SF2A 2017
C. Reylé, P. Di Matteo, F. Herpin, É. Lagadec, A. Lançon, Z. Meliani, F. Royer (eds)

THE PROGRAMME "ACCURATE MASSES FOR SB2 COMPONENTS"*

J.-L. Halbwachs[1], F. Arenou[2], H.M.J. Boffin[3], B. Famaey[1], A. Jorissen[4], F. Kiefer[5], J.-B. Le Bouquin[6], D. Pourbaix[4], P. Guillout[1], R. Ibata[1], Y. Lebreton[7,8], T. Mazeh[9], A. Nebot Gómez-Morán[1] and L. Tal-Or[10]

Abstract. Accurate stellar masses are requested in order to improve our understanding of stellar interiors, but they are still rather rare. Fortunately, the forthcoming Gaia Mission will provide astrometric measurements permitting the derivation of the orbital inclinations of nearby binaries which are also observed as double-lined spectroscopic binaries (SB2s) with ground-based telescopes. A programme of radial velocity (RV) measurements was initiated in 2010 with the Sophie spectrograph of the Haute-Provence observatory in order to derive accurate SB2 orbits for a large set of stars. Therefore, combined SB2+astrometric orbits will be derived thanks to Gaia, and masses with errors around 1 % are expected for both components. The programme includes 70 SB2s, and the accurate SB2 orbits of 24 of them were already derived. In addition, two complementary programmes devoted to southern stars or to late-type dwarf stars were also initiated with the HERMES and the CARMENES spectrographs, respectively. Interferometric measurements were obtained with the VLTI/PIONIER for 7 SB2s, and were taken from other sources for 4 others. Currently, combined "visual binary" (VB) +SB2 solutions were derived for 7 binaries, leading to the masses of the components and to the parallaxes. The parallaxes from the Hipparcos 2 catalogue were corrected for orbital motion and compared to our solution, confirming the high quality of Hipparcos 2.

Keywords: binaries: spectroscopic, binaries: visual, Astrometry

1 Introduction

Mass is the most crucial input in stellar internal structure modelling. It predominantly influences the luminosity of a star at a given stage of its evolution, and also its lifetime. The knowledge of the mass of stars in a non interacting binary system, together with the assumption that the components have same age and initial chemical composition, allows us to determine the age and the initial helium content of the system and therefore to characterise the structure and evolutionary stage of the components. Such modelling provides insights into the physical processes governing the structure of the stars and gives constraints on the free physical parameters of the models, provided the masses are known with high accuracy (Lebreton 2005). Therefore, modelling stars with extremely accurate masses (at the 1 % level), in different ranges of masses, would allow to firmly anchor the models of the more loosely constrained single stars.

* BASED ON OBSERVATIONS PERFORMED AT THE HAUTE-PROVENCE OBSERVATORY

[1] Université de Strasbourg, CNRS, Observatoire astronomique de Strasbourg, UMR 7550, F-67000 Strasbourg, France
[2] GEPI, Observatoire de Paris, PSL Research University, CNRS, Université Paris Diderot, Sorbonne Paris Cité, Place Jules Janssen, F-92195 Meudon, France
[3] ESO, Av. Alonso de Cordova 3107, 19001, Casilla, Santiago 19, Chile
[4] FNRS & Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, boulevard du Triomphe, 1050 Bruxelles, Belgium
[5] Institut d'Astrophysique de Paris, CNRS, UMR 7095, 98bis boulevard Arago, F-75014 Paris
[6] UJF-Grenoble 1/CNRS-INSU, UMR 5274, Institut de Planétologie et d'Astrophysique de Grenoble (IPAG), F-38041 Grenoble, France
[7] LESIA, Observatoire de Paris, PSL Research University, CNRS UMR 8109, Université Pierre et Marie Curie, Université Paris
[8] Institut de Physique de Rennes, Université de Rennes 1, CNRS UMR 6251, F-35042 Rennes, France
[9] School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
[10] Institut für Astrophysik (IAG), Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany

At present, accurate masses are still rare, but the Gaia astrometric satellite could dramatically change this situation. Astrometric orbits will be obtained for several systems which are already known as spectroscopic binaries (SBs). When the radial velocities (RVs) of both components of an SB are measured, i.e. for double-lined SBs (SB2s), the products $\mathcal{M}_1 \sin^3 i$ and $\mathcal{M}_2 \sin^3 i$ may be derived from the orbital elements; therefore, when the inclination i of the orbit will be derived from Gaia observations, so will be the masses of the components, $\mathcal{M}_1$ and $\mathcal{M}_2$. In addition, the semi-major axis of a photocentric orbit is related to the luminosity ratio of the components, allowing to derive the individual magnitudes in the Gaia G band.

