SF2A 2013
L. Cambrésy, F. Martins, E. Nuss and A. Palacios (eds)

IMPROVED SB2 ORBITS FOR HIP 12081 AND HIP 87895*

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Abstract. We are observing a selection of about 70 double-lined binaries (SB2s) with the T193/SOPHIE in order to improve their orbital elements. Our goal is to obtain the masses of the components with a 1 % accuracy when the astrometric observations of Gaia are available.

After 6 semesters of observations, the two best observed stars are HIP 12081 and HIP 87895. These stars are used to verify that the 1 % accuracy could really be obtained at the end of the programme. The radial velocities of their components were derived using the TODMOR algorithm, and their orbital elements were calculated. It appears that the minimum masses of the components of HIP 12081 are already both obtained with an accuracy around 0.5 %. For HIP 87895, the relative precisions of the minimum masses of the primary and of the secondary component are 2.7 and 1.5 %, respectively, but they were obtained from only 9 spectra and they should be improved once more observations have been obtained.

Ancient interferometric observations of HIP 87895 are also taken into account and the actual masses of the components are derived. Although these measurements are far from being as accurate as those expected from Gaia, the relative errors of the masses are only 2.6 and 1.5 % respectively. We thus conclude that our programme would lead to masses with the announced accuracy if the observations are continued.

Keywords: binaries: spectroscopic, Stars: fundamental parameters, stars: individual: HIP 12081, HIP 87895

1 Introduction

The double-lined spectroscopic binaries (SB2s) are at the root of the less model–dependent methods used to derive the stellar masses. Their orbital elements are used to derive the products $\mathcal{M}_* \sin^3 i$, where $\mathcal{M}_*$ is the mass of a component and i is the inclination of the orbital plane. Therefore, when the inclination may be obtained from another technique, such as eclipse observations or astrometric measurements, the accuracy of the masses amply depends on that of the SB2 orbital elements.

Gaia will provide an opportunity to derive stellar masses with errors around 1 %, by combining Gaia astrometry with accurate SB2 orbital elements. For that purpose, a large observation program is going on at the Observatoire de Haute-Provence (OHP) with the T193/SOPHIE, in order to improve the orbital elements of a selection of known SBs (Halbwachs & Arenou 2009). The observed sample contains 207 SBs: 50 known SB2s, but also 157 stars which are known as SB1s, since the components of some of them may be separated for the first time thanks to the SOPHIE spectrograph.

In Sect. 2, we present the number of spectra and the classification of the programme stars after 6 semesters of observations. Two stars (HIP 12081 and HIP 87895) are selected on the basis of the number and of the distribution of the measurements they received, and their radial velocities (RV) were obtained as explained in Sect. 3. The spectroscopic orbital elements of these stars, including the minimum masses of their components, are derived in Sect. 4 and 5. The actual masses of the components of HIP 87895 are derived from interferometric measurements in Sect. 6. Sect. 7 is the conclusion.

* BASED ON OBSERVATIONS PERFORMED AT THE HAUTE-PROVENCE OBSERVATORY

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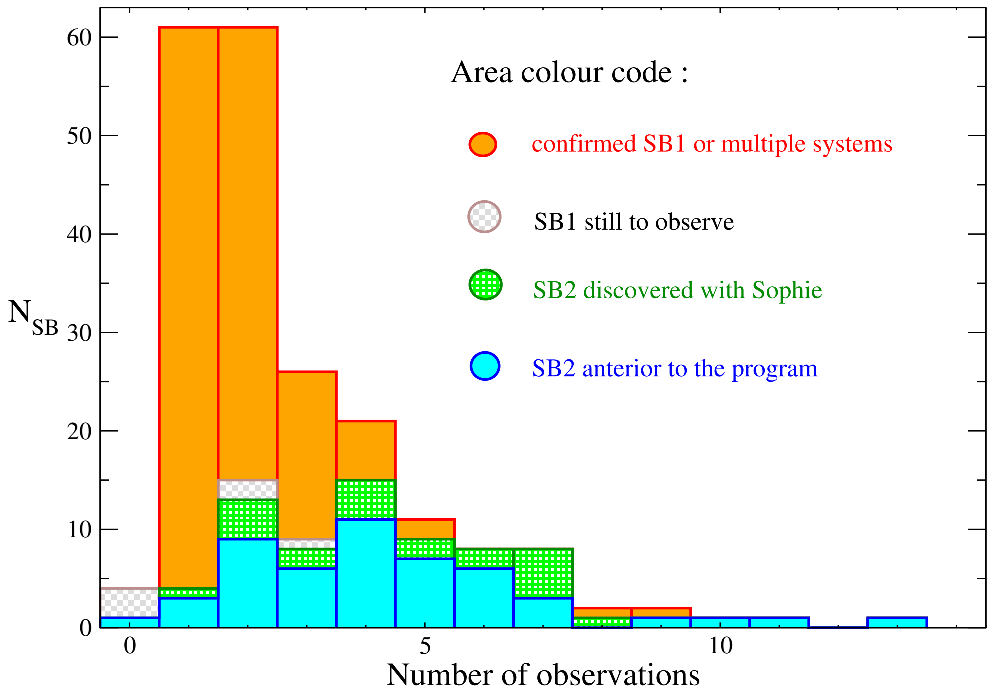

