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Exploring the brown dwarf desert with Hipparcos*

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Abstract. The orbital elements of 11 spectroscopic binaries with brown dwarf candidates ($\mathcal{M}_2 \sin i$ between 0.01 and 0.08 $\mathcal{M}_\odot$) are combined with the Hipparcos observations in order to derive astrometric orbits. Estimations of the masses of the secondary components are thus calculated. It appears that 5 secondary masses are more than $2\,\sigma_{\mathcal{M}_2}$ above the limit of 0.08 $\mathcal{M}_\odot$, and are therefore not brown dwarfs. 2 other stars are still discarded at the $1\,\sigma_{\mathcal{M}_2}$ level, 1 brown dwarf is accepted with a low confidence, and we are finally left with 3 viable candidates which must be studied by other means.

A statistical approach is developed, based on the relation between the semi–major axes of the photocentric orbit, a_0, their errors, σ_{a_0}, and the frequency distribution of the mass ratios, q. It is investigated whether the set of values of a_0 and σ_{a_0} obtained for the sample is compatible with different frequency distributions of q. It is concluded that a minimum actually exists for $\mathcal{M}_2$ between about 0.01 and 0.1 $\mathcal{M}_\odot$ for companions of solar–type stars. This feature could correspond to the transition between giant planets and stellar companions. Due to the relatively large frequency of single brown dwarfs found recently in open clusters, it is concluded that the distribution of the masses of the secondary components in binary systems does not correspond to the IMF, at least for masses below the hydrogen–ignition limit.

Key words: astrometry – stars: binaries: general – stars: binaries: spectroscopic – stars: formation – stars: fundamental parameters – stars: low-mass, brown dwarfs

1. Introduction

The concept of *Brown Dwarf Desert* emerged in the late 80s, when the first precise radial velocity surveys were completed (Campbell et al. 1988, Marcy & Benitz 1989; see also the review by Marcy & Butler 1994). These projects were initiated in order to detect companions with substellar masses. They resulted in the detections of a few previously unknown spectroscopic binaries (called SBs hereafter), but they all had companions more massive than the hydrogen burning limit. The first brown dwarf candidate, HD 114762, was finally discovered by Latham et al. (1989), but the idea that brown dwarfs were rare among binary companions was not dissipated. Other possible brown dwarf SB components were found later by CORAVEL, and their frequency seemed to be in fair agreement with a constant distribution of mass ratios (Mayor et al. 1992).

However, the orbital elements of a SB are not sufficient to derive the mass of the secondary component. When the mass of the primary component is known (usually from a mass–spectral type relation) it is only possible to derive a lower limit, that, for small mass ratios, is close to $\mathcal{M}_2 \sin i$, where i is the inclination of the orbital plane. Therefore, systems containing brown dwarf candidates may be normal double stars in reality, but with orbital planes with orientations close to pole–on. As a matter of fact, this could happen with HD 114762, although the question is still open (see the notes in Sect. 2.6 hereafter).

It became clear that brown dwarfs exist in long–period binary systems when Gl 229B was discovered by Nakajima et al. (1995). Rebolo et al. (1998) used also direct imaging for discovering the brown dwarf companion of G196-3. Recently, a long period binary brown dwarf system, DENIS-P J1228.2-1547, was detected by Martin et al. (1999). Until now, however, only one short period binary containing a certain brown dwarf was found: it is PPL 15, a brown dwarf star in the Pleiades that is in fact a SB2 (Basri and Martin 1998). Due to selection effects, all the binaries with brown dwarf secondary components have low–mass primaries, and no H–burning star with a short period brown dwarf companion has been unambiguously detected. Therefore, the question of the frequency of brown dwarf companion around solar–type stars is still open.

After the discovery of a possible Jupiter–like planet orbiting 51 Peg (Mayor & Queloz 1995), the number of candidate low–mass objects rose rapidly. However, in contrast to brown dwarf candidates, planets candidates are much more frequent than expected from a constant distribution of mass ratios (Butler & Marcy 1997, Mayor et al. 1998b, Mazeh et al. 1998). This supports the idea that planetary and stellar companions were generated from two different processes. The maximum mass

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for a planet could be about 5 or 7 Jupiter masses, and the lower masses that could be produced by the "star forming process" is still to determine.

Another alternative, envisaged by Mayor et al. (1997), was proposed with conviction by Black (1997). Black pointed out that, contrarely to the giant planets of the solar system, several planet candidates have orbits with large eccentricities, like the stellar companions in the same range of semi–major axis. He suggested that these extrasolar planets were in fact produced by the same process as stellar secondaries. Therefore, the flat distribution of minimum secondary masses above 7 Jupiter masses should just be the tail of the peak observed for the planetary masses. However, a large eccentricity could also be produced by interaction between the planet and other bodies orbiting the central star, such as the gaz disk (Goldreich & Tremaine 1980, Artymowicz 1992), planetesimals (Levison et al. 1998), other planets (Lin & Ida 1997) or another star (Holman et al. 1997; for a general discussion, see Artymowicz 1998, and Marcy & Butler 1998). The distribution of the masses of the low–mass companions is then the touchstone of these two hypotheses.

The actual masses of the brown dwarf candidates in SBs can be determined only by estimating the inclinations of the orbits. Since the close companions are too faint to currently allow direct observations of their motions, the only approach that could be used is the derivation of the elements of the astrometric orbits drawn by the photocenters of the binaries. This method is applied in this paper, using the observations of the ESA Hipparcos satellite.

2. The brown dwarf candidates observed with Hipparcos

2.1. The sample

The SB1 having companions with $\mathcal{M}_2 \sin i$ between 0.010 and 0.080 $\mathcal{M}_\odot$ were collected from the literature. All these stars are included in the Hipparcos catalogue. Gl 623 was not included in the sample, although its spectroscopic orbit (Marcy & Moore 1989) provides a minimum secondary mass below the brown dwarf limit. This was decided since this double star was discovered as an astrometric binary (Lippincott & Borgman 1978), and as a speckle binary (McCarthy 1983). This origin would introduce a bias against a light secondary mass. Actually, Marcy & Moore derived the orbital inclination and concluded that the companion is probably a late M dwarf. This was confirmed by direct observation with the Hubble Space Telescope (Barbieri et al. 1996). The orbital inclination of the astrometric orbit was confirmed by the analysis of the Hipparcos data (Martin & Mignard 1998).

Finally, the sample contains 11 stars, coming in majority from the CORAVEL survey of G–K dwarf stars (Mayor et al. 1992). These stars are listed in Table 1.

2.2. Calculation of the semi–major axes of the astrometric orbits

The Hipparcos satellite performed high–quality astrometric observations from the end of 1989 to March 1993. The Hipparcos abscissae of the 11 brown dwarf candidates found in SB1 stars were extracted from the *Hipparcos Intermediate Astrometric Data* which were supplied with the catalogue (ESA 1997, CD-ROM 5). The elements of the SB orbits were taken into account in the computation of the elements of the astrometric orbits. It was assumed that the luminosities of the secondary components were negligible, since the stars should be SB2 otherwise; as a consequence, the semi-major axis of the astrometric orbit, a_0, is also that of the orbit of the primary component, a_1. The astrometric elements a_0, i, and the parallax, Π, are related to the spectroscopic element $a_1 \sin i$ with the equation:

$$\frac{a_1 \sin i}{149.6} = \frac{a_0}{\Pi} \times \sin i \qquad (1)$$

where $a_1 \sin i$ is in million kilometers and a_0 in the same unit as Π.

The spectroscopic orbital elements P, T, e, ω were kept within their error intervals, and $a_1 \sin i$ was also introduced as a supplementary observation, with its associated weight. All the astrometric elements and the remaining orbital elements (namely $\alpha, \delta, \Pi, \mu_{\alpha*}, \mu_\delta, a_0, i, \Omega$), were derived in the computation through a least-square procedure using the full covariance matrix between the observations.

The input SB parameters and the astrometric elements relevant for our purpose are presented in Table 1. The proper motions, that are included in the astrometric solution, were also recomputed and they are presented in Table 2, with the goodness–of–fit of the new solutions. The four astrometric orbits with the largest semi–major axes are presented in Figs. 1, 2, 3, and 4. Since the Hipparcos individual measurements are one-dimensional abscissae along great-circles, and thus do not give individually α and δ, these figures have been obtained the following way: a clustering has been done on the abscissae as a function of the observing date. For each cluster of at least 4 measurements within less than 100 days, the astrometric residual with respect to the predicted position given the parallax and proper motion was computed. These residuals are shown in α and δ in the upper part of the figure, as a function of date; the x error bars reflect the dispersion of the measurement dates, while the y error bars are the positional precision obtained by least-squares minimization.

2.3. Validation of the method

Due to the low masses of the secondary components, we have obtained some astrometric semi–major axes, a_0, that were not significantly larger than their errors, σ_{a_0}. Since these data must be taken into account in the statistical study of the sample, it was necessary to be sure of their properties. For that purpose, we selected a set of stars that are not binaries, and that belong to the same sample of nearby stars as the majority of the brown dwarf candidates (thus, their parallaxes and proper motions are all within the same range). Among the nearby F7–G–K stars monitored with CORAVEL, we found 16 stars with constant radial velocities observed at least 20 times during more than 10 years; these stars were: HIP 544, 3093, 3419, 3765, 9884,

Table 1. The SBs with brown dwarf candidates observed with Hipparcos. The lower set of numbers are errors. As explained in the text, $\mathcal{M}_2$ is overestimated when a_0 is small, but $\mathcal{M}_2 + 2 \times \sigma_{\mathcal{M}_2}$ is actually the limit of the secondary mass corresponding to the 97.7% percentile. The references of the orbits are coded as follows: (1) forthcoming paper, (2) Mazeh et al. 1996, (3) Tokovinin et al. 1994.