For all these reasons, an observational programme was initiated in 2010, using the SOPHIE spectrograph and the 193 cm telescope of the Observatory of Haute-Provence (OHP). This programme is presented in details in Sections 2 and 3. In addition, two complementary RV programmes were initiated on other telescopes, and also an interferometric programme. These related programmes are presented in Sections 4 and 5 hereafter. Thanks to the RVs and to the interferometric measurements, it was possible to derive the masses of the components of a few binaries, as well as the parallax of these systems. The Hipparcos parallaxes were thus verified, as explained in Section 6.

2 The target list

Two lists of targets are used to manage the OHP programme. The principal one, which is called the "main sample" hereafter, was extracted from a selection of about 200 SBs (single-lined or double-lined) fainter than 6th mag and for which the probability to obtain the component masses with an accuracy better than 1 % was estimated to be larger than 20 %, at least if it is possible to derive the RV of the secondary component. Seventy SB2s were eventually retained on the basis of our first observations, including 24 which were previously known as SB1s and for which the secondary component was detected with SOPHIE. The selection process is described in details in Halbwachs et al. (2014). The spectral types of the primary components are between A0 and M2. The majority of stars are on the main sequence, but 6 SB2s have a late-type giant primary component. Rough estimates of the masses of the secondary components may be derived from the spectral types of the primary components and from the mass ratios of the systems. Masses between 0.3 and 2 $\mathcal{M}_\odot$ are then obtained. The "primary spectral type vs secondary mass" diagram of the main sample is shown in Fig. 1.

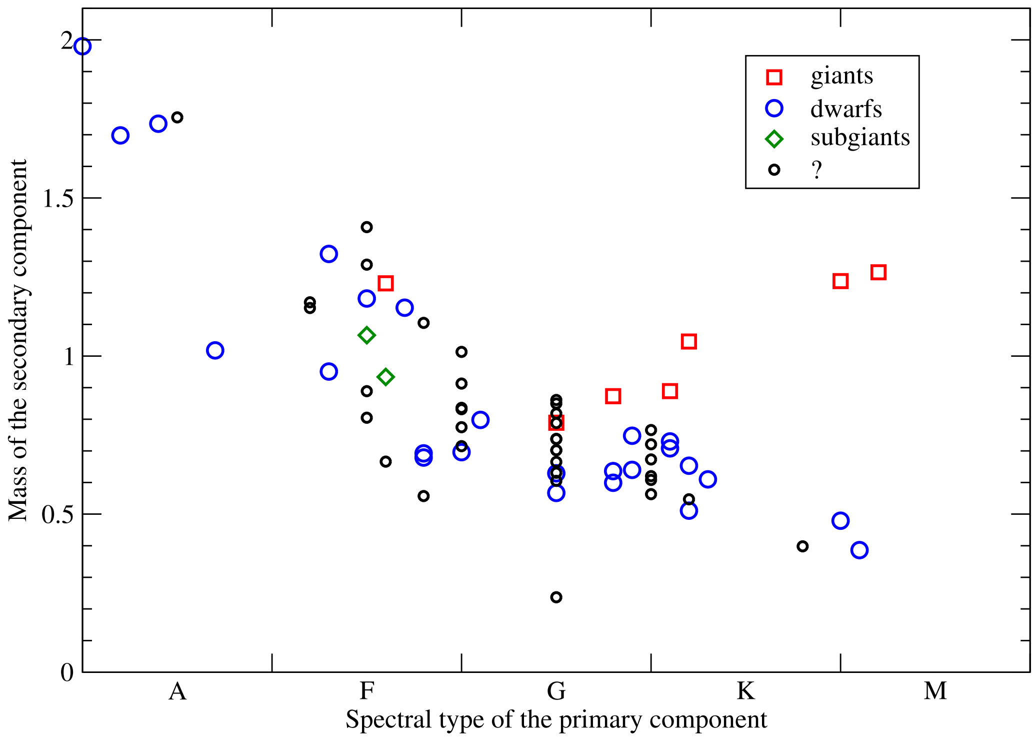

Fig. 1. The "primary spectral type vs secondary mass" diagram of the main sample.