Fig. 1. Histogramme of the programme stars according to the numbers of spectra they received.

2 Status of the programme

The observing programme began in April 2010, and, after 6 complete semesters, we have collected 572 spectra. Each component was detected for 21 SB1s. Some of them were announced in Halbwachs et al. (2011). One hundred and thirty SB1s were discarded from the observations, since they were confirmed as SB1s, or appeared to be multiple systems. The status of 6 SB1s is still uncertain. These stars have eccentric orbits, low RV semi-amplitudes, and long periods; therefore, we are still waiting for the moment when the difference between the velocities of the components could be sufficient to separate the components on the spectrum.

The distribution of the stars according to their status and to their numbers of spectra is presented in Fig. 1. It thus appears that the majority of the SB2 stars received only 4 spectra or even less. It is worth noticing that the minimum number of spectra to derive an SB2 orbit is theoretically 4, when the RV of both components are obtained from each of them. However, if we want to check the reliability of the RV uncertainties for each component, it is necessary to derive the individual orbit of each component, and a minimum of 7 RV measurements is required. In practice, it is also necessary to have observations nearly equally distributed on at least a complete period. The following criteria are finally retained for selecting SB2s usable to derive an assessment: a minimum of 8 RV measurements for each components, and a minimum of one period covered by the observations. Two stars were thus selected, which are HIP 12081 and HIP 87895.

3 Derivation of the Radial Velocities with TODMOR

The RVs of each one of the binary components, as well as their atmospheric parameters and the flux ratio between them, were determined from the SOPHIE spectra using TODMOR (Zucker & Mazeh 1994; Zucker et al. 2004) — a two-dimensional correlation algorithm. In TODMOR, the cross-correlation functions are calculated separately for each echelle order, and then combined to a single cross-correlation function according to the scheme proposed by Zucker et al. (2003).

To construct the templates we used the Phoenix library of synthetic spectra (Hauschildt et al. 1999), with varying values of effective temperature $T_{\rm eff}$, surface gravity $\log g$, metallicity $[m/H]$ and rotational velocity $v \sin i$. The library spans the following intervals in atmospheric parameters: $3000{\rm K} < {\rm T}_{\rm eff} < 10000{\rm K}$, $-0.5 < \log g < 5.5$ (cgs), and $-1.5 < [m/H] < +0.5$. The spacing in $T_{\rm eff}$ is 100K for $T_{\rm eff} < 7000$K, and 200K elsewhere. The spacing in $\log g$ and $[m/H]$ is 0.5 dex. The interval and spacing of $v \sin i$ values in our algorithm are free

Table 1. Best set of template parameters used in TODMOR, and orbital elements of the SB2 orbits. The numbers of measurements separated by "+" refer to the primary and to the secondary components. The two values of σ_{o-c} refer to the RVs of the primary and of the secondary components.

