Cross-Match of WDS KOI Objects with Gaia DR2

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Abstract: The WDS catalog contains in total 2,640 pairs with the designation KOI. So far (per end of August 2018) only 835 such objects have been confirmed by at least a second observation. Out of these 835 confirmed KOI objects 594 or ~71% were recovered as GAIA DR2 pairs. This statistic has been broken down to separation classes to check the performance of GAIA DR2 for resolving doubles in more detail. Additionally 1,043 KOI objects with so far only one observation have been confirmed by GAIA DR2 raising the percentage of confirmed KOI objects from ~32% to ~62%. Finally the matched KOI objects were checked for being potential binaries by means of common parallax.

Regarding GAIA Performance: With an update of the WDS data base in September 2018 with GAIA DR1 matches the number of confirmed KOI objects increased from 835 to 1,167 so the added value of GAIA DR2 compared to DR1 is not only the availability of proper motion and parallax data beyond TGAS but also in a significant larger number of confirmed objects.

1. Introduction

As follow up to our report "KOI objects in the WDS catalog" (Knapp&Nanson 2019) we checked this time the complete range of WDS KOI objects against the GAIA DR2 catalog.

Using the CDS TAP-VizieR tool in total 2,640 KOI objects were selected from the WDS catalog. Using the CDS X-match tool these objects were then for the primary cross-matched with DR2 with a search radius of 5" around the given WDS J2000 position. Due to the density of DR2 objects this yielded 5,237 objects. With the given GAIA DR2 J2000 positions and the WDS data for separation and position angle the J2000 position for the secondary was calculated with the caveat that GAIA DR2 provides for a few of the components of the KOI objects no proper motion values and thus the calculated positions were a mix of J2000 and J2015.5 coordinates. These calculated positions were again matched with GAIA DR2 but this time with 2" search radius for the secondaries giving 3,218 objects including the unavoidable self-matches for the primaries for objects with a separation below the 2" search radius.

As next step a drill down process was started after calculating separation and position angle for the found pairs (observation epoch J2015.5):

- Eliminating the self-matches of the primaries mentioned above
- Eliminating all pairs with a difference between calculated and WDS position angle larger than 15°
- Eliminating all pairs with a difference between calculated and WDS separation larger than 25%
- Sorting the objects by discoverer ID and checking for multiple matches made clear which objects had to be checked in detail to keep the best matches with the given WDS parameters not only for position angle and separation but also for the magnitudes
- Finally the remaining matches were checked for a corresponding magnitude delta between the components with a cut for the difference of 3 magnitudes
- As nearly all magnitudes for KOI objects are given in the red band a second check regarding the magnitudes was done to eliminate all objects with Gmags brighter than given WDS mags larger than 1.5mag – this leaves still some room for magnitude

errors in WDS as well GAIA DR2
- End result were then 1,636 remaining KOI to GAIA DR2 matches considered to be valid.

An update of the WDS catalog based on the ~80,000 GAIA DR1 matches from our report on estimating visual magnitudes (Knapp&Nanson 2018) became effective during September 2018 also for a good part of the KOI objects rendering the per end of August 2018 given number of observations for some objects as obsolete.

2. Results

The details of this cross-match and drill down process are as follows:

- 120 KOI objects are (in the WDS "precise *last* only" list) given with a separation smaller than 0.4" with 55 of them confirmed with more than 1 observation – no match is to be expected for this class of objects as this is the declared resolution limit of GAIA DR2 (Arenou et al. 2018)
- 128 KOI objects are listed with 0.4 to 1 arcsecond separation with 73 of them confirmed with more than 1 observation. 17 such objects were recovered as GAIA DR2 pairs which means a hit rate of 23%. In total 31 objects in this class were resolved in GAIA DR2 which means 14 new confirmations but also that only about 24% of the KOI pairs in this range got a hit. Taking the recovery rate for the confirmed objects as expectation for the rest of so far unconfirmed objects in this range we can estimate the number of KOI bogus objects in this class to be zero
- 305 KOI objects are listed in WDS with a separation between 1 and 2 arcseconds with 109 of them confirmed with more than 1 observation. 83 such objects were recovered as GAIA DR2 pairs means a hit rate of 76%. In total 202 objects in this class were resolved in GAIA DR2 which means 119 new confirmations. If we take the 76% ratio as expectation for this class of objects we can expect ~40 bogus KOI objects here
- 645 KOI objects are listed in WDS with a separation between 2 and 3 arcseconds with 206 of them confirmed by more than 1 observation. 165 such objects were recovered as GAIA DR2 pairs means a hit rate of 80%. In total 468 objects in this class were resolved in GAIA DR2 which means 303 new confirmations. If we take the 80% ratio as expectation for this class of objects we can expect ~60 bogus KOI objects here
- 1,442 KOI objects are listed in WDS with a separation of larger than 3 arcseconds with 392 of them confirmed by more than 1 observation. 340 such objects were recovered as GAIA DR2 pairs means a hit rate of 87%. In total 972 objects in this class were resolved in GAIA DR2 which means 632 new confirmations. If we take the 87% ratio as expectation for this class of objects we can expect ~325 bogus KOI objects here.

