Physical Double Stars in GAMBLES

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Abstract: The GAMBLES (Gaia Assorted Mass Binaries Long Excluded from SLoWPoKES) project combines the data from TGAS (Tycho-Gaia Astrometric Solution) with the SloWPoKES (Sloan Low-mass Wide Pairs of Kinematically Equivalent Stars) approach to identify binaries. This report takes a critical look at this effort

Introduction

Brian Skiff made me aware of the interesting GAMBLES report combining data from the SDSS and GAIA projects to identify wide binaries assumed to have a gravitational relationship, despite the large distance between the components.

GAMBLES Objects

The GAMBLES project (Oelkers et al. 2017) combines the information from SDSS and TGAS (Michalik et al. 2015) for finding additional binary candidates based on a numerical cut process described in §3.1, but relies additionally on the galactic model used for SLoPoKES (Dhital et al. 2012) for evaluating if a pair is to be considered as a bona-fide binary.

Listed in Table 1 are a few randomly chosen GAMBLES objects from a total of 8660 GAMBLES objects (available for download under https://filtergraph.com/gambles - be aware that this is a living portal and that the data set might get updated. But any changes should be documented) with an assessment if these objects might be considered being binary based upon the existing TGAS proper motion (Table 1) and parallax data (Table 2). For CPM assessment counter-checking UCAC5 catalog (Zacharias et al. 2017) proper motion data was used and in a few cases for counter-counter-checking also the PM data calculated from comparing 2MASS and GAIA DR1 positions. As several GAMBLES objects are combined TGAS/SDSS objects (meaning that only one component is a TGAS object and the second is missing) I had also in such cases resorted to position comparison between 2MASS and GAIA DR1 for CPM assessment. I would have liked to be able to do an additional counter-check based on the announced GPS1 proper motion catalog (Tian et. al 2017) but at the time of writing this report (May 2017) this source was not yet available via VizieR.

Thirteen out of 22 randomly selected GAMBLES objects are (based on proper motion data from TGAS or from comparison of 2MASS to GAIA DR1) rated as solid CPM pairs with the rest a mixed bag of “might be” to “not at all”. The counter-check with UCAC5 gives surprisingly often a different picture compared with TGAS even if UCAC5 is based on plate solving with TGAS objects as reference stars so one would expect rather similar values here. TGAS proper motion data is based on position comparison of Tycho-2 to GAIA DR1 and the given error range is may be a bit over-optimistic (see Knapp 2017 - Physical Double Stars in TGAS). A potential Tycho-2 data quality issue (see for example the high error rate in the Tycho Double Star catalog according to Knapp/Gould 2016) might be involved here – once more, a lecture to never trust a single source.

Most of the positive rated GAMBLES objects in Table 1 show a separation of less than 20" and are already included in the WDS catalog – this demonstrates again as already stated in my report “Physical Double Stars in TGAS” (Knapp 2017) that most optical close pairs with magnitudes sufficient for visual observation are already very well covered by the traditional double

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Table 1. CPM Rating for the Selected GAMBLES Objects Based on GAIA Dr1 (Observation Epoch 2015

Description of the table contents:

- ID gives the GAMBLES ID of the selected object

- RA and Dec give the GAIA DR1/UCAC5 coordinates for the brighter component in decimal degrees format as these values are directly usable for calculating Sep and PA. Be aware that GAMBLES gives in many cases the coordinates for the fainter component as primary

*- Sep gives separation in arc seconds calculated from the GAIA DR1/UCAC5 coordinates of both components as SQRT(((RA2-RA1)*cos(Dec1))^2+(Dec2-Dec1)^2) in radians (Buchheim 2008)*

*- PA gives position angle in degrees calculated from the GAIA DR1/UCAC5 coordinates of both components as arctan((RA2-RA1)*cos(Dec1))/(Dec2-Dec1)) in radians depending on quadrant (Buchheim 2008). This parameter is not given in the GAMBLES data set*

- M1 and M2 give Gmags from GAIA DR1

- pmRA1 and pmDE1 with e_pm1 give the proper motion data for A and pmRA2, pmDE2 and e_pm2 for B from TGAS and UCAC5 and in a few cases from comparison 2MASS to GAIA DR1 positions

- Ap indicates the aperture used (for GAIA DR1 the calculated circular surface diameter)

- Me indicates the WDS code for the used observation method

- V/Epoch gives the V5-value of the SLoWPoKES galactic model cut in the header line and the observation epoch in the UCAC5 line. Epoch for the header line is in all cases 2015.0 (GAIA DR1)

- CPM Rat gives the rating of the CPM assessment based on comparison of the given PM data (see Appendix A for description)

