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Investigating the Innermost Jet Structures of Blazar S5 0716+714 Using Uniquely Dense Intra-day Photo-polarimetric Observations

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Abstract: The sub-hour timescale variability commonly observed in blazars—widely known as *intra-day* or *microvariability*—has been extensively studied in optical photo-polarimetric bands over the past 25–30 years. In addition, there have been comprehensive theoretical discussions on the topic, with various models and scenarios proposed; however, the phenomenon still remains relatively poorly understood. Here we present the summary of our optical microvariability studies over the past few years based on multi-frequency photo-polarimetric Whole Earth Blazar Telescope (WEBT) observation campaigns. The primary objective of the study was to explore the characteristics of the source microvariability on timescales of a few minutes to a few days using exceptionally dense photo-polarimetric observations. The results show that the source often displays fast variability with an amplitude as large as 0.3 mag within a few hours, as well as color variability on similar time scales often characterized by "bluer-when-brighter" trend. Similarly, the correlation between variability in flux and polarization appears to depend upon the configuration of the optical polarization angle relative to the positional angle of the innermost radio core of the jet. Other fascinating observations include a sudden and temporary disappearance in the observed variability lasting for $\sim$6 h. In addition, the modeling of individual *microflares* strongly suggests that the phenomenon of microvariability can be best explained by convolved emission from compact emission sites distributed stochastically in the turbulent jet. Besides, analysis of some of the well resolved micro-flares exhibiting high degrees of polarization points towards a complex magnetic geometry pervading the jet with the possible presence of small-scale regions of highly ordered and enhanced magnetic field similar to so-called "magnetic islands".

Keywords: particle acceleration; turbulence; polarization; radiation mechanisms: non-thermal; galaxies: active; BL Lacertae objects: individual (S5 0716+714); galaxies: jets

1. Introduction

Blazars define a subclass of radio galaxies exhibiting some extreme properties, such as high luminosity, rapid flux variability across the electromagnetic spectrum, highly polarized non-thermal emission, etc. These extreme properties are believed to be the result of Doppler boosting of the emission taking place in the relativistic outflows which emanate from the region near black hole and travel nearly along the line-of-sight (e.g., [1]). Rapid variability on timescales ranging from a few minutes up to a few days—widely known as microvariability or intra-day or intra-night variability—are a commonly observed phenomenon in blazars, and it is considered to originate close to the central engine [2]. The understanding of the physical conditions leading to the observed rapid variability, along with other active galactic nuclei (AGN) processes, might be considered key to the further understanding of galactic evolution and thereby cosmic evolution in general. For these reasons, multifrequency microvariability studies could be one of the most relevant tools that can offer important insight into the physical conditions prevailing in the innermost regions of blazar jets, including the nature of the dominant particle acceleration and energy dissipation mechanism, magnetic field geometry, jet content, etc. There have been numerous attempts to model the phenomenon by relating the sources of the microvariability to a wide range of possible physical processes occurring either in the accretion disk and/or in the jet; the various scenarios include emission sites revolving around the supermassive black hole, various magnetohydrodynamic instabilities, shocks traveling down the turbulent jet, projection effects due to jet orientation (such as [2–4]). However, the exact details of the underlying processes are still under debate. In such context, detailed photo-polarimetric variability study programs designed to address specific facets of the issue could play an important role in revealing the underlying physics.

