Counter-Check of WDS Farihi Objects with GAIA DR2

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Abstract: The topic of this report is the recovery of 68 WDS FAR objects in GAIA DR2 with the intention to counter-check proposed potential gravitational relationship and assumed minimum distances between the components of these pairs.

1. Introduction

The Farihi et al. 2006 and 2010 papers on White Dwarf–Red Dwarf systems caught my attention with the approach to estimate the smallest possible distance between components of double stars with Monte Carlo simulation using photometry based distance estimations. I decided to cross-match the WDS FAR objects with GAIA DR2 and to counter-check for potential gravitational relationship (PGR) using GAIA DR2 RA, Dec and parallax data for a Monte Carlo simulation of the distance between the components of the double stars.

2. Cross-Match of WDS FAR Objects with GAIA DR2

The number of FAR objects, 68, is rather small so I decided to do the cross-match with GAIA DR2 manually by entering the RA/Dec coordinates into Aladin bringing up the DSS image for this position, loading the GAIA DR2 catalog on top and identifying the corresponding DR2 objects. In case of a positive cross-match for both components the data was copied into a spreadsheet executing a Monte Carlo simulation with sample size 120,000 using the RA, Dec and Plx values as mean values for a normal distribution with the given error range as standard deviation. The resulting Plx and Sep values were then used to calculate the distance between the components of the double star with the law of cosines to estimate the likelihood of a distance smaller than 200,000 AU (~1 parsec) considered as threshold for potential gravitational relationship (Knapp 2019) as well as the minimum, median and maximum distance covering the GAIA DR2 error range values.

Out of the 68 FAR objects, 23 are listed with a separation smaller than 0.4 arcseconds (the declared GAIA DR2 resolution limit) and for this reason not suited for cross-matching.

Out of the remaining 45 FAR objects 9 objects lack resolution in GAIA DR2 for at least one component and 36 could be matched successfully with GAIA DR2 objects but with 6 of them lacking parallax data necessary for PGR assessment. From the remaining 30 objects only 7 have a likelihood > 50% for a potential gravitational relationship and an additional 3 have a likelihood > 40%. 10 objects seem far outside the distance range allowing for PGR and can be considered as most likely optical pairs and another 10 pairs have a PGR likelihood between 3 and 18%, mostly due to rather large Plx errors, resulting in a huge spread in the likely distances and for this reason also most likely opticals.

Table 1 lists the following 2015.5 GAIA DR2 based data for the successfully cross-matched 30 FAR objects:

- WDS_ID WDS ID
- FAR FAR object number
- C Component (AB if blank)
- PA Position angle in degrees
- e_PA Error position angle
- Sep Separation in arcseconds
- e_Sep Error separation
- Vest1 Estimated Vmag1 calculated from GAIA DR2 G/B/R-mags
- e_Vest1 Error Vmag1 estimation (Vmag1 estimated only from Gmag if blank)
- Vest2 Estimated Vmag2 calculated from GAIA DR2 G/B/R-mags

- e_Vest2 Error Vmag2 estimation (Vmag2 estimated only from Gmag if blank)
- pmRA1 Proper motion RA1 in mas/yr
- pmDE1 Proper motion DE1 in mas/yr
- pmRA2 Proper motion RA2 in mas/yr
- pmDE2 Proper motion DE2 in mas/yr
- CPMR Common proper motion rating
- CPMS Common proper motion score
- Notes Notes

14 out of these 30 objects are with a CPM score >50% positively assessed for likely common proper motion.

The estimation of the visual magnitudes is based on GAIA DR2 G/B/R-mags using the formula

Vest = 3.9379083526304 + 0.269235360436179*Gmag^1.36701081887491 - 0.123879978164097*[Gmag-Rmag] - 0.943379695375539*[Gmag-Bmag]

with a regression coefficient of 0.999 and a standard deviation of 0.064 derived by statistical analysis using nonlinear regression with the UBVRI catalogs of Landolt&Clem (VizieR II/183A, J/AJ/146/88 and J/AJ/152/91) after eliminating a few outliers due to questionable cross-match results with GAIA DR2. This estimation formula shares the photometry caveats of GAIA DR2 for very bright (<10Gmag) and very faint (>18Gmag) objects according to Evans et al. 2018 and Riello et al. 2018. In case of missing GAIA DR2 Bmag and Rmag data the visual magnitude was estimated with an average delta of +0.318 to Gmag.

