A Giant Step: from Milli- to Micro-arcsecond Astrometry
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Taming the binaries

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Abstract. Astrometric binaries are both a gold mine and a nightmare. They are a gold mine because they are sometimes the unique source of orbital inclination for spectroscopic binaries, thus making it possible for astrophysicists to get some clues about the mass of the often invisible secondary. However, this is an ideal situation in the sense that one benefits from the additional knowledge that it is a binary for which some orbital parameters are somehow secured (e.g. the orbital period). On the other hand, binaries are a nightmare, especially when their binary nature is not established yet. Indeed, in such cases, depending on the time interval covered by the observations compared to the orbital period, either the parallax or the proper motion can be severely biased if the successive positions of the binary are modelled assuming it is a single star. With large survey campaigns sometimes monitoring some stars for the first time ever, it is therefore crucial to design robust reduction pipelines in which such troublesome objects are quickly identified and either removed or processed accordingly. Finally, even if an object is known not to be a single star, the binary model might turn out not to be the most appropriate for describing the observations. These different situations will be covered.

Keywords. binaries: general, astrometry, methods: data analysis

1. Why worrying about binaries?

1.1. *Binary effect*

Before wondering what binaries can do for you, it is worth wondering what could happen if you do not care about them. The parallactic term in the equation of the stellar motion is a periodic term with a period of one year. Any additional signal with a period close to one year, e.g. a binary, therefore jeopardizes the derivation of the parallax. So, if the object is not known to be a binary and a single star model is assumed in the derivation of the parallax, the latter could be severely biased.

A similar bias can be noticed on the proper motion of long period binaries when the observations do not cover an integral multiple of the orbital period. In such a case, the orbital motion adds up to the proper motion and, when the single star model is assumed, the resulting proper motion is affected.

Those two situations are illustrated in Fig. 1 with two Hipparcos entries. In the left panel (R Hya=HIP 65835), the star was originally processed as a Variability Induced Mover (i.e. a case where the strong correlation between the total brightness of source and the position of the photocentre was explained with a binary model with one variable component, hereafter VIM). The resulting parallax was 1.62 ± 2.43 mas. Correcting for additional effects and adopting the basic single star model, Pourbaix *et al.* (2003) derived a parallax of 8.44 ± 1.0 mas, very consistent with other astrophysical results (Whitelock *et al.* 2000).

The second example is V815 Her (HIP 88848) taken from Fekel *et al.* (2005). The Hipparcos observations of that object could not be satisfactory fitted with any model and

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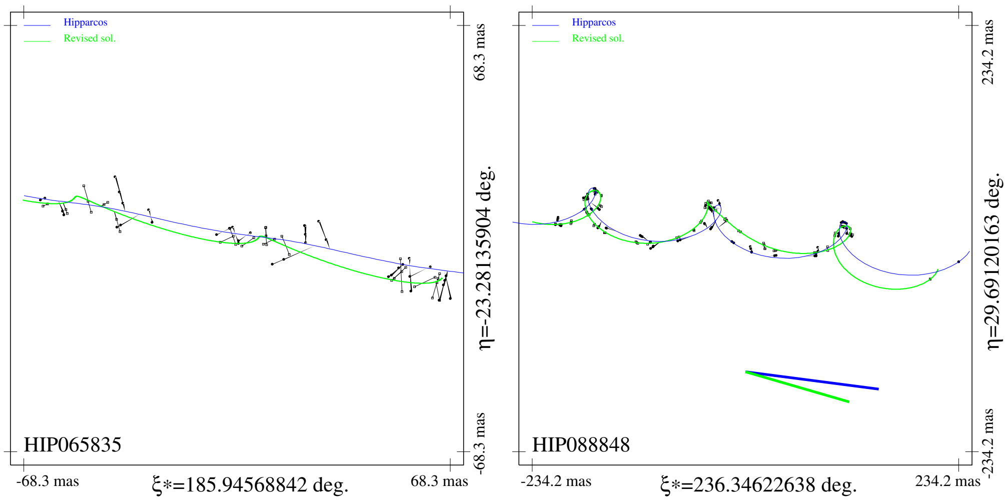

Figure 1. Incorrect binary assumption affecting the parallax (left panel) or the proper motion (right panel).

a stochastic solution was therefore originally adopted. The resulting proper motion was $(138.07, -18.58)$ mas/yr. Fekel and his collaborators noticed a third component in that stellar system, with an orbital period of 2092 days. Once that orbit is accounted for, the Hipparcos data yield an excellent fit leading to a revised proper motion of $(106.59, -30.84)$ mas/yr. This value is consistent with the long time-baseline proper motions(e.g. Tycho-2, Høg *et al.* 2000).

1.2. *Binary fraction*

At this point, even if one agrees that binaries can bias the astrometric solution, one could still argue that their number is so small that they will pop up in large sample as some additional noise. Well, depending on the stellar population, the observed binary fraction ranges from 15% in the lower end of the main sequence up to 80% in the upper end. Such a high binary fraction is also observed out of the Galactic plane (18% of the halo stars seem to be binaries, Carney *et al.* 2003).

Even though those fractions are pretty high, those binaries are not all troublesome for the astrometrist. Indeed, unless they are very nearby, close binaries (with period of a few days) are not and will not be resolved by any foreseen neither space nor ground based program. Despite the high precision, even the photocentre might not be distinguished from the barycentre of the system, thus making that system indistinguishable from a genuine single star … on the astrometric grounds.

Actually, despite the high fraction of binaries and the increasing observation precision, astrometry is the least affected detection technique. Indeed, the period and distance act against astrometric detection. The further the system, the smaller the angular disturbing effect of the companion (unlike spectroscopic detection).

Mother nature also plays against astrometric binaries. Denoting a_r the semi-major axis of the relative orbit of the secondary (the fainter component) around the primary (the brighter star) and a_0 the semi-major axis of the orbit of the photocentre around the centre of mass, the two are related through

$$a_0 = (\frac{M_2}{M_1 + M_2} - \frac{I_2}{I_1 + I_2})a_r \tag{1.1}$$

where M denotes the mass and I the intensity of the related component. When the secondary is much fainter than the primary (falling below the detection limit), relation (1.1) reduces to $a_0 = a_1$, i.e. the size of the photocentric orbit is the same as the absolute orbit of the primary. As the secondary becomes brighter, a_0 decreases. In the extreme case of a perfect twin system, a_0 vanishes completely. Unfortunately, although nature does not really favour that kind of systems, it does not favour systems with $I_1 >> I_2$ either (Halbwachs *et al.* 2003).

1.3. *From astrometry to astrophysics*

So far, we have shown why astrometrists should worry about binaries. What about the other areas of astronomy? Well, anybody who uses the parallax of the object to change its apparent magnitude into its luminosity should worry about the binary nature. Since correcting for the binary nature might require the full orbital model to be known, being aware of the binary nature of an object already allows those scientists to discard it from their sample. So, for those researchers, getting a hint that a star is double is already enough (maybe to get rid of it). At the other end of the spectrum, there are scientists interested in getting more than just a detection. Among them, there are those who want to study the distribution of the orbital parameter (e.g. as a function of the spectral type, ...). However, in order to carry out such an investigation, one needs as many well studied binaries as possible.

As already mentioned, spectroscopic detection of binaries is not affected by the distance to the systems. Spectroscopists are therefore pretty efficient in discovering binaries. However, the spectroscopic orbit lacks a key parameter which prevent them from being useful for astrophysics: the orbital inclination. Both the semi-major axis and the mass of the companion are entangled with the inclination. For instance, only the product of the mass with the sine of the inclination comes out of the equations.

$$\frac{(a_1 \sin i)^3}{P^2} = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2}$$

Without the inclination, this product is essentially useless to the astrophysicist, even if M_1 is assumed from some stellar model.

That is where astrometry becomes important to the eyes of astrophysicists. They suddenly remember that if some orbital model can fit the astrometric wobble caused by the binary, the inclination can be obtained and the true mass of the secondary retrieved (Jancart *et al.* 2005). In the case of extrasolar planets, even when the astrometric orbit could not be fitted, the absence of orbit was sometimes enough to give an upper bound of the mass of the companion (Perryman *et al.* 1996). Some nevertheless tried to fit an orbit despite the low signal to noise ratio and ran into troubles (Zucker & Mazeh 2000, 2001).

2. Binary detection

2.1. *Ground-based observations*

In order to detect the binary (or non-single) nature of an object, one can rely upon several spectroscopic (yield spectroscopic binaries), photometric (eclipsing binaries), or optical (visual or astrometric binaries) observations. In the first and third case, one seeks any departure from the motion of a single star whereas, in the second case, one looks for a typical shape of the light curve. Whereas, for spectroscopic binaries, two independent observations are theoretically enough, more observations are required for the visual/astrometric cases and even more are needed for the eclipsing cases (as it

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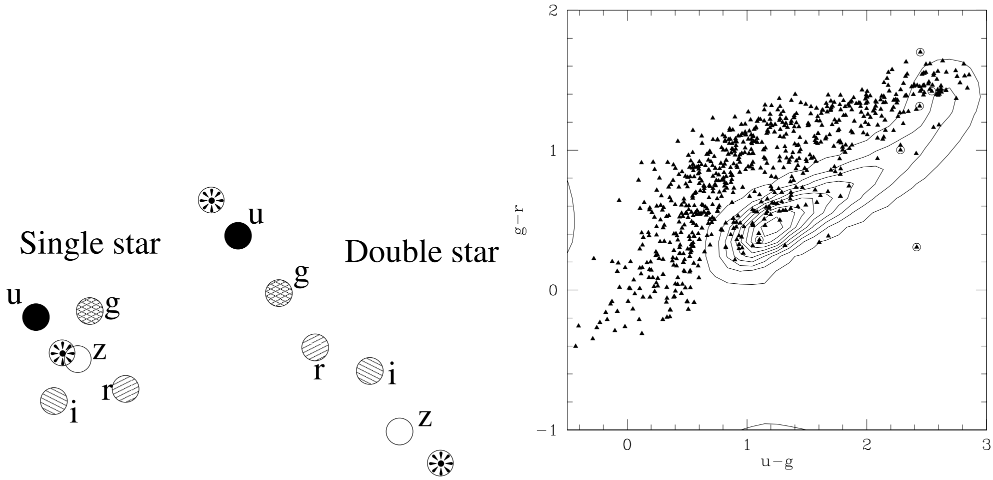

Figure 2. Positions of the photocentres according to the effective wavelength of the photometric filter (left panel) and binaries identified through that displacement of the photocentre in the SDSS DR5 (right panel).

requires a typical shape of the light curve rather than any departure from the constant radial velocity model for spectroscopic binaries).

Several teams are very active, sometime over a period exceeding the lifetime of their original instrument, and keep feeding the catalogues of optically resolved binaries (Hartkopf *et al.* 2001b; Mason *et al.* 2001) or even of astrometric orbits (Hartkopf *et al.* 2001a). Some of these teams presented their results during this meeting so a few others are listed here: McAlister and the CHARA Team continue with the Array (Bagnuolo *et al.* 2006), the work begun with speckle interferometry (McAlister 1997), Armstrong and Hummel who began with Mark III (Hummel *et al.* 1994) and then moved to NPOI (Armstrong *et al.* 1998; Hummel *et al.* 1998) and/or VLTI, and Davis and colleagues resolving binaries with the Sydney University Stellar Interferometer (Davis *et al.* 2005).

Besides those regular techniques (and the subsequent orbits), there are also less usual methods combining photometry and precise astrometry. The first approach consists in looking for a correlation between the position of the photocentre and the total brightness of the source (VIM). Such a method was suggested by Wielen (1996) and globally successfully applied to the Hipparcos observations (Pourbaix *et al.* 2003). Whereas a fixed configuration was assumed for Hipparcos, this assumption will be relaxed for Gaia (Halbwachs & Pourbaix 2005).

In case of VIM, one needs several observations of both the position of the photocentre and the total brightness of the source. An alternative/complementary approach consists in obtaining several positions at different wavelengths at just one epoch (Christy *et al.* 1983; Sorokin & Tokovinin 1985). In case of a single star, the scatter of those positions reflects the precision of the measurements (left panel of the left panel of Fig. 2). With a binary, those positions are scattered along the segment between the two stars. The presence of such an alignment is thus a hint for a double star (maybe an optical pair). That technique was applied (Pourbaix *et al.* 2004) to the SDSS data and yielded about 750 double stars (right panel of Fig. 2) when using the SDSS Data Release 5 (Adelman-McCarthy et al. 2007). This method extends the detection limits well within the stellar locus whereas a purely photometric approach would be limited to photometric outliers (Smolčić *et al.* 2004). The two methods are complementary.

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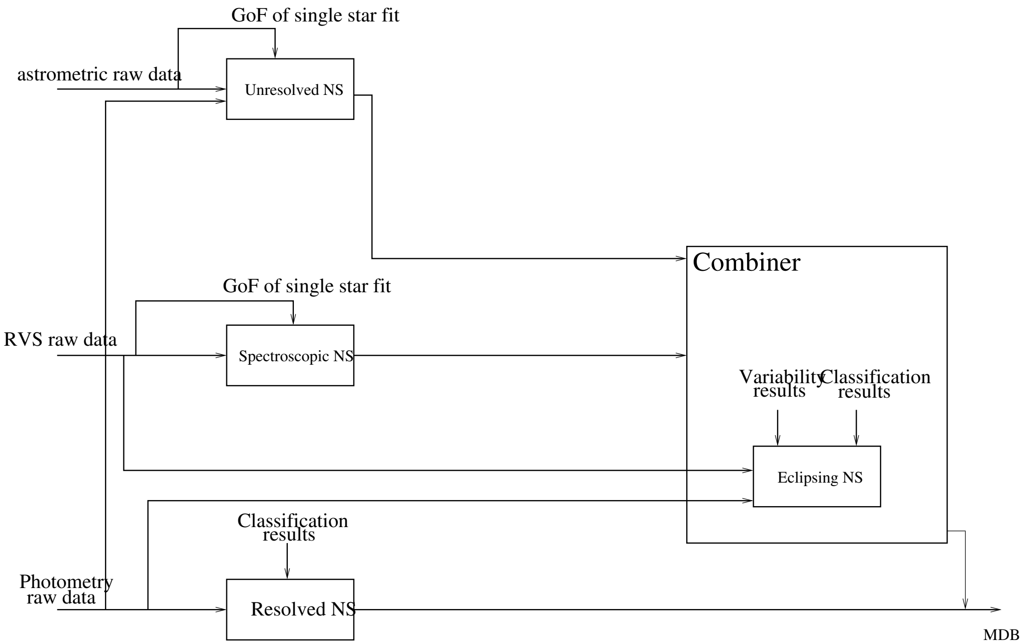

Figure 3. When entering the Object Processing coordination unit, each binary goes to a specific sub-pipeline depending on the nature of the observations yielding its detection.

2.2. *Hipparcos, a gold mine for binary seekers*

Even though the Hipparcos catalogue was released ten years ago (ESA 1997; Perryman 2008), there are still teams who are screening it for some binary signatures. Usually, those teams look for the astrometric signal of known binaries (e.g., Torres *et al.* 2006; Fekel *et al.* 2007). The goal is then to improve the understanding of those objects by obtaining the orbital inclination (the original Hipparcos astrometric solution can also be substantially revised).

Another use of the Hipparcos catalogue consists in comparing its proper motions (based on 3 years of observations) with the long time-baseline ones (e.g. Tycho-2 Høg *et al.* 2000). A discrepancy between the two proper motions is a strong hint towards a long period binary (Makarov & Kaplan 2005; Goldin & Makarov 2006; Frankowski *et al.* 2007)

3. Besides detection: the Gaia approach

In the Gaia data processing pipeline, binaries are identified as stellar objects with a poor fit in either of the different branches of the reduction which assumes a single star model (i.e. CU3, 5 and 6 Mignard *et al.* 2008). The Object Processing coordination unit #4 then picks up those outlying objects and dispatches them to sub-pipelines for further processing accordingly. The choice of a particular branch depends on the type of the observations in which the binary nature of the source was identified (Fig. 3).

The pipeline for astrometric binaries is depicted in Fig. 4. It consists in a cascade of models with increasing complexity. A quality indicator (generically called Goodness of Fit) is used to assess the solution. If it is good enough, the cascade stops and the solution is accepted. Otherwise, the data are transfered to the following box and the corresponding model fitted and evaluated.

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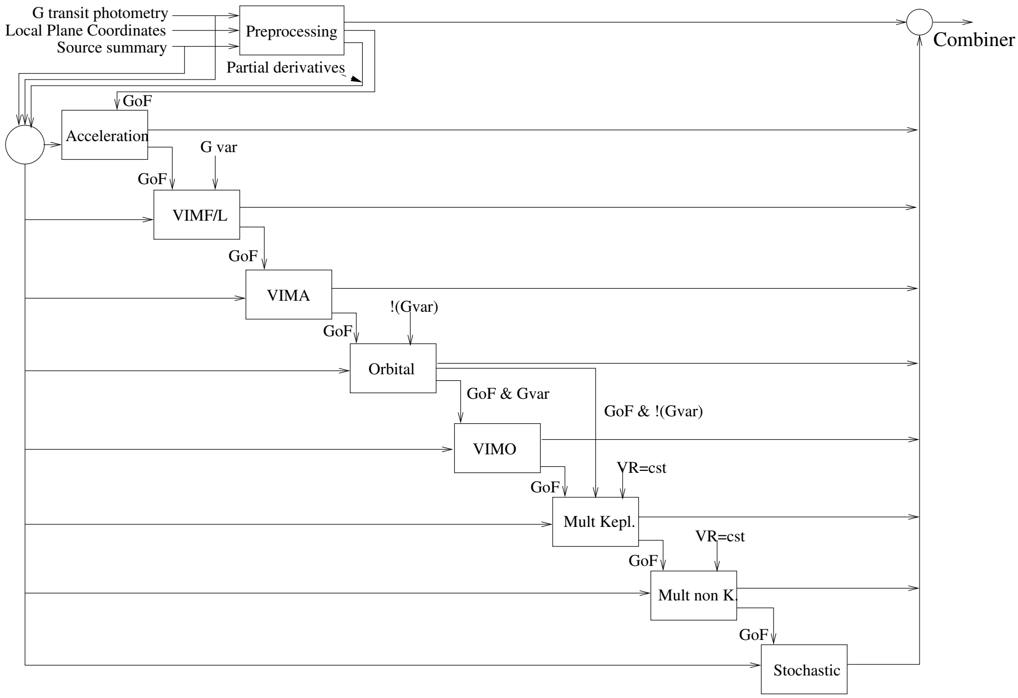

Figure 4. Specific pipeline for the binaries detected through their astrometric wobble

The cascade includes special considerations for binaries with a variable component, i.e. VIM, with either Fixed configuration, a Linear motion, an Accelerated motion or requiring a full Orbital solution. It also copes with extrasolar planetary systems with, potentially, a non-Keplerian description of the observed trajectory of the photocentre.

We are confident that although one will not obtain an orbital solution for the astrometric binaries detected by Gaia, the simplest model confidently describing the data will always be adopted.

4. Conclusion

If one does not want some astrometric results to be compromised, binaries have to be detected as early as possible in the data reduction pipeline and then processed with some dedicated models. Those two tasks are clearly identified and their implementation already quite advanced in Gaia DPAC (Mignard *et al.* 2008).

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