BL Lac S5 0716+714 is one of the best-studied blazars (redshift; $z = 0.31 \pm 0.08$) observable by the most of the current instruments operating across wide range of electromagnetic frequencies, including TeV instruments. Being a bright and highly variable source with nearly 100% duty cycle, it has been a favourite target for a large number of multifrequency studies. At radio frequencies, it is classified as a flat-spectrum, intra-day variable, and superluminal source. The radio observations on milliarc-second scales reveal jet features traveling with apparent speeds reaching up to $37c$ [5–7], and also a very high brightness temperature of the compact core [8]. The X-ray spectrum of the continuum emission appears to have a concave shape, displaying a transition from the synchrotron to the inverse-Compton emission components (see e.g., [9,10]). S5 0716+714 has also been detected by γ-ray instruments such as the *Compton* EGRET, AGILE, *Fermi*-LAT satellites and also by the MAGIC Cherenkov telescope (see, e.g., [11–14] and references therein). In particular, there have been numerous optical microvariability studies of S5 0716+714 which reported many interesting results, including achromatic behavior, red noise-type power spectra, and in some cases, correlation between flux and polarization degree [15–18]. In this proceeding, we present the summary of our optical microvariability studies on S5 0716+714, over the past few years, based on multifrequency photo-polarimetric Whole Earth Blazar Telescope (WEBT) [18,19] observation campaigns in 2009 and 2014 (the data collected by the WEBT Collaboration are stored in the WEBT archive; for questions regarding their availability, please contact the WEBT President Massimo Villata: `villata@oato.inaf.it`).

2. Multi-Site Extended WEBT Campaigns

An ideal microvariability study program requires continuous monitoring of the target source for an extended period of time, usually a few days with a sampling rate of a few minutes. The statistical analysis of the detailed changes in flux, spectra, and polarization properties allows us to characterize the short time scale variability properties, leading to a robust conclusion on the source of the microvariations. As a broader scheme, when we include a large number of sources in the program, we might arrive at a true statistical characterization of the underlying processes.

Most of the previous optical intra-day monitoring programs, on the other hand, are associated with individual observing sites; and hence they are either limited to the length of the astronomical night, (typically 6–8 h), or they are a collection of the many nightly observations interrupted by the following daylight. As a result, an uninterrupted view of the gradual evolution of the source is mostly missed. In this backdrop, with a main objective of studying the variability properties in this rather unexplored time domain, we planned and organized two multi-site coordinated observation campaigns through the Whole Earth Blazar Telescope (WEBT) consortium: WEBT 2009 and WEBT 2014. Below, we summarize these campaigns, along with the main results obtained from each of them.

2.1. Multi-Site Campaign on S5 0716+714 in 2009 and Results

The first of the WEBT observation campaigns on blazar 0716+714 took place during 23–26 February 2009. The campaign, involving 19 observatories located at various longitudes around the globe, resulted in exceptionally dense observations, mainly in R-band, spanning ∼72 h with a few minor interruptions. The resulting light curves(presented in the top left panel of Figure 1) were subjected to various analysis methods, including time series analysis, noise analysis, etc. The temporal features in the light curves were then modeled in the framework of the shock-in-jet scenario, with the assumption that the shock traveling down the turbulent jet lights up the individual density-enhanced (compact) sites of varying sizes lying at various distances from the central engine. Consequently, by using a specific set of parameters, the pulse emission from such individual emission sites could be convolved to reproduce the temporal features in the light curve. The details of the formulation of particle acceleration by the relativistic shock and the subsequent synchrotron emission by the energetic particles are discussed in [20], and the modeling procedure with the relevant physical parameters is explained in [19]. The main results yielded by the modeling include the size distribution of the compact emission sites and the corresponding injection parameters required for the enhanced synchrotron emission. The distribution of the compact emission sites(as shown in the bottom left panel of Figure 1) seems to prefer a distribution with emission sites of relatively small sizes—typically $\lesssim$60 astronomical units (AU). This is consistent with the turbulent jet scenario, in which the larger regions are likely to get disrupted or disintegrated into smaller ones due to turbulence. On the other hand, while the particle injection rate does not define any preferential distribution, there seems to be some discreteness in the observed injection rate(as marked by the magenta vertical lines in the bottom right panel of Figure 1), which, however, might be linked to the discreteness in the size of the emission sites.

