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BULGARIAN-SERBIAN COOPERATION: CCD OBSERVATIONS OF VISUAL DOUBLE STARS IN THE PERIOD 2004-2022

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Abstract. Visual binaries have been studied for more than 200 years, from wide pairs resolvable by the naked eye toward more close ones being resolved by using various observational techniques of high angular resolution such as speckle interferometry, lunar occultations, adaptive optics, etc. With classic CCD technique it is not possible to resolve systems with small separation between the components. Wide stellar systems, with a separation greater than 2 arcseconds, have large orbital periods in general. For many of them there are no many observations, the observations over a short orbital arc or they have a low accuracy. Because of this, as many as possible new observations of wide double stars should be performed.

The Serbian-Bulgarian cooperation concerning the study of visual double and multiple stars started in 2004 with CCD observations of such objects. Here we present a brief overview of the most interesting results obtained during our collaboration. Begun as a regional Balkan project, this cooperation in 2012 was continued in the form of a bilateral cooperation between the Bulgarian Academy of Sciences and Serbian Academy of Sciences and Arts.

1. INTRODUCTION

Systematic observations of double and multiple stars have been carried out for more than 200 years. Their study makes possible more accurate determination of masses and distances, as well as a better understanding of stellar formation and evolution. The results of measurements have been collected and the corresponding database is kept by the United States Naval Observatory. The Washington Double Star Catalogue (WDS)[1] has been constantly updated and contains the data for

[1] http://www.astro.gsu.edu/wds/

more than 154,000 pairs. The orbital elements have been obtained for a small number of them, about 3450, and they can be found in the Sixth Catalog of Orbits of Visual Binary Stars, (ORB6)[2]. For about 1280 pairs it has been established that their components are not at the same distance, i.e., that they are not gravitationally bound. For them the linear elements of motion have been determined and they are given in the Second Catalog of Rectilinear Elements (LIN2)[3].

Observations of double and multiple stars have been carried out at the Astronomical Observatory of Belgrade for more than 70 years. Until 1994, micrometer measurements of relative coordinates between component pairs were made, and after that observations were made with CCD cameras. Since 2004 till now a group of astronomers from Belgrade Observatory have visited many times the National Astronomical Observatory Rozhen (NAOR) in Bulgaria and taken frames of visual double and multiple stars. Series of observations have been made with a CCD camera attached to the 2-m telescope. Only during the observations made in 2004 the CCD camera Photometrics CE200A was used. Later observations made between 2005 and 2018 have been performed with the CCD camera VersArray 1300B. For measurements made since 2019, a CCD camera Andor iKon-L was used. Until now we have made 27 series of observations of the above mentioned stars. Table 1 shows the dates of observation series at NAO Rozhen, the number of observation nights, the number of observation pairs and the references in which the results were published. A total of 4398 pairs were measured (during the first 24 series of observations). The results: position angles, angular separations, orbital and linear solutions, have been published in Pavlović et al. (2005, 2013), Cvetković et al. (2006, 2007, 2010, 2011, 2015, 2016, 2017, 2018, 2019, 2021). The measurements of the frames for 137 pairs obtained in 2021 and in 2022 (the last three series) to be published soon.

In June of 2011 the first CCD observations of double and multiple stars with the 60 cm telescope from the new Astronomical Station on the mountain of Vidojevica (ASV) were started. During the autumn of 2011 we observed the same objects at both NAOR and ASV. We noticed that the measured separations (ρ_{NAOR}, ρ_{ASV}) differ for the same pairs of stars and the differences increase with increasing angular separation. Therefore, we measured the angular separations between the images of stars visible in our CCD frames. The separation depends on the pixel scale, i.e. the focal length of the telescope. The result of determining the focal length of the 60 cm telescope at the ASV more precisely is given in the paper Cvetković et al. (2012b), and for the 2 m NAOR telescope in the paper Cvetković et al. (2013).

