Abstract. Hipparcos Intermediate Astrometric Data (IAD) have been used to derive astrometric orbital elements for spectroscopic binaries from the newly released Ninth Catalogue of Spectroscopic Binary Orbits (SB9). This endeavour is justified by the fact that (i) the astrometric orbital motion is often difficult to detect without the prior knowledge of the spectroscopic orbital elements, and (ii) such knowledge was not available at the time of the construction of the Hipparcos Catalogue for the spectroscopic binaries which were recently added to the SB9 catalogue.

Among the 1374 binaries from SB9 which have an HIP entry (excluding binaries with visual companions, or DMSA/C in the Double and Multiple Stars Annex), 282 have detectable orbital astrometric motion (at the 5% significance level). Among those, only 70 have astrometric orbital elements that are reliably determined (according to specific statistical tests), and for the first time for 20 systems. This represents a 8.5% increase of the number of astrometric systems with known orbital elements (The Double and Multiple Systems Annex contains 235 of those DMSA/O systems).

The detection of the astrometric orbital motion when the Hipparcos IAD are supplemented by the spectroscopic orbital elements is close to 100% for binaries with only one visible component, provided that the period is in the 50 - 1000 d range and the parallax is > 5 mas. This result is an interesting testbed to guide the choice of algorithms and statistical tests to be used in the search for astrometric binaries during the forthcoming ESA Gaia mission.

Finally, orbital inclinations provided by the present analysis have been used to derive several astrophysical quantities. For instance, 29 among the 70 systems with reliable astrometric orbital elements involve main sequence stars for which the companion mass could be derived. Some interesting conclusions may be drawn from this new set of stellar masses, like the enigmatic nature of the companion to the Hyades F dwarf HIP 20935. This system has a mass ratio of 0.98 but the companion remains elusive.

Key words. Astrometry – Binaries: spectroscopic – Binaries: astrometric – Stars: mass
allowing us to derive at least the companion’s mass (Sect. 6.1). This information will then be combined with the position of the system in the eccentricity – period diagram to diagnose postmass-transfer systems (Sect. 6.2).

Another important motivation of the present paper is to test on the IAD, algorithms designed (i) to detect astrometric binaries and (ii) to determine their orbital parameters in the framework of the future ESA cornerstone mission Gaia. IAD are indeed very similar to what will be available at some stage of the Gaia data reduction process. The fit of an orbital model to the IAD is greatly helped with a partial knowledge of the orbital elements, coming from the spectroscopic orbit (Pourbaix 2004). In the present context, orbital elements like eccentricity $e$, orbital period $P$ and one epoch of periastron passage $T_0$ are provided by the spectroscopic orbits listed in $S_{Bp}$. With Gaia, these elements may come (in the most favourable circumstances) from the spectroscopic orbit derived from the on-board radial-velocity measurements.

2. The Hipparcos data

During 3 years and for about 118 000 stars, the Hipparcos satellite (ESA 1997) measured tens of abscissae per star, i.e., 1-dimensional positions along precessing great circles. Corrections like chromatic effects, satellite attitude, ... were then applied to these abscissae. It was decided that the residuals $(\Delta v)$ of these corrected abscissae (with respect to a 5-parameter single-star astrometric model) would be released together with the Hipparcos Catalogue. They constitute the IAD (van Leeuwen & Evans 1998). In order to make the interpretation of these residuals unambiguous, the released values were all derived with the single-star model, no matter what model was used for that catalogue entry. It is then possible for anybody to fit any model to these IAD to seek further reduction of the residuals.

2.1. The orbital model

The fit of the IAD with an orbital model is achieved through a $\chi^2$ minimization:

$$
\chi^2 = \left( \Delta v - \sum_k \frac{\partial v}{\partial p_k} \Delta p_k - \sum_i \frac{\partial v}{\partial o_i} o_i \right)^t V^{-1} \left( \Delta v - \sum_k \frac{\partial v}{\partial p_k} \Delta p_k - \sum_i \frac{\partial v}{\partial o_i} o_i \right),
$$

where $\Delta p_k$ is the correction applied to the original (astrometric) parameter $p_k$ [where $(p_1, p_2, p_3, p_4, p_5) \equiv (\alpha, \delta, \varpi, \mu_\alpha, \mu_\delta)$], $o_i$ are the orbital parameters and $V$ is the covariance matrix of the data. $\Delta v_j, \partial v_j/\partial p_k$, and $V (j = 1, \ldots, n; k = 1, \ldots, 5)$ and the Main Hipparcos solution are provided, $n$ is the number of IAD available for the considered star [see van Leeuwen & Evans (1998) for details]. Equation (1) thus reduces to

$$
\chi^2 = (\Delta v - \sum_k \frac{\partial v}{\partial p_k} \Delta p_k - y \frac{\partial v}{\partial p_1} - x \frac{\partial v}{\partial p_2})^t V^{-1} (\Delta v - \sum_k \frac{\partial v}{\partial p_k} \Delta p_k - y \frac{\partial v}{\partial p_1} - x \frac{\partial v}{\partial p_2})
$$

where $(x, y)$ is the relative position of the photocenter with respect to the barycenter of the binary system given by

$$
x = AX + FY
$$

$$
y = BX + GY
$$

with

$$
X = \cos E - e
$$

$$
Y = \sqrt{1 - e^2} \cos E.
$$

$A, B, F, G$ are the Thiele-Innes constants (describing the photocenter orbit), $e$ is the eccentricity and $E$ the eccentric anomaly.

2.2. Outliers screening

Even in the original processing, not all the observations were used to derive the astrometric solution. Some of the observations were flagged as outliers and simply ignored if their residuals exceeded three times the nominal (a priori) error for those measurements. These outlying observations are identified by lower case ‘$f$’ or ‘$n$’ flags in the IAD file (instead of upper case ‘$F$’ or ‘$N$’ flags, corresponding to processing by the FAST or NDAC consortium, respectively). Since the model (and therefore the residuals) is going to be revised, so must be the outliers. Because the Thiele-Innes model is a linear one (see Eq. 2), its solution is unique and it may therefore be used to screen out the outliers of the orbital model.

All observations are initially kept. The observation with the largest residual using the orbital model is removed and the model fitted again without it. If the original residual exceeds three times the standard deviation of the new residuals, the observation is definitively discarded (since the number of observations is always less than 300, random fluctuations should yield less than 1 observation with a residual larger than $3\sigma$). The process is then repeated with the new largest residual, and so on. Otherwise, the observation is restored and the whole process is terminated.

A total of 3 486 observations (out of 84 766) are thus removed. 60% of these outliers turn out to come from the NDAC processing even though the two consortia essentially contribute for the same amount of data. The percentage of outliers is ten times larger than in the original Hipparcos processing.

3. The sample

Among the $\sim$118 000 stars in the Hipparcos catalogue, some 179 181 were flagged as double and multiple systems (DMSA) and 235 of them, the so-called DMSA/O, have an orbital solution. Our sample consists of the $S_{Bp}$ entries with a HIP number, excluding DMSA/C entries (i.e., resolved binaries
not suited for IAD processing). The sample contains 1,374 HIP+SB9 entries which cover an extensive period and eccentricity range (see Figs. 1 and 2).