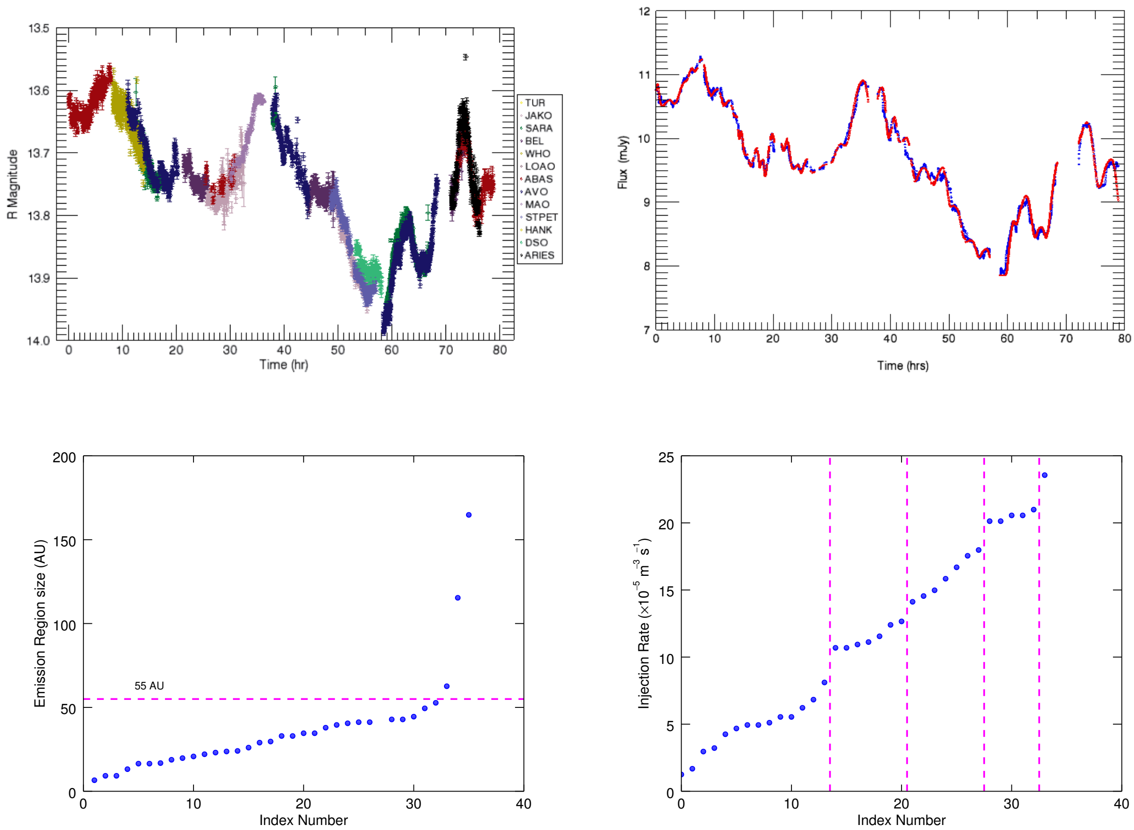

Figure 1. (**Top left**): Light curves in R band resulting from WEBT campaign in 2009. Light curves in various colors represent observations from corresponding observatories listed on the plot; (**Top right**): Smoothed light curve (blue) and model (red); (**Bottom left**): Distribution of the emission region sizes; (**Bottom right**): Distribution of the Injection rate [19].

2.2. Multi-Site Photo-Polarimetric Campaign on S5 0716+714 in 2014 and Results

The WEBT 2009 observation campaign resulted in detailed light curves with unprecedentedly dense observations that allowed one to constrain the (sub-)structures of the innermost regions of the jet. However, because the campaign was primarily focused on single photometric band (R-band) observations, spectral and photometric information were missing to further constrain the jet processes. Therefore, to extend the study to include the simultaneous multi-band photo-polarimetric behavior of the source (and at the same time being encouraged by the outstanding participation by the observers in the previous campaign), we conducted a similar WEBT campaign in early March 2014. The campaign, lasting for five consecutive days (2–6 March), resulted in observations perfectly suited for an in-depth analysis of microvariability in the source. The data gathered during the period are shown in Figure 2; the vertical lines on Figure 2 mark the microflares we considered for the detailed analysis. The list of the participating observatories and other details on the observational campaign are described in [18].