Some side results:
- KOI 652 AC might be a duplicate of KOI 652 AB despite listed with 3 observations
- KOI1316 AC might be a duplicate of KOI 316 AB despite listed with 3 observations
- KOI2579 AB and AC are nearly undecidable matches, AC was selected due to a better match with the given magnitudes. It seems possible that AB and AC are duplicates
- KOI6969 B and KOI 6970 B are identical
- KOI7126 B is a double itself, two measurements A;Ba and A;Bb are given as match for KOI7126 AB
- KOI2283 AB comes with a separation delta >20% for the second observation but is a perfect match with the first observation
- KOI 959 comes with an angular distance from the given J2000 position larger than 4" but this is explained by very fast proper motion. This object is also listed in GAIA DR2 with a rather bright secondary compared to the given WDS magnitude but this is still considered to be a correct match.

To counter-check our processes for being consistent we located the 30 GAIA DR2 matches from our first KOI report (Knapp&Nanson 2019) in the final list and eliminated them to avoid duplicated reporting.

In Table 1 the first 20 rows of the list of the cross-matched KOI objects are given with a subset of the data. The full list with all columns can be downloaded from the JDSO website as "KOI XX DR2":.

3. Check for Binaries

Finally the found matches were checked for being potentially binaries by calculating the distance between the components of the pairs using the parallax data provided by GAIA DR2 which was the case for at least a part of the objects. After eliminating all objects with missing or negative parallax values or Plx values smaller than 3 times the given parallax error range 564 pairs remained available for assessment according to Knapp 2018 (see Appendix A). Only 4 pairs qualified as being probable physical pairs, which is less than 1% of the

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Cross-Match of WDS KOI objects with GAIA DR2

Table 1: Results cross-match WDS KOI objects with GAIA DR2

WDS	Disc	Comp	RA	Dec	Sep	PA	Gmag1	Gmag2	Plx1	Plx2	pmRA1	pmDec1	pmRA2	pmDec2
18410+4355	KOI3245		280.2495197	43.91506649	1.52743	184.553	12.41836	15.42990	1.9464	2.4805	8.389	-9.518	4.973	-8.831
18414+4350	KOI5457		280.3420874	43.83342728	1.33796	131.231	12.36358	12.36656	2.7475	3.5644	8.425	1.472	6.868	2.789
18426+4745	KOI 533		280.6414331	47.75205808	2.82135	255.145	14.66114	20.48529	1.6032	2.9229	8.221	25.512	5.213	23.154
18428+4355	KOI2486	AC	280.6903699	43.91905386	6.23914	84.954	12.97476	19.74163	2.0868	0.6172	6.855	-23.145	-3.963	-8.477
18437+4405	KOI1985		280.926162	44.08780364	2.78140	154.656	13.70406	18.03290	3.2413	3.0707	3.246	-24.711	2.953	-25.079
18442+4259	KOI4599		281.0436156	42.97565439	2.04427	80.883	15.30131	19.93481	0.9977	0.0320	0.283	-19.197	2.332	-14.154
18442+4319	KOI2734		281.0491988	43.32259957	2.34910	89.036	15.78024	19.17308	1.1620	0.2177	5.054	1.280	-1.670	-7.056
18445+4317	KOI4419	AB	281.1162646	43.28231994	3.96294	115.525	15.11679	20.49738	3.7793	-0.7957	-26.761	-27.821	-1.121	-1.685
18454+4340	KOI6925		281.356505	43.65860363	2.49519	126.857	15.77305	17.58996	2.9496	2.9140	-26.187	45.110	-26.093	45.903
18454+4418	KOI1820		281.3487514	44.29525246	3.70873	180.296	13.50332	20.15283	2.4682	2.1648	-7.230	3.248	5.900	1.011
18462+4414	KOI4799		281.5526276	44.22864001	3.50937	283.289	14.24587	20.22990	1.3471	-1.2733	-8.959	18.921	-1.927	-4.832
18463+4304	KOI3995		281.5757503	43.06812594	3.75982	116.810	13.31339	14.85094	0.7267	0.6290	8.050	-0.380	-5.240	-1.715
18466+4157	KOI3284	AC	281.6457236	41.95106862	3.96370	3.854	14.48515	16.80051	5.1035	1.2625	-16.762	-4.921	4.658	-5.412
18466+4335	KOI5427		281.6596045	43.58789916	3.06132	175.714	15.00100	18.72624	0.8306	0.3328	-0.117	2.447	1.854	3.081
18468+4224	KOI2914	AB	281.6915657	42.39744618	3.78573	231.351	12.13935	17.73056	1.2469	0.1011	-7.688	-15.501	1.265	-11.026
18473+4249	KOI4136		281.8231767	42.81119787	3.67657	108.592	13.95949	20.16504	0.7689	0.5617	-1.800	9.022	0.152	-1.004
18481+4338	KOI1818		282.0354942	43.63124905	2.31928	230.341	14.04304	20.07801	1.7124		0.198	-0.801		
18481+4423	KOI2385		282.0173492	44.38576419	3.54624	337.061	15.81119	20.49753	1.0424	-0.1559	-5.533	3.727	-5.275	-11.031
18485+4418	KOI4399	AB	282.1288496	44.30294392	2.11639	16.942	11.97393	17.66495	4.7145	6.7850	0.273	-39.979	0.867	-38.607
18486+4214	KOI 667		282.1544897	42.23459339	2.98301	133.005	17.25899	17.28079	0.7087	0.2418	-4.527	-3.782	-2.123	-5.837