![Fig. 1. Period-eccentricity diagram for the selected SB9 objects with an HIP entry.](image1)

![Fig. 2. Distribution of the orbital periods for the selected SB9 objects with an HIP entry.](image2)

Even though a grade characterizes the quality of the spectroscopic orbits listed in SB9, those grades were not considered a priori in the present processing, which uses the most recent orbit available. The quality of the spectroscopic orbit will be checked at the end of the process, in the discussion of Sect. 4 relative to the detection efficiency of the astrometric wobble.

### 4. Astrometric wobble detection

#### 4.1. Detection assessment

We check whether an orbital motion lies hidden in the IAD using two mathematically equivalent methods of orbit determination, the Thiele-Innes and Campbell approaches. In both cases, the eccentricity, orbital period and the time of passage at periastron are taken from the spectroscopic orbit. For multiple systems, we always use the shortest period. This choice may not necessarily be the best one, but its validity is anyway assessed a posteriori by the periodogram test (see below).

In the Thiele-Innes approach, the remaining four orbital parameters are derived through the Thiele-Innes constants $A, B, F, G$ obtained from the $\chi^2$ minimization of the linear model expressed by Eq. (2). The semi-major axis of the photocentric orbit ($a_0$), the inclination ($i$), the latitude of the ascending node ($\Omega$) and the argument of the periastron ($\omega$) (also known as Campbell’s elements) are then extracted from the Thiele-Innes constants, using standard formulae (Binnendijk 1960). In the Campbell approach, on the other hand, two more parameters, $\omega$ and the semi-amplitude of the primary’s radial-velocity curve $K_1$ are adopted from the spectroscopic orbit. Here, only two parameters of the photocentric orbit ($i$ and $\Omega$) are thus derived from the astrometry. This model is non-linear. The Campbell approach implicitly assumes that there is no light coming from the companion, since the spectroscopic elements constrain $a_1$ according to

$$a_1 \sin i = \omega \frac{K_1 \sqrt{1 - e^2}}{2\pi}.$$  \hfill (3)

The IAD, on the other hand, give access to the photocentric orbit characterized by $a_0$, and we assume that $a_1 = a_0$. If this assumption does not hold, the solutions derived from the Thiele-Innes and Campbell approaches will be inconsistent, and will be rejected a posteriori by the consistency check described in Sect. 5.

We quantify the likelihood that there is an orbital wobble in the data with a F-test evaluating the significance of the decrease of the $\chi^2$ resulting from the addition of four supplementary parameters (the four Thiele-Innes constants) in the orbital model (Pourbaix & Arenou 2001):

$$P_{r2} = P_r(F(4, n-9) > \hat{F}),$$  \hfill (4)

where $\hat{F} = \frac{n - 9 \chi^2_T - \chi^2_S}{\chi^2_S}$ follows a $F$-distribution with $(4, n-9)$ degrees of freedom, $n$ is the number of available IAD for the considered star, $\chi^2_T$ and $\chi^2_S$ are the $\chi^2$ values associated with the orbital and single-star models, respectively. $P_{r2}$ is the probability that the random variable $F(4,n-9)$ exceeds the given value $\hat{F}$, it is thus the first-kind risk associated with the rejection of the null hypothesis ‘there is no orbital wobble present in the data’. The $P_{r2}$ test is a $\chi^2$-ratio test; it is therefore insensitive to scaling errors on the assumed uncertainties.
An alternative – albeit non-equivalent – way to test the presence of an orbital wobble in the data is to test whether the four Thiele-Innes constants are significantly different from 0. The first kind risk associated with the rejection of the null hypothesis ‘the orbital semi-major axis is equal to zero’ may be expressed as

\[ Pr_3 = Pr(\chi^2_{ABFG} < \chi^2_3), \]

where \( \chi^2_{ABFG} = X^tC^{-1}X \), \( X \) is the vector of components \( A, B, F, G \) and \( C \) is its covariance matrix. \( Pr_3 \) is thus the probability that \( \chi^2_3 \), the \( \chi^2 \) random variable with 4 degrees of freedom, exceeds the given value \( \chi^2_{ABFG} \). The \( Pr_3 \) test, being based on the \( \chi^2_{ABFG} \) statistics, is an absolute test, and it is therefore sensitive to possible scaling errors on the assumed uncertainties.

\[ \begin{align*}
F^{2T1} &= \left( \frac{9\nu}{2} \right)^{1/2} \left[ \left( \frac{\chi^2_3}{\nu} \right)^{1/3} + \frac{2}{9\nu - 1} \right], \\
\end{align*} \]

where \( \nu = n - 9 \) is the number of degrees of freedom. If the Thiele-Innes model holds, we expect \( F^{2T1} \) to be approximately normally distributed with zero mean and unity standard deviation.\(^1\) Bad fits correspond to large \( F^2 \) values, abnormally good fits to large negative values. 

Fig. 3 compares \( F^2 \) with \( Pr_3 \) and reveals that the two tests are not simple substitutes of one another: there are systems which fail at the \( Pr_3 \) test but comply with the \( F^2 \) test and conversely. The situation becomes clearer when one realizes that the upper envelope corresponds to the condition \( Pr_3 < 0.05 \), which may be translated into a lower bound on \( \chi^2_{ABFG}/\chi^2_3 \): solutions retained by the \( Pr_2 \) test have large \( \chi^2_{ABFG}/\chi^2_3 \) ratios. There are two ways to fulfill such a condition: If \( \chi^2_T \) is small (i.e., \( F^2 \) is small, or abnormally good fits), then even small \( \chi^2_{ABFG} \) values (i.e., large \( Pr_3 \)) comply with the \( Pr_2 \) test. This explains why the \( Pr_2 \) test does not eliminate systems with large \( Pr_3 \) when their Thiele-Innes fit is abnormally good. Conversely, if \( \chi^2_{ABFG} \) is large (i.e., \( Pr_3 \) is small), then even large \( \chi^2_T \) values (i.e., large \( F^2 \) or bad Thiele-Innes fits) comply with the \( Pr_2 \) test. This explains why at small \( Pr_3 \) values, even bad Thiele-Innes fits (large \( F^2 \) values) are retained. This would typically be the case of a DMSA/X system where the Thiele-Innes model brings a substantial improvement with respect to the single-star model (i.e., \( \chi^2_{ABFG} = \chi^2_S - \chi^2_T \) is large, or \( Pr_3 \) is small), but the overall quality of the Thiele-Innes fit remains poor (large \( F^2 \)).