2 http://www.astro.gsu.edu/wds/orb6/orb6frame.html
3 http://www.astro.gsu.edu/wds/lin2/lelements.html

Table 1: An overview of the number of observation nights, the number of observation pairs and the references in which the results were published

Date	Numb. Observ. Nights	Number of pairs	References
October 2004	1	27	Serb. Astron. J. **171**, 2005
October 2005	1.5	35	Serb. Astron. J. **172**, 2006
December 2006	1	67	Serb. Astron. J. **174**, 2007
July 2009	1	35	Serb. Astron. J. **180**, 2010
September 2010	3	202	Astron. Journal **142**, 2011
March and October 2011	3	337	Astron. Journal **146**, 2013
April and November 2012	6	453	Astron. Journal **149**, 2015
April and October 2013 March and October 2014	7	721	Astron. Journal **151**, 2016
April 2015	4	801	Astron. Journal **153**, 2017
March/April and October 2016	4	450	Astron. Journal **156**, 2018
April and October 2017 April and November 2018	5	939	Astron. Journal **158**, 2019
March and November 2019 March and November 2020	4	331	Astron. Journal **162**, 2021
		4398	
April and October 2021	2	74	unpublished
March 2022	3	63	unpublished

2. RESULTS

Using only our observations we analyzed a multiple system registered in ADS - Aitken Double Stars catalogue as ADS 48. Its number in the Washington Double Star Catalog is 00057+4549. Our aim is to establish which of the seven components (A, B, C, D, E, P and F) are gravitationally bound, i.e. have an orbital motion around the mass center, and which of them are mutually very distant in space so that only their projections are close in the field of view. We used the measuring results from our CCD frames obtained between 1994 and 2011. The first CCD frames of ADS 48 multiple system at our disposal were obtained in 1994. We also obtained frames of this system at NAOR in 2004, 2005, 2006, 2010 and 2011, as well as three times at ASV in 2011. The selected CCD frames obtained from 1994 to 2011 as well as the detailed analysis of the system ADS 48 is given in the paper Cvetković et al. (2012a). The conclusions combined with the criteria based on celestial mechanics lead us to the following: i) within the system ADS 48 only stars A and B are gravitationally bound; ii) component F has common proper motion with A and B, but is not bound to them; iii) all other components considered here form optical pairs with AB.

Using the measurements obtained by us from the CCD observations at NAO Rozhen we have calculated the first orbits for two binaries: WDS 00152+2722 = J 868 given in Novaković (2007) and WDS 07106+1543 = J 703 given in Cvetković and Ninković (2008).

Three orbits were corrected for pairs WDS 03342+4837 = BU 787 AB, WDS 21289+1105 = STF 2799 AB and WDS 22234+3228 = WOR 11. The orbital elements are given in Cvetković et al. (2011).

We analyzed one more pair, WDS 03342+4837 = BU 787 AB. This pair belongs to a multiple system. It was discovered in 1881 and denoted as BU 787 AB. The components D and E were discovered later. The first orbit was calculated (Erceg 1984). The orbital elements and the new Hipparcos parallax yield 2600$M_\odot$ for the total mass of the system. This is an unrealistic value. Four measurements were performed at NAOR enable us to recalculate the orbit. But, all measurements show a linear trend and we are the first who calculated the linear solution for this pair. Additional analysis indicated that it is most likely an optical pair. Both recalculated orbit and linear solution are published in Cvetković et al. (2011).

Preliminary orbital elements for the pair J 703 published in 2008 were the first calculation of the orbital elements for it. There are three measurements for this pair obtained after 2008: two in 2011 and one in 2012. They have significant residuals in separation from the orbit. Also, the measurements show a linear trend and we are the first who calculated the linear solution for this pair. It is given in Cvetković et al. (2015).

In addition to these two pairs, BU 787 AB and J 703, measurements for another 30 observed pairs show a linear trend and we are the first who calculated their linear solutions. The results of their analysis are given in Table 2 and in the next section.