In 2013, it was decided to observe also targets brighter than 6th mag. So bright stars are observed with Gaia, but it is expected that their astrometric measurements will be less accurate than those of the moderately faint stars. Above all, these bright targets were used as backup targets when the weather was too bad to observe the main sample. In practice, it was then possible to perform a few observations with bad weather conditions, but, fortunately, this happened rarely and the SBs of the backup sample received very few observations. In practice, however, the backup sample includes some SB1s (4 so far) for which we were able to detect the secondary spectrum.

3 Present status

In early August 2017, we had collected 1183 spectra, and we had also found 21 additional ones in the SOPHIE archive. The status of the main sample is presented in Fig. 2, which is a "orbit coverage vs number of spectra" diagram. The orbital elements of an SB2 may be reliably derived when the number of RV measurements of each component is larger than 11: this limit makes possible to derive SB1 orbits with at least 5 degrees of freedom, and therefore to estimate the weights of the RVs of each component in the computation of the elements of the SB2 orbit (see Halbwachs et al. 2016). On another side, it is requested that the orbit is covered by the observations, i.e. that the time span ΔT is longer than the period. The area delimited in the upper right corner of Fig. 2 contains the SB2s for which the orbital elements could be derived. Nevertheless, additional observations are still required for some of these stars: the secondary RV is not always measurable, and the RV measurements must also be distributed among all the phases of the orbit.

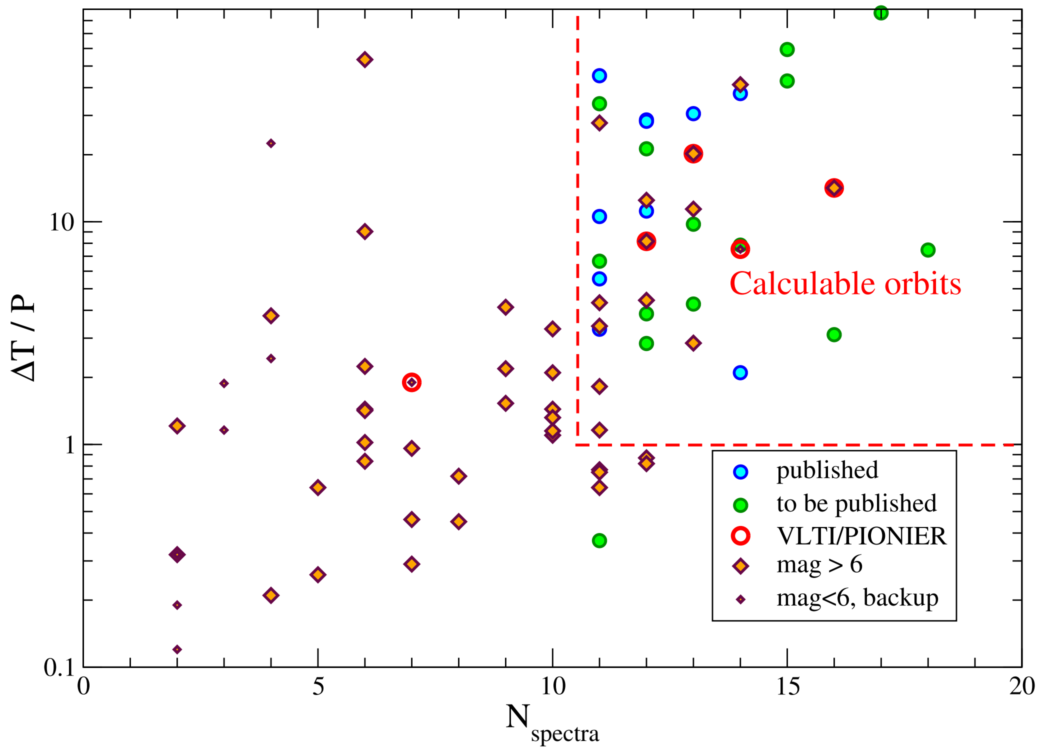

Fig. 2. The "number of spectra vs orbit coverage" diagram of the sample. The orbital elements may be calculated for the stars in the upper right corner, when the RV of the secondary was actually derived at least 11 times, and when the measurements are distributed all over the orbit.