HIP HD/BD	P *days*	$T_\circ$ HJD -2440000	e	ω $\circ$	$a_1 \sin i$ $10^6 km$	Source	Π *mas*	a_0 *mas*	Sp.T. $\mathcal{M}_1$	$\mathcal{M}_2$ min	$\mathcal{M}_2$
13769	554.58	8595.24	0.558	70.57	9.732	CORAVEL	39.94	9.85	K2 V	0.042	0.176
18445	1.25	9.39	0.067	8.06	0.981	(1)	1.15	0.90	0.74		0.019
19832	716.68	8567.1	0.074	246.4	13.295	CORA+Elo	42.19	17.15	K5 V	0.045	0.245
-04 782	2.89	48.9	0.029	24.1	0.551	(1)	1.47	0.81	0.67		0.014
21482	1.787992	8998.25	0.002	293.	0.258	CORAVEL	55.98	0.31	dK5	0.048	0.171
283750	0.000002	0.96	0.005	193.	0.001	(1)	1.30	0.66	0.67		0.442
21832	1474.9	7763.5	0.356	80.2	14.31	CFA+CORA	35.14	3.42	G2 V	0.039	0.039
29587	10.2	45.8	0.095	13.3	1.62	(1)	1.09	2.37	1.00		0.025
50671	297.708	15663.50	0.952	115.07	6.752	CORA+Elo	28.64	1.39	G1 V	0.055	0.060
89707	0.006	0.15	0.001	1.45	0.087	(1)	0.86	0.41	1.05		0.018
62145	271.165	10607.41	0.784	264.43	2.475	Elodie	67.47	8.39	K3 V	0.016	0.137
110833	0.472	1.26	0.010	1.31	0.068	(1)	0.75	0.62	0.72		0.011
63366	103.258	9055.31	0.139	340.64	2.327	Elodie	47.79	4.13	K0 V	0.032	0.199
112758	0.030	1.33	0.010	4.38	0.030	(1)	0.87	0.72	0.79		0.041
64426	83.90	7710.	0.35	214.	0.64	CFA	25.34	1.06	F9 V	0.010	0.105
114762	0.08	2.	0.05	10.	0.04	(2)	1.73	0.93	0.82		0.097
70950	2599.0	4664.	0.716	241.85	22.22	CORA+Elo	45.81	8.36	K3 V	0.034	0.042
127506	68.6	136.	0.044	2.69	1.77	(1)	1.10	4.15	0.75		0.020
77152	147.956	8809.49	0.608	29.30	3.265	CORAVEL	21.18	1.64	G0 V	0.044	0.166
140913	0.060	1.03	0.029	3.16	0.184	(1)	1.05	0.63	1.10		0.069
113718	454.66	6890.8	0.520	239.1	13.296	CORAVEL	54.51	11.31	K4 V	0.064	0.161
217580	0.94	3.4	0.022	3.8	0.429	(3)	1.39	0.79	0.69		0.013

Table 2. The proper motions and the goodness–of–fit of the new astrometric solutions, computed by taking the spectroscopic orbital elements into account.

HIP	$\mu_{\alpha *}$ mas/yr	$\sigma_{\mu_{\alpha *}}$ mas/yr	μ_δ mas/yr	σ_{μ_δ} mas/yr	GOF
13769	15.14	1.01	−32.30	0.88	0.54
19832	85.95	1.79	−88.53	1.95	−0.07
21482	232.33	1.30	−147.21	1.11	1.67
21832	536.69	3.96	−418.87	3.07	−1.42
50671	−219.53	0.79	296.48	0.71	−0.90
62145	−379.70	0.59	−183.56	0.53	−0.29
63366	−827.18	0.79	197.98	0.66	1.12
64426	−582.61	1.13	−1.66	0.96	−0.86
70950	−479.13	2.23	201.05	3.30	−0.67
77152	−87.50	0.53	38.70	0.72	−1.95
113718	395.23	1.15	−209.46	0.87	−0.96

13402, 16537, 17147, 21818, 37826, 39157, 57939, 70319, 83601, 97675 and 115331. It was assumed that these stars were in reality all astrometric binaries, but with $a_0 \approx 0$ mas (in fact, HIP 16537 is actually an astrometric binary, but its 25–years period is so long that the orbital motion is confused with the proper motion on the duration of the Hipparcos mission). Their astrometric elements, including a_0, were derived assuming the orbital elements of the SB orbits of the brown dwarf candidates. However, in place of the original $a_1 \sin i$, the very small value of 1000 km was assumed; at a distance of 10 pc, 1000 km corresponds to an angle of only 0.0007 mas.

It was possible to calculate astrometric orbits for all the single stars, using the elements of the SB orbits with periods shorter than the duration of the Hipparcos mission; that was a bit more than 3 years. For sake of clarity, these orbits will be called *pseudo–orbits* hereafter. Two brown dwarf candidates have periods longer than this limit: with the 6.8–year period of HIP 70950, the calculation barely converged, and half of the 16 pseudo–orbits had $a_0/\sigma_{a_0} > 3$ (for 2 pseudo–orbits, this ratio was larger than 200!). With the elements of HIP 21832 (period of 4 years) one case had $a_0 = 4.2\sigma_{a_0}$. It is concluded that our estimations of a_0 and σ_{a_0} are dubious when they concern stars with periods longer than about 3 years, simply due to the fact that the orbital displacements and the proper motions are then hardly distinguished, though an acceleration term may be present (solutions labelled G in the Hipparcos Double and Multiple Star Annex). It should be noted however that in the case of HIP 70950 the acceleration term is not significant at a $1 - \sigma$ level.

Among the 9 remaining brown dwarf candidate orbits, that of HIP 21482 is exceptionally brief: less than 2 days. Since the observations of the satellite were concentrated in sequences of about 10 hours to a few days, it may be suspected that a so short

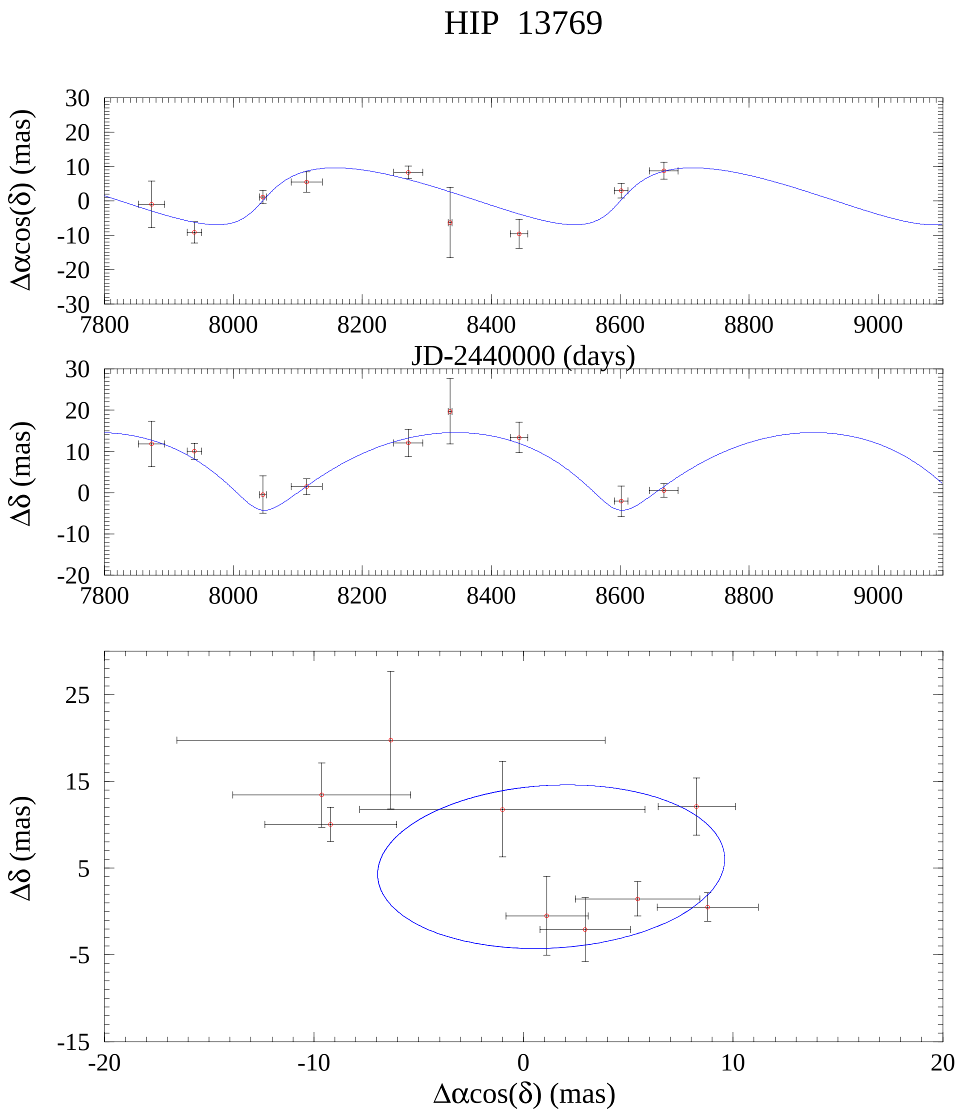

Fig. 1. The astrometric orbit of HIP 13769, derived from the Hipparcos observations, taking the elements of the SB orbit into account.

period could also be a case different from the others. Moreover, this star is not very relevant in our study: even if the mass of the secondary component was as large as that of the primary, a_1 would be as small as 0.89 mas (and a_0 would be null due to the equal masses and brightnesses). For these reasons, this orbit was ignored in the validation. Therefore, only the 128 pseudo–orbits coming from the applications of the elements of the 8 remaining SB orbits on the Hipparcos observations of the 16 single stars are considered hereafter.