Table 2 lists the following 2015.5 GAIA DR2 based data for the successfully cross-matched 30 FAR objects using Monte Carlo simulation with a sample size of 120,000 allowing for an assessment for potential gravitational relationship (PGR):

- WDS_ID WDS ID
- FAR FAR object number
- C Component (AB if blank)
- Plx1 Parallax1 in mas
- e_Plx1 Error parallax1
- Plx2 Parallax2 in mas
- e_Plx2 Error parallax2
- Min_Dist_AU Minimum distance between the components in AU from GAIA DR2 data
- Far_MD_AU Minimum distance between the components in AU according to Farihi et al. 2010
- Median_AU Median distance between the components in AU from GAIA DR2 data
- Max_Dist_AU Maximum distance between the components in AU from GAIA DR2 data
- PGRS Potential gravitational relation ship score
- P_min Minimum orbit period using the minimum distance as semi-major axis with zero inclination and 2 Sun masses
- P_med Median orbit period using the median distance as semi-major axis with zero inclination and 2 Sun masses
- e_Plx1R Parallax1 error rating ("OK" if <0,5% and "X" if larger indicating a relia bility issue)
- e_Plx2R Parallax2 error rating ("OK" if <0,5% and "X" if larger indicating a reliability issue)

7 out of these 30 objects are with a PGR score >50% (means percentage of simulation results with a distance between the components smaller than 200,000 AU) positively assessed for being likely bound by gravitation but only 2 of them have a parallax error relation e_Plx/Plx <0.5% for both components making the positive PGR assessment for the other 5 objects somewhat questionable.

The Farihi et al. 2010 report gives for 10 out of the listed 30 FAR objects estimations for a minimum distance between the components and for 7 of these the GAIA DR2 data based estimations come very close to the Farihi et al. 2010 values even if in most cases for objects considered likely rather not physical due to large parallax error values causing a huge spread regarding distances. This also means that the given minimum distances have to be taken with the caveat that the likelihood for these distances is extremely small.

Summary

Only about 50% out of the 68 FAR objects could be recovered in GAIA DR2. Separations <0.4 arcseconds means below the self-declared resolution limit of GAIA DR2 (Arenou at al. 2018) are the main reason for a lack of resolution and most of these objects are so far still WDS listed with only 1 observation. Eight of the in total 36 objects listed with so far only 1 observation were positively cross-matched with GAIA DR2 raising the percentage of confirmed FAR objects from 47 to 59%.

The percentage of likely physical pairs is even with allowance for unfavourable parallax error relation with 7 out of 30 objects in the average of WDS CPM

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Table 1: 30 FAR objects with CPM assessment and estimated Vmags

