The “True” Movement of Double Stars in Space

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Abstract: Common movement of any kind (proper motion, transverse velocity, radial velocity, total or spatial velocity) of double star components is neither a sufficient nor a necessary criterion to consider a double star as likely physical. This proposition is substantiated by analysis of the movement of double star components in space and confirmed by counter-checking with double stars listed in the 6th Catalog of Orbits of Visual Binary Stars. An earlier suggested assessment scheme for potential gravitational relationship (PGR) based on the likely distance between the components of a double star is discussed more in detail.

1. Introduction

Several recent papers like for example:

- Harshaw 2018 with the statement that in general, doubles with an orbit should have common proper motion
- Greaves 2019 with the assumption that common radial velocity allows for the conclusion that a double star is physically related
- Bryant 2019 with the assumption that common spatial velocity allows for the conclusion that a double star is physically related
- Jiménez-Esteban et al. 2019 with the idea that co-moving systems should be considered as physically bound
- Winter et al. 2019 with the statement “A wide companion would have a similar proper motion to its primary and would thus appear to move in the same direction at the same speed across the sky”

made me aware, that the common notion that common movement of any kind is required for a double star to be considered as likely physical needs a closer look. I have reported myself a considerable number of double stars as likely physical by means of common proper motion (Knapp 2018 – 495 and 2126 CPM pairs) for which a critical review already took place (Knapp 2019) with the result that only ~20% of these pairs are potentially bound by gravitation. See also Appendix B for a counter-check of object samples from the reports mentioned above.

2. Data on Movement of Double Stars

RA/Dec coordinates, angular separation, position angle, magnitude, spectral class, proper motion, parallax, radial velocity and in best case orbital elements are the data usually used to describe the properties of double stars. The “true” movement through space of the components of a double star can at least for a given point of time derived from such data and used for the purpose to draw conclusions if a double star might be considered physical or not. During the work on the “A Catalog of High Proper Motion Stars in the Southern Sky” report (Knapp and Nanson 2019) I became aware that especially common proper motion (meaning very similar to identical proper motion vector length and direction) is not necessarily required for a double star to be considered physical but also that common proper motion pairs are very often most likely not (or not anymore) bound by gravitation.

The term “motion” suggests that proper motion data indicate a specific movement of stars – but as a matter of fact these data reflect “only” the position change of a star in the used RA/Dec coordinate system between two observation epochs given as *pmRA* and *pmDE* in mas/yr for RA and Dec calculated as

The "True" Movement of Double Stars in Space

$$pmRA = \left(RA2 - RA1\right)\frac{\cos\left(DE1\right)}{\Delta t}$$

and

$$pmDE = \frac{DE2 - De1}{\Delta t}$$

with *RA1*and *DE1* for the coordinates of observation 1 and *RA2* and *DE2* for the coordinates of observation 2 and Δ*t* for the time delta between the observations. The cosine of *DE1* is needed due to the spherical property of the coordinate system with the caveat that this formula is sufficiently precise only for small position deltas which is usually the case even for stars with very high proper motion.

Proper motion data thus depend on the time frame given and are for this reason not constant values but usually slightly changing when considering different time frames and as already mentioned proper motion data give no direct information on star movement itself but reflect only the effects of the true motion of the star related to the RA/Dec coordinate system.

Identical proper motion vector length and direction values might even stand for very different star movement depending on the distance of the star – for example a *pmVL* (proper motion vector length calculated from *pmRA* and *pmDE* as $mVL = (pmRA^2 + pmDE^2)^{1/2}$) of 50mas/yr indicates a star movement perpendicular to our line of sight (transverse or tangential velocity *Vt*) of ~145km/s if the distance to the star is 100 light years but only ~14.5km/s with a distance of 10 light years. The distance of a star in parsecs can easily be calculated with the simple if less reliable parallax inversion *d* = 1000/*Plx* or be determined by looking up the VizieR I/347 catalog ("Distances to 1.33 billion stars in Gaia DR2" from Bailer-Jones et al. 2018) and the distance in light years can then be calculated by multiplication of parsec with 3.261631. The transverse velocity can in a shortcut be calculated directly from *pmVL* and *Plx* as

$$Vt = 4.74\frac{pmVL}{Plx}$$

But also transverse velocity *Vt* is not the "true" movement of a star because it does not reflect the depth of the space, but only the apparent tangential star movement.

The movement of the star along the line of sight away from or towards our solar system is the radial velocity *Vr*, usually given in km/s and can be quite high even if proper motion and, consequently, the transverse velocity is near zero.

Finally the combination of transverse and radial velocity using Pythagoras' theorem gives the overall star velocity V in space again in km/s:

$$V = \sqrt{Vt^2 + Vr^2}$$

Here the proper motion data joins in again as the proper motion vector direction indicates in combination with the direction of the radial velocity the plane of the star's movement (up/down and left/right) and the angle between total and radial velocity indicates if the movement is more radial if zero to 45° or more transverse if 45 to 90°, both in relation to the RA/Dec coordinate system.

GAIA DR2 provides for many objects not only precise coordinates but also proper motion, parallax and radial velocity data so everything is in place to calculate the movement of a star through space if only for a specific point of time.

It is usually assumed that if significantly high movement data values overlap each other for both stars within the given error range this allows for assessing a double star for being likely a physical pair – the WDS catalog uses for such cases the code "V" standing for "Proper motion or other technique indicates that this pair is physical". Indeed the selection of double stars by criteria of this kind certainly increases the chance for a positive hit significantly if only because high motion values are mostly connected with stars rather close to

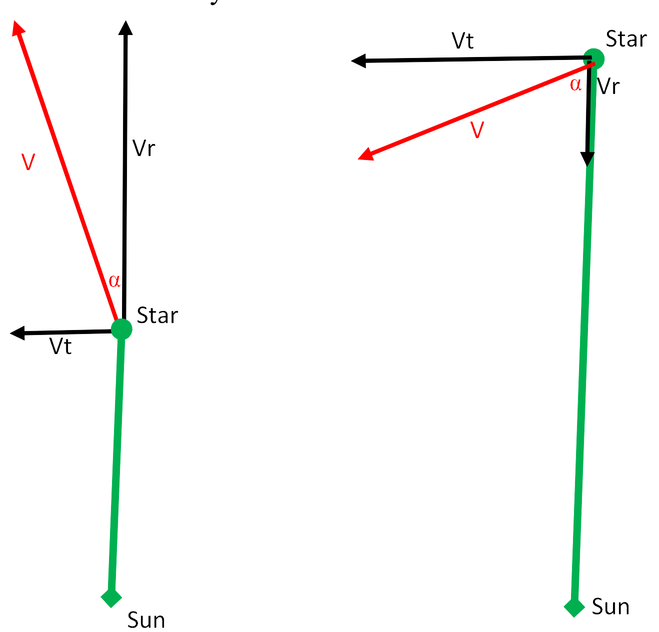

Figure 1: Velocity of stars. Vt = transverse velocity, Vr = radial velocity, V = total velocity of the star, α = angle of total velocity

The "True" Movement of Double Stars in Space

our solar system. Yet the likelihood that common proper motion pairs qualify for PGR seems to be in average less than 25% as is shown for example in two reports on such objects (Knapp 2019 on KPP and SKF objects). And the overall quality of such a selection process is certainly less than satisfying because the hit rate gets the larger the larger the error range gets and on the other side it leads to the exclusion of double stars being very well likely physicals – so common proper motion, common transverse velocity, common radial velocity, common total velocity, common parallax are obviously not sufficient criteria to declare a pair of stars as likely physical. Stars close enough for potential gravitational relationship (PGR) will in many if not most cases not have "common" movements due to gravitational forces as even the most simple idea of an orbit defines the movements of the secondary as significant different from the movements of the primary depending on the position of the secondary in the orbit. The speed of the secondary in very eccentric orbits can change from nearly zero in apastron (maximum distance to barycenter) to 100km/s or more in periastron (smallest distance to barycenter) and can thus be a significant part of the total velocity of the secondary. The total velocity of the secondary is for this reason often very different from the total velocity of the primary.

This means in consequence a total switch of perspective: Not common but over time changing movement of the components of a visual double star over time is useful for assessing if a pair is likely physical or optical. This concept is already some time in use if so far mostly for detecting the wobble of the primaries of visually unresolved pairs. For example searching for radial velocity variations is especially useful for detecting binaries with very short periods (Ashley at al. 2019) or looking for proper motion anomalies helps to detect so far unrecognized companions (Graczyk at al. 2019). A recent paper on the topic of proper motion anomalies (Kervella et al. 2019) gives a detailed discussion of this approach aiming at the detection of long period orbit multiples by comparing long term proper motion values based on comparison of Hipparcos to GAIA DR2 coordinates with the short term proper motion values of Hipparcos and GAIA DR2. And Bessel published already 175 years ago his report about variations of the proper motion values of Sirius (Bessel 1844) assumed to be caused by an unseen companion – visually resolved for the first time about 20 years later.

3. True Movement of Double Star Components with Gravitational Relationship

While in many cases gravitational relationship might simply mean traveling through space close enough to influence the direction and velocity of nearby star movements for some time to a measurable extent the most interesting form of such a relationship is a common center of gravitation (barycenter) with both stars traveling on ellipses around this center.

As the movement of the barycenter of a star system is usually not zero what we see is a wobble of the primary along the path of the barycenter and a larger wobble of the secondary along the path of the primary depending on the masses and other properties of the components of the star system like velocity and direction and speed of spin. This effect on the primary is true even for very unequal masses of the components – even the Sun wobbles due to the effects of the masses of the planets.

The basic model of a double star orbit corresponds to the movement of planets around a star: A low mass secondary moves on an elliptical path around a high mass primary with the barycenter inside the primary as shown in Figures 2 to 4. This basic model is obviously more fiction than fact but certainly a useful concept for describing true physical pairs.

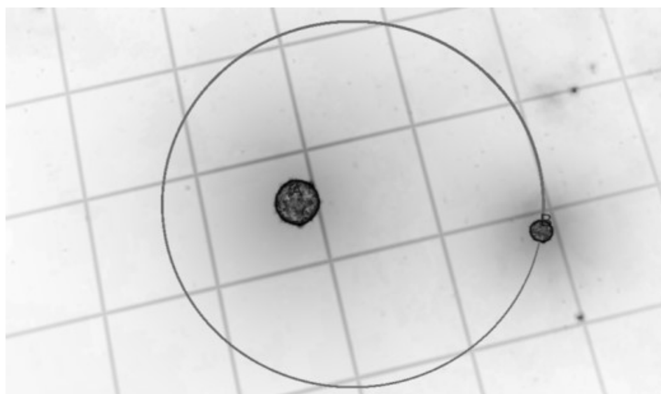

Figure 2: Basic model of an orbit

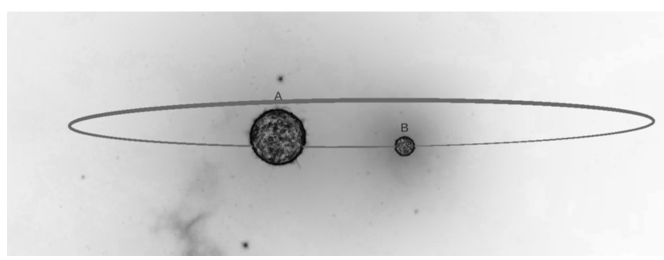

Figure 3: Same apparent orbit seen with different plane

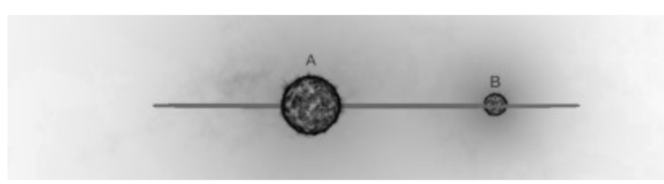

Figure 4: Same apparent orbit seen from the side – B seems to move just back and forth

The "True" Movement of Double Stars in Space

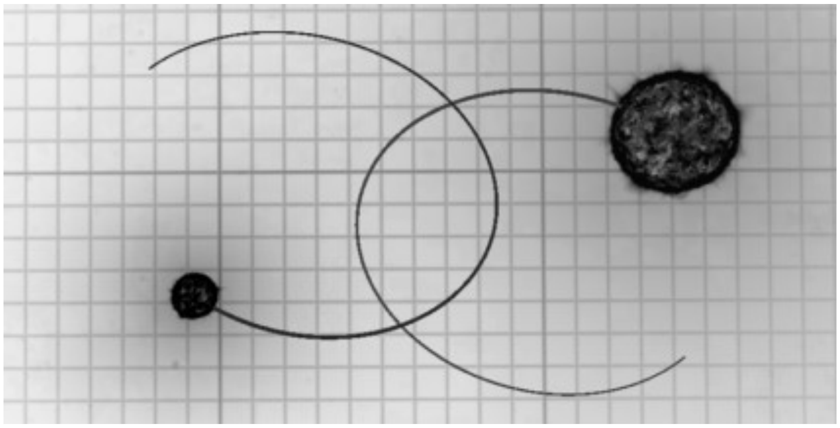

Figure 5. Two stars move on separate orbits around the barycenter

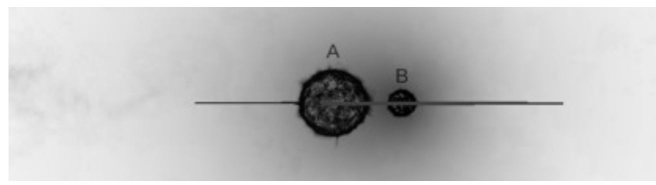

Figure 6. Same two orbits seen from the side – again B seems to simply move back and forth

The more realistic model of a double star orbit: Two components move on their own ellipses around the barycenter of the system (Figures 5 and 6).

Adding some velocity to the double star as system gives a more dynamic picture: The primary wobbles along the movement of the barycenter, the secondary moves in a spiral around the path of the primary (Figures 7 and 8).

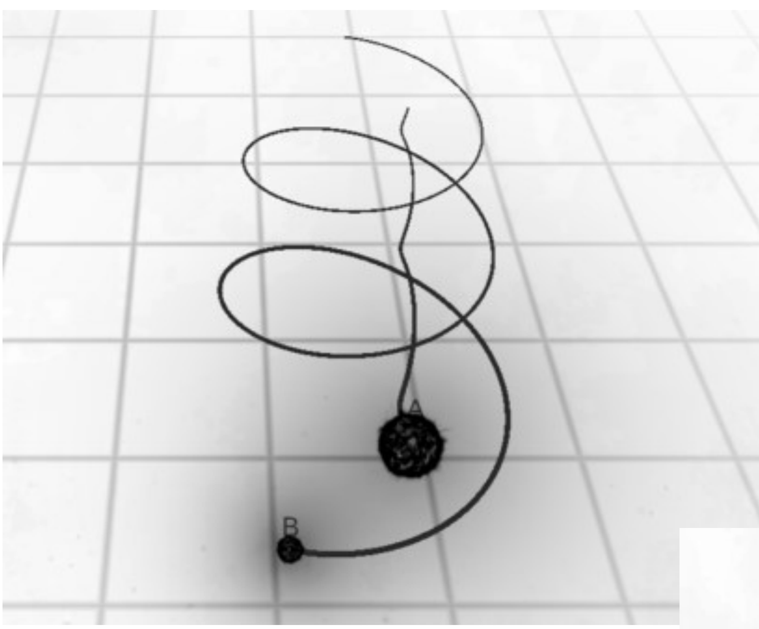

Figure 7. Primary wobbles along the movement of the barycenter, the secondary moves in a spiral around the path of the primary

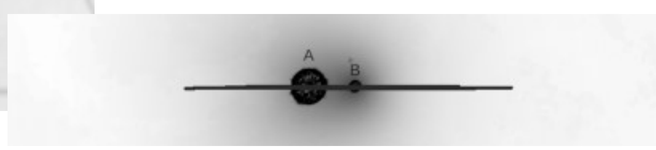

Figure 8. Same scenario seen from the side – again B seems to move back and forth

The "True" Movement of Double Stars in Space

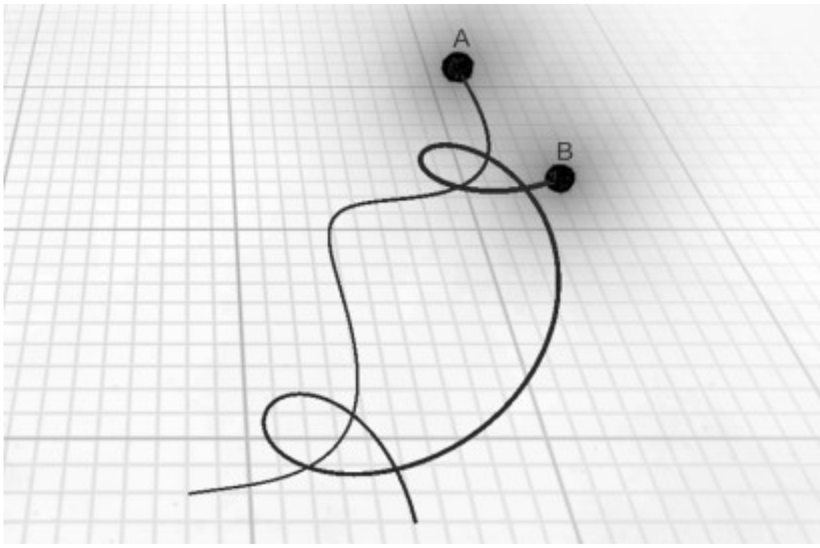

Figure 9: Wobble of the primary more pronounced by larger mass of the secondary

Similar scenario as above but wobble of the primary gets more pronounced due to a larger mass of the secondary, illustrated in Figure 9.

Another possible scenario is a high velocity binary system with equal mass components moving more or less parallel with similar speed despite very eccentric orbits just overtaking each other from time to time combined with switching lanes as illustrated in Figure 10. This scenario allows for common proper motion as well as common transverse, radial and total velocity despite gravity influences between the components. Such a scenario is certainly possible but rather not the rule.

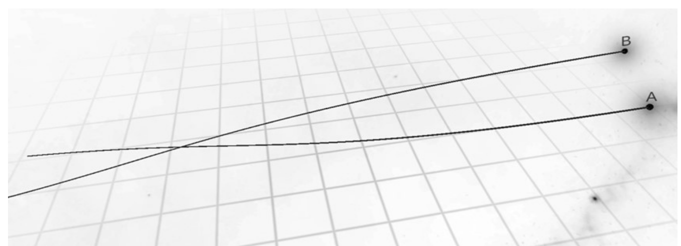

Figure 10: Fast moving double star system

Next we have the scenario of high total velocity stars crossing the path of other stars nearby leading to changes for the path of all involved stars without inducing an orbit, Figure 11.

Similarly there is the scenario of stars born in the same cloud of dust and gas traveling with similar speed in similar direction but without noticeable gravitational relationship between at least most of the stars – this is then the field of Open Clusters.

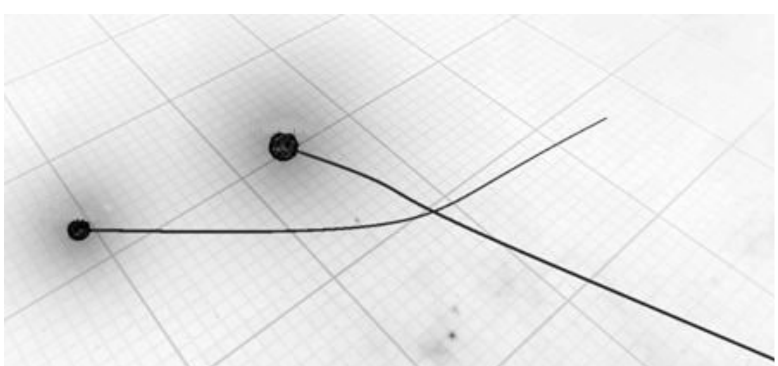

Figure 11: Crossing paths

The "True" Movement of Double Stars in Space

The different scenarios described above support very strongly the proposition that common movement data of any kind starting with common proper motion up to common total velocity seem to be no good criteria for assessing a double star for PGR. At least in cases with rather fast orbits speed and direction of the motion of especially the secondaries depend very much on the current position in the orbit and there is only a random chance that at any given point in an orbit both components share common movement values.

A closer look at the data of a double star with a known orbit provides additional evidence for this proposition. The example of the 6th orbit catalog object KR 60 AB shows clearly the effect of the orbit on the apparent proper motion of the secondary – in Figure 12, the black line represents the proper motion for the primary (assuming that the barycenter is within or close to the primary) and the red line for the secondary for the time frame 1950 to 1968 (just for demonstration, not to scale) – it is obvious, that the components of a double star with an orbit do not have common movement of any kind besides being members of a system with additional movements added to the path of the barycenter. Only the rare case of an observation epoch delta equal to the orbit period would provide common proper motion for a pair with a fast orbit and in case of a slow orbit any small observation epoch delta might also provide common proper motion if the data changes are smaller than the error range of the measurements – but both cases are rather exceptions than the rule.

4. Cross-matching WDS 6th orbit catalog with GAIA DR2

According to Lindegren et al. 2018 (see conclusions paragraph) GAIA DR2 does not discriminate between the movement of a binary system and the by gravitationally-induced extra movement of the components within the system. Both the parallax and the proper motion values are calculated under the assumption that each object is a single star. The deviation from the single star model may be large enough to give for the components of a star system incorrect proper motion and parallax values depending on the properties of a binary like mass, velocity, distance between the components and the different aspects of the observations like number of observation epochs and scanning angles with respect to the plane of a potential orbit. According to Graczyk et al. 2019 this might be a minor issue for close binaries not resolved but examples like KR 60AB give very good evidence for such issues with visually resolved binaries: While the parallaxes for both components are similar enough to suggest PGR with 100% likelihood the given proper motion values result in completely different proper motion vectors caused by the extra orbit motion as demonstrated by the CDS Aladin tool (see Image 1). A side effect of this issue are definitely wrong J2000 positions calculated by CDS VizieR using the GAIA DR2 J2015.5 positions and applying the given proper motion data. This situation seems to be a regular pattern especially for binaries with a rather short period orbit.

That the given parallax error range is in such cases

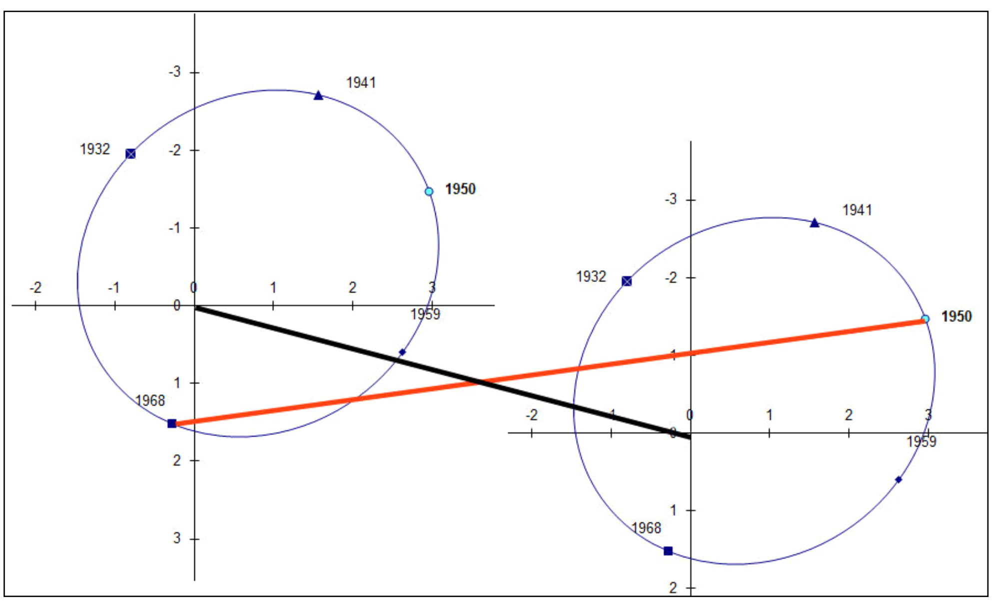

Figure 12: Example Orbit KR 60 AB

The “True” Movement of Double Stars in Space

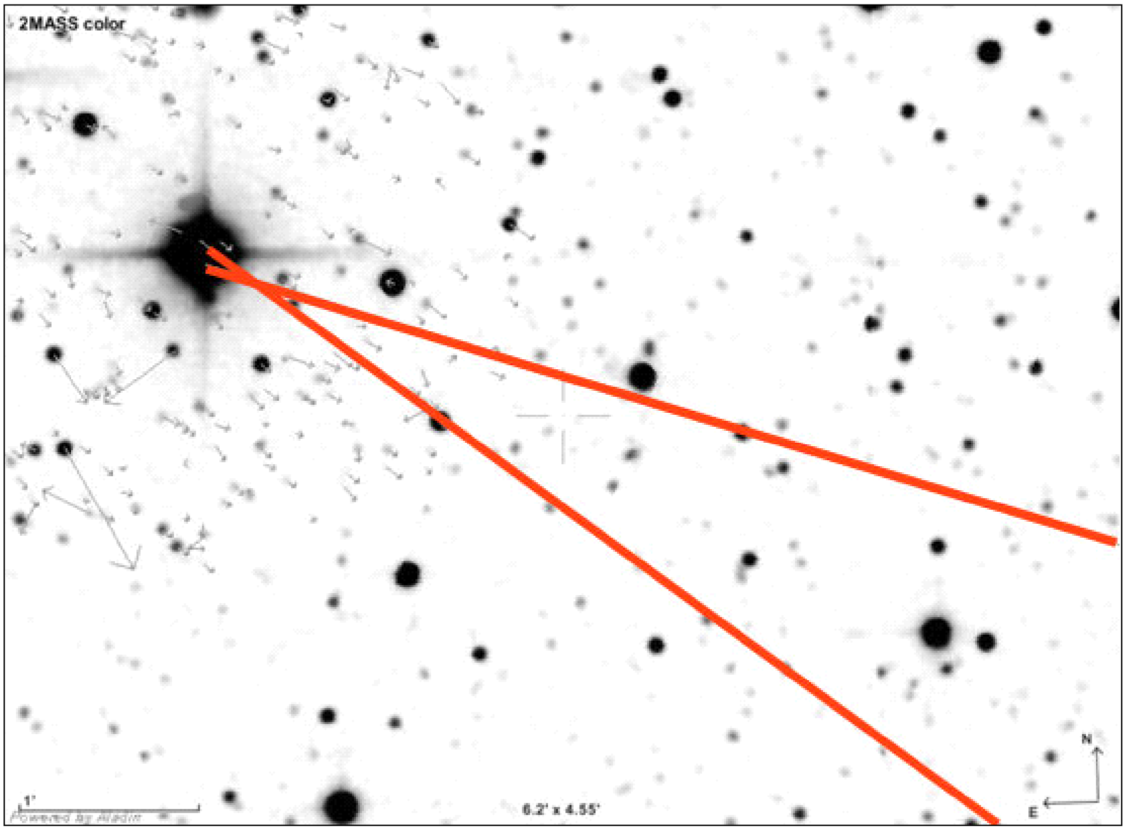

Image 1: GAIA DR2 proper motion vectors for KR 60AB according to CDS Aladin

often rather large when compared with the GAIA DR2 average might be a hint that there is also a minor issue with the given parallax values.

With the caveat that this DR2 data issue might result in proper motion and parallax errors far beyond any given error range a cross-match of the WDS 6th orbit with the GAIA DR2 catalog should provide additional evidence for the proposition that common movement of any kind is neither a sufficient nor a required condition to consider a double star as physical and that the criterion “distance between the components” is far more efficient. This statement refers not only to proper motion but also to transverse velocity and spatial velocity – especially proper motion alone seems to me no longer of significance because it represents only a small part of the relevant data necessary to calculate the spatial movement of a star. But common spatial movement (same speed and direction) might be of interest even in the case of small to no PGR likelihood, indicating that these stars are potentially born in the same molecular cloud if the spatial distance is smaller than 100 light years.

The WDS 6th orbit catalog lists per end of Nov 2018 a total of 2,941 suggested orbits for 2,868 objects as for a few objects two or more different orbits were calculated. These apparent orbits are the projection of the true orbits on the plane of the sky (Alzner 2012) with the movement of the barycenter considered to be identical with the movement of the primary and are listed with a grade rating 1 to 9 suggesting very high to very low reliability. The WDS catalog lists 2,179 objects with note code “O” indicating a given orbit – the difference to the number of 6th orbit catalog are explained by the large number of orbits with grade 9 considered not reliable enough to give an “O”.

A first attempt to cross-match WDS objects with an orbit with GAIA DR2 was already done in Knapp and Nanson 2019 (HPMS3 catalog, Appendix B) but this time the intention is to go more into the details and to check as many WDS objects as possible with code “O” for common movement and for PGR based on parallax and angular separation of the components.

About 2/3 of the WDS code “O” objects have a separation of less than 0.4 arcseconds meaning below the GAIA DR2 resolution limit (Arenoux et al. 2018) – this limitation reduces the number of objects suited for

The "True" Movement of Double Stars in Space

cross-matching to 883.

The cross-match with DR2 for the primaries of these 883 objects was then done with CDS X-match with a search radius of 10 arcseconds around the J2000 positions to avoid possible position issues due to high proper motion and other movements. The total number of matches was 1,400 including all resolved secondaries up to 10 arcsecond separation. The usual next step would have been the cross-match for the secondaries based on the calculated positions with the given separation and position angle but to avoid again issues with orbit induced changes of separation and position angle I decided to work through this list manually limiting this way the overall cross-matching process to the pairs with less than 10 arcseconds separation. The manual matching process allows also for checking for missing primaries not found within the 10" search radius.

Results of the manual matching process:

- 103 or close to 12% of the selected WDS 6th orbit catalog objects were not found at all simply due to missing DR2 objects for the primary
- For 393 or close to 45% of the selected WDS 6th orbit catalog objects no secondary was found in DR2 mostly with separations below 1" (a known weakness of DR2 – see Knapp 2019, Cross-Match of WDS TDS/TDT objects with GAIA DR2)
- 5 of the selected WDS 6th orbit catalog objects could not be matched with DR2 due to combined components like for example for STF1196AB,C
- The remaining 344 pairs or 39% were considered correct matches.

Next step was then checking for proper motion and parallax data with the result that 77 pairs had to be eliminated due to missing proper motion and parallax data necessary for assessment regarding common proper motion and potential gravitational relationship with a meagre remaining number of 267 pairs suited for assessment.

These numbers suggest that the double star resolution performance of GAIA DR2 is overall quite poor.

Next step was then to check these 267 objects for common movement of any kind:

- Proper motion: Only 18 means less than 7% of these pairs were found with proper motion data similar enough to allow for positive CPM assessment according to the Knapp & Nanson scheme (see Appendix A) – this strongly suggests that common proper motion is not a suitable criterion for detecting physical pairs
- Radial velocity: Out of the 267 pairs only 34 (only about 13%) have DR2 radial velocity data for both components with 12 of them with overlapping error range as minimum criterion for common radial velocity – besides the fact that radial velocity data is still scarce this also indicates that common radial velocity seems of limited value for detecting physical pairs
- Total or spatial velocity: Existing radial velocity data allows for calculating total velocity. Only 6 cases out of the 34 pairs with radial velocity data available resulted in total velocity values similar enough to be considered common– so also common total velocity does not seem to provide any significant information valuable in this context.

Next step was then to check these 267 pairs for PGR based on distance between the components using the Knapp 2018 assessment scheme (see Appendix A). Several examples were additionally counter-checked with a Monte Carlo simulation (sample size 30,000) using normal distributions for the GAIA DR2 RA, Dec and Plx values with the given error range as standard deviation to get closer insights:

- 173 (about 65% out of 267) pairs got a positive assessment result for PGR by the criterion of distance between the components likely less than 200,000 AU. This shows that this criterion seems valuable for detecting probably physical pairs with good likelihood for an orbit. Examples are:
    - ◊ STF3007AB: Figure 13. With the given data for position and parallax and error range more than 99% of the simulation sample provide a distance below 200,000 AU with a mean value of ~60,000 AU and an asymmetrical distribution (see graph below) due to the simple fact that zero is a natural limit for a distance. The position angle 2015.5 does even with some allowance not match very well with the

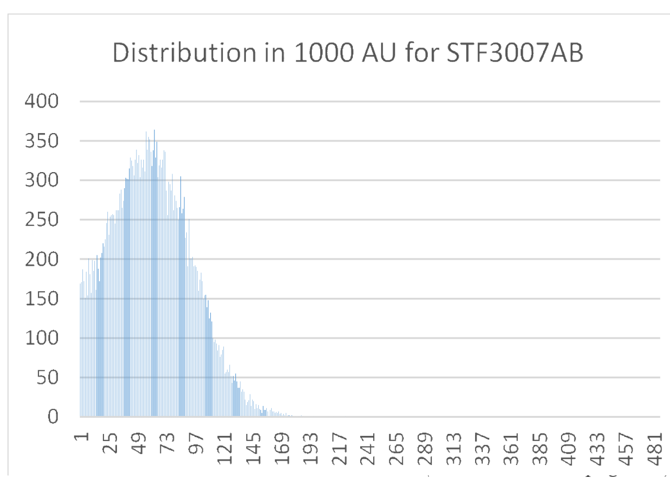

Figure 13: Distance distribution in 1000 AU for STF3007AB

The “True” Movement of Double Stars in Space

orbit data for 2016. The given orbit period is with 2161 years very long and the so far 276 observations cover only less than one tenth of the assumed orbit if in a rather conclusive part. Smallest distance by simulation is ~225 AU suggesting an orbit period of at least 2,400 years (using this distance as minimum semi-major axis of a potential orbit applying Keplers 3rd law with about Sun mass for both components). The currently given orbit might be a bit questionable but the likelihood for gravitational relationship seems quite high. A rather long period orbit might also be the reason that the proper motion values are similar enough for a positive CPM rating.

- ◊ WIR 1AB: Figure 14. This is a pair with a likelihood of 100% for a distance of less than 8,000 AU with a mean value of ~2,800 AU. The 2015.5 values for separation and position angle are a good match with the orbit values for 2016 and the 68 observations so far cover a good and significant part of the orbit with a period of 359 years. The smallest distance by simulation supports the given period so this seems to be a very solid physical pair even if the suggested orbit period would require a much smaller distance than the mentioned mean value. The proper motion values are very different resulting in a negative CPM rating.
- ◊ KAM 3AB: Figure 15. Simulation gives 100% likelihood for a distance less than 10,000 AU with a mean value of ~2,200 AU. Position angle and separation 2015.5 are a good match for the calculated orbit values. The given orbit shows a high eccentricity with the so far recorded observations in a not very conclusive part of the orbit so the orbit period might be much longer than currently assumed with 452 years. According to the simulation the smallest possible distance is ~ 79 AU suggesting a smallest possible orbit period of 500 years. Anyway this looks like a very high likelihood for gravitational relationship. The proper motion vector length is too different to allow for a positive CPM rating

- 15 of the assessed pairs were considered positive for both common proper motion and common parallax criteria which means that only 3 pairs showed common proper motion but with components too distant to suggest gravitational relationship. To check the possibility that common proper motion provides very well evidence for a like-

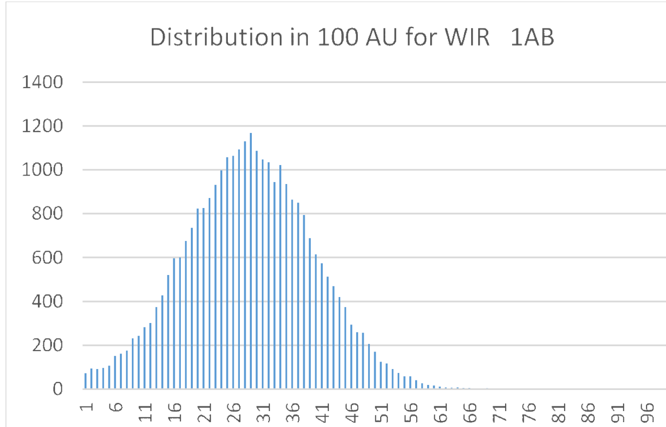

Figure 14: Distance distribution in 100 AU for WIR 1AB

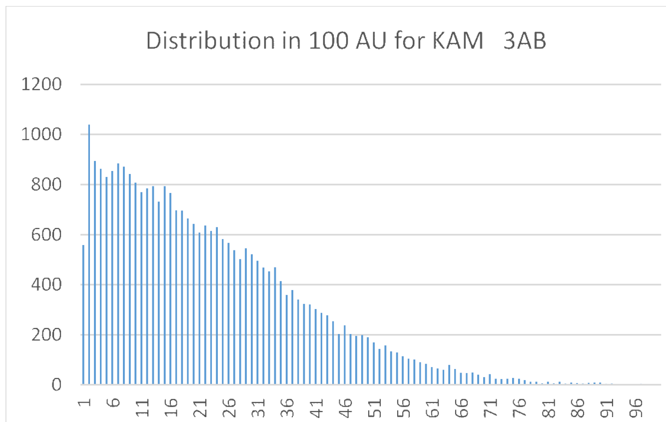

Figure 15: Distance distribution in 100 AU for KAM 3AB

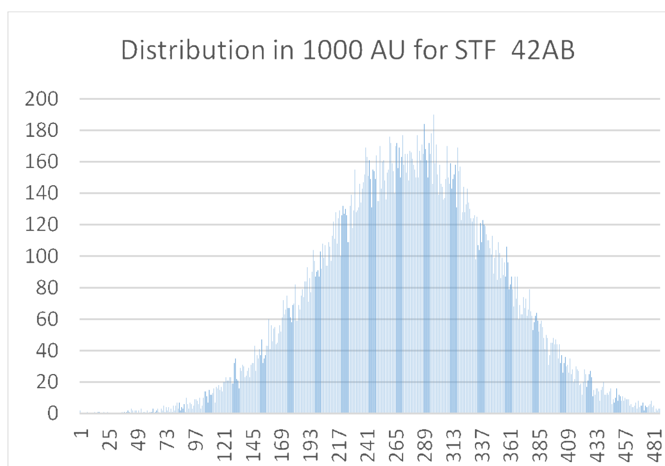

Figure 16: Distance distribution in 1000 AU for STF 42AB

The "True" Movement of Double Stars in Space

ly physical pair this needs also a closer look:

◊ STF 42AB: Figure 16. With the given data for position and parallax and error range about 15% of the simulation sample provide a distance below 200,000 AU with a mean value of ~275,000 AU and a distribution shown in the graph below. Position angle and separation 2015.5 match with some allowance very well with the orbit data for 2016 so this might be a valid orbit based on 142 observations but the given period is with 1900 years rather long and the observations cover only a small part of the assumed orbit. According to several runs of the simulation the spread for the smallest possible distance is very high and with a very tiny likelihood the smallest possible distance is ~300 AU suggesting a smallest possible orbit period of ~3,500 years. This suggests a small "might be" likelihood for gravitational relationship but with a significant longer orbit period than currently assumed

◊ I 226AB: With the given data for position and parallax and error range only a few outliers out of the simulation sample provide a distance between the components of less than 200,000 AU making the likelihood of any gravitational relationship close to zero. Position angle and separation 2015.5 do not very well match with the orbit data for 2016 and the number of observations is only 18 so this might be not such a valid orbit especially as the period is with 3,556 years very long and the observations so far cover only a tiny fraction of the assumed orbit. According to several runs of the simulation the spread for the smallest possible distance is very high and with a very tiny likelihood the smallest possible distance is ~2,500 AU suggesting a smallest possible orbit period of ~90,000 years. I 226AB seems with the given evidence to be most likely not physical

◊ STF2454AB: With the given data for position and parallax and error range about 24% of the simulation sample provide a distance below 200,000 AU with a mean value of ~380,000 AU and a rather flat distribution. Position angle and separation 2015.5 match with some allowance very well with the orbit data for 2016 so this might be a valid orbit based on 177 observations. The observations cover so far only about one third of the assumed orbit with a period of 560 years. The simulation suggests a smallest possible distance of ~100 AU meaning a smallest possible orbit period of ~700 years. Together this suggests a "might be" likelihood for gravitational relationship.

Back to the 94 (35% out of 267) pairs with a negative assessment for PGR – these need a closer look to find an explanation for the negative assessment:

- For 31 of these pairs "negative" assessment means simply a likelihood less than 50% as for the following examples:

  ◊ STF 2: With the given data for position and parallax and error range about 4% of a 30,000 simulation sample provide a distance below 200,000 AU with a mean value of ~3,250,000 AU. The huge spread caused by a rather large parallax measurement error for the primary makes this result questionable and suggests an "undecidable" likelihood for gravitational relationship due to poor parallax data quality. Position angle and separation 2015.5 match even with some allowance not this well with the orbit data for 2016. The given period is with 3,267 years very long and the so far 210 observations cover only about one tenth of the assumed orbit and this in a not very conclusive part. This one has to wait for better parallax data to come to a more conclusive assessment

  ◊ BU 391AB: A similar situation with parallax data like for STF 2 but less severe – 16% likelihood for a distance below 200,000 AU with a mean value of ~750,000 AU and again a very large spread. This suggests again an "undecidable" likelihood for gravitational relationship due to poor parallax data. Position angle and separation 2015.5 match very well with the orbit data for 2016. The given period is with 616 years not very long and the so far 79 observations cover only about one sixth of the assumed orbit but in a very conclusive part. The smallest possible distance by simulation would correspond with the given period. This one has also to wait for better parallax data to come to a more conclusive assessment but looks much better than STF 2

  ◊ STF 73AB: Figure 17. With the given data for position and parallax and error range about 14% of a 30,000 simulation sample provide a distance below 200,000 AU with a mean value of ~270,000 AU and a standard deviation of ~60,000. The parallax values for

The "True" Movement of Double Stars in Space

the components are similar but do not even overlap within the error range – so at first look rather not physical. But then position angle and separation 2015.5 match very well with the orbit data for 2016 and the orbit with a period of 168 years is nearly fully covered with so far 727 observations – this might then be one of the suspected cases with questionable GAIA DR2 parallax data due to the extra motion of an orbit. The GAIA DR2 data quality parameters indicate some issues with the data for the secondary with a high percentage of bad measurements and a suspected duplicity issue – may be a third component is involved.

◊ STT 21: Figure 18. With the given data for position and parallax and error range about 40% of a 30,000 simulation sample provide a distance below 200,000 AU with a mean value of ~290,000 AU with a large spread and a distribution shown in the graph below. Position angle and separation 2015.5 match very well with the orbit PA data for 2016 but not very well with separation. The given period is with 450 years not very long and the so far 128 observations cover a large but not significant part of the assumed orbit. According to simulation the smallest possible distance would be ~140 AU giving a smallest possible orbit period of ~1,170 years. This suggests a "might be" likelihood for gravitational relationship but with a much longer than assumed orbit period.

- For the remaining 63 pairs the negative assessment result means indeed a likelihood for PGR close to zero as for the following examples:

◊ HJ 2036: Figure 19. With the given data for position and parallax and error range only a few outliers of a 30,000 simulation sample provide a distance between the components of less than 200,000 AU making the likelihood of any gravitational relationship close to zero. Position angle and separation 2015.5 match very well with the orbit data for 2016 but the given period is with 1443 years very long and the 115 observations so far cover only a small fraction of the assumed orbit. The parallax error range seems acceptable for both components and the calculated distance between the components is in average about 10 light years – any gravitational relationship seems very questionable here.

◊ BU 1216: The parallax data suggests here a

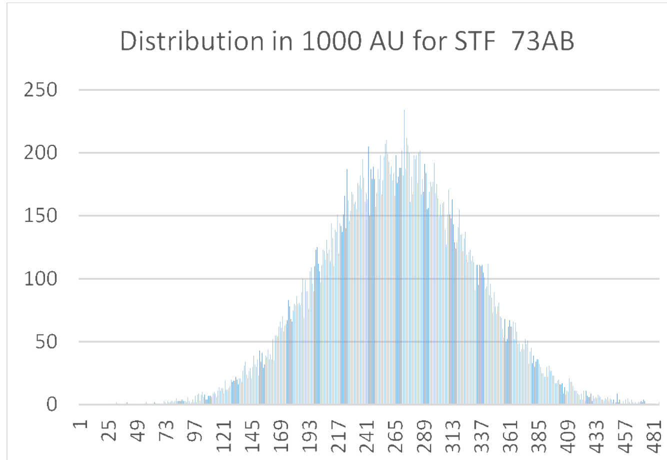

Figure 17: Distance distribution in 1000 AU for STF 73AB

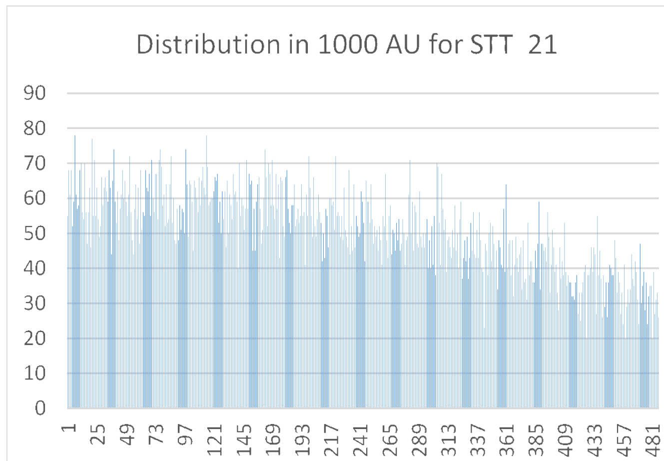

Figure 18: Distance distribution in 1000 AU for STT 21

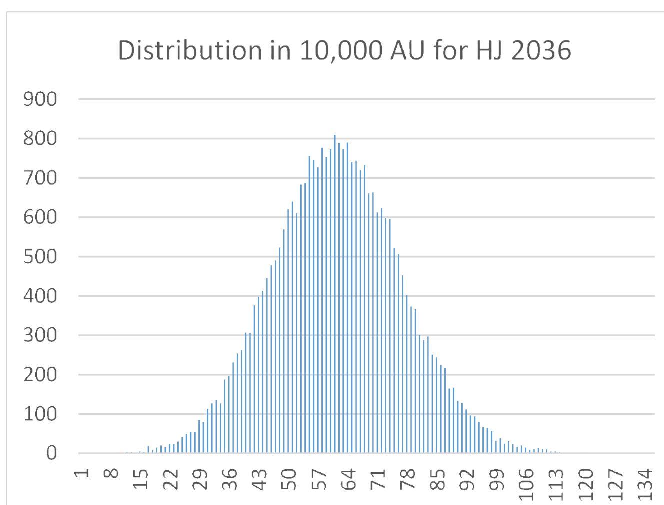

Figure 19: Distance distribution in 10,000 AU for HJ 2036

The "True" Movement of Double Stars in Space

zero likelihood for a distance between the components smaller than 200,000 AU with an average distance of 7,200,000 AU and a huge spread. The observation history with 82 observations covers a good but not very significant part of the calculated orbit. With some allowances the 2015.5 separation and PA values correspond acceptable with the orbit values for 2015 yet the given evidence speaks clearly against any gravitational relationship

◊ STF2118AB: With the given positions and parallax values only a few outliers out of a 30,000 simulation sample are within a distance of less than 200,000 AU between the components meaning a near zero likelihood for gravitational relationship. 281 observations starting with 1830 cover about half the calculated orbit with a period of 422 years. The 2015.5 measurements do not match very well with the orbit 2016 separation values putting a question mark on the reliability of the calculated orbit – overall it seems very questionable that STF2118AB should be a pair with gravitational relationship especially as the GAIA DR2 parallax values do not even overlap within the error range

◊ STT 507AB: The parallax values are completely different if with a rather larger error range excluding any possibility of gravitational relationship. The 2015.5 values for separation and position angle are at best a moderate match with the orbit values for 2016. The number of 135 observations cover about 1/3 of the orbit with a period of 566 years but the spread of the measurements compared to the calculated orbit seems a bit large – rather not a physical.

The full cross-match data set is available for downlodad from the JDSO website as fixed format text file "WDS_O_GE_0.4_X_DR2_R10.txt".

Note for HU 66BC: Confusing WDS data for HU 66: Bad match with 6th orbit catalog and STT 351 AC.

Finally I had a look at a small random sample of WDS code "O" objects with separations larger than 10 arcseconds and for this reason not included in the cross-match process described above:

◊ GRB 34AB: Figure 20 With the given data for position and parallax and error range 100% of the simulation sample suggest a distance less than 1,000 AU with a mean value ~300 AU and a standard deviation of ~136 AU. The 2015.5 values for separation and

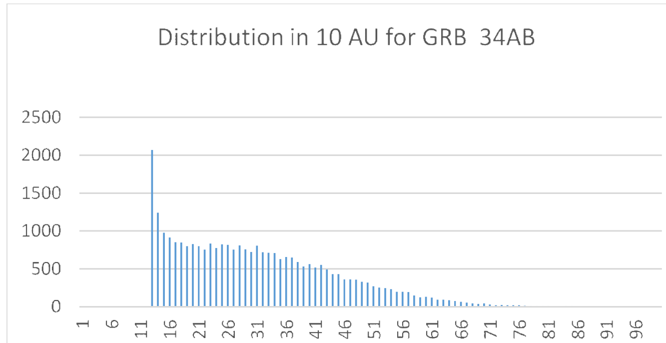

Figure 20: Distance distribution in 10 AU for GRB 34AB

position angle are with some allowances a good match for the calculated orbit values for 2016 but the observations so far cover only a small part of the orbit period of 1,253 years so the reliability of the calculated values is a bit questionable. The likelihood for PRG seems extremely high but the orbit period might, according to the distances from to the simulation sample, be somewhat longer although also the given period is covered by the simulation results

◊ LDS1017: Figure 21 With the given data for position and parallax and error range 100% of the simulation sample suggest a distance less than 8,000 AU with a mean value ~2,640 AU and a standard deviation of ~1,330 AU. The 2015.5 values for separation and position angle (reversed) are with some allowances a

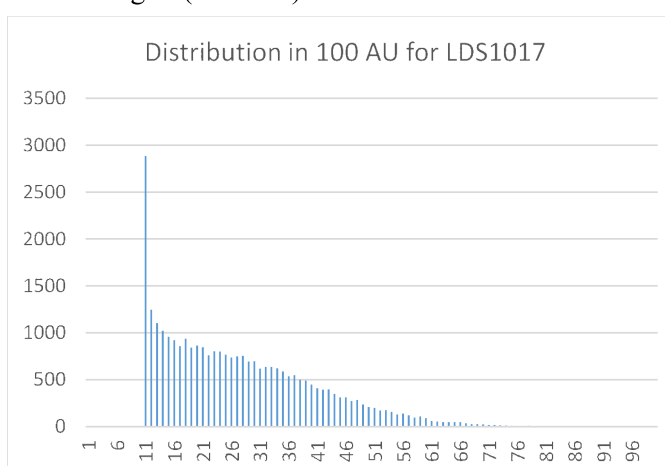

Figure 21: Distance distribution in 100 AU for LDS1017

good match for the calculated orbit values for 2016 but the observations so far cover only a tiny part of the suggested orbit period of 360 years so the reliability of the calculated values is a bit questionable. The likelihood for PRG seems very high but the orbit period might, according to the distances from to the simulation sample, be significantly longer, the data from the simulation suggest even >20,000 years

◊ STF1217: Figure 22. With the given data for position and parallax and error range 100% of the simulation sample suggest a distance less than 100,000 AU with a mean value ~25,700 AU and a standard deviation of ~15,800 AU. The 2015.5 values for separation and position angle are with some allowances a good match for the calculated orbit values for 2016 but the observations so far cover only a tiny part of the orbit period of 1,600 years so the reliability of the calculated values is a bit questionable. Some likelihood for PRG seems given but the orbit period might according to the distances from to the simulation sample be significantly longer, the data from the simulation suggests even >25,000 years

5. Cross-Matching WDS L-Coded Objects with Gaia DR2

The WDS catalog lists per end of 2018 ~1,500 such systems with code "L" meaning significant but apparently not Keplarian motion since their discovery – a few of these systems might according to the description of the "L" code be long-period physicals but most of them are most likely optical pairs. This means that the assessment scheme for PGR should provide here only a very small number of positive results as proof of concept for a reliable hit rate not only for positive but as well also for negative assessment results.

For this purpose all L-coded WDS objects were twice cross-matched with GAIA DR2 with a 5 arcsecond search radius around the J2000 positions for the primary and the secondary. After elimination of all obviously wrong and suspect matches 1,196 objects with a delta in separation of less than 20% and a delta in position of less than 15° and reasonable delta in magnitudes were kept and only 32 (less than 3%) of these were assessed as likely physicals and 97% as most likely opticals.

A closer look at a few L-coded objects assessed as likely physical:

- STF 49: Figure 23. With the given data for position and parallax and error range 100% of a

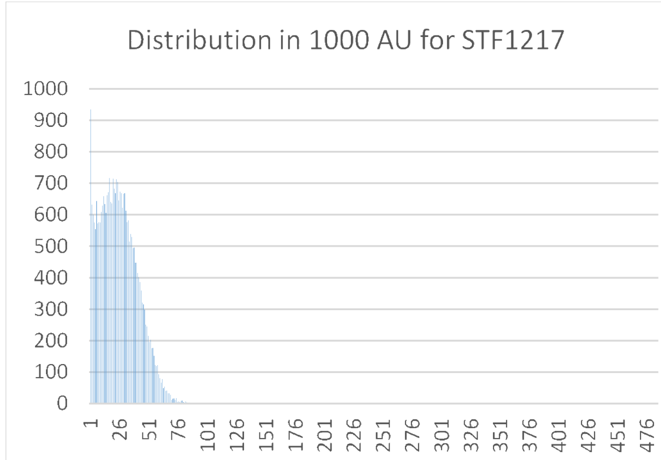

Figure 22. Distance distribution in 1000 AU for STF1217

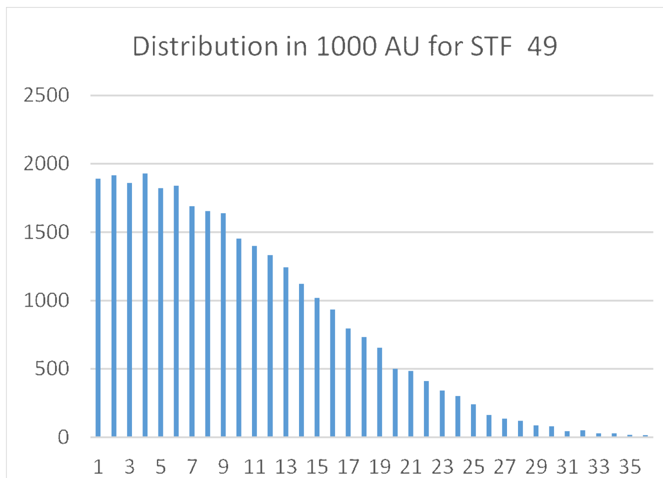

Figure 23. Distance distribution in 1000 AU for STF 49

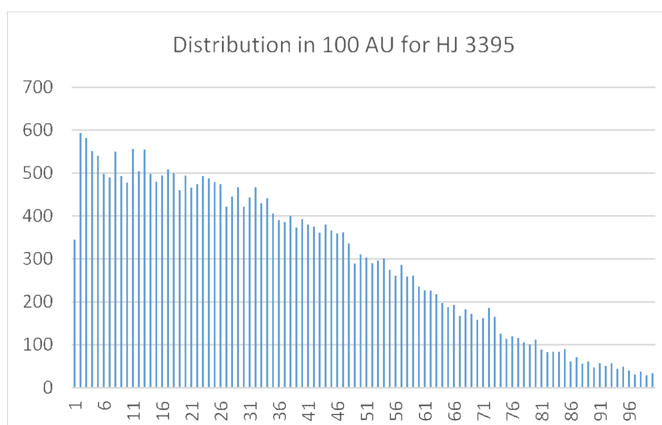

Figure 24: Distance distribution in 100 AU for HJ 3395

The "True" Movement of Double Stars in Space

30,000 simulation sample provide a distance below 200,000 AU with a mean value of ~9,450 AU and a rather large standard deviation. This suggests a realistic chance for gravitational relationship even if the mean distance value would mean a long-period orbit according to the smallest simulation results at least ~2,600 years.

- HJ 3395: Figure 24. With the given data for position and parallax and error range 100% of the simulation sample provide a distance below 200,000 AU with a mean value of ~3,400 AU and a very asymmetric distribution with 17% likelihood for a distance even below 1,000 AU. Most likely a physical pair if with a long-period orbit according to the smallest simulation results larger than ~460 years
- STF 315: Figure 25. With the given data for position and parallax and error range, 75% of the simulation sample provide a distance below 200,000 AU with a mean value of ~138,000 AU with a rather asymmetric distribution. If this distance is close enough for a realistic chance for an orbit is questionable, but there will be most likely some kind of gravitational relationship between the components.

The full cross-match data set is available for download from the JDSO website as fixed format text file "Code_L_XX_DR2_2x5s.txt".

6. Discussion of the Concept of the Assessment Scheme for Potential Gravitational Relationship (PGR)

PGR means a measureable influence of the tidal force of a single star/system on the movement of another single star/system. Gravitation works regardless of the underlying theory without a distance limit so basically all stellar objects are assumed to be in their movements influenced by gravitation. As relativistic effects seem here of little concern the equations of Newton and Kepler will provide good enough approximations. MOND suggests according to Banik 2019 additional orbit speed for wide pairs with distances between the components larger than 7,000 AU, but such small differences get lost in the overall error range of the data currently available.

To look for a radius of the gravitational field of a star might not be the best idea because in different directions nearby stars are in different large distances so the outer rim of the gravitational field of a star is most certainly not a perfect sphere and the hypothetical Oort cloud might be a fiction as there is so far no evidence that the number of objects expected to float here in

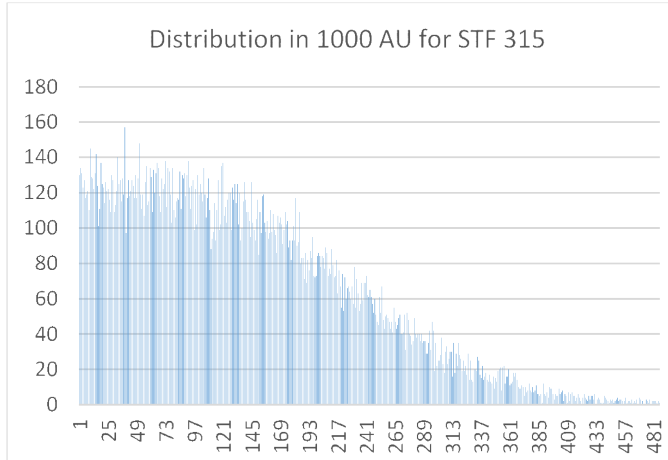

Figure 25: Distance distribution in 1000 AU for STF 315

space is large enough to be called a "cloud". But the assumption that a radius of ~100,000 AU corresponds with the outer rim of the gravitational field of the Sun seems plausible at least in the direction of Alpha Centauri generally considered the nearest star system next to the solar system with a distance of ~4.35 light years (Kervella et al 2016). The gravitational pull of the Sun is at 100,000 AU quite soft – about 20 days would be needed for a free floating low mass object there to move one single meter closer to the Sun if no other forces are involved and 5.6 million years would be needed to get such an object consumed by the Sun again if no other forces are involved allowing for example for a swing-by or even an orbit. Alpha Centauri (with >2 Sun masses for A plus B plus C) would already largely compensate this minimal movement and at 115,000 AU distance the free floating would go on indefinitely. On the other side even the huge distance of 100,000 AU between two stars allows for an orbit if with a very long period of ~22.5 million years and a very slow speed of only ~ 0.13km/s – an orbit of truly cosmic scale but certainly possible. Also to consider is the fact that the average star mass might be a bit smaller than the Sun mass (Winters et al. 2019) but this seems of minor consequence as gravitation works only linear with mass.

The vexing question here is how to detect such ultra-long period binaries with any degree of certainty. The availability of Gaia single position measurements over several years, in addition to the currently published summarized ones, might allow for conclusions here. I asked the Gaia team if such data will be available in the future and the answer was positive. While the measurement errors will certainly be greater than “real” changes in positions, such a data row should allow the detection of a trend in the position changes.

The average distance between single stars or star systems in our Galaxy might be somewhere around the distance between our Sun and the closest single stars/ star systems nearby as there is no reason to assume that this distance is unusual. And even if this distance might be smaller than the galactic average, there remains the fact that the effective distribution of stars in space is far from equal—areas of higher density like the Solar neighborhood are separated by areas with thin star populations and the likelihood for gravitational relationship is most certainly higher in dense populated star areas. The number of stars within 100 parsec from our solar system is according to GAIA DR2 700,055 giving an average distance between the stars of ~7.3 light years (by taking a sphere volume with a radius of 100 parsec divided by equal distributed 700,000 stars). But there are some caveats regarding this number:

- The GAIA DR2 resolution of double stars is limited with 0.4 arcseconds and the resolution record for double stars with a separation up to 1 arcsecond is with an average of 36% (Knapp 2019 on TDS/TDT objects) rather low. The number of resolved systems might to some degree compensate the number of not resolved opticals but certainly by far not completely
- A small number of Gaia DR2 parallaxes is “horrendously wrong” (Lindegren et al. 2018, slide 47) – for example ~60 very faint objects are listed with a parallax larger than 760mas suggesting a distance to our Sun of less than ~4 light years and this result is highly questionable. The relation to the number of ~1,720 Gaia DR2 objects within a distance of 10 parsec would then suggest a contamination rate of ~3.5% wrong parallaxes far beyond the given error range not counting the negative parallaxes. Gaia DR2 might have some specific issues with the nearby stars because there seems to be a significant large positive bias in the parallax values for these stars compared with the overall given small negative bias of about -0.05mas (Schönrich et al. 2019). But the total number of objects is large enough to render these facts as of little significance for the average distance between stars
- Several hundred objects with very high proper motion >600mas/yr are missing, but again the total number of objects is large enough to render this fact as of little significance
- The main issue remaining is the question of overall resolution rate of Gaia DR2 for all existing stars within this distance besides the question of stars fainter than ~20Gmag.

Overall there seems currently no serious star count estimation possible based on Gaia DR2 numbers. The number of missed stars is hard to estimate due to the different star density in the different areas – the higher the star density the higher the number of missed stars. Additionally the reliability of Gaia degrades heavily with fainter stars. But even if the “real” number of stars is assumed to be twice the Gaia DR2 count we get ~ 6 light years as average distance between single stars or star systems and this seems still a bit too high.

That single stars and star systems are equally distributed in space is, as already mentioned, an oversimplification because there are certainly areas of different star density with the consequence of average distances between star systems being likely smaller than equally distributed. Then there is the special case of open clusters: For example Lodieu et al. 2019 suggest for the Hyades cluster members to be bound up to a distances of 9 parsec from the barycenter of the cluster – this might be a bit over-optimistic but the gravitation effects within open clusters are different from single stars and several of the (in Lodieu et al. 2019 table C.1) listed objects have despite very large angular separations a >50% likelihood for gravitational relationship.

As a resort data from the RECONS “Solar Neighborhood” project (Henry et al. 2018) should allow for a precise counter-check. The 100 star systems closest to our solar system (using the RECONS list from http://www.recons.org/TOP100.posted.htm) suggest with assumed equally distribution an average distance of ~4.8 light years while the based on parallax and angular separation precisely calculated average distance between star systems is with 4.3 light years about 10% smaller (see Appendix C for the full table). GAIA DR2 suggests a few new members to this list even after eliminating the objects with obvious wrong parallaxes and the large number of very faint and for this reason suspect objects – on the other side several objects of the RECONS list are missing in GAIA DR2 due to the issue with very high proper motion objects. Some interesting side results from the RECONS counter-check: Distances between star systems vary from ~1 to ~10 light years with 16 cases below 3 light years suggesting potential gravitational relationship, especially Procyon and Luyten's Star seem close enough to be considered a system. All numbers given here do not take the spread caused by parallax data errors into account but this effect is with the very large parallax values given here of little concern.

It is certainly a bit arbitrary to declare a specific number as threshold for assumed gravitational relationship but ~3 light years or 200,000 AU seem with the given intelligence to be a reasonable choice. At such a distance there might still be some minimal gravitational relationship between two average mass stars in case of areas of thin star population but in most cases there will be most likely zero individual gravity besides the tidal force of the Galaxy even if this is a static point of view because all stars move through space with velocities large enough to change the relationship betweeb stars over time significantly. Bailer-Jones et al. 2018 for example expects 700 stars to come closer than 5 pc to the Sun over the next 15 million years with 26 of them having a >50% chance to come closer than 1 pc meaning serious gravitational disturbance of our solar system. We might not even have to wait millions of years for such a scenario to happen – several of the stars within the 10pc radius have a significant negative velocity means are moving towards our solar system and this might reduce the time span of a possible close encounter to less than a few 100,000 years.

The calculation of the distance between two stars is basically easy with the given distance of the stars from the sun using the simple parallax inversion or the Bailer-Jones GAIA DR2 Distances catalog (VizieR I/347) and the angular separation applying the law of cosines. Yet special attention is needed regarding data quality (issues with duplicity, numbers of visibility periods used and other issues discussed extensively in the GAIA DR2 documentation) and the parallaxes should have a reasonable size and a small measurement error range. The reason for this requirement is simply the exponentially increasing distance between two stars with decreasing parallax, but also the exponentially growing spread for the distance caused by an increasing relative error range. For example an error range of 0.04mas means for a pair with 5 arcsecond separation and parallaxes of ~40mas a spread of a few thousand AU in the distance between the components and for a pair with parallaxes of ~4mas already a spread of several hundred thousand AU. See Figure 26.

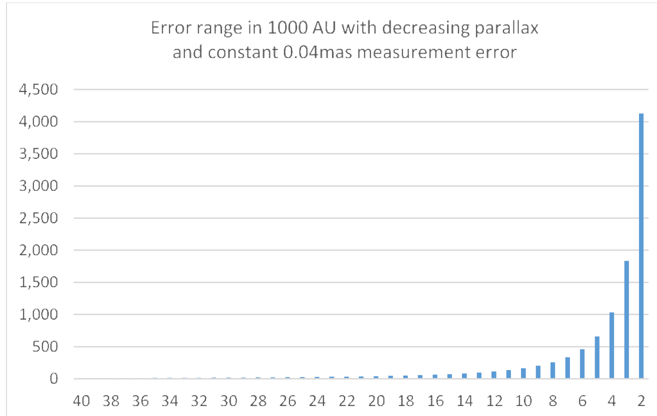

Figure 26: Error range in 1000 AU with decreasing parallax

With positions and parallaxes available for a pair of stars the ad hoc expectation is that the calculated distance for the components of such a pair should correspond with the mean value of a normal distribution for this distance – at least this expectation was the base for the "realistic distance" value in the proposed PGR assessment scheme. But the mentioned non-linear effect of parallax errors has the consequence that this is the case only for large parallax values with a small error range but not for small parallax values with an in relation large error range. The requirement to stick with parallax data with a very small error relative error is often severely disregarded as for example by Igoshev and Perets 2019 according to the mentioned selection criterion "We keep only stars with measured parallax and proper motion with relative errors which are less than a third of their value". This is a reasonable approach to eliminate all objects with negative parallaxes including the very small ones potentially negative when applying the error range as standard deviation for a confidence interval of 99.73%. I used this approach myself in my first attempts for the PGR assessment scheme to get a grip on this issue and even Schönrich at al. 2019 work with a Plx/e_Plx ratio of 4 as data quality cut despite postulated highest precision requirements. Meanwhile it seems clear that a small parallax value with such an error size is close to meaningless at least for estimating the distance between double star components as explained above. As to expect also the difference between the lower and upper bound on the confidence interval of the estimated distances according to Bailer-Jones et al. 2018 gets in such cases quite huge – in some cases even larger than 1,000 parsec as for example for HD 313070 with Plx of 0.4269 and e_Plx of 0.0672 despite a seemingly solid Plx/e_Plx ratio of 6.35.

Using Monte Carlo simulation for the parameters involved makes quickly clear that the exponential effects of parallax errors for small parallax values results in average distance values much larger than expected combined with a very flat distribution with a huge standard deviation. For this reason the proposed PGR assessment scheme requires parallaxes > 5mas with an error range smaller than 0.5% (or Plx/e_Plx ratio >200) to work properly. These requirements reduce drastically the number of usable GAIA objects to ~430,000 so for a first impression this assessment scheme might be used also with data not meeting fully these requirements but the result needs then a very critical second look.

7. Summary

Selecting double stars with common but significant movement of any kind is basically a good approach for finding with some likelihood physical pairs but is combined with the high risk of selecting pairs with obviously no chance of gravitational relationship because the distance between the components is simply too large. So the concept of looking for common movements of any kind provides always a mixed bag of results missing at the same time good candidates for likely physical pairs with components close enough for PGR but movement data values different enough to be considered not "common". If star movement data is for whatever reasons considered as relevant for assessing a pair as potentially physical it is strongly to recommend to have additionally a closer look at the spatial distance between the components of a pair (based on parallax and angular separation) whether PGR seems likely or rather not. With accurate data on the mass of the components it would then be possible to compute the gravitational forces with some precision, but without this data, the assumption that all stars have on average a sun-like mass and that ~1 parsec distance between single stars or systems in our near Galaxy area can be considered as the edge of the gravitational field should work as an useful compromise. With a distance of less than 200,000 AU (~3 light years or ~1 parsec) between two stars gravitational relationship seems at least possible and using my assessment scheme for PGR gives an idea about the likelihood of being potentially physical or not.

The simple calculation of the distance between components using the given parallaxes leads to a wrong expectation about the average value of such a distance caused by the non-linear spread depending on parallax size and error range. Using the given GAIA DR2 coordinates and the parallax as mean values and the given error ranges as standard deviations of an assumed normal distribution (or alternatively use Bailer-Jones 2018/ VizieR I/347 distances) it is possible to calculate (at least approximately by numerical simulation) the probability for measurement results giving a specific distance between the components. This result can then be interpreted as likelihood that the pair in question has indeed a spatial distance between the components less than this specific distance. The proposal that a distance of 200,000 AU is a reasonable threshold for PGR is supported by the fact that this approach works reasonable good for positive as well as for negative results by the high hit rate when applied on the WDS code "O" objects as well as by the low hit rate when applied on the WDS code "L" objects.

The results of a Monte Carlo simulation can also be used to determine the smallest possible spatial distance between double star components as estimation of the minimum value for the semi-major axis of a potential orbit with zero inclination as for example done in Farihi et al. 2010 using photometric distance estimations. With the parallax data available in GAIA DR2 this can now be done with comparatively little effort and much higher precision – but it should be added that the likelihood for such minimum distances is usually very small so it makes sense to have also a look at the largest possible distance. And for a reasonable large PGR likelihood over 50% it is certainly better to stick with the average or median distance of such a simulation.

