UPPER MASS LIMITS FOR KNOWN RADIAL VELOCITY PLANETS FROM HIPPARCOS INTERMEDIATE ASTROMETRIC DATA

Sabine Frink

Astronomisches Rechen-Institut Heidelberg, Mönchhofstrasse 12–14, 69120 Heidelberg, Germany
E-mail: sabine@ari.uni-heidelberg.de

ABSTRACT

For all 104 extrasolar planetary candidates known today, we calculate the expected peak-to-peak astrometric signatures, using the spectroscopic elements, primary star masses and the Hipparcos parallaxes. For those eight stars with expected astrometric signatures larger than 1 mas, we fit an orbital model to the Hipparcos Intermediate Astrometric Data, using again the spectroscopic elements; the only two free parameters in the fit are thus the inclination and the ascending node. In no case the astrometric signature of the companion is detected in the Hipparcos Data. However, the non-detection of this astrometric signatures places stringent constraints on the upper mass limits of the companions; in all eight investigated cases the substellar nature of the companion could be established. The derived 3σ upper mass limits are: $15\,\mathrm{M}_J$ for υ And d, $16\,\mathrm{M}_J$ for 14 Her, $44\,\mathrm{M}_J$ for HD 38529 c, $20\,\mathrm{M}_J$ for HD 33636, $2.5\,\mathrm{M}_J$ for ϵ Eri, $43\,\mathrm{M}_J$ for HD 168443 c, $31\,\mathrm{M}_J$ for HD 39091, and $6.3\,\mathrm{M}_J$ for 55 Cnc d. Three of those systems have been investigated before by Zucker & Mazeh (2001), and our results for υ And d and 14 Her are in excellent agreement. The results for ϵ Eri differ by about an order of magnitude. Zucker & Mazeh (2001) used somewhat different orbital elements for ϵ Eri, but the effect is too large to be caused by differences in the orbital elements. We caution however that our results for ϵ Eri and especially 55 Cnc d are less reliable because their orbital periods exceed the time baseline covered by the Hipparcos measurements.

1. INTRODUCTION

Radial velocity surveys have been extremely successful in discovering planets (see e.g. Marcy et al. 2000). However, from the radial velocities only the minimum mass $m_2 \cdot \sin i$ can be extracted. In contrast to that, all orbital parameters, including inclination, are accessible to astrometry. Almost all the stars harboring planets have been observed by Hipparcos, and even if the astrometric precision of Hipparcos is not sufficient to detect the astrometric signature of the planetary companion (see e.g. Pourbaix & Arenou 2001), its non-detection can provide upper mass limits in the substellar regime for many of the radial velocity planets.

This approach was first followed by Perryman et al. (1996), who examined the Hipparcos Intermediate Astrometric Data for the three radial velocity planets known at that time: 47 UMa, 70 Vir and 51 Peg. For none of those stars any indication of a companion was found in the Hipparcos data, but for 47 UMa a companion more massive than 7–22$\,\mathrm{M}_J$ could be excluded, while for 70 Vir the upper mass limit of any orbiting companion with the given spectroscopic parameters was 38–65$\,\mathrm{M}_J$. These upper mass limits unambigously established the substellar nature of the companions around 47 UMa and 70 Vir. In contrast to that, no meaningful upper mass limit for the short-period planet around 51 Peg could be derived.

Using the same technique, Mazeh et al. (1999) were able to derive an upper mass limit for the outermost planet in the υ And system of $10.1\,\mathrm{M}_J$. In a more systematic study, Zucker & Mazeh (2001) investigated the Hipparcos Intermediate Astrometric Data for all 47 known radial velocity planets at that time. For 13 systems altogether (including 47 UMa, 70 Vir and υ And) they were able to derive upper mass limits for the companions in the substellar regime from the non-detection of their orbits in the Hipparcos data, again establishing the substellar nature of those companions. An upper mass limit based on the Hipparcos data was also derived for the companion to the K giant primary ι Dra (Frink et al. 2002).