In the Campbell approach, the situation is somewhat more complicated since the model expressed by Eq. 1 does not depend linearly upon the model parameters \( i \) and \( \Omega \). Therefore, the quantity \( \chi^2_C \) extracted from the minimization of Eq. 1 does not follow a \( \chi^2 \) distribution with \( n - 2 \) degrees of freedom (Lupton 1993). Since the non-linear model may be linearized at the expenses of adding more parameters (e.g., the coefficients of a Fourier or Taylor expansion), \( n - 2 \) overestimates the number of degrees of freedom (Pourbaix 2005). Overestimating the number of degrees of freedom affects all the statistical tests using the \( \chi^2_C \) value. In particular, the first kind risk \( Pr_1 \) extracted from an equation similar to Eq. 1 (substituting \( \chi^2_C \) by \( \chi^2_T \)) is underestimated (Pourbaix 2005). Since this threshold is used to reject solutions which have \( Pr_1 \) larger than the adopted threshold, it may nevertheless be used, keeping in mind that not enough solutions are in fact discarded by the \( Pr_1 \) test. It is very likely, though, that these unacceptable solutions will be screened out by the other tests.

The combination of these four statistical indicators allows us to flag 282 stars as astrometric binaries at the 5% level (i.e.,

\[ F^2 > 2.37 \]

The analysis of the single-star fits for the whole Hipparcos Catalogue reveals that the \( F^2 \) statistics has a mean 0.21 and standard deviation 1.08 (ESA 1997). This indicates that the formal errors have been slightly underestimated. Since the same formal errors are used to compute \( \chi^2_T \), the \( F^2 \) statistics for the Thiele-Innes fits has been assumed to have the same parameters as for the single-star fits. Consequently, the 5% threshold corresponds to \( F^2 = 2.37 \).
Fig. 4. $F_2$ (goodness of fit) versus $P_{r3}$ for systems complying with $P_{r2} < 5\%$. The envelope of these points is well reproduced with the theoretical curve (solid line) assuming $P_{r2} = 5\%$ and 59 observations (which corresponds to the average number of observations for the considered systems). The dashed line corresponds to $P_{r2} = 1\%$.

$P_{r1}, P_{r2}, P_{r3} < 0.05$ and $F_2 < 2.37$ among the 1374 HIP+$S_{B9}$ sample stars defined in Sect. 3.

4.2. Detection rate

The 282 astrometric binary stars passing the four tests described in Sect. 4.1 at the 5\% level are listed in Table 1. Italicized entries correspond to the 122 stars passing the $P_{r1}, P_{r2}$ and $P_{r3}$ tests at the more stringent 0.006\% level and $F_2 < 2.37$. These stars thus represent prime targets for future astrometric observations or, if both components are visible, interferometric observations (see also Table 1A of Taylor et al. 2003), as they are astrometric binaries, but with orbital elements not always reliably determined (see Sect. 5).

We present the detection rate as a function of the parallax $\varpi$ and the orbital period $P$ in Table 2 and Figs. 5 and 6. A striking property of the astrometric-binary detection rate displayed in Fig. 5 is its increase around $P = 50$ d, due to the Hipparcos scanning law which does not favour the detection of shorter-period binaries. Similarly, the detection rate drops markedly for periods larger than 2000 d, corresponding to twice the duration of the Hipparcos mission. Worth noting are therefore the 5 astrometric orbits detected with periods larger than 5000 d: HIP 116727 ($P = 24135$ d), HIP 5336 ($P = 8393$ d), HIP 7719 ($P = 7581$ d), HIP 11380 ($P = 6194$ d) and HIP 33420 ($P = 6007$ d). The reason why the astrometric motion of HIP 116727 could be detected despite such long an orbital period, is that Hipparcos caught it close to periastron ($e = 0.39$), when the orbital motion is the fastest. Table 2 further reveals that the detection rate exhibits little sensitivity to the parallax (provided it is larger than 5 mas; otherwise, the IAD are not precise enough to extract the orbital motion), but rather that it is the orbital period which plays the most significant role. The detection rate in the most favourable cases lies in the range 50 to 80\%. It must be stressed, however, that all the undetected astrometric binaries in those bins are either SB2 systems, systems with a composite spectrum or with a spectroscopic orbit of poor quality (the SB2 and composite-spectrum systems have components of similar brightness, so that in most cases, the photocenter of the system does not differ much from its barycenter, making the orbital motion difficult to detect; see Eq. 8 below). If we remove these entries from the sample, the detection rate is close to 100\%. The orbital parameters of the detected binaries are further analyzed in Sect. 5. Such an analysis is made necessary when one realizes that the orbital inclinations derived by the Thiele-Innes and Campbell approaches do not always yield consistent values (Fig. 7), contrary to expectations. Sect. 5 therefore presents further criteria used to evaluate the reliability of the derived astrometric orbital elements (and, in particular, the consistency between the two sets of orbital parameters, Thiele-Innes versus Campbell).

Fig. 5. Percentage of astrometric binaries detected among $S_{B9}$ stars as a function of orbital period. The error bars give the binomial error on each bin.

4.3. The DMSA/O entries

Among the 1374 binaries from $S_{B9}$, 122 are flagged as DMSA/O in the Hipparcos catalogue. We detect 89 of these (or 75\%) (irrespective of $\varpi$). The detection rate climbs to 81.7\% (85/104) for orbital periods longer than 100 d. It is worth exam-
Table 1. The 282 stars flagged as astrometric binaries ($P_{r1}, P_{r2}, P_{r3} < 0.05$ and $F_{2\text{III}} < 2.37$; see text). Italicized entries identify the 122 stars passing the $P_{r1}, P_{r2}$ and $P_{r3}$ tests at the more stringent 0.006% level, and $F_{2\text{III}} < 2.37$.

| HIP | HIP | HIP | HIP | HIP | HIP | HIP | HIP | HIP | HIP |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 443 | 7564 | 13055 | 22961 | 31681 | 43436 | 52419 | 60292 | 73440 | 81170 |
| 677 | 7719 | 14273 | 23402 | 32713 | 43413 | 52444 | 60998 | 74087 | 82706 |
| 1349 | 8645 | 15394 | 23453 | 32761 | 43357 | 52650 | 61724 | 75379 | 82860 |
| 1955 | 8903 | 15900 | 23743 | 32768 | 43903 | 52958 | 62437 | 75695 | 83575 |
| 2081 | 8922 | 16369 | 23922 | 33420 | 44124 | 53238 | 62915 | 75718 | 83947 |
| 2865 | 9110 | 17136 | 23983 | 34164 | 44455 | 53240 | 63406 | 76267 | 84677 |
| 3300 | 9121 | 17296 | 24419 | 34608 | 44946 | 53425 | 63592 | 76574 | 84886 |
| 3362 | 10340 | 17440 | 24984 | 35412 | 45075 | 53763 | 64422 | 76600 | 84949 |
| 3504 | 10514 | 17683 | 25048 | 36042 | 45333 | 54632 | 66422 | 76634 | 85985 |
| 3572 | 10644 | 17932 | 25776 | 36377 | 46005 | 55016 | 66522 | 77634 | 85985 |
| 3951 | 10723 | 18782 | 26001 | 36429 | 46613 | 55022 | 67195 | 77678 | 86400 |
| 4166 | 11231 | 19248 | 26291 | 37908 | 46893 | 56731 | 67234 | 77801 | 86722 |
| 4252 | 11349 | 20070 | 27246 | 38414 | 47205 | 57791 | 67480 | 78689 | 87895 |
| 4584 | 11380 | 20087 | 28537 | 39341 | 47461 | 58590 | 67927 | 79101 | 88788 |
| 4754 | 11465 | 20284 | 29276 | 39424 | 49561 | 59148 | 68072 | 79195 | 88946 |
| 4843 | 11843 | 20482 | 29740 | 39893 | 49841 | 59495 | 68682 | 79358 | 89773 |
| 5336 | 11923 | 20935 | 29982 | 40240 | 50005 | 59468 | 69112 | 80042 | 89008 |
| 5881 | 12062 | 21123 | 30277 | 40326 | 50801 | 59551 | 69879 | 80166 | 89937 |
| 6867 | 12472 | 21433 | 30338 | 41784 | 50966 | 59609 | 70293 | 80816 | 90659 |
| 7078 | 12709 | 21673 | 30501 | 42327 | 51157 | 59856 | 72848 | 80968 | 91751 |
| 7145 | 12716 | 21727 | 31205 | 42542 | 52085 | 60061 | 72939 | 80816 | 91751 |
| 7487 | 12719 | 22407 | 31646 | 42673 | 52271 | 60129 | 73199 | 81023 | 91751 |

Table 2. Detection rate (expressed in %) as a function of orbital period and parallax. The percentage is given along with its binomial error; the total number of stars in the bin is listed between parentheses. For $\varpi > 5$ mas and $100 \leq P(d) \leq 3000$, the detection rate comes close to 100% when removing SB2 systems, systems with composite spectra or with a poor-quality spectroscopic orbit.

| Parallax (mas) | 0–100 | 100–2000 | 2000–3000 | 3000–5000 | any $P$ |
|---------------|-------|-----------|-----------|-----------|--------|
| over 15       | 16±3 (177) | 69±5 (81) | 58±14 (12) | 9±12 (12) | 35±3 (292) |
| 10–15         | 7±2 (106) | 69±7 (42) | 80±18 (5)  | 18±19 (5)  | 26±3 (162) |
| 5–10          | 8±2 (232) | 51±6 (74) | 65±12 (17) | 18±14 (5)  | 21±2 (336) |
| 0–5           | 7±1 (351) | 24±3 (170) | 4±4 (25)   | 5±5 (21)   | 12±1 (584) |
| any $\varpi$  | 9±1 (866) | 45±3 (367) | 39±6 (59)  | 28±7 (43)  | 21±1 (1374) |

- the star is in fact SB2 and possesses an astrometric orbit obtained from ground-based interferometric or speckle observations; for those cases, the DMSA/O solution only provides $e_{o}$, with all other parameters taken from the ground-based astrometric solution (HIP 2912, HIP 10064, HIP 13531, HIP 14328, HIP 14576, HIP 24608, HIP 28360, HIP 55266, HIP 57565, HIP 96683, HIP 105431);
- as indicated in a DMSA/O note, the orbital solution is in fact of poor quality ("Spectroscopic orbit unreliable. Probably single" sic), and does not comply with our more stringent tests (HIP 10366, HIP 24727, HIP 26563, HIP 35550, HIP 45527);
- more orbital elements have been imposed than done here (e.g., the inclination, from the eclipsing nature of the star: HIP 100345; also HIP 23414 ≡ $\epsilon$ Aur);
- the period provided by the DMSA/O solution is totally different from the one listed in $S_{20}$ (HIP 8882, HIP 17847, HIP 63613, HIP 82020, HIP 91009 = BY Dra), sometimes because the system is a triple one (HIP 85333, HIP 100345);
- the solution has been marginally rejected by our tests, i.e., $P_{r1}, P_{r2}$ or $P_{r3}$ are only slightly larger than 5% (HIP 5778, HIP 32578, HIP 68756) or $F_{2}$ is slightly larger than 2.37 (HIP 8833, HIP 59750), or similarly, the DMSA/O solution is of too low a quality to comply with the tests devised in the present paper (HIP 10324, HIP 12623, HIP 21273).

HIP 85749 is the only DMSA/O solution not belonging to any of the above categories. HIP 85749 has not been flagged.
as an astrometric binary by our reprocessing, because $P_{r1} = 0.26$, although $P_{r2}$, $P_{r3}$ and $F2$ do qualify the star as an astrometric binary.

5. Orbit assessment

The upper panel of Fig. 7 reveals that, even though orbital solutions pass the $P_{r1}$, $P_{r2}$ and $P_{r3}$ tests, meaning that an astrometric orbital motion has been detected, these solutions do not necessarily yield Thiele-Innes and Campbell orbital elements that are consistent with each other. The inverse-S shape observed in Fig. 7 results from the following properties: (i) in the absence of an orbital signal in the IAD and when the spectroscopic radial-velocity semi-amplitude $K_1$ is small, the Campbell solution tends to $i_{CI} \sim 0^\circ$ or $180^\circ$, while the Thiele-Innes solution tends to $i_{TI} \sim 90^\circ$ [Pourbaix 2004]; (ii) the physical solutions fall on the diagonal, although this diagonal is polluted with unphysical solutions having $i_{TI} \sim 90^\circ$. The lower panel of Fig. 7 displays the 122 stars complying with the $P_{r1}$, $P_{r2}$ and $P_{r3}$ tests at the 0.006% level. It clearly shows that the consistency between the Thiele-Innes and Campbell solutions may be improved considerably by decreasing the probability threshold to 0.006%.

To remove the remaining inconsistent solutions, it is necessary to assess the reliability of the derived orbital elements. This may be done in at least two ways:

- The consistency between the Thiele-Innes and Campbell elements could be checked directly by computing error ellipsoids around the two sets of orbital elements and estimating whether or not they intersect. This method has not been applied here, because it is very time-consuming.
- Empirical tests have been devised which check that (i) the astrometric orbital signal has the same period as the adopted spectroscopic period; (ii) the astrometric orbital elements should not be too much correlated with each other. This test was already used by Pourbaix & Boffin [2003] in a similar context.

The empirical approach has been preferred here, with the two tests involved now described in turn.

First, the consistency between the astrometric period and the adopted spectroscopic period is checked through a periodogram-like test. For 600 periods uniformly distributed in log $P$ between 0.1 and 1200 d, the best 9-parameter (Thiele-Innes) fit is computed (the eccentricity and periastron time are kept unchanged). The resulting $\chi^2$ is plotted against the period, thus generating a Scargle-like periodogram [Scargle 1982]. Its standard deviation $\sigma$ is computed. An orbital motion with the expected (spectroscopic) period is then supposed to be present in the IAD if the $\chi^2$ at that period is smaller than the periodogram mean value by more than $\xi\sigma$, with $\xi$ chosen of the order of 3.

Second, the correlation existing between the Thiele-Innes orbital elements may be estimated through the efficiency parameter $\epsilon$ [Eichhorn 1989], expressed by

$$\epsilon = \sqrt{\frac{\sum_{k=1}^{p} \lambda_k}{\sum_{k=1}^{p} V_{kk}}}$$

where $\lambda_k$ and $V_{kk}$ are respectively the eigenvalues and the diagonal terms of the covariance matrix $V$ and $p$ denotes the number of parameters in the model. For an orbital solution to be reliable, its covariance matrix should be dominated by the diagonal terms, and the efficiency $\epsilon$ should then be close to 1 [Eichhorn 1989].

The 70 orbital solutions retained when adopting $\xi = 3$ and $\epsilon > 0.4$ are listed in Table 4. 20 of them being new orbital solutions not already listed in the DMSA/O annex. Fig. 8 presents the distribution of their orbital periods. In Fig. 9 comparing the inclinations derived from the Thiele-Innes and Campbell solutions, the retained orbits now fall close to the diagonal, as expected.

Neither the parallax nor the proper motions differ significantly from the Hipparcos value for the stars of Table 4. They have therefore not been listed.

To increase the science content of this paper, Table 5 lists the astrometric orbital elements for a second category of sys-

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Fig. 6. Left panel: Period-parallax diagram for the selected $S_H$ objects with an HIP entry. Middle panel: Period-parallax diagram for non-detected objects. Right panel: Stars flagged as astrometric binaries by the $P_{r1}$, $P_{r2}$ and $P_{r3}$ tests at the 5% level and with $F2_{TI} < 2.37$. 
Table 3. The 70 orbital solutions (Campbell solutions) passing all consistency tests. The column labelled ‘Ref.’ provides the reference for the spectroscopic orbit used. In the case where a system is listed in the DMSA/O annex, the column labelled ‘DMSA’ compares the orbital semi-major axes and the inclinations from the DMSA/O annex and from this work.

| HIP   | \(a_0\) (mas) | \(e\)   | \(i\) (°) | \(\omega_1\) (°) | \(\Omega\) (°) | \(T_0\) (JD - 2400000) | \(P\) (d) | DMSA \((a/a_{\text{hip}}; i/i_{\text{hip}})\) | Ref.                  |
|-------|---------------|---------|----------|-----------------|-------------|-------------------------|---------|---------------------------------|---------------------|
| 677   | 7.26±0.38     | 0.53    | 102.7±9.7| 77.5            | 103.4±5.8   | 47374.6                 | 96.7    | O(1.12;0.97)                    | Pourbaix (2000)     |
| 1349  | 20.98±0.56    | 0.57    | 74.7±2.1 | 4.7             | 352.3±3.3   | 34233.3                 | 411.4   | O(1.05;0.93)                    | Bopp et al. (1970)  |
| 1955  | 4.68±0.25     | 0.33    | 108.0±7.5| 18.7            | 299.0±8.3   | 35627.6                 | 115.3   | 5                               | Barker et al. (1967) |
| 3504  | 7.4±1.1       | 0.11    | 107.2±4.3| 79.0            | 274.5±4.7   | 41665.0                 | 1033.0  | O(1.04;1.06)                    | Ait & Levy (1978)   |
| 6867  | 5.57±0.46     | 0.00    | 46.3±4.0 | 0.0             | 340.2±5.2   | 19544.9                 | 193.8   | O(1.13;0.92)                    | Luvin (1936)        |
| 7078  | 7.95±0.15     | 0.31    | 85.6±4.7 | 188.2           | 160.5±3.7   | 29000.4                 | 134.1   | O(1.28;0.97)                    | Wrieth & Pugh (1954)|
| 8068  | 2.71±0.28     | 0.31    | 70.8±4.7 | 188.2           | 160.5±3.7   | 29000.4                 | 134.1   | O(1.28;0.97)                    | Wrieth & Pugh (1954)|
| 80816 | 11.37±0.51    | 0.55    | 53.8±2.3 | 24.6            | 341.9±3.8   | 15500.4                 | 410.6   | O(1.03;1.16)                    | Plummer (1930)      |

**Note:** All values are given with their respective uncertainties.
Table 3. Continued.

| HIP     | \(a_0\) (mas) | \(e\) | \(i\) (°) | \(\omega_1\) (°) | \(\Omega\) (°) | \(T_0\) (JD - 2400000) | \(P\) (d) | DMSA Ref. | Ref. |
|---------|----------------|-------|-----------|-----------------|-------------|------------------------|-------|-----------|------|
| 82860   | 6.58 ± 0.32    | 0.21  | 56.1 ± 4.0 | 339.0          | 228.7 ± 4.5 | 39983.6                | 52.1  | O(0.98;0.90) | Abt & Levy (1976) |
| 83575   | 9.11 ± 0.58    | 0.22  | 61.2 ± 3.5 | 348.0          | 19.5 ± 4.3   | 46806.0                | 790.6 | O(1.04;1.03) | Griffin (1991)    |
| 86400   | 12.71 ± 0.78   | 0.23  | 18.4 ± 1.1 | 140.5          | 274.2 ± 2.7  | 47724.9                | 83.7  | O(0.92;0.41) | Tokovinin (1991)  |
| 87895   | 29.81 ± 0.62   | 0.41  | 72.7 ± 1.2 | 134.8          | 177.4 ± 1.0  | 47714.6                | 881.8 | O(1.09;1.07) | Pourbaix (2000)   |
| 88788   | 10.09 ± 1.04   | 0.378 | 153.9 ± 2.3 | 137.0          | 341.4 ± 5.8  | 46139.0                | 2017.0| Griffin (1992) |                  |
| 89937   | 50.30 ± 0.23   | 0.41  | 80.08 ± 0.70 | 119.9         | 232.42 ± 0.83 | 46005.6                | 280.5 | O(1.25;1.07) | Pourbaix (2000)   |
| 90659   | 9.1 ± 1.1      | 0.50  | 142.1 ± 3.0 | 56.0           | 353.1 ± 6.0  | 42925.5                | 1284.0| O(0.97;1.01) | Griffin (1980)    |
| 91751   | 6.41 ± 0.53    | 0.21  | 59.5 ± 4.9  | 78.0           | 295.8 ± 7.0  | 42928.5                | 485.3 | O(1.05;1.05) | Griffin (1982b)   |
| 92512   | 3.16 ± 0.25    | 0.11  | 106.1 ± 11  | 274.3          | 0 ± 37       | 19258.2                | 138.4 | O(1.02;1.09) | Young (1920)      |
| 93244   | 12.80 ± 0.44   | 0.27  | 87.5 ± 6.6  | 82.0           | 58.7 ± 3.9   | 41718.5                | 1270.6| O(0.94;1.00) | Griffin (1982b)   |
| 95028   | 3.0 ± 0.7      | 0.37  | 19.4 ± 4    | 161.0          | 242.9 ± 10.0 | 43811.9                | 208.8 | Griffin (1982b)|                  |
| 95066   | 9.15 ± 0.54    | 0.83  | 75.2 ± 8.6  | 152.7          | 129.7 ± 6.7  | 33420.2                | 266.5 | O(1.18;1.05) | Franklin (1952)   |
| 95575   | 8.14 ± 0.25    | 0.15  | 98.2 ± 7.8  | 63.3           | 208.1 ± 5.7  | 47746.4                | 166.4 | X              | Tokovinin (1991)  |
| 99848   | 5.5 ± 1.2      | 0.30  | 65.5 ± 8.3  | 218.2          | 0 ± 227      | 33141.8                | 1147.8| O(1.04;1.02) | Wright (1970)     |
| 99965   | 14.06 ± 0.39   | 0.08  | 92.2 ± 3.6  | 243.0          | 303.9 ± 4.5  | 50218.0                | 418.8 | O(0.87;0.94) | Griffin (2002a)   |
| 100437  | 5.35 ± 0.57    | 0.76  | 54.2 ± 6.4  | 108.1          | 249.7 ± 8.2  | 49281.0                | 1124.1| Griffin & Fitter (2000)| |
| 101093  | 19.79 ± 0.05   | 0.03  | 104.0 ± 1.6 | 83.7           | 95.4 ± 1.7   | 16214.5                | 840.6 | O(1.39;1.01) | Abt (1961)        |
| 101847  | 3.82 ± 0.81    | 0.0   | 147.7 ± 5.9 | 0.0            | 314.0 ± 1.3  | 23358.8                | 205.2 | 5              | Lucy & Sweeney (1971)|
| 103519  | 7.48 ± 0.64    | 0.44  | 32.4 ± 2.4  | 148.1          | 306.2 ± 4.0  | 39186.1                | 635.1 | O(1.02;0.94) | Radford & Griffin (1975)|
| 105969  | 10.65 ± 0.75   | 0.13  | 157.0 ± 1.3 | 192.0          | 236.6 ± 3.9  | 47479.0                | 878.0 | X              | McClure (1997)    |
| 109176  | 4.07 ± 0.27    | 0.00  | 80.13 ± 0   | 0.0            | 188.11       | 45320.0                | 10.2  | 5              | Fekel & Tomkin (1983)|
| 111170  | 26.67 ± 0.73   | 0.38  | 63.4 ± 1.7  | 171.6          | 82.0 ± 1.9   | 43995.0                | 630.1 | O(1.14;1.07) | Pourbaix (2000)   |
| 112158  | 15.62 ± 0.85   | 0.38  | 72.7 ± 1.9  | 5.6            | 208.6 ± 2.3  | 15288.7                | 818.0 | O(1.15;1.03) | Crawford (1901)   |
| 113718  | 12.16 ± 0.93   | 0.54  | 24.3 ± 1.8  | 247.7          | 328.6 ± 5.6  | 48280.0                | 468.1 | O(1.10;0.41) | Latham et al. (2002)|
| 114421  | 7.82 ± 0.47    | 0.66  | 114.3 ± 5.2 | 240.8          | 120.8 ± 7.2  | 16115.6                | 409.6 | O(1.26;0.93) | Spencer Jones (1928b)|

The orbits derived in the present analysis and the DMSA/O ones generally agree well. For HIP 677 (= \(a0\) And), a visual and SB2 system, there are astrometric orbits based on ground-based interferometric measurements already available (Pan et al. 1992; Pourbaix 2000). The inclination of \(103^\circ \pm 10^\circ\) found here is consistent with the value \(105.7^\circ \pm 0.2^\circ\) obtained by Pan et al. (1992). The only new constraint of interest provided by the IAD-derived photocentric orbit lies in a consistency check between that photocentric semi-major axis \(a_0 = 7.3 \pm 0.4\) mas (Table 3) and the relative semi-major axis \(a = 24.1 \pm 0.1\) mas (Pan et al. 1992; Pourbaix 2000), with the following relation to be satisfied (Binnendijk 1960):

\[
a_0 = a(\kappa - \beta),
\]
correspond to the astrometric motion, or that the IAD do not constrain its period well enough.

6. Some astrophysical implications

6.1. Masses

Masses of the components of spectroscopic binaries with one visible spectrum (SB1) are encapsulated in the mass function

\[ f(M_1, M_2) = \frac{M_1^3 \sin^3 i}{(M_1 + M_2)^2} \equiv \frac{Q \sin^3 i}{P^2} \]  

(9)

where \( M_1 \) and \( M_2 \) are the masses of the primary and secondary components, respectively. The knowledge of the inclination as given in Table 4 gives directly access to the generalized mass ratio \( Q \) listed in Table 6. To go one step further and have access to the masses themselves, supplementary information must be injected in the process. For main-sequence stars, this may come from the mass – luminosity relationship. The mass of the main-sequence primary component is estimated directly from its Hipparcos \( V \) magnitude using Table 15.7 of Cox (2000), and then into masses using Table 19.18 of Cox (2000). The corresponding masses are listed in Table 4. The major uncertainty on \( M_2 \) comes from the uncertainty on \( M_1 \) rather than from \( i \). To fix the ideas, an uncertainty of 0.1 mag on \( B - V \) translates into an uncertainty of 0.2 (or 0.1, 0.05) \( M_\odot \) on \( M_1 \), and of 0.045 (0.032, 0.027) \( M_\odot \) on \( M_2 \) for \( 0 \leq M_V < 4 \) (or \( 4 \leq M_V < 6 \), \( 6 \leq M_V \), respectively). The position of stars from Table 4 on the main sequence has been checked from the Hertzsprung-
Fig. 7. Comparison of the orbital inclinations derived by the Thiele-Innes and Campbell approaches. The 282 stars displayed in the upper panel all comply with the 4 criteria for astrometric wobble detection (namely $P_{r_1}$, $P_{r_2}$ and $P_{r_3} < 0.05$ and $F_2[1] < 2.37$; see text), but their astrometric orbital elements are not always reliably determined as not all points fall along the diagonal. The lower panel displays the 122 stars complying with the $P_{r_1}$, $P_{r_2}$ and $P_{r_3}$ tests at the 0.006% level.

Russell diagram drawn from the Hipparcos data. In particular, it has been checked that the $B - V$ color is not the composite of the two components (in which case, the above procedure to derive $M_1$ may not be applied). Only HIP 47461 (= HD 83270) belongs to that category (as confirmed by Ginestet et al. [1991]), so that neither masses are given in Table 6.

Individual systems of interest are discussed in Sect. 6.1.1.