It was found that the pseudo–orbits had inclinations systematically very close to zero. The explanation of this characteristic is in Eq. (1) above: when the actual a_0 is null or close to zero, the calculation provides values that are usually between 0 and the error σ_{a_0}; a_0 is determined mainly by the scatter of the observations while i is not directly affected. Therefore a_0 is overestimated and the excess in a_0 is compensated by underestimating i in order to provide the right $a_1 \sin i$. Consequently, the distribution of the errors of the inclinations is rather complex, and related to a_0, σ_{a_0}, $a_1 \sin i$ and Π. For that reason, in order to avoid confusion, the inclinations obtained in the calculation of the orbital elements are not mentioned in this paper; the discussion hereafter is exposed only in terms of a_0 and σ_{a_0}.

For a pseudo–orbit, a_0 is related to the residuals of the coordinates of the star. We assume hereafter that the right ascension and the declination residuals both obey a normal distribution with the same standard deviation (this is an approximation, however; in practice, the errors in RA are on average slightly larger than the errors in declination, ESA 1997). Therefore, we represent a_0 as a vector in a two–dimension space, and we assume that each coordinate of a_0 obeys a normal distribution with the standard deviation σ_{a_0}. The norm of this vector then obeys a Rayleigh distribution, and the distribution of a_0/σ_{a_0} is:

$$f_{a_0/\sigma_{a_0}}(\frac{a_0}{\sigma_{a_0}} \mid a_{0_{actual}} = 0) = \frac{a_0}{\sigma_{a_0}} \times \exp[-\frac{1}{2}(\frac{a_0}{\sigma_{a_0}})^2] \qquad (2)$$

This theoretical distribution is drawn in Fig. 5, where it is compared to the histogram of a_0/σ_{a_0} found for the 128 pseudo–orbits. The mean and the standard deviation of the Rayleigh distribution are respectively $\sqrt{\pi/2} = 1.25$ and $\sqrt{2 - \pi/2} = 0.66$. They are both very close to the values actually obtained,

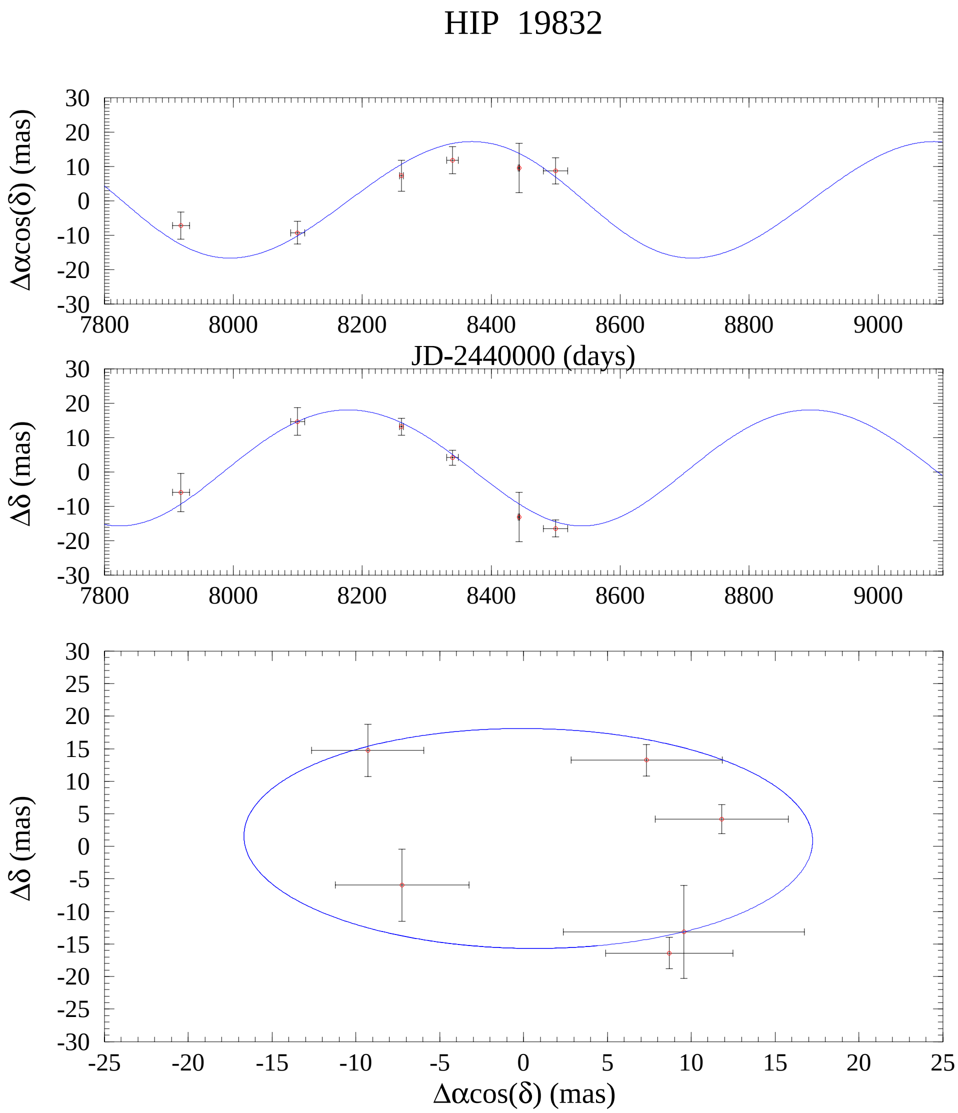

Fig. 2. Same as Fig. 1, for HIP 19832.

that are 1.31 and 0.68. The compatibility between the two distributions is verified by a χ^2–test at the 19% level of significance. That means that, if Eq. (2) is true, the probability to get a fit worse than the histogram in Fig. 5 is 19%. The agreement looks therefore rather good, but, in fact, this threshold is undervaluated. The χ^2–test was based upon the hypothesis that the 128 values of a_0/σ_{a_0} are not correlated. That means that no tendency in favour of large or of small values of a_0/σ_{a_0} should come from any set of orbital elements (P, $T_\circ$, e, ω), or from the Hipparcos observations of any single star. In reality, the size of a pseudo–orbit depends on the scatter of the astrometric observations, and the hypothesis of no correlation between the values of a_0/σ_{a_0} derived for the same single star was rejected at the 1% level. Therefore, the histogram contains correlated values, and the agreement with the distribution in Eq. (2) is better than 19%.

When a_0 is not equal to zero in reality, the measured value is related to the actual one, $a_{0_{actual}}$, by the relation:

$$a_0 = \sqrt{(a_{0_{actual}} + \Delta_{a_x})^2 + {\Delta_{a_y}}^2} \tag{3}$$

where Δ_{a_x} and Δ_{a_y} both obey a normal law with the standard deviation σ_{a_0}. a_0 thus obeys the Rayleigh distribution when $a_{0_{actual}}$ is null; when $a_{0_{actual}}$ is large, the distribution of the errors of a_0 coming from Eq. (3) is the classical 1–dimension normal distribution with the standard deviation σ_{a_0}.

2.4. The masses of the brown dwarf candidates

The masses of the secondary components are derived from the mass function, $f_{\mathcal{M}}$. Expressing $f_{\mathcal{M}}$ as a function of the masses on one side, and as a function of $a_1 \sin i$ and of the period, P, on the other side, we have:

$$\frac{{\mathcal{M}_2}^3 \sin^3 i}{(\mathcal{M}_1 + \mathcal{M}_2)^2} = 0.03985 \times \frac{(a_1 \sin i)^3}{P^2} \tag{4}$$

where $a_1 \sin i$ is expressed in million kilometers, P is in days, and the masses of the components, $\mathcal{M}_1$ and $\mathcal{M}_2$, are in solar masses. Since $a_1 \sin i$ and P are obtained from the spectroscopic orbit, $\mathcal{M}_1$ and $\sin i$ are still needed for deriving $\mathcal{M}_2$. $\mathcal{M}_1$ is simply obtained from the spectral type of the primary component.