ID	RA	Dec	Sep	PA	M1(G)	M2(G)	pmRA1	pmDec1	e_pm1	pmRA2	pmDec2	e_pm2	Ap	Me	V/Epoch	CPM Rat
2020 +0005	305.238879	0.094009067	56.713	260.114	8.57	9.84	18.989	-4.502	0.078	18.850	-4.890	1.597	0.96	Hg	0.002	AABC
Solid CPM object. Ident with WDS object SKF 926 (not listed as such in GAMBLES object table)																
	305.2388789	0.0940092	56.712	260.114	8.574	9.843	19.60	-3.80	3.394	20.40	-3.20	1.980	0.20	Eu	2000.636	AACC
Counter-check with UCAC5 – similar result despite some PM data differences																
1937 +3922	294.5132404	39.43318098	644.615	234.240	11.158	11.196	-2.58	-14.76	1.593	-0.80	-14.37	1.641	0.96	Hg	0.036	CACC
PM direction too different to be considered CPM. No WDS object																
	294.5132403	39.4331811	644.615	234.240	11.158	11.196	-0.60	-13.90	1.838	-0.50	-14.50	1.838	0.20	Eu	2002.670	AACC
Counter-check with UCAC5 – quite interesting difference in pmRA1 changing the CPM assessment significantly																
							3.10	-17.91	8.20	2.50	-18.01	5.78				AACC
Counter-counter-check based on position comparison 2MASS to GAIA DR1 confirming rather the UCAC5 assessment																
TYC 3135-516-1	294.3251152	39.32853957	6.511	312.939	11.196	16.131	2.50	-18.01	5.78	-45.46	13.66	10.60	0.96	Hg	2015.0	CCCB
The secondary of GBL1937+3922 is an optical double itself. GAIA DR1 data. PM data calculated from position comparison with 2MASS																
	294.325102	39.328613	5.681	314.343	11.5	15.9							1.30	E2	2000.321	
2MASS data. M1 and M2 estimated Vmags from J- and K-band																
1938 +4253	294.3499308	42.76026185	1,397.479	47.431	9.505	12.256	-1.47	-17.55	1.710	0.34	-16.90	1.854	0.96	Hg	0.036	CACC
PM direction far too different to be considered CPM. No WDS object																
	294.3499308	42.7602619	1,397.479	47.431	9.505	12.256	-2.30	-17.60	1.980	-0.90	-17.20	1.697	0.20	Eu	2003.379	BACC
Counter-check with UCAC5 – quite interesting differences in pmRA change the CPM assessment slightly																
							-5.62	-24.83	5.13	-1.37	-20.15	5.13				CCCC
Counter-counter-check based on position comparison 2MASS to GAIA DR1																
0625 -6119	96.20651963	-61.86119024	3,913.386	11.620	11.360	12.340	-0.80	14.86	1.878	-1.93	14.11	2.015	0.96	Hg	0.050	BACC
Potential CPM, but not very convincing. No WDS object																
	96.2065197	-61.8611903	3,913.386	11.620	11.360	12.340	-3.00	13.70	1.487	-1.20	14.10	1.556	0.20	Eu	1998.859	CACC
Counter-check with UCAC5 – difference in pmRA1 changes the CPM assessment																
							-1.63	12.05	5.74	7.33	20.51	5.74				CCCC
Counter-counter-check based on position comparison 2MASS to GAIA DR1																

Table 1 continues on next page.

Table 1 (continued) CPM Rating for the Selected GAMBLES Objects Based on GAIA Dr1 (Observation Epoch 2015