The orbital elements of one SB2 were derived although it was not observed over a complete period: HIP 77122 has an eccentric orbit with a 11-year period, and it was observed near the periastron which is the only part of the orbit where it is possible to derive the RVs of both components. So, we have derived an accurate orbit by fixing the period to a value obtained taking into account old measurements.

The RVs of the binary components are derived twice: a preliminary estimation is computed from the cross-correlation function (CCF) of each spectrum with a template. This CCF is a product of the Sophie reduction pipe-line, and the quality of the RVs thus obtained is quite sufficient to monitor the observations: these RVs may

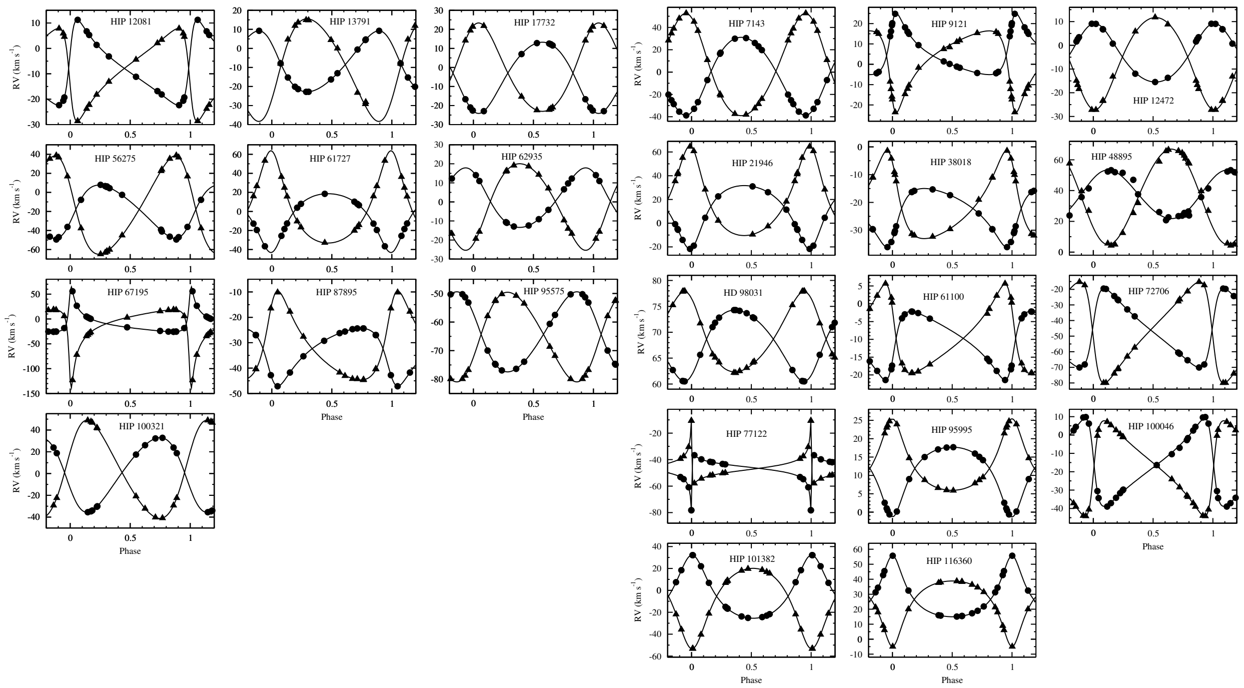

Fig. 3. Left: The 10 spectroscopic orbits derived from the RV measurements obtained with TODCOR in Kiefer et al. (2016). Right: The 14 additional spectroscopic orbits derived from the RV measurements obtained with TODCOR (Kiefer et al. 2017)

be used to improve the orbital elements used to compute ephemerides and to plan observations, and possible outliers may be detected. Nevertheless, the final RVs are derived from a new reduction using the TODCOR algorithm (Zucker & Mazeh 1994; Zucker et al. 2004). They are significantly different from the preliminary values, but more reliable, as shown in Halbwachs et al. (2017). So far, our observations lead to high-quality orbital elements for 24 SB2s: 10 SB2s in Kiefer et al. (2016), and 14 in Kiefer et al. (2017) (Fig. 3). Among the 48 components of these binaries, 32 have minimum masses more accurate than 1 %.