The distributions of $M_1$, $M_2$ and $q = M_2/M_1$ for the 29 systems with main sequence primaries are displayed in Fig. [11]. The $q$ distribution appears to be strongly peaked around $q = 0.6$, but this feature very likely results from the combination of two opposite selection biases. Our sample is biased against systems with $q \sim 1$ (since these systems would gener-

Table 5. The 39 systems with a DMSA/O entry which do not fulfill the 2 tests assessing the reliability of the astrometric orbital elements, namely $\xi < 3$ and $\epsilon > 0.4$ and the probability tests at the 0.006% level (see text). Columns with ‘n’ correspond to failed tests.

| HIP  | $\xi$ | $\epsilon$ | $P_{r}$ | Rem. |
|------|-------|-------------|---------|------|
| 443  | y     | y           | y       | n    |
| 5336 | y     | n           | y       | y    |
| 10644| y     | y           | n       | y    |
| 10723| n     | y           | y       | y    |
| 12709| y     | n           | y       | y    |
| 12719| n     | y           | y       | y    |
| 16369| n     | y           | y       | n    |
| 17296| n     | y           | y       | n    |
| 17440| y     | n           | y       | y    |
| 17932| y     | y           | n       | n    |
| 20070| n     | y           | y       | y    |
| 20807| n     | n           | y       | y    |

DMSA/O solution provides only $a_0$

| HIP  | $\xi$ | $\epsilon$ | $P_{r}$ | Rem. |
|------|-------|-------------|---------|------|
| 20482| n     | y           | y       | y    |
| 21123| n     | n           | y       | n    |
| 23453| n     | y           | y       | y    |
| 23922| n     | n           | y       | y    |

DMSA/O solution from scratch providing a period different from the $S_{SB}$ one

| HIP  | $\xi$ | $\epsilon$ | $P_{r}$ | Rem. |
|------|-------|-------------|---------|------|
| 29982| n     | n           | y       | y    |
| 30501| n     | y           | n       | y    |
| 31205| n     | y           | y       | n    |
| 32761| y     | n           | y       | n    |
| 49841| y     | n           | y       | y    |
| 52419| n     | y           | y       | y    |

DMSA/O solution from scratch providing a period different from the $S_{SB}$ one

| HIP  | $\xi$ | $\epsilon$ | $P_{r}$ | Rem. |
|------|-------|-------------|---------|------|
| 56731| y     | n           | y       | y    |
| 58590| n     | y           | n       | y    |
| 59459| n     | y           | n       | y    |
| 59856| n     | n           | n       | n    |
| 68682| y     | n           | y       | y    |
| 75669| y     | n           | y       | y    |
| 76267| n     | y           | n       | y    |
| 80166| n     | y           | n       | y    |
| 81023| n     | y           | y       | y    |
| 89808| n     | y           | y       | y    |
| 92175| n     | y           | n       | y    |
| 92818| y     | n           | y       | y    |
| 99675| y     | n           | y       | y    |
| 109554| n    | n          | n       | n    |
| 110130| y   | y          | n       | y    |
| 113860| y  | y          | y       | y    |

DMSA/O solution from scratch providing a period different from the $S_{SB}$ one

| HIP  | $\xi$ | $\epsilon$ | $P_{r}$ | Rem. |
|------|-------|-------------|---------|------|
| 99675| y     | n           | y       | y    |
| 109554| n    | n          | n       | n    |
| 110130| y   | y          | n       | y    |
| 113860| y  | y          | y       | y    |
Fig. 8. Distribution of the orbital periods for the 70 solutions retained.

Fig. 9. Comparison of the inclinations derived from the Thiele-Innes constants and from the Campbell elements for the 70 systems retained. Compare with Fig. 7.

Fig. 10. Comparison of the inclinations derived from the Thiele-Innes constants and from the Campbell elements for the 1304 systems not retained. The 39 rejected systems with a solution in the DMSA/O annex (Table 5) are represented by a filled square.

Although one would be tempted to attribute the $M_2 = 0.6 \, M_\odot$ peak to a population of white dwarf (WD) companions, it is more likely to result from the two selection biases described above.

In the absence of a mass – luminosity relationship for giants, the mass of the companion cannot be derived reliably.

6.1.1. Masses for some specific systems

**HIP 677 = α And**

As already discussed in Sect. 5, HIP 677 is known to be a SB2 and visual binary [Ryabchikova et al. 1999; Pourbaix 2000]. Masses are thus already available in the literature, namely $M_1 = 3.6 \pm 0.2 \, M_\odot$, $M_2 = 1.78 \pm 0.08 \, M_\odot$ [Ryabchikova et al. 1999] or $M_1 = 3.85 \pm 0.22 \, M_\odot$, $M_2 = 1.63 \pm 0.074 \, M_\odot$ [Pourbaix 2000].

**HIP 20935 = HD 28394**

This F7V star is a member of the Hyades cluster. It has a mass ratio $q = M_2/M_1$ of 0.98. However, it falls exactly along the main sequence as defined by the other stars of our sample. There is thus no indication that this star has composite colors, as it should if the companion is a main sequence F star as well. A white dwarf (WD) companion of mass 1.1 $M_\odot$ is not without problems either. Böhm-Vitense (1995) has searched the IUE International Ultraviolet Explorer archives for spectra of F stars from the Hyades, in order to look for possible WD companions. No excess UV flux is present at 142.5 nm for HIP 20935, which implies that the WD must be cooler than
Fig. 11. Upper panel: Distribution of the mass ratio \( M_2/M_1 \) for systems from Table 3 with a main-sequence primary star. Lower panel: Distributions of \( M_1 \) (dashed line) and \( M_2 \) (solid line).

about 10000 K. For a 1.1 M\(_{\odot}\) WD, this implies a cooling time of more than 1 Gyr (Chabrier et al. 2000), incompatible with the Hyades age of 800 \( 10^6 \) y. The remaining possibility is that the companion is itself a binary with two low-luminosity red dwarfs.

**HIP 105969 = HD 204613**

This star is known as a subgiant CH star (Luck & Bond 1982) and the system should therefore host a WD companion (McClure 1997). Interestingly enough, the mass inferred for this WD companion is 0.49 M\(_{\odot}\), just large enough for a 2 M\(_{\odot}\) AGB progenitor to have gone through the thermally-pulsing asymptotic granule branch phase (see Fig. 3.10 in Groenewegen 2003) to synthesize heavy elements by the s-process of nucleosynthesis. Those heavy elements were subsequently dumped onto the companion (the current CH subgiant) through mass transfer.

### 6.2. \((e, \log P)\) diagram

With the availability of extensive sets of orbital elements for binaries of various kinds (e.g., Duquennoy & Mayor 1991 for G dwarfs, Matthieu 1992 for pre-main sequence binaries, Mermilliod 1996 for open-cluster giants, Carney et al. 2001 for blue-straggler, low-metallicity stars, Latham et al. 2002 for halo stars), it has become evident that long-period \((P > 100 \text{ d})\), low-eccentricity \((e < 0.1)\) systems are never found among un-evolved (i.e., pre-mass-transfer) systems. This indicates that binary systems always form in eccentric orbits, and the shortest-period systems are subsequently circularized by tidal effects. On the contrary, binary systems which can be ascribed post-mass-transfer status because they exhibit signatures of chemical pollution due to mass transfer (like barium stars, some subgiant CH stars, S stars without technetium lines...) are often found in the avoidance region \((P > 100 \text{ d}, e < 0.1)\) of the \((e, \log P)\) diagram. Mass transfer indeed severely modifies their orbital elements, which often end up in this region (Jorissen 2003; Jorissen & Van Eck 2005).