Parameter	HIP 12081	HIP 87895
$T_{\rm eff,A}$ [K]	6600	6000
$\log g_{\rm A}$ [dex]	4.5	4.5
$v \sin i_{\rm A}$ [km s^{-1}]	10	$\lesssim 1$
$T_{\rm eff,B}$ [K]	6000	4500
$\log g_{\rm B}$ [dex]^a	4.5	4.5
$v \sin i_{\rm B}$ [km s^{-1}]	4	$\lesssim 1$
[m/H] [dex]	−0.5	0.0
α [flux ratio]	0.53	0.03
N_{meas} SOPHIE	10 + 10	9 + 8
ΔT (days)	883	1008
Period (days)	443.402 ± 0.114	877.97 ± 1.56
T_0 (BJD−2 400 000)	55906.166 ± 0.979	55651.712 ± 15.0
e	0.58596 ± 0.00130	0.42093 ± 0.00220
ω (deg)	284.240 ± 0.179	135.209 ± 0.362
V_γ (km/s)	-6.4297 ± 0.0175	-30.8650 ± 0.0269
K_1 (km/s)	16.7484 ± 0.0455	11.4134 ± 0.0166
K_2 (km/s)	18.1598 ± 0.0399	17.242 ± 0.212
$a_1 \sin i$ (Gm)	82.747 ± 0.203	124.996 ± 0.353
$a_2 \sin i$ (Gm)	89.719 ± 0.165	188.82 ± 2.33
$\mathcal{M}_1 \sin^3 i$ ($\mathcal{M}_\odot$)	0.54092 ± 0.00259	0.9612 ± 0.0260
$\mathcal{M}_2 \sin^3 i$ ($\mathcal{M}_\odot$)	0.49888 ± 0.00275	0.63629 ± 0.00964
σ_{o-c} (km/s)	0.0428/0.0711	0.0301/0.224

^{a}: Parameter values assumed without optimization.

parameters set by the user, since each synthetic spectrum chosen from the library is convolved with a rotational profile G(v) (e.g., Gray (2005), p. 465; Santerne et al. (2012)) and a Gaussian representing the instrumental broadening of the lines, just before calculating cross-correlation function.

First, we applied TODMOR only to the spectra taken close to quadratures, varying the values of the primary and secondary atmospheric parameters and the flux ratio between them, to derive the best set of template parameters — the one that yielded the highest two-dimensional correlation peak. Then, we fixed all template parameters and applied TODMOR to all of the observed spectra to derive the primary and secondary RVs in each exposure.

The best set of template parameters are listed in Table 1. Fig. 2 shows the TODMOR results for the third SOPHIE exposure of HIP 87895. The upper and lower panels of the figure show primary and secondary *cuts* through the two-dimensional correlation function that run through the correlation peak. The primary cut (upper panel) is parallel to the primary RV axis, freezing the secondary velocity at its derived velocity, while the secondary cut (lower panel) runs parallel to the secondary RV axis, freezing the primary velocity at its derived velocity.

We note that in the upper panel the correlation drops by ~ 0.5 when moving away from the peak, because we change the velocity of the *primary* template in the model. On the other hand, the correlation in the lower panel drops only by ~ 0.003, because we change the velocity of the *secondary* template, which contributes only $\sim 3\%$ of the light. The additional peak in the lower panel at the primary RV is probably caused by imperfect modeling of the primary line profiles, which prevents correct derivation of the secondary RV from exposures made close to alignment.