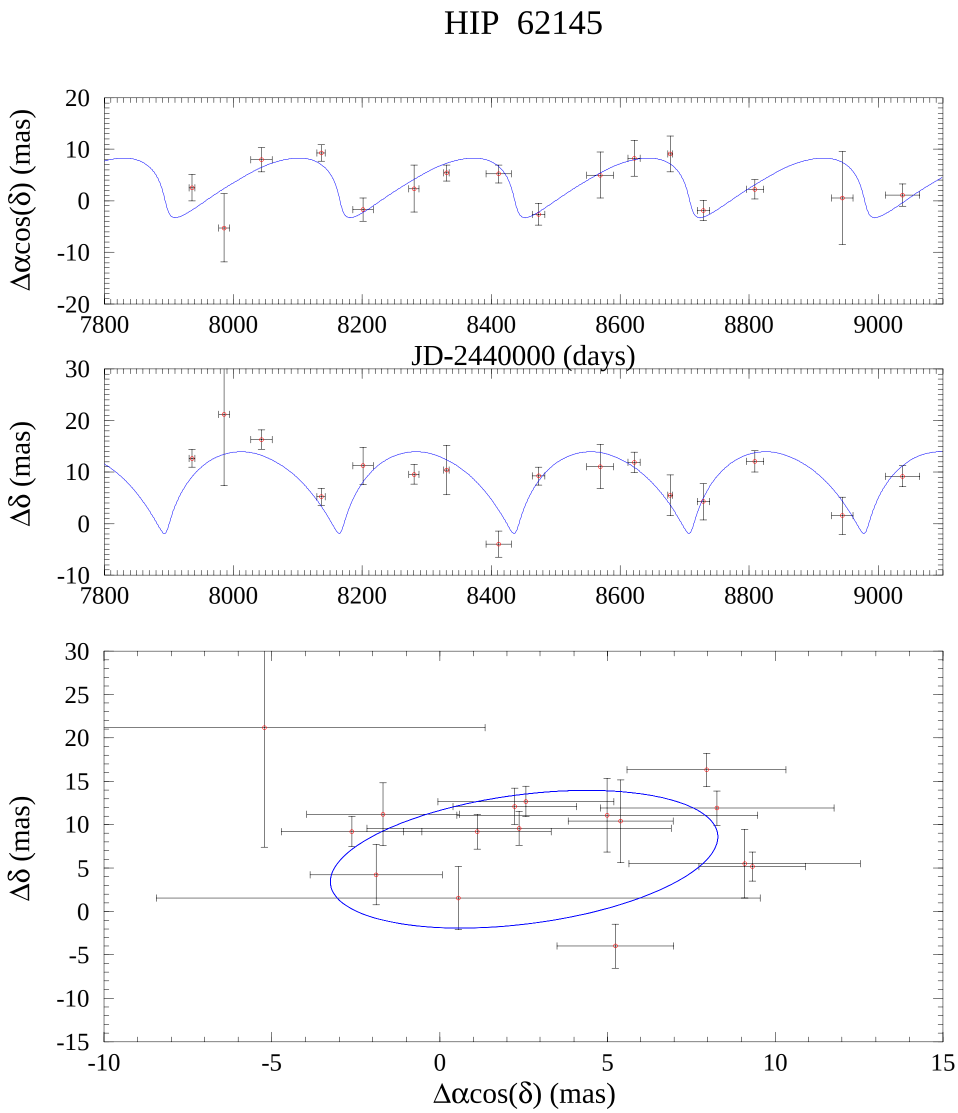

Fig. 3. Same as Fig. 1, for HIP 62145.

Apart from exceptions quoted in the notes (Sect. 2.6 hereafter), the spectral types are coming from the Hipparcos catalogue, and the primary masses were derived from the mass–spectral type relation of Schmidt–Kaler (1982). The minimum secondary masses, "$\mathcal{M}_2$ min", were calculated assuming $\sin i = 1$ in Eq. (4). The masses $\mathcal{M}_2$ were computed by taking $\sin i$ from Eq. (1).

A simple examination of Table 1 shows that, among the 11 brown dwarf candidates, only 3 have $\mathcal{M}_2$ under the limit of 0.08 $\mathcal{M}_\odot$. However, since a_0 was overestimated when it is small, $\sin i$ and therefore $\mathcal{M}_2$ are overestimated. Before concluding if these stars are really brown dwarfs, it is necessary to consider the errors in the masses, taking the bias of a_0 into account.

2.5. Calculation of the errors of the secondary masses

The major contribution to the error budget of $\mathcal{M}_2$ comes from the error of a_0, that is given in Eq. (3). When a_0 is not several times larger than σ_{a_0}, the distribution of the errors is not gaussian, and even not symmetric. In order to provide error intervals with the same meaning as usually, the percentiles of the actual values of a_0 were calculated. Therefore, instead of assuming that the actual a_0 should be in the interval $[a_0 - 2.\sigma_{a_0}, a_0 + 2.\sigma_{a_0}]$, we have derived from Eq. (3) the values of $a_{0_{actual}}$ such that the measured a_0 corresponds to the percentiles 2.3% and 97.7% (converting the errors from a_0 to $a_{0_{actual}}$ was done by iteration, and required a few dozen lines of code). Errors in the sense of ± 1 or $\pm 2\, \sigma_{a_0}$ intervals were thus derived, and they were used to calculate the error interval of $\mathcal{M}_2$, taking also into account the errors of the elements of the SB orbits (in fact, only the errors of the periods were relevant in this computation). The errors of $\mathcal{M}_1$ were ignored in the budget, since $\mathcal{M}_2$ varies as ${\mathcal{M}_1}^{2/3}$; therefore, they would be usually a minor contribution when compared to the other ones. For simplicity, only one error is indicated in Table 1. It is defined as:

$$\sigma_{\mathcal{M}_2} = \frac{\mathcal{M}_2(97.7\%) - \mathcal{M}_2}{2} \tag{5}$$

where $\mathcal{M}_2(97.7\%)$ is the percentile 97.7% of the distribution of $\mathcal{M}_2$.

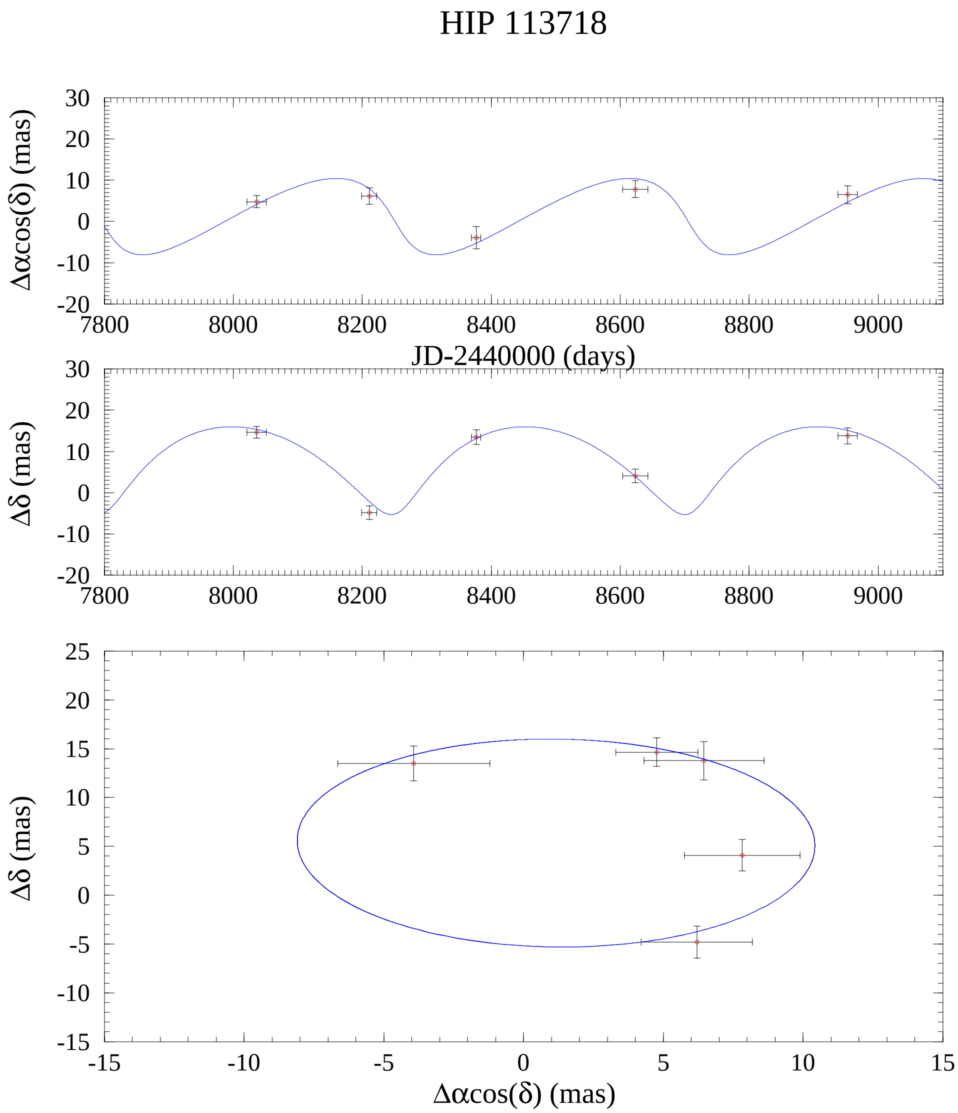

Fig. 4. Same as Fig. 1, for HIP 113718.

It is then confirmed that 5 brown dwarf candidates have masses definitely larger than the limit of 0.08 $\mathcal{M}_\odot$: for HIP 13769, 19832, 62145, 63366 and 113718, the excesses of mass are larger than 2 $\sigma_{\mathcal{M}_2}$. A sixth star, HIP 77152, has a low probability to be a brown dwarf, since $\mathcal{M}_2(15.9\%)$ (the limit corresponding to $\mathcal{M}_2 - \sigma_{\mathcal{M}_2}$ for a normal distribution) is 0.081 $\mathcal{M}_\odot$.

