, and probability >99.5%.

Figure 4. Left: temporal fitting of the flare’s first peak. Right: photon index plotted with photon flux to show the brighter and harder trends.

Figure 5. One day bin gamma-ray LC with photon spectral index.
The intrinsic opening angle is estimated from observations by Pushkarev et al. (2009), and they found that the average intrinsic opening angles for a sample of BL Lacs is 2.4 ± 0.6 degrees and for quasars it is 1°2 ± 0°1. In the Pushkarev et al. (2009) sample, Ton 599 is listed as J1156+295, and the intrinsic opening angle is derived as 0°58. For an opening angle 0°58, the location of the emission region is estimated as 3.24 × 10^{15} cm, which is near the boundary of the BLR (2.4 × 10^{17} and 2.98 × 10^{17} cm) dissipation region estimated by Wu et al. (2018) and Pian et al. (2005), respectively. Therefore, at the time when the photon emission of the flare reaches 42 GeV, the γ-ray emission region must have been located outside or at the edge of the BLR. Pushkarev et al. (2017) also calculated the intrinsic opening angle for 65 sources from the MOJAVE-1 sample. They found that the intrinsic opening angles for these 65 sources lie between 0°1 to 9°4, with a median of 1.3°. The range of opening angles suggests that the location of the emission region must lie between 1.88 ± 10^{17} and 2.00 ± 10^{15} cm. The location of the emission region estimated for Ton 599 (3.24 × 10^{15} cm) is found to be in this range.

### 3.4. Spectral Analysis

The spectral analysis of pre-flare and flare observed at the end of 2017 is presented in this section. Likelihood analysis is done with four different spectral models mentioned in Prince et al. (2018). The SEDs data points are fitted with four spectral models (PL, LP, PLEC, and BPL) discussed in Prince et al. (2018), the fitted parameters are presented in Table 2 and the plots are shown in Figure 6. Fitting the gamma-ray SEDs data points with these four models will help us to constraints the gamma-ray emission region. Inside the BLR, photon–photon pair production ($\gamma\gamma \rightarrow e^+e^-$) can attenuate the gamma-ray flux and as a result we expect to see a break in the gamma-ray spectrum. A break in the gamma-ray spectrum can be examined by fitting the gamma-ray SEDs data points with LP/BPL/PEC. In other cases, when the emission region is outside the BLR or within the MT, a simple PL could be a good fit to the SED data points. In Table 2, the quality of the unbinned fit is presented by the Log(likelihood) value, and the model with a large value of ΔLog(likelihood), with respect to PL, is preferred over the lower one. All three models, LP, PLEC, and BPL, are compatible with the SED data points. A clear spectral hardening is seen with increasing flux, when the source travels...
from the pre-flare to the flaring state. For PL, between the pre-flare and the flare the flux rises from 2.45 ± 0.15 to 11.00 ± 0.02 (×10−7 ph cm−2 s−1) and the spectral index (Γ) changes from 2.26 ± 0.05 to 1.94 ± 0.01. A break in the γ-ray spectrum is seen during the flare while fitting the SED with BPL. It shows a rising spectrum before break and a falling spectrum after the break. Before the break the BPL photon index Γ1 is 1.79 and the break energy Ebreak is 1.11 GeV, and after the break BPL photon index Γ2 is 2.11. This suggests that the peak of the IC mechanism probably lies in the LAT energy band and the shape of the γ-ray spectrum likely reflects the distribution of emitting electrons.

3.5. Fractional Variability (Fvar)

The variability seen at all frequencies and timescales in blazars is a completely random process. It is more prominent during the flare and the flare profile depends on the particle acceleration and energy dissipation. The amplitude of variation depends on jet parameters like magnetic field, viewing angle, particle density, and the efficiency of acceleration (Kaur & Baliyan 2018). To determine the variability amplitude in all energy bands, good quality data are required across the entire electromagnetic spectrum. Observation of Ton 599 across the entire electromagnetic spectrum makes it possible to determine the variability amplitude using the fractional root mean square (rms) variability parameter (Fvar) introduced by Edelson & Malkan (1987) and Edelson et al. (1990).