ID	RA	Dec	Sep	PA	M1(G)	M2(G)	pmRA1	pmDec1	e_pm1	pmRA2	pmDec2	e_pm2	Ap	Me	V/Epoch	CPM Rat
1024 - 4504	156.2412682	-45.06972645	2.291	259.166	9.551	9.907	3.98	30.47	1.149	3.49	30.17	1.179	0.96	Hg	0.001	AAAA
Perfect CPM candidate. Ident with WDS object HU 1475 (not listed as such in GAMBLES object table)																
	156.2412683	-45.0697264	2.291	259.158	9.551	9.907	4.20	31.50	2.404	2.30	31.10	2.970	0.20	Eu	1999.018	BABA
Counter-check with UCAC5 - PM data bit different from TGAS but still good CPM candidate																
0247 - 0600	41.87501175	-6.014436302	2.348	11.507	10.582	10.767	39.23	-30.67	1.477	39.53	-30.67	1.616	0.96	Hg	0.001	AAAA
Perfect CPM candidate. Ident with WDS object J 1245 (not listed as such in GAMBLES object table). Neither UCAC5 nor 2MASS object for B																
1354 - 1507	208.5424539	-15.12756763	2.433	110.940	9.499	9.754	-4.39	-18.57	1.684	-4.21	-18.67	1.729	0.96	Hg	0.001	AABB
Solid CPM candidate. Ident with WDS object SKI 7 (not listed as such in GAMBLES object table)																
	208.5424539	-15.1275675	2.433	110.952	9.499	9.754	-5.40	-20.60	2.759	-5.00	-21.30	3.394	0.20	Eu	1999.511	AACB
Counter-check with UCAC5 - PM data bit different from TGAS but still good CPM candidate																
1627 +3417	246.8204146	34.29165966	2.443	178.647	10.446	11.395	-4.29	22.59	1.080	-5.29	21.62	1.072	0.96	Hg	0.001	BAAB
Good CPM candidate. Ident with WDS object POP 1 (not listed as such in GAMBLES object table). Neither UCAC5 nor 2MASS object for B available																
2331 - 3317	352.775089	-33.28837406	10.182	297.045	9.169	10.720	12.65	3.68	0.229	12.72	3.99	0.301	0.96	Hg	0.001	AAAB
Solid CPM candidate. Ident with WDS object SEE 487 (not listed as such in GAMBLES object table)																
	352.7750889	-33.2883742	10.182	297.046	9.169	10.720	11.10	4.00	2.263	12.90	3.30	1.697	0.20	Eu	1998.834	BCCB
Counter-check UCAC5. PM data differences for A large enough to change CPM assessment																
							7.79	2.09	5.97	13.91	3.27	5.97				ACCC
Counter-counter-check 2MASS to GAIA DR1 - PM vector direction similar but length rather different																
2313 +4000	348.2769516	40.00282844	14.234	284.931	7.568	9.527	74.04	2.61	0.088	73.76	2.79	0.510	0.96	Hg	0.001	AAAB
Solid CPM candidate. Ident with WDS object STF 2992 (not listed as such in GAMBLES object table)																
	348.2769517	40.0028283	14.234	284.933	7.568	9.527	71.00	10.10	3.253	72.80	3.70	2.828	0.20	Eu	2002.663	BAAB
Counter-check with UCAC5. Large difference in pmDE, but still good CPM candidate																
2233 - 3815	338.4315751	-38.25942098	18.747	305.230	10.226	10.236	23.34	-26.69	0.960	22.94	-26.80	1.010	0.96	Hg	0.001	AAAB
Solid CPM candidate. No WDS object																
	338.431575	-38.2594211	18.747	305.232	10.226	10.236	22.70	-26.80	1.414	22.80	-26.70	1.414	0.20	Eu	1998.772	AAAB
Counter-check with UCAC5 - PM data quite similar																
1150 +0529	177.6056927	5.4839787	78.15	325.5	10.17	16.13	57.23	-25.83	9.96	55.62	-20.42	10.30	0.96	Hg	0.001	BBCC
GAIA DR1 data (lacking PM and Plx data for B). PM calculated from position comparison with 2MASS. Some probability of CPM but PM error rather large																
	177.6054560	5.4840850	78.07	325.5	10.26	15.60							1.30	E2	2000.181	
2MASS data. M1 and M2 estimated Vmags from J- and K-band																
0024 +1053	6.1630134	10.8872868	26.04	58.0	10.36	18.08	67.30	-19.95	6.84	67.01	-18.24	6.84	0.96	Hg	0.001	AABB
Solid CPM candidate. GAIA DR1 data. M1 and M2 are G-band. PM data calculated from position comparison with 2MASS																
	6.16273800	10.8873670	26.03	58.1	10.57	17.51							1.30	E2	2000.532	
2MASS data. M1 and M2 estimated Vmags from J- and K-band																
0019 - 0442	4.7872519	-4.7102533	32.93	172.6	10.51	18.20	-13.90	-37.63	5.66	-13.39	-34.63	6.14	0.96	Hg	0.001	ABCB
Good CPM candidate. GAIA DR1 data. M1 and M2 are G-band. PM data calculated from position comparison with 2MASS																
	4.78731500	-4.7100830	32.98	172.6	10.73	17.43							1.30	E2	1998.705	
2MASS data. M1 and M2 estimated Vmags from J- and K-band																
0005 - 2039	1.4893554	-20.6487599	24.09	219.2	10.31	10.86	-6.77	-49.66	1.16	-6.50	-49.65	0.97	0.96	Hg	0.001	AAAB
Solid CPM candidate. Ident with WDS object HJ 3236 already Z-coded for similar parallax (not listed as such in GAMBLES object table)																
	1.4893553	-20.64876	24.094	219.176	10.309	10.856	-7.30	-49.30	1.556	-7.50	-49.00	1.556	0.20	Eu	1999.607	AAAB
Counter-check UCAC5: CPM assessment confirmed																

Table 1 concludes on next page.

Table 1 (conclusion) CPM Rating for the Selected GAMBLES Objects Based on GAIA Dr1 (Observation Epoch 2015

