A New Concept for Counter-Checking of Assumed Binaries

Wilfried R.A. Knapp

Vienna, Austria
wilfried.knapp@gmail.com

Abstract: The CPM assessment scheme presented a year ago (Knapp & Nanson 2017) proved to be a very useful concept for counter-checking of assumed CPM pairs using the most reliable catalog data for either star positions or proper motion available. Suggestions to make the proposed letter based scheme easier to understand led in consequence to an extension of the letter based scheme and a concept for transforming this scheme into an estimated probability for a pair being physical. The obvious usability of this concept for checking any double star for being a potential common proper motion pair made it necessary to make some modifications to allow for undecidable cases due to insignificant proper motion values.

1. Introduction

Together with John Nanson I presented in “A New Concept for Counter-Checking Assumed CPM Pairs” (Knapp and Nanson 2017) a scheme for a rating system for common proper motion pairs based on the following criteria:

- Proper motion vector direction: If equivalent within the given error range
- Proper motion vector length: If identical within the given error range
- Relation of given error range to proper motion vector length.

Taking the letter based scheme of financial rating agencies as the basis for this model, this led then to a CPM assessment scheme of AAA for a solid CPM candidate, BBB for a good CPM candidate and CCC for a rather obvious optical pair.

The “working horse” for this approach was the comparison of 2MASS to URAT1 (and later on GAIA DR1) with a proper motion error range of ~6mas. New catalogs like TGAS (subset of GAIA DR1 with parallax and proper motion data) and UCAC5 made it possible to use directly the proper motion data from these catalogs with a then much smaller error range of less than 2 mas with some caveats regarding UCAC5 (see Knapp and Bryant 2018).

During this ongoing process of using new and more precise catalogs I decided to extend this scheme to a fourth letter standing for the criterion angular separation in relation to proper motion speed (separation/pm<1000 following Halbwachs 1986) to check if the components of an assumed CPM pairs were reasonably close in distance (used for the first time in Knapp 2017).

2. Description of the new concept

The letter based rating scheme was several times considered as being not in all cases very easy to understand – while AAAA and CCCC or similar ratings are quite clear in their meaning it seems rather not so obvious what for example a CACB rating might mean. Such comments were often combined with suggestions how to do better. The most promising idea was a 100 point rating scheme representing the assumed probability for being physical with for example 90 to 100 points for being almost certainly physical down to below 10 for being almost certainly optical.

The simplest form of doing this by adding up numbers for the given letters was quickly dismissed as a lack of similar proper motion direction and speed can-not be substituted by a small error size or a rather small distance if only partially.

The next possible form was then the multiplication of numbers corresponding with the letters starting with a value of 1 for an A giving for AAAA a simple 1*1*1*1=1 or 100% as perfect CPM candidate down to 0*0*0*0 for CCCC rating giving zero or 0% for an almost certainly optical pair. But it got quickly clear that the range below 50% could not be covered very well this way as a C rating was given for values outside the doubled error range. But assuming the logic of standard deviation a small percentage of values might very well be outside the double but within the triple error range.

The next step was then adding a "D" to the rating scheme for values outside the double but inside the triple error range and giving C-values a small but larger than zero probability.

Finally I ended up with the following procedure:

- Proper motion vector direction: A=1, B=0.8, C=0.2 and D=0.01
- Proper motion vector length: A=1, B=0.8, C=0.4 and D=0.05
- Proper motion error size: A=1, B=0.95, C=0.8 and D=0.65 – just representing the fact that a larger error range reduces somewhat the reliability of the given proper motion data
- Angular separation/pm speed: A=1, B=0.97, C=0.95 and D=0.92 – just representing the fact that increasing angular separation increases the chance for lucky hits.

Table 1 shows results for the most interesting combinations.

While such a probability number is certainly easier to understand than a letter-based rating scheme, it got quickly clear that also some information is lost as the letters A to D give for each position valuable information so I decided to keep the letter based scheme as it is (including the extension to "D") and simply add the probability number as additional information.

The next step was the addition of a verbal meaning for a given probability estimation as defined in Table 2.

Table 1. Translating Letter Based CPM Rating into a CPM Score.

CPM Rat	CPM Score
AAAA	100
AAAC	95
AABC	90
AABD	87
AACB	78
ABBD	70
ABCA	64
BBBB	59
BBCA	51
BBCD	47
ACAA	40
ACCC	30
BCCB	25
CBCB	12
CCDA	5
DDDD	0

Table 2. Verbal CPM Assessment

CPM Score	Verbal Assessment
100	Most certainly physical
90-99	Almost certainly physical
75-89	Most probably physical
55-74	Probably physical
45-54	Undecidable
25-44	Probably optical
10-25	Most probably optical
0-9	Almost certainly optical

3. Extension of the CPM Assessment Scheme for General Use

So far the CPM assessment concentrated on the counter-check of assumed CPM pairs and was in some cases by the way used also for the CPM assessment of double stars with unknown CPM status as for example in Knapp 2017 on the Jonckheere objects in Auriga. But when I tried to apply this CPM assessment model together with Tom Bryant (Knapp & Bryant 2018) in a larger scale on WDS objects without any CPM flag at all, it quickly became clear that there are so many objects with too small proper motion to allow for any conclusive CPM assessment. This is true only for objects with slow proper motion for both components or else the difference between the proper motion vector length is usually large enough to conclude "almost certainly optical". So I had to add an additional criterion for proper motion data values too small and in relation the proper motion error data too large to allow for conclusive CPM assessment and ended up with root over the sum of all square pm RA and DE error values being larger than 30 percent of the added proper motion vector length for both components. If this condition is given, then “but undecidable with given PM data” is added to the verbal description.

4. Adaptation of the CPM Assessment Scheme for Very Small Proper Motion Error Values

The coming GAIA DR2 will provide proper motion data with an error range far smaller than currently even TGAS. The combination of large proper motion vectors with very small error values leads then to extraordinary requirements making it rather impossible to get an “A” for proper motion direction and speed despite very similar values. So I decided to introduce a lower threshold for both criterions with the consequence that proper motion direction is considered to be worth an “A” if the difference is less than 0.36° (1‰ of 360°) and proper motion speed is considered to be worth an “A” if the difference is less than 1‰ of the average proper motion speed. Both threshold values are first attempts and over time adaptions might be necessary.

5. Extension of the CPM Assessment Scheme for Gravitational Relationship

Again with the coming GAIA DR2 in mind providing not only proper motion but also parallax data to a much greater extent than DR1, I decided to include an assessment also for potential gravitational relationship in the line of my TGAS report (Knapp 2017) with some modifications by calculating the distance between the components of a double star for three scenarios using the law of cosines

$$c = \sqrt{a^2 - 2ab\cos(\gamma) + b^2}$$

with

- a,b = distance vectors for the stars A and B in light years calculated as (1000/Plx)*3.261631
- γ = angular separation in degrees
- c = smallest possible distance between A and B in lightyears

- Best case: The given Plx errors are applied on the given Plx values to determine the smallest possible distance between the components A and B
- Realistic case: The given Plx values are used to calculate the distance A to B without considering the Plx error range
- Worst case: The given Plx errors work to full extent in opposite directions giving the largest possible distance between A and B.

The assessment for a potential gravitational relationship between the components of a double star is then based upon the simple approach of assuming average means Sun-like star mass with a then assumed gravitational “border” at the outer rim of the Oort cloud at ~100,000 AU. If the worst case distance between the components is therefore less than 200,000 AU then potential gravitational relation is assumed to be given with high probability because of the (staying with the example of our Sun) then overlapping Oort cloud.

The rating scheme is again letter based as follows:

- "A" for worst case distance less than 200,000 AU (means touching Oort clouds for two stars with Sun -like mass), "B" for realistic case distance less than 200,000 AU, "C" for best case distance less than 200,000 AU and “D” for above
- "A" for Plx error less than 5% of Plx, "B" for less than 10%, "C" for less than 15% and “D” for above

Additionally a Plx Score is calculated with multiplication of the following values and the result by 100:

- Plx distance: A=1, B=0.8, C=0.2 and D=0.01
- Plx error: A=1, B=0.95, C=0.8 and D=0.65

6. Combining CPM and Plx Rating as a Test for Being a Binary

A binary star is defined by gravitational bound components in best case with a known orbit. CPM alone is certainly not sufficient to consider a pair being a binary as same proper motion speed and direction might just be random especially with increasing separation. The same is the case for stars with similar Plx data but very different proper motion values. Combining CPM and Plx rating by simply multiplying the scores gives then an estimated overall probability for a pair being a binary. Objects with a high probability for being a binary without having a known orbit should in a next step seriously be checked for a potential orbit.

7. Description of Details and Usage of the Check CPM & Plx Spreadsheet

In the spreadsheet developed for the CPM counter-check the following formulas and checks are used:

- Proper motion vector direction: Calculated from the RA Dec coordinates as

$$\theta = \arctan\left[\frac{\left(RA_1 - RA_2\right)\cos\left(Dec_1\right)}{Dec_2 - Dec_1}\right]$$

  in radians depending on quadrant (Buchheim 2008).
- Proper motion vector length: Calculated from the RA Dec coordinates as

$$PM = \sqrt{\left[\left(RA_1 - RA_2\right)\cos\left(Dec_1\right)\right]^2 + \left(Dec_2 - Dec_1\right)^2}$$

  in radians (Buchheim 2008).

- Proper motion vector length error estimation e_PMVL: Calculated as SQRT(e_RA^2+e_Dec^2) with e_RA and e_Dec as given IGSL RA and Dec errors with upper threshold of 5% and lower threshold of 0.1% from the average PMVL
- Proper motion vector direction error estimation e_PMVD: Calculated as arctan(e_PMVL/PMVL) in degrees assuming the worst case that e_PMVL points in the right angle to the direction of the proper motion vector means perpendicular with upper threshold of 2.86° (corresponding with 5% e_PMVL threshold) and lower threshold of 0.36° (0.1% from 360)
- Check for identical PMVD by comparison Δ PMVD with e_PMVD
- Check for identical PMVL by comparison Δ OMVL with e_PMVL
- Check relationship of position error size to pm vector length
- Check relationship of proper motion speed to angular separation. This check corresponds to some degree to the significance criterion according to Caballero et al 2010
- Best case distance: Smallest possible distance using Plx values plus/minus Plx errors
- Realistic case distance: Distance using given Plx values
- Worst case distance: Largest possible distance using Plx values plus/minus Plx errors
- Check best/realistic/worst case distances for being < 200,000 AU
- Check relationship of Plx error to Plx value
- Multiplying CPM and Plx score for an estimated overall probability for being binary.

The spreadsheet can be downloaded from the JDSO website as "CPM and PLX CHK V6 Double Line".

The spreadsheet is filled with a sample of TGAS objects selected for similar very fast proper motion regardless of separation to test it with extreme data constellations. Side effect of this test is the re-discovery of LDS 93 being almost certainly a binary and of STT 593 being most probably a binary.

Usage of the spreadsheet for single double star objects:

- Locate the object in Aladin
- Select GAIA DR2 as catalog overlay
- Click both components to get the data
- Copy the data for use with Excel
- Paste the data into a spreadsheet designed on your own to arrange the data as needed in the CPM&Plx spreadsheet. This procedure needs an additional step for Excel language versions using a decimal separator different from the decimal point – for example the decimal comma in the German version: in this case after copying the data into the spreadsheet you need to simply change all "." into "," for all fields marked after the paste command.
- Paste the data into the input columns CPM&Plx spreadsheet

Usage of the spreadsheet for double star lists (created for example for using the TAP VizieR service):

- Make sure the list includes all data in content and format necessary for use with the CPM&Plx spreadsheet with one line per component
- Copy the data lines for the number of objects needed
- Paste the data in the input columns of the CPM&Plx spreadsheet.

8. Summary

The approach presented here for checking double stars for potential common proper motion and gravitational relationship is a tool useful for the assessment of double stars for being "real" physical pairs not only moving with similar speed in similar direction but also with components close enough to be gravitationally bound.

Known weaknesses of this approach:

- Pairs with an orbit (regardless if known or not) might get a bad CPM score as a side effect of small differences in PMVD and PMVL depending on the plane and speed of the orbit and the speed of the proper motion as well. A good Plx rating is in such a case a strong indicator for a physical pair despite the bad CPM rating if the differences in proper motion direction and speed seem still reasonable. On the other side if for a pair with a "known" orbit both CPM and Plx ratings are bad then this is a strong hint that this might be no physical pair despite the WDS note code "O" (two such examples are STF 619 and STF 2789)
- Even a fourfold AAAA CPM combined with a double AA Plx result is still no "proof" that this is actually a binary but the odds are certainly very high and in a next step a potential orbit could be a follow up research topic for such an object
- Only one data set is used. Even if highest data reliability is assumed to be given with GAIA DR2 – never trust a single source.

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- GAIA DR1 catalog
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