4 Other RV programmes

The OHP programme was complemented with two others, which are based on a similar selection. These programmes are presented hereafter:

1. **The HERMES programme**. Since the latitude of OHP is around +44 deg we had not selected SBs with declination lower than -5 deg. However, the stars with declination between -5 and -30 deg are easily observable from the La Palma Observatory (Canary Islands) with the HERMES spectrograph mounted on the Mercator telescope (Raskin et al. 2011). Fifty-height SB1s and SB2s were selected in a first step, and, after some observations, 7 of them were eventually retained.

2. **The CARMENES programme**. About 150 SB1s were observed with SOPHIE, but the secondary component was detected for only 20 of them. The CARMENES spectrograph mounted on the 3.5m telescope of Calar Alto is much more efficient than SOPHIE to detect late-type secondaries, since it is working in the infrared range. Twenty-three SB1s were selected among the OHP targets because their secondary components were expected to have spectral types at least as late as M. After one year, the secondary component was detected for 9 SBs, and it is even possible to derive an accurate orbit for 2 of them. For the 7 others, the number of RV measurements is too small to improve the orbital elements, but it is possible to derive the mass ratio.

5 SB2 resolved by interferometry

Gaia will provide astrometric orbits, i.e. the motion of the photocentre of each binary around the barycentre, in addition to the single-star parameters, which are the position, the proper motion and the trigonometric parallax. Contrarily to an astrometric orbit, an interferometric orbit is a "visual binary" (VB) orbit, describing the motion of one component (usually, the faintest one) with respect to the brightest one. However, a combined SB2+VB orbit provides most of the elements of an SB2+astrometric orbit: it includes the period and the eccentricity, the masses of the components, the three angles defining the orientation of the orbit, and also the parallax. Therefore, it is highly relevant to collect enough interferometric measurements to derive combined SB2+VB orbits for some stars of our sample. This will make possible a verification of the masses derived for our programme, but also of the parallaxes.

Among the 24 SB2s with improved orbital elements, 4 binaries were resolved by interferometry in the past, and they were sufficiently observed to derive their orbital inclinations. In addition, we obtained interferometric observations with the PIONIER instrument of the ESO Very Large Telescope Interferometer (VLTI) for 7 binaries: 3 SB2s of the OHP main sample, 2 of the OHP backup sample, and 2 of the HERMES program. The apparent relative orbits of 3 of these binaries were derived in Halbwachs et al. (2016). They are presented in Fig. 4 with three others that will be published soon (Boffin et al. 2017).