Description of the table content:

WDS = WDS ID
Disc = Discoverer code
Comp = Components
RA = RA observation epoch 2015.5 in degrees
Dec = Dec observation epoch 2015.5 in degrees
Sep = Separation in arcseconds
PA = Position angle in degrees
Gmag1 = Gmag1
Gmag2 = Gmag2
Plx1 = Parallax 1 in mas
Plx2 = Parallax 2 in mas
pmRA1 = Proper motion RA 1 in mas
pmDec1 = Proper motion Dec 1 in mas
pmRA2 = Proper motion RA 2 in mas
pmDec2 = Proper motion Dec 2 in mas

pairs listed with usable Plx data. As the average ratio in the WDS catalog is about 15% V- or T-coded this result is quite a disappointment and raises the question why KOI objects are WDS listed as double stars at all.

In Table 2 the first 20 rows of the list of the cross-matched KOI objects are given with a subset of the data. The full list with all columns can be downloaded from the JDSO website as "KOI XX DR2 Plx".

4. Summary

To sum up the results above we get 2,520 KOI objects with a separation larger than 0.4" with 780 of them with two or more observations. 605 such objects were recovered in GAIA DR2 which means (not counting the objects with separation below 0.4") an overall hit rate of 77.5%. In total 1,673 KOI objects got resolved in GAIA DR1/2 which means close to 900 new confirmations. And overall we have to expect that ~ 425 KOI objects are most probably bogus (which means close to 17%) if we don't find other reasons for them to be not resolved in GAIA DR2 as for example extreme faintness beyond the GAIA resolution limit. Counter-checking this assumption for objects with separation >3" we found that indeed in most cases red magnitudes in the range of 20 mag or even fainter are given so the number of bogus objects to expect should be significantly smaller.

Taking a look at the GAIA DR2 recovery performance we find that pairs below 0.4" separation are generally not covered (Arenou at al. 2018). Pairs between 0.4 and 1.0" separation have a hit rate of ~23% and for objects with separation larger than 1" we find a hit rate of 76%, larger than 2" of 80% and larger than 3" of 87%. These values are slightly inferior to those of doubles with brighter secondaries (see for example Knapp 2018 on Tycho Double Stars) but obviously good enough to be of interest for getting confirmations for neglected WDS objects and especially important seems the possibility to check pairs for being potentially binaries using the GAIA DR2 parallax data.

Overall summary: While there are certainly very good reasons that KOI objects are of interest for the Kepler mission, there are with very few exceptions, certainly no reasons that KOI objects should be of interest as double stars – so any effort to get confirmation for the remaining WDS KOI objects with currently only one observation is probably of little use. But one object is certainly of special interest: KOI 959 – currently without proper motion and parallax data in GAIA but according to the LSPM catalog probably a pair with very fast common proper motion.

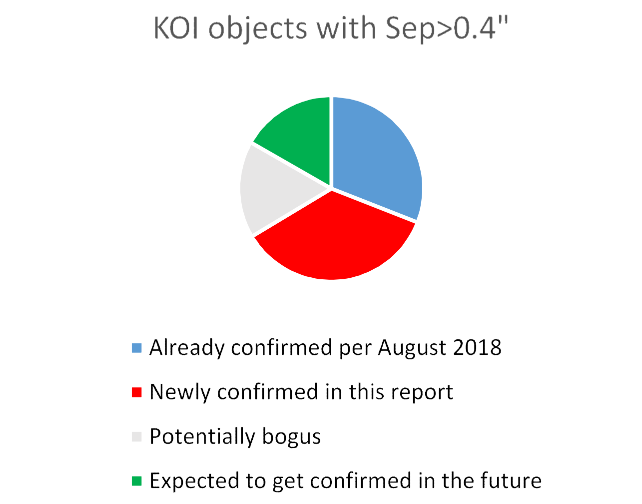

Figure 1: Confirmation status of WDS KOI objects

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Cross-Match of WDS KOI objects with GAIA DR2