3. THE NATURE OF MOVEMENTS

Two linear elements, V_x and V_y , are used to calculate the velocity V of relative motion of the secondary with respect to the primary. Also, we can calculate the relative proper motion μ_{rel} for 32 pairs by using the components of the proper motion, $\mu_{\alpha\cos\delta}$ and μ_δ, for primary A and secondary B. They are taken from Gaia DR3[4]. The Gaia DR3 catalogue is available from June 2022. It contains parallaxes for both components of all pairs from our sample. Table 2 gives data for the 32 pairs with linear solutions. The columns are: 1 − WDS designation; 2 − discovery designation on whose basis it is possible to identify each pair; 3 − the relative proper motion μ_{rel}; 4 − the velocity V of relative motion of the secondary with respect to the primary; 5 and 6 − the primary parallax π_A and the secondary parallax π_B, respectively, from Gaia DR3.

[4] http://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=I/355/gaiadr3

Table 2: The relative proper motion μ_{rel}, the velocity V of relative motion of the secondary with respect to the primary, the primary parallax π_A and the secondary parallax π_B for 32 pairs with their WDS numbers and discoverer's designations

WDS Design.	Discoverer	μ_{rel}	V	π_A	π_B
α,δ (2000)	Designation	("/yr)	("/yr)	(mas)	(mas)
00057+4549	STT 547AC	0.8984	0.8991	86.800	0.923
00057+4549	STT 547AD	0.8996	0.8919	86.800	1.186
00057+4549	STT 547AE	0.8921	0.8952	86.800	2.364
00057+4549	POP 217AP	0.9048	0.9049	86.800	1.508
00251+1824	HJ 621	0.0773	0.0746	13.628	3.107
01057+3304	MLB 444	0.1019	0.1078	**3.617**	**3.473**
02516+4803	HJ 2160AB	0.0242	0.0250	1.073	2.456
03342+4837	BU 787AB	0.0382	0.0324	5.936	1.633
04312+5858	STI 2051AB	0.1043	0.1110	**181.244**	**181.273**
04556+1653	HJ 3263	0.0785	0.0754	2.828	0.839
05490+6342	TDS 197	0.2339	0.2215	1.371	11.177
05492+2941	BRT 2521	0.0888	0.0899	7.673	1.178
05535+4434	ES 1379	0.0607	0.0614	6.126	0.566
06092+6424	MLB 259	0.0378	0.0360	2.991	1.474
06277+2249	J 1092AB	0.0506	0.0547	1.537	4.056
07106+1543	J 703	0.0838	0.0847	12.162	2.751
08081+4916	HJ 2428	0.0736	0.0729	2.893	4.150
08089+1213	J 375AB	0.0523	0.0526	5.443	4.140
08503+0125	J 74	0.0545	0.0566	4.498	1.685
09388+0242	J 78	0.0742	0.0691	7.735	5.967
14031+1154	HJ 2699BC	0.1793	0.1897	12.212	6.890
14307+8308	LDS 1800	0.1022	0.1375	2.231	6.714
17046+3900	HJ 2804AB	0.0957	0.0945	5.578	3.490
18120+4355	ES 1419	0.0802	0.0794	4.338	1.371
18269+2950	HJ 1325	0.0152	0.0155	**0.546**	**0.423**
18489+1615	STF 2400AB	0.0735	0.0716	11.423	1.424
18580+6159	ES 1843	0.0356	0.0384	2.809	1.970
19289+3515	POP 34AB	0.1348	0.1536	16.822	0.380
19500+0637	J 1336AB	0.0442	0.0485	1.072	4.574
20087+1223	J 1338	0.0727	0.0753	0.318	5.839
22415+3256	J 2376AB	0.0667	0.0682	15.437	5.191
23581+2840	HJ 995	0.1135	0.1087	2.701	6.696

Then, we compared μ_{rel} with V for all 32 components in the linear solutions. As can be seen from Table 2, the values of V are in excellent agreement with μ_{rel} for all pairs. It is an argument in favor that the components are not gravitationally bound, i.e., that it is an optical pair. Another argument in favor of this is that the component parallaxes π_A and π_B are different. They are different for 29 pairs in our sample. For the remaining three pairs, which component parallaxes are approximately equal, additional criteria should be applied to determine the nature of their movements. These parallaxes are given in bold face in Table 2.