Fractional variability is used to compare the variability amplitudes across the entire electromagnetic spectrum and can be estimated using the relation given in Vaughan et al. (2003),

\[
F_{\text{var}} = \frac{S^2 - \sigma^2}{r^2},
\]

where \(\sigma^2_{\text{rms}} = S^2 - \sigma^2\) is excess variance, \(S^2\) is the sample variance, \(\sigma^2\) is the mean square uncertainty of each observation, and \(r\) is the sample mean.

The fractional variabilities for all wave bands are provided in Table 3. It is clear that the source is most variable in γ-rays and then UV, optical, and radio (at 15 GHz). Because of the large error bar in the X-ray data I could not estimate the fractional variability. The Fvar is 0.73 in γ-rays, 0.53 in the UVW2-band, 0.50 in the optical B-band, and 0.07 in the radio (at 15 GHz). It is found that Fvar increases with energy, suggesting that a large number of particles are producing the high-energy emission. Similar fractional variability behavior is also seen for other FSRQs like CTA 102, as observed by Kaur & Baliyan (2018), where they found a trend of large fractional variability toward higher energies. An increase in fractional variability is also seen in TeV blazars. Patel et al. (2018) and Sinha et al. (2016) have noted an increase in fractional variability from the radio to X-rays and a decrease in high energy from γ-rays to hard X-rays. An opposite trend was reported by Bonning et al. (2009), where variability amplitudes decreased toward shorter wavelengths (IR, optical, and UV), which suggests the presence of steady thermal emission from accretion disks.

3.6. Correlations

From Figure 2, it is very clear that the flares in γ-rays, X-rays, and the optical and UV bands are mostly correlated. The radio flare at 15 GHz was noted a few days after the γ-ray flare. Detailed studies of correlations have been done in this particular section. A cross-correlation study of flux variations in different energy bands can give an idea of whether emissions in different bands are coming from the same emission region in the jet; if not, then that indicates the relative distance between the emitting zones. I have performed the correlation studies using the discrete correlations function (zDCF) formulated by Edelson & Krolik (1988). It provides insight into emission in different energy bands. Suppose there are two discrete data sets \(a_i\) and \(b_j\) and they have standard deviation \(\sigma_a\) and \(\sigma_b\), the discrete correlations for all measured pairs \((a_i,b_j)\) are defined as

\[
\text{UDCF}_{ij} = \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sqrt{(\sigma_a^2 - e_a^2)(\sigma_b^2 - e_b^2)}},
\]

where each pair is associated with a pairwise lag \(\Delta t_{ij} = t_j - t_i\). The parameters \(e_a\) and \(e_b\) are the measurement errors associated with data sets \(a_i\) and \(b_j\), respectively. Binning the UDCF in time will directly result in DCF(τ). Averaging the UDCF over \(M\) number of pairs for which \((τ - Δτ/2) ≤ Δt_{ij} < (τ + Δτ/2),\)

\[
\text{DCF}(τ) = \frac{1}{M} \sum \text{UDCF}_{ij},
\]

and the error on DCF is defined as

\[
\text{σ}_{\text{DCF}}(τ) = \frac{1}{M - 1} \left\{ \sum \left( \text{UDCF}_{ij} - \text{DCF}(τ) \right) \right\}^{1/2}.
\]

Discrete correlation functions (DCFs) are plotted in Figure 7 for different combinations like γ-X-rays, γ-Swift M2, γ-Swift -V, and γ-OVRO (15 GHz).

In γ-X-ray correlations it is found that there is no time lag between γ-ray and X-ray emission and the maximum DCF is 0.55. The strong correlation and zero time lag between γ-rays and X-rays suggests that the emissions originated from the same region or a very close-by region.