ID	RA	Dec	Sep	PA	M1(G)	M2(G)	pmRA1	pmDec1	e_pm1	pmRA2	pmDec2	e_pm2	Ap	Me	V/Epoch	CPM Rat
0135 - 6522	23.8725391	-65.3661761	2.70	183.9	10.14	10.58	11.22	-12.70	0.97	10.47	-12.96	0.88	0.96	Hg	0.001	AABB
Solid CPM candidate. Ident with WDS object DON 19 (not listed as such in GAMBLES object table)																
	23.8725392	-65.3661761	2.704	183.862	10.143	10.582	10.60	-11.30	1.414	12.50	-16.50	2.687	0.20	Eu	1998.617	CCCB
Counter-check UCAC5: PM data suggests rather optical																
2234 +2820	340.1710704	27.93949539	10,337.344	286.394	10.851	11.805	-39.25	-13.60	2.014	-39.90	-13.83	3.779	0.96	Hg	0.001	AABC
Solid CPM candidate – although the relationship separation to pm speed is far beyond 1000 years																
	340.1710703	27.9394953	10,337.344	286.394	10.851	11.805	-39.10	-15.60	1.697	-34.70	-11.80	1.556	0.20	Eu	2001.708	BCAC
Counter-check UCAC5: No confirmation of CPM																
2259 +1212	345.526058	10.44132718	13,548.208	339.324	10.800	11.962	40.97	4.31	3.594	44.68	2.42	3.576	0.96	Hg	0.016	BBBC
Weak CPM candidate. Primary ident with WDS object J 294 (J 294 AB potential physical with orbit – similar direction but slightly different speed)																
	345.5260581	10.4413272	13,548.208	339.324	10.800	11.962	42.20	5.50	1.838	43.30	0.70	1.769	0.20	Eu	2000.830	CAAC
Counter-check UCAC5: Rather not CPM while J 294 AB gets “solid CPM candidate” assessment																
0756 - 6049	119.1878974	-60.81503214	621.288	260.207	8.343	9.437	-4.28	12.02	0.989	-4.82	11.11	0.819	0.96	Hg	0.009	BBBC
Weak CPM candidate. Primary ident with WDS object HJ 4027																
	119.1878975	-60.8150322	621.843	260.216	8.343	9.437	-3.40	10.10	2.263	-3.10	10.20	2.404	0.20	Eu	1998.889	AACC
Counter-check UCAC5: Better CPM assessment than with TGAS																
0218 +5954	34.80717753	59.65993771	1,940.901	334.758	11.296	12.136	15.64	-14.63	1.277	17.38	-14.38	2.405	0.96	Hg	0.009	BBCC
Weak CPM candidate																
	34.8071775	59.6599378	1,946.154	334.432	11.296	12.136	15.60	-14.80	1.697	15.60	-13.60	1.697	0.20	Eu	2003.694	AABC
Counter-check UCAC5: Better CPM assessment than with TGAS																
0038 - 0110	9.7459680	-1.1633681	26.79	166.4	9.47	16.96	0.89	109.80	8.24	-0.06	107.63	8.24	0.96	Hg	0.001	AABB
Solid CPM candidate. PM data calculated from position comparison 2MASS to GAIA DR1. No UCAC5 object for companion. GBL0038-0110 covers components AC from a CPM triple with B missing in GAMBLES with data given below																
	9.7459680	-1.1633681	11.05	354.4	9.47	12.91	0.89	109.80	8.24	1.39	110.64	8.24	0.96	Hg	2015.0	AABB
AB pair. Solid CPM candidate. PM data calculated from position comparison 2MASS to GAIA DR1. No UCAC5 object for companion																
0005 +1620	1.3513841	16.3288810	89.11	336.9	8.50	8.68	32.25	-29.73	0.08	32.39	-29.33	1.60	0.96	Hg	0.001	AAAC
Solid CPM candidate. WDS object STTA 255 already V-coded																
	1.3513842	16.3288811	89.106	336.936	8.496	8.677	35.00	-30.10	2.687	34.10	-29.00	2.687	0.20	Eu	2000.879	AABC
Counter-check with UCAC5 - PM data quite similar																

Physical Double Stars in GAMBLES

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star observer community. This hit rate gets somewhat smaller with increasing separation but there are still a lot of already WDS listed pairs included in the GAMBLES data set. A check of the first 150 GAMBLES objects sorted by angular separation (means up to about 30") shows that only 1/3 of these objects are not already included in the WDS catalog with a good part of them with magnitudes fainter than 18mag, meaning not really suited for visual observation. A WDS counter-check has been done but in most cases we find an "NA" in the GAMBLES WDS_MATCH column, even if a corresponding WDS object obviously exists. Only for 6 of these about 100 WDS objects did we find a reference in the WDS_MATCH column.

Table 2 shows for TGAS objects the check for a potential gravitational relationship based on the given Plx data with the GAMBLES distance value given for comparison.

The used assessment criteria for gravitational relationship with less than 200,000 AU distance between the components might be an over-simplification but you certainly have to have very good arguments to argue for a gravitational relationship with distances larger than that. This means that only about 5% of the 8,860 GAMBLES objects fulfill this criterion and more than 80% are listed with a distance of more than 1,000,000 AU.

Not counting the objects with missing Plx data for the secondary we get 3 objects with an AA, 4 with an AB, and 1 with an AC rating meaning a reasonable probability of gravitational relationship between the components for, in total, 8 out of 17 objects. But even the objects with an AA rating have only a rather small chance in this regard - if we assume the given Plx values as mean values of a normal distribution and the given Plx error as standard deviation then this would give for example for HU 1475 a probability of only ~7% for a distance below 200,000 AU. For most GAMBLES objects, the measured parallax is quite small with relatively large error values. Quite interesting is the pattern that the distance given by GAMBLES is in all cases very near the assumed best case with a rather constant uplift. Explanation from the corresponding author "... we also used the approximation of Fischer & Marcy 1992 to calculate the true separation and not the projected separation. They used a Monte Carlo simulation to attempt to convert from a projected to true separation between stars by taking into account different binary orientations. This approximation led to a~1.26d where d is the projected separation ...". But this means that GAMBLES works generally with an overly optimistic approach regarding distances between the components ignoring the measured GAIA Plx differences as well as the often huge error range in relation to the small Plx values.