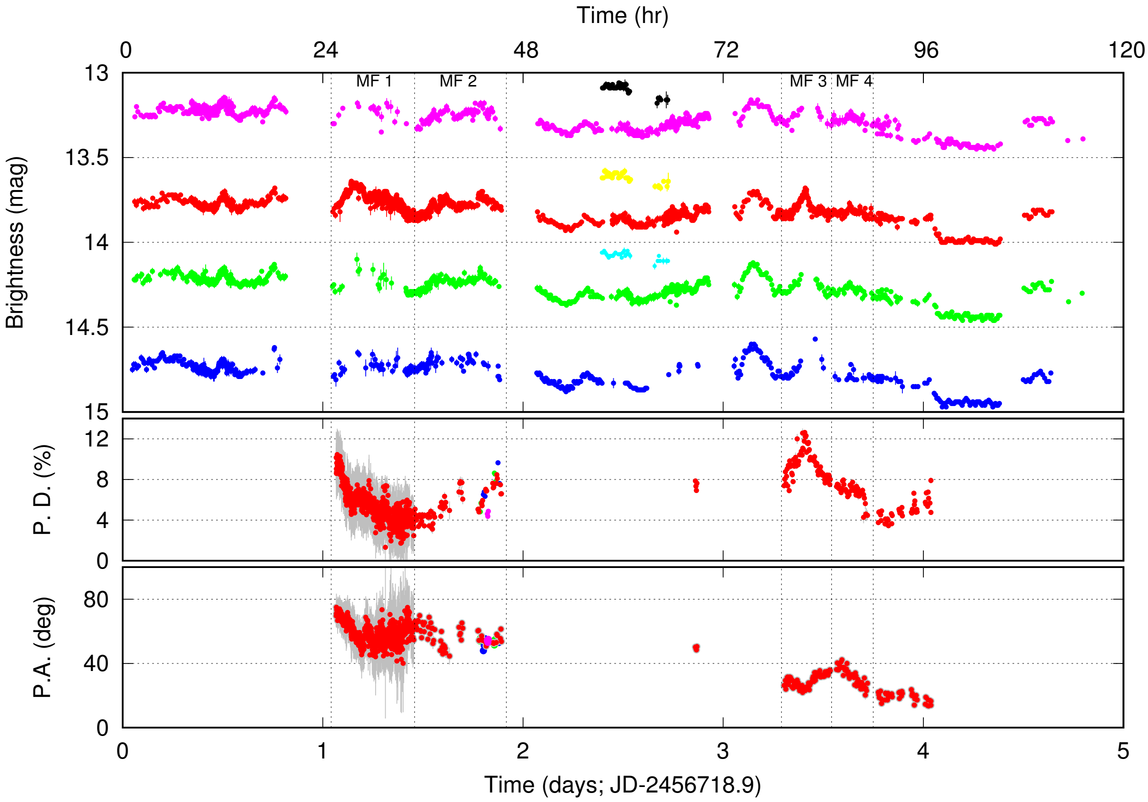

Figure 2. (**Top**): WEBT light curves in optical bands B (blue), V (green), R (red), I (magenta), J (black), H (yellow), and K (cyan); (**Middle**): Polarization degree (P.D.) in bands R (red) and B (blue); (**Bottom**): Polarization angle (P.A.) in bands R (red) and B (blue) [18].

As explained earlier, one of the primary motivations of these extended campaigns was to probe the temporal behavior of the source in the rather-unexplored time domain spanning from more than 12 h up to few days, without major interruption in between. For this reason, we searched for the possible characteristic (dominant) timescale present in the light curve by carrying out a Lomb–Scargle periodogram. The analysis revealed two prominent peaks at $\sim$3 and $\sim$5 h, as seen in the left panel of Figure 3. The significance of these peaks was estimated by using a large number of simulated light curves of red-noise type assigned with the same mean, standard deviation, and sampling as that of the observed light curve. The best-fit spectral power-law slope used for the simulations was estimated by following the power response method described in [21]. Although the peaks are seen above the 99% confidence contour (red), there are indications that these might not represent a significant departure from the underlying red-noise behavior of blazar variability.