WDS_ID	FAR	C	PA	e_PA	Sep	e_Sep	Vest1	e_Vest1	Vest2	e_Vest2	pmRA1	pmDE1	pmRA2	pmDE2	CPMR	CPMS	Notes
01083-3535	2		174.818	0.000	111.06771	0.00006	14.39173	0.00599	15.70410	0.00298	-38.296	-51.810	-38.254	-52.359	AAAC	95	
01186-2255	24		10.495	0.016	1.09295	0.00031	15.87625	0.01901	17.99490		34.990	-78.381	31.323	-82.705	DCAA	0	
01481-2533	26		334.006	0.002	2.32277	0.00006	16.04866	0.03364	14.35283	0.03157	133.908	-59.481	132.596	-56.811	ABAA	80	
02081+1336	27		10.196	0.009	1.25242	0.00019	14.46451	0.07342	15.08326	0.03683	44.764	-6.944	43.665	-6.811	ACAA	40	
02107-1507	28		38.344	0.003	2.62369	0.00012	16.00829	0.01528	15.51693	0.01587	33.755	60.475	34.987	56.633	CDAA	1	
03502-1335	32		263.044	0.031	1.06009	0.00056	15.71560		15.20378	0.05706	173.772	65.855	174.233	61.555	BAAA	80	
03591-2312	3		350.560	0.008	1.18173	0.00017	15.43053	0.01604	17.52806	0.10529	1.498	18.713	1.273	17.604	ADAA	5	
04202+3336	4		134.379	0.000	70.18403	0.00021	15.00384	0.00658	17.79442	0.02048	83.671	-175.117	83.717	-174.562	AAAB	97	
06291+4131	5		250.536	0.000	102.68132	0.00013	14.76988	0.00836	17.59708	0.01016	-10.587	-114.047	-10.698	-72.911	DDAC	0	
08271+2844	6	AB	120.528	0.003	3.34283	0.00015	14.01596	0.00791	16.61598	0.01176	-17.811	-13.164	-20.363	-13.677	CDAB	1	
09040+1349	7		174.780	0.002	3.76571	0.00011	15.99784	0.00542	16.54942	0.00691	-115.579	-22.206	-115.208	-26.764	CAAA	20	
09357+0222	56		167.209	0.010	1.22713	0.00022	16.21239	0.11185	16.65560		-5.101	-68.614	-6.733	-68.581	BAAA	80	
09384+7242	9		81.927	0.000	81.47100	0.00006	15.49111	0.00577	15.23911	0.00356	-55.128	-52.879	-56.645	-66.621	DDAB	0	
09524+4454	34	AB	121.444	0.002	2.88979	0.00012	15.77952	0.01576	16.40319	0.00877	-10.014	47.958	-14.335	45.177	DDAA	0	
10180+0721	11	AC	49.750	0.000	38.13383	0.00017	16.96490		17.15805	0.00889	-32.602	-26.032	-25.923	-30.340	DDAB	0	
10199+1217	12		337.779	0.000	50.23598	0.00019	15.54241	0.00836	16.76349	0.01407	-26.974	-20.274	-26.540	-20.045	ABAC	76	
12068+4450	13	BC	279.543	0.000	84.33665	0.00009	14.83166	0.00712	18.06783	0.01783	-41.500	-8.229	-64.994	-23.140	DDAC	0	WDS M2 in error?
12130+4610	63		83.266	0.013	1.06905	0.00024	14.77219	0.02032	16.52360		24.736	-57.249	27.242	-53.313	DDAA	0	WDS PA in error?
13006+5904	15		236.972	0.001	16.06750	0.00016	15.19067	0.00429	18.06895	0.01964	39.105	71.447	37.432	71.897	BAAB	78	
13104-1427	64		165.234	0.006	2.13540	0.00022	16.43476	0.10013	17.67277	0.16128	-51.756	-2.620	-51.159	-2.489	ABAA	80	
13360+4829	38		73.295	0.001	3.00494	0.00007	13.83375	0.00596	16.14048	0.01206	-134.097	-42.980	-127.551	-47.549	CDAA	1	
14150-0511	39		255.441	0.003	3.51168	0.00017	16.50544	0.01552	16.58284	0.00932	-5.051	-0.327	-5.423	-0.775	DDAB	0	
14376+3652	41		318.364	0.008	1.26588	0.00017	17.13000		16.45300	0.06010	-88.535	-104.037	-91.044	-105.056	ABAA	80	
14460+3329	42		285.532	0.014	0.67790	0.00017	15.94485	0.00876	16.02996	0.07784	29.430	-23.977	29.449	-24.190	AAAA	100	
15409+5253	17		69.046	0.002	2.85461	0.00009	16.21295	0.02449	16.02600	0.00557	18.057	9.444	16.640	8.120	BDAB	4	
16204+5223	45	AC	281.338	0.002	3.20549	0.00009	15.39742	0.00503	16.66030	0.01264	53.459	-17.421	-1.374	-11.831	DDAA	0	
16221+1214	18		311.205	0.000	62.48143	0.00005	8.81819	0.00181	14.45046	0.00479	64.784	-68.144	63.604	-66.828	ABAB	78	
17011+3016	19		330.254	0.000	149.10761	0.00005	14.81652	0.00588	14.66394	0.00993	19.874	-71.172	21.883	-70.069	BAAC	76	
18272+0404	20		126.138	0.000	60.28963	0.00034	13.76584	0.00379	19.13152	0.10610	-248.997	-284.164	-251.366	-286.433	AAAB	97	
21004+3426	1		104.419	0.001	46.44519	0.00057	15.48317	0.00502	19.44530		128.383	109.245	127.185	109.319	AAAB	97	

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Table 2: 30 FAR objects with PGR assessment and estimated minimum distances between the components