Only 145 GAMBLES objects have a reasonable small Plx error range of less than 5% (necessary for an A rating) and only ~1,280 have a Plx error range between 5 and 10% (necessary for a B rating) – this means that over 80% of the GAMBLES objects show a Plx error beyond a reasonable error range rendering any conclusions from this data rather as basically suspect.

Another interesting aspect of the GAMBLES data set is that around 8,000 of the listed objects (meaning the vast majority) have a huge angular separation of more than 1,000 up to 38,000 arcseconds, which means over 10 degrees. Such huge angular separations of the objects increase the probability of similar PM and Plx values by pure chance.

Overall common proper motion rating statistic

Running the proper motion rating scheme (see Appendix A) over all GAMBLES objects resulted in the following statistic:

Out of 8,660 objects 5,049 were rated with AA## beginning with 13 AAAA (meaning a perfect CPM candidate) to 322 AACC (meaning a good CPM candidate with caveat regarding pm data error larger than 10% of pm vector length and with relation separation/proper motion>1000 years)

Next, 1,559 objects have an AB## rating (meaning a potential CPM pair) with very similar proper motion vector direction, but caveats regarding somewhat different PM vector length

Finally, we have 2,052 objects with a rating starting with ACBC down to a few with CCCC, meaning most probably not CPM pairs.

Summary

In total the combination of the results of table 1 and 2 suggests that about 1/3 of the GAMBLES objects are in effect not only travelling with similar speed parallel through space but that they are close enough to be considered being in a gravitational relationship. The GAMBLES report states that only a few objects of the total data set might be false positives but this seems to be overly optimistic considering the given error range of the used TGAS/SDSS data.

The fact that many GAMBLES objects are already included in the WDS catalog but not declared as such allows the conclusion that the WDS counter-check was not done very carefully, but also that the GAMBLES selection process is valid, demonstrated by rediscovering already known double stars.

If it makes sense to add the rest of the GAMBLES

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Table 2. PM evaluation data and Plx Rating for the selected GAMBLES Objects

ID: GAMBLES object ID
- PMVD: Proper motion vector direction in degrees for A and B and delta AB
- PMVL: Proper motion vector length for A and B and delta AB derived from GAIA DR1 pm values
- Plx: Parallax A and B end parallax error A and B from GAIA DR1
- Dist GBL: Distance (rounded) between the components in AU according to GAMBLES
- Dist AB min: Approx. minimum distance between the components in AU assuming equal averaged Plx
- Dist AB Plx: Approx. distance between the components in AU according to the given GAIA DR1 parallax values
- Dist AB max: Approx. maximum Distance between the components in AU according to the given GAIA DR1 Plx values with full error range applied
- Plx Rating:
- Distance Rating for potential gravitational relationship with "A" for less than 200,000 AU (assuming average mass stars like our sun with then overlapping Oort clouds), "B" for less than 300,000 AU (with some probability for a smaller distance within the given Plx error range) and "C" for above
- Rating for relationship Plx error to Plx value with "A" for less than 5%, "B" for less than 10% and "C" for above

ID	PMVD A	PMVD B	Δ PMVD	PMVL A	PMVL B	Δ PMVL	Plx A	Plx B	e_Plx A	e_Plx B	Dist GBL	Dist AB min	Dist AB Plx	Dist AB max	Plx Rat
2020 +0005	103.34	104.54	1.21	19.52	19.47	0.04	4.08	4.13	0.34	0.35	17,406	13,725	611,908	9,105,412	CB
SKF 926: Very small probability for gravitational relationship. Plx error reasonable small compared to Plx data															
1937 +3922	189.93	183.20	6.73	14.98	14.39	0.59	2.01	1.97	0.28	0.42	408,094	320,711	2,108,221	43,004,199	**CC**
Most probably no gravitational relationship															
1938 +4253	184.79	178.84	5.94	17.61	16.90	0.71	2.61	2.63	0.28	0.33	672,036	531,372	802,213	18,849,498	**CC**
No reason to assume gravitational relationship															
0625 -6119	356.92	352.23	4.70	14.88	14.24	0.64	2.08	2.15	0.34	0.45	2,334,920	1,820,218	3,706,458	39,253,422	**CC**
Distance between the components beyond any probability of gravitational relationship															
1024 -4504	7.44	6.60	0.84	30.73	30.37	0.36	7.30	7.33	0.31	0.27	394	313	115,646	2,368,500	**AA**
HU 1475: High probability of gravitational relationship															
0247 -0600	128.02	127.81	0.21	49.79	50.03	0.24	5.77	5.79	0.25	0.24	512	406	123,484	3,160,444	**AA**
J 1245: High probability of gravitational relationship															
1354 -1507	193.30	192.71	0.59	19.08	19.14	0.06	4.40	4.40	0.27	0.35	697	553	553	6,761,671	**AB**
SKI 7: Good probability of gravitational relationship but Plx error in relation to Plx value rather high															
1627 +3417	349.24	346.25	2.99	23.00	22.26	0.74	3.28	3.25	0.22	0.26	941	745	580,495	10,052,294	**CB**
POP 1: Most probably no gravitational relationship															
2331 -3317	73.80	72.60	1.20	13.17	13.33	0.15	4.69	4.68	0.25	0.25	2,739	2,171	94,001	4,806,996	**AB**
SEE 487: Potential gravitational relationship seems plausible															
2313 +4000	87.98	87.83	0.15	74.09	73.81	0.27	5.08	5.06	0.28	0.25	3,538	2,802	160,515	4,400,349	**AB**
STF 2992: Potential gravitational relationship seems plausible															
2233 -3815	138.84	139.43	0.59	35.45	35.28	0.18	3.39	3.39	0.29	0.31	6,965	5,530	5,530	10,919,104	**AB**
No WDS object. Potential gravitational relationship seems plausible															
1150 +0529	157.04			67.81			9.23		0.84		11,619				
No PM and Plx data for B available. Plx error for A rather large															