Similarly, McGrath et al. (2002) managed to place an upper limit on the mass of the companion to ρ^1 Cnc of about $30\,\mathrm{M}_J$ using astrometric observations acquired with the Hubble Space Telescope Fine Guidance Sensors. Using the same instrument, Benedict et al. (2002) were the first to really detect the astrometric signature of an extrasolar planet and to derive its mass; the companion to Gl 876 has a mass of $1.89\pm0.34\,\mathrm{M}_J$.

As the radial velocity surveys continue, extending their time baselines to 10 years and more, numerous planetary candidates with periods of several years or longer are being found. Since, in contrast to the radial velocity signal, the astrometric signature of an extrasolar planet is larger for larger periods, this increases the prospects of finding planets for which the astrometric signature can be more

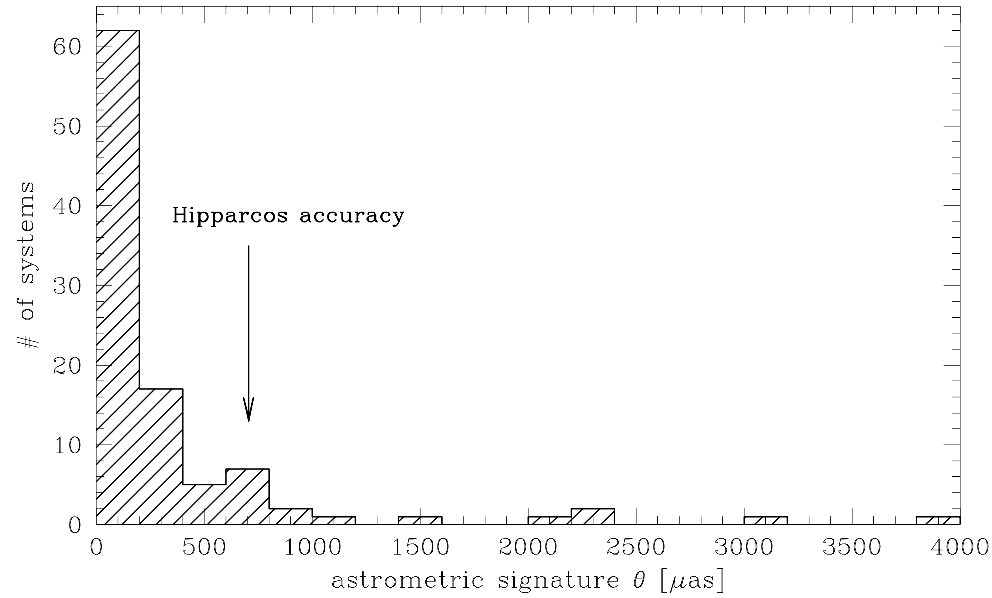

Figure 1. Histogram of the expected minimum astrometric signatures of all known 104 extrasolar planetary candidates known today. As can be seen, the planetary candidates found via radial velocity searches tend to have very small astrometric signatures, since the radial velocities are more sensitive towards smaller orbits and shorter periods, whereas the sensitivity of the astrometric method increases for wider orbits and longer periods. However, there are eight systems known today for which those expected minimum astrometric signature should be larger than 1 mas. The median end-of-mission positional accuracy of Hipparcos is indicated in the plot; note that the single measurement accuracy is considerably larger.

easily measured.

We have computed the expected astrometric signatures for all 104 extrasolar planetary candidates known today, and re-analyzed the Hipparcos Intermediate Astrometric Data for those eight stars with astrometric signatures of 1 mas and larger. Three of those stars had been investigated before by Zucker & Mazeh (2001); for the other five stars we derive new upper mass limits and thereby establish their substellar nature.

2. ASTROMETRIC SIGNATURES

The astrometric signature θ is defined as the total amount of angular displacement of the primary star in the course of one revolution of the primary and the unseen companion around their common center of gravity. For circular orbits, Kepler's Third Law gives, in appropriate units:

$$\theta_{\rm circ} = 191\,\mu{\rm as} \cdot \frac{P\,[{\rm yr}]^{2/3} \cdot m_2\,[{\rm M}_J]}{d\,[10\,{\rm pc}] \cdot m_1\,[M_\odot]^{2/3}}$$

Here, P is the period in years, m_2 the companion mass in Jupiter masses, d the distance in parsec, and m_1 the mass of the primary in solar masses. It can be seen that long periods and small primary star masses greatly enhance the astrometric sensitivity, as do small distances to the system and small primary star masses. For eccentric orbits, the geometric projection of the orbit as seen from earth has to be taken into account, so that the observed astrometric signature θ becomes:

$$\theta = \theta_{\rm circ} \cdot \sqrt{1 - (e \cdot \sin\omega)^2}$$

Here, e denotes the eccentricity, and ω denotes the longitude of the periastron.

