SHORT-TERM AND LONG-TERM FLUX VARIABILITY OF EXTRA-GALACTIC OBJECTS USEFUL FOR THE FUTURE GAIA CRF

G. DAMLJANOVIĆ[1], F. TARIS[2], M.D. JOVANOVIĆ[1]

[1] Astronomical Observatory, Belgrade - Serbia - gdamljanovic@aob.rs - miljana@aob.rs
[2] SYRTE, Observatoire de Paris - France - francois.taris@obspm.fr

ABSTRACT. Some Active Galactic Nuclei (AGN) objects (quasars - QSOs, blazars, for example) are well known for their rapid flux variability across the whole electromagnetic spectrum. They are variable on diverse time-scales, from minutes through months to even decades. There are three classes of variability: intraday - IDV (from a few minutes to several hours), short-term - STV (from several days to months), and long-term variability - LTV (from months to decades). In case of IDV, the flux changes is by a few tenths of magnitude, but in cases of STV and LTV it could be more than magnitude (even few magnitudes). Photometry is a powerful tool to investigate AGNs by measuring their variability time-scales, amplitude and duty cycle. Quasars have got a fundamental role in the evolution of their host galaxies, and they are used to build the International Celestial Reference Frame (ICRF). It is of importance that their proper motions are negligible because of their extreme distances. The visual-wavelength Gaia astrometry of the micro-arcsecond domain has got significant positional offsets with the radio VLBI positions of QSOs. We did optical observations of QSOs (visible in both, optical and radio domain, and important for ICRF - Gaia CRF link) to study their flux and color variability on short-term and long-term time-scales. Some results of five objects (1535+231, 1556+335, 1607+604, 1722+119, and 1741+597) are presented, here.

1. INTRODUCTION

The Hipparcos Catalog - HIgh Precision PARallax COllecting Satellite of European Space Agency (ESA) mission (ESA 1997) with positions, proper motions, and parallaxes for about 118000 stars on the International Celestial Reference System (ICRF), equator J2000, and epoch 1991.25, replaced the FK5 at 1997 after IAU XXIII General Assembly in Kyoto. Last few years, it is going on the Gaia ESA space astrometry mission (Global Astrometric Interferometer for Astrophysics): astrometrically, photometrically, and spectroscopically surveying the full sky. The plan was to observe about one billion sources for astrometry (until 20 magnitude in V band), and about 150 million ones for spectroscopy (until 16 mag); see paper (Prusti 2012). The goal is the Gaia Celestial Reference Frame (Gaia CRF) in the future, quasars based one. Until now, there are two solutions: the Gaia DR1 which was appeared in September 2016, and Gaia DR2 (in April 2018). The first one was the Tycho-Gaia astrometric solution for about two million stars (using 14 months of observations), and the second one was based just on Gaia data for about 1.3 billion stars at J2015.5 plus 0.4 billion faint sources (using 22 months of Gaia satellite observations).

The Gaia optical astrometry is going to the dawn of micro-arcsecond level, but at that level there is the appearance of positional offsets between the radio and optical positions of quasars (QSOs) that define the ICRF. The radio positions of QSOs are determined using VLBI data. Mentioned offsets are of importance for astrometry and reference frame, they currently put a limit for the accuracy and definition of the CRF at non-radio wavelengths. It is limiting research in different topics (proper motions, Earth orientation and ephemerides, geodesy, secular aberration, trajectories of stars in our galaxy, etc.). The reasons for optical/radio offsets could be due to real astrophysical processes associated with the Active Galactic Nuclei (AGN) that power quasars (jet launching/orientation), or real physical offsets between the AGN and its host galaxy. It is necessary to investigate AGNs properties which could affect apparent positions, and it is of importance to understand: physical nature of quasar optical/radio offsets, AGN/source galaxy physics (jet launching, obscuration, luminosity/obscuration variability, dual/binary AGN, AGN-source galaxy effects and interactions, etc.), lensed QSOs, and other effects. One of important task is to produce highly reliable and statistically complete multi-wavelength samples of AGN and their host galaxies, and it is in line with out investigation. The AGNs (mostly QSOs in the case of ICRF objects) are well known for their flux variability at diverse time-scales: intraday (IDV, from a few minutes to several hours), short-term (STV, from several days to months), and long-term variability (LTV, from months to decades). Using optical observations of QSOs and relative photometry, we investigated their flux and color variability on short-term and long-term time-scales to support ICRF - Gaia CRF link.