The companion masses derived in Sect. 6.1 offer the opportunity to check whether systems falling in the avoidance region of the \((e, \log P)\) diagram could be post-mass transfer systems (most probably then with a WD companion). In total, 8 systems fall in this region, as displayed on Fig. 12: HIP 6867 (= HD 9053 = \( \gamma \) Phe; M0 III), HIP 8922 (= HD 11613 = HR 551; K2), HIP 10514 (= HD 13738; K3.5 III), HIP 24419 (= HD 34101; G8 V), HIP 32768 (= HD 50310 = HR 2553; K1 III), HIP 99965 (= HD 193216; G5 V), HIP 101093 (= HD 195725; A7 III) and HIP 101847 (= HD 196574; G8 III).

None of these ‘avoidance-region’ systems offer conclusive evidence for hosting a WD companion, but at least do not contradict it either.

HIP 6867 has a circular orbit and a rather short orbital period (193.8 d) given its late spectral type. The orbit is therefore likely to have been circularized by tidal effects rather than by mass transfer (Jorissen et al. 2004). In this specific case, there is therefore no need for the companion to be a WD.

HIP 24419 has too small a companion mass (0.21 M\(_{\odot}\)) to host even a He WD. This system could nevertheless have gone through a so-called ‘case B’ mass transfer (occurring when the primary was on the first giant branch).

For HIP 8922, HIP 10514, HIP 32768, HIP 99965, HIP 101093 and HIP 101847, we could not find in the literature any information that could help us in assessing the nature of their companion. In the case of HIP 99965 though, the companion’s mass of 0.56 M\(_{\odot}\) would certainly not dismiss it of being a WD.
Table 6. Masses and mass ratios for the 29 systems with main-sequence primaries passing all consistency tests.

| HIP  | \( M_1 (M_\odot) \) | \( M_2 (M_\odot) \) | \( M_2/M_1 \) | \( Q = \frac{M_2^2}{(M_1+M_2)^2} \) | Sp. Type | Rem. |
|------|-----------------|-----------------|-------------|-----------------|---------|------|
| 1349 | 0.98            | 0.55            | 0.56        | 0.0711          | G2      |      |
| 1955 | 1.13            | 0.48            | 0.42        | 0.0420          | GO      |      |
| 7078 | 1.21            | 0.70            | 0.58        | 0.0953          | F6      |      |
| 8903 | 1.86            | 1.05            | 0.56        | 0.1358          | A5      |      |
| 11231| 1.01            | 0.68            | 0.67        | 0.111           | G2      |      |
| 12062| 0.95            | 0.44            | 0.47        | 0.0449          | G5      |      |
| 20935| 1.13            | 1.11            | 0.98        | 0.2732          | F7      | not a composite spectrum despite a mass ratio close to unity |
| 24419| 0.90            | 0.21            | 0.24        | 0.0079          | G8      |      |
| 34164| 1.09            | 0.66            | 0.61        | 0.0954          | G0      |      |
| 39893| 0.95            | 0.52            | 0.55        | 0.0649          | G3      |      |
| 47461| -               | -               | -           | 0.0863          | F2      | composite spectrum |
| 63406| 0.82            | 0.23            | 0.28        | 0.0114          | G9      |      |
| 72848| 0.79            | 0.45            | 0.56        | 0.0581          | K2      |      |
| 73440| 1.03            | 0.15            | 0.14        | 0.0023          | G0      |      |
| 75379| 1.26            | 0.68            | 0.54        | 0.0842          | F5      |      |
| 79101| 3.47            | 1.31            | 0.38        | 0.0976          | B9      |      |
| 80346| 0.50            | 0.13            | 0.26        | 0.0054          | M3      |      |
| 80686| 1.05            | 0.37            | 0.36        | 0.0259          | G0      |      |
| 82860| 1.18            | 0.52            | 0.44        | 0.0482          | F6      |      |
| 86400| 0.72            | 0.39            | 0.54        | 0.0475          | K3      |      |
| 87895| 0.99            | 0.68            | 0.69        | 0.1129          | G2      |      |
| 89937| 1.18            | 0.77            | 0.65        | 0.1195          | F7Vvar  |      |
| 95028| 1.40            | 0.50            | 0.36        | 0.0353          | F5      |      |
| 95575| 0.78            | 0.38            | 0.49        | 0.0405          | K3      |      |
| 99965| 0.88            | 0.56            | 0.63        | 0.0840          | G5      |      |
| 105969| 1.01           | 0.49            | 0.49        | 0.0528          | Dwarf Ba/Subgiant CH |
| 109176| 1.25           | 0.80            | 0.64        | 0.1233          | F5      |      |
| 11170| 1.08            | 0.70            | 0.65        | 0.1083          | F7      |      |
| 113718| 0.76          | 0.18            | 0.24        | 0.0067          | K4      |      |

One should mention as well that HIP 10514 and HIP 101847 are listed in the Perkins catalog of revised MK types for the cooler stars (Keenan & McNeil 1989) without any mention whatsoever of spectral peculiarities. They are therefore definitely not barium stars, despite falling in the ‘avoidance region’ of the eccentricity – period diagram generally populated by barium stars. If we are to maintain that the ‘avoidance region’ can only be populated by post-mass-transfer objects – thus implying that the companion to HIP 10514 and all the stars discussed in the present section must be WDs – then we must accept at the same time that systems following the same binary evolution channel as that of barium stars do not necessarily end up as barium stars! Or in other words, binarity would not be a sufficient condition for the barium syndrome to develop (these systems would thus add to the non-barium binary systems listed in Jorissen & Boffin 1992).

7. Conclusions

The major result of this paper is that the detectability of an astrometric binary using the IAD is mainly a function of the orbital period (at least when the parallax exceeds 5 mas, i.e., about 5 times the standard error on the parallax); detection rates are close to 100% in the period range 50 – 1000 d (corresponding to the mission duration) for systems not involving components with almost equal brightnesses (i.e., SB2 systems or systems with composite spectra). These are more difficult to detect, because the photocenter motion is then much smaller than the actual component’s motion.

A consistency test between Thiele-Innes and Campbell solutions has been designed that allowed us to (i) identify wrong spectroscopic solutions, and (ii) retain 70 systems with accurate orbital inclinations (among those, 29 involve main sequence primaries and 41 giant primaries). Among those 70 retained solutions, 20 are new astrometric binaries, not listed in the DMSA/O.
This number of 70 systems passing all quality checks seems small with respect to the 122 DMSA/O systems with an S\textsubscript{B9} entry. A detailed check reveals, however, that many systems present in the DMSA/O either have inaccurate astrometric orbits that would not fulfill our statistical tests, or have inaccurate spectroscopic orbital elements that make the astrometric solution unreliable anyway, or have only a \(m_0\) derived from the IAD, all other elements being taken from spectroscopic and interferometric/visual orbital elements.

Masses \(M_2\) for the companions in the 29 systems hosting a main-sequence primary star have been derived, using the mass-luminosity relation to estimate \(M_1\). This was not possible for systems hosting giant primaries.

The possibility that the region \(e < 0.1\), \(P > 100\) d of the \((e, \log P)\) diagram is exclusively populated by post-mass transfer systems has been examined, but could not be firmly demonstrated.

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