DUPLICITY AND MASSES

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ABSTRACT

Duplicity is still the only hypothesis-free method to derive stellar masses. Whereas other techniques such as asteroseismology rely upon some stellar model, orbits of binary stars yield quantities directly related to either the sum of the masses or the individual masses of the two components. However, in order to derive those individual masses, it is necessary to combine at least two types of observations, e.g., visual and spectroscopic or photometric and spectroscopic. Gaia will make the three of them available but their combination will be an efficient source of masses for sub-groups of binaries only. For instance, given the precision of the radial velocities, how many orbital visual binaries (for which the mass sum is therefore accessible) will lead to a spectroscopic orbit required to derive the mass ratio and thus the individual masses?

Key words: Gaia; Binaries; Stellar masses.

1. INTRODUCTION

It is not a secret that most astrophysicists look forward to the mass of their favorite stars. Despite the tremendous progress achieved in asteroseismology and its growing capacity in providing masses of individual stars, it still relies upon stellar models and therefore on calibrators (Eggenberger et al. 2004). In that respect, binaries are and will remain the only supplier of hypothesis-free stellar masses (Pourbaix 2000).

All dynamicists want bias-free motion, so they want binaries to be either identified and modelled appropriately or removed. For instance, they expect the proper motion and radial velocity to be either those of a single star or of the centre of mass of a binary system (Jorissen et al. 2004). However, that is not only true for the final results but also for the actual Gaia data processing. For instance, the Global Iterative Solution should use genuine single stars only and binaries should therefore be identified and removed.

So, clearly, binaries are important whether one belongs to one community or the other and that is why different working groups pay attention to them. This paper focuses on binaries as suppliers of stellar masses. We first establish in Section 2 why those masses are hypothesis-free but also why none of the detections, alone, will likely lead to the individual mass of the two components (Sections 3,4, and 5). Section 6 illustrates the benefit of combining results from two detection of different nature.

2. TWO-BODY PROBLEM: KEPLER'S LAWS

Still nowadays, any derivation of stellar masses in binary systems relies upon Kepler's laws, especially the third one which states a relation between the semi-major axis of the orbit (a), the period (P) and the two masses (M_1 and M_2):

$$\frac{a^3}{P^2} = M_1 + M_2. \tag{1}$$

This relation remains that simple as long as a is reckoned in AU, P in years and M in $M_\odot$. Moreover, a is the semi-major axis of the true relative orbit of one component with respect to the other ($a = a_1 + a_2$ where a_1 and a_2 are the semi-major axes of the absolute orbits of each component, i.e., with respect to the centre of mass). Therefore, some tricks will be required if the orbit is inclined (i then denotes the inclination of the orbital plane with respect to the plane orthogonal to the line of sight) or if only one component is detected.

Depending on the detector and the way the system appears, the available orbital information changes substantially:

Observed	Derived
One set of RVs (SB1)	$a_1 \sin i$
	$f(M) = \frac{(M_2 \sin i)^3}{(M_1+M_2)^2}$
Two sets of RVs (SB2)	$a \sin i$ and $\frac{M_2}{M_1}$
Eclipses (EB)	inclination
Relative positions (VB)	angular size of a inclination
Absolute motion (AB1, AB2)	a_1 [a_2], inclination

With Gaia, visual binaries (VB) are just a particular case of astrometric binaries (AB2) for which the orbital motion during the mission will not be large enough to allow for orbit fitting. No single type but AB2 yields the individual masses. Owing to the small aperture, only

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the close nearby systems are expected to be processed as AB2 (i.e., two stars well separated exhibiting a significant orbital motion over the mission).

It is nevertheless possible to combine the information coming from different detections to derive the individual masses. For instance, the only information missing to retrieve the two masses from a double-lined spectroscopic binary is the inclination of the orbital plane. If either one exhibits an astrometric wobble that can be modelled as an orbital signature or if the light curve exhibits eclipses, the inclination, hence, the masses can be derived. The different combinations are summarized below:

	SB1	SB2	EB	AB1	AB2
VB	-	M_1, M_2	-	M_1, M_2	M_1, M_2
SB1			-	-	M_1, M_2
SB2			M_1, M_2	M_1, M_2	M_1, M_2
EB					M_1, M_2

EB–SB2 is by far the most numerous combination providing stellar masses and, still, accounts for a few hundred systems only (Andersen 1997). The bias towards that combination is easy to understand. The higher the inclination the more likely the eclipses as well the larger the radial velocity amplitude *mutatis mutandis*.

The same argument can be reversed to explain why there are so few VB-SB2. However, by the time Gaia results are released, ground-based interferometry (VLTI, Keck, PTI) should substantially increase their number if one gives these objects the opportunity to be observed with those instruments. For instance, Array scientists target W UMa whose period is only 8 hours and orbit a few mas large. However, most of these interferometers are made of small instruments thus limiting them to bright objects (Delplancke et al. 2003).

3. GAIA OUTCOME FOR ASTROMETRIC BINARIES

Detecting the astrometric wobble caused by a companion is one thing, deriving the orbital parameters is another thing … way more difficult than the former. Whereas the detection is all that matters to the dynamicists, the orbit is required in order to derive the mass sum or individual masses.

The double blind test initiated by the Planetary Systems Working Group (PSWG) offers a good opportunity to assess the capabilities of Gaia in terms of orbit fitting. According to Casertano et al. (2004), orbits with a signal-to-noise below 2.5 or with a period larger than the mission duration are essentially missed (Figure 1).

Instead of using simulated data, one can also look at the Hipparcos catalogue (ESA 1997) to see how many orbital solutions were derived with no additional information (e.g., spectroscopic or interferometric orbit). Among the 118 218 stars of the Hipparcos catalogue, 235 belong to the Double and Multiple Star Annex/Orbital solution (0.2%) and 45 had their orbit derived from scratch

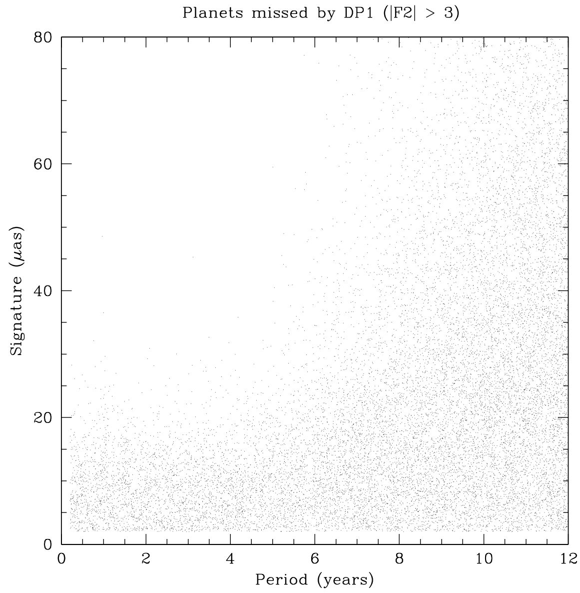

Figure 1. Distribution of the systems for which no good astrometric orbit could be derived from scratch (excerpt from T1 report of the blind test carried on by the PSWG, Casertano et al. 2004)

(0.04%). Assuming the percentage remains constant, one expects 460 000 orbits with Gaia.

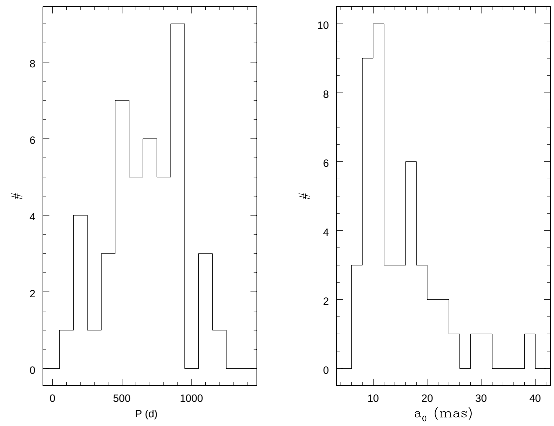

Figure 2. Periods and semi-major axes of the 45 Hipparcos DMSA/O systems for which an orbit was derived with no a priori knowledge

The distribution of the periods and semi-major axes of these 45 systems are plotted in Figure 2. None has a semi-major axis below 8 mas, essentially corresponding to a $S/N \sim 5$ which is twice as high as the conclusion of the blind test. The 460 000 orbits are thus likely to be a lower bound. According to Söderhjelm (2005), the number of orbital solutions reaches several millions. His result should nevertheless be taken with caution since his orbital systems are not *stricto senso* orbital ones (their orbit are not derived from scratch) but rather systems better modelled with an orbital solution when an *a priori* orbit is used as a starting point. In that respect, the PSWG blind test is the first ever realistic simulation and test of what

Gaia will achieved in terms of orbital solution (Lattanzi et al. this volume).

4. GAIA OUTCOME FOR SPECTROSCOPIC BINARIES

As described by Jancart & Pourbaix (2005)

- The amplitude of the radial velocity, K, decreases as the orbital period increases. Although this makes perfect sense based on the definition of K, Pourbaix et al. (2004b) noticed a lack of small K (below 20 km s^{-1}) at short periods (below 1 d). This is likely to be an observational bias which will be addressed by Gaia.
- For safety reasons, our current investigation of SB1 systems does not consider any system with $S/N < 3$. This means that few solutions with large P are presently analyzed.
- Realistic simulations show that, at a noise level of 10km/s, only 5% of the K differ from the true K by less than 10% assuming $P \sim 100$ d is first recovered at a 10% level with respect to the true period (i.e., only 0.25% of good K above 100 days). This conclusion is scanning law independent, i.e., the position on the sky does not change anything in this conclusion.
- At the other end of the period range, one notices a steep decrease of the percentage of recovered K for periods below 0.1 day. This is essentially due to the scanning law and the temporal distribution of the RVS data.

In SB9 (Pourbaix et al. 2004b), double-lined spectroscopic binaries account for 40% of the systems. For them also, one notices a lack of small amplitudes below 1 day (Figure 3). Only 0.5% of the SB2 systems have periods below 0.8 day. At $P \sim 100$ d, the maximum separation of the radial velocities is still above 50 km/s. Any Gaia double-lined spectroscopic binary with $P < 100$ d is therefore likely to have its orbit derived, thus making $M \sin i$ available for both components.

5. GAIA OUTCOME FOR ECLIPSING BINARIES

Whereas spectroscopic and astrometric binaries are essentially orthogonal, the spectroscopic and eclipsing binary set largely overlap. It is therefore not a surprise if several investigations have already covered that topic (e.g., Munari et al. 2001; Zwitter et al. 2003; Marrese et al. 2004).

Regardless of Gaia, the eclipsing binaries with known period account for 13% of the General Catalog of Variable Stars (Kholopov et al. 1998) and the shortest period is

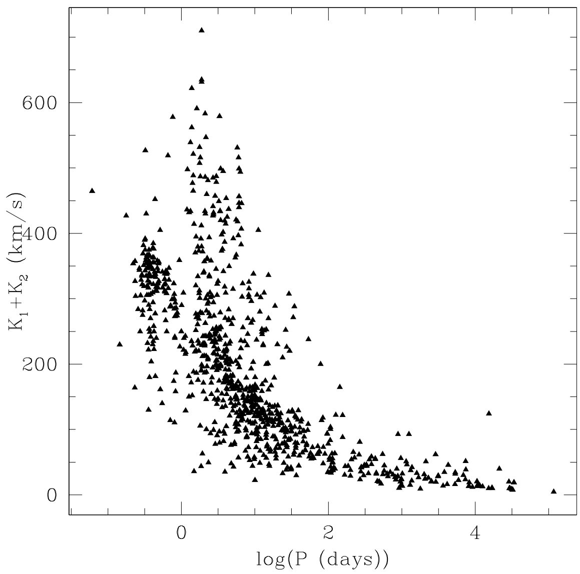

Figure 3. Distribution of the sum of the amplitudes of SB2 systems after Pourbaix et al. (2004b).

0.056 d. Only 0.05% of the eclipsing binaries have periods below 0.1 d (23% below 0.8 d).

Once again, Hipparcos can be used to evaluate Gaia perspectives. The former detected 501 (0.4%) eclipsing binaries; all the periods (477) are above 0.13 d. Munari et al. (2004) therefore estimate the number of Gaia eclipsing binaries with $V \leq 13$ to be close to 64 000. The 0.13 d limit comes from the scanning law but, still, only 3 GCVS eclipsing binaries have a period below that threshold so the scanning law blows out very few systems.

6. FRUITFUL COMBINATIONS

Let us now illustrate two typical cases where combining two types of observations substantially improves the quality of the fit and gives access to the individual masses of the components.

6.1. EB–SB2

As indicated in Section 2, alone neither SB2 nor EB yield the masses of the components. However, the former yield $M \sin i$ for both components. The eclipses then ensure that the sine is close to unity, thus leading to the masses. Regardless of Gaia, such a combination has already shown its efficiency and it is actually the largest supplier of very accurate stellar masses (Popper 1980; Andersen 1991, 1997).

Using Carquillat et al. (1982) estimate that 25% of the eclipsing binaries are SB2, Munari et al. (2004) conclude that about 16 000 EB–SB2 should be identified by Gaia ($V \leq 13$). However, their initial 64 000 is based on 0.8% of EB in Hipparcos, instead of 0.4%. On the other hand,

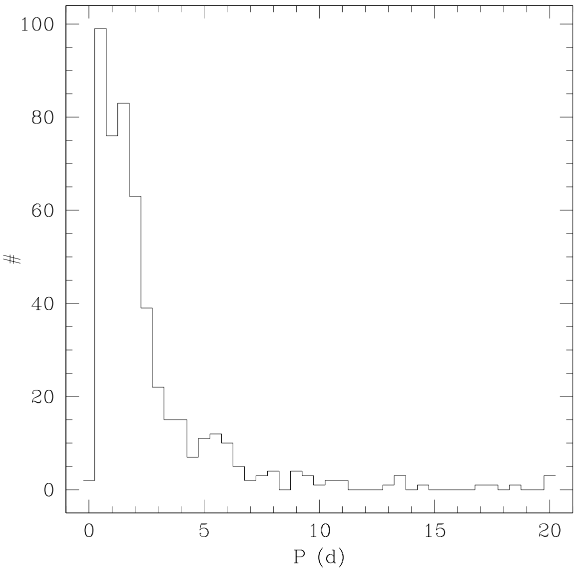

Figure 4. Distribution of the periods of Hipparcos eclipsing binaries

the percentage after Carquillat et al. needs to be revised as well. There are 352 eclipsing binaries which belong to SB9 and 214 are actually double-lined, i.e., 60%. This double revision leads to nearly 20 000 systems with good individual masses.

It is worth keeping in mind that the Gaia Nyquist frequencies for SB and EB are different (Eyer & Bartholdi 1999) as long as the photometry is based on the broad band filters. Indeed, the temporal distributions of the two sets of data are very different. RVS data are multiples of 6h apart whereas BBP data are 1h 46min and 4h 15min apart. This means that, despite the 0.1 d constraint on the period of spectroscopic binaries, eclipsing binaries can help picking up the right period among the aliases with the RVS-based power spectrum, even at frequencies higher than the RVS Nyquist frequency.

6.2. HIP 88848: Changing a Mess into Science

HIP 88848 (V815 Her, $V = 7.7$) has long been known as a 1.81 d spectroscopic binary (Nadal et al. 1974). It was observed by Hipparcos but no satisfactory astrometric solution could be fitted. It was therefore assigned a stochastic solution (DMSA/X). Despite the stochastic solution, Pourbaix et al. (2004a) could not find any trace of the 1.81 d period in the observation.

Fekel et al. (2005) have lately identified a third component in that system, with a period of 2092 d. Once that orbit is used to constrain the fit of the Hipparcos data with an orbital model, the result is very impressive. The uncertainty on the derived orbital inclination is only 2° which makes this value worth keeping for the astrophysicists.

Owing to the long period, the orbital motion was confused with the proper motion. The revised proper motion matches the Tycho-2 value (Høg et al. 2000) at the 2σ level, compared to the 30σ level with the stochastic solution.

7. CONCLUSIONS

Even though Gaia is primarily an astrometric mission, the quite poor quality of the radial velocities (with respect to precision achieved today with ground-based instruments) where astrometry is effective will make the combination of astrometric and RVS data rather rare.

Fortunately, the combination of photometry and spectroscopy will be much more productive. There should be between 16 000 and 20 000 eclipsing SB2 systems, i.e., about 35 000 individual masses known to within a few percents.

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