

PRELIMINARY ASTROMETRIC MASSES FOR PROPOSED EXTRASOLAR PLANETARY  
COMPANIONS

Short Title: Preliminary Masses of Planetary Companions

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## ABSTRACT

As a first step in the implementation of an astrometric survey we have reduced the *Hipparcos* Intermediate Astrometric Data (IAD) for 30 stars that currently exhibit small amplitude periodic radial velocity variations. We only consider systems with periods longer than 10 days, where the motion is attributed to the presence of an “extrasolar planetary companion” to the star. While our results are to be used as guidance in the selection of targets for confirmation with the Multichannel Astrometric Photometer (MAP) (Gatewood 1987), and future space-based astrometric missions (e.g., FAME, SIM), they have implications for our understanding of these companions. Our initial results from this data set indicate that true, as contrasted with minimum, companion masses range from stellar to astrometric limits that indicate substellar mass, however only one of which is near the minimum mass obtained by radial velocity observations. Although our studies should be considered preliminary until additional astrometric data is available, they are suggestive of a characteristic that appears to be common to a significant fraction of these systems, small  $\sin(i)$ . This in turn suggests that the sample of stars that have been examined for possible planetary mass companions may be biased. Moreover, if correct, these results provide a natural explanation for the fact that the orbital properties of these “extrasolar planets” are statistically indistinguishable from those of binary stars.

Subject Headings: Stars: Planetary Systems, Stars: Binaries: Spectroscopic

## 1. INTRODUCTION

High-precision radial-velocity studies (e.g., Extrasolar Planets Encyclopedia, Extrasolar Planet Search) have detected small, but periodic, variations in the motion of 46 stars. This motion is generally interpreted as indicating the presence of companions with minimum masses ranging from approximately 1 to 10 Jupiter masses. