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Multiband study of bright blazars sample with SAO RAS telescopes

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We present some results of multiband study of variability of a bright blazars sample. The collaborative studies using optical and radio telescopes of Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS), Crimean Astrophysical Observatory (CrAO RAS) and Institute of Applied Astronomy (IAA RAS) revealed numerous manifestations of flux variation on various timescales: from hours to years. The radio 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 telescopes. Additionally we 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 4FGL-DR2 catalogue. A significant correlation between the radio, optical, and γ-ray bands is found for all presented blazars. The discovered properties of multi wavelength variability suggest that the mechanisms dominating the radio–γ-ray variations are not substantially different. The detected quasi-periodic oscillations for blazars AO 0235+164 and Ton 599 of are tentative, as the time span of the observations includes fewer than 3-4 full cycles for all the data sets. These results as well as hypothesis about double supermassive black holes in their centres should be interpreted with caution, given the limited number of observed cycles and the influence of red noise.

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1. Introduction

Active Galactic Nuclei (AGN) lie within the focus of interest of astrophysicists since discovery of the first quasar – 3C273 in 1963 by M. Schmidt. The most massive studies of AGNs had been conducted since the end of the 80s – the beginning of the 90s, as they were the most distant objects in the Universe with huge energy release in a wide spectral range: from γ-radiation to radio waves. It is well known that the AGN phenomenon is caused by the presence of a supermassive black hole with a mass from few million to few billion solar masses in centre of massive galaxy. The accretion disk around the central engine as well as relativistic jet are sources of powerful ionizing radiation across all electromagnetic spectrum.

Blazars are a specific type of AGNs known for their relativistic jets aligned with the observer's line of sight, which causes the radiation to be highly Doppler boosted ([1]). The fluxes over various ranges of frequencies, polarization and spectra of blazars are strongly variable from radio to γ-rays on different time-scales, ranging from minutes to several decades (e.g., [2] and references therein).

Until the end of the first decade of the new century, AGNs kept record parameters among all sources in the Universe, afterwards they were partially superseded by γ-ray bursts, which had been the most distant known objects for some years (for example, GRB090423 with redshift=8.2 [3]). But now the most distant sources are extremely young galaxies with $z = 11$–13, which are revealing by JWST (see, for example,[4]).

Within the last two decades AGNs have become the objects of the main interest in extragalactic astronomy as a possible source of high-energetic neutrinos.

2. Studies of bright blazars in SAO RAS and Crimean Astrophysical Observatory between 2000 and 2020

A long-term optical monitoring campaign was initiated at the SAO RAS 1-meter reflector by N. S. Kardashev with colleagues in 2001 and had been continuing for about 20 years. Some observations were accompanied by simultaneous radio observations with the 22-m radio telescope of the Crimean Astrophysical Observatory at 22.2 and 36.8 GHz frequencies. The initial observing sample included near one dozen blazars, which were distributed over the northern hemisphere and selected by their radio flux ($\sim$1 Jy).

The observations with the optical telescope Zeiss-1000 were conducted with a CCD photometer in the Cassegrain focus, which is equipped with a 2048×2048 pixels back-illuminated E2V chip CCD 42-40 (1 pixel corresponds to 0.23" on sky). Details of the instrumental setup are described in [5].

We obtained the radio and optical light curves for these blazars and detected some short-duration flares in the R band for blazars [HB89] 0235+164 and [HB89] 0954+658 in 2001–2003 [6] and for the blazar DA 55 and radio quasar 2134+004 in 2005–2006 [7]. Typical brightness variations reached 0.2 mags over an interval of about 15 minutes. The radio flux variations for DA 55 and 2134+004 reached 1.5 Jy over about 15 minutes, and that for 2145+067 reached 2 Jy over 2 hours. For other objects from the sample we detected chaotic variation of radio flux, but without any optical features. Overall, we did not detect significant correlation between the radiation in the optical and radio bands in these observations.

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2.1 Behavior of the blazar S4 0954+658 in 2014–2015

The blazar S4 0954+658 is among the most interesting objects in our sample. This is a BL Lac object showing a smooth continuum and the absence of any appreciable emission or absorption features. It was found in radio surveys of the 70s, being brighter than 1 Jy at the 6 cm wavelength, and later was identified with an optical object (see [8] and references therein). The blazar was also very active in the γ-ray range. As our own and literature data showed, its brightness was quite unstable, especially in 2011. The maximal variations in the B band reached 2 mags, and the short-time brightness variations reached several tenths of a magnitude over several hours, thus confirming the activity of S4 0954+658 on both short and long-time scales. Evidence for correlation between flare events in the optical and radio bands in short time intervals has been noted, with a time lag 7−14 days.