On the other hand, only one star seems to have a secondary mass with the 97.7% percentile below 0.08 $\mathcal{M}_\odot$. Unfortunately, it is HIP 70950, that has a period much longer than the duration of the Hipparcos mission. Our result concerning this star is then dubious. However, two stars have still the $1\,\sigma$ percentile at the left of the brown dwarf limit: HIP 21832 ($\mathcal{M}_2(84.1\%) = 0.059\mathcal{M}_\odot$) and HIP 50671 ($\mathcal{M}_2(84.1\%) = 0.076\mathcal{M}_\odot$). Nevertheless, the period of the former is a bit longer than the Hipparcos mission, and only the latter may be accepted as brown dwarf, but with a low confidence.

Two stars are still remaining: HIP 21482 and HIP 64426. These stars have the two shortest periods, and their astrometric orbits are in fact too small for Hipparcos.

2.6. Notes to individual objects

– HIP 13769 = HD 18445. The star is Gl 120.1C, a distant companion of HIP 13772 ($\rho = 29''$). SB discovered by Duquennoy & Mayor (1991). The star is quoted as "duplicity–induced variability", and "ambiguous double–star solution" in the Hipparcos catalogue. The first solution is: $\Delta H = 3.89$ mag, $\theta = 172°$, $\rho = 5\farcs09$; the alternative is: $\Delta H = 1.54$ mag, $\theta = 187°$, $\rho = 0\farcs11$, fixed component. Assuming the period, parallaxes and masses in Table 1, the semi–major axis of the relative orbit, a, should be $0\farcs05$ and the first solution is clearly ruled out. The alternative does not look better, however, since the application of the mass–luminosity relation of Söderhjelm (1999) leads to $\mathcal{M}_2 = 0.7\mathcal{M}_\odot$ instead of 0.176 $\mathcal{M}_\odot$, and the system should be double–lined. Moreover, with a period of only 1.5 year, the secondary component should not seem to be fixed. Considering the goodness–of–fit of our solution (0.54), it seems that these possible additional companions could just be artefacts.

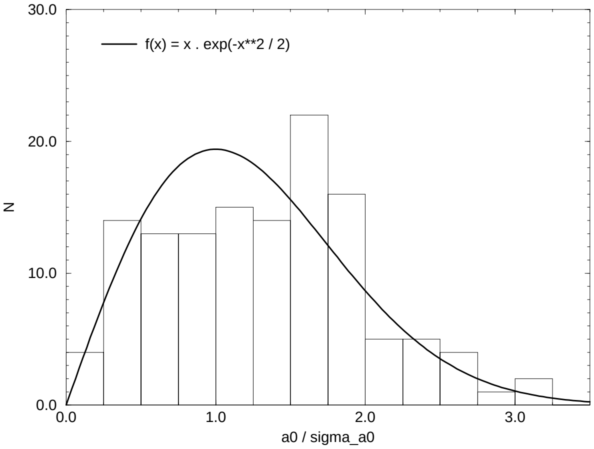

Fig. 5. a_0/σ_{a_0} for 128 astrometric *pseudo–orbits* derived for single stars. The orbital elements $(P, T_\circ, e, \omega)$ of 8 SBs with periods between 83 days and 3 years were applied to the Hipparcos astrometric observations of 16 single stars, assuming $a_1 \sin i$ = 1000 km. The distribution of the norm of a 2–dimension vector obeying the normal distribution on both axes is represented for comparison; it is accepted by a χ^2–test at the 19% level.

According to the mass–luminosity relation of Henry & McCarthy (1993), the difference of magnitudes in the K photometric band should be $\Delta K = 3.4$ mag. If our estimation of $a = 0\farcs05$ is correct, the system could then be separated with an 8–meter class telescope with adaptive optic.

- HIP 19832 = BD -04 782. The astrometric solution in the Hipparcos catalogue is quoted "stochastic solution (probably astrometric binaries with short period)". SB discovered by Mayor et al. (1997). According to our results, $a = 0\farcs06$, and, in the IR, $\Delta K = 2.4$ mag. The system should then be separated with an 8–meter telescope with adaptive optic.
- HIP 21482 = HD 283750. The star is Gl 171.2A = CCDM J04368+2708A, member of a pair with wide separation (2 armin). It is also V833 Tau, a BY Dra type variable. SB discovered by Griffin et al. (1985). According to the catalogue, this star were of K2 type, with an unknown luminosity class. The type dK5, provided by Gliese & Jahreiss (1991) was prefered, since it fitted better the $B - V$ colour index. Since the rotation of the primary component is synchronous with the orbit, Glebocki & Stawikowski (1995) assumed that the rotation axis was parallel to the axis of the orbit, and they estimated the inclination: $i = 22° \pm 10°$, and the mass of the companion: $\mathcal{M}_2 = 0.128 \pm 0.037\ \mathcal{M}_\odot$.
- HIP 21832 = HD 29587. A former IAU radial velocity standard, that appeared to be SB to Mazeh et al. (1996) and to the CORAVEL team (Mayor et al. 1997). Since the period exceeds the duration of the Hipparcos mission, our estimation of a_0, and, consequently of $\mathcal{M}_2$ are dubious (see Sect. 2.3 above). The apparent semi–major axis should be $a \approx 0\farcs09$, but, even if the secondary component is at the hydrogen–burning limit, ΔK is as large as about 6.7 mag.
- HIP 50671 = HD 89707. The star is Gl 388.2. SB discovered by Duquennoy & Mayor (1991). The companion is the only brown dwarf candidate, with a period shorter than the duration of the Hipparcos scientific mission, and that is effectively confirmed within the $1\,\sigma$–interval. It would be difficult to separate the components, since $a \approx 0\farcs026$ and $\Delta K > 7$ mag.
- HIP 62145 = HD 110833. The star is Gl 483. SB discovered by Mayor et al. (1997). The Hipparcos catalogue provides an "orbital solution" with a period similar to the spectroscopic one, but assuming $e = 0$. Assuming the parameters in Table 1, a should be $0\farcs05$ with $\Delta K = 3.7$ mag; the components could then be separated with the VLT with adaptive optic.
- HIP 63366 = HD 112758. The star is Gl 491A and IDS 12539S0918A. SB discovered by Mayor et al. (1997). The faint B component ($\Delta m = 4.9$ mag) was observed since 1945, with a separation between $1\farcs6$ in and $0\farcs77$ (McAlister et al. 1987). The period is not known, but it should be about one century, and the astrometric short–period orbit should not be affected. In spite of the large Δm, a "duplicity-induced variability" is quoted in the Hipparcos catalogue. However, our astrometric reduction seems reliable, since the goodness–of–fit was ameliorated from 3.89 to 1.12. The doubt, if any, will be dissipated when it is possible to distinguish the companion of the SB, with $a = 0\farcs02$ and $\Delta K = 3.5$ mag.
- HIP 64426 = HD 114762. A former IAU radial velocity standard, until Latham et al. (1989) found it was a SB with a brown dwarf candidate companion. Since the star is metal–deficient, the primary mass in Table 1 was not extracted from the mass–spectral type relation, but it was taken from Gonzalez (1998): $\mathcal{M}_1 = 0.82 \pm 0.03\ \mathcal{M}_\odot$. Assuming the alignment of the rotational axis with the orbital axis, it was inferred that the companion could be a late M dwarf star (Cochran et al. 1991, Hale 1995), since the rotational velocity of the primary is null or very small for a F–type star. However, this question is still debated, since Mazeh et al. (1996) argued that a halo F dwarf may be a very slow rotator. The only certain restriction about the inclination is: $i < 89°$, since Robinson et al. (1990) failed to detect any eclipse. It will certainly be hard to separate the components, since our estimations are: $a \approx 0\farcs009$ and $\Delta K \approx 5.4$ mag.
- HIP 70950 = HD 127506. The star is Gl 554. SB discovered by Mayor et al. (1998a). Due to the long period, and also to the errors of P and $T_\circ$ in the SB orbit, the astrometric solution is considered as very uncertain (see Sect. 2.3 above). Anyway, the semi–major axis of the relative orbit should be about $a = 0\farcs16$, and, if the companion is a red dwarf, it could be easily separated in the IR with a 8–meter telescope (at the hydrogen–burning limit, ΔK would be 5.5 mag).
- HIP 77152 = HD 140913. The star is a former IAU radial velocity standard turned into SB with brown dwarf candidate thank to Stefanik et al. (1994), and to Mazeh et al. (1996). Assuming our results, $a \approx 0\farcs013$ and $\Delta K \approx 5.2$ mag.
- HIP 113718 = HD 217580. The star is Gl 886. SB discovered by Tokovinin et al. (1994); $a_1 \sin i$ was recalculated, since it was erroneous in the original publication (another misprint

concerned the mass function, that is $4.53\ 10^{-4} \pm 4.4\ 10^{-5}$ $\mathcal{M}_\odot$ instead of $4.12\ 10^{-4} \pm 4.5\ 10^{-4}\ \mathcal{M}_\odot$). Unresolved by speckle interferometry (Blazit et al. 1987). According to our result, one may expect a relative orbit with $a = 0\farcs06$ and $\Delta K = 3.5$ mag; the components could then be separated with the VLT, when the adaptive optic will be available.

In conclusion, among 11 brown dwarf candidates, 5 are definitely rejected, 1 is discarded with a low confidence, 1 is confirmed with a low confidence, 2 might have been confirmed if their periods were not too long, and 2 are outside the range of application of Hipparcos; among these two, however, one (HIP 21482) was rejected as brown dwarf independently from astrometric observations. Thus, 3 of the 11 remains as viable brown dwarf candidates, since we can't derive any conclusion about them.

The validity of our estimations of $\mathcal{M}_2$ could be confirmed in the future by direct observations of the companions, using a 8–meter class telescope with adaptive optic in the IR. The systems with $\Delta K < 3.5$ mag and $a > 0\farcs05$ will be valuable targets for the VLT, when the adaptive optic (NAOS) will be in operation. Later, in 2002, when the Astronomical Multiple BEam Recombiner (AMBER) will be in use, components as close as $0\farcs01$ with $\Delta K < 8$ mag will be separated (information about VLTI instruments are delivered by ESO 1999).

3. Does a brown dwarf desert exist in the distribution of the mass ratios?

In this section, the astrometric orbits obtained with Hipparcos for the SBs with brown dwarf candidates are used to derive general constraints on the frequency of non–planetary companions with masses below 0.08 $\mathcal{M}_\odot$. For that purpose, a global approach is followed, that is based on the computation of the probability to obtain semi–major axes a_0 smaller than those which were found with Hipparcos. This probability, also called the cumulative relative frequency, or the *distribution function* of a_0, $F_{a_0}(a_0)$, is related to several parameters. When the spectroscopic orbital elements, the parallax, and the error σ_{a_0} are taken into account, $F_{a_0}(a_0)$ still depends on f_q, the distribution of the mass ratios (in this paper, q is defined as $q = \mathcal{M}_2/\mathcal{M}_1$).

The method of derivation of $F_{a_0}(a_0)$ is explained in Appendix A. It is based on the distribution of the errors of a_0 that was derived in the previous section. It is applied to the brown dwarf candidates, assuming the f_q that are presented hereafter. The sets of $F_{a_0}(a_0)$ which correspond to the different f_q are finally submitted to a Kolmogorov–Smirnov test, in order to reject the mass ratio frequencies that are not compatible with the astrometric orbits.

3.1. $F_{a_0}(a_0)$ *for different distributions of mass ratios*

The distribution of the mass ratios is still poorly constrained for close binaries, and several f_q are possible. Our calculations of $F_{a_0}(a_0)$ are based on the following ones:

1. The constant distribution, that was found by Duquennoy & Mayor (1991), and by Halbwachs et al. (1998) from an homogeneous sample of nearby main–sequence F7 to K type SBs observed with CORAVEL.
2. The distribution constant for $\mathcal{M}_2 \geq 0.08\mathcal{M}_\odot$, with no brown dwarf companions.
3. The increasing distribution that was still compatible, at the 5% level of significance, with the sample of nearby F7–K dwarfs (Halbwachs et al. 1998). This distribution was a single segment from $q = 0$ to $q = 1$, and its slope was defined by the condition: $(f_q(1) - f_q(0))/f_q(1) = 0.87$.
4. It is usually admitted that the distribution of the secondary masses in wide binaries is similar to the initial mass function of the stars (IMF) (Abt & Levy 1976). The shape of f_q is more controversial for close binaries like SBs, but Halbwachs (1987) found it was close to the IMF–like distribution at least for $q > 0.3$. The present sample is adequate to investigate the range of the small mass ratios, and it seems relevant to re-consider that question. For that purpose, we chose the log–normal IMF distribution, proposed by Miller & Scalo (1979), but expressed in the form presented by Zinnecker et al. (1993). Converting the distribution of $\log \mathcal{M}$ in a distribution of $\mathcal{M}$, it appears that, for a fixed $\mathcal{M}_1$, the distribution of the mass ratios is:

$$f_q(q) \propto \frac{1}{q}\ \exp[\,-b_\mathcal{M} \times (\ln \frac{q\,\mathcal{M}_1}{c_\mathcal{M}})^2\,] \tag{6}$$

with $b_\mathcal{M} = 0.2$ and $c_\mathcal{M} = 0.1\ \mathcal{M}_\odot$. When it is expressed as a function of $\ln \mathcal{M}$, this IMF distribution has a maximum for $\ln \mathcal{M} = \ln c_\mathcal{M}$, and the standard deviation $\sigma_{\ln \mathcal{M}} = 1/\sqrt{b_\mathcal{M}}$. When it is expressed as a function of the secondary mass, $\mathcal{M}_2$, or of the mass ratio q, its shape is quite different, however. The maximum then corresponds to:

$$\mathcal{M}_{2_{Max}} = c_\mathcal{M}\ \exp(-\frac{1}{2\,b_\mathcal{M}}) \tag{7}$$

Assuming the values above, one obtains a distribution with a sharp peak on $\mathcal{M}_{2_{Max}} = 0.0082\ \mathcal{M}_\odot$. When compared to the log–normal expression of the function, the position of the maximum is thus shifted toward a much smaller value.

All these distributions are presented in Fig. 6 and 7. They were used to derive the values of F_{a_0} that are presented in Table 3.

3.2. *Tests of the mass ratio distributions*

A simple examination of Table 3 reveals that, when the constant f_q is assumed, $F_{a_0}(a_0)$ is usually rather large: for instance, the median value is 74.7%. This suggests that the constant f_q could not be the true distribution of the mass ratios of binary stars, since it corresponds to semi–major axes that are, statistically, smaller than the ones which are found. This simple observation contains the basic principle of the test used in this section.

As a matter of fact, when independent values of a distribution function are considered, they inevitably obey the constant

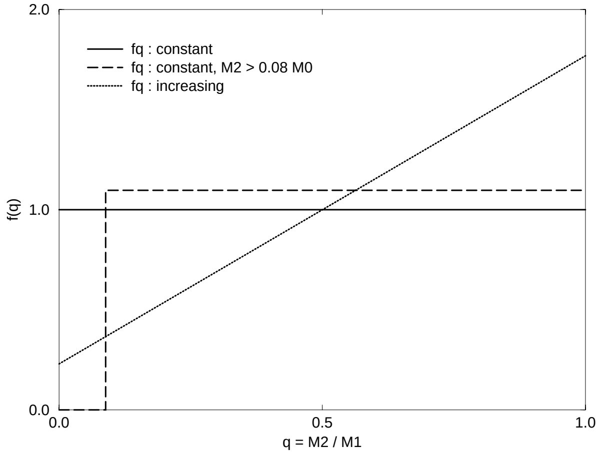

Fig. 6. The three simple distributions of the mass ratios used in the test. The distribution constant for $\mathcal{M}_2 > 0.08\ \mathcal{M}_\odot$ is represented in the case $\mathcal{M}_1 = 0.9\ \mathcal{M}_\odot$.

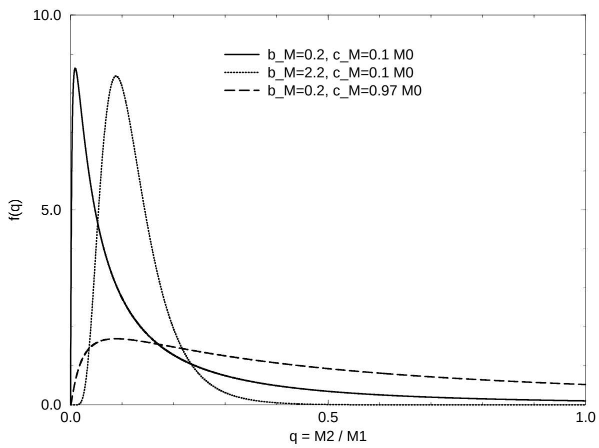

Fig. 7. The log–normal distribution, represented here for $\mathcal{M}_1 = 0.9\mathcal{M}_\odot$, and for various sets of $b_\mathcal{M}$ and $c_\mathcal{M}$. The solid line is the original one ($b_\mathcal{M} = 0.2$, $c_\mathcal{M} = 0.1$), with a maximum for $\mathcal{M}_{2_{Max}} = 0.0082\ \mathcal{M}_\odot$. The others are both corresponding to $\mathcal{M}_{2_{Max}} = 0.08\ \mathcal{M}_\odot$.

frequency distribution. Therefore, if the distribution of mass ratios used for calculating $F_{a_0}(a_0)$ is true, 10% of the SBs should have $F_{a_0}(a_0)$ less than 0.1, 20% should have $F_{a_0}(a_0)$ less than 0.2, and so on. The test of Kolmogorov–Smirnov is used to estimate whether the maximum difference between these expected proportions and the values of $F_{a_0}(a_0)$ is significant; we use the variant of the test where the distance is defined independently of the sense of comparisons in sorting the data. When the significance of the test is less than 5%, it is commonly considered that the model used to calculate F_{a_0} is false, and the f_q that was assumed is rejected.

It must be emphasized that this method is free of selection effects, since it was possible to derive a_0 and σ_{a_0} for all the SBs of the sample; F_{a_0} was derived from the spectroscopic elements of the SBs, and the biases against detection of SBs, that are related to some of these elements (such as the semi–amplitude of radial velocity, K_1, e, and P), have no effect on the probability

Table 3. The distribution function of a_0, for the brown dwarf candidates with $P < 3$ years. The frequency distributions of f_q assumed in the calculations are: the constant distribution (1), the constant distribution with $\mathcal{M}_2 > 0.08\mathcal{M}_\odot$ (2), the increasing distribution (3), and the log–normal distribution of $\mathcal{M}_2$ corresponding to the IMF of Miller & Scalo (1979) (4). $a_{1_{bd}}$ is the actual value of a_0 if the mass of the companion were corresponding to the brown dwarf limit, ie $0.08\mathcal{M}_\odot$; it is expressed in unit of σ_{a_0}.