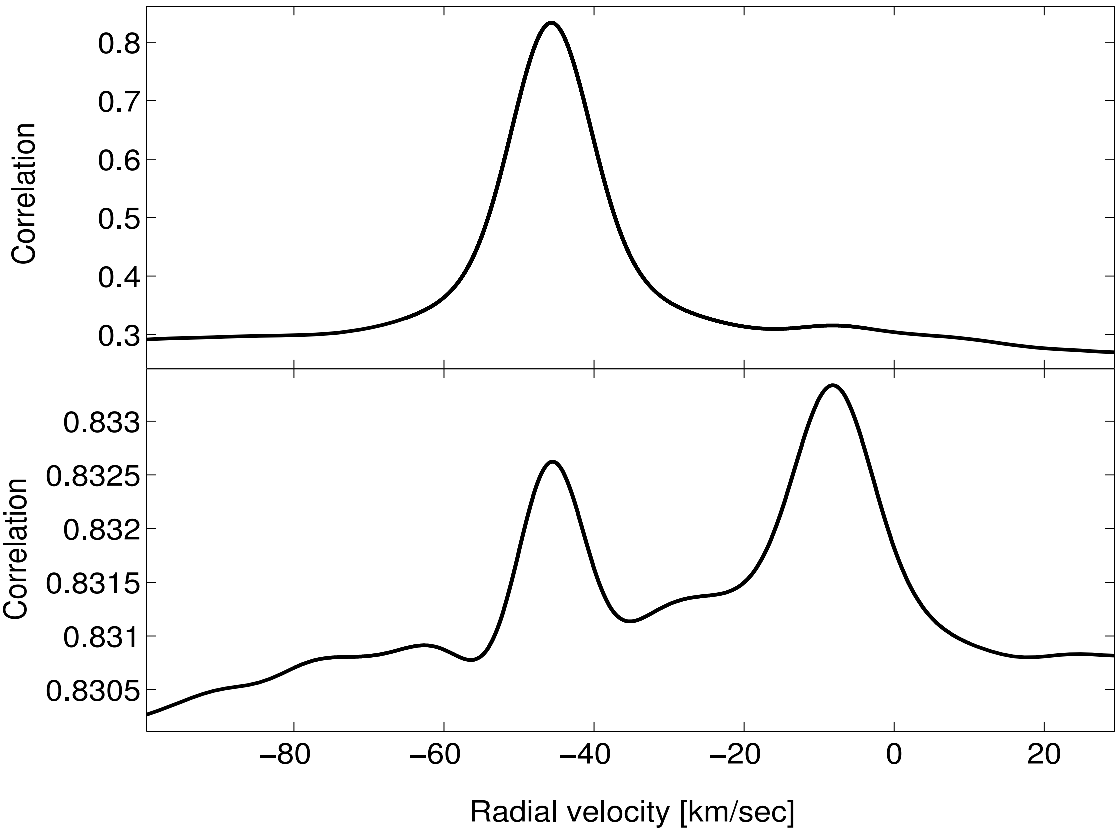

Fig. 2. TODMOR plot for the third SOPHIE exposure of HIP 87895. The upper and lower panels show the primary and secondary *cuts* through the two-dimensional correlation function. Note the different scale.

4 Spectroscopic orbit of HIP 12081

Ten spectra of HIP 12081 were obtained, and the radial velocities of both components were derived for each of the 10. The flux ratio of this system is rather large (0.53), and the accuracy of the RVs is altered by the contamination of the spectrum of each component by that of the other. The uncertainties thus are around 70 m/s for the RV of the primary component, and around 90 m/s for that of the secondary. The elements of the SB1 orbit were derived for the primary and for the secondary component, and the F_2 estimator of the goodness-of-fit (Stuart & Ord 1994) was -1.16 and +1.39, respectively. Since F_2 is a random variable obeying the standard normal distribution, we infer that the uncertainties of the RVs obtained from TODMOR are quite reliable, and they are assumed hereafter.

Another point to be verified is the coincidence of the zero of the RVs of the primary and of the secondary components. Using inadequate templates would introduce a shift of the RVs of one component with respect to the other. This shift is added to the unknowns of the model, and it is thus found that the secondary RVs could be smaller than the primary ones, with the difference: (-95.1 ± 56.8) m/s. This value is not significant, however, since it may be obtained at random with a 9.3 % probability. It is probably much smaller than -95.1 m/s in reality, and it was decided to ignore it.

The solution derived from the SOPHIE measurements is presented in Table 1. It thus appears that the minimum masses of the components, $\mathcal{M}_{1,2} \sin^3 i$, are obtained with errors as small as 0.48 and 0.55 %. It is quite possible that the masses will be evaluated with errors smaller than 1 % once the Gaia astrometric measurements are available, although this is not certain: the final errors will depend on the actual inclination of the system (Halbwachs & Arenou 2009).