We have computed the expected astrometric signatures for all of the 104 extrasolar planetary companions known to date, and plotted them as a histogram in Fig. 1. Note that the computed astrometric signatures are lower limits only, due to the unknown inclinations and companion masses. As can be seen, most astrometric signatures are quite low, well beyond what Hipparcos would have been able to measure. However, there are a few systems with expected astrometric signatures of 1 mas and larger, and those are listed in Table 1, along with the Hipparcos parallaxes, primary star masses, and periods and minimum companion masses as derived from the radial velocity curves that were used in the calculation of the astrometric signatures.

3. UPPER MASS LIMITS DERIVED FROM THE HIPPARCOS INTERMEDIATE ASTROMETRIC DATA

For those eight stars with expected astrometric signatures larger than 1 mas, listed in Table 1, we fitted an orbiting companion to the Hipparcos Intermediate Astrometric Data, following the procedure described in van Leeuwen & Evans (1998). The spectroscopic elements

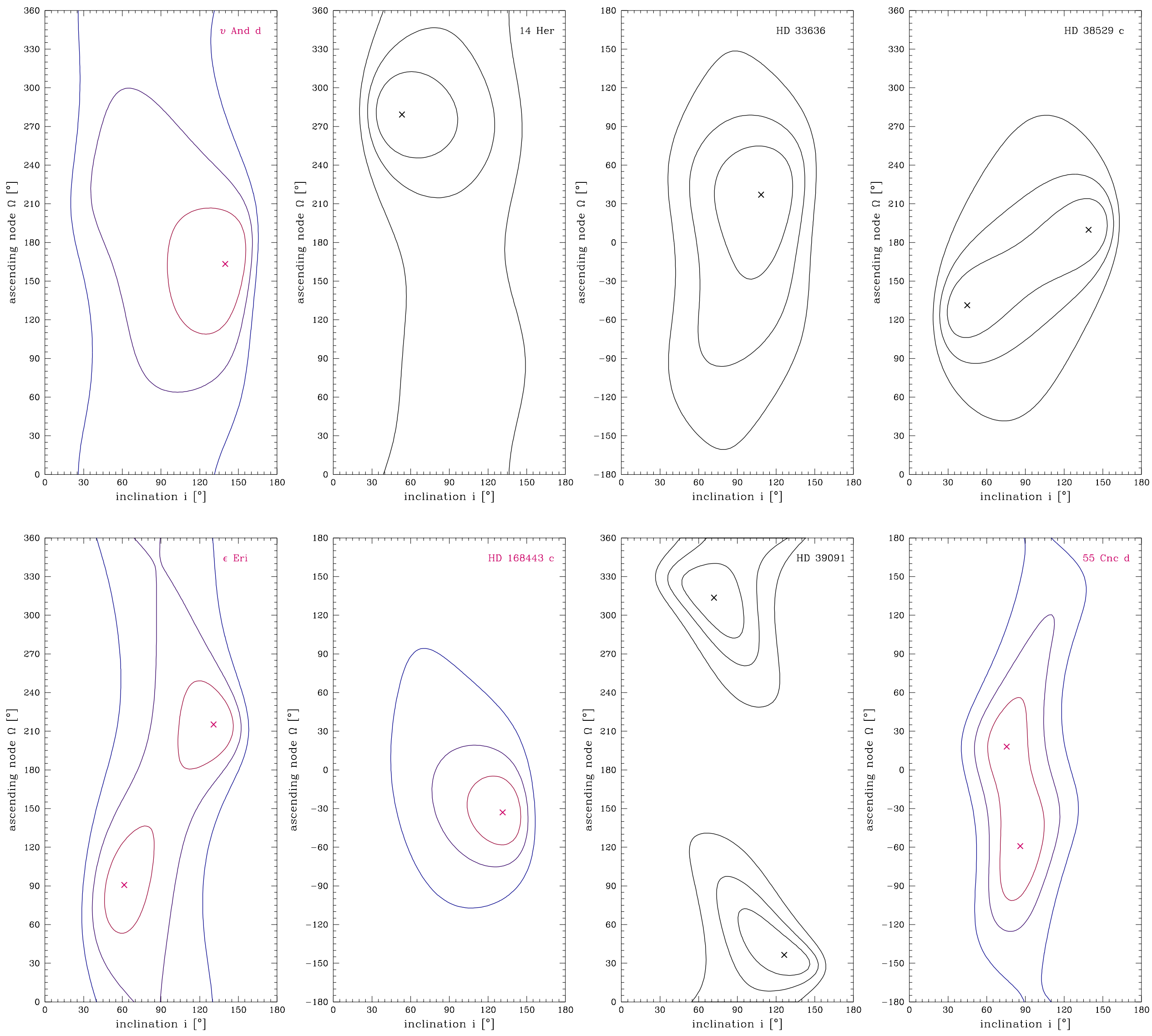

Figure 2. The plots show the 1, 2 and 3σ contours of planetary companion χ^2 fits to the Hipparcos Intermediate Astrometric Data for eight stars with known radial velocity planets. The only two free parameters in the fit were the inclination i (x-axis) and the ascending node Ω (y-axis); the other orbital elements were taken from the radial velocity fits, and the astrometric parameters were unchanged from the solution in the Hipparcos Catalogue. The crosses denote the formal minima of the fit, although in most cases the astrometric signature of the companion was not detected (and the contours span almost the entire parameter range). However, inclinations close to 0° or 180° can be excluded in all cases, which yields stringent upper limits on the companion masses.

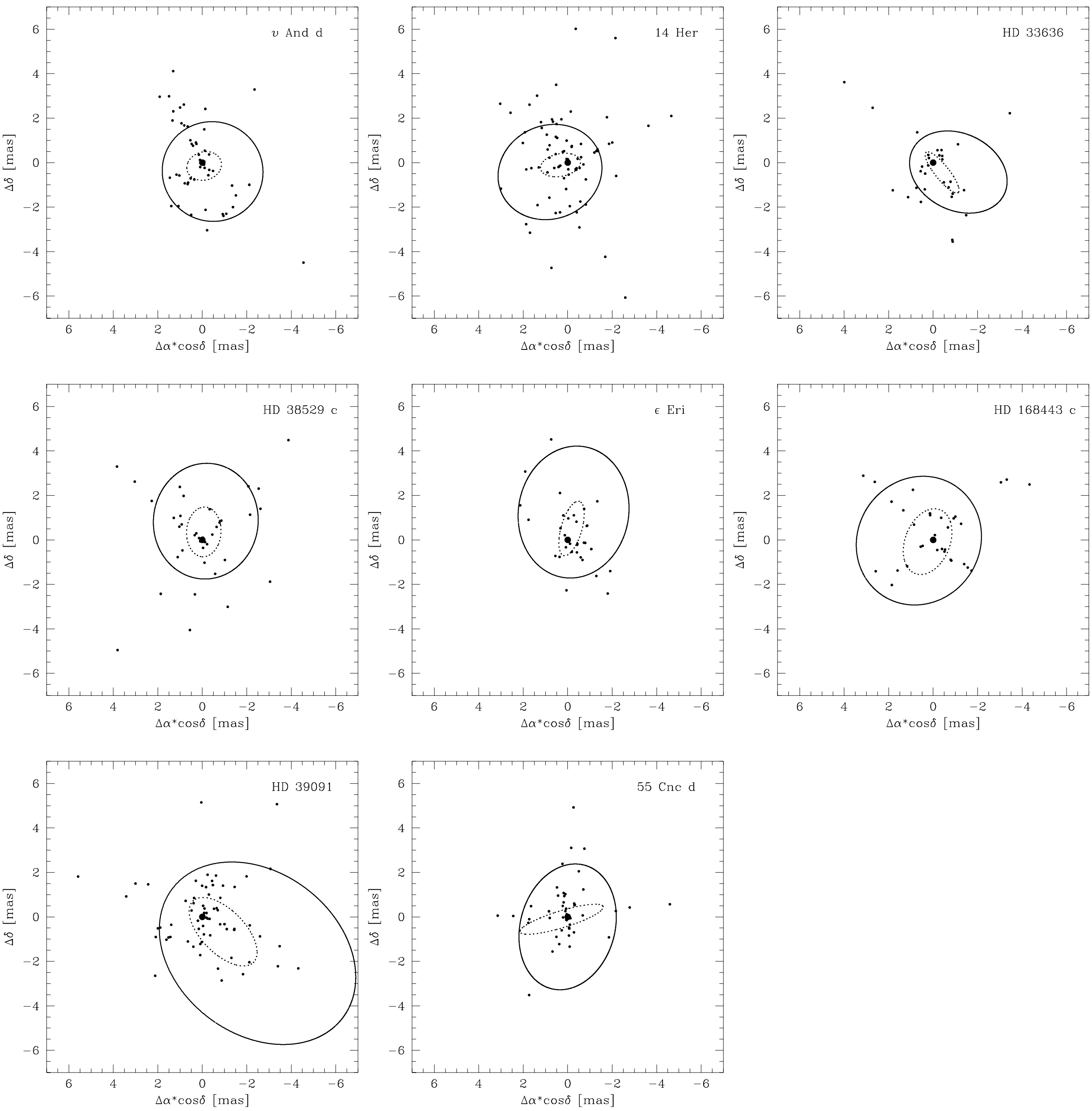

Figure 3. Illustration of the abscissa measurements and possible astrometric orbits fitted to them for all eight stars investigated. The small dots denote the individual abscissa residuals with respect to the single star solution given in the Hipparcos Catalogue; the mean position of the star according to that solution is indicated by the big dot at (0,0). The inner dashed line corresponds to the best-fit solution, whereas the outer solid line corresponds to the astrometric orbit with the highest mass that is consistent with the data (3σ limit, corresponding to the upper mass limits quoted in Table 1). The abscissa residuals from both data reduction consortia, FAST and NDAC, are plotted, so that the number of points in the plots is about twice as high as the actual number of measurements. The 1-dimensional measurements are indicated by dots for clarity; the actual position of the star at the time of measurement could be anywhere on the line running through the plotted dot and perpendicular to the connection of the dot and the mean position (big dot).

Table 1. Listed are those eight stars with known radial velocity companions that have expected astrometric signatures θ larger than 1 mas. Following the object identification in the first column, the Hipparcos number and the parallax π from the Hipparcos Catalogue along with its standard error are given in columns 2 and 3. The primary star mass M_1 which was used for the computation of the astrometric signatures is given in column 4, and columns 5 and 6 list the period P and the minimum companion mass $m_2 \cdot \sin\, i$ derived from the radial velocity solutions. The computed astrometric signature θ is given in column 7, and column 8 gives the 3σ upper limit on the companion mass, which was derived from a fit to the Hipparcos Intermediate Astrometric Data. Although astrometric motion is not detected in most cases, the Hipparcos data still allow to establish the substellar nature of all investigated companions.

Object	HIP no.	π [years]	M_1 [mas]	Period [M$_\odot$]	$m_2 \cdot \sin\, i$ [M$_J$]	θ [mas]	m_2 [M$_J$]
υ And d	7513	74.25 ± 0.72	1.3	3.5	3.8	1.0	< 15
14 Her	79248	55.11 ± 0.59	1.00	4.8	4.9	1.2	< 16
HD 38529 c	24205	34.85 ± 1.33	1.39	6.0	12.8	1.5	< 44
HD 33636	27253	23.57 ± 0.92	0.99	6.7	9.3	2.2	< 20
ϵ Eri	16537	310.75 ± 0.85	0.8	7.0	0.9	2.3	< 2.5
HD 168443 c	89844	26.40 ± 0.85	1.01	4.8	17.1	2.4	< 43
HD 39091	26394	54.92 ± 0.45	1.10	5.7	10.4	3.1	< 31
55 Cnc d	43587	79.80 ± 0.84	0.95	14.7	4.0	3.8	< 6.3

were taken from the initial discovery paper of the companion and any available updates from the corresponding website; the values we used for the spectroscopic elements of each investigated star, along with the appropriate references, are listed in Table 2.

The only two free parameters in the fit were the inclination i and the ascending node Ω; the other five astrometric parameters (position and proper motion in right ascension and declination and parallax) were unchanged from the solutions in the Hipparcos Catalogue.

The results of the χ^2 fits are shown in Figure 2. The solid lines denote the 1, 2 and 3σ contours of the χ^2 fit, while the crosses denote the formal minima of the fit. In some cases there are two minima, when the Hipparcos data did not clearly constrain the direction of the orbital motion. The fact that the χ^2 contours span large regions of the parameter space in most cases indicates that astrometric motion has not actually been detected. However, in all cases inclinations close to 0° or 180° can be excluded with high confidence, since otherwise the companion would have been so massive that Hipparcos would have seen the astrometric signature easily. Thus, these inclinations can be excluded, which yields upper limits on the companion masses. Those upper limits (conservatively derived from the 3σ contours) are listed in the last column in Table 1.

In all investigated cases the substellar nature of the companion could be established. In addition, in two cases (ϵ Eri and 55 Cnc d) the derived upper limits would even establish the *planetary* nature of the companion. However, these results have to be treated with caution since they correspond to the two longest orbits examined here, 7 years for ϵ Eri and 14.7 years for 55 Cnc d. In contrast to that, Hipparcos only measured for 3.4 years, so that part of the orbital motion may have been absorbed in the proper motion. We plan to test this possibility by using different proper motions that were derived from observations with a longer epoch difference. Furthermore, our result for ϵ Eri disagrees with that of Zucker & Mazeh (2001), who derived an upper mass limit of $22\,\mathrm{M}_J$, by almost an order of magnitude. Part of this discrepancy might stem from the fact that Zucker & Mazeh (2001) used somewhat different values for the spectroscopic orbital elements than we did here. The results for the other two stars in common between Zucker & Mazeh (2001) and our work, υ And d and 14 Her, are in excellent agreement.

Figure 3 gives an illustration of the Hipparcos measurements for all eight stars along with the possible astrometric orbits fitted to them. The individual Hipparcos abscissa residuals with respect to the mean position of the star are indicated by small dots; the actual measured position of the star at the observed epoch could be anywhere on a line running through this dot and perpendicular to the connecting line between the dot and the big dot symbolizing the mean position in the center. The inner dashed line indicates the formal best-fit astrometric orbit, whereas the outer line represents the orbit with the highest mass that would be consistent with the data at the 3σ level.

REFERENCES

Benedict, G.F., McArthur, B.E., Forveille, T., Delfosse, X., Nelan, E., Butler, R.P., Spiesman, W., Marcy, G., Goldman, B., Perrier, C., Jeffreys, W.H., Mayor, M., 2002, ApJ 581, L115

Butler, R.P., Marcy, G.W., Fischer, D.A., Brown, T.M., Contos, A.R., Korzennik, S.G., Nisenson, P., Noyes, R.W., 1999, ApJ 526, 916

Butler, R.P., Marcy, G.W., Vogt, S.S., Fischer, D.A., Henry, G.W., Laughlin, G., Wright, J.T., 2003, ApJ 582, 455

Table 2. The spectroscopic parameters that were used in the analysis of the Hipparcos Intermediate Astrometric Data for those eight stars with expected astrometric signatures larger than 1 mas.