A weak point of the proposed PGR assessment scheme is the still often insufficient quality of the available data despite the huge step forward with GAIA DR2. Cross-matching components of multiple systems with GAIA DR2 objects seems often like kind of poking into the soft parts of this catalog:

- No resolution below 0.4 arcseconds angular separation
- Resolution performance between 0.4 and 1.0" separation far below 50%
- Insufficient coverage of the solar system neighborhood star population mostly due to insufficient coverage of very high proper motion stars
- Parallax data often of little value for calculating the distance between double star components beginning with "horrendously wrong" over negative to parallax values with an insufficient error range ratio
- All objects are treated as single stars even when obviously components of a star system without distinction between the proper motion of the barycenter of star systems and the extra motion of the components due to gravitational relationship with negative effects on proper motion and parallax data quality.

Additionally GAIA DR2 parallax data show a systematic bias of -0.03 to -0.05mas (depending on source and method applied - see Schönrich et al. 2019) although this is in the given context at least for rather large parallax values usually of little concern.

But according to the GAIA data release scenario (https://www.cosmos.esa.int/web/gaia/release) there is qualified hope that future GAIA data releases should do better in all mentioned aspects.

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- 2MASS, DSS2 and PS1 images
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- GAIA DR2 catalog
- SIMBAD
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- Washington Double Star Catalog
- 6th Catalog of Orbits of Visual Binary Stars
- 6th Orbits_Calculator by Brian Workman
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9. References

Alzner A., Argyle R.W., 2012, “The Orbital Elements of a Visual Binary Star”, *Observing and Measuring Visual Double Stars*, R.W. Argyle, ed., Chapter 7, Patrick Moore’s Practical Astronomy Series. Springer, New York, NY.

F. Arenou, X. Luri, C. Babusiaux, et al., 2018, “Gaia Data Release 2: Catalogue validation”, *Astronomy & Astrophysics*, **616**, A17.

P. Ashley, R & Farihi, J & R. Marsh, T & J. Wilson, D & T. Gaensicke, B., 2019, “Evidence for bimodal orbital separations of white dwarf-red dwarf binary stars”, 10.1093/mnras/stz298

C.A.L. Bailer-Jones, J. Rybizki, M. Fouesneau, G. Mantelet and R. Andrae, 2018, “Estimating distances from parallaxes. IV. Distances to 1.33 billion stars in Gaia data release 2”, *Astronomical Journal*, **156**, Number 2, pp 58.

C.A.L. Bailer-Jones, J. Rybizki, R. Andrae, M. Fouesneau, 2018, “New stellar encounters discovered in the second Gaia data release”, *A & A*, **616**, A37.

Banik, Indranil, 2018, “A new line on the wide binary test of gravity”, *Monthly Notices of the Royal Astronomical Society*, **480** (2), 2660–2688

Bessel, F. W., 1844, “On the variations of the proper motions of Procyon and Sirius”, *Monthly Notices of the Royal Astronomical Society*, **6**, 136-141

Bryant, Tom, 2019, “New Doubles Found Using Data from the Gaia DR2 Catalog”, *Journal of Double Star Observations*, **15** (1), 89.

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.

Dariusz Graczyk, Grzegorz Pietrzynski, et al., 2019, “Testing Systematics of GAIA DR2 Parallaxes with Empirical Surface Brightness Color Relations applied to Eclipsing Binaries”, arXiv:1902.00589v1.

Greaves, John, 2019, “Using the Six Astrometric Parameters from Gaia DR2 II : Common Radial Velocity Pairs”, *JDSO*, **15** (1), 77.

Harshaw, Richard, 2018, “Gaia DR2 and the Washington Double Star Catalog: A Tale of Two Databases”, *JDSO*, **14**)4),734.

Todd J. Henry, Wei-Chun Jao, Jennifer G. Winters, et al., 2018, “The Solar Neighborhood XLIV: RECONS Discoveries within 10parsecs”, *The Astronomical Journal*, **155**, 265 (23pp).

Andrei P. Igoshev, Hagai B. Perets, 2019, “Wide binary companions to massive stars and their use in constraining natal kicks”, draft arXiv:1901.05972v1.

Jiménez-Esteban, F. M., Solano, E. and Rodrigo, C., 2019, “A catalogue of bright wide binary and multiple stars from GAIA-DR2 and the Virtual Observatory”, arXiv:1901.03730, draft version submitted Jan 11th. Accepted to be published in the Astronomical Journal

P. Kervella, F. Mignard, A. Mérand and F. Thévenin, 2016, “Close stellar conjunctions of α Centauri A and B until 2050”, arXiv:1610.06079v1 [astro-ph.SR].

Pierre Kervella, Frédéric Arenou, François Mignard, Frédéric Thévenin, 2019, “Stellar and substellar companions of nearby stars from Gaia DR2 - Binarity from proper motion anomaly”. arXiv:1811.08902v2

Knapp, Wilfried R. A., 2018, “495 Common Proper Motion Pairs so far not WDS Listed”, *JDSO*, **14** (3), 546.

Knapp, Wilfried R. A., 2018, “2126 Common Proper Motion Pairs so far not WDS Listed”, *JDSO*, **14** (3), 587.

The "True" Movement of Double Stars in Space

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

Knapp, Wilfried R. A., Nanson, John, 2019, "A Catalog of High Proper Motion Stars in the Southern Sky (HPMS3 catalog)", JDSO, **15** (1), 21.

Knapp, Wilfried R. A., Nanson, John, 2019, "A Catalog of High Proper Motion Stars in the Northern Sky (HPMSNS catalog)", *JDSO*, **15** (1), 42.

Knapp, Wilfried R. A., 2019, "Cross-Match of WDS TDS/TDT objects with DAIA DR2", *JDSO*, **15**)1). 178.

Knapp, Wilfried R. A., 2019, "Recovery of KPP objects in GAIA DR2", submitted to DSSC 27 Dec 18, 2018

Knapp, Wilfried R. A.. 2019, "Recovery of SKF objects in GAIA DR2", submitted to DSSC 27 Oct 21, 2018.

L. Lindegren, J. Hernández, A. Bombrun, et al., 2018, "Gaia Data Release 2 – The astrometric solution", *A & A*, **616**, A2.

L. Lindegren, J. Hernandez, A. Bombrun, et al., 2018, "Gaia DR2 astrometry", Astronomical Conference Vienna, August 2, 2018.

N. Lodieu, R. L. Smart, A. Pérez-Garrido and R. Silvotti, 2019, "A 3D view of the Hyades stellar and sub-stellar population", submitted to *Astronomy & Astrophysics*, arXiv:1901.07534v1.

X. Luri, A.G.A Brown, L. Sarro, et al., 2018, "Gaia Data Release 2. Using Gaia parallaxes", *A & A*, **616**, A9.

Ralph Schönrich, Paul McMillan and Laurent Eyer, 2019, "Distances and parallax bias in Gaia DR2", arXiv:1902.02355v1.

Jennifer G. Winters, Todd J. Henry, Wei-Chun Jao, et al., 2019, "The Solar Neighborhood XLV. The Stellar Multiplicity Rate of M Dwarfs within 25 PC", draft version arXiv:1901.06364 [astro-ph.SR]

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

Description of the Plx rating procedure (according to Knapp 2018)

- Two rating factors are used: Distance between the components in AU and relationship Plx error to Plx value. The distance between the components is calculated from the inverted Gaia DR2 parallax data (if positive) and the angular separation using the law of cosine

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

- with a and b = distance vectors for the stars A and B in lightyears calculated as (1000/Plx)*3.261631 and γ = angular separation in degrees calculated for small position deltas as

$$\gamma = \sqrt{\left[abs\left(RA1 - RA2\right)\cos\left(DE1\right)\right]^2 + \left(DE2 - DE1\right)^2}$$

and for large position deltas as

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

Realistic case distance is based on the given Plx values and the best and worst case scenario uses the given e_Plx data on the Plx values to estimate a smallest and largest possible distance within this error range applied once (threefold might be better)
- "A" for worst case distance, "B" for realistic case distance and "C" for best case distance 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 0.5% of Plx, "B" for less than 1%, "C" for less than 1.5% and “D” for above

The letter based scoring is then transformed into an estimated likelihood for being potentially gravitationally bound.
- A Plx Score of
- less than 10 means a likelihood of or near zero
- less than 50 means a likelihood lower than 50%
- larger than 50 means a likelihood larger than 50%
- equal 100 means a likelihood of 100%
- for a distance between the components smaller than 200,000 AU.

These likelihoods are based on the assumption that RA and DEC coordinates as well as parallaxes are normal distributed measurements with the given error range as standard deviation.

Appendix B

Counter-check of object samples from some of the 2019 reports mentioned in the introduction:

- Greaves 2019 – 15 objects listed in table 1: 12 out of the 15 objects qualify for a likely gravitational relationship, a respectable ratio due to a selection process concentrating on objects with rather large parallax values with a small error range. Three objects were less convincing:
  - ◊ GRV1252: Not very close parallax values and a rather larger parallax error for the primary result in a zero likelihood for a gravitational relationship despite the nearly ident radial velocity. Using the error range values for positions and parallaxes in a simulation gives an average value for the distance between the components over 30 light years – so this is most certainly no physical
  - ◊ GRV1256: 35% likelihood for a distance between the components of less than 200,000 AU with a mean value of ~300,000 AU and a rather large standard deviation give a quite flat distribution – despite very similar radial velocity in best case a "might be" physical
  - ◊ GRV1261: 12% likelihood for a distance between the components of less than 200,000 AU with a mean value of ~600,000 AU and a rather large standard deviation give a quite flat distribution – despite very similar radial velocity with overlapping error range a "rather not" physical
- Bryant 2019 – sample of 140 objects from the table in the Appendix starting with page 92: 46 or 33% out of the 140 objects qualify at first look for a likely gravitational relationship but only 31 or 22% make the cut for the PGR assessment scheme with a parallax value > 5 - so the assessment result for the objects not meeting this cut threshold is not valid. The rest of 94 objects are assessed as "might be" to "rather not" physicals despite the within the error range overlapping spatial velocity. The reason for this result is to be found in the object selection process with as it seems a preference towards very small parallax values leading despite the rather small error range to a huge spread regarding the likely distances between the components. Small parallaxes mean also less reliable data quality (Luri et al. 2018) and exponentially increasing distances for a given angular separation even with ident parallax values. A few examples for the objects with invalid "positive" assessment combined with small parallax values:
  - ◊ 4620459781916118528: The parallax values ~4,25 combined with the given angular separation suggest a distance between the components of ~161,000 AU but the simulation with the given error range for positions and parallaxes suggests an average distance of 262,500 AU with a likelihood of 45% for a distance below 200,000 AU so this is a "might be" case
  - ◊ 5056129616471590784: Very small but nearly ident parallax values suggest a distance between the components of ~157,000 AU but the simulation using the error range suggests an average distance between the components of ~350,000 AU making gravitational relationship rather unlikely and the likelihood of ~4% for a distance below 200,000 AU makes this look a "rather not" case
  - ◊ 5895171990539248000: This is another example with a positive rating at first look but due to the small parallax values of less than 3 combined with a rather large error range the average distance by simulation is larger than 1,000,000 AU or 15 light years making gravitational relationship very questionable. The likelihood for a distance below 200,000 AU is 12% so this seems also a "rather not" physical

Jiménez-Esteban et al. 2019 – 3,055 doubles from the total data set of 3,741 multiples available for download: 152 or 5% out of the 3,055 objects qualify at first look for a likely gravitational relationship but a second look shows that only 58 such pairs have a parallax value larger than 5 corresponding with a valid assessment and 94 come with much smaller parallax values down to below 1 by chance with more or less identical parallax values allowing for the conclusion of a distance between the components of less than 200,000 AU. But with parallax values this small this means then within the given parallax errors an extremely flat distribution of distances with an average distance far beyond this threshold. Reporting such pairs as likely physicals needs then very good additional reasons beyond common parallaxes. A few examples:

- GroupID 66: Rather ident parallax values of 1.76 mas suggest together with the angular separation of 25.3 arcseconds a distance between the components of ~94,000 AU but the likelihood for a distance < 200,000 AU is with the given error range only about 3%
- GroupID 85: Similar situation, only slightly better – the given data suggest a distance between the components of ~64,000 AU but the likelihood for a distance < 200,000 AU is with the given error range only about 5%

The "True" Movement of Double Stars in Space

- GroupID 807: Rather ident parallax values of 1.23 mas suggest together with the angular separation of 34.25 arcseconds a distance between the components of ~99,500 AU but the likelihood for a distance < 200,000 AU is with the given error range only about 2%
- GroupID 5 to give a positive example: Very similar parallax values of ~17,6 suggest despite the huge angular separation of 837 arcseconds a distance between the components of ~71,000 AU and the likelihood for a distance < 200,000 AU is with the given error range 99%

Appendix C

Table with distances between the 100 star systems closest to the solar system based on the RECONS list per 01 Jan 2012:

Nr	RA	Dec	Plx	Name	Lyrs	To Nr	Name
1	217.42916666666700	-62.67944444444440	768.85	Proxima Centauri	6.569	2	
2	269.45208333333300	4.69333333333333	545.51	Barnard's Star	5.512	7	
3	164.12166666666700	7.01472222222222	419.10	Wolf 359	3.896	11	
4	165.83416666666700	35.97000000000000	393.25	Lalande 21185	4.055	3	
5	101.28708333333300	-16.71611111111110	380.02	Sirius	5.251	14	
6	24.75541666666670	-17.95027777777780	373.70	BL Ceti	3.204	19	
7	282.45583333333300	-23.83611111111110	337.22	Ross 154	5.512	2	
8	355.47791666666700	44.17500000000000	316.37	Ross 248	1.837	16	GX Andromedae
9	53.23250000000000	-9.45833333333333	311.22	epsilon Eridani	5.084	6	
10	346.46666666666700	-35.85305555555560	305.08	Lacaille 9352	4.123	12	
11	176.93500000000000	0.80444444444445	298.14	Ross 128	3.896	3	
12	339.63916666666700	-15.30194444444440	289.50	EZ Aquarii A	4.031	40	
13	316.72458333333300	38.74944444444440	286.08	61 Cygni A	4.769	37	
14	114.82541666666700	5.22500000000000	285.17	Procyon	1.018	22	Luyten's Star
15	280.69458333333300	59.63027777777780	283.83		4.179	35	
16	4.59541666666667	44.02305555555560	279.87	GX Andromedae	1.837	8	Ross 248
17	330.84041666666700	-56.78611111111110	276.07	epsilon Indi A	4.299	26	
18	127.45625000000000	26.77694444444440	275.80	DX Cancri	4.988	14	
19	26.01708333333330	-15.93750000000000	273.97	tau Ceti	1.615	21	YZ Ceti
20	53.99875000000000	-44.51250000000000	272.01	Henry et al. 1997. Henry et al. 2006	3.721	25	
21	18.12750000000000	-16.99888888888890	269.08	YZ Ceti	1.615	19	tau Ceti
22	111.85208333333300	5.22583333333333	266.23	Luyten's Star	1.018	14	Procyon
23	281.27208333333300	-63.96333333333330	259.50	Henry et al. 2006	5.255	38	
24	43.25375000000000	16.88138888888890	259.41	Henry et al. 2006	3.680	34	

Table continues on the next page.

Appendix C

Table with distances between the 100 star systems closest to the solar system based on the RECONS list per 01 Jan 2012 (continued).

Nr	RA	Dec	Plx	Name	Lyrs	To Nr	Name
25	77.91916666666670	-45.01833333333330	255.67	Kapteyn's Star	3.721	20	
26	319.31375000000000	-38.86750000000000	253.44	AX Microscopii	4.214	46	
27	162.06125000000000	-39.93500000000000	248.53	Jao et al. 2005. Costa et al. 2005	5.809	42	
28	336.99791666666700	57.69583333333330	248.06	Kruger 60 A	4.575	8	
29	97.34750000000000	-2.81388888888889	244.44	Ross 614 A	3.843	22	
30	247.57541666666700	-12.66250000000000	234.38	Wolf 1061	7.420	76	
31	12.29125000000000	5.38861111111111	232.70	van Maanen's Star	4.324	41	
32	1.35166666666667	-37.35750000000000	230.32		4.324	10	
33	188.32166666666700	9.02083333333333	227.90	Wolf 424 A	4.546	11	
34	30.05500000000000	13.05222222222220	224.80	TZ Arietis	3.680	24	
35	264.10791666666700	68.33916666666670	220.47		4.179	15	
36	162.05250000000000	-11.33722222222220	220.30		5.731	11	
37	298.47583333333300	44.41527777777780	220.20	G 208-044 A	4.769	13	
38	262.16625000000000	-46.89527777777780	220.11		1.835	51	EV Lacertae
39	176.42875000000000	-64.84138888888890	216.12	WD 1142-645	2.140	42	
40	343.31958333333300	-14.26361111111110	214.47	Ross 780	4.031	12	
41	1.68250000000000	-7.53944444444444	213.00		4.450	31	
42	161.08833333333300	-61.21000000000000	209.70	Henry et al. 2006	2.140	39	WD 1142-645
43	166.36916666666700	43.52666666666670	205.67		3.045	44	
44	152.84208333333300	49.45416666666670	205.53		3.045	43	
45	154.90166666666700	19.86944444444440	204.60		5.591	54	
46	323.39166666666700	-49.00888888888890	202.03		4.214	26	
47	54.89666666666670	-35.42805555555560	201.40		4.022	48	
48	43.76541666666670	-47.01444444444440	201.37	Costa et al. 2005	3.966	80	
49	63.81791666666670	-7.65277777777778	200.65	omicron 2 Eridani	2.523	65	
50	341.70708333333300	44.33388888888890	198.21	EV Lacertae	4.817	28	
51	264.26541666666700	-44.31916666666670	198.09		1.835	38	
52	271.36375000000000	2.50000000000000	195.96	70 Ophiuchi A	6.090	70	
53	297.69583333333300	8.86833333333333	195.40	Altair	3.722	70	
54	134.56208333333300	19.76194444444440	191.20	EI Cancri	3.798	90	
55	90.01458333333330	2.70666666666667	190.77	Henry et al. 2006	3.302	63	
56	75.48916666666670	-6.94638888888889	187.92	Henry et al. 2006	2.776	63	
57	144.89791666666700	-24.80777777777780	187.30	Burgasser et al. 2008	6.435	36	
58	176.92250000000000	78.69111111111110	187.26		7.123	35	
59	206.43250000000000	14.89138888888890	184.72	Wolf 498	6.143	33	
60	67.79916666666670	58.97722222222220	180.52	Stein 2051	9.238	75	

Table continues on the next page.

The "True" Movement of Double Stars in Space

Appendix C

Table with distances between the 100 star systems closest to the solar system based on the RECONS list per 01 Jan 2012 (continued).

Nr	RA	Dec	Plx	Name	Lyrs	To Nr	Name
61	103.70416666666700	33.26805555555560	178.11		2.617	84	
62	278.90791666666700	32.99833333333330	176.50	Reid et al. 2003	6.574	37	
63	82.86416666666670	-3.67722222222222	175.99	Wolf 1453	2.776	56	
64	313.13750000000000	-16.97472222222220	175.03		7.106	79	
65	63.83125000000000	-9.58527777777778	174.34	Vrba et al. 2004	2.523	49	
66	293.09000000000000	69.66111111111110	173.79	sigma Draconis	3.138	81	
67	92.64416666666670	-21.86472222222220	173.77		6.580	93	
68	85.53875000000000	12.48944444444440	171.50	Ross 47	3.883	55	
69	266.64250000000000	-57.31916666666670	171.10		4.800	51	
70	289.23041666666700	5.16888888888889	170.96	Wolf 1055	3.722	53	
71	224.36666666666700	-21.41555555555560	170.62		3.292	100	
72	290.20000000000000	-45.55750000000000	169.17	Jao et al. 2005	3.342	86	
73	233.05375000000000	-41.27555555555560	168.52		5.685	100	
74	3.86708333333333	-16.13388888888890	168.35		4.855	41	
75	12.27625000000000	57.81527777777780	168.23	eta Cassiopei A	4.945	99	
76	258.83750000000000	-26.60277777777780	168.12	36 Ophiuchi A	6.383	51	
77	357.30208333333300	2.40111111111111	168.02		5.239	41	
78	116.16750000000000	3.55250000000000	167.19	Ross 882	4.177	107	
79	302.79958333333300	-36.10111111111110	166.26		3.208	86	
80	49.98166666666670	-43.06972222222220	165.47	82 Eridani	3.966	48	
81	267.02791666666700	70.87472222222220	164.70		3.138	66	
82	138.59500000000000	52.68666666666670	163.73		5.008	44	
83	302.18166666666700	-66.18194444444450	163.71	delta Pavonis	6.377	69	
84	107.50750000000000	38.52944444444440	163.41	QY Aurigae A	2.617	61	
85	144.39541666666700	29.52805555555560	163.30	Vrba et al. 2004	4.118	90	
86	303.47250000000000	-45.16388888888890	161.35		3.208	79	
87	218.57000000000000	-12.51944444444440	160.78	HN Librae	3.782	71	
88	352.96750000000000	19.93722222222220	159.88	EQ Pegasi	3.850	106	
89	229.86166666666700	-7.72222222222222	157.80	Wolf 562	4.334	87	
90	135.09833333333300	21.83472222222220	156.87	Henry et al. 2006	3.798	54	
91	189.70458333333300	-38.38166666666670	156.78	Henry et al. 2006	9.831	27	
92	258.03291666666700	45.66583333333330	156.32		3.219	94	
93	88.79041666666670	-4.17138888888889	156.05	WD 0552-041	3.124	63	
94	247.82666666666700	40.86500000000000	156.00		3.219	92	
95	253.87000000000000	-8.33638888888889	154.96	Wolf 630 A	6.825	76	
96	246.35250000000000	54.30416666666670	153.14		4.216	92	

Table concludes on the next page.

Appendix C

Table with distances between the 100 star systems closest to the solar system based on the RECONS list per 01 Jan 2012 (conclusion).

Nr	RA	Dec	Plx	Name	Lyrs	To Nr	Name
97	145.69333333333300	-68.88500000000000	153.05	Jao et al. 2005	6.573	42	
98	184.75125000000000	11.12527777777780	152.90	GL Virginis	7.130	33	
99	348.32083333333300	57.16833333333330	152.84		4.945	75	
100	224.16041666666700	-28.16416666666670	152.49		3.292	71	
				Average distance Lyrs	**4.298**		
				Minimum distance Lyrs	**1.018**		
				Maximum distance Lyrs	**9.831**		
				Objects with distance to the next star smaller than 3 Lyrs	**16**		
Additional nearby objects:	Additional nearby objects:	Additional nearby objects:	Additional nearby objects:	Additional nearby objects:	Additional nearby objects:	Additional nearby objects:	Additional nearby objects:
101	165.01791666666700	22.83305555555560	149.32	Ross 104	6.200	105	
102	322.40333333333300	17.64333333333330	149.01	Ross 775 A	7.983	106	
103	134.73458333333300	8.47388888888889	147.66	Henry et al. 2006	4.496	107	
104	222.84750000000000	19.10055555555560	147.57	ksi Bootis A	7.136	59	
105	162.71708333333300	6.80805555555556	147.15	EE Leonis	6.200	101	
106	344.14500000000000	16.55333333333330	146.37	Ross 671	3.850	88	
107	122.98958333333300	8.77444444444444	146.30	Ross 619	4.177	78	
108	45.46416666666670	-16.59333333333330	143.81	Henry et al. 2006	7.935	65	