2. INSTRUMENTS AND RESULTS

For investigation of photometry of QSOs useful for the link ICRF - Gaia CRF (Bourda et al. 2011) we realized the "Serbian-Bulgarian mini-network telescopes" from 2013 to use six telescopes at three sites: Rozhen National Astronomical Observatory (NAO) and Belogradchik AO in Bulgaria, and Astronomical Station Vidojevica (ASV) of Astronomical Observatory in Belgrade (Serbia). Also, to support our cooperation, two SASA-BAS joint research projects between Serbian (SASA) and Bulgarian (BAS) Academy of Sciences are established: "Observations of ICRF radio-sources visible in optical domain" (during period 2014-2016), and "Study of ICRF radio-sources and fast variable astronomical objects" (2017-2019). The telescopes are:

1.) 60 cm ASV (from 2010, Cassegrain, CCD Apogee Alta U42 and E47, CCD SBIG ST10 XME),

2.) 1.4 m ASV (from mid-2016 via Belissima project, Ritchey-Chrétien, CCD Apogee Alta U42, CCD Andor iKon-L),

3.) 2m Rozhen (Ritchey-Chrétien, CCD VersArray 1300B, CCD Andor iKon-L),

4.) 60 cm Rozhen (Cassegrain, CCD FLI PL09000),

5.) Schmidt-camera 50/70 cm at Rozhen (CCD FLI PL16803),

6.) 60 cm Belogradchik (Cassegrain, CCD FLI PL09000).

Also, telescopes Joan Oró 0.8 m - TJO (robotic one, the Montsec Astronomical Observatory, Catalonia, Spain, Cassegrain, CCD FLI PL4240-1-B, CCD Andor iKon-L), and Leopold Figl 1.5 m (the University of Vienna, Austria, R.C., CCD SBIG ST10 XME) were used. All data were done using Johnson UBV and Cousins $R_c I c$ filters. The CCD images were reduced by subtracting bias and dark, and divided by flat field (also, frames were corrected for bad pixels, etc.). After that, the relative photometry was applied via few comparison stars. Magnitudes of V-band and R-band of these stars were calculated via *ugriz* SDSS Catalog ones and suitable transformations between V, R filters and ugriz SDSS (Chonis and Gaskell 2008). And we took some comparison stars of 1722+119 from the paper (Doroshenko et al. 2014). For example, the V-band and R-band data of the object 1741+597 are presented on Figs. 1 and 2, respectively: VBRL (Vidojevica, Belogradchik, Rozhen, and Leopold Filg) data during 2013-2015, TJO - Joan Oró data during 2014-2015, and MJ data using 60 cm and 1.4 m ASV telescopes from mid-2016 to mid-2019; MJ means data which were collected by Miljana D. Jovanović (PhD student at Belgrade University). All in all, it is about six years long data set. Mentioned three groups of data are consistent between each other (see Figs. 1 and 2). The F-test was applied to investigate variability of V-band and R-band light-curves of objects and their comparison stars; there is no variability of comparison stars and object 1556+335. Other objects (1535+231, 1607+604, 1722+119, and 1741+597) show flux variability. The object 1741+597 is presented in Figs. 1-4 because its big flux variability (about 2 magnitudes in V and R bands). Some points of light-curves were rejected by applying the

3σ criteria; the reason for that was the bad tracking during observations, bad weather conditions, etc. For relative photometry, we used our finding charts of presented objects with their comparison stars.