Within the course of the photometrical monitoring of this source with the SAO RAS 1-meter reflector, we detected powerful optical flares between the end of 2014 and the beginning of 2015: the flux in the R band reached ~ 13.3 mags (~ 15 mJy) from the end of December to February 12, 2015, as it shown in Fig. 1 (see [9, 10]). Joint analysis of the radio data in the range from 4.8 to 36.8 GHz with the optical and near-infrared data in broadband filters allowed us to make a preliminary conclusion about the parameters of the binary supermassive black hole in the center of the blazar ([8]).

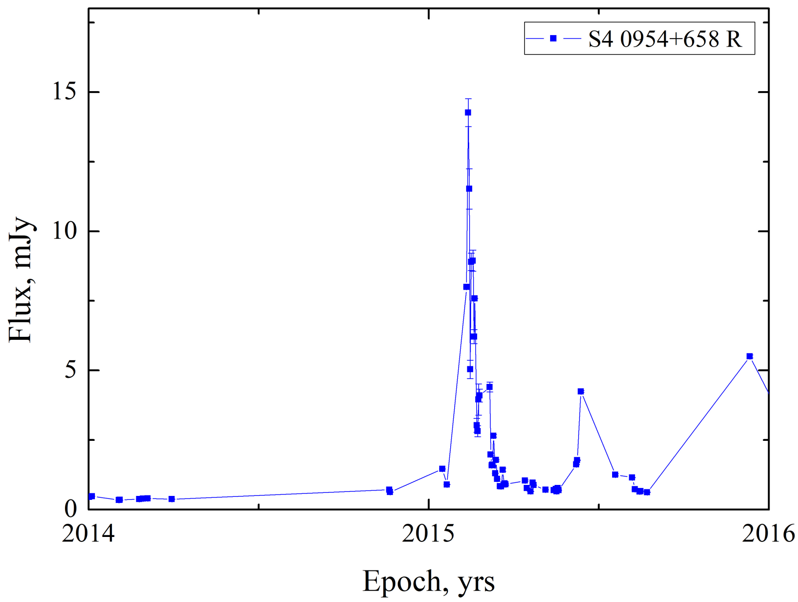

Figure 1: The light curve of blazar S4 0954+658 during 2014-2015.

2.2 An unique multiple flare of the quasar TXS 0917+624 in 2017–2018

The quasar TXS 0917+624 have been identified with a powerful 1 Jy flat-spectrum radio source [12]. Its detailed studies with the 100 meter Bonn radio telescope in the 80–90s gave some indications of significant variation of radio flux on the day and intraday scales. The source was generally found to be strongly variable with the amplitude variation at a 10-–15% level and on time scales in the range of 0.8-–1.6 days. Surprisingly, the data taken with 100 meter Bonn radio telescope in 2000–2001 demonstrated the absolute disappearing of intraday variation at levels above few tenth parts of a percent ([13]).

Only our own measurements of its brightness were published at the time [6]. Unfortunately, within that time interval TXS 0917+624 have been in a low activity stage: its brightness (about 20 mag in the R band) did not allow us to make any conclusion about the variation state. The photometrical monitoring with the 1-m reflector, nevertheless, was prolonged. We were lucky: after 15 years of flux fluctuation between 18 and 19 mags, the brightness of the quasar at the end of 2016 exceeded the 18 mag level, and it became brighter (see Fig. 2).

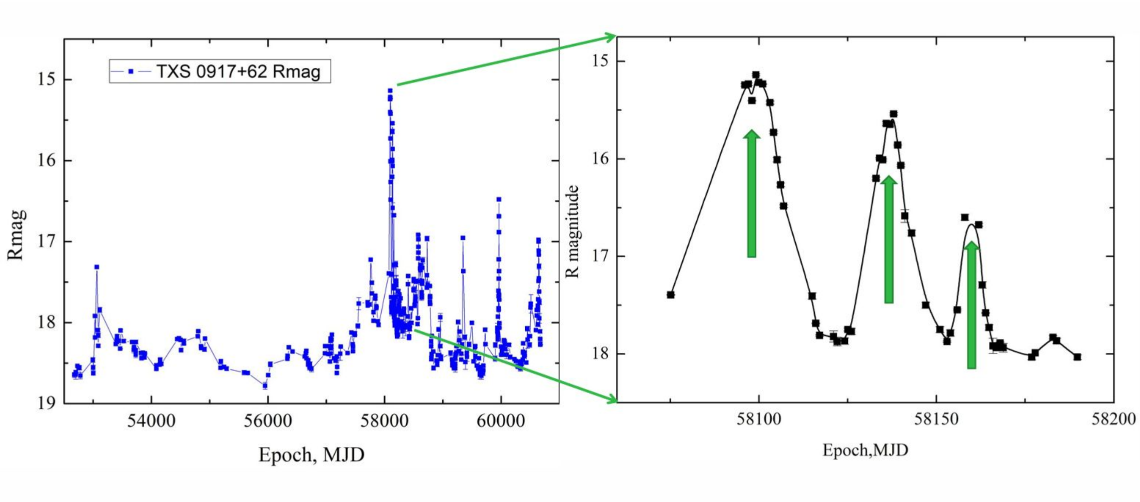

Figure 2: A unique multiple flare of the QSO TXS 0917+624 during December 2017 – February 2018. The left graph presents total R band light curve in time interval 2004-2025. The right graph presents fragment of light curve corresponding to epoch of brightest flares, marked by arrows.

The most interesting phenomenon dates back to the border between 2017 and 2018. Starting from the $R \sim 17.5$ mag level in mid-November, the flux of the quasar increased up to $R \sim 15.2$ mag within ~ 30 days. After the maximum near December 15th, the object started to dim and within 20 days returned to the level of $R \sim 18.0$ mag. Since a quiet state within 10 days, the flares of TXS0917+624 repeated twice but with lower amplitudes and shorter durations (2.2 and 1.5 mags, respectively). The distance between the peaks decreased sequentially from $\sim$35 to $\sim$25 days.

3. The last multi-wavelength studies of some blazars

The additional possibilities in AGN studies appeared at SAO RAS after setting into operation of the complex of 0.5-m telescopes in 2019–2020. All these instruments aimed at providing broadband photometric investigations across one-degree fields. The main characteristics of the instrumental complex of an AS-500/2 reflector are presented in [14]. In order to improve the system parameters, we have installed a smaller but more sensitive detector in 2023 July: the back-illuminated electron-multiplying CCD camera Andor IXon$^{\mathrm{EM}}$+897 with 512×512 pixels chip.

Since 2023 we reported some papers with results of multi-wavelength studies of some blazars - $S4\,0954+658$, AO 0235+164, Ton 599 ([5, 15, 16]) based on the radio-to-γ-ray data covering a period from late 90th to last years. The radio data are represented by the measurements from the RATAN-600 (SAO RAS), RT-32 (IAA RAS) and RT-22 (CrAO RAS) telescopes. The optical measurements were collected with the SAO RAS 1-m and 0.5-m reflectors. The archive data at 230 GHz from the Submillimeter Array and the γ-ray data from the Fermi-LAT mission were used.

The blazar $S4\,0954+658$ ([5]) demonstrated broadband activity with the variability amplitude of flux densities up to 100% in the optical and radio domains. In the period of 2015–2023 the blazar had been showing the historically highest activity in the radio wavelengths, and we detected multiple radio flares of varying amplitude and duration. The large flares last on average from 0.3 to 1 year at 22–36.8 GHz. The optical flares are shorter and last 7–50 days. In the most active epoch of 2015–2023 the characteristic time scale of variation at 5–22 GHz is about 100 days and about 1000 days for the state with lower activity in 2009–2015. We found a general correlation between the optical, radio, and γ-ray flux variations, suggesting that we observe the same photon population from different emission regions. We estimated linear size R_{lin} of these regions as 0.5-2 pc, following the expression

$$R_{lin} = \frac{c * t_{obs} * \delta}{(1+z)}, \tag{1}$$

where c - light speed, t_{obs} - time delay between high- and low-energy emission (~100 days), δ - Doppler factor, lying between 6 and 35.

The comprehensive analysis of multi-wavelength data for blazar AO 0235+164 ([15]) revealed a significant correlation between different spectral bands with time delays up to 1.7 yrs. The relation between time delay and frequency is well described by a linear law. The revealed features of multi wavelength variability for the quiet period and for flaring states suggest that the mechanisms dominating the radio–γ-ray variations of AO 0235+164 are not substantially different. The blazar shows a total variability period of ~6 yrs for all wavelength bands, and 1.4–2.3 yrs during the low state, which may reflect its general properties.