Table 2: Results of assessment for being physical based on parallax and separation

WDS	Disc	Comp	Plx1	Plx2	Sep	BCD	RCD	WCD	Plx Rat	Plx Sco	Notes
18410+4355	KOI3245		1.9464	2.4805	1.52743	15850508.017	22818415.946	29160027.344	DA	1	S
18414+4350	KOI5457		2.7475	3.5644	1.33796	2873818.599	17205963.673	36338144.104	DC	1	S
18426+4745	KOI 533		1.6032	2.9229	2.82135	25762451.788	58090858.781	76181092.372	DD	1	S
18437+4405	KOI1985		3.2413	3.0707	2.78140	660576.175	3535547.397	6623453.156	DA	1	S
18454+4340	KOI6925		2.9496	2.9140	2.49519	837.386	854342.051	4057733.658	CA	20	
18463+4304	KOI3995		0.7267	0.6290	3.75982	26568968.732	44088264.456	62200298.193	DA	1	S
18466+4157	KOI3284	AC	5.1035	1.2625	3.96370	111908741.111	122964300.287	135384296.690	DA	1	S
18485+4418	KOI4399	AB	4.7145	6.7850	2.11639	11187317.184	13351313.219	15285207.435	DA	1	S
18486+4214	KOI 667		0.7087	0.2418	2.98301	339258237.035	562003973.585	934741185.595	DC	1	S
18489+4816	KOI1287		0.6860	0.6786	2.54694	3547.337	3278900.755	53657800.601	CB	19	
18507+4135	KOI6023	AC	0.5536	0.3341	3.43035	163761613.959	244791429.943	338977656.864	DB	1	S
18516+4150	KOI6702		0.8687	0.9094	1.76030	1976.126	10626833.763	23764459.274	CA	20	
18526+4508	KOI 42	AB	6.7495	6.8521	1.66390	245.712	457600.373	974432.771	CA	20	
18533+4150	KOI 852	AC	0.7854	0.5447	5.95329	70854369.779	116054520.334	168540844.889	DB	1	S
18533+4824	KOI3564		1.6115	1.5645	4.87474	807709.538	3845265.758	6901710.092	DA	1	S
18534+4112	KOI4016	AC	4.0534	2.4449	3.33564	20880342.231	33479174.676	51250369.791	DB	1	S
18534+4112	KOI4016	AD	4.0534	3.8398	5.54167	1135102.139	2830788.847	4614794.780	DA	1	S
18534+4833	KOI 344	AB	2.1559	2.6572	4.14546	8282194.595	18050078.369	26088412.888	DB	1	S
18535+4149	KOI 510		1.1785	1.1002	2.39097	1988.705	12456464.145	35427245.260	CB	19	
18536+4131	KOI2542		3.8392	5.3342	0.76280	10853296.271	15057934.450	19647372.050	DA	1	S

Description of the table content:

WDS = WDS ID

Disc = WDS discoverer code

Comp = Components (AB if blank)

Plx1 = Parallax for primary

Plx2 = Parallax for secondary

Sep = Separation in arcseconds

BCD = Best case distance A to B in AU

RCD = Realistic case distance A to B in AU

WCD = Worst case distance A to B in AU

Plx Rat = Letter based rating for potential gravitational relationship with first letter for distance and second letter for error size

Plx Sco = Estimated probability for potential gravitational relationship

Notes = Suggested WDS code either "T" for physical or "S" for optical, else blank

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- Washington Double Star Catalog
- GAIA DR2 catalog
- Aladin Sky Atlas
- CDS TAP-VizieR TAP
- CDS X-match

Appendix A
Description of the Plx Rating Procedure

- The distance vector of the two components of a pair is calculated with the naive approach 1/Plx +/- error range and the distance between the components is then calculated using the law of cosines with the two resulting vectors and the given angular separation
- "A" for worst case distance (Plx with errors applied for largest possible result), "B" for realistic case distance (using given Plx without error) and "C" for best case distance (using Plx with errors applied for smallest possible result) less than 200,000 AU (means touching Oort clouds for two stars with Sun-like mass) and "D" for above
- "A" for Plx error less than 5% of Plx, "B" for less than 10%, "C" for less than 15% and "D" for above

The letter based scoring is then transformed into an estimated probability for being potentially gravitationally bound