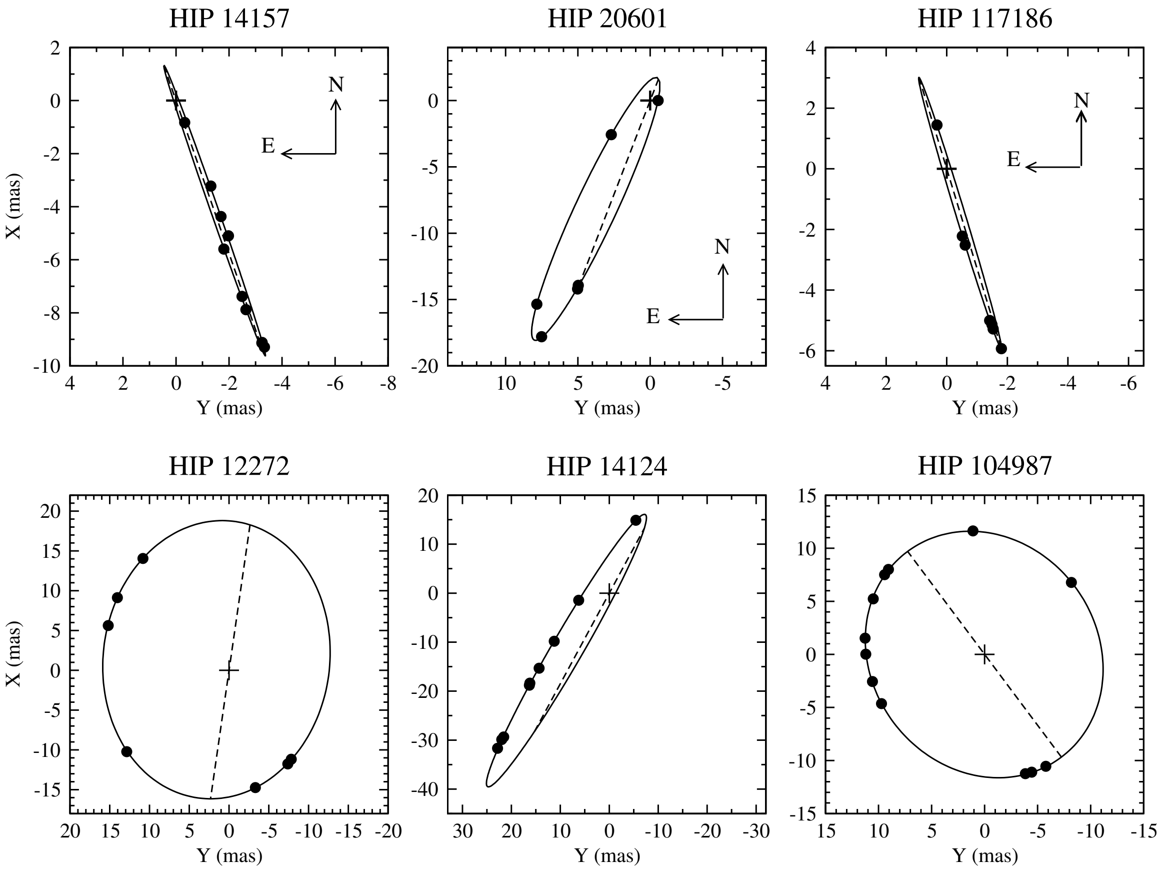

Fig. 4. Up : The 3 first interferometric orbits obtained with PIONIER (Halbwachs et al. 2016). Down : Three other PIONIER orbits (Boffin et al. 2017).

6 Verification of the Hipparcos parallaxes

It is too early to verify the Gaia parallaxes of astrometric binaries, but we can still verify the results of the Hipparcos mission. We consider the Hipparcos 2 reduction (van Leeuwen 2007), but we can't compare directly our parallaxes with those provided in the catalogue: The Hipparcos 2 parallaxes were computed ignoring the orbital motion, and they must be corrected on the basis of a combined SB2+astrometric solution. In practice, the correction is not important for most of the binaries, but it is really significant when the period is close to one year (see *e.g.* Pourbaix & Jorissen 2000)