WDS_ID	FAR	C	Plx1	e_Plx1	Plx2	e_Plx2	Min_Dist_AU	Far_MD_AU	Median_AU	Max_Dist_AU	PGRS	P_min	P_med	e_Plx1R	e_Plx2R
01083-3535	2		10.7057	0.0595	10.6278	0.0361	10351		145795	686777	68	748767	39581917	X	OK
01186-2255	24		7.2530	0.2038	5.4608	0.1751	2754941		9338012	16207877	0	3251261359	20289211205	X	X
01481-2533	26		12.5663	0.0530	12.7320	0.0395	184	184	213041	603735	44	1772	69916094	OK	OK
02081+1336	27		4.9783	0.1038	5.6562	0.0653	1387745	238	4966706	9061911	0	1162380240	7870206942	X	X
02107-1507	28		10.5992	0.0663	10.1552	0.0818	3224	294	852339	1820221	0	130176	559502627	X	X
03502-1335	32		14.7511	0.0884	13.6212	0.4774	88	62	1163143	3977230	3	587	891934477	X	X
03591-2312	3		3.0243	0.0726	2.8607	0.1454	389	365	4067618	23672370	3	5453	5833023812	X	X
04202+3336	4		13.8287	0.0653	15.2195	0.1811	573875		1363621	2096296	0	309107218	1132202514	OK	X
06291+4131	5		17.1892	0.0631	6.8860	0.0908	16332922		17955283	19738695	0	46933109142	54096838651	OK	X
08271+2844	6	AB	6.5589	0.1550	6.6245	0.0713	497	604	582290	4656651	18	7888	315931017	X	X
09040+1349	7		17.7470	0.0661	17.8166	0.0771	211		56056	328508	99	2174	9436509	OK	OK
09357+0222	56		7.9095	0.1664	7.5771	0.1203	161	137	1144310	4024451	6	1451	870360135	X	X
09384+7242	9		12.3262	0.0490	7.4810	0.0236	10341538		10838150	11400426	0	23646191793	25369753042	OK	OK
09524+4454	34	AB	16.0519	0.0915	16.1291	0.1193	178	188	92050	536696	86	1689	19857268	X	X
10180+0721	11	AC	5.0748	0.1231	3.8713	0.0969	3515865		12629020	19990522	0	4687397244	31910820179	X	X
10199+1217	12		9.4445	0.0745	9.4716	0.1042	5175		204035	1574695	49	264683	65529994	X	X
12068+4450	13	BC	8.3051	0.0442	5.1134	0.0949	12487301		15503522	19082640	0	31375190996	43403928757	X	X
12130+4610	63		7.8174	0.1483	7.6169	0.1284	134	145	726846	3820816	14	1102	440602755	X	X
13006+5904	15		15.4197	0.0530	15.5909	0.1477	1035		151873	686450	65	23668	42082945	OK	X
13104-1427	64		5.4565	0.1262	5.7514	0.1334	378	288	1946105	7338016	4	5226	1930336375	X	X
13360+4829	38		27.0914	0.0367	27.0585	0.0610	111	100	14997	98255	100	828	1305799	OK	OK
14150-0511	39		3.0784	0.1412	2.9173	0.0809	1151	1360	3912304	20898722	3	27776	5502149031	X	X
14376+3652	41		7.4300	0.1153	7.6277	0.1139	167	201	732083	3319939	13	1539	445372900	X	X
14460+3329	42		4.4038	0.1280	4.4267	0.1383	158	192	1350700	8938710	8	1414	1116148299	X	X
15409+5253	17		5.4955	0.0582	5.5861	0.0275	513		609694	2569226	14	8265	338494621	X	OK
16204+5223	45	AC	11.1969	0.0500	1.5316	0.0445	100584844	503	116246909	135816266	0	717269424766	891159873312	OK	X
16221+1214	18		17.9599	0.0399	17.9485	0.0443	3465		26356	165634	100	145006	3042310	OK	OK
17011+3016	19		20.7275	0.0363	7.2880	0.0259	17916663		18351010	18810481	0	53922395056	55895064142	OK	OK
18272+0404	20		22.4153	0.0864	22.9758	0.2584	2669		224452	678579	41	98024	75607930	OK	X
21004+3426	1		19.0453	0.0446	19.0156	0.3701	2427		143953	1013216	65	84990	38834251	OK	X

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pairs thus not especially impressive. The concept of using the distances of the components with their angular separation for a Monte Carlo simulation to get an indication for the likely space distance between the components and in consequence for the minimal orbit period seems a valid one with the caveat that the likelihood for such minimum distances is often extremely small.