During the last decades, the TeV blazar Ton 599 has systematically experienced major outbursts detected in a wide wavelength range from radio to γ-rays. In our work ([16]) we present an analysis of its quasi-periodic variability across multiple wavelengths over an observing baseline 1983–2025.

The γ-ray, optical, and radio light curves are found to be highly correlated with time lags between 0 and 360 days, which indicates that they are triggered by the same population of particles. Using statistical methods of periodicity search, we revealed several quasi-periodic components with characteristic periods of between 1.4 and 7.5 yrs. The result is consistent with the detection of periodic components in the 1997–2011 light curves, which means that we observe the same mechanism causing long-term periodic variability.

A model of a binary supermassive black hole (SMBH) with a precessing jet, applied to the radio light curves of Ton 599, yields best-fitting parameters with orbital periods ~1.5 yrs and precession periods ~6.5 yrs. This result implies the existence of an SMBH system modulating emission through both the orbiting and jet precession effects, with differing observed periods possibly reflecting frequency-dependent emission regions along a structured, stratified jet.

Nonetheless, the short-term periodicity and fast flares (as shown in Fig. 3) likely arise from internal jet shocks, which aligns with typical blazar behavior. For example, it can be suggested

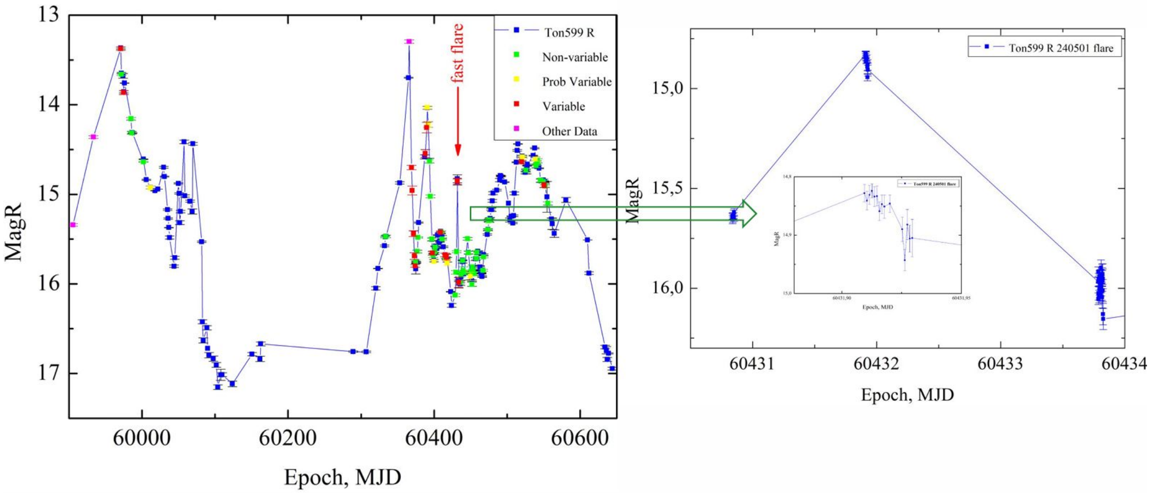

Figure 3: The blazar Ton 599 R band light curve in 2023-2024 according to our data taken with AS-500/2 reflector (left). The color symbols indicates of optical flux intra- night variability grade. The enlarged fragment of the fastest flare within this time interval (epoch MJD 60432, right picture).

that parameters of fast flare at epoch MJD 60432 correspond to size of emission region ~ 0.002 pc according to expression (1).

4. Conclusions

The results of the intensive multiband studies of the blazar sample over the last decades allowed us to note the importance of the comprehensive investigation of the AGN phenomenon. The use of a quite modest but specialized instrument gives important data which may disclose the enigma of Active Nuclei. Results of our last studies pointed out on some properties of electromagnetic emission for some blazars over broad spectral range, i.e. common origin of high-energy photons and radio waves from the same population of relativistic particles, presence of time lag for flares in different spectral bands, indication on quasi-periodical variation of blazar emission and so on. One should also note the necessity for long-term radio and optical observations of these objects. It is very likely that our collaborative efforts may result in the extension of the observing facilities.

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