HIP	$\frac{a_{1_{bd}}}{\sigma_{a_0}}$	$F_{a_0}(a_0)$ $f_q:(1)$	$F_{a_0}(a_0)$ $f_q:(2)$	$F_{a_0}(a_0)$ $f_q:(3)$	$F_{a_0}(a_0)$ $f_q:(4)$
13769	5.35	85.6 %	59.8 %	72.4 %	96.7 %
19832	7.91	89.6 %	77.4 %	80.0 %	96.0 %
21482	0.24	9.7 %	9.2 %	9.4 %	9.9 %
50671	4.49	19.2 %	1.2 %	14.3 %	27.5 %
62145	8.28	89.2 %	43.8 %	79.5 %	94.9 %
63366	2.51	87.7 %	62.6 %	76.8 %	95.1 %
64426	0.88	43.3 %	17.7 %	39.9 %	45.5 %
77152	1.32	70.8 %	43.0 %	58.8 %	83.0 %
113718	7.60	74.7 %	59.3 %	60.9 %	89.5 %

to get an astrometric semi–major axis smaller or larger than that which have been found. Moreover, as for the calculation of the confidence intervals of $\mathcal{M}_2$, the overestimation of a_0 has no effect on our conclusions, since the error law of this parameter was taken into account in the computation of $F_{a_0}(a_0)$.

Among all the hypothetical f_q that are assumed, only the log–normal IMF is significantly rejected, with a threshold of 1.4%. The constant one comes just after, but it is not rejected since the significance of the test is 12%. This conclusion is not definitive, however. We see in Table 3 that for some stars, $F_{a_0}(a_0)$ does not really depend on f_q. The most obvious case is HIP 21482, for which $F_{a_0}(a_0)$ varies between 9.2 and 9.9%. This behavior arises from the very short period of this binary (less than 2 days); even if the mass of the secondary component were the largest possible one, the actual value of a_0 would be smaller than the error σ_{a_0}. $F_{a_0}(a_0)$ depends then almost completely on the assumed frequency of the errors, but not on f_q.

The selection of the sample is then modified in order to remove the stars with periods so short or parallaxes so small that they cannot be relevant for investigating f_q. Hereafter, we call $a_{1_{bd}}$ the actual semi–major axis that would produce the astrometric orbit if the mass of the secondary were exactly equal to the brown dwarf limit: $\mathcal{M}_2 = 0.08\mathcal{M}_\odot$. The significance of the test is derived again, discarding the stars with $a_{1_{bd}}/\sigma_{a_0}$ smaller than a given threshold. In practice, we consider successively the subsamples defined by $a_{1_{bd}}/\sigma_{a_0}$ larger than 0.5, 1, 2 and 3, because this amounts to discarding one more SB at each time. The results are summarized in Fig. 8. It appears from this figure that the most significant rejections of f_q are obtained when the 2 SBs with $a_{1_{bd}} < 1\,\sigma_{a_0}$ are discarded. When the selection is more severe, the number of SBs remaining in the sample is so small that the significance of the test is degraded.

The constant f_q is then finally rejected at the 1.2% level of significance. On the other hand, when this distribution is restricted to secondary masses larger than $\mathcal{M}_2 = 0.08\mathcal{M}_\odot$, it is

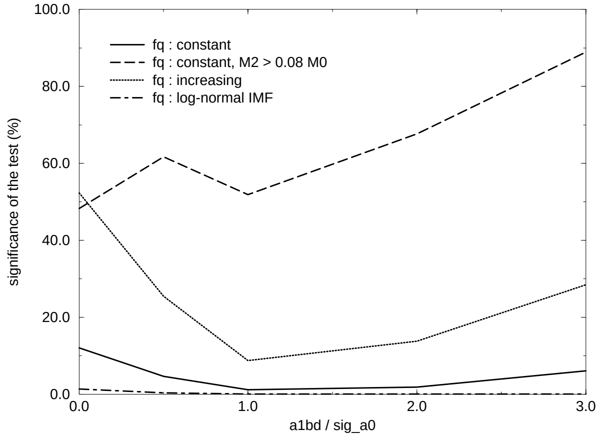

Fig. 8. The variations of the significance of the Kolmogorov–Smirnov test of $F_{a_0}(a_0)$, in relation with the frequency distribution of the mass ratios, f_q, and with the selection threshold of the sample, $a_{1_{bd}}/\sigma_{a_0}$; $a_{1_{bd}}$ is the semi–major axis that would have the astrometric orbit if $\mathcal{M}_2 = 0.08\mathcal{M}_\odot$.

very well accepted, with the 52% level. This does not mean that brown dwarf companions necessarily don't exist in close binaries: the rejection level of the increasing f_q is still 8.8% when $a_{1_{bd}}/\sigma_{a_0} > 1$. This distribution, which is defined for secondary masses close to zero, may then be considered as questionable, but it cannot be certainly rejected.

The Miller–Scalo log–normal distribution is severely rejected, with a significance of 0.09% for the selected sample. This result is not surprising, when the shape of this f_q is considered in Fig. 7: with a fast drop after a sharp maximum around 8 Jupiter masses, the vast majority of candidate brown dwarfs should be confirmed as true brown dwarfs. However, the large proportion of objects between 8 $\mathcal{M}_{Jupiter}$ and 0.08 $\mathcal{M}_\odot$ that provides the Miller–Scalo IMF was not directly derived from star counts. It comes from parameters that were chosen to fit actual star counts above the brown dwarf limit. We want to verify if a log–normal IMF would be rejected in any case. Since we don't know the errors of the parameters $b_\mathcal{M}$ and $c_\mathcal{M}$ in Eq. (6), we just considered two log–normal distributions of $\mathcal{M}_2$ with the maximum at $\mathcal{M}_{2_{Max}} = 0.08\ \mathcal{M}_\odot$: the former was ($b_\mathcal{M} = 2.2$, $c_\mathcal{M} = 0.1\ \mathcal{M}_\odot$); it is much sharper than the Miller–Scalo distribution, since $\sigma_{\ln \mathcal{M}}$ is now only 0.48 instead of 1.58. The latter was ($b_\mathcal{M} = 0.2$, $c_\mathcal{M} = 0.97\ \mathcal{M}_\odot$); the standard deviation is that of the Miller–Scalo distribution, but the maximum corresponds now to $\ln 0.97\ \mathcal{M}_\odot$. These distributions are both represented in Fig. 7. They are certainly too far from the original distribution to fit the IMF. Nevertheless, they are also rejected since they still contain too many light–mass companions. With the SBs having $a_{1_{bd}} > \sigma_{a_0}$, the significances of the tests are 0.08 and 0.6%, respectively. Therefore, if the IMF actually is a log–normal distribution, then the low–mass secondaries of solar–type close binaries certainly don't obey the IMF.

We want still to verify the robustness of our results. Two stars of our sample (HIP 13769 and HIP 63366) have the flag H52 set to "duplicity–induced variability", and although this flag is purely photometric, their astrometric solutions could, in principle, be disturbed by the luminosities of the additional companions. These perturbations should not be important, however: first at all, according to the Hipparcos catalogue, the flag "duplicity–induced variability" just "indicates entries where there is a possibility that the H_p magnitudes may be disturbed". In these cases, it seems unlikely that the measurements of any of these two stars were really perturbed: the former has a companion 0.5 mag brighter, but with a separation of 29 $''$, and the perturbation is considered as unlikely for separations larger than about 17 $''$; the latter has a companion too faint for contributing significantly to the brightness of the system. Moreover, the reliabilities of our solutions are confirmed by their goodness–of–fit. In spite of these arguments, the rejection thresholds are computed again by discarding these two stars from our sample. Again, we ignore the fact that one brown dwarf candidate (HIP 21482) was certainly rejected although our results are not relevant for its case. The number of stars with $a_{1_{bd}} > 1\,\sigma_{a_0}$ decreases then from 7 to 5, and the rejection threshold of the constant distribution is now exactly 10% (3.5% when only one star is discarded). Therefore, it is still dubious that this distribution corresponds to reality; again, it does not fit to the large number of brown dwarf candidates which are finally above the hydrogen–ignition limit. As previously, the log–normal IMF–like distribution is certainly rejected, since the threshold is still 2% (6% when $c_\mathcal{M} = 0.97\ \mathcal{M}_\odot$). At the opposite, although our sample includes HIP 50671, that was confirmed as brown dwarf at the $1\,\sigma_{\mathcal{M}_2}$ level, the constant distribution restricted to $\mathcal{M}_2 > 0.08\mathcal{M}_\odot$ is very well accepted at the 90% level. Therefore, the existence of this only confirmed brown dwarf is not sufficient to demonstrate that brown dwarf companions actually exist in solar–type close binaries: it may just come from statistical noise.

It is then concluded that the frequency of companions of solar–type stars is falling at lower masses below the hydrogen–burning limit. Moreover, it does not fit with a log–normal IMF distribution.