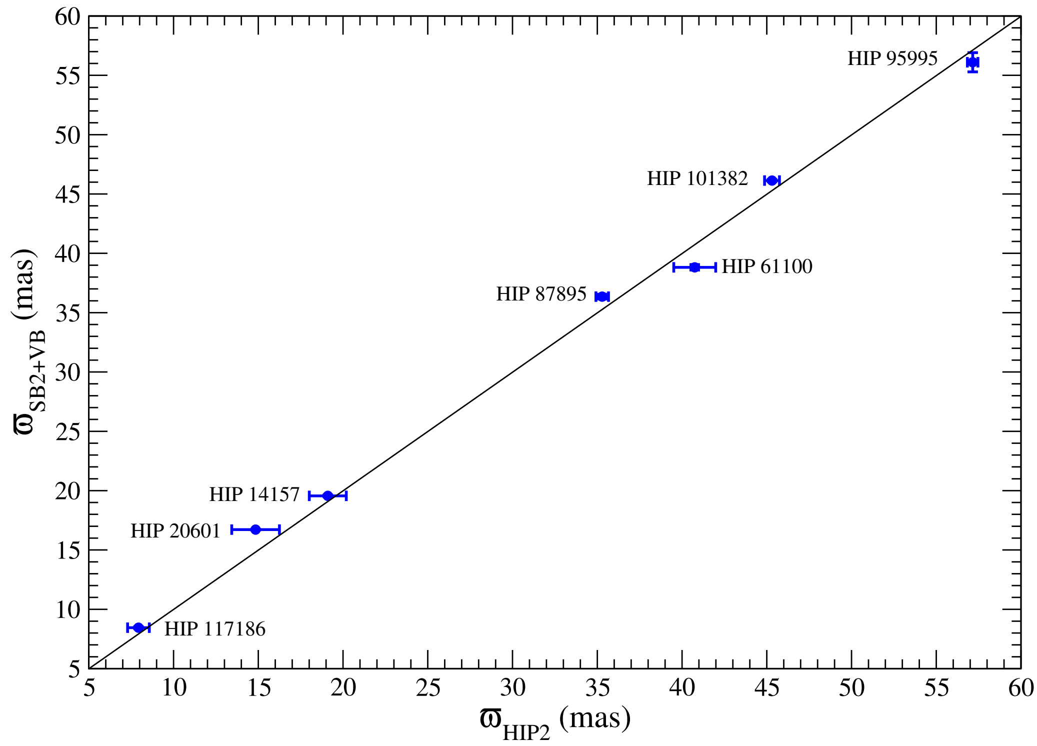

Fig. 5. Comparison of the corrected Hipparcos 2 parallaxes with the SB2+VB solutions.

We consider now the binaries for which we have an SB2+VB orbit based on accurate RV measurements. We count 7 SB2, including 1 from the HERMES programme. Among these binaries, only 3 were observed with PIONIER because the RV observations are still not completed for the binaries observed by Boffin et al. (2017). The interferometric measurements of the 4 other binaries are from other sources.

The SB2+VB parallaxes are compared to the corrected Hipparcos 2 parallaxes in Fig. 5. Since the error bars represent 1 standard deviation, it is obvious that the agreement is rather good. It is also visible that, HIP 95995 excepted, the uncertainties of the SB2+VB parallaxes are much better than that of Hipparcos 2. Therefore, they will be usable for the verification of the Gaia parallaxes, at least for the stars brighter than 6th mag.

7 Conclusions

About 80 double stars are observed through three independent programmes in order to improve their SB2 orbital elements. Thanks to this effort, it will be possible to derive the masses of several double star components with an accuracy better than 1 % when the astrometric transits of the Gaia mission will be delivered. The reliability of these masses will be verified on the basis of about a dozen interferometric binaries. For these stars, the parallax is derived from a VB+SB2 orbit, and we have verified the reliability of the Hipparcos 2 parallaxes. A similar verification will be possible for the parallaxes coming from Gaia, at least for the bright stars.

This project was supported by the french INSU-CNRS "Programme National de Physique Stellaire" and "Action Spécifique *Gaia*". PIONIER is funded by the Université Joseph Fourier (UJF), the Institut de Planétologie et d'Astrophysique de Grenoble (IPAG), and the Agence Nationale pour la Recherche (ANR-06-BLAN-0421, ANR-10-BLAN-0505, ANR-10-LABX56). The integrated optics beam combiner is the result of a collaboration between IPAG and CEA-LETI based on CNES R&T funding. We are grateful to the staff of the Haute–Provence Observatory, and especially to Dr F. Bouchy, Dr H. Le Coroller, Dr M. Véron, and the night assistants, for their kind assistance. We made use of the SIMBAD database, operated at CDS, Strasbourg, France. This research has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant-agreement numbers 291352 (ERC)

References

Boffin, H., Le Bouquin, J.-B., Halbwachs, J.-L., et al. 2017, A&A, (in preparation)

Halbwachs, J.-L., Arenou, F., Pourbaix, D., et al. 2014, MNRAS, 445, 2371

Halbwachs, J.-L., Boffin, H., Le Bouquin, J.-B., et al. 2016, MNRAS, 455, 3303

Halbwachs, J.-L., Kiefer, F., Arenou, F., et al. 2017, in Proceedings SF2A 2017 (this volume), ed. C. Reylé, P. Di Matteo, F. Herpin, E. Lagadec, A. Lançon, & F. Royer, SF2A (arXiv:1710.02301)

Kiefer, F., Halbwachs, J.-L., Arenou, F., et al. 2017, MNRAS, (in preparation)

Kiefer, F., Halbwachs, J.-L., Arenou, F., et al. 2016, MNRAS, 458, 3272

Lebreton, Y. 2005, in The Three-Dimensional Universe with Gaia, ESA SP-576, ed. C. Turon, K. O'Flaherty, & M. Perryman (ESA), 493

Pourbaix, D. & Jorissen, A. 2000, A&AS, 145, 161

Raskin, G., van Winckel, H., Hensberge, H., et al. 2011, A&A, 526, 69

van Leeuwen, F. 2007, A&A, 474, 653

Zucker, S. & Mazeh, T. 1994, ApJ, 420, 806

Zucker, S., Mazeh, T., Santos, N.C., Udry, S., & Mayor, M. 2004, A&A, 426, 695