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

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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. If we take the 23% ratio as expectation for this class of objects we can estimate the number of KOI objects here 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 which 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 which 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
- KOI 1316 AC might be a duplicate of KOI 316 AB despite listed with 3 observations
- KOI 2579 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
- KOI 6969 B and KOI 6970 B are identical
- KOI 7126 B is a double itself, two measurements A;Ba and A;Bb are given as match for KOI 7126 AB
- KOI 2283 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

(Continued on page 245)
### Table 1: Results cross-match WDS KOI objects with GAIA DR2

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**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 roughly 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.

References


Knapp, Wilfried R.A. and Nanson, John – 2019, KOI objects in the WDS catalog, submitted to JDSO August 10th
Table 2: Results of assessment for being physical based on parallax and separation

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<td>20888412.888</td>
<td>DB</td>
<td>1</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>18536+4131</td>
<td>KOI12542</td>
<td>3.8392</td>
<td>5.3342</td>
<td>0.76280</td>
<td>10853296.273</td>
<td>15057934.450</td>
<td>19647372.050</td>
<td>DA</td>
<td>1</td>
<td>S</td>
<td></td>
</tr>
</tbody>
</table>

Description of the table content:
- **WDS** = WDS ID
- **Disc** = WDS discoverer code
- **Comp** = Components (AB if blank)
- **Plx** = 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
Cross-Match of WDS KOI objects with GAIA DR2

Acknowledgements
The following tools and resources have been used for this research:

- 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