4. Conclusions

We used the astrometric measurements of Hipparcos to derive the masses of the brown dwarf candidates with reliable error intervals. 9 SBs with periods shorter than 3 years and $\mathcal{M}_2 \sin i$ between 14 and 61 $\mathcal{M}_{Jupiter}$ were considered, with the following results: 5 SB components were clearly ruled out as brown dwarf candidates by our analysis and a sixth one was still discarded independently. It would be possible to observe the stellar companions of 4 of these 6 SBs with IR imaging when adaptive optics are available on an 8–meter class telescope. On the other hand, no companion is confirmed as brown dwarf at the $2\,\sigma_{\mathcal{M}_2}$ level; only one has $\mathcal{M}_2 + \sigma_{\mathcal{M}_2} = 0.075\mathcal{M}_\odot$, just below the limit of hydrogen ignition.

A subsample of 7 SBs was extracted for investigating the feature of the distribution of mass ratios near the star–brown dwarf separation. A statistical method free of selection effects provides evidence that the astrometric semi–major axes of these systems are significantly too large to permit the frequency distribution of q to be constant when $\mathcal{M}_2$ is less than $0.08\mathcal{M}_\odot$. At the opposite, an excellent fit is obtained when it is assumed that brown dwarf companions don't exist in solar–type close binary systems, and that the distribution of mass ratios is constant for $\mathcal{M}_2 > 0.08\mathcal{M}_\odot$. However, the existence of brown dwarfs among the secondary components of close binaries cannot be excluded, and we can just conclude that the range between approximately 10 to 80 Jupiter masses corresponds to a minimum of the frequency distribution of $\mathcal{M}_2$.

Therefore, planets and stellar companions are probably belonging to two distinct classes of objects, as Butler & Marcy (1997) claimed, and contrary to the hypothesis of Black (1997). When only the minimum masses were considered (Butler & Marcy 1997, Mayor et al. 1998b), this distinction was not obvious, since the frequency of planets was emerging from a nearly constant distribution of secondary masses. Mazeh et al. (1998) found a gap between $\log(\mathcal{M}_2 \sin i/\mathcal{M}_\odot) = 1$ and $\log(\mathcal{M}_2 \sin i/\mathcal{M}_\odot) = 1.5$, but the rising branch for $\log(\mathcal{M}_2 \sin i/\mathcal{M}_\odot) > 1.5$ was just obtained by plotting the constant distribution of $\mathcal{M}_2 \sin i$ with a logarithmic scale. We have shown that the separation between planets and stellar companions actually exists in the distribution of $\mathcal{M}_2$, and not only in the distribution of $\log(\mathcal{M}_2 \sin i)$.

The formation of planetary systems and of binary stars is not unambiguously explained, and several models are possible. Two models are proposed for the giant planets. In the solar systems, they could have been formed by accretion of gas around rocky cores, or by gaz instability in the solar nebula (Pollack 1984). These models were both re–visited recently (Artymowicz & Lubow 1996, Boss 1997, Bodenheimer et al. 1999). They could explain the origin of planets as massive as 7 $\mathcal{M}_{Jupiter}$, and also the large eccentricities of the orbits (Artymowicz et al. 1998), or the close separations (Trilling et al. 1998). Like giant planets, the stellar secondary components of SBs are assumed to be formed in accretion disks. Several disk fragmentation processes are invoked (see references in Bonnell 1997). The minimum mass is not clearly fixed, but it ranges from about 10 $\mathcal{M}_{Jupiter}$ to 0.1$\mathcal{M}_\odot$ (Bonnell & Bastien 1992, see also references in Mazeh et al. 1998), in agreement with our result.

We also want to check whether the scarcity of brown dwarfs that we found among secondary components is apparent also in the IMF of single stars. It is obvious that the log–normal distribution of Miller & Scalo (1979) cannot be used for the low–mass companions in binary systems, since it provides an enormous amount of brown dwarfs. This distribution is not the only law that was proposed for the IMF, but it is the only one that is rising in the range of the low masses. The most common expression of the IMF is the linear log–log relation, first proposed by Salpeter (1955), that produces less and less stars when larger masses are considered. The rising branch of the log–normal distribution is permitted since it concerns objects with very small masses for which very few data are available. In fact, recent studies of the brown dwarf frequency in open clusters have shown that the IMF is a rather flat or slowly rising function of $\log \mathcal{M}$ near the stellar–substellar boundary (Martin et al. 1998, Hambly et al. 1999, Bouvier et al. 1998). Therefore, it may be concluded that the large number of rejections of candidate brown dwarfs that we obtain implies that *below the hydrogen ignition limit, the distribution of the masses of secondary components in short–period binary systems with solar–type primaries is not similar to the IMF*. A similar conclusion was derived by Reid & Gizis (1997) from a search of low–mass binaries with wide separations (14 to 825 a.u.). It seems then that the discrepancy between the IMF and f_q is observed on the whole range of separation.

In a forthcoming paper, the astrometric measurements of Hipparcos will be taken into account in the derivation of the distribution of the mass ratios of an unbiased sample of spectroscopic binaries. This will be an opportunity to extand the comparison between the IMF and f_q to the complete range of the mass ratios, and to derive other constraints about the process of binary star formation.

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Appendix A: Calculation of the distribution functions of a_0

The distribution function $F_{a_0}(a_0)$ is the probability to derive from the astrometric observations of Hipparcos a semi–major axis smaller than the one which was actually obtained. For each star, it depends on the standard deviation σ_{a_0}, the error distribution of a_0, the elements of the SB orbit, the mass of the primary component, and the frequency distribution of the mass ratios of binary stars, f_q. The uncertainties of $a_1 \sin i$ and of Π are sufficiently small to be ignored here. Therefore, hereafter, a_1 is the actual value of the semi–major axis of the astrometric orbit of the primary component, whereas the computation provides the value a_0 and the error σ_{a_0}.

We define the distribution function $F_{a_0|a_1,\sigma_{a_0}}(a_0)$ as the probability to derive a semi–major axis smaller than a_0, assuming fixed values for a_1 and σ_{a_0}. For a given SB, we call φ_{a_1} the frequency distribution of the possible values of a_1; φ_{a_1} depends on the SB orbital elements, the mass of the primary component, the parallax, and f_q. The functions F_{a_0}, $F_{a_0|a_1,\sigma_{a_0}}$, and φ_{a_1} are related by the equation:

$$F_{a_0}(a_0) = \int_{a_1 \sin i}^{a_{1_{Max}}} \varphi_{a_1}(a_1) \times F_{a_0|a_1,\sigma_{a_0}}(a_0)\, da_1 \qquad \text{(A.1)}$$

where $a_{1_{Max}}$ is the maximum value of a_1; it comes from $a_1 \sin i$, when $\sin i$ is derived from the ratio $f_\mathcal{M}/\mathcal{M}_1$, assuming $q = 0.7$; this upper limit of q is adopted since the SB should be double–lined if q were larger. $F_{a_0|a_1,\sigma_{a_0}}(a_0)$ is known, since it depends only on the distribution of the errors of a_0. Therefore, before calculating $F_{a_0}(a_0)$, we just need to compute $\varphi_{a_1}(a_1)$.

The value of $a_1 \sin i$ is fixed, and $\varphi_{a_1}(a_1)$ may be changed in the distribution of $X = 1/\sin i$, called $\varphi_{1/\sin i}(X)$. Since $a_1 = a_1 \sin i \times X$, Eq. (A.1) becomes:

$$F_{a_0}(a_0) = \int_1^{(\frac{1}{\sin i})_{Max}} \varphi_{1/\sin i}(X) \times F_{a_0|a_1,\sigma_{a_0}}(a_0)\, dX \quad \text{(A.2)}$$

with

$$(\frac{1}{\sin i})_{Max} = \frac{0.7 \times \mathcal{M}_1{}^{1/3}}{1.7^{2/3} \times f_{\mathcal{M}}{}^{1/3}} \quad \text{(A.3)}$$

since it is assumed that q cannot be larger than 0.7.

The problem is now to derive $\varphi_{1/\sin i}$, the frequency of $1/\sin i$ when the elements of the SB orbit are known, and assuming a frequency distribution of q. For a given SB, q depends only on $1/\sin i$, and $\varphi_{1/\sin i}$ is related to the overall frequency of $1/\sin i$, $f_{1/\sin i}$ by the relation:

$$\varphi_{1/\sin i}(X) \propto f_{1/\sin i}(X) \times f_q(q(X))\, dq(X) \quad \text{(A.4)}$$

where $q(X)$ is the solution of the equation:

$$\frac{q^3}{(1+q)^2} = X^3 \times \frac{f_{\mathcal{M}}}{\mathcal{M}_1} \quad \text{(A.5)}$$

Since the overall frequency of the inclinations is $f_i(i) = \sin i$, it is easy to derive $f_{1/\sin i}(X)$, and Eq. (A.4) becomes:

$$\varphi_{1/\sin i}(X) \;\propto\; \frac{1}{X^2\sqrt{X^2-1}} \times f_q(q(X)) \times \frac{q(X)\,(1+q(X))}{3+q(X)} \quad \text{(A.6)}$$

Finally, since $\varphi_{1/\sin i}(X)$ is a frequency distribution, it must also satisfy to the condition:

$$\int_1^{(\frac{1}{\sin i})_{Max}} \varphi_{1/\sin i}(X)\, dX = 1 \quad \text{(A.7)}$$

For any frequency distribution of the mass ratios, $F_{a_0}(a0)$ is thus computed for each brown dwarf candidate, by applying Eqs. (A.2), (A.3), and (A.5) to (A.7).

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