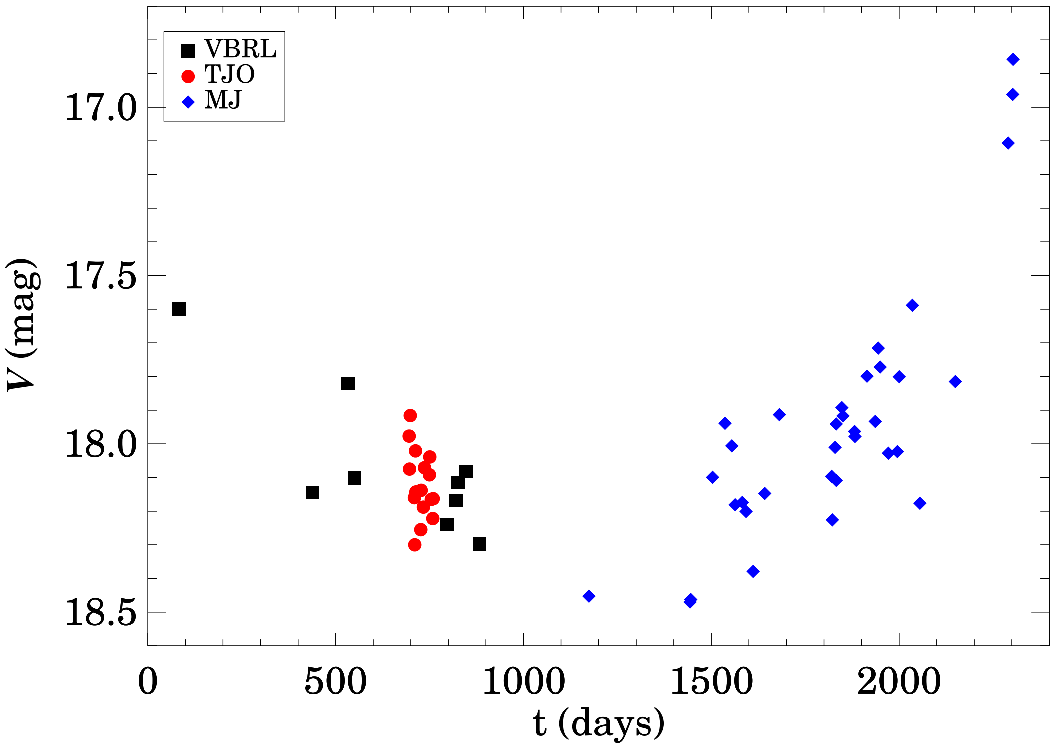

Figure 1: Data of V (mag); object 1741+597, $t = JD - 2456400.0$.

To determine the period, phase, and amplitude of sinusoidal term we used the Least Squares Method (LSM). The minimum period for LSM is about 0.3 yr (in line with the Nyquist frequency), and the maximum one is about 12 yr (double observational period) with step of 0.1 yr; observational period is about 6 yr. The linear, semiannual, and annual terms were removed (Rani et al. 2009, Kesteven et al. 1976) to get the input data for LSM; see residuals of V and R on Figs. 3 and 4 (points), respectively. The solution of our interest is the best fit using LSM, or associated with a minimum standard deviation of differences between curve (see Figs. 3 and 4) and input data; that solution for each object is done in Table 1. The presented curve is combination of few obtained sinusoids of our interest here (see Table 1), and the final residuals (Figs. 3 and 4) are differences between that curve and the input data. The results are presented in Table 1: object, filter, period, and amplitude (with standard deviation). There are few periods per object. For the same object, in V-band some quasiperiods are slightly different from R-band results because of different number of input points, not enough input data for LSM, etc. With more data (in the future) it is possible to get more precise results. Some of presented quasiperiods (in Table 1) could be artificial ones; it is necessary to investigate the physics of these quasiperiods for each object separately. As criterion to present calculated period (in Table 1), we took into account each harmonic which period in V-band is close to R-band one, and which value of A is bigger than suitable σ_A value. The final residuals were investigated using Abbe's criterion, and it was concluded that the final residuals could be explained with random variations.

