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A SELECTION OF SB WHICH COULD GET ACCURATE MASSES FROM GAIA ASTROMETRY

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Abstract. Gaia will provide astrometric measurements accurate enough for deriving the masses of spectroscopic binary (SB) components with uncertainties around 1 %. A list of a bit less than 100 SB is set up for that purpose. However, the spectroscopic elements of these systems need to be derived again from accurate radial velocity measurements in order to achieve a 1 % accuracy on the masses.

1 Introduction

Several progresses in our knowledge of double stars are expected from the forthcoming Gaia mission. The statistical properties of binaries, which are clues for the understanding of their formation process, will be derived from samples larger from the present ones by several orders of magnitude (Halbwachs et al. 2003a). Ten years ago, Halbwachs & Arenou (1999) pointed out that the astrometric Gaia measurements could lead to the masses of a lot of components of double-lined spectroscopic binaries (SB2). The elements of the SB2 orbit lead to the products $\mathcal{M}_1 \sin^3 i$ and $\mathcal{M}_2 \sin^3 i$, where $\mathcal{M}$ refers to component masses and i to the inclination of the orbital plane. Up to the present time, accurate stellar masses have been obtained from SB2 which are also eclipsing binaries. The inclinations of these systems are then derived from the analysis of the light curve. This method is quite reliable, but it may be applied only to few SB2, since it requires inclinations very close to $\pi/2$. Moreover, eclipsing binaries have usually short periods and close components, and are therefore not representative of single stars since they often suffer from mass exchange between the components. At the opposite, an astrometric orbit is easier to derive when the period is close to the time span of the observations (5 years with Gaia) than when the components are close. For these reasons, masses derived from SB orbits and inclinations coming from the astrometric observations of the forthcoming Gaia satellite would be quite relevant, if their uncertainties would be sufficiently small. In practice, it is considered that errors around 1 % or less are required for improving the models of stellar physics.

2 A method for selecting SB that could provide accurate masses

Let us consider a binary for which we have a list of radial velocity (RV) measurements and a list of astrometric measurements. In practice, the most efficient method for deriving the orbital elements of such system consists in using together the measurements of all kinds in a sole computation. However, our purpose hereafter is to select known SB for which Gaia could provide an important missing information, that is the sinus of the inclination. The SB elements of these binaries were usually obtained from RV measurements with moderate uncertainties, i.e. a few hundreds of m/s, or even around 1 km/s. Therefore, we have estimations of $\mathcal{M}_1 \sin^3 i$ and $\mathcal{M}_2 \sin^3 i$ which are not very accurate, but may be greatly improved by measuring again the RV of these stars with a CCD-spectrovelocimeter. The RV errors are then around 1 m/s for stars with small RV amplitudes, and it should be a few tens of m/s for a typical SB. For selecting the SB which could receive accurate masses, it is assumed hereafter that the spectroscopic elements of the binaries may be derived with negligible errors. Then, the elements period P, eccentricity e, periastron epoch T_0, periastron argument ω, and projected semi-major axis of the photocenter $a_0 \sin i$ are fixed in the derivation of the astrometric orbit, and the errors of the

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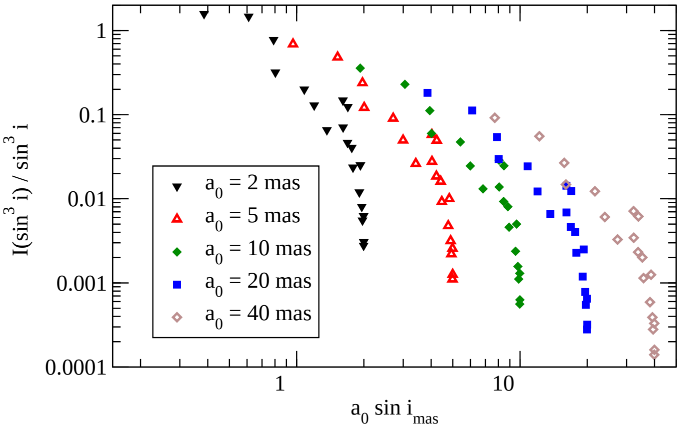

Fig. 1. Uncertainties of $sin^3 i$ derived from Gaia astrometric observations for simulated SB with various semi-major axes.

masses will come only from the errors of the astrometric measurements. The selection problem consists then in evaluating the uncertainty of $\sin^3 i$ (i.e., of i) that may be expected on the basis of the SB elements. It is not difficult to calculate $a_0 \sin i$ from the elements of the SB orbit and from the distance of the system, assuming a mass-luminosity relation: For the wavelengths used by Gaia astrometry, the difference of magnitudes between main sequence components is simply $\Delta G = -7.3 \log q$, where q is the mass ratio.

It comes from simulations that, for periods shorter than 5 years, Gaia could provide inclinations with uncertainties $I(i)$ which roughly obey the equation:

$$I(i) = \frac{3}{a_0 \sin i} \tag{2.1}$$

where $a_0 \sin i$ is in mas and $I(i)$ is in degrees. This relation is only approximate (by a factor of about 2), since the actual error will depend on parameters like the eccentricity of the orbit and the position angle of the periastron, and on the observation epochs. A consequence of Eq. **??** is that the relative error of $\sin^3 i$ is then related to both $a_0 \sin i$ and $\sin^3 i$, since it is:

$$\frac{I(\sin^3 i)}{\sin^3 i} = 3 \, \frac{I(i)}{\tan i} \times \frac{\pi}{180} \tag{2.2}$$

Therefore, it is impossible to predict the uncertainties of the masses which may be obtained from Gaia astrometric measurements for a given SB2. This is illustrated by Fig. **??**, where the relative errors of $\sin^3 i$ are plotted as a function of $a_0 \sin i$ for a few simulated SB2 with different a_0. It appears that the relative error of $\sin^3 i$ is dramatically rising when the inclination decreases.

In a rough approximation, it comes from Eq. **??** and **??** that we will get masses with errors smaller than 1 % when the actual inclinations are larger than the limit:

$$i_{min} = \arctan \frac{5\pi}{a_0 \sin i} \tag{2.3}$$

where $a_0 \sin i$ is again in mas. As a consequence, it is only possible to derive a probability to obtain masses with an error better than 1 %, assuming a statistical distribution for the inclinations. Since it is reasonable to assume that the orientations of the orbits with respect to the plane of the sky are isotropic, we assume hereafter that the distribution of i is $f(i) = \sin i$. This relation applies to all binaries in space, and we assume it hereafter for any known SB, except for those for which the inclinations are already known thanks to Hipparcos astrometry.

It is worth noticing that a priori estimations of the inclinations could be obtained from $\mathcal{M}_1 sin^3 i$ by evaluating the masses of the primary components from their spectral types. However, this method would be hazardous, since it would introduce a bias in favour of the systems with primaries less massive than expected from the mass – spectral type relation. It is safer to discard it for that reason.

3 A list of stars which could get masses with a 1 %–accuracy

Our purpose is to search masses better than 1 %. Since it is not possible to compute a priori the expected accuracy of a component mass, we select the SB for which the probability to get such accurate masses is larger than 50 %. We consider SB2, but also SB1 when the minimum mass ratio is larger than 0.3. The secondary spectra could then be visible on high-resolution CCD observations.

In order to obtain accurate RV measurements, only the stars brighter than 12.5 mag and with declinations above -5 degrees are considered hereafter; moreover, the stars brighter than 6 mag are discarded from the selection, since they will not receive accurate astrometric measurements from Gaia. Three lists of known SB were thus prepared:

1. The nearby G-K dwarf binaries with astrometric orbits derived from Hipparcos (Halbwachs et al. 2003b). This list contains 25 SB with inclination errors less than 15 degrees. The mass ratios of these systems are coming from SB2 orbits or from the astrometric solution.

2. The SB9 catalogue (Pourbaix et al. 2009). This up-to date catalogue contains 776 SB with F to M spectral types and periods between 30 days and 10 years.

3. A list of SB members of common proper motion (CPM) systems (Halbwachs, Mayor & Udry, 2007). This list contains 34 SB with unpublished orbits and periods longer than 30 days.

The distances of the stars were derived from various methods. The trigonometric parallaxes were used when their uncertainties are better than 20 %. Otherwise, a spectroscopic parallax was derived. When the luminosity class of the star was not known, it was inferred from the reduced proper motion, $H = V + 5 \log \mu + 5$, where μ is the proper motion in arcsec. When $H > 0$, the star was assumed to be a dwarf, otherwise it is a giant. For the stars of the SB9 list, the spectroscopic parallaxes were corrected for extinction, using the coordinates of the stars and a galactic extinction model (Arenou et al., 1992).

For each SB, thousands of simulated binaries were generated, assuming known the actual elements and generating the unknown parameters like i and Ω, the position angle of the periastron. For each virtual binary, Gaia astrometric measurements were produced with a simple model (Halbwachs 2009), and the inclination of the orbit was derived from these observations, assuming the elements of the SB orbit. The proportion of virtual systems with inclination errors better than 1 % was thus obtained. The SB was selected when this rate was larger than 50 %. At the end, 96 SB were retained: 10 nearby G-K dwarfs with Hipparcos astrometric orbits, 78 SB9 stars, and 8 CPM stars. The faintest is a 10.17 mag star. Seven stars are earlier than F5 and 2 are of M-type, but the vast majority are G-K stars.

4 On the accuracy of $\mathcal{M} \sin^3 i$

We have selected SB for which $\sin^3 i$ may be found at the 1 % level of accuracy, assuming that the SB orbital elements are perfectly known. In this section, we want to be sure that $\mathcal{M} \sin^3 i$ may be accurately derived with a few high-precision RV measurements. For that purpose, RV measurements were generated with the following hypotheses: (a) The observation epochs obey a Poisson distribution, with an average number of 14 RV measurements within 7 years, starting from 2011; (b) the standard error of the epoch measurements is 50 m/s. Again, thousands of virtual SB were generated for each of the 96 SB of the list, and the standard deviation of the errors of $\mathcal{M}_1 \sin^3 i$ and $\mathcal{M}_2 \sin^3 i$ are computed. Figure **??** shows the selected SB plotted in a eccentricity vs relative error of $\mathcal{M}_1 sin^3 i$ diagram. About 50 SB in our selection should get $\mathcal{M}_1 \sin^3 i$ with errors less than 1 %. This is rather encouraging, since, for simplicity, the measurements already available were not taken into account in the computations above. In reality, they will be considered and the periods of the binaries – and therefore the $\mathcal{M} \sin^3 i$ terms – will be much more accurate than in the simulations. This concerns especially the periods larger than 7 years, and which were not covered with the simulated RV. Moreover, it is visible on Fig. **??** that the accuracy of $\mathcal{M}_1 sin^3 i$ is falling when the eccentricity increases, especially when it is larger than 0.6. Again, the accuracy should be much better in reality, if the observation epochs are not taken at random but chosen in order to observe near the periastron, each time this would be feasible.

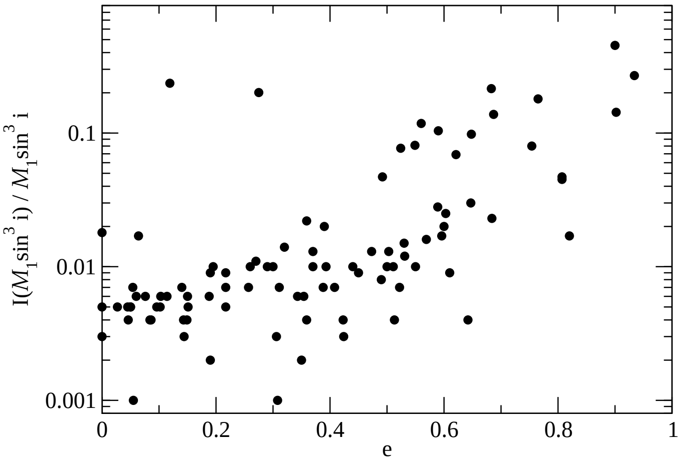

Fig. 2. Uncertainties of $\mathcal{M}_1 sin^3 i$ derived from high-precision RV measurements as a function of eccentricity.

5 Conclusion

We have prepared a list of 96 SB which could get masses with a 1 % accuracy if the elements of their spectroscopic orbits are derived again from high precision RV measurements. An accuracy of 50 m/s, which is quite feasible now, should be sufficient for that purpose. Would the RV observations begin in 2011, more than one hundred stars (2 per SB) could get accurate masses as soon as the Gaia astrometric measurements will be delivered.

This research has made use of the VizieR catalogue access tool and of the SIMBAD database, operated at CDS, Strasbourg, France

References

Arenou, F., Grenon, M., Gómez, A. E., 1992, A&A 258, 104

Halbwachs, J.-L., 2009, MNRAS 394, 1075

Halbwachs, J.-L., Arenou, F., 1999, Baltic Astronomy 8, 301

Halbwachs, J.-L., Arenou, F., Eggenberger, A., Mayor, M. & Udry, S., 2003a, in Gaia Spectroscopy, Science and Technology, ed. U. Munari, ASP Conf. Ser. 298, 339

Halbwachs, J. L., Mayor, M., Udry, S. & Arenou, F., 2003b, A&A 397, 159

Halbwachs, J. L., Mayor, M. & Udry, S., 2007, in Binary Stars as Critical Tools and Tests in Contemporary Astrophysics, IAU Symposium no. 240, ed. W.I. Hartkopf, E.F. Guinan & P. Harmanec, p. 427, Cambridge U. Press

Pourbaix, D., Tokovinin, A. A., Batten, A. H., Fekel, F. C., Hartkopf, W. I., Levato, H., Morell, N. I., Torres, G. & Udry, S., 2009, SB9: 9th Catalogue of Spectroscopic Binary Orbits, VizieR On-line Data Catalog: B/sb9. Originally published in: 2004, A&A 424, 727