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

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**Abstract.** Apart from the case of the visual binaries for which the mass ratios can be found dynamically, the *Hipparcos* astrometric data can also provide masses from the photocentric orbits of double-lined spectroscopic binaries (SB2s). This method is applied to HIP 111170 with the following results: $M_1 = 1.89 \pm 0.40\ M_\odot$ and $M_2 = 1.04 \pm 0.20\ M_\odot$. It is estimated that the number of SB2s from the 8th catalogue of orbital elements of SB systems, for which the masses of the components could be derived with the *Gaia* astrometric observations, is about 80. Taking into account the evolution of the number of SB2s, the final estimate is about 160 systems at the end of the *Gaia* project. This number could be easily exceeded later, if particular efforts were dedicated to the ground-based observations of SBs, 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 dynamical stellar masses may be estimated from the *Stellar Mass Catalogue* (Belikov 1995). It includes 156 detached systems, for which the masses of the components were derived by 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; their orbital elements include $M_1 \sin^3 i$ and $M_2 \sin^3 i$, where $M_1$ and $M_2$ are masses of the components and $i$ is the orbit inclination; $i$ is derived from the interpretation of the light curves, i.e. from a model including radii and limb darkening of the stars. Nevertheless, the calculation of the inclinations of 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. Contrary to the first category above, the mass ratio is now derived from the spectroscopic orbit. The determination of masses is then purely dynamical, but, unfortunately, only 11 systems belong to this single model-free category.

An additional fifth category provided substantial results when 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 they 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 & Mignard 1998, Martin et al. 1998, Söderhjelm 1999).

The sixth category of mass calculation also benefit from *Hipparcos*. It concerns SB2s which 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 $M_1 \sin^3 i$ and $M_2 \sin^3 i$. In order to illustrate this method, it is applied hereafter to HIP 111170. The elements of the spectroscopic orbit are taken from Duquennoy & Mayor (1991), and the astrometric orbit in Fig. 1 is 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: $M_1 = 1.89 \pm 0.40 M_\odot$ and $M_2 = 1.04 \pm 0.20 M_\odot$.

The *Gaia* satellite, that is expected to be launched within about 10 years, would widely increase the number of stars with known masses, since its astrometric 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. SB2 STARS WITH KNOWN MASSES AFTER GAIA

### *2.1. Conditions for the calculation of 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 component masses. From this case, and also from a few other cases that will be published separately, it is inferred 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 $\mu$as 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, i.e. 5 years, should be retained for the mass calculation from the photocentric orbit. This condition is not very restrictive, however, since long-period SB2s are very rare, and they usually are known as VBs; masses of their components are already known.

When the components of a binary are similar in mass and in brightness, the photocenter coincides with the barycenter, and $a_0$ is zero. However, if the components can be separated, and, if the period is shorter than 5 years, a "visual-like" orbit can be found and the inclination obtained; (in reality, *Gaia* will provide more than

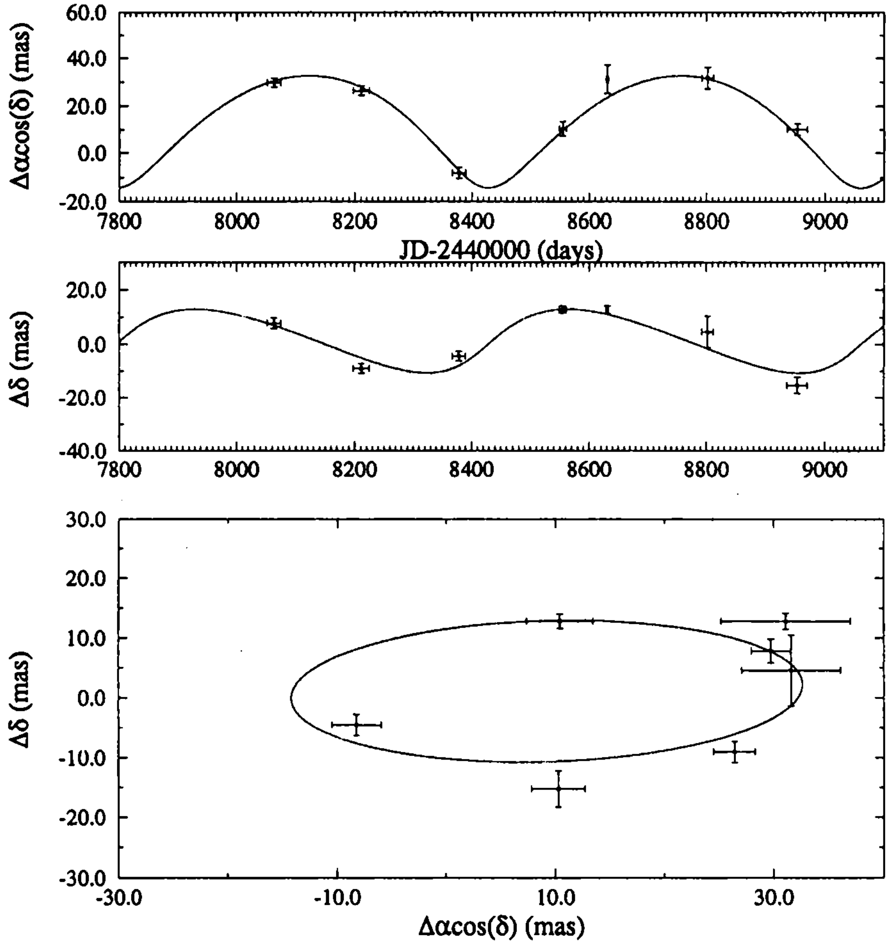


**Fig. 1.** The orbit of the photocenter of the double-lined spectroscopic binary HIP 111170 obtained from the *Hipparcos* observations, using the orbital elements by Duquennoy & Mayor (1991). The semi-major axis is $a_0 = 23.5 \pm 1.4$ mas and the inclination is $56.9 \pm 3.3$ deg; taking into account the elements of the spectroscopic orbit and their errors, the masses of the components are $M_1 = 1.89 \pm 0.40\ M_\odot$ and $M_2 = 1.04\ \pm 0.20\ M_\odot$.

VB orbit: the VB orbit is based on the motion of one component around another; with *Gaia* the motions of both components around the barycenter of the system will be observed). It is expected that components as close as 1 or 2 mas will be distinguished in the *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, i.e. be of the order of 15 mas. However, this condition is not very important since the vast majority of binaries, for which the components will be separated, will also receive the 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 of the 8th catalogue to SBs*

The criteria determined in the previous section were applied to the 437 SB2s of the 8th 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 accepted that the distance from the center of a component to the first point of Lagrange must be as large as twice the star radius. The radii, masses, $B$–$V$ color indices and absolute magnitudes of the primary components were derived from the spectral types, using the relations from Schmidt-Kaler (1982).

The secondary components were assumed to be the main-sequence stars, in agreement with Halbwachs (1986); their masses and other parameters, were calculated from the primary masses and the mass ratios. The semi-major axes of the relative orbits, $a$, were derived from the masses and periods, using the relation: $a^3/P^2 = M_1 + M_2$.

For deriving $a_0$, the magnitudes of the components were converted to the *Gaia* astrometric passband, using the $B$–$V$ vs. $V$–$I$ relation from Caldwell et al. (1993). $a_0$ was not derived when the calculations gave the brightest $V$ magnitude for the secondary component (for instance, when the mass ratio was larger than one for a binary with the 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, five SB2s were finally discarded because for them negative $\Delta V$ values were obtained.

*Gaia* will then permit the calculation of the inclinations of 91 detached SB2s of the 8th catalogue: 89 will have a photocentric orbit, and, among others, 2 will have a relative orbit with $a > 15$ mas.

**Table 1.** Statistics of spectral types and luminosity classes of the SB2 primary stars from the 8th catalogue which are not eclipsing binaries and for which the orbital inclinations could be found by *Gaia*.

| | O | B | A | F | G | K |
|---|---|---|---|---|---|---|
| Supergiants | 1 | | | | | |
| Giants | | 1 | 1 | 4 | 7 | 4 |
| Subgiants | | 1 | | 10 | 2 | |
| Dwarfs | | 6 | 13 | 14 | 7 | 8 |

Among these 91 stars, 12 are eclipsing binaries, and their inclinations are already known. Statistics of spectral types of other 79 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. Statistics of the number of binaries in the consecutive catalogues of orbital elements of spectroscopic binary systems, from the 2nd to the 8th (Campbell 1910, Moore 1924, 1936, Moore & Neubauer 1948, Batten 1967, Batten et al. 1978, 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. In 2015, when the reduction of the *Gaia* project will be completed, their number should be about 3000. *Gaia* would then provide masses of the components of about 160 SB2s.

Actual number of such stars could be much larger, however, if the efforts were made to observe the stars with variable radial velocities, discovered in the course of the surveys related to *Hipparcos*. Their number could be increased even more after the *Gaia* mission, by observing from the ground the SBs, which will be detected from radial velocity measurements done by the satellite.

## 3. CONCLUSIONS

The number of stars for which dynamical masses have been found without any additional hypothesis is still very low (only about three dozens), although it increased significantly after *Hipparcos*. The

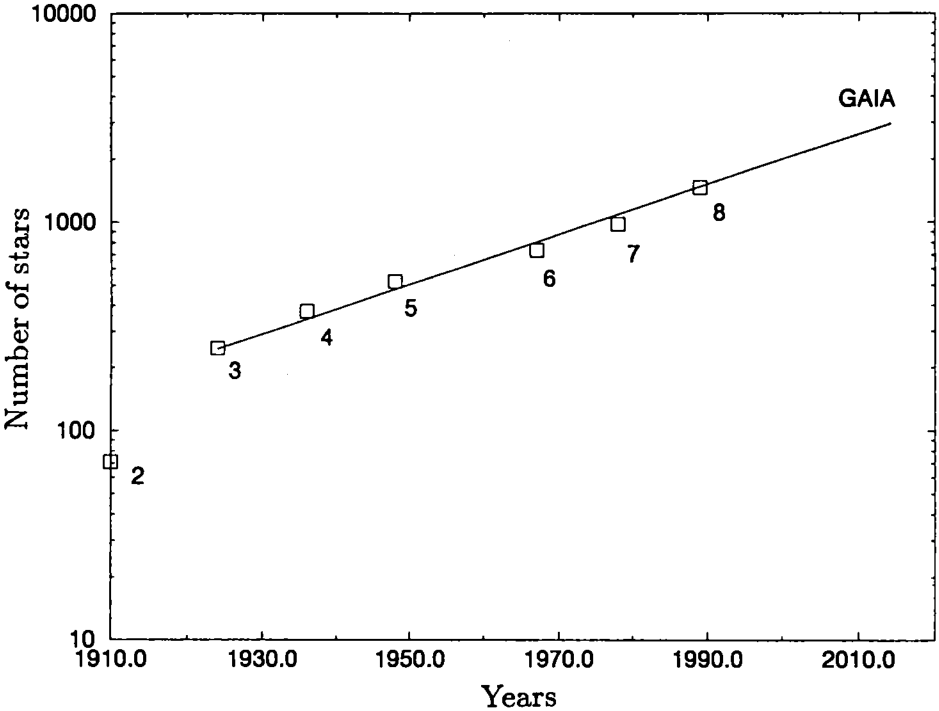


**Fig. 2.** Evolution of the number of spectroscopic binaries with known orbital elements from the 2nd to the 8th catalogues. The number should be about 3000 in 2015, when the reduction of the *Gaia* data will be completed.

situation should change drastically with *Gaia*: except the visual binaries, for which the mass ratios will be found dynamically, the number of SB2s with known orbital inclinations should be as large as ~160. However, the final number of such stars will be amply in excess of this estimation when the orbital elements will be obtained for all SBs known at the end of the *Gaia* mission.

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