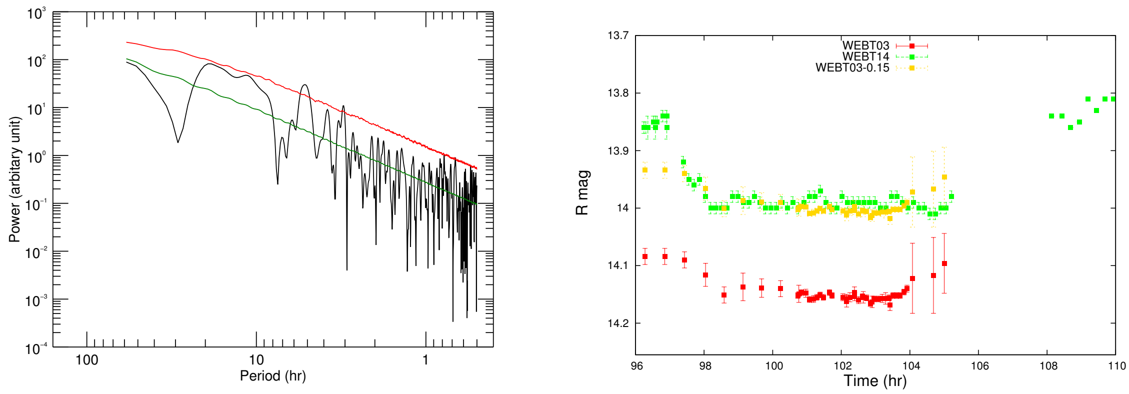

Figure 3. (**Left**): Lomb–Scargle periodogram (black) with simulated average periodogram (green) and 99% confidence level (red); (**Right**): A ∼6 h plateau of diminished variability seen in the light curve (green) and a similar episode from WEBT 2003 (red, yellow) [18].

It is interesting to note that around the 97th hour, the flux level in all four bands went down by a few tenths of a magnitude and remained almost constant for ∼6 h, creating a "plateau" in the light curves (refer to Figure 2), without appreciable change in the spectra, as shown by the right panel of Figure 4. In particular, in the R-band, the flux dropped by 0.15 mag and remained at a low flux level of ∼14.0 mag, as represented in the right panel of Figure 3. The figure also shows (in the red) a strikingly similar episode witnessed during the similar WEBT campaign in 2003 (see [8]).

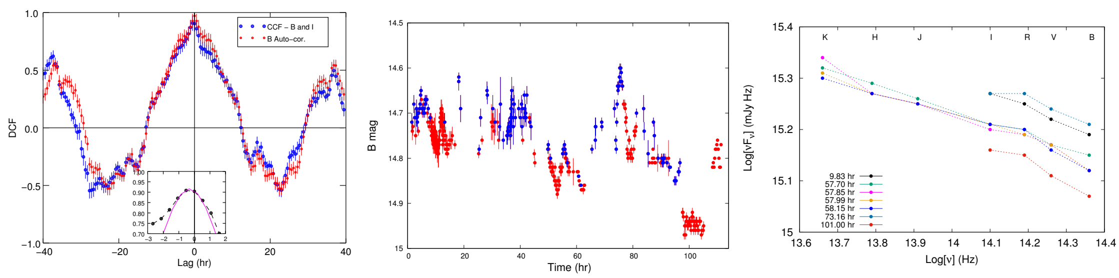

Figure 4. (**Left**): Discrete correlation function between B- and I-band light curves (blue) and auto-correlation function for B-band light curve (red). A positive lag indicates leading of B-band emission; (**Middle**): B-band light curve with blue color representing smaller B-I value (i.e., *bluer* color); (**Right**): The blazar spectra at the times listed on the plot [18].