Table 2 continues on next page.

Table 2 (conclusion). PM evaluation data and Plx Rating for the selected GAMBLES Objects

ID	PMVD A	PMVD B	Δ PMVD	PMVL A	PMVL B	Δ PMVL	Plx A	Plx B	e_Plx A	e_Plx B	Dist GBL	Dist AB min	Dist AB Plx	Dist AB max	Plx Rat
0024 +1053	167.06			64.14			5.09		0.61		6,324				
No PM and Plx data for B available. Plx error for A rather large															
0019 -0442	200.65			45.39			4.54		0.58		8,814				
No PM and Plx data for B available. Plx error for A rather large															
0005 -2039	187.76	187.46	0.31	50.12	50.07	0.04	5.92	5.93	0.30	0.28	5,124	4,063	58,897	3,487,054	**AA**
HJ 3236: High probability of gravitational relationship															
0135 -6522	138.53	141.08	2.55	16.94	16.66	0.28	3.27	3.24	0.27	0.25	1,044	827	584,068	10,718,215	**CB**
DON 19: Most probably no gravitational relationship															
2234 +2820	250.88	250.88	0.00	41.54	42.23	0.69	4.00	4.12	0.57	0.92	3,194,200	2.509.117	2.924.303	19.373.526	**CC**
No WDS object. No reason to assume gravitational relationship															
2259 +1212	83.99	86.91	2.92	41.20	44.75	3.55	5.42	5.31	0.79	0.79	3,179,490	2,499,722	2,621,096	12,668,197	**CC**
Primary ident with WDS object J 294: No reason to assume gravitational relationship															
0756 -6049	336.53	340.41	3.88	12.11	12.76	0.65	2.30	2.35	0.28	0.31	336,683	264,619	1,926,394	24,570,070	**CC**
Primary ident with HJ 4027: No reason to assume gravitational relationship															
0218 +5954	129.60	133.10	3.50	22.55	21.42	1.14	2.57	2.53	0.44	0.25	959,694	757,274	1,477,724	21,954,031	**CC**
No WDS object. No reason to assume gravitational relationship															
0038 -0110	1.22			106.94			14.09		0.38		2,523				
No PM and Plx data for B or C available. Plx error for A quite small – looks despite the missing Plx data for B and C rather promising for gravitational relationship															
0005 +1620	132.67	132.16	0.51	43.86	43.70	0.16	4.74	4.72	0.77	0.38	23,733	18,799	185,349	10,092.053	**AC**
Good probability for gravitational relation despite a rather large PM error for A															

Physical Double Stars in GAMBLES

(Continued from page 47)

objects to the WSD catalog if not already included is unclear to me – it would boost the number of the infamous 999.9" separation WDS objects from currently ~500 to 8,500 with zero appeal for visual observation or imaging. In terms of already very optimistically calculated distances between the components we get values up to 3,194,200 AU or more than 50 light years (GBL 2234+2820) – that such a distance would allow any conclusions regarding gravitational binding energy seems questionable to me. Even more disturbing is the fact that the Plx-based distance estimation between the components seems extremely optimistic. With these usually rather small Plx values, an already small error range means a potentially huge distance range, rendering speculations about gravitational relationship even more questionable.

By chance, I checked for one of the objects (GBL0756-6049) in the adjacent star field and found that this object is obviously part of the open cluster NGC 2516. Looking at the other components of this cluster, I found more than 20 cluster components listed as GAMBLES objects. Another example for such a situation is GBL0157+3755 being, along with many other GAMBLES objects, part of the open cluster NGC 752. This suggests that it would be necessary to check the GAMBLES data set not only for already known double stars, but also for open clusters. In other areas of the sky, the density of GAMBLES objects with similar proper motion is quite obvious (for example around GBL0213+5940, see Figure 1) suggesting the detection of an unknown open cluster.