A previous orbit was obtained by Griffin (2005), based on 47 RV observations. Since these RV received all

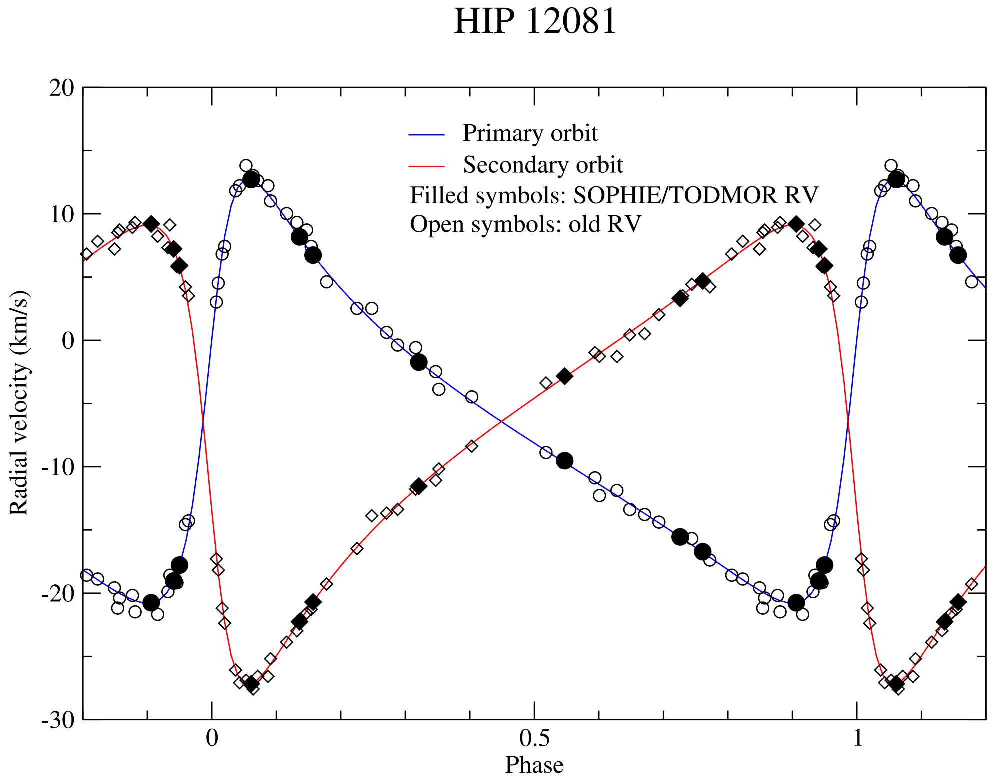

Fig. 3. SB2 orbit of HIP 12081, assuming the elements in Table 2. The circles are the RV measurements of the primary component, and the diamond that of the secondary component. The old measurements are from Griffin (2005).

the same weight, we fix their uncertainties to 0.57 km/s, in order to recover the Griffin's orbit with $F_2 = 0$. The uncertainties of the relative errors of the minimum masses are as large as 2.0 and 1.9 %, respectively. However, when these measurements are added to the SOPHIE RVs to derive again the orbital elements, the uncertainty of the period is significantly improved (see the new elements in Table 2, and the plot of the orbit in Fig. 3). As a consequence, the relative errors of the minimum masses are finally 0.46 and 0.52 %, respectively. It is worth noticing that the improvement with respect to the results obtained from our RVs alone is nearly negligible.

5 Spectroscopic orbit of HIP 87895

Eight spectra of HIP 87895 were obtained during the first six semesters of the programme, but a ninth spectrum has been obtained in May 2013. The secondary component is much fainter than the primary one (the flux ratio is only 3 %, see Table 1), and it was not possible to derive the RV of the secondary from one of the spectra. The RV uncertainties are about 30 m/s for the primary component, but 450 m/s for the secondary. It is possible, however, that the uncertainties of the RV of the secondary component were overestimated: when a SB1 orbit is derived from these measurements, the goodness-of-fit is $F_2 = -1.99$, and the probability to be so far from 0 by random is only 4.7 %. Alternatively, $F_2 = 0$ when the uncertainties are divided by 7.9, leading to actual errors around 60 m/s. This will be clarified in the future, once more measurements are available; for the moment, the uncertainties estimated by TODMOR are assumed. It is worth noticing that the SB1 orbit of the primary component is obtained with $F_2 = 1.42$, which is quite acceptable, but which could also suggest that the primary RVs have uncertainties that could be around 68 % larger than that assumed. Anyway, the SB2 orbit in Table 1 was obtained with $F_2 = -0.03$, indicating that the overestimation of the errors of one component, if it really exists, is perfectly compensated by the possible underestimation of the errors of the other. At the end, in view of the mean residuals of the SB2 orbit, Table 1 confirms the idea that the uncertainties of the secondary RVs are smaller than assumed, but by a factor of about 2 rather than 7.9. On the other side, the uncertainties of the primary RVs seem a bit larger than the assumed 30 m/s.

Another point to be verified is the possible shift between the RVs of both components. A calculation indicated that this shift could be (152 ± 183) m/s. Its large uncertainty makes the shift not significant at all,

Table 2. The orbital elements of the SB2 orbits when the ancient measurements are added to the SOPHIE RVs.Data about the SOPHIE observations alone are in Table 1

Parameter	HIP 12081	HIP 87895
N_{meas} Ancient	47 + 47	106 + 16
$RV_{SOPHIE} - RV_{Ancient}$	0.4195 ± 0.0634	1.9108 ± 0.0483
ΔT (days)	4486	13041
Period (days)	443.3377 ± 0.0335	881.6355 ± 0.0785
T_0 (BJD−2 400 000)	55906.160 ± 0.979	55650.250 ± 0.789
e	0.58560 ± 0.00121	0.41776 ± 0.00123
ω (deg)	284.241 ± 0.172	135.328 ± 0.327
V_γ (km/s)	-6.4285 ± 0.0609	-30.8955 ± 0.0446
K_1 (km/s)	16.7659 ± 0.0421	11.4010 ± 0.0161
K_2 (km/s)	18.1578 ± 0.0372	17.190 ± 0.201
$a_1 \sin i$ (Gm)	82.848 ± 0.191	125.585 ± 0.170
$a_2 \sin i$ (Gm)	89.726 ± 0.157	189.35 ± 2.21
$\mathcal{M}_1 \sin^3 i$ ($\mathcal{M}_\odot$)	0.54178 ± 0.00247	0.9627 ± 0.0248
$\mathcal{M}_2 \sin^3 i$ ($\mathcal{M}_\odot$)	0.50025 ± 0.00260	0.63850 ± 0.00910
σ_{o-c} SOPHIE (km/s)	0.0490/0.0722	0.0394/0.202
σ_{o-c} Ancient (km/s)	0.634/0.541	0.84/1.24

and leads to assume that it is probably negligible.

The orbital elements of HIP 87895 were derived from the SOPHIE RVs, and they are summarized in Table 1. The relative uncertainties of the minimum masses of the two components are 2.7 and 1.5 %, respectively.

This star was observed in the past, and McAlister et al. (1995) collected RVs from 5 different sources. They obtained 106 measurements of the primary component, but the secondary was observed only 16 times. Again, the uncertainties were derived from the weights, and all the secondary RVs receive $\sigma_{RV} = 2.43$ km/s. With so large errors, it is not surprising that, despite the number of measurements, the relative errors of the masses of the orbit of McAlister et al. were as large as 7.7 and 4.3 %, respectively.

The calculation of the elements was done again, adding the ancient RVs to the SOPHIE RVs. The results are in Table 2, and the orbit is plotted on Fig. 4. Again, the extension of the timespan of the observation leads to significantly improve the accuracy of the period. Nevertheless, the final relative uncertainties of the minimum masses of the two components are 2.6 and 1.4 %, respectively, instead of 2.7 and 1.5 %. The improvements due to the ancient measurements are very small when the minimum masses are considered.

6 Masses of the components of HIP 87895

HIP 87895 is not only known as a SB, but it is also a "visual" binary, with 24 observations of the position of the secondary with respect to the primary recorded in the on-line catalogue described in Hartkopf, Mason & McAlister (2001). Twenty-one observations were performed with telescopes with diameters between 1 and 6 m, and have very large errors. Fortunately, 3 were obtained from an interferometer with a 110 m long base and have separations with errors around 0.3 or 0.4 mas. So it is possible to derive the inclination of the orbit, and the masses of the components.

The common solution obtained from all these data is not satisfactory, since we obtained $F_2 = 4.81$. This comes obviously from the censoring of the measurements when the actual separation is too close for the telescope: only measurements with large overestimation of the angular separation are then possible. This appears clearly on Fig. 5, where the 3 measurements in the South have all very large errors when the components were very close in reality. In order to avoid this problem, we decided to keep only the 3 observations obtained with a long-base interferometer. It is worth noticing that the astrometric measurements are two-dimensional, and that the contribution of the astrometric data results in adding to the orbit only three more elements (the inclination,

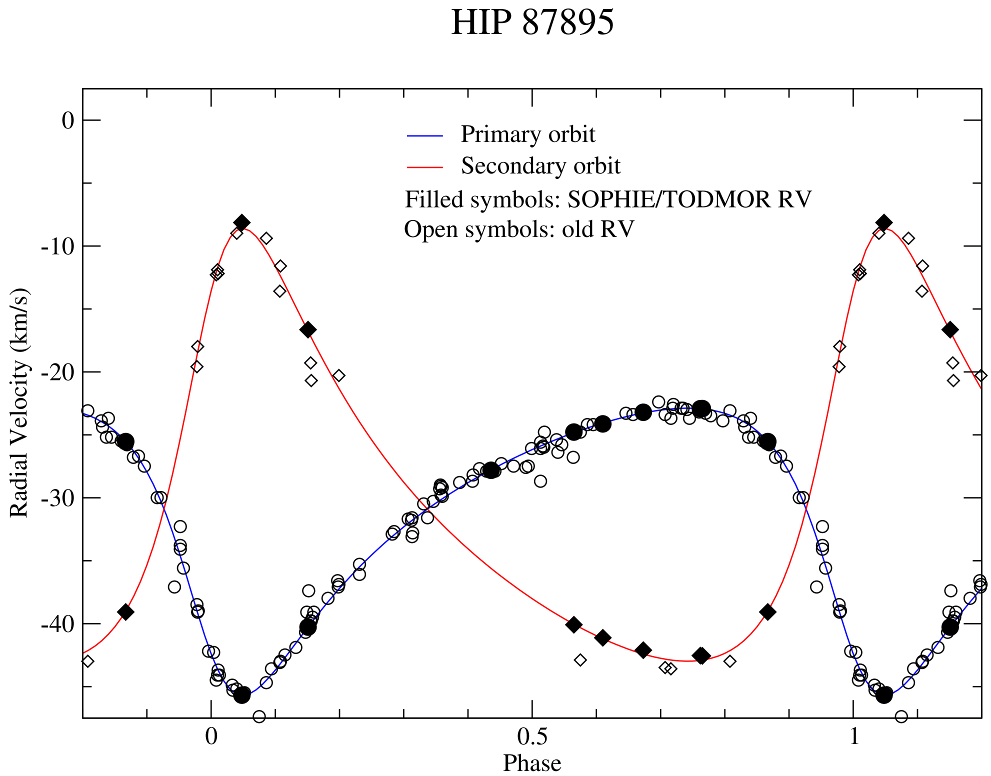

Fig. 4. SB2 orbit of HIP 87895. The circles are the RV measurements of the primary component, and the diamond that of the secondary component. The old measurements are from McAlister et al. (1995).

the position angle of the ascending node, and the parallax of the system). Therefore, only two astrometric measurements would even have been sufficient.

A combined solution was thus obtained from all the RVs and from the 3 accurate astrometric measurements. The inclination is (72.852 ± 0.367) deg, and the masses are $\mathcal{M}_1 = (1.1033 \pm 0.0292)\mathcal{M}_\odot$ and $\mathcal{M}_2 = (0.7317 \pm 0.0113)\mathcal{M}_\odot$. The relative uncertainties are 2.6 and 1.5 %, ie almost the same as for the minimum masses obtained from the spectroscopic data alone. For comparison, McAlister et al. (1995) found $\mathcal{M}_1 = (1.16 \pm 0.12)\mathcal{M}_\odot$ and $\mathcal{M}_2 = (0.77 \pm 0.05)\mathcal{M}_\odot$.

The combined solution includes also the parallax of the binary, which is $\varpi = (36.629 \pm 0.220)$ mas. Again, this result is much better than that of Pourbaix (2000), who found $\varpi = (37. \pm 1.8)$ mas. The improvement is due to the quality of the long-base interferometric measurements, but also to that of the RVs obtained from SOPHIE and TODMOR.

