Using the Six Astrometric Parameters from Gaia DR2 I: Confirming Common Proper Motion Pairs in the Washington Double Star Catalog

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Abstract: The release of Gaia DR2 has led to the availability of up to seven million objects with six astrometric parameters from an homogeneous source with which a star's Galactic position can be very tightly defined. Here an example is given by way of confirming 159 common proper motion GRV objects listed in the Washington Double Star Catalog and extending the use of the data in order to say more about the stars.

Introduction

April 25, 2018 saw the release of data release 2 from the Gaia satellite consortia (Gaia Team, 2018). This will be the last major release for several years and for the first time includes extra astrometric data other than that of position, including proper motions, parallaxes and over seven million radial velocities. This means there are now sufficient data in the Gaia catalog release to enable the definition of a large number of stars astrometrically in a six parameter space.

One example of potential use would be the confirmation of known common proper motion pairs that heretofore have only been defined via their positions on the sky and their measured, usually relatively high, proper motions. With Gaia DR2 not only can these four astrometric parameters be more accurately and precisely defined for these pairs but in many cases parallax data can be added as well. Furthermore the sixth astrometric parameter of Radial Velocity is also available for the relatively brighter pairs thus enabling the possibility of defining the pairs relative to their nature in terms of both Galactic position and movement (kinematics) and also their potential Galactic Population membership.

Accordingly the current paper attempts to give an example based on the GRV discovery objects contained within the Washington Double Star Catalog (WDS) (eg Mason et al 2001).

Methodology

The GRV discovery objects contained within the WDS were chosen as a subset because the author is fully familiar with the methods, software, practices, resources and sources used in deriving these objects (Greaves 2004a, 2004b, 2005, 2008, and further source references therein), and further is aware of the homogeneity of approach in their derivation. Accordingly the WDS was used to export its included GRV discovery pairs as a reference source. This was then positionally matched against the Gaia data release 2 dataset via the CDS Strasbourg's X-Match Service (http://cdsxmatch.u-strasbg.fr/xmatch), a highly useful utility for the interrogation of immensely large catalogs that includes the ability to upload user defined source lists of positional data against which these catalogues can be crossmatched, or for that matter the capability of crossmatching large catalogues at CDS against each other based on positional proximity. In that way the GRV subset of data were matched against Gaia DR2 using only a 2 arcseconds match radius. The GRV objects were published to epoch and equinox J2000 and the cross matching facility matches on that coordinate, although the Gaia DR2 coordinates provided are formally epoch 2000 on the ICRS. The secondary of every GRV pair from WDS had already had its position reverse calculated from the data for the each of the primary's position, last position angle, and last separation as quoted by the WDS.

This resulting dataset included the astrometric data from the WDS with additions from Gaia DR2. In the former case primarily discover identifier, positions to epoch and equinox J2000 (including the derived position of the secondary calculated from WDS data), last separation and last position angle of the pair, as well as the individual proper motions for each of the pair. The Gaia DR2 data included the position to epoch J2000 for each of the pair, their epoch 2015.5 positions, their individual parallaxes, their individual proper motions, their Gaia DR2 G magnitudes (although not used within any analyses), their parallaxes, their proper motions and their radial velocities, as well as the quoted errors for each of these quantities.

It should be noted here that although the CDS Strasbourg (http://cds.u-strasbg.fr/) provides the Gaia DR2 release complete with epoch J2000 positions, the primary processing of the data it presents is to the mean epoch of 2015.5. As with the date of an amateur measurement of a double star being taken as the reference, similarly the Gaia DR2 data should be based on the epoch 2015.5 positions. The author personally always prefers to plot positional data at the epoch of observation for illustrative and especially analysis purposes. The epoch and J2000 position acts as an index for cross referral with other data sources and with indexing, whilst the 2015.5 epoch position is the measured and least processed positional data, that is the former is derived from the latter. Thus any separations and position angles presented here for potential update within the WDS are dated epoch 2015.5. No doubt future Gaia data integration is a WDS project to come.

There is much online documentation for the Gaia project (https://gea.esac.esa.int/archive/documentation/index.html), and similarly for data release 2, which is a complete reprocessing, as not even the magnitudes are the same as those derived for Gaia data release 1, the data having been reprocessed to differing criteria and a new passband definition (see https://www.cosmos.esa.int/web/gaia/iow_20180316). In these analyses the magnitudes are retained merely as placeholders for the pairs and were not used in any other way. Past explorations of large amounts of Gaia DR2 and The Carlsberg Meridian Telescope CCD Drift Scan Survey data (CMC) (Evans et al 2002) have shown that G ~ CMC r' (unpublished work), and as noted in the CMC paper their r' is equivalent to the more widely used SDSS r'. As the Gaia G passband stretches from just overlapping Johnson U passband to inside Johnson-Cousins I_c passband, transformation of Gaia magnitudes to Johnson V is always going to be non-trivial, especially without color information. Worse still is the potential for confusion with SDSS g' (often referred to as just g by other surveys), a passband that mostly encompasses Johnson B and V passbands. No use of the two color magnitudes was made in these analyses either as they provide no easy interpretation, for example perusal of the graph in the above link reveals that both the "blue" and "red" magnitudes readily overlap the 656 nm H-alpha wavelength, a spectral line that can be quite a significant contributor to the continuum flux in many types of stars, including very red ones and very blue ones, with that contribution not always being photospheric. For this reason it is not clear how the Gaia RP-BP magnitude derived color can be of any easy utility. Tests made by the author on significant numbers of stars (again unpublished work) have ironically revealed that Gaia DR2 RP magnitudes do not match against SDSS r' magnitudes as well as the Gaia DR2 G magnitudes do (there is less scatter for the latter), despite the far more similar passband range of the former to SDSS r'. Consequently Gaia DR2 G magnitudes will be considered as sufficiently like SDSS r' and other broad passband red magnitudes as to be equivalent in this work, and roughly comparable to the ones provided in the WDS for the GRV pairs.

In terms of the astrometric data, the primary remit of the Gaia mission, things are clearer. The Gaia experiment full processing documentation is immense and involved, and to some extent dispersed when multiple pieces of Gaia data are being considered at once in the whole, both in terms of their accuracy and mutual interpretation (parallax and proper motion derivation are interdependent and have to be mutually allowed for, for example). Fortunately the CDS VizieR presentation of the data contains a ready summary of the presumed (and derived) accuracy for each parameter, even defining them as a function of G magnitude range (see ftp://cdsarc.u-strasbg.fr/pub/cats/I/345/ReadMe). The quoted accuracy is of course both fantastic and amazing. There is little or nothing available against which to test these claims for the astrometric data as they are at least two orders of magnitude improvement in many instances. Things have to be tested against Gaia, not Gaia against things. Gaia itself is being anchored against a very large number of point source quasars, themselves at distances where no measurable transverse positional motion should be possible.

Radial velocity measurements in Gaia are not from high dispersions and here is where potentially the quoted representative accuracy cannot be trusted. The full documentation also notes that there are still systematic errors. Otherwise a difference of up to a couple of kilometers per second velocity for yelloworange G ~ 10 very close pairs could be a hint of potential orbital motion. Nevertheless Gaia DR2 can give up to 10 kms^{-1} difference in radial velocity between common proper motion pairs even for pairs with well matching parameters including very similar parallaxes, and within that context here a difference of up to 10 kms^{-1} has been allowed.

However, close common proper motion pairs can be enlightening in terms of stated and potential accuracy of Gaia parallaxes, especially the smaller parallaxes. In practice in this analysis selection criteria allowed for a fairly generous ratio of larger parallax value per pair to smaller parallax value per pair upper limit of 1:1.3 to be used. The cut off point was somewhat arbitrary, the ratio was used instead of the difference as this should scale better across orders of magnitude. The difference of the base 10 logarithm of the parallaxes might have been more order scale independent, but an arbitrary cut off point would still have been necessary and as there are at present no rigorous models of Galactic structure against which a 'null hypothesis' (in crude terms, an extremely low probability of two things being randomly, that is coincidentally, associated) statistical test can be made then whatever method is used is prone to arbitrary, and consequently subjective, rules of thumb. Similarly the cutoff point for minimum parallax used is just below 1.5 milliarcseconds (mas). The quoted representative errors for Gaia DR2 allow even lower values, so again this figure is somewhat arbitrary, but comfortably above that promised by Gaia. No matter how intuitive a set of thresholds may appear, and no matter how contextually rooted, they are still not objective, a subjective user dependent decision is being made.

Designing such a statistical test would be very much beyond this author's capabilities anyway. An interesting consequence of using statistical tests will be outlined briefly in paper II, but basically in practice statistical tests often fare no better then subjective tests for borderline cases, likely due to the fact that they and/or the phenomenon being tested are often nonlinear. The safest and most rigorous test of a physically associated pair of stars is one with sufficient history of measurements that a firm orbit has not only been defined, but the pair has been seen to repeat it more than once (such stars exist, e.g. optically demonstrated for Sirius, whilst interferometically demonstrated for Capella and even the eclipsing binary Algol).

Basically for common proper motion pairs the core rules of thumb are to try to ensure that the values of properties possessed by two stars are sufficiently higher then the realistic errors on those values to ensure the perceived signal is not just fortuitous alignment within a large randomly distributed sample, and, to use as many independent parameters as possible to allow an intuitive decision that nevertheless is based on consideration of the facts and more widely accepted theories or models. Should this be felt to be self evident, I have seen work describing extremely low valued proper motions of less than 10 mas y^{-1} as common proper motion pairs, despite the proper motions quoted being of the same scale as the quoted typical errors of the source data. Also the expression "realistic errors" was used. These are errors picked up via practical use. Often catalogue quoted errors are not necessarily related to reality.

This is where not only the extra accuracy but the extra parameters provided by Gaia data release 2 in the context of double stars becomes highly significant and of fundamental utility. All six parameters are used in this study. A combination of any single new parameter in tandem with the improved accuracy that Gaia data release 2 presents for the traditional four could have been used, especially as there are more parallax measures in the data than radial velocity ones, however in this first instance the attempt was to be more rigorous. As some very low radial velocities are included in the results it could readily be argued that such low values are little different from having no values at all, given their likely accuracy. However, they are still measures and if a pair have similar, albeit barely above noise level, radial velocities then the data are telling us more than null values do. That is, that the pair both have insignificant but detectable radial velocity, so the radial velocity values are not disparate.

For instance, GRV1247 would pass the parallax tests. There is no radial velocity from Gaia DR2 for the primary however, likely due to how bright it is. Gaia DR2 radial velocity for the secondary agrees well with the value from the independent RAVE data release 5 (Kunder et al 2017). Published radial velocities for the primary cited in SIMBAD at the CDS appear to be mostly the same very old measure repeated from several sources, that is the other papers have used the same source themselves. Nevertheless –11 kms^{-1} is very different from +32 kms^{-1}, not only in magnitude but also in vector! Subsequently parallax as a sole additional criterion has therefore not been used in this study. GRV1247 is a common proper motion pair at the same distance. The primary is a spectral class A star and likely quite young, the secondary is a late G to early K spectral class star and if associated with the nearby x-ray source is possibly showing enhanced chromospheric activity, another possible indication of youth for a yellow-orange dwarf.

In which case it is possible to hypothesize an alternative scenario. Youthfulness gives the possibility of the pair being not long removed from an area of common formation. With a relatively nearby common source point and with little travel time since leaving it they may just be passing roughly in the same transverse motion relative to us and not have separated far as of yet. Equally it is possible that such a pair is relatively young as the spectral type A star has not evolved into a white dwarf as of yet and consequently the pair may not have orbited the Galaxy more than once or twice, or traversed the Galactic Disc more than a few times. If that much. The Sun's orbit is variously described as 225 to 250 million years and thus has completed at least 18 full orbits and 36 plus Disc crossings in its lifetime, for example. If the two stars were purely separating only in the line of sight radial direction at 40 kms^{-1} it would take them nearly a million years to widen the gap by around a parsec, or very roughly a hundred thousand years to separate further by 0.1 parsecs. In other words there is insufficient data to test whether this is a physical pair or a pair only as viewed at a snapshot in time. A more up to date radial velocity for the primary could be sufficient to affirm or debunk physicality, however.

Accordingly only full six parameter solutions were used in the analyses, even if this meant many fainter GRV objects, and many fainter companions to brighter GRV objects, could not even be tested due to lack of radial velocity measures for them in Gaia DR2. Another reason was highlighted during preliminary use of the data: quite close parallax values can be quite different distance values, after all parallax is reciprocal to distance as defined in practice, and if taken at face value they seem to indicate that some pairs are separated by only thousands to tens of thousands of Astronomical Units (ie hundredths to tenths of a parsec) perpendicular to the line of sight yet according to their parallax difference one is up to a parsec or even more behind the other. As there are apparently no equivalent cases where the converse is true this seems to be related to parsec accuracy more than reality. They can't all be in extremely long period extremely eccentric mutual orbit with the one of the pointy ends pointed towards us.

This does not mean that the converse cannot be applied using only parallax as a sole extra astrometric parameter with the traditional four provided sufficiently assessed minimum threshold measures are used. The current methodology chooses to affirm potential relationships between common proper motion pairs contained in the WDS, utilizing a specific subset as test case simply because the author has a reasonable familiarity with how the test objects were derived. It is in fact much easier to dismiss objects listed as common proper motion pairs that are likely not physically connected. In that instance good quality parallax measures alone for both stars within a pair will suffice if care is taken for both difference threshold and lower usable limit choices. For example, the stars apparently co-moving alongside 51 Pegasi (Greaves 2006) have parallaxes showing them to be significantly farther away than 51 Pegasi for them to actually be truly co-moving in an associated way, rather than an incidental one. This can be seen despite them being too faint to have radial velocity measures from Gaia. In this case their individual distances may need further examination in terms of their own relationship to each other.

This shows that the wider the apparent separation between stars on the sky the more likely it is for even relatively high and rarer proper motions common between two stars not to have any actual meaning. It will be interesting to see in time how small this distance can be. This could lead to a group of objects that are in fact (relatively) high common proper motion objects yet nevertheless completely unassociated, and more similar in nature to the linear solution pairs catalogued in the WDS, and certainly not "physical".

On the other hand the point raised earlier in the methodology and objects highlighted in the results suggest that rejection solely based on parallax measures from Gaia DR2 may not be quite that straightforward or safe, especially for more distant objects.

Finally another reason for using all six parameters is that they enable the derivation of UVWXYZ, the first three being of more practical use than the latter three which describe an object's position in three dimensions relative to the Galactic Centre. The first three (UVW) are velocity components relative to the Galactic Centre (although the sign of their values is relative to the Local Standard of Rest) and their use will be described more in the Discussion section. When used in tandem with similar data that have been categorized in past publications in terms of Population membership it is possible to use this data to assess the below listed "affirmed" 159 GRV common proper motion pairs in terms of their potential for either Thin Disc, Thick Disk, or Halo membership. The result surprised the author.

The derivation of these stellar kinematics however presents something of a blackbox part to the methodology. In researching the formulae for derivation of these values the author came across the following website http://kinematics.bdnyc.org/query. This academic based resource not only avoided the learning, understanding and eventual encoding into a computer language that would have been needed to derive UVWXYZ data for the stars, but also the laborious finding of sufficient source data to test the eventual product against. The site even has the special features of enabling the upload of a coordinate list, rather than having to key the data in one at a time, and on the fly interactive graphing of the results (hover over a data point in the graphs and the values can be read). The graphs are geared towards comparing the results to nearby young stellar associations and aimed at brown dwarf researchers, but those reference plots can be readily ignored and the graphs still used. However a three dimensional plotting utility is more informative. All "space velocities", that is stellar kinematics, used in this paper were derived via that site's application. The plots here presented were generated in TOPCAT (Taylor 2005), an increasingly essential tool in modern astronomical data access and manipulation, albeit coming with something of a learning curve and at times pedantic non-intuitive nature relative to other software. You also need to be confident enough to use runtime JAVA on your personal computer and confident enough for that JAVA to have internet access capabilities, given recent concerns of JAVA vulnerability.

When using the BDNYC source list upload facility the user must remember Gaia data release 2 presents parallax in milliarcseconds so the values from Gaia must be divided by a thousand before being reciprocalised to give the distance in parsecs, but other than that all units from Gaia are usable as is via that service. Remember for very small angles distance in parsecs is simply the reciprocal of the parallax in arcseconds and no trigonometric functions are required. And 0.0015 to 0.03 arcseconds are very small angles. In practice the mean parallax, mean proper motions and mean radial velocities were used, but the positional data of the primary and the differences in separation are relatively negligible.

The results from the Population assessment led to another possible source of data being utilised for further assessment and the subset of 159 sources' coordinates were uploaded into a crossmatch search against the public release of LAMOST (eg Lou 2015) data release 3 via the search engine at http://dr3.lamost.org/search . This not only provided spectral types for some of the affirmed objects but also radial velocity measures for comparison with the Gaia data release 2 measures. The main reason for using it however was to utilise the metallicity measures it provides as an extension to the Population assessment, albeit for only a very small number of the objects.

Results

The GRV objects in WDS primarily come from four papers, based on two different sources. Greaves 2004a was the initial paper (see references therein for source data). Unfortunately after publication an error was realised, in that the original cross matching code had been written by the author in a very ancient incarnation of BASIC, consequently it was very slow when significant amounts of data were processed. A colleague kindly agreed to convert it to a more modern language, PERL, which would be more suited to utilising modern computer hardware resources, specifically use more RAM to do the work. However, it turned out that the code was not converted but re-written from scratch with more clever algorithms to save processing time, and in the process an error was made that caused an entire quadrant of the sky to be neglected and not sampled. This gap was not particularly noticed even at galley proof stage of the paper, probably being considered a consequence of the data being used, a natural thinning of objects. After publication the problem was realised, the code fixed, and re-processing of the quadrant of data undertaken. Just before an attempt was started to publish the 'gap' a request from the CDS during the process of putting the data files into their archives (common for files over a certain size published in professional papers at that time apparently) led to the new objects being added at their request to that dataset, given that they were from the same data source and processing method outlined in the paper. Consequently 2004b is larger than 2004a which it is connected to because the missing quadrant is filled in.

The Greaves 2005 and 2008 data are on the whole much fainter, as usually are the handful of GRV pairs within the WDS that were not formally published, but submitted to USNO directly after incidental discovery during analyses unrelated to common proper motion work. This is reflected in the distribution of the GRV identifier numbers in the results' table. The fainter objects are least likely to have radial velocities available for both stars in a pair within Gaia data release 2. It is no great surprise then that only 2 of the 159 pairs resulting from the analysis are not from Greaves 2004b, these pairs too being relatively bright objects. This gives some idea of the applicable magnitude range against which Gaia DR2 data can be used in this way. It also highlights the number of successes relative to the 1200+ originally published. Of course not all objects had both stars of a pair crossmatched fully for all six parameters so that in itself causes significant reduction.

Four astrometric parameters from Gaia, derived position angle and separation values at epoch 2015.5 and some LAMOST spectral types and comparative LAMOST radial velocities are presented in Table 1. It should be noted that Gaia data are barycentric reductions (referenced to the centre of gravity of the Solar System) whilst the LAMOST radial velocities are heliocentric, however the difference between the two has been taken as negligible as far as the precision of the data quoted in this paper are concerned. This would not be the case for exoplanet radial velocity work for example. This work simply assumes that the precision of radial velocity work used here is far above the barycentric heliocentric difference of the two sources. For the Gaia data internal to itself there is no problem, as it is all on the same barycentric system. However that does mean that technically the derived position angles and separations are to a barycentric reference frame for epoch 2015.5, whereas in a sense the modern WDS values for same are to equinox J2000 and epoch of whenever the observation was made. Based on the assumption of negligible difference and the higher accuracy of the Gaia data the separation and position angle are quoted here both to one decimal more than the WDS norm, and the direct Gaia astrometric parameters to a precision felt acceptable given their accuracy. The published values were used in analyses

Finally if the parallaxes are converted into distances it is found that many of these objects that match reasonably well according to the other five parameters would be several to in some cases tens of parsecs behind their neighbour if derived distance criteria were used instead of the parallaxes directly. The readme to the data file quotes uncertainties of 0.04 milliarcseconds for objects with Gmag brighter than 15. In that case this list of results would be reduced drastically. In fact using even 1 millarcsecond as uncertainty would reduce the list to less than a hundred. The worst cases tend to be for the more distant objects, or conversely the smaller parallaxes, although not always in all cases. If only parallax had been used as an extra parameter without radial velocity coincidence more objects would have been rejected. Proper motion and parallax both cause change of position of a star, it may well be that later versions of Gaia data resolve these issues.

GRV 140 is a quite wide pair with relatively small proper motion and radial velocity but a Gaia parallax distance difference of 126 parsecs, based on which it is possibly safest to discard it. Adding the quoted Gaia parallax error to the smaller value (error = 0.131) and subtracting the quoted parallax error from the larger value (error = 0.053) in the tables roughly halves the discrepancy, but that's still over 60 parsecs! On the other hand GRV 1156 has a distance difference of 39 parsecs but proper motions very near the 100mas^{-1} mark, whilst GRV 198 has well sized and well matching proper motions and well matching high radial velocities yet is supposedly 11.5 parsecs apart in the line of sight. At the other extreme GRV 1 has a relatively low but well matching common proper motions and relatively small radial velocities that are in fair agreement, and is a wide pair, but with parallaxes below 2 milliarcseconds that are exactly the same to 3 decimal places, such that the pair are ostensibly both 536 parsecs away giving a true angular separation of over 39,000 Astronomical Units or approximately a fifth of a parsec! Yet apparently moving together.

The author often finds that common proper motion pairs help define the true potential of accuracy for an astrometric catalogue better than the quoted errors. The assumption here is that Gaia parallaxes don't particularly improve the true projected separation situation for binaries except for possibly the nearest objects. However they are still phenomenal in their accuracy and depth even given the above.

It should be noted that the table does not include the coordinate positions from Gaia for right ascension and declination, although these were used in the space kinematics analyses as mentioned in the methodology. The pairs have been already predicted to be common motion at publication based on their proximity, and the derived separation takes the place of coordinate system, as it is the intercomparison of each pair's distance and transverse (x,y) and radial (z) motions that are being undertaken. The proximity on the sky of a pair of stars considered as being connected is taken as read.

Discussion

As mentioned in the methodology the availability of all six astrometric parameters allows a star's stellar kinematics to be derived, and its "space motion". These are usually referred to as UVWXYZ. The latter three are positional, X is the distance from the Sun with positive values being towards the direction of Galactic Center and negative ones away from, Y is in relation to the Sun's motion with positive being in the same direction, whilst Z is the distance out of the Galaxy's plane with positive being "above", they are all relative to the Sun and in parsecs.

UVW are velocity vectors in kilometres per second. U is positive in the line towards the Galactic Centre and negative away from, V is positive in the direction of the Sun's motion and negative when opposite to it, and, W is the velocity perpendicular to the plane of the Galaxy and positive towards the North Galactic Pole whilst negative away from it. These space velocities will be the ones used here, nevertheless all six derived quantities as presented here in Table 2. UVW are also corrected for the Sun's peculiar motion compared to the Local Standard of Rest. This latter has various values across the literature, even modern values don't agree particularly, however the differences are small, and indeed small in absolute terms as well (no value for the Sun is larger than say 13 kms^{-1}), so any difference in correction used by differing literatures sources for their values of UVW relative to the Local Standard of Rest would make negligible difference to the representation given in Figure 1. That is, the derived Gaia data are being compared to themselves whilst their comparison with literature values of potentially varying Local Standard of Rest correction is to a scale that makes the latter small enough to be ignorable.

Finding sources of reference data against which to compare these values turned out to be non-trivial. Much in the literature describes Stellar Populations, their character and statistics, but few sources give lists of stars with well established Population membership also including UVW values for all of Thin Disc, Thick Disc and Halo populations and these were much harder to find. Some included such data but the data were used in graphing and any tabular data did not make any statement about the Population membership of individual stars. In the end a small subset of Thin and Thick Disc data were used from Bensby et al (2005). Halo stars where provided by Roederer (2009) taking a subset of the most metal poor ([Fe/H] < -2.0) and nearby from the whole provided. Another benefit of these two sources was the small sample involved which made illustration easier.

These were all plotted accordingly using TOPCAT in a “3D” scatter plot, with the GRV, Thin Disc, Thick Disc and Halo objects being kept in separate data subsets, as represented in Figures 1a, 1b and 1c, and the results examined. Figure 1a shows the parameter space zoomed into so that only the GRV objects (black dots) and Thin Disc stars (blue dots) are visible, with the Sun represented by the open symbol. Figure 1b shows the parameter space zoomed out enough (velocities are increasing as we zoom out) to show the Thick Disc stars (green dots) as well, with the Sun now hidden by adjacent objects. Figure 1c finally zooms the velocity parameter space out far enough to allow the Halo stars (red dots) to be included. The three Populations are reasonably distinct within the plot although there is some suggestion of overlap at the border of Thick Disc and Halo objects.

The author was instantly surprised by the results. Possibly due to bias based on the properties of very high proper motion stars in the Solar Neighborhood the author had expected the GRV objects to be Halo stars with a smattering of Thick Disc objects, or possibly mostly Thick Disc stars. A bright example of a nearby object belonging to the latter Population having very high proper motion would be Arcturus. The expectation had been that due to their high transverse and radial motions relative to the Sun these objects would not be of the same Population as the Sun, which is a Thin Disc star. Similarly Thin Disc stars lie within the main bulk of the Galaxy which for objects of similar age to or older than the Sun would have orbits that have crossed the Disc dozens of times since birth, and generally spent far more time relatively nearer to other stars and things like Giant Molecular Clouds than Thick Disc or halo stars do, so for every fainter common proper motion pair there is more chance of having been dis-

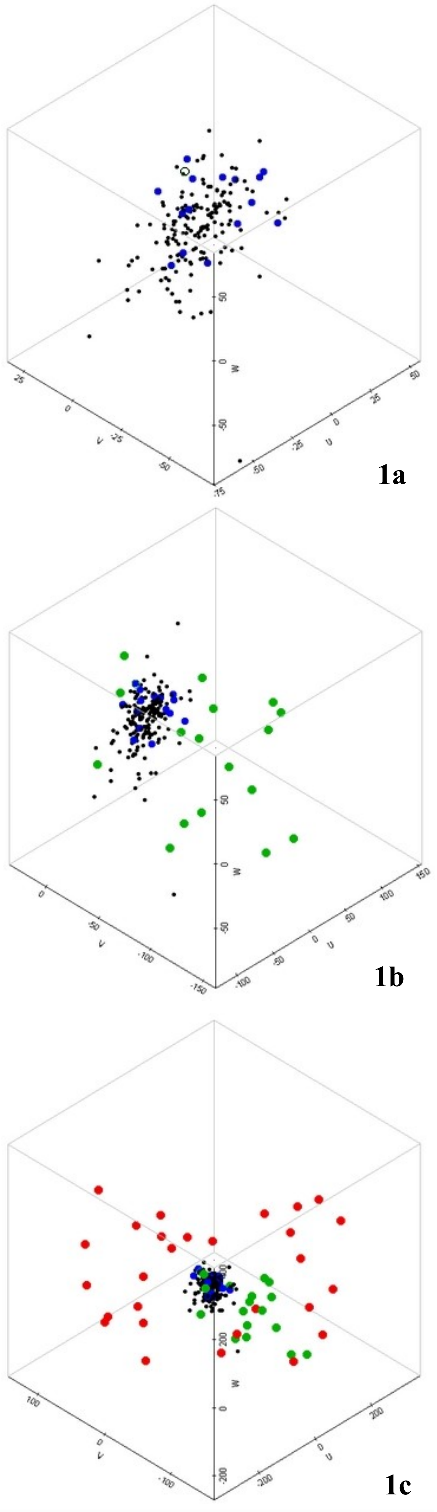

Figure 1. The UVW parameter space (in km^{-1}) for the GRV objects taken from a mean for each pair. Black dots represent the GRV pairs, blue dots Thin Disc stars, Green Dots Thick Disk stars and red dots Halo stars. The images are zoomed relative to the parameter space increasing in scale outwards from a) to b) to c)

rupted and rendered apart giving their relatively wide separations and seeming lack of mutual orbital binding the further away they get.

It appears that the vast majority of these GRV objects are in fact Thin Disc stars. Possibly all bar one.

Therefore simple intuition didn't work here as it had naively been expected that the younger Thin Disc would mostly have prograde orbits more circular and of little inclination with respect to themselves and the Sun travelling at somewhat similar overall velocity to the Sun, whereas the increasingly dispersed Thick Disc and especially Halo stars would have more random orbits, yet V values for the GRV objects are quite negative at times. The relatively small motions in terms of low to very low proper motions in respect to nearby "Extreme Population I" stars, that is very young Thin Disc stars, and local star forming regions such as the Orion OB associations and the Sco-Cen associations as well as nearer to much nearer T associations such as the ones in the Taurus-Auriga Dark Cloud to young Moving Groups like the TW Hydræ and the epsilon Chameleontis ones, or even the Hyades, had led the author to expect high proper motion stars could not be Thin Disk stars. Although the GRV common proper motion pairs here are mostly of larger UVW values than in young groups, they are on the whole nowhere near high enough to be anything other than Thin Disc. Except GRV 920 which has by far the highest radial velocity of the 159 objects. It is usually loosely considered that stars (that aren't runaway stars) with high radial velocity away from the Sun are possible Population II candidates, that is Halo stars. GRV 920 lies well outside the parameter space of the vast majority of GRV objects in all of UVW on Figure 1 on the border with the green dotted Thick Disc stars.

There are some other not as pronounced outliers from the main clump of stars and accordingly extra data were obtained in the hope of clarification. The data were crossmatched against LAMOST data release 3 to provide metallicity values, specifically [Fe/H]. The spectral type determinations and LAMOST radial velocities for comparative purposes were included in Table 1, whilst these [Fe/H] values are included in Table 2 along with UVWXYZ. Unfortunately only a very few pairs had data for both stars, but at least one star from each pair was matched in over a third of the cases. For the few with data for both stars the metallicity can also work as a further test for common proper motion pairs consisting of similar stars following the astrometric tests.

[Fe/H] is the ratio in the spectrum of a star between the iron (Fe) and hydrogen (H) content, the ratio being derived via measuring the strengths of their spectral lines relative to each other within the spectrum. The value is expressed as the logarithm to base 10 relative to the Sun's metallicity, such that a star with [Fe/H] of –2 would have 10^{-2} that of the Sun, that is 0.01 or one hundredth for that of the Sun. A value of 10^{1} would have 10 times the metallicity of the Sun (a number to the power of 1 is itself), although such a value should not be expected. The Sun's metallicity is 0.0, that is 10^{0} which is 1 (any number to the power of 0 is 1), that is the Solar metallicity is one times its value, which in logarithm to the base 10 is 0. Thus the actual metallicity quoted for a star in this way is 10 to the power of that value relative to the Sun. "Metallicity" in astronomy usually means anything that isn't hyrdrogen, and usually Fe/H is used as representative of that. The commonest isotope of iron (^{56}Fe) has a highly stable nucleus which is why Type II supernovae occur due to massive stars not being able to generate fusion from it once they've got that far in their evolution from fusing lighter elements along the way, and the element is well represented in optical spectra and thus this ratio is often the first used to define a star's metallicity.

Halo stars can have [Fe/H] metallicities up to –2.0 to –2.5, especially for objects like RR Lyræ variables, but can have values down to around –1 or so. Thick Disc stars have metallicities of around –0.5 to –1.0 or so (literature differs) but with no firm border and considerable overlap with Halo stars at the one end and Thin Disc stars at the other. Thin Disc stars will be in the value range of –0.5 to +0.5 in general, again with some overlap with Thick Disc stars at their lower border. Metallicity is also generally presumed to be related to age, although location of formation will also be a factor, so Halo stars are usually considered the oldest, up to the age of the Galaxy, due to their low metallicity as the Galaxy is presumed to have its metal content enriched over time as the more supernovæ (and other phenomena) occur over that time. Thin Disc stars as a whole are considered the youngest on average, up to the age of the Sun and beyond, whilst Thick Disk stars are considered to lie between the two, again with considerable overlap between the other two Populations.

Accordingly the metallicity provided by LAMOST was compared against a handful of other outliers, albeit those outliers not being all that extremely outlying. Unfortunately, no values were available for GRV 920. Of the other candidates some of the outliers had borderline metallicities of around the –0.5 mark so are candidates but not confirmed Thick Disc members, but some had positive values which suggests they are just as likely if not more likely to be Thin Disc members. Most of the Thin Disc candidates had more Sun like or higher

(Text continues on page 75)

Table 1. Four astrometric parameters for 159 confirmed WDS included GRV common proper motion pairs. theta and rho are calculated from the Gaia data and are for epoch 2015.5, the last four columns are from LAMOST data release 3. All other numerical values are directly from Gaia data release 2. Key : theta is position angle in degrees, rho is separation in arcseconds, pi are parallax in milliarcseconds, mu are proper motions in milliarcseconds, rv are radial velocities in kilometres per second, Gmag is the Gaia G magnitude and sp the spectral class from LAMOST

Name	**theta**	**rho**	**piA**	**piB**	**muraA**	**mudeA**	**muraB**	**mudeB**	**rvA**	**rvB**	**GmagA**	**Gmagb**	**spA**	**spB**	**rvA**	**rvB**
GRV 1	350	73	1.866	1.866	-17.2	-25.2	-17.1	-25	15.5	11.2	11.1	11.8				
GRV 4	19.1	7.28	2.65	2.672	18.9	-8.1	19	-8.3	-51.4	-44.4	10.9	12.1		G3		-43.1
GRV 7	230.5	37.36	6.304	6.277	116.7	22.8	116.6	21.1	3.2	2.9	10	10.6				
GRV 12	174.4	45.85	4.783	4.576	42.2	-25.8	42.8	-26.6	0	-1.8	11	11				
GRV 18	0	16.09	4.245	4.274	25.8	-30.4	25.8	-30.4	-39	-37	10.4	11				
GRV 19	4.3	14.24	11.817	12.201	33.3	-21.5	31.5	-29.2	33.1	32.8	10.7	11.5				
GRV 26	250.3	34.91	5.62	5.554	51.8	-51.7	50.2	-50.5	-13.7	-14.4	9.9	11.8				
GRV 28	172.9	15.02	5.883	5.963	36.2	-17.2	35.7	-17.6	10.9	10.4	9.7	10.8				
GRV 29	129.7	80.99	8.417	8.381	42.1	39.9	42.1	39.6	0.3	-0.2	9.3	10.5				
GRV 31	15.2	22.25	3.839	3.577	-40.2	20.2	-40.6	19	-24.8	-21.6	10.7	11.8				
GRV 33	171.4	20.8	3.12	3.048	20.5	-13.1	20.5	-13.3	-20.6	-20	11	12.4				
GRV 36	349.7	66.68	6.028	6.012	12.9	-23	13.4	-22.4	13	12.8	9.2	10.7				
GRV 40	357.5	55.11	29.85	29.579	20	-42	27.3	-34.5	-49.9	-38.9	8.5	9.1				
GRV 41	51.3	18.15	4.553	4.642	17.1	-22.7	15.7	-20.6	-5	-8.6	11	11.2				
GRV 44	167.1	43.94	5.592	5.58	11	-15.6	10.9	-15.6	7.6	8.1	11.4	11.9	F9		-2.9	
GRV 51	239.7	60.31	4.456	4.432	52.2	-24.8	52.4	-25	-14.3	-12.1	9.8	12				
GRV 58	188	33.09	8.495	8.351	-12.8	-11.7	-12.5	-10.4	-15.8	-15.1	8.7	9				
GRV 61	190.7	37.43	3.95	4.001	19.5	19	18.7	19.7	-2.3	-0.5	10.5	11.6	F5	G0	-5.3	-11.5
GRV 74	239.1	12.42	4.268	4.25	38.8	-23.8	39.1	-23.6	-2.3	-0.4	10.5	10.9				
GRV 92	9.4	41.18	2.601	2.845	40.1	-20.3	39.2	-19.3	7.4	12.3	8.1	10.5				
GRV 120	53.8	23.63	4.12	4.171	14.2	-30.8	12.2	-29.6	12.1	12.4	10.5	11.6				
GRV 123	46.8	12.08	11.161	11.022	94.2	-27.1	95	-26.8	49.5	49.1	10.2	10.5	G7		49.6	
GRV 131	128.4	23.63	3.74	3.753	49	-21.9	49	-22.3	32	30.2	12.8	13.1				
GRV 132	45.5	26.24	6.92	6.757	-16.1	-34.9	-15.9	-35.8	-27.3	-25.8	9.9	11.3	K3		-28.9	
GRV 138	53.1	32.77	9.409	9.314	86.7	21.2	85.7	23.2	52.7	53	11.2	11.6				
GRV 140	38.4	84.54	1.593	1.993	-16.6	-28.6	-17.2	-28.1	-7.7	-12	12.1	12.3				
GRV 144	14.9	20.19	2.781	2.84	17.3	-10.6	17.5	-10.6	-12	-10.5	11.6	12		F9		-18.8
GRV 147	276.3	9.95	4.194	4.242	21.8	-29.9	22.8	-30.3	3.5	2.8	11.9	12.3				
GRV 150	353.2	12.16	3.716	3.104	-17.8	16.2	-20	14.3	-1.3	-1.5	10.8	11.6				
GRV 152	292.3	46.3	3.098	3.094	98.6	-15.3	98.4	-15.5	34.9	34.9	11.5	11.5	G3		32.3	
GRV 155	317.2	9.03	2.237	2.146	32.4	-14	32.3	-14.9	36.8	39	11.5	11.6				
GRV 158	216.6	13.99	4.497	4.738	-14.2	-14.2	-14.8	-13.7	1.7	4.2	10.3	11.4	F7		1.9	
GRV 163	272.2	23.71	4.61	4.57	38.5	-17.6	37.3	-17.8	-13.5	-12.3	10.8	12.2		G7		-20.5
GRV 174	134.6	14.15	2.227	2.224	12.5	-18.2	12.7	-18.2	-3.1	-2.7	12.3	12.3				
GRV 178	294.4	12.98	5.588	5.445	-24.1	-10.9	-20.9	-10.8	-1.7	-3.2	10.5	11.9				
GRV 182	14.1	25.09	6.137	6.249	13.7	-20.9	12.9	-20.7	29.6	27.2	11.2	11.7				
GRV 188	124.7	21.86	4.754	4.365	-18.5	-20.4	-19	-20.7	-28.7	-27.7	11.9	12.5	G7	G7	-30.6	-37.8
GRV 190	236.7	22.06	8.425	8.54	63.7	32.9	63.9	32.6	40.1	39.5	10.5	11.9	F9		36.5	
GRV 193	25.3	24.28	2.938	2.88	13.4	-38.3	13.7	-38.2	-0.7	-3.6	11	12.1				
GRV 194	161	51.51	3.536	3.506	-11	-27.4	-10.7	-27.6	-13.2	-13	11.9	12.3	F9		-13.1	

Table 1 continues on the next page.

Table 1 (continued). Four astrometric parameters for 159 confirmed WDS included GRV common proper motion pairs. theta and rho are calculated from the Gaia data and are for epoch 2015.5, the last four columns are from LAMOST data release 3. All other numerical values are directly from Gaia data release 2. Key : theta is position angle in degrees, rho is separation in arcseconds, pi are parallax in milliarcseconds, mu are proper motions in milliarcseconds, rv are radial velocities in kilometres per second, Gmag is the Gaia G magnitude and sp the spectral class from LAMOST

Name	**theta**	**rho**	**piA**	**piB**	**muraA**	**mudeA**	**muraB**	**mudeB**	**rvA**	**rvB**	**GmagA**	**Gmagb**	**spA**	**spB**	**rvA**	**rvB**
GRV 198	49	21.26	7.96	7.292	32.1	-55.3	33.4	-57.7	86	82	10.2	12.2	G3		77.6	
GRV 210	179.1	37.1	4.776	4.774	21.6	26.8	20.8	26.2	2.7	3.2	11.7	11.9	F9	G6	-3.9	-2.9
GRV 219	344	12.67	6.312	4.871	54.8	-81.9	54.1	-75.6	18	17.9	11.6	12.4				
GRV 221	66.3	11.57	5.554	5.725	-38.8	-29.6	-38.9	-29.3	-32.1	-30.5	9	11.4	F9		-34.6	
GRV 225	3	12.23	4.406	4.472	33.5	-25.7	33.9	-25.1	-18.2	-17.6	11.5	12.2				
GRV 226	4.6	11.23	8.101	8.065	9.8	-18.6	9.8	-19.2	28.5	28.5	11.8	12				
GRV 228	351.4	11.98	10.33	10.387	17.6	-14	20	-14.8	42.1	43.3	8.6	11.8	F6	K5	37.1	43.1
GRV 229	331.2	11.05	3.644	4.166	22.4	15.5	23.4	14.8	58.7	63.1	12	12.9	K3		82.3	
GRV 230	340.8	15.31	2.902	2.986	-24.7	14.5	-25.7	13.9	44.6	41.6	10.4	11.6				
GRV 236	353.3	57.43	6.987	7.043	13	17.7	13	18	-23.7	-22.4	9.8	12.2				
GRV 238	344.9	36.55	6.251	6.312	-18.1	30.3	-18.2	30.9	-27.6	-28.1	9.3	9.5				
GRV 244	152.8	14.57	2.01	2.026	18.7	-11.9	16.9	-14	-6.6	-7	11.7	12.6				
GRV 249	207.2	14.56	2.542	2.575	-16	-11.4	-17.3	-12.4	-29.9	-29.9	11.7	11.8				
GRV 255	133	13.83	4.723	4.791	-33.1	-11.6	-32.7	-11.5	27.4	32.4	11.4	12.7				
GRV 265	67.4	12.07	8.101	8.08	61.7	33	61.4	33.2	-26.5	-27.8	12	12.2				
GRV 269	170.1	21.31	6.433	6.248	25.4	-22.4	25.5	-23.4	-30.6	-34.2	9.5	11.1				
GRV 271	82.8	23.35	3.037	2.988	15.6	24.1	15.4	23.7	-0.3	1.2	10.4	10.5				
GRV 274	18.5	20.77	4.823	4.901	14.1	-14.5	14.5	-14.2	6.3	4.9	11.9	12.2				
GRV 278	208.3	13.38	5.341	5.307	-18.8	-19.6	-18.7	-19.7	-49	-49.6	12.1	12.2				
GRV 281	221.7	35.49	5.63	5.675	14.1	17.3	14	17.8	-31.1	-33.5	8.7	8.9				
GRV 300	19.5	24.15	4.809	5.136	-12.9	-26.3	-12.6	-27	-7.1	-9.4	10.3	11.6				
GRV 311	21.5	9.74	2.282	2.293	11.6	-11.4	11.5	-11.2	-12.6	-14.5	11	12.5				
GRV 312	318.9	15.56	3.521	3.476	19.6	25.6	19.1	25.9	3.4	5.6	11.6	12.7				
GRV 320	152.1	31.34	2.445	2.261	16.6	12.9	15.9	11.3	-34.7	-34.7	12	12.6				
GRV 329	339.3	66.67	2.149	2.134	-12	-23.4	-8.8	-16.7	14.2	19.2	10.4	12.1				
GRV 339	312.2	15.47	4.448	4.401	-9.8	-33	-9.8	-33	33	32.3	11.9	13.2				
GRV 347	7.9	22.44	1.952	1.885	-19.6	-24.3	-19.4	-24.5	27.7	27.6	11.8	13				
GRV 348	80.8	14.79	3.359	3.294	9.6	-13.1	9.9	-13	-34.1	-34.2	10.3	12.7				
GRV 353	82.9	19.64	5.021	4.944	14.6	-57.4	14.3	-57.2	20.7	20.6	11	11.9				
GRV 361	102.9	27.99	4.408	4.419	21	-13.8	23.5	-13.1	-19.5	-22.5	9.5	11.2				
GRV 364	156.5	40.28	4.477	4.595	-21.5	-48.4	-21.5	-48.2	65.5	56	10.4	11.8				
GRV 377	335.7	27.28	1.497	1.615	-22.9	-19.4	-23.6	-19.5	15	17.4	11.9	11.9				
GRV 383	124	21.19	6.321	6.248	-50.3	-55.9	-50.1	-55.9	-6.2	-7.4	11.4	11.9				
GRV 403	116	33.5	3.45	3.448	67.4	25.7	67.5	25.8	-46.9	-48.1	11.2	11.3				
GRV 406	287.2	10.47	2.542	2.485	54.4	35.9	55.5	36.4	-58.4	-60	11.7	12.3				
GRV 413	200.3	35.7	3.331	3.492	42.6	13.9	42.5	13.8	-9.9	-12.5	11.2	11.9				
GRV 421	184.8	14.6	5.899	5.92	19.5	29	19.2	29.2	-21.9	-28.5	11.8	12.7				
GRV 424	326.6	12.11	5.107	5.072	10.7	-19.4	10.7	-19.2	-47.7	-47	9.5	11				
GRV 427	201.1	18.23	1.47	1.425	-11.1	-12.1	-11.2	-12.2	22.3	16.1	11.4	12.3				
GRV 708	190.8	32.34	5.712	5.742	57.4	-51.4	58.6	-52.7	59.5	60.4	10.8	11				

Table 1 continues on the next page.

Table 1 (continued). Four astrometric parameters for 159 confirmed WDS included GRV common proper motion pairs. theta and rho are calculated from the Gaia data and are for epoch 2015.5, the last four columns are from LAMOST data release 3. All other numerical values are directly from Gaia data release 2. Key : theta is position angle in degrees, rho is separation in arcseconds, pi are parallax in milliarcseconds, mu are proper motions in milliarcseconds, rv are radial velocities in kilometres per second, Gmag is the Gaia G magnitude and sp the spectral class from LAMOST

Name	theta	rho	piA	piB	muraA	mudeA	muraB	mudeB	rvA	rvB	GmagA	Gmagb	spA	spB	rvA	rvB
GRV 712	159.4	37.98	8.085	7.973	12.8	-47.5	13.2	-47	-17.3	-16.8	10.4	10.8	G3	F9	-19.9	-18.7
GRV 724	270.1	9.28	2.824	2.903	15.7	-15.6	15.5	-15.5	41.4	43	10.7	11.8	F7	G1	39.6	40.1
GRV 729	73.7	9.63	2.925	2.931	-10.1	-35.7	-10.3	-35.6	47	47	11.8	11.9	G0	G1	43.6	48.4
GRV 731	266.5	27.66	7.024	7.089	-24.3	-25.7	-24	-25.6	28.8	32	12.4	12.4				
GRV 734	48.4	36.43	3.813	3.845	8.4	-27.7	8.2	-26.3	-9.4	-11.7	10	11.3	F7		-20.4	
GRV 735	312.2	26.32	1.848	1.906	9.6	-17.3	11.3	-15.8	-30.9	-29.5	11.1	12.2	F5		-32.7	
GRV 737	56.3	23.8	6.366	5.992	-37.5	-76.3	-37.4	-77.4	31.6	33.4	9.5	10.7				
GRV 739	250.8	19.27	5.807	5.803	-30.4	-42.5	-30.6	-42.4	61.4	61.2	9.6	12.1				
GRV 744	193.3	43.52	5.325	4.538	-15.1	-25.4	-18.1	-25.8	23.7	30.5	9.4	11	F5		21.2	
GRV 747	110.9	23.28	6.4	6.44	-19.1	-33.6	-19.5	-33.6	58.8	58.2	9.6	10.9				
GRV 750	337.2	21.78	3.143	3.043	11.7	-22.6	11.3	-22.6	3.1	-0.3	9.7	9.9				
GRV 751	239.8	41.26	7.268	7.276	-20.8	-41	-20.3	-41.3	-57.4	-56.8	10.5	11.3	G7	K0	-61.1	-61.2
GRV 752	212.2	12.43	1.82	1.617	-8.4	-8.9	-8.3	-8.8	13.5	10.3	12.7	12.7		G3		10.2
GRV 757	303.4	9.49	3.734	4.026	-42.9	-10.9	-42.3	-11.7	24.2	24.6	10.2	11				
GRV 758	113.2	26.76	3.714	3.19	-20.8	-12.6	-20.8	-12.9	35.8	44.3	10.9	10.8				
GRV 759	235.7	15.05	3.349	3.372	11.9	-40.8	12.8	-39.9	20.7	20.1	11.3	12.7				
GRV 764	25.6	14.72	3.277	3.4	-25.8	31	-25.5	31	30.7	30.3	10.8	11.5				
GRV 770	51.9	40.94	7.168	7.218	12	-28.6	12.1	-28.6	-21.4	-21.4	10.7	11.6				
GRV 772	174.5	20.19	1.941	1.892	15.5	-15.9	14.4	-15.5	-16.2	-19.8	10.9	11.8		F5		-17.6
GRV 775	326.9	32.23	19.567	20.291	59.5	-85.1	52.4	-81.3	4.4	5.6	8.7	9	K0		0.1	
GRV 777	261.5	6.98	2.527	2.485	12.8	-30	13.3	-30.2	-58.4	-59	11.6	12	F5	F2	-60.7	-61.5
GRV 778	213.8	24.02	4.42	4.468	-32.4	11.6	-32.2	11.8	29.9	30.3	9.5	12				
GRV 779	28.1	28.85	2.391	2.495	-23.4	-14.3	-23.1	-14.5	38.6	37.4	11.7	12.3				
GRV 780	96.6	18.26	3.694	3.795	-22.3	-16.5	-20.7	-18	23.4	24.6	11.2	11	G2		14.2	
GRV 782	139.3	32.32	4.919	4.986	31.7	-20.9	31.8	-19.8	-35	-35.6	10.2	11				
GRV 789	16.4	13.02	6.502	6.352	29.6	-91.7	29.3	-92.3	-75.9	-75.2	9.6	12	G0		-86.8	
GRV 791	104.6	12.72	2.258	2.291	-16.4	-19.2	-16.7	-19.2	63.8	63	11.7	12				
GRV 798	130.3	81.1	3.402	3.516	18.1	-34	18.1	-34.9	-20	-16.2	12	12.3	G8	G7	-25	-24.5
GRV 799	179.6	37.77	6.435	6.397	-30.4	-65.1	-30.8	-66.6	11.5	14.4	9.7	10.1				
GRV 810	127.8	27.03	4.111	4.077	-36.9	-38.9	-37	-38.8	-18.5	-17.3	12	12.5				
GRV 811	210.4	26.85	8.759	8.816	38.4	-81.1	38.1	-80.6	-6.3	-3.3	10.3	11.7		K5		-16.3
GRV 813	321.4	42.86	3.834	3.795	-15.6	-23.7	-15.5	-23.5	-25.2	-25.9	10.5	11.2			-26.2	
GRV 814	204.8	22.17	2.468	2.531	-30.9	-10.7	-30.9	-11.1	12.2	11.1	11.1	11.9	F0		7.7	
GRV 816	192.2	63.15	3.796	3.297	17	-28.4	14.4	-21	-1.9	-0.2	9.6	11.6	G2		-13.7	
GRV 817	122.6	43.7	3.768	3.741	-26.9	-32.1	-27.7	-32.2	-13.9	-14.3	10.4	11.1		F9		-19
GRV 818	298.9	45.05	2.982	2.828	-28.3	-14.1	-28.3	-14.2	36.9	37.3	12.3	11.8		G1		35.5
GRV 829	62	29.6	5.773	5.71	21.3	-35	21.4	-34.8	-17.6	-18.7	11.9	11.9		G8		-23
GRV 837	267.1	10.82	9.001	8.994	68.7	-157.1	69.3	-156.7	-31.6	-29.2	10.8	11.6				
GRV 847	350.1	32.78	3.786	3.831	-15.7	14.7	-16.3	14.9	-11.8	-13.8	9.1	9.7				
GRV 848	215.2	26.4	3.208	3.287	-95	-18.6	-95.3	-19	-50.3	-55	12	12.7		G7		-38.2

Table 1 concludes on the next page.

Table 1 (conclusion). Four astrometric parameters for 159 confirmed WDS included GRV common proper motion pairs. theta and rho are calculated from the Gaia data and are for epoch 2015.5, the last four columns are from LAMOST data release 3. All other numerical values are directly from Gaia data release 2. Key : theta is position angle in degrees, rho is separation in arcseconds, pi are parallax in milliarcseconds, mu are proper motions in milliarcseconds, rv are radial velocities in kilometres per second, Gmag is the Gaia G magnitude and sp the spectral class from LAMOST

Name	**theta**	**rho**	**piA**	**piB**	**muraA**	**mudeA**	**muraB**	**mudeB**	**rvA**	**rvB**	**GmagA**	**Gmagb**	**spA**	**spB**	**rvA**	**rvB**
GRV 849	229.5	28.21	4.412	4.247	12.1	-32	13.7	-33.4	3.4	1.3	11.8	12.2	K1		5.4	
GRV 850	140.6	69.08	4.122	3.707	29.5	-30.1	29.1	-32.5	-36.9	-33.1	11.4	11.6	F9	F9	-36.5	-36.4
GRV 852	328.6	14.1	6.101	6.407	-49.7	-72.2	-48.2	-75.3	-17.9	-17.6	9.9	12.2	G1		-27.2	
GRV 856	241.9	8.71	2.471	2.516	-20.5	-32.6	-20.6	-32.5	85.8	86.6	11.7	11.9				
GRV 860	231.7	30.49	3.398	3.393	23.6	-15	23.7	-15.1	8.9	8.5	12.2	12.4				
GRV 863	204.6	8.36	6.662	7.54	28	21.3	27	21.8	-16.9	-16.1	10.3	11.6				
GRV 865	235.5	69.33	5.547	5.492	57.5	-53.7	56.8	-52.9	1.9	1.2	10.5	11.1				
GRV 868	55.2	61.39	4.929	5.578	-31.7	-21.2	-29.3	-21.1	-32.9	-32.8	10.4	11.7				
GRV 871	230.3	61.89	3.227	3.354	15.9	-11.2	12.3	-15.4	-4.2	-2	9.5	11				
GRV 872	332	67.94	4.069	4.074	-67.4	22.3	-67.5	21.5	-6	-2.9	11.9	12.4				
GRV 873	299.2	60.16	5.281	5.255	73.7	-27.8	73.1	-28.1	-11.5	-10.6	10.7	12.4	F2		-15.9	
GRV 875	92.6	27.15	5.069	5.054	-14.5	9.8	-14.3	9.9	-2.2	-2.2	11.2	11.1				
GRV 879	87.1	8.92	4.09	4.105	-16.5	-13.5	-16.1	-12.7	-57.2	-56.2	11.7	12.3		G8		-65.4
GRV 890	32.8	41.89	5.907	5.939	-28.1	31	-28	35.6	-60.1	-59	9.2	10.7				
GRV 897	214.4	29.97	2.684	2.498	-39.4	21.6	-38.9	21.3	-46.9	-45.3	10.6	11.8		F9		-42.9
GRV 905	15.2	14.67	5.12	5.182	-13.7	-29.4	-13.1	-29.5	-2.3	-3.1	11.6	11.8				
GRV 907	162.7	21.08	2.502	2.501	-37.7	-30.8	-37.1	-31.6	-20.7	-22	8.9	12.4		G7		-28.2
GRV 912	254.5	20.75	6.135	6.181	-21.1	-17.8	-21	-17.9	-26.2	-25.3	11.4	12.6	F9		-30.9	
GRV 913	91.5	8	3.209	3.233	-22.7	-19.1	-22.4	-19.2	-28.1	-27.4	10.8	11.8				
GRV 918	347.2	14.05	2.519	2.537	21.3	-30.9	21.3	-31.1	5.6	6.5	11.5	12.7				
GRV 919	354.6	45.17	10.839	8.424	-24.5	-28.9	-20.4	-25	-13.9	-14.4	10.1	10		G3		-18.4
GRV 920	195.2	11.77	6.803	6.811	-27.6	-16.1	-26.7	-16.2	-129.9	-129	10.6	12				
GRV 921	207.1	15.6	4.869	4.857	11.6	-22.1	11.3	-22.6	14.4	14.1	11.1	11.2				
GRV 923	306.8	19.3	4.498	4.427	-13.9	-26.9	-14.1	-27	11.3	12.7	9.5	12.6				
GRV 929	70.2	69.74	19.235	19.179	-14.8	-11.2	-4.1	-15.3	-7.3	-6.2	8.1	9.6				
GRV 930	318.5	30.5	4.584	4.618	-15.8	10	-14.6	7.9	-41.7	-40.5	10.7	11.5				
GRV 932	355.1	20.61	4.255	4.262	-17.1	49.7	-17.1	49.7	-54	-54.3	11.1	12	G3		-63.6	
GRV 943	272.6	17.39	4.144	4.154	-17.8	-30.1	-17.7	-29.9	1	0.4	11.4	11.7				
GRV 946	41.2	20.25	6.262	6.272	-54.3	55.6	-54.3	55.3	-45.6	-45.3	10.3	11.4				
GRV 952	328	22.64	4.361	4.358	-26.9	26.1	-27.1	26.3	-56	-55.9	12.1	13.1				
GRV 956	263.6	24.29	15.015	14.652	-72.5	53.9	-70.8	54.5	-22.3	-24.8	8.6	10.7				
GRV 957	29.7	11.5	2.578	2.483	-13.6	28.1	-13.8	27.3	-57.4	-56.5	10.7	11.1				
GRV 958	211.3	49.93	19.033	19.064	-46.8	-150.9	-50	-144.2	31.7	30.3	9.1	9.7		G9		26.7
GRV 959	355.6	24.21	3.629	3.604	-14.7	-45.4	-15.1	-45.6	38.4	38.4	9.9	10.5				
GRV 962	166.5	20.86	3.68	3.674	13.5	-11.7	13.4	-11.5	-5	-3.6	10.5	10.8	F0		-8.2	
GRV 966	83.5	27.78	5.385	4.894	4.7	16.2	13.7	10.8	0.3	-2	10	11.9				
GRV 970	153.7	44.18	10.461	10.535	-54.6	-22	-55	-22.8	-11.5	-11.8	9.6	11				
GRV1156	207.3	30.44	3.968	4.685	-98.6	0	-98.8	-0.7	-7.2	-8.7	10.4	11.6				
GRV1163	170.7	17.4	4.916	5.86	66	-28.1	74.5	-29.9	15.6	14.1	13.5	12.9				

Table 2: UVWXYZ values for the GRV pairs and individual metallicities. UVW are in kms-1 and XYZ are in parsecs.

Name	U	V	W	X	Y	Z	[FeH]A	[FeH]B
GRV 1	16.16	0.09	-17.01	-10.25	68.86	-114.47		
GRV 4	7.87	-42.25	23.04	-27.07	72.09	-53.82	0.2	
GRV 7	-21.48	-5.56	-4.13	-4.78	21.24	-33.25		
GRV 12	-6.1	-10.2	-4.41	-6.94	28.22	-44.83		
GRV 18	7	-33.46	19.99	-14.84	38.81	-41.46		
GRV 19	-10.65	19.39	-24.77	-5.64	14.1	-14.24		
GRV 26	-1.08	-20.26	4.58	-10.27	23.32	-36.78		
GRV 28	-8.69	1.93	-9.9	-15.13	29.22	-26.44		
GRV 29	-7.66	0.84	2.72	-7.22	15.47	-24.39		
GRV 31	20.63	-11.03	14.01	-31.79	55.63	-20.98		
GRV 33	1.39	-18.67	12.21	-23.63	45.08	-63.09		
GRV 36	-4.94	4.3	-12.29	-14.42	26.32	-28.7		
GRV 40	19.23	-33.56	21.83	-3.71	6.14	-4.39		
GRV 41	0.86	-9.4	2.45	-15.18	26.12	-45.21		
GRV 44	-4.25	2.53	-7.29	-19.2	30.85	-26.13	-0.06	
GRV 51	-4.08	-18.95	6.07	-20.56	29.8	-43.06		
GRV 58	9.82	-11.09	4.93	-15.43	22.16	-12.33		
GRV 61	-5.65	-1.44	5.8	-30.61	43.12	-34.03	-0.49	-0.42
GRV 74	-5.83	-10.99	-2.85	-26.78	32.09	-41.21		
GRV 92	-17.99	-8.03	-8.98	-56.11	59.69	-41.44		
GRV 120	-8.67	-2.7	-12.47	-40.62	25.7	-36.42		
GRV 123	-41.11	14.54	-25.23	-15.9	10.45	-12.08	-0.13	
GRV 131	-27.14	-8.24	-21.24	-42.28	14.9	-49.43		
GRV 132	22.37	-13.76	7.7	-26.92	16.31	-18.59	0.03	
GRV 138	-40.52	0.48	-35.73	-16.31	2.81	-20.96		
GRV 140	20.84	-8.25	-8.46	-94.73	28.49	-98.27		
GRV 144	4.9	-10.66	7.96	-62.42	20.65	-59.92	0.14	
GRV 147	-3.97	-9.01	-4.85	-44.35	17.71	-35.1		
GRV 150	3.64	7.61	1.42	-56.05	21.2	-42.24		
GRV 152	-44.78	-23.84	-10.1	-57.18	12.66	-55.6	-0.47	
GRV 155	-34.27	-11.98	-21.98	-81.73	16.14	-77.93		
GRV 158	0.41	0.96	-5.83	-43.55	17.05	-27.28	-0.08	
GRV 163	5.98	-12.16	9.92	-42.19	9.95	-32.98	-0.64	
GRV 174	0.29	-11.98	-1.98	-95.69	32.61	-48.98		
GRV 178	4.86	1	-3.19	-38.76	9.94	-21.27		
GRV 182	-20.87	-6.17	-18.84	-30.61	-2.14	-26.23		
GRV 188	27.13	-1.25	10.42	-44.73	0.86	-31.7	0.19	0.21
GRV 190	-38.72	-0.34	-13.58	-24.68	1.54	-16.04	-0.03	
GRV 193	6.71	-15.06	-2.44	-66.28	-8.45	-54.05		
GRV 194	14.67	-6.83	-3.07	-63.4	13.31	-29.06	0.12	

Table 2 continues on the next page.

Table 2 (continued). UVWXYZ values for the GRV pairs and individual metallicities. UVW are in kms-1 and XYZ are in parsecs.

Name	U	V	W	X	Y	Z	[FeH]A	[FeH]B
GRV 198	-72.95	-6.11	-42.44	-28.66	1.5	-15.84	-0.06	
GRV 210	-3.67	2.19	7.83	-49.09	16.36	-8.01	0.09	0.08
GRV 219	-17.1	-20.26	-5.49	-43.19	0	-11.57		
GRV 221	32.51	5.12	1.11	-41.02	-7.24	-15.18	-0.07	
GRV 225	18.18	-5.8	9.07	-52.08	-14.44	-15.86		
GRV 226	-28.03	-4.64	-3.81	-30.65	-1.67	-3.79		
GRV 228	-42.18	-6.16	-3.52	-23.92	-2.05	-2.51	0.07	-0.22
GRV 229	-57.88	-19.81	-5.89	-58.76	-20.74	-14.69	-0.07	
GRV 230	-42.47	-1.73	-13.69	-80.24	-23	-15.59		
GRV 236	-19.27	-12.59	-3.65	26.11	23.79	4.68		
GRV 238	-21.06	-19.41	0.4	25.04	30.08	7.24		
GRV 244	1.08	-4.4	-13.88	48.89	109.92	29.59		
GRV 249	-6	-30.78	-0.74	42.81	86.17	17		
GRV 255	26.63	15.66	3.71	38.72	35.33	-3.82		
GRV 265	-18.41	-20.95	-8.09	12.19	28.24	2.91		
GRV 269	-21.37	-25.06	-2.45	26.69	28.66	-4.55		
GRV 271	-8.02	7.82	-0.81	55.8	60.69	-9.48		
GRV 274	4.34	2.45	-5.55	35.63	36.23	-7.88		
GRV 278	-14.75	-47.44	-0.78	19.12	42.84	2.08		
GRV 281	-22.64	-23.44	1.92	25.78	35.76	-3.58		
GRV 300	-0.4	-10.74	1.11	33.58	36.13	-9.75		
GRV 311	-7.64	-12.86	-5.41	66.47	84.23	-20.76		
GRV 312	-5.82	10.06	-2.06	43.91	54.55	-14.24		
GRV 320	-25.62	-25.52	0.86	52.38	91.42	-13.67		
GRV 329	18.64	8.6	-3.67	54.12	102.07	-16.78		
GRV 339	21.8	24.85	-7.73	24.37	50.25	-8.57		
GRV 347	27.68	19.08	-2.06	45.32	121.31	-14.51		
GRV 348	-17.6	-29.6	3.97	40.55	59.94	-20.27		
GRV 353	16.05	12.8	-14.25	20.84	44.72	-9.1		
GRV 361	-14.95	-16.21	1.56	35.64	38.34	-21.65		
GRV 364	47.5	31.98	-24.57	34.23	37.78	-20.95		
GRV 377	28.17	-0.88	0.22	96.23	110.66	-65.63		
GRV 383	10.49	-11.36	2.74	15.19	35.56	-9.31		
GRV 403	-44.94	-28.31	7.28	37.98	53.45	-30.89		
GRV 406	-56.63	-32.35	14.54	50.55	74.46	-42.34		
GRV 413	-17.79	-5.79	-4.02	33.27	58.76	-28.46		
GRV 421	-12.32	-22.34	5.68	9.41	40.46	-7.98		
GRV 424	-22.07	-38.84	16.54	23.72	37.28	-21.46		
GRV 427	16.04	16.96	-2.26	24.02	169.79	-20.62		
GRV 708	-52.74	-32.8	-0.12	-41.42	-13.2	-3.92		

Table 2 continues on the next page.

Table 2 (continued). UVWXYZ values for the GRV pairs and individual metallicities. UVW are in kms-1 and XYZ are in parsecs.

Name	U	V	W	X	Y	Z	[FeH]A	[FeH]B
GRV 712	18.39	-2.1	-0.7	-29.91	-8.47	-1.83	-0.16	-0.1
GRV 724	-34.61	-25.03	6.4	-79.35	-35.66	7.32	0	-0.01
GRV 729	-44.51	-20.98	3.25	-80.69	-16.49	22.51	0.01	0.06
GRV 731	-29.02	-10.49	2.73	-32.94	-9.16	9.29		
GRV 734	12.05	-5.17	-3.95	-59.36	-19.63	18.82	-0.18	
GRV 735	31.66	-3.15	-7.15	-121.56	-36.94	39.99	-0.15	
GRV 737	-28.61	-22.38	-2.44	-36.1	-13.91	11.84		
GRV 739	-55.45	-24.71	13.75	-38.06	-12.82	15.55		
GRV 744	-25.99	-6.89	8.05	-44.56	-3.27	23.95	0.01	
GRV 747	-44.84	-36.26	12.17	-30.37	-21.28	11.88		
GRV 750	1.73	-9.43	2.03	-69.79	-16.61	37.23		
GRV 751	47.32	16.06	-28.63	-28.53	-12.95	14.14	0.15	0.15
GRV 752	-12.16	-7.93	-1.05	-122.93	-38.7	67.49	-0.2	
GRV 757	-26.44	-8.79	-0.16	-52.97	-20.04	30.73		
GRV 758	-35.55	-16.74	11.41	-58.99	-24.94	33.81		
GRV 759	-8.18	-22.97	6.63	-56.54	-37.05	31.06		
GRV 764	-31.29	-3.79	11.96	-54.48	-35.05	37.56		
GRV 770	17.89	6.39	-11.15	-24.36	-17.21	17.85		
GRV 772	21.7	0.78	-5.7	-88.19	-69.4	66.5	0.03	
GRV 775	1.51	-7.05	2.9	-7.42	-7.83	6.41	0.3	
GRV 777	48.62	-5.8	-35.83	-73.36	-14.29	66.08	-0.18	-0.33
GRV 778	-27.34	-8.17	13.15	-38.74	-20.93	35.02		
GRV 779	-33.15	-17.33	14.92	-72.44	-28.91	66.25		
GRV 780	-18.81	-15.07	8.36	-44.08	-28.2	41.46	0.07	
GRV 782	28.79	13.25	-17.9	-31.06	-24.85	31.08		
GRV 789	54.01	23.45	-50.53	-22.51	-19.49	25.03	-0.62	
GRV 791	-44.33	-27.68	38.23	-69.91	-30.38	79.19		
GRV 798	18.73	0.43	-12.36	-36.75	-38.89	48.59	0.13	0.19
GRV 799	-9.67	-15.16	4.93	-23.99	-8.39	29.53		
GRV 810	3.98	-0.44	-23.35	-25.4	-34.96	43.15		
GRV 811	11.09	-4.59	-4.96	-11.01	-17.66	19.4	-0.01	
GRV 813	8.88	9.59	-23.64	-23.76	-41.01	45.27	-0.2	
GRV 814	-16.21	-10.67	0.64	-50.93	-27.16	81.69	0.02	
GRV 816	8.37	-5.04	-1.1	-26.13	-39.78	52	0.14	
GRV 817	2.64	-2.48	-19.04	-24.64	-35.76	50.47	0.2	
GRV 818	-21.19	-25.7	20.87	-32.86	-42.76	67.07	0.07	
GRV 829	9.91	6.37	-16.21	-6.29	-24.82	35.22	-0.31	
GRV 837	23.16	-6.77	-29.23	-5.53	-7.27	26.24		
GRV 847	-5.26	4.82	-12.63	-6.57	-15.61	63.42		
GRV 848	-18.61	-16.3	-58.42	-12.49	-7.86	75.55	-0.37	

Table 2 concludes on the next page.

Table 2 (conclusion). UVWXYZ values for the GRV pairs and individual metallicities. UVW are in kms-1 and XYZ are in parsecs.

Name	U	V	W	X	Y	Z	[FeH]A	[FeH]B
GRV 849	6.97	-6.62	2.37	-7.78	-8.44	56.59	0.35	
GRV 850	10.95	11.78	-33.71	2.56	-27.58	57.55	0.17	0.2
GRV 852	1.45	-16.21	-18.22	-6.97	-1.03	39.35	0.06	
GRV 856	1.14	-34.41	81.11	1.88	-19.13	98.4		
GRV 860	10.49	-0.27	7.82	6.24	-4.42	73.23		
GRV 863	-2.45	10.08	-14.14	9.34	-9.99	32.44		
GRV 865	16.57	-2.43	-1.88	8.34	-6.28	44.08		
GRV 868	-11.59	-2.76	-31.77	12.6	-7.37	45.29		
GRV 871	5.74	-0.41	-5.01	21.81	-6.63	72.48		
GRV 872	-20.06	-6.19	2.23	23.85	-13.24	55.01		
GRV 873	12.11	6.67	-15.58	16.66	-5.8	44.06	-0.5	
GRV 875	-4.62	0.05	-0.07	22.54	-9.84	42.84		
GRV 879	-19.63	-8.1	-52.92	19.95	2.34	57.61	-0.39	
GRV 890	-38.78	1.61	-45.98	22.32	-0.2	35.83		
GRV 897	-34.22	-21.32	-30.26	35.56	33.31	83.28	0.15	
GRV 905	1.9	-7.5	-1.69	23.73	14.65	39.72		
GRV 907	-13.75	-26.08	-10.89	64.82	16.7	74.21	0.33	
GRV 912	-18.72	-8.86	-16.17	29.6	5.77	27.18	-0.06	
GRV 913	-19.38	-15.33	-16.62	55.07	13.17	53.09		
GRV 918	18.36	1.44	-2.81	40.07	50.55	74.96		
GRV 919	-8.16	-8.45	-9.05	16.92	7.96	18.01	0.06	
GRV 920	-56.27	-70.7	-92.85	16.12	18.74	27.16		
GRV 921	12.98	4.41	7.24	28.45	21.89	36.8		
GRV 923	11.6	-3.93	7.73	39.68	16.41	35.98		
GRV 929	-5.34	-2.48	-3.46	10.74	2.9	6.76		
GRV 930	-32.81	-14.88	-20.33	40.02	18.56	31.72		
GRV 932	-39.47	-25.97	-30.22	29.01	33.07	38.87	-0.38	
GRV 943	5.25	-8.39	1.31	44.03	27.29	30.78		
GRV 946	-35.78	-28.25	-14.27	22.62	24.45	21.94		
GRV 952	-35.92	-38.96	-20.6	30.06	39.22	29.09		
GRV 956	-22.36	-10.13	-1.7	14.02	7.21	5.95		
GRV 957	-40.33	-37.76	-20.02	49.94	69.57	49.27		
GRV 958	29.55	7.85	10.86	10.14	6.62	5.06	-0.04	
GRV 959	32.65	16.89	19.22	36.55	47.84	33.96		
GRV 962	-1.3	-2.32	-6.66	56.1	31.4	22.13	-0.01	
GRV 966	-2.96	2.24	-1.08	31.44	32.18	18.48		
GRV 970	-4.99	-12.48	0.12	14.72	16.46	8.93		
GRV1156	-23.53	-12.02	-9.79	2.94	-13.24	56.17		
GRV1163	-12.41	-11.03	-14.97	-9.9	9.03	-44.42		

(Continued from page 66)

metallicities with near zero or positive values, although results were not rigorous enough to more than suggest.

For the barely a dozen pairs with [Fe/H] available for both stars in the pair all but one had values within 0.1 of each other, adding another piece of circumstantial evidence to their relationship. However GRV 777 had a difference between stars in [Fe/H] of 0.15, which may be thought a little large for a non-interacting pair, whilst GRV 228 has a difference as high as 0.29.

Overall, albeit based on a quite small sample, the above analysis suggests that for confidently assessed common proper motion pairs in the general neighborhood of the Sun the majority are mostly, if not near exclusively, Thin Disc objects. This is not necessarily the case for fainter red dwarf pairs nor brighter naked eye brightness pairs, both of which tend to be much closer to the Sun than the stars sampled here.

Conclusion

Gaia data provide extra astrometric parameters that enable at least the not too faint common proper motion pairs contained within the WDS to be further checked for commonality as opposed to random association beyond the already utilized parameters of just proximity and their common proper motion, with the latter also being able to be refined. Further they allow the pairs to be categorized with respect to their likely Population membership within the Galaxy. Additional data from other ongoing surveys, and possibly the eventual final data release as well, allow the adding of metallicity information to further qualify the Population membership assessment. This could lead in time to hints on their mechanism of creation, or more importantly whether there is a reason these often wide pairs with no hint of orbital motion haven't been disrupted yet in the cases where they are Thin Disc stars.

Hopefully in time enough data will be available to address whether a major apparent property of common proper motion pairs is a selection effect or real, and if real how come this property comes about and is it essential to their longevity? Basically, why do so many common proper motion pairs appear to be virtually twins when it comes to luminosity and color (and consequently mass)? Is this just a false impression? Is this a selection effect of observation? Is this a selection effect of the survival mechanism and/or changes? Is this a selection effect of formation? Or a combination of some of these. It may simply be that given the multiple possibilities of how they could come about and the relative numbers of stars available that there are just the right amount of them found and things are as they should be. In which case why not more uneven pairs or more trinaries or higher multiples? Hierarchical valid close multiples exist, though not overly common. Tertiaries and other stars in such close multiples can often be much fainter and often have much greater separations, so possibly it could be a selection effect for ever more distant stars, for although modern surveys often go quite deep there are few older surveys with decent faint object data to give proper motions to compare against, or even reliably match up (the more faint you go the more background field stars there are). In other words, they are not necessarily too faint to be seen but too faint to be recognized for what they are.

Nevertheless the extra data do add extra dimensions for the appreciation of these double stars to the amateur. One of the beauties of astronomy for amateurs is that quite a lot of astrophysics can be done via the simple plotting and/or arithmetic manipulation of end product numbers. When this can be combined with observational work a pastime results that can be both intellectually and aesthetically rewarding.

Paper II provides some examples of ways to use the Gaia data to reduce one selection effect by addressing high relative motion stars of low proper motion that can be shown to be likely associated, that is the heretofore unrecognized common radial velocity pairs. With these objects the increased resolution provided by Gaia allowing smaller separations also permits the identification of close to very close pairs that remain mostly to almost unresolved in wide field surveys on modern large telescopes yet are wide enough for amateurs to follow for several years to even decades in order to establish any sign of orbital motion. Some illustrative examples will be given which should enable people to find their own project stars from the source data should they so wish.

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