Not as dense but similarly impressive, are the regions around GBL0717-4603 and GBL0753-6039, suggesting again the detection of an unknown open clusters giving the GAMBLES project a completely different scope (see also Appendix C and D on draft reports Oh et al. 2016 and Andrews et al. 2017).

A minor issue is the missing position angle usually given for double stars. While it is easy to calculate this value using the positions given for both components, the number of digits provided for the positions is too small to get sufficiently precise results.

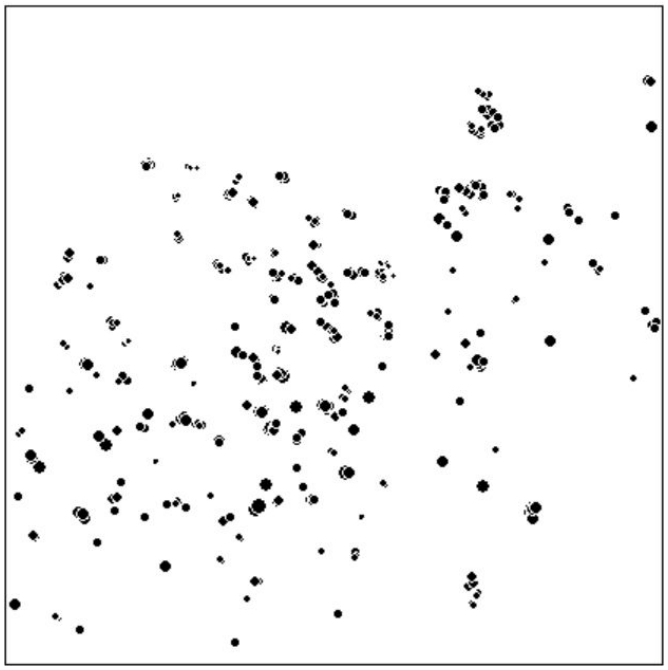

Figure 1. Density of GAMBLES objects around GBL0213+5940 (FoV 2°) suggesting an open cluster

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- Washington Double Star Catalog
- 2MASS All Sky Catalog
- SDSS7/9 Catalog
- SLoWPoKES I/II Catalog
- GAMBLES dataset from the Filtergraph portal per end of April 2017
- GAIA DR1 Catalog including TGAS
- UCAC5 catalog
- Aladin Sky Atlas v9.0
- VizieR
- AstroPlanner v2.2
- ARI's Gaia Services (http://gaia.ari.uni-heidelberg.de/)

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Appendix A - Description of the CPM rating procedure

Four rating factors are used: Proper motion vector direction, proper motion vector length, size of position error in relation to proper motion vector length according to Knapp and Nanson 2017 with extension for relation separation to proper motion speed:

- Proper motion vector direction ratings: "A" for identical direction within the error range (given by assuming the worst case of the position error pointing in right angle to the PM vector), "B" for similar direction within the double error range, and "C" for outside
- Proper motion vector length ratings: "A" for identical length within the error range (given by assuming the worst case of the position error pointing in the direction if the PM vector), "B" for similar length within the double error range, and C for outside
- Error size ratings: "A" for error size of less than 5% of the proper motion vector length, "B" for less than 10%, and "C" for a larger error size
- Relation separation to proper motion speed: "A" for less than 100 years, "B" for less than 1000 years and "C" for above

To compensate for excessively large position errors resulting in an "A" rating despite rather high deviations an absolute upper limit is applied regardless of calculated error size:

- Proper motion vector direction: Max. 2.86° difference for an "A" and 5.72° for a "B"
- Proper motion vector length: Max. 5% difference for an "A" and 10% for a "B"

- To compensate for any overly small error "allowance" (result of a combination of very small position error with large PM vector length) the following exceptions are applied:
- If the PM vector direction difference is larger than this calculated "allowed" error but still less than 0.5° then an "A" is given, a "B" is given for larger than 0.5 but less than 1 degree, and a "C" is given if above
- If the PM vector length difference is larger than this calculated "allowed" error but still less than 0.5% then an "A" is given, a "B" is given for larger than 0.5 but less than 1 percent, and a "C" is given if above.

Appendix B – Quotes from the private email communication with Ryan Oelkers

Re missing position angle: "For our purposes, we didn't need it in the analysis and the referee didn't ask for it so I didn't include it. With the filtergraph portal, however, we can update the data set based on suggestions. I can add this for an update to the next version"

Re the given primary is often the fainter component of the pair: "We estimated the masses of the objects with the photometry and then, depending on which object was larger, we marked that as the primary"

Re imprecise check for WDS matches: "I only had time to do a very basic match, which as you say was not very precise. I can certainly do a more robust match and update the portal"

Re angular separations larger than 1,000 arc-seconds: "This was actually a request by the referee. We no longer limited the TGAS-TGAS search to be within 180" and instead set a maximum separation of ~15pc so we didn't exclude wide co-moving pairs at close heliocentric distances"