Object	P [days]	T_0 [JD]	e	ω	a_2 [AU]	$m_2 \cdot \sin i$ [M$_J$]	references
υ And d	1284.	2450064.	0.27	260°	2.53	3.8	(3), (1)
14 Her	1753.1	2451353.8	0.38	15°	2.85	4.9	(4), (5), (1)
HD 38529 c	2447.3	2448764.	0.53	343°	3.56	12.8	(6), (1)
HD 33636	2207.4	2460043.7	0.33	13°	3.71	9.3	(7), (1)
ϵ Eri	2548.7	2448936.4	0.43	7°	3.40	0.9	(8), (9), (10), (1)
HD 168443 c	1739.5	2452014.5	0.23	64°	2.85	17.1	(11), (12), (2)
HD 39091	2063.8	2450060.2	0.62	331°	3.29	10.4	(13), (1)
55 Cnc d	5360.	2452785.	0.16	201°	5.9	4.0	(14), (1)

(1) updated elements on `http://www.exoplanets.org/` (2) updated elements on `http://obswww.unige.ch/~udry/planet/`
(3) Butler et al. 1999 (4) Udry et al. 2000 (5) Butler et al. 2003 (6) Vogt et al. 2002 (7) Fischer et al. 2001
(8) Campbell et al. 1988 (9) Cumming et al. 1999 (10) Hatzes et al. 2000 (11) Marcy et al. 1999 (12) Udry et al. 2002
(13) Jones et al. 2002 (14) Marcy et al. 2002

Campbell, B., Walker, G.A.H., Yang, S., 1988, ApJ 331, 902

Cumming, A., Marcy, G.W., Butler, R.P., 1999, ApJ 526, 890

Fischer, D.A., Marcy, G.W., Butler, R.P., Vogt, S.S., Frink, S., Apps, K., 2001, ApJ 551, 1107

Frink, S., Mitchell, D.S., Quirrenbach, A., Fischer, D.A., Marcy, G.W., Butler, R.P., 2002, ApJ 576, 478

Hatzes, A.P., Cochran, W.D., McArthur, B., Baliunas, S.L., Walker, G.A.H., Campbell, B., Irwin, A.W., Yang, S., Kürster, M., Endl, M., Els, S., Butler, R.P., Marcy, G.W., 2000, ApJ 544, 145

Jones, H.R.A., Butler, R.P., Tinney, C.G., Marcy, G.W., Penny, A.J., McCarthy, C., Carter, B.D., Pourbaix, D., 2002, MNRAS 333, 871

Mazeh, T., Zucker, S., Dalla Torre, A., van Leeuwen, F., 1999, ApJ 522, L149

Marcy, G.W., Butler, R.P., Vogt, S.S., Fischer, D., Liu, M.C., 1999, ApJ 520, 239

Marcy, G.W., Cochran, W.D., Mayor, M., 2000, in: *Protostars and Planets IV*, eds. V. Mannings, A.P. Boss, & S.S. Russell, University of Arizona Press, p. 1285

Marcy, G.W., Butler, R.P., Fischer, D.A., Laughlin, G., Vogt, S.S., Henry, G.W., Pourbaix, D., 2002, ApJ 581, 1375

McGrath, M.A., Nelan, E., Black, D.C., Gatewood, G., Han, I., Stepinski, T.F., Targett, T., 2002, ApJ 564, L27

Perryman, M.A.C., Lindegren, L., Arenou, F., Bastian, U., Bernstein, H.H., van Leeuwen, F., Schrijver, H., Bernacca, P.L., Evans, D.W., Falin, J.L., Froeschlé, M., Grenon, M., Hering, R., Høg, E., Kovalevsky, J., Mignard, F., Murray, C.A., Penston, M.J., Petersen, C.S., Le Poole, R.S., Söderhjelm, S., Turon, C., 1996, A&A 310, L21

Pourbaix, D., Arenou, F., 2001, A&A 372, 935

Udry, S., Mayor, M., Queloz, D., 2000, in: *Planetary Systems in the Universe*, IAU Sym. 202

Udry, S., Mayor, M., Naef, D., Pepe, F., Queloz, D., Santos, N.C., Burnet, M., 2002, A&A 390, 267

van Leeuwen, F., Evans, D.W., 1998, A&AS, 130, 157

Vogt, S.S., Butler, R.P., Marcy, G.W., Fischer, D.A., Pourbaix, D., Apps, K., Laughlin, G., 2002, ApJ 568, 352

Zucker, S., Mazeh, T., 2001, ApJ 562, 549