Significant correlation has been seen in γ-ray and optical (V-band) emission with a small time lag, and the peak DCF is noted as 0.85. Similar kinds of behavior are also seen in γ-ray and UV (M2 filter) emission with a peak DCF of 0.90. Larionov et al. (2013) found a small lag in γ-ray and optical emission for S50716+71 and at the same time they also noted an emergence of radio knot K3. Finally, they concluded that all these events are co-spatial. Similar results were also noticed for CTA 102 (Larionov et al. 2016; Kaur & Baliyan 2018) during the outbursts of 2012 and 2017, with remarkable similarities in two-energy emission. Significant correlation and small time

| Waveband | Fvar | err(Fvar) |
|----------|------|----------|
| γ-ray    | 0.730| 0.019    |
| U        | 0.514| 0.008    |
| B        | 0.503| 0.007    |
| V        | 0.485| 0.009    |
| W1       | 0.537| 0.009    |
| M2       | 0.531| 0.007    |
| W2       | 0.536| 0.008    |
| OVRO (15 GHz) | 0.071| 0.004    |
lags in $\gamma$-ray and optical/UV can be explained by leptonic models, where it is assumed that the optical/UV emission is mostly the synchrotron emission from the jets and the $\gamma$-ray emission is the product of IC scattering of optical/UV photons by the relativistic electrons present in the jets. It is believed that if $\gamma$-ray emission is a product of IC scattering of soft photons off the same electrons producing the optical radiation, then its variations can be expected to be simultaneous or delayed with respect to the optical radiation, which could be the result of modeling the non-thermal flares with shocks in a jet model (Sikora et al. 2001; Sokolov et al. 2004; Sokolov & Marscher 2005). This kind of behavior has already been seen in a few other blazars like 4C 38.42 (Raiteri 2012), 3C 345 (Schinzel et al. 2012), and 3C 454.3 (Bonning et al. 2009; Vercellone 2010; Raiteri et al. 2011). Interestingly, the opposite behavior is also seen in a few blazars: $\gamma$-rays leading with optical radiation, e.g., FSRQ PKS 1510–089 (Abdo et al. 2010a; D’Ammando et al. 2011) and in 3C 279 (Hayasida et al. 2012). This can be explained by considering fast decay in the energy density of external seed photons, which are responsible for the IC emission along the jet axis, and comparing to the decay in magnetic field energy density, which is responsible for the synchrotron emission.

A complex correlation between gamma-ray and optical radiation has also been addressed by Marscher (2014) by considering the effect of turbulence in the jets. Since the magnetic field is embedded in the jets, turbulence in jets can cause turbulent magnetic fields, which will affect mostly the synchrotron emission, and can lead to optical variability; however, a turbulent magnetic field cannot affect the $\gamma$-ray radiation. In other words, a $\gamma$-ray emission region could be better aligned along the line of sight, which can lead to a higher Doppler factor of high-energy flux, compared to the optical emitting region.

A correlation study between $\gamma$-rays and IR/optical/UV has also been done before for other blazars, e.g., Bonning et al. (2009), Vercellone et al. (2009), Raiteri et al. (2011), Jorstad et al. (2013), Larionov et al. (2013), and Cohen et al. (2014), where they suggested the co-spatial origin of $\gamma$-ray and IR/optical/UV emission. It is also possible that the nature of correlation between two emitted fluxes changes with epochs and can be viewed as the product of different processes and/or different particle populations being involved in the high activity.

The right plot of the lower panel of Figure 7 shows the correlation between $\gamma$-rays and radio (OVRO; 15 GHz). A lag of 27 days in the radio emission at 15 GHz is noted with a DCF peak of 0.84. Since the $\gamma$-ray and optical emission is well correlated with a small time lag, this suggests that radio emission also lags with the optical by the same amount as with the $\gamma$-rays.