7 Conclusion

After 3 years of observations, two stars of our program received enough SOPHIE observations for a first verification of the quality of data. It was found that, when the two components have similar brightnesses, the minimum masses of the components may be obtained with uncertainties quite smaller than 1$\tilde{\%}$, even when the number of spectra is only 10. When the secondary component is faint, the uncertainties of the RVs obtained from TODMOR are a bit large, and the errors of the minimum masses may be around 2 or 3 %. However this was obtained from only 9 spectra, and the accuracy should be much better when more observations will be available.

Errors around 2.7 and 1.5 % were obtained for the masses of the components of HIP 87895, using only 3 interferometric relative positions with errors around 0.3 mas. Since Gaia will provide astrometric measurements in a large quantity and with a much better accuracy, and taking into account the fact that the orbit of the Gaia photocenter will be only 9 times smaller than the relative orbit, we still expect an improvement with the astrometric data by a factor around 2 or 3. In conclusion the announced accuracy of 1 % should be reached for a large part of the 140 components of our programme, if the observations are continued.

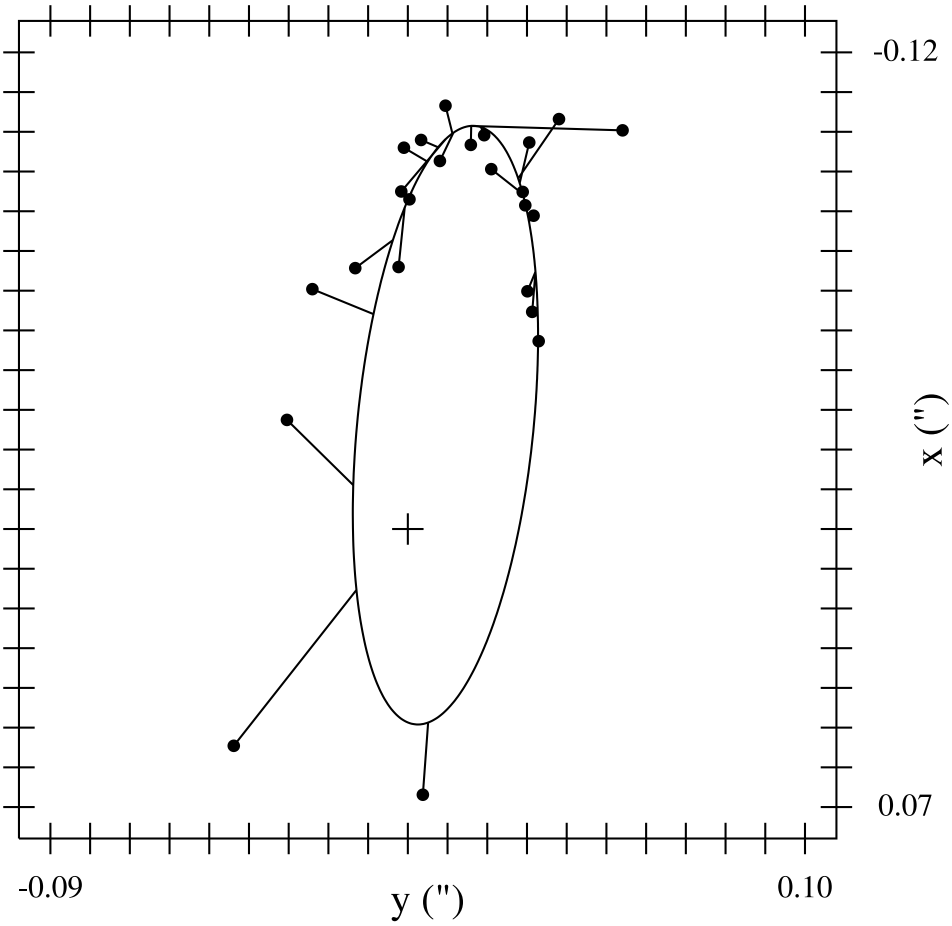

Fig. 5. A preliminary solution of “visual” orbit of HIP 87895, obtained combining the RVs and the apparent positions. It is easy to recognize the three long-base interferometric measurements, since they fit perfectly the orbit.

This programme is supported by the PNPS and by the Action Spécifique Gaia. We are grateful to the staff of the OHP for their kind assistance. Jean-Baptiste Salomon participated to the observations. The SB9 database, `http://sb9.astro.ulb.ac.be/`, (Pourbaix et al. 2004) was used to recover the ancient measurements.

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