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- Aladin Sky Atlas v10.0
- GAIA DR2 catalog
- CDS VizieR
- Washington Double Star Catalog

References

F. Arenou, X. Luri, C. Babusiaux, C. Fabricius, A. Helmi, T. Muraveva, A. C. Robin, F. Spoto, A. Vallenari, T. Antoja, T. Cantat-Gaudin, C. Jordi, N. Leclerc, C. Reylé, M. Romero-Gómez, I-C. Shih, S. Soria, C. Barache, D. Bossini, A. Bragaglia, M. A. Breddels, M. Fabrizio, S. Lambert, P.M. Marrese, D. Massari, A. Moitinho, N. Robichon, L. Ruiz-Dern, R. Sordo, J. Veljanoski, P. Di Matteo, L. Eyer, G. Jasniewicz, E. Pancino, C. Soubiran, A. Spagna, P. Tanga, C. Turon, C. Zurbach, 2018, "Gaia Data Release 2: Catalogue validation", *Astronomy & Astrophysics*, **616**, A17.

D. W. Evans, M. Riello, F. De Angeli, J. M. Carrasco, P. Montegriffo, C. Fabricius, C. Jordi, L. Palaversa, C. Diener, G. Busso, M. Weiler, C. Cacciari, and F. van Leeuwen, 2018, "Gaia Data Release 2. The photometric content and validation", *Astronomy & Astrophysics*, **616**, A4.

J. Farihi, D. W. Hoard and S. Wachter, 2010, "White Dwarf–Red Dwarf Systems resolved with the Hubble Space Telescope. II. Full Snapshot Survey Results", *The Astrophysical Journal Supplement Series*, **190**, 275–296.

J. Farihi, D. W. Hoard and S. Wachter, 2006, "White Dwarf–Red Dwarf Systems resolved with the Hubble Space Telescope. I. First Results" *The Astrophysical Journal*, **646**, 480-492.

Knapp, Wilfried R. A., 2018, "A New Concept for Counter-Checking of Assumed Binaries", *Journal of Double Star Observations*, **14**, (3), 487.

M. Riello, F. De Angeli, D. W. Evans, G. Busso, N. C. Hambly, M. Davidson, P. W. Burgess, P. Montegriffo, P. J. Osborne, A. Kewley, J. M. Carrasco, C. Fabricius, C. Jordi, C. Cacciari, F. van Leeuwen, G. Holland, 2018, "Gaia Data Release 2: Processing of the photometric data", *Astronomy & Astrophysics*, **616**, A3.

Appendix A

Description of the CPM rating procedure (according Knapp and Nanson 2017 and Knapp 2018):

- Four rating factors are used: Proper motion vector direction, proper motion vector length, size of position error in relation to proper motion vector length and relation separation to proper motion speed
- Proper motion vector direction ratings: "A" for within the error range of identical direction, "B" for similar direction within the double error range, "C" for direction within the triple error range and "D" for outside
- Proper motion vector length ratings: "A" for identical length within the error range, "B" for similar length within the double error range, "C" for length within the triple error range and "D" for outside
- Error size ratings: "A" for error size of less than 5% of the proper motion vector length, "B" for less than 10%, "C" for less than 15% and "D" for a larger error size
- Relation separation to proper motion speed: "A" for less than 100 years, "B" for less than 1000 years, "C" or less than 10000 years and "D" for above

To compensate for the extremely small proper motion GAIA DR2 errors resulting in a worse than "A" rating despite only very small deviations an absolute lower limit is applied regardless of calculated error size:

- Proper motion vector direction: Max. 1° difference for an "A"
- Proper motion vector length: Max. 1% difference for an "A"

The letter based scoring is then transformed into an estimated likelihood for being CPM

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Description of the PGR assessment procedure:

- GAIA DR2 data for RA/Dec and Plx are used for a Monte Carlo simulation assuming a normal distribution for these parameters with the given error range as standard deviation. The distance between the components is calculated from the inverted simulated parallax data and the simulated angular separation using the law of cosines

$$c = \sqrt{a^2 - 2ab\cos\gamma + b^2}$$

with *a* and *b* = distance vectors for the stars A and B in light years calculated as (1000/Plx)*3.261631 and γ = angular separation in degrees calculated as

$$\gamma = \arccos\left[\sin(DE1)\sin(DE2) + \cos(DE1)\cos(DE2)\cos\left(\text{abs}(RA1 - RA2)\right)\right]$$

- The potential gravitational relationship score (PGRS) is the percentage of simulation results <200,000 AU (~1 parsec) out of the simulation sample with a size of 120,000 corresponding with the likelihood that the real distance is samller than 200,000 AU
- The smallest, median and largest distance is the smallest, median and largest result of the simulation sample