Time delay uncovered by DCF analysis can reveal the relative locations of the emission regions at different wave bands, which depend on the physics of the jets and high-energy

![Figure 7. DCF is plotted for all four combinations: $\gamma$-X-ray, $\gamma$-Swift M2, $\gamma$-Swift-V, $\gamma$-OVRO(15 GHz) from left to right, for the flare Ton 599 at the end of 2017.](image-url)
radiation mechanisms. The lag of 27 days in the radio emission with γ-rays/optical clearly indicates that these two emissions are from two different locations in the jets. The observed time lag between the γ-rays and radio can be used to determine the distance between two emitting regions using the equation given in Fuhrmann et al. (2014):

$$\Delta r_{\gamma,r} = \frac{\beta_{\text{app}} c \Delta t}{\sin \theta},$$

(9)

where $\theta$ = viewing angle of the source, $\beta_{\text{app}}$ = apparent jet speed, and $\Delta t$ = observed time lag. Using $\Delta t = 27$ days, and $\theta = 4\degree.3$, $\beta_{\text{app}} = 16.13$ from Liodakis et al. (2017), I found $\Delta r_{\gamma,r} \sim 5$ pc. This means the radio emitting region is located far away from the AGN central engine. It is possible that the high energy and radio emission region have different apparent speeds, as well as different viewing angles, which further implies that they have different Doppler factors. A similar situation is also observed by Raiteri & Villata (2013) for BL Lacertae, where they found a lag of 120–150 days between γ-rays/optical to radio and the distance between two emitting regions to be in a range of 6.5–8.2 pc. Rani et al. (2014) found a time lag of 82 days between γ-ray and radio emission for S5 0716+714; the distance between two emission regions is estimated to be in the range of 2.9–4.4 pc (Rani et al. 2015), for $\beta_{\text{app}} = 6–8$ c and viewing angle ($\theta$) = $6\degree–9\degree$.

Alternatively, flares that are delayed and appear late at lower frequencies can be seen as a clear indication of opacity effects, in the context of a shock-in-jet model (Marscher & Gear 1985; Valtaoja et al. 1992), due to synchrotron self-absorption. A shock is formed close to the core where the jet is optically thick to radio frequencies, but transparent to high energy, and a component at the core of the jet producing an optical/γ-ray flare propagates along the jets, and after some time the jet becomes optically thin to detect the radio flare.

4. Conclusions

At the end of 2017 blazar Ton 599 went into a long flaring episode spanning the entire electromagnetic spectrum. Flaring was first reported in γ-rays, followed by the other wave bands. A long delay in the radio flare was observed by OVRO at 15 GHz as seen from Figure 2. Ton 599 was not very variable in X-rays but its variability can be seen in γ-rays and the UV/optical. In γ-rays, during the flaring episode a maximum flux of 12.63 × 10^{-7} was noticed with a photon index of 1.81 and a clear brighter and harder spectral behavior is seen (Figure 4). Large variations in DoP and PA are seen during the flaring period, which can be explained by a shock-in-jet model. Almost all the peaks of the flare show a symmetric profile. The rise and decay times of one of the peaks are found to be 2.22 ± 0.14 and 2.30 ± 0.13 days. Two 42 GeV photons are detected during the flaring period with probabilities of 99.7% and 99.8%. For the γ-rays, the size of the emission region is estimated to be 1.88 × 10^{16} cm using 1 day as the fastest variability time, and the location of the emission region is found to be at the outer edge of the BLR. The gamma-ray SED for the pre-flare and flare are fitted with four spectral models: PL, LP, PLEC, and BPL. For the flare, PLEC gives a better fit to the SED data points over LP and BPL. A break in the γ-ray spectrum at 1.11 GeV is seen, which suggests the peak of the IC mechanism lies in the LAT energy band and the shape of the photon spectrum likely reflects the distribution of emitting electrons. Ton 599 has shown a trend of high variability with increasing energy. A strong correlation has been seen between γ-X-rays, γ-UV, γ-optical, and γ-radio (15 GHz). A good correlation with a lag of a few days suggests the γ-ray and optical/UV are co-spatial. On the other hand, a lag of 27 days has been observed between γ-ray and radio (15 GHz) emission, suggesting the presence of two different emission zones. The separation between these two emission regions is estimated to be ∼5 pc. Detailed gamma and radio observations are needed to probe the two different emission regions and a multi-wavelength SED analysis is also required to place better constraints on the different emission mechanisms that are taking place in the jets of blazar Ton 599.

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