ON THE DERIVATION OF THE MASSES OF SB2 COMPONENTS WITH GAIA ASTROMETRY

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Abstract. Apart from the case of the visual binaries for which the mass ratios were dynamically found, the Hipparcos astrometric data may also provide stellar masses from the photocentric orbits of double–lined spectroscopic binaries (SB2s). This method is applied to HIP 111170, with the results : $\mathcal{M}_1 = 1.89 \pm 0.40\mathcal{M}_0$ and $\mathcal{M}_2 = 1.04 \pm 0.20\mathcal{M}_0$. It is estimated that the number of SB2s of the 8^{th} *catalogue of orbital elements of SB systems* for which the masses of the components would be derived with the Gaia astrometric observations is about 80. Taking into account the evolution of the number of SB2s, the final estimation is about 160 systems at the end of the Gaia project. This number could be easely exceeded later, if particular efforts were dedicated to the on–ground observations of the SBs that will be discovered from the Gaia radial velocity measurements.

Key words: Astrometry, stars: masses, binaries: spectroscopic, individual: HIP 111170

1 INTRODUCTION

The mass of a star is a parameter that is rarely dynamically calculated, without the help of a model or a standard relation to another quantity. It may be derived only for binary star components, but it is still necessary to combine at least two different techniques of observations.
Before the results of the Hipparcos project were published (ESA, 1997), the status of the knowledge of the dynamical stellar masses may be summarized from the content

of the *Stellar Mass Catalogue* (Belikov, 1995). It includes 156 detached systems, for which the masses of the components were derived from four different methods :

1. The visual binaries (VBs) with known distances, for which the mass ratios were derived from the magnitudes of the components. Therefore, these masses cannot be considered as purely dynamical, since they depend on the mass–luminosity relation. 56 systems belong to this category.

2. The double–lined spectroscopic binaries (SB2s) that are also eclipsing binaries; the orbital elements of the SB2s include $\mathcal{M}_1 \sin^3 i$ and $\mathcal{M}_2 \sin^3 i$, where $\mathcal{M}_1$ and $\mathcal{M}_2$ are the masses of the components, and i is the inclination of the orbit; i is derived from the interpretation of the light curves, *ie* from a model including the radii and the limb darkening of the stars. Nevertheless, the calculation of the inclinations of the eclipsing binaries is considered as reliable, and the masses thus obtained are usually of good quality. This class contains 88 binaries.

3. The inclination of the orbit of a SB2 may also be derived by polarimetry; this concerns only one system.

4. The binaries that are visual and SB2 simultaneously. Contrarely to the first category above, the mass ratio is now derived from the spectroscopic orbit. The determination of the masses is then purely dynamical, but, unfortunately, only 11 systems belong to this single model–free category.

An additionnal fifth category provided substantial results when the astrometric observations of the Hipparcos satellite (ESA, 1997) became available : the mass ratio of a VB may be derived from the apparent motions of the components, even when these ones are observed only on a short part of their orbits. Since Hipparcos provided also accurate trigonometric parallaxes, the masses were obtained for the components of 29 VBs for which the orbital elements were known before the mission (Martin and Mignard, 1998, Martin et al, 1998, Söderhjelm, 1999).

A sixth category of mass calculation also benefit from Hipparcos : It consists in SB2s that are also astrometric binaries; when the elements of the spectroscopic orbit are taken into account, the photocentric orbit is accurately determined from the Hipparcos observations, and its inclination is calculated. The masses of the components are then derived from $\mathcal{M}_1 \sin^3 i$ and $\mathcal{M}_2 \sin^3 i$. In order to illustrate this method, it is applied hereafter to HIP 111170. The elements of the spectroscopic orbit were taken from Duquennoy and Mayor (1991), and the astrometric orbit in

Fig. 1 was derived from the Hipparcos astrometric data. The semi–major axis of the photocentric orbit is $a_0 = 23.5$ mas, and the inclination of the orbit is $i = 56.9 \pm 3.3$ deg. Therefore, the masses of the components are : $\mathcal{M}_1 = 1.89 \pm 0.40 \mathcal{M}_0$ and $\mathcal{M}_2 = 1.04 \pm 0.20 \mathcal{M}_0$.

The Gaia satellite, that would be launched within about 10 years, would widely increase the number of stars with known masses, since its astrometrical accuracy will be much higher than that of Hipparcos. The number of SB2s for which the masses of the components would be found at the end of the Gaia project is estimated hereafter.

2 The SB2s with known masses after Gaia

2.1 The conditions for the calculation of the masses

The inclination of the orbit of a binary may be found only when the semi–major axis of the photocentric orbit, a_0, is sufficiently large. For HIP 111170, with $a_0 = 23.5$ mas, the error of the inclination alone generates an uncertainty of 11 % on the masses of the components. From this case, and also from a few others that will be published separately, it is infered that the masses may be derived with errors smaller than about 15 % when a_0 is larger than 30 mas and when the astrometric precision is less than 1.5 mas. Since the precision of Gaia should be between 4 and 10 microarcsec for the bright stars, it is assumed that the inclinations of the SB2 orbits will be found when a_0 is more than 0.15 mas. However, this condition applies only to orbits that are entirely observed. Therefore, only the SB2s with periods shorter than the expected duration of the Gaia mission, that is 5 years, should be retained for the calculation of the masses from the photocentric orbit. This condition is not very restrictive, however, since long-period SB2s are very rare, and are also known VBs; the masses of their components are then already known.

When the components of a binary are similar in mass and in brightness, the photocentre coincides with the barycentre, and a_0 is null. However, if the components may be separated, and, if the period is shorter than 5 years, a “visual–like” orbit may be found, and the inclination is then obtained; (in reality, these binary stars are not simply VBs, but even the orbits of the components around the barycentres of the systems are calculated). It is expected that components as close as 1 or 2 mas will be distinguished in Gaia transits. It is hazardous to determine how wide must be the relative orbit to permit the derivation of its inclination; it is arbitrarily set hereafter that the semi–major axis, a, should be larger than 10 times the minimum measurable separation, *ie* 15 mas. This condition is not very important however, since the vast majority of binaries for which the components will be separated will also receive an astrometric orbit; even when the limit of a is assumed to be equal to the minimum measurable separation, the number of SB2s with "visual–like" orbits but without astrometric orbits remains small.

2.2 Application to the SB2s of the 8^{th} catalogue

The criteria determined in the previous section were applied to the 437 SB2s of the 8^{th} catalogue of orbital elements of spectroscopic binaries (Batten et al., 1989). Only the binaries with components certainly detached were considered : for security the condition was that the distance from the centre of a component to the first point of Lagrange must be as large as twice the radius of the star. The radii, the masses, the $(B-V)$ colour indices, the absolute magnitudes of the primary components were derived from the spectral types, using the relations in Schmidt–Kaler (1982). The secondary components were assumed to be main–sequence stars, in agreement with Halbwachs (1986); their masses, and, therefore, their other parameters, were calculated from the primary masses and from the mass ratios. The semi–major axes of the relative orbits, a, were derived from the masses and from the periods, using the relation : $a^3/P^2 = \mathcal{M}_1 + \mathcal{M}_2$. For deriving a_0, the magnitudes of the components were converted in the photometric Gaia band, thank to the $(B-V)$ *vs* $(V-I)$ relations in Caldwell et al. (1993). a_0 was not derived when the calculation gave the brightest V magnitude for the secondary component (for instance, when the mass ratio is larger than one for a binary with a main-sequence primary component); such stars were not considered as possible astrometric binaries, but they were still considered as "visual–like" binaries when a was larger than 15 mas. Therefore, 5 SB2s were finally discarded because the calculation gave negative ΔV.

Gaia will then permit the calculation of the inclinations of 91 detached SB2s of the 8^{th} catalogue : 89 will have a photocentric orbit, and, among the others, 2 will have a relative orbit with $a > 15$ mas. Among this total of 91 stars, 12 are eclipsing binaries and their inclinations are then already known. The statistic of the spectral types of the 79 other systems is presented in Table 1.

2.3 The number of SB2s at the end of the Gaia mission

The results presented above refer to the 1469 spectroscopic orbits that were available in 1989. A statistic of the number of binaries in the consecutive *catalogues of orbital elements of spectroscopic binary systems*, from the 2^{nd} to the 8^{th} (Campbell, 1910, Moore, 1924, 1936, Moore and Neubauer, 1948, Batten, 1967, Batten et al., 1978, Batten et al., 1989), is presented in Fig. 2. It appears that, since 1924, the number of SB orbits increases regularly by a factor of 1.31 every 10 years. It should then be about 3000 in 2015, when the reduction of the Gaia project will be completed. Gaia would then provide the masses of the components of about 160 SB2s. The actual number could be much larger, however, if a particular effort were dedicated to the observations of the stars with variable radial velocities that were discovered in the course of the surveys related to Hipparcos; and it could still increase considerably after the Gaia mission, by observing from the ground the SBs that will be found from the radial velocity measurements that will be performed by the satellite.

3 Conclusions

The number of stars for which dynamical masses have been found without any additional hypothesis is still very low (about 3 dozens), although it increased significantly with Hipparcos. The situation should dramatically change with Gaia, since, apart from the visual binaries for which the mass ratios will be dynamically found, the number of SB2s for which the orbital inclinations will be derived could be as large as about 160. However, the final number will be amply in excess of this estimation when the orbital elements of all the SBs that will be known at the end of the Gaia mission will be obtained.

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Captions to the figures

Fig. 1. The orbit of the photocentre of the double–lined spectroscopic binary HIP 111170 obtained from the Hipparcos observations, using the orbital elements by Duquennoy and Mayor (1991). The semi–major axis is $a_0 = 23.5 \pm 1.4$ mas and the inclination is $56.9\,\mathrm{deg} \pm 3.3\,\mathrm{deg}$; taking into account the elements of the spectroscopic orbit and their errors, the masses of the components are $\mathcal{M}_1 = 1.89 \pm 0.40 \mathcal{M}_0$ and $\mathcal{M}_2 = 1.04 \pm 0.20 \mathcal{M}_0$.

Fig. 2. The evolution of the number of spectroscopic binaries with orbital elements, from the 2^{nd} to the 8^{th} catalogue. The number should be about 3000 in 2015, when the reduction of the Gaia data will be completed.