Table 3: The speed of relative motion μ, the characteristic speed of relative motion μ^* and the normalized relative motion μ′ for 32 pairs which are identified by their WDS numbers and discoverer's designations

WDS Design. α,δ (2000)	Discoverer Designation	μ ("/yr)	μ^* ("/yr)	μ′
00057+4549	STT 547AC	0.93651	0.01607	58.3
00057+4549	STT 547AD	0.91173	0.01645	55.4
00057+4549	STT 547AE	0.93990	0.02252	41.7
00057+4549	POP 217AP	0.87604	0.04865	18.0
00251+1824	HJ 621	0.08390	0.00452	18.6
01057+3304	MLB 444	0.10376	0.00043	240.1
02516+4803	HJ 2160AB	0.03213	0.00007	450.8
03342+4837	BU 787AB	0.03704	0.00282	13.1
04312+5858	STI 2051AB	0.10175	0.13230	**0.8**
04556+1653	HJ 3263	0.08431	0.00026	327.8
05490+6342	TDS 197	0.29292	0.00017	1754.5
05492+2941	BRT 2521	0.10240	0.00197	52.0
05535+4434	ES 1379	0.06624	0.00141	46.9
06092+6424	MLB 259	0.03457	0.00048	72.0
06277+2249	J 1092AB	0.05374	0.00016	332.9
07106+1543	J 703	0.08686	0.00289	30.0
08081+4916	HJ 2428	0.07765	0.00054	142.8
08089+1213	J 375AB	0.05402	0.00089	60.6
08503+0125	J 74	0.05876	0.00069	85.8
09388+0242	J 78	0.06944	0.00316	22.0
14031+1154	HJ 2699BC	0.12684	0.00340	37.3
14307+8308	LDS 1800	0.12619	0.00068	185.8
17046+3900	HJ 2804AB	0.10571	0.00126	84.1
18120+4355	ES 1419	0.08356	0.00066	126.3
18269+2950	HJ 1325	0.02183	0.00004	567.0
18489+1615	STF 2400AB	0.07898	0.00361	21.9
18580+6159	ES 1843	0.03934	0.00047	83.2
19289+3515	POP 34AB	0.15468	0.00518	29.9
19500+0637	J 1336AB	0.04701	0.00010	456.3
20087+1223	J 1338	0.07717	0.00001	5479.4
22415+3256	J 2376AB	0.06813	0.00558	12.2
23581+2840	HJ 995	0.10480	0.00044	239.3

To answer the question concerning the nature of motion of these pairs we need observations covering very long time intervals. Otherwise, the only possibility is to apply existing criteria for establishing whether the pair is gravitationally bound or not. We applied the method given in Tokovinin and Kiyaeva (2016). The characteristic speed of relative motion μ^* was calculated by using formula 2 from this paper, and the speed of relative motion μ was calculated by using the quantities obtainable from formulae 4 and 5. The normalized relative motion $\mu' = \mu/\mu^*$ was used in that paper as the criterion of determining the motion nature. A physical pair has $\mu' < 1.5$. When the normalized relative motion is $\mu' > 1.5$, the double star is an optical pair.

Then, we can compare these speeds, μ and μ^*. Optical pairs usually move substantially faster than the characteristic speed. As can be seen in Table 3, relative motion μ is much higher than the characteristic speed of relative motion μ^* in all pairs except in the case of pair STI 2051 AB. Its the normalized relative motion $\mu' = 0.8$. As the parallaxes of both components are almost equal (see Table 2), this pair is most likely a long-period binary.

4. CONCLUSIONS

From 2004 until now we have obtained several thousand CCD frames of double and multiple stars at NAOR. The data were published and sent to the international databases. There is a small number of pairs for which the star images were not visually separated and the measurements could not be carried out. The reasons are the proximity of the components and the limiting capabilities of the CCD camera and seeing.

Using our observational data, we have calculated the first orbits for two binaries, recalculated three orbits and for the first time calculated linear solutions for 32 pairs. By applying the criteria for establishing the nature of the movement, it was confirmed that the components are not gravitationally bound in 31 pairs. Only one pair is most likely a long-period binary.

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