The variability in the light curves of all four bands seemed to track well throughout the period. A high correlation between the B- and I-band light curves, with a small possible lead of B-band over the I-band variability by ∼30 min can be seen in the left panel of Figure 4. For the source, a similar inter-band lag of ∼11 min has also been reported previously (see [22]). In addition, the source also exhibited color (B-V) variability of an amplitude of ∼0.15 mag, displaying the characteristic "bluer-when-brighter" trend claimed for S5 0716+714 already in the past (e.g., [12,22,23]), and found in other BL Lacs as well (e.g., [24,25]). The trend observed during the period is represented in the middle panel of Figure 4, which shows the color-coded B-band light curve for the source: the blue symbols correspond to bluer color, defined by the lower 30 percentile B-I color value, and red symbols to larger values of B-I (i.e., redder color). In the figure, it is seen that flux maxima in the light curve appear bluer than flux minima.

During the campaign, densely sampled R-band polarimetric observations were obtained in two continuous sets (Epoch I and Epoch II)—20 and 22 h long in duration, respectively. The correlation study between flux and the polarization degree (PD), employing the discrete correlation function method by [26], revealed a high correlation between them: with a ∼2 h lead of PD for Epoch I and a zero lead/lag for Epoch II, as shown in the left and the right panel of Figure 5, respectively. Further, some of the well-resolved microflares were modeled by decomposing the flaring component from the relatively slowly changing background component in the light curve. The details of the modeling procedure, and the results for one of the distinctly resolved microflares are discussed in [15]. The results showed that such microflares are highly polarized (up to 60%) in general, with a flux-polarization anti-correlation trend, as shown in Figure 6.

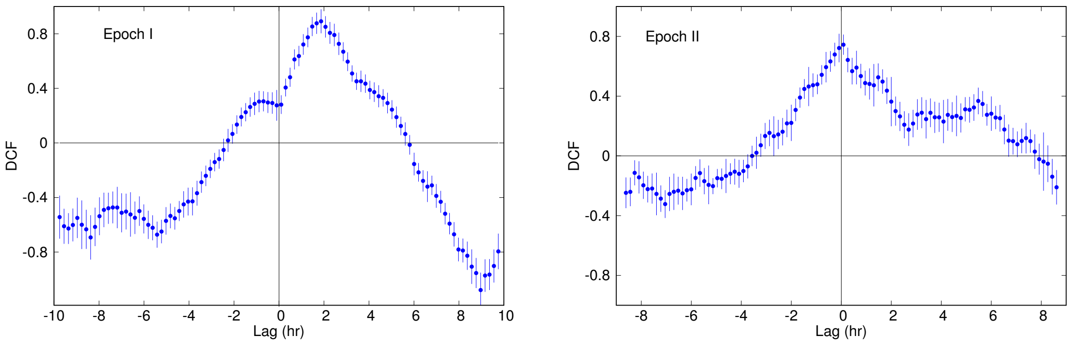

Figure 5. (*Left*): Discrete correlation function (DCF) between flux and polarization degree for Epoch I; (*Right*): Discrete correlation function between flux and polarization degree for Epoch II [18].