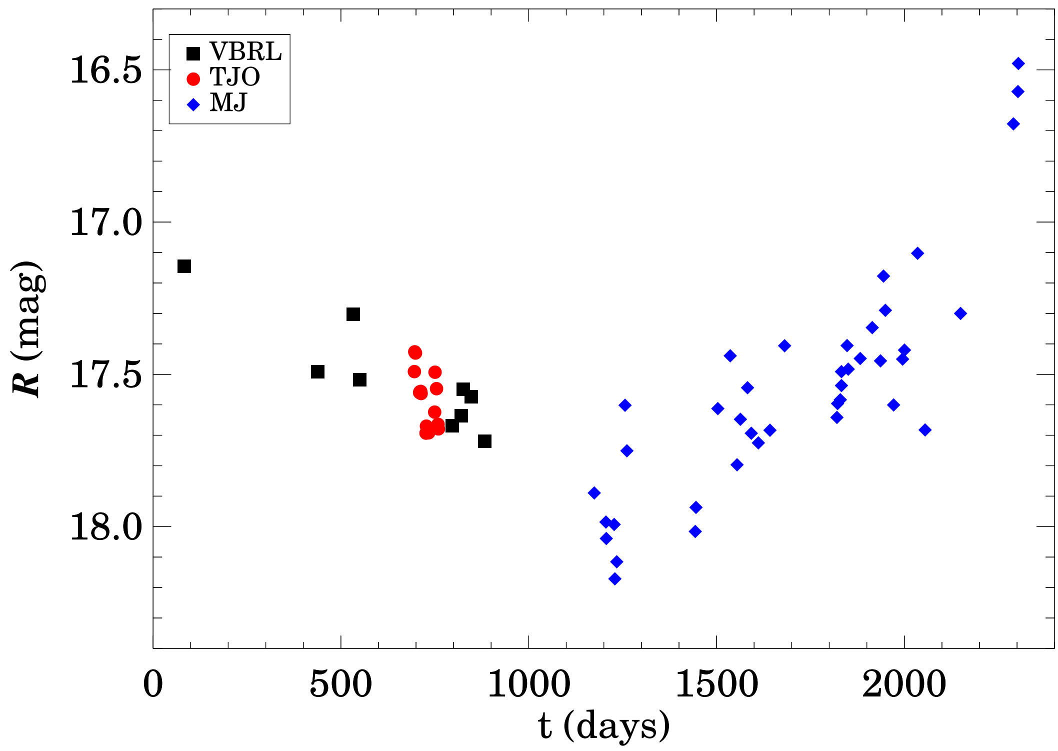

Figure 2: Data of R (mag); object 1741+597, $t = JD - 2456400.0$.

Object	Filter	Period (y)	$A \pm \sigma_A$ (mag)
1535+231	V	0.57, 0.88, 1.21	0.158(0.028), 0.132(0.025), 0.133(0.022)
	R	0.57, 0.87, 1.21	0.233(0.028), 0.143(0.024), 0.122(0.022)
1607+604	V	0.94, 1.89, 4.10	0.051(0.017), 0.088(0.014), 0.047(0.013)
	R	0.87, 1.99, 3.69	0.045(0.012), 0.067(0.010), 0.062(0.009)
1722+119	V	0.83, 0.88, 1.08, 1.52, 1.77, 3.43, 4.43	0.392(0.052), 0.126(0.030), 0.122(0.028), 0.461(0.037), 0.169(0.024), 0.217(0.032), 0.150(0.021)
	R	0.82, 0.88, 1.10, 1.52, 1.90, 3.55, 4.76	0.399(0.049), 0.122(0.024), 0.134(0.017), 0.386(0.039), 0.184(0.034), 0.139(0.020), 0.265(0.026)
1741+597	V	0.70, 0.90, 1.17, 1.59, 3.07, 4.97	0.178(0.023), 0.119(0.033), 0.205(0.027), 0.110(0.018), 0.159(0.020), 0.119(0.017)
	R	0.67, 0.85, 1.18, 1.58, 3.49, 5.66	0.131(0.021), 0.177(0.025), 0.214(0.030), 0.121(0.017), 0.140(0.019), 0.102(0.015)

Table 1: The amplitudes of quasiperiods for objects: 1535+231, 1607+604, 1722+119, 1741+597.

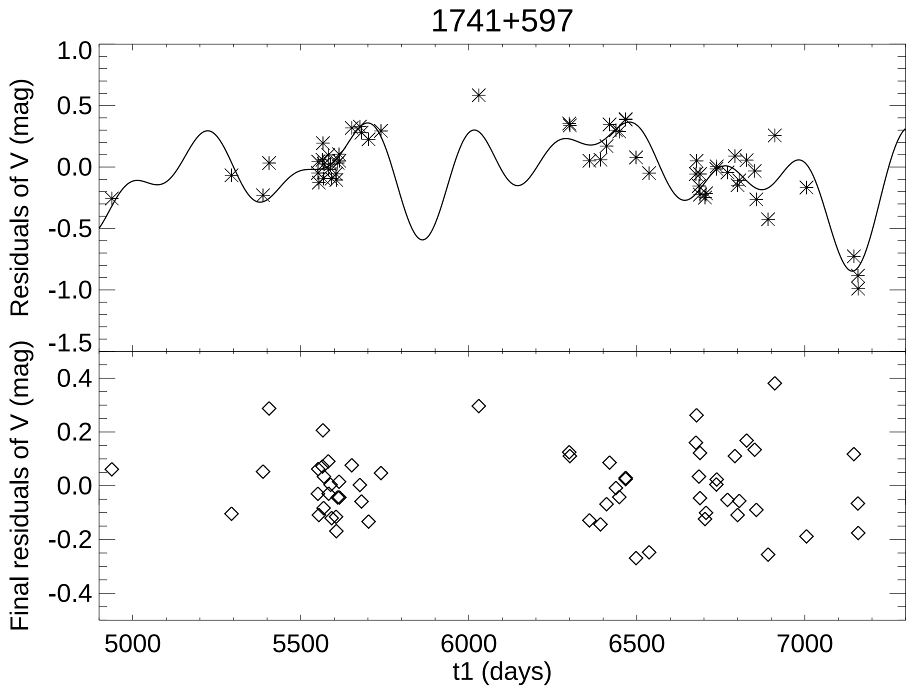

Figure 3: Residuals of V (mag); object 1741+597, $t_1 = JD - 2451544.5$.

3. CONCLUSION

Between the visual-wavelength Gaia astrometry of the micro-arcsecond domain and radio VLBI positions of QSOs has got significant positional offsets. It is of importance to investigate these offsets for precise ICRF - Gaia CRF link. Because of it, we did optical observations of QSOs, visible in optical and radio domains (about 47 objects), important for mentioned link (Bourda et al. 2011) to study their flux and color variability on short-term and long-term time-scales. Here, we presented some results for five objects: 1535+231, 1556+335, 1607+604, 1722+119, and 1741+597. After F-test, one object (1556+335) and comparison stars of all objects did not show flux variability. Some results of mentioned objects are presented in Table 1: periods, and amplitudes (with standard deviations). The input three sets of data for the object 1741+597 in V and R bands (as an example) are on Figs. 1 and 2. The curves (using few sinusoids as results determined via LSM) with residuals are on Figs. 3 and 4. After Abbe's criterion, the final residuals could be explained with random variations. Some of presented quasiperiods in Table 1 could be artificial ones. For now, we presented quasiperiods (in Table 1) which result (calculated period) in V-band is close to R-band one, and that value of A is bigger than suitable σ_A value. Also, semiannual and annual terms were removed (Rani et al. 2009, Kesteven et al. 1976). It is important to continue mentioned investigation via physics of calculated quasiperiods, and using more data for LSM.

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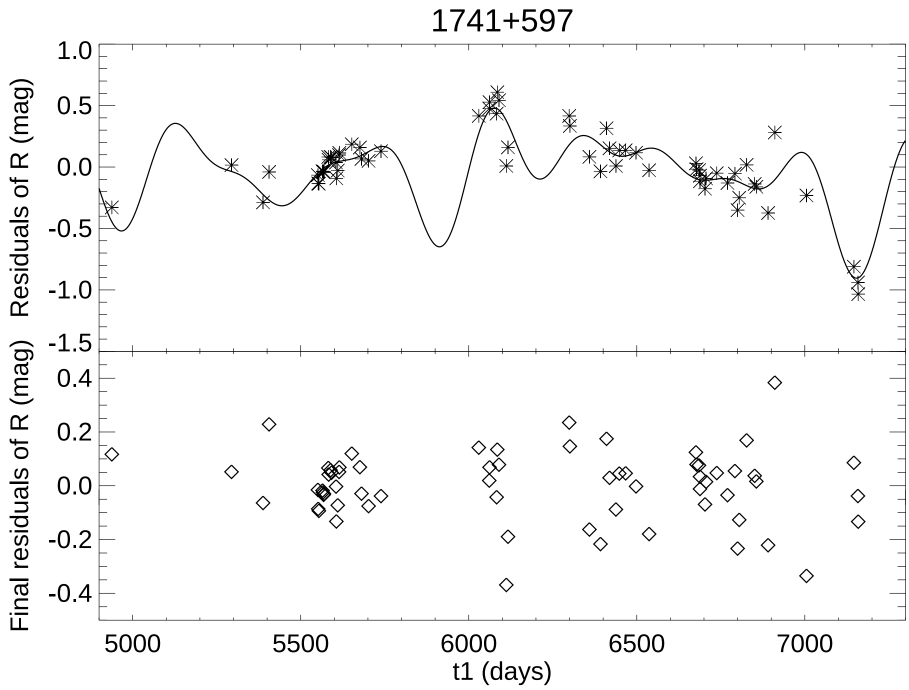

Figure 4: Residuals of R (mag); object 1741+597, $t_1 = JD - 2451544.5$.

4. REFERENCES

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