Re many GAMBLES objects are either components of already known open clusters or strongly indicate open clusters so far not known: "I agree! There have actually been two other papers which have similar findings in TGAS …"

Re doubts about gravitational relationship for extremely wide pairs like GBL2234+2820: "Also the binary you mention at the end (GBL2234+2820) isn't included in our high-fidelity sample, the lifetime is way too short and the binding energy is too low, so we agree that it is likely the object would have already dissipated gravitationally"

Appendix C – Quick check of Andrews et al. 2017 (Wide Binaries in Tycho-Gaia)

Ryan Oelkers made me aware of this draft paper with the topic of wide binaries in TGAS with a different selection process compared to GAMBLES based on Bayesian probabilities with a counter-check for matches with several well-known open clusters like Pleiades etc. At the time of this research (May 2017) the complete data set was not available to me so I had to put up with the printed table of 10 objects.

Despite the different selection process I would have expected some overlap with GAMBLES but to my surprise only the second object of this table has a corresponding GAMBLES object. As to expect all of the objects with an angular separation below 30" are already included in the WDS catalog. From the other objects (means neither included in GAMBLES nor in WDS) only two show proper motion similar enough to assume CPM. Caveat:

Table Appendix C: Quick-check of objects from Andrews et al. 2017

Tycho-2 ID	CPM	Plx	Comment
2789-319-1 2789-1122-1	ACCC	CC	Rather not convincing CPM and Plx rating. Plx value quite small with in relation huge error
594-134-1 594-81-1	AABC	AC	Quite good CPM and Plx rating. Corresponds with GAMBLES object (GBL0000+0952)
7526-320-1 7526-515-1	AAAC	CB	Quite good CPM and not very convincing Plx rating
4014-3283-1 4014-1005-1	AAAB	AA	Nearly perfect CPM and perfect Plx rating. Corresponds with WDS object STI 1248
2271-911-1 2271-1988-1	ACAB	CB	Mixed bag of CPM and Plx rating. Corresponds with WDS object ES 221
3254-569-1 3254-1352-1	CBCC	CC	Rather not convincing CPM and Plx rating. Plx value quite small with in relation large error
9137-1774-1 9137-1708-1	AAAB	CB	Quite solid CPM and less convincing Plx rating. Corresponds with WDS object GLI 290
4298-598-1 4298-574-1	ACCC	CB	Rather not convincing CPM and Plx rating
1-1016-1 1-168-1	AABC	CC	Quite good CPM but less than convincing Plx rating
1729-1129-1 1729-1118-1	BCAC	CB	Rather not convincing CPM and Plx rating. Corresponds with WDS object TVB 2

Appendix D – Quick check of Oh et al. 2016 (Co-moving stars in Gaia DR1)

Ryan Oelkers made me aware of this draft paper with the topic of wide commoving stars in TGAS again with a different selection process compared to GAMBLES combined with a focus on detection of open clusters and very wide pairs. The result are 13,085 co-moving star pairs including well known but also newly detected open clusters and a large number of very wide pairs. At the time of this research (May 2017) the complete data set was not available to me so I had to put up with the printed table of 10 objects.

There is obviously some overlap with GAMBLES objects but not with pairs but with components of different pairs—obviously mostly stars of open clusters with a multitude of possibilities to combine members as pairs. Only 2 out of 10 objects are not overlapping with GAMBLES. Caveat: This result refers to the draft version of this paper and might change with the final version

Table Appendix D: Quick-check of objects from Oh et al. 2016

GAIA source ID	CPM	Plx	Comment
2492823414036945924413715238994758 40	AAAC	CA	Very solid CPM but less convincing Plx rating. Both components are included in GAMBLES but with different companions – obviously part of an open cluster
2490872811676624644419016946624929 28	AAAC	CA	Very solid CPM but less convincing Plx rating. Both components are included in GAMBLES but with different companions – obviously part of an open cluster
6493375512282112066786500935624320	ABAC	CB	Quite solid CPM but less convincing Plx rating. Both components are included in GAMBLES but with different companions – obviously part of an open cluster (Pleiades)
4365362497182237444413569210106712 32	ABAC	CA	Quite solid CPM but less convincing Plx rating. Both components are included in GAMBLES but with different companions – obviously part of an open cluster
3953625835302703488400870672928935552 0	CCAC	CA	Rather negative CPM and Plx rating. Both components are included in GAMBLES but with different companions
637303052866976006518808590620352 0	ABAC	CA	Quite solid CPM but less convincing Plx rating. Both components are included in GAMBLES but with different companions – obviously part of an open cluster (Pleiades)
1873311936758998016187331207419794739 2	AAAC	CB	Quite solid CPM but less convincing Plx rating
5814505765886192512581499741938072294 4	AAAC	CB	Quite solid CPM but less convincing Plx rating. One component is included in GAMBLES but with a different companion
350903157411208832352510643410053632	AABC	CA	Quite good CPM but less convincing Plx rating
641142410028104966761828148471654 4	CCAC	CA	Less than convincing CPM and Plx rating. Both components are included in GAMBLES but with different companions – probably part of an open cluster