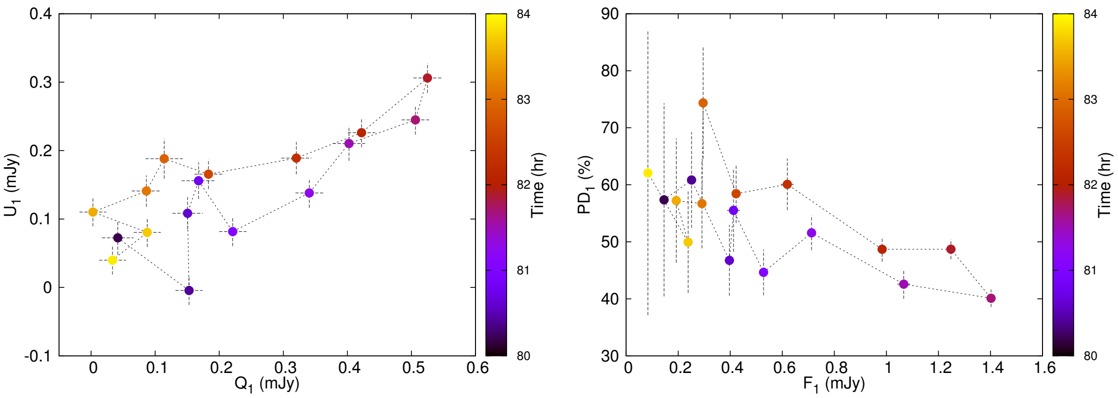

Figure 6. (*Left*): Evolution of Stokes' parameter, Q and U, for the flare component; (*Right*): Flux-PD plot for the flare component [18].

3. Discussion and Conclusions

Both of the WEBT campaigns were conducted within a scheme framed to study the statistical properties and the temporal behavior of the optical variability in the blazar on timescales from a few minutes up to a few days in great detail. In particular, the studies were motivated by the search for a possible blazar periodicity in previously-unexplored or hardly-explored time domains. In both the campaigns, the analyses performed on the resulting exceptionally-dense observations led to a number of interesting results, pointing to some important conclusions about the nature of microvariability in the source (summarized below).

To investigate the statistical properties of rapid blazar variability of the source over the given timescales, and to search for a possible characteristic timescale present in the light curve, a thorough timing analysis was performed. The results indicate that on timescales of a few minutes to a few days, the variability properties closely resemble the red noise type consistent with a random-walk process. Although hints for quasi-periodic oscillations in the blazar light curve at timescales of $\sim$3 h and $\sim$5 h were detected, the in-depth analysis involving Monte Carlo simulations indicated that the significance may not lie far from a pure red-noise power spectrum. Similarly, the modeling on the WEBT 2009 light curve suggests that the observed optical flux is produced in compact emission sites within the turbulent outflow, with a range of sizes and distances from the core, and these compact emission sites may be identified with either turbulent cells, merging magnetic islands related to magnetic reconnection, or small-scale internal shocks. A high correlation between B- and I-band emission implies that the radiations at both frequencies are emitted by a co-spatial beam of electrons at the single emission site, whereas the characteristic bluer-when-brighter trend may be explained by assuming an underlying steady electron energy spectrum of a concave shape, superimposed on a strongly fluctuating magnetic field. In such a scenario, the electrons with lower energies $E_e \propto 1/\sqrt{B'}$ in an amplified magnetic field intensity B' would produce enhanced synchrotron emission at a given observed frequency, representing, in the present context, microflares with bluer color (flatter spectra). On the other hand, the 6 h plateau seen both in the 2014 and the 2003 campaigns can be used to place a constraint on the upper limit for the S5 0716+714 black hole mass, which can be estimated as $\mathcal{M} \simeq 4 \times 10^9 M_\odot$ for a maximally spinning supermassive black hole (SMBH) ($r_{isco} \simeq r_g$), and $\mathcal{M} \simeq 3 \times 10^8 M_\odot$ for very low spin values ($r_{isco} \simeq 6\, r_g$) (For details on the calculations, see [18]). The study of the polarization properties revealed that any coherent correlation between flux and polarization properties (e.g., PD leading the total flux changes, hysteresis in the PD-F plane) might depend on the particular configuration of the orientation of ambient magnetic field in relation to the direction of the radio core of the jet. In addition, microflares with highly-polarized emission suggest relatively isolated regions of highly-ordered magnetic field in the comoving frame of the jet.

To sum up, the phenomenon of microvariability/intra-day variability most likely results from the innermost regions of the inhomogeneous turbulent blazar jet, where some of the well-resolved particle or/and magnetic field-enhanced regions could be distributed stochastically. These regions—when energized by a particle acceleration mechanism (such as turbulence or magnetic reconnection)—dissipate the energy in the form of non-thermal emission. To distinguish among various possible particle acceleration processes shaping the rapid blazar variability, a further systematic investigation of polarization properties and statistics (duty cycle, cell size distribution, etc.) may be required.

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