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CONTROL STARS AROUND QUASARS SUITABLE FOR THE ICRF – GAIA CRF LINK

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Abstract. Some quasars (QSOs) which were observed by Gaia satellite in optical and by Very Long Baseline Interferometry (VLBI) in radio wavelength will be used to link Gaia CRF and International Celestial Reference Frame. Monitoring photometry stability of candidate sources is of importance for this link. During six years (2013–2019) we observed 47 candidate sources (mostly QSOs), in V and R bands. Their brightness was determined by using differential photometry. In the same manner was obtained the brightness of several control stars around each QSOs. We tested brightness variability of QSOs and stars using F–test. The test shows that most of control stars are suitable for photometry and could be used as comparison stars. The results of five selected objects and their control stars are presented here.

1. INTRODUCTION

The early third Gaia data release (Gaia EDR3) is available since 3 December 2020, the full Gaia DR3 data release will be available in the first half of 2022. The Gaia EDR3 contains data for about 1.8 billion sources and provides full astrometric information (positions, parallaxes, and proper motions) for about 1.5 billion sources (Gaia Collaboration et al. 2020).

The third data realization of the International Celestial Reference Frame (ICRF3) was adopted in August 2018 (Charlot et al. 2020). The ICRF3 is based on data at radio frequencies obtained by very long baseline interferometry (VLBI). The Gaia CRF (based on the observations at optical wavelength) and the ICRF (based on the VLBI observations at radio wavelengths) could be linked using a set of quasars (QSOs) visible in the optical and radio domains. We observed for about six years (2013 – 2019) the 47 candidates sources for this link with high astrometric quality proposed by Bourda et al. (2011). These sources are mostly QSO, the others are BL Lacertae – BL Lac and Seyfert galaxies type 1, they are all subgroup of Active Galactic Nuclei (AGNs). One of the important properties of AGNs, flux variability could be correlated with astrometric possitions of AGNs centroids (Taris et al. 2011). Because of that it is necessary to monitor their brightness changes for the link between two reference frames over a longer period of time. The brightness was calculated using differential photometry with a few comparison stars from the vicinity of objects. By increasing the number of comparison stars the accuracy of the objects brightness is improved. Therefore we add new control stars, the brightness of which is determined in the same manner. After testing some of these control stars could be used as comparison ones and also for testing the brightness of comparison stars.

The subject of this paper is investigation of brightness variability of control stars of five AGNs which have been the most observed objects. Of these five objects, two are QSOs (1553+231, and 1556+335) and three are BL Lac (1607+604, 1722+119, and 1741+597). They were observed for about 50 nights. For object 1722+119 the first finding chart was given in Smith et al. (1991), but stars are too far from the object and very bright. The second was given in Fiorucci and Tosti (1996), the stars are located near the object, but some stars are very bright in comparison with the object. Because of this we select comparison and control stars for this object from paper Doroshenko et al. (2014). In the paper Jovanović (2019) are presented charts of the fields of the objects and their (comparison and control) stars. In paper Damljanović et al. (2020) are presented analysis of objects brightness variability and calculated amplitudes of their quasiperiods from the similar data sets.

2. OBSERVATIONS AND PHOTOMETRY

The observations were made using eight different telescopes. The most of the data are obtained using two telescopes located at Astronomical Station Vidojevica (ASV) of the Astronomical Observatory of Belgrade, and telescope Joan Oró 80 cm - TJO (robotic one) located at the Montsec Astronomical Observatory, Catalonia, Spain. As for the other five telescopes, three are located at the Rozhen NAO in Bulgaria, one at Belogradchik, Bulgaria and one Leopold Figl at Vienna, Austria. The details about the used telescopes, their mirror diameters and mounted CCD cameras, are presented in Table 1.

Every night CCD images mostly per V and R filters have been obtained. For reduction of CCD images and bad pixels maps were used bias, dark and flat frames obtained for the same nights (dark frames for hot, and flat for dead pixel map). This was performed using Image Reduction and Analysis Facility – the IRAF scripting language (ascl:9911.002) (Tody 1986, 1993). The corrections for cosmic rays was perfomed using Laplacian Cosmic Ray Identification method (Pieter G. van Dokkum 2001).

The brightness of objects and control stars was determined using differential photometry with two comparison stars, with MaxIm DL software. The stars were chosen from the Sloan Digital Sky Survey Data Release 14 (SDSS DR14) catalogue (Abolfathi et al. 2018). The stars of 1722+119 were chosen from paper Doroshenko et al. (2014), because the field of 1722+119 was not covered by SDSS. The comparison and control stars were selected from the object vicinity following several criteria. We chose stars which are not variable, not too bright or faint in comparison with the object, or not very blue or red, etc. The transformation from the SDSS DR14 (PSF g, r, i) magnitudes to the Johnson-Cousins (V and R), was performed using equations (Chonis and Gaskel 2008):

$$V = g - (0.587 \pm 0.022)(g - r) - (0.011 \pm 0.013), \tag{1}$$

$$R = r - (0.272 \pm 0.092)(r - i) - (0.159 \pm 0.022), \tag{2}$$

where $14.5 < g, r, i < 19.5$, $0.08 < r - i < 0.5$ and $0.2 < g - r < 1.4$.

Table 1: Telescopes and cameras.

Telescope with mirror diameter	CCD Camera	CCD resolution	Pixel size (μm)	Pixel scale (arcsec pix^{-1})	Field of view (arcmin)
ASV 60cm	Apogee Alta U42	2048x2048	13.5x13.5	0.466	15.8x15.8
	SBIG ST10 XME	2184x1472	6.8x6.8	0.230	8.4x5.7
	Apogee Alta E47	1024x1024	13.0x13.0	0.450	7.6x7.6
ASV 1.4m	Apogee Alta U42	2048x2048	13.5x13.5	0.243	8.3x8.3
	Andor iKon-L	2048x2048	13.5x13.5	0.244	8.3x8.3
TJO 80cm	FLI PL4240-1-B	2048x2048	13.5x13.5	0.364	12.3x12.3
	Andor iKon-L	2048x2048	13.5x13.5	0.361	12.3x12.3
Rozhen 2m	Andor iKon-L	2048x2048	13.5x13.5	0.176	6.0x6.0
	VersArray 1300B	1340x1300	20.0x20.0	0.261	5.6x5.6
Rozhen 60cm	FLI PL09000	3056x3056	12.0x12.0	0.330	16.8x16.8
Rozhen 50/70cm	FLI PL16803	4096x4096	9.0x9.0	1.080	73.7x73.7
Belogradchik 60cm	FLI PL09000	3056x3056	12.0x12.0	0.335	16.8x16.8
LFOA 1.5m	SBIG ST10 XME	2184x1472	6.8x6.8	0.150	5.6x3.8

In Table 2 are details of objects and their two comparison (A and B) and control stars: coordinates, the V_C and R_C magnitudes of stars (obtained using mentioned equations for stars from SDSS DR14, and those from Doroshenko et al. (2014)), and with V_O and R_O (average magnitudes from our observations). During the six years period of observation, one object 1556+335 had the most stable brightness. The brightness standard deviations of this object in both bands are of the order of about of 0.01, similar to the standard deviations of stars. The standard deviations of other objects are ten times bigger. The differences of extremal magnitudes of objects 1535+231, 1607+604, 1722+119, and 1741+597 are about 1.0, 0.4, 2.0, 1.7 magnitudes in both filters, respectively. Objects with the highest brightness changes have the highest standard deviations. Objects 1535+231, 1607+604, 1722+119, and 1741+597 have standard deviations around 0.2, 0.1, 0.5, and 0.3, respectively.

The V_C and R_C magnitudes of stars (initial values for differential photometry calculated from SDSS DR14) and calculated values V_O and R_O (from our observations) are in good agreement within the limits of errors. The standard deviations of control stars are similar to the ones of comparison.

3. METHODS AND RESULTS

We use the 3σ rule to reject some data and the Shapiro-Wilk test of normality (Razali and Wah 2011) to confirm that tests which require normal data distribution can be applied.

To investigate the brightness variability of objects and control stars we use the F-test described by de Diego (2010). We define three test hypotheses:

1) H_1: $Var(S-A) = Var(S-B)$, alternative H_{a1}: $Var(S-A) > Var(S-B)$,

2) H_2: $Var(S-A) = Var(A-B)$, alternative H_{a2}: $Var(S-A) > Var(A-B)$,

3) H_3: $Var(S-B) = Var(A-B)$, alternative H_{a3}: $Var(S-B) > Var(A-B)$.

Test statistics which correspond to these hypotheses are:

$F_1 = \frac{Var(S-A)}{Var(S-B)}$, $F_2 = \frac{Var(S-A)}{Var(A-B)}$, and $F_3 = \frac{Var(S-B)}{Var(A-B)}$.

Table 2: The coordinates, V and R magnitudes (index C refers to calucalted using SDSS DR14, and O to observed values) with standard errors of objects and their comparison and control stars; period July 2013 — August 2019 using our observations.

Object No.	$\alpha_{J2000.0}(^o)$	$\delta_{J2000.0}(^o)$	$V_C \pm \sigma_{V_C}$(mag)	$R_C \pm \sigma_{R_C}$(mag)	$V_O \pm \sigma_{V_O}$(mag)	$R_O \pm \sigma_{R_O}$(mag)
1535+231	234.31041	23.01126			18.472 ±0.233	18.275 ±0.261
2 (A)	234.31491	23.01831	17.200 ± 0.031	16.658 ± 0.038	17.229 ±0.031	16.750 ±0.067
3	234.30004	23.02486	15.983 ± 0.030	15.633 ± 0.031	16.002 ±0.022	15.707 ±0.059
4 (B)	234.25178	23.01917	16.232 ± 0.024	15.867 ± 0.029	16.225 ±0.012	15.916 ±0.067
7	234.29312	22.96096	16.470 ± 0.027	15.973 ± 0.036	16.451 ±0.026	15.958 ±0.021
8	234.35917	23.01592	15.860 ± 0.035	15.149 ± 0.050	15.841 ±0.024	15.142 ±0.028
1556+335	239.72993	33.38851			17.455 ±0.063	16.988 ±0.052
2 (A)	239.71950	33.39110	17.336 ± 0.030	16.850 ± 0.038	17.352 ±0.032	16.883 ±0.034
3 (B)	239.69035	33.40959	16.381 ± 0.027	16.095 ± 0.030	16.371 ±0.021	16.074 ±0.021
5	239.76798	33.38778	16.271 ± 0.030	15.916 ± 0.031	16.283 ±0.022	15.931 ±0.022
6	239.74562	33.39003	16.198 ± 0.030	15.825 ± 0.031	16.225 ±0.022	15.876 ±0.021
7	239.74317	33.37370	15.552 ± 0.030	15.188 ± 0.031	15.568 ±0.022	15.223 ±0.017
8	239.73398	33.37219	15.743 ± 0.040	14.897 ± 0.064	15.763 ±0.032	14.966 ±0.016
1607+604	242.08560	60.30783			17.400 ±0.126	16.956 ±0.095
2 (A)	242.02882	60.28951	17.068 ± 0.027	16.619 ± 0.031	17.069 ±0.027	16.616 ±0.031
3 (B)	242.02526	60.31162	16.864 ± 0.025	16.423 ± 0.032	16.876 ±0.018	16.441 ±0.025
4	241.97352	60.35552	15.195 ± 0.025	14.781 ± 0.031	15.164 ±0.042	14.729 ±0.041
5	242.09638	60.34816	15.630 ± 0.031	14.965 ± 0.044	15.620 ±0.046	14.938 ±0.036
7	242.16854	60.37746	16.856 ± 0.024	16.467 ± 0.031	16.839 ±0.043	16.424 ±0.061
1722+119	261.26810	11.87096			15.571 ±0.467	15.085 ±0.482
C2	261.27167	11.86997	13.173 ± 0.005	12.570 ± 0.006	13.201 ±0.034	12.623 ±0.024
C3	261.24375	11.86636	14.078 ± 0.012	13.600 ± 0.008	14.095 ±0.025	13.628 ±0.024
1	261.31208	11.89125	13.445 ± 0.009	12.848 ± 0.010	13.466 ±0.037	12.873 ±0.027
2 (A)	261.30458	11.86519	14.823 ± 0.008	14.691 ± 0.012	14.822 ±0.011	14.686 ±0.005
5	261.25667	11.91311	15.873 ± 0.010	15.385 ± 0.016	15.880 ±0.047	15.387 ±0.027
9	261.23333	11.87083	15.809 ± 0.008	15.332 ± 0.014	15.815 ±0.027	15.346 ±0.020
10	261.23875	11.87083	16.142 ± 0.011	15.699 ± 0.019	16.144 ±0.023	15.716 ±0.021
C4 (B)	261.28958	11.85344	15.665 ± 0.009	15.164 ± 0.013	15.667 ±0.024	15.169 ±0.018
1741+597	265.63334	59.75186			18.011 ±0.307	17.549 ±0.305
2	265.62329	59.75176	15.565 ± 0.029	15.204 ± 0.054	15.602 ±0.033	15.268 ±0.044
3 (A)	265.57081	59.75387	16.673 ± 0.029	16.314 ± 0.053	16.674 ±0.019	16.332 ±0.022
4	265.68412	59.76861	16.376 ± 0.034	15.795 ± 0.067	16.407 ±0.042	15.830 ±0.040
5	265.61457	59.79547	16.154 ± 0.031	15.704 ± 0.056	16.187 ±0.034	15.760 ±0.025
6	265.68288	59.71901	16.126 ± 0.038	15.684 ± 0.064	16.125 ±0.033	15.686 ±0.037
7 (B)	265.59766	59.71686	16.633 ± 0.039	16.124 ± 0.074	16.634 ±0.015	16.111 ±0.012

The designations $Var(S-A)$, $Var(S-B)$ and $Var(A-B)$ refer to the variances of magnitude differences between S (control stars or objects) and comparison stars (A or B). The F_i ($i = 1, 2, 3$) statistics were compared with the critical value (which corresponds to the significance level 0.001 and number of freedom $N-1$, where N is the number of data). The null hypotheses of non variability is discarded when the F_2 and F_3 values are greater than critical. The $F_1 = F_2/F_3$ values should be around 1, because the tested brightness should be variable in the same manner for both comparison stars A and B ($Var(S-A)$ and $Var(S-B)$ should be close to each other). The F_2 and F_3 values, along with number of data points N, and critical values F_c (for N and $\alpha = 0.001$) are listed in Table 3, for both filters, for objects and their control stars.

The F_1 values are around 1 (for objects and stars) as it is expected, except for control stars of 1535+231, in the R band. The test shows that the brightness of most of the control stars could be considered as non-variable. The F_2 and F_3 exceed the critical values for about 20% stars, which corresponds to data obtained with low quality CCD camera. These data are not rejected because they are close to the average ones within the limits of standard deviations, and they are not excluded after implementing 3σ rule. One object, 1556+335, has the most stable brightness. The other objects have the F_2 and F_3 values significantly greater than critical. It is noticeable that the objects with greater changes in brightness (1722+119 and 1741+597) have higher $F_{2,3}$ values.

Table 3: The F–test results.

Object	N	F_2, F_3	F_c	N	F_2, F_3	F_c
Band		V			R	
1535+231	43	31.00 , 34.50	2.66	48	18.96 , 19.65	2.51
3	43	1.78 , 2.08	2.66	48	4.03 , 1.34	2.51
7	12	1.16 , 1.47	7.76	16	1.05 , 6.16	5.54
8	20	1.14 , 1.53	4.47	24	1.20 , 6.46	3.85
1556+335	41	3.12 , 2.34	2.73	50	1.23 , 1.77	2.46
5	41	1.01 , 1.38	2.73	50	1.06 , 1.71	2.46
6	20	2.53 , 2.01	4.47	27	2.60 , 2.31	3.53
7	20	2.25 , 2.05	4.47	27	2.07 , 3.42	3.53
8	19	1.79 , 1.19	4.68	27	1.98 , 3.85	3.53
1607+604	44	22.26 , 20.29	2.63	48	8.64 , 7.10	2.51
4	39	3.47 , 2.43	2.80	42	1.62 , 1.65	2.69
5	44	3.64 , 3.31	2.63	48	1.81 , 1.50	2.51
7	26	2.57 , 2.38	3.63	27	2.09 , 2.74	3.53
1722+119	36	202.59 , 192.64	2.93	40	1389.46 , 1387.88	2.76
C2	34	1.59 , 2.87	3.04	34	2.70 , 1.82	3.04
C3	36	1.12 , 3.00	2.93	35	1.73 , 1.18	2.98
1	34	1.58 , 1.75	3.04	34	4.22 , 3.43	3.04
5	36	2.23 , 1.37	2.93	40	4.63 , 3.87	2.76
9	36	1.03 , 2.82	2.93	40	2.89 , 1.63	2.76
10	36	1.42 , 1.77	2.93	39	3.25 , 2.28	2.80
1741+597	50	115.13 , 115.12	2.46	56	153.09 , 155.53	2.34
2	50	1.26 , 1.80	2.46	56	2.13 , 3.92	2.34
4	50	1.90 , 1.03	2.46	56	1.05 , 1.07	2.34
5	50	1.31 , 1.69	2.46	56	1.02 , 1.29	2.34
6	50	1.03 , 1.38	2.46	56	1.43 , 2.28	2.34

4. CONCLUSIONS

One of the important properties of AGNs is flux variability. Because of this it is important to monitor flux changes of AGNs which will be used for the link for reference frames Gaia CRF and ICRF. We tested the data (collected for about six years) of some

AGNs which are candidates for the link between the mentioned frames. The test shows that four objects are variable in the V and R bands. The accuracy of photometry will be improved with the higher number of non-variable stars. For that reason we also tested stars from the objects vicinity. The magnitudes of stars which were determined from the observations are in good agreement with the input values for the differential photometry, in line with their standard errors (see Table 2). After implementing the F–test it is concluded that most of the stars (80%) do not have significant changes in brightness, and we consider that they are suitable for photometry. We will continue with observations and investigations of short term changes in brightness of stars and objects. Our plan is also to investigate Intra Day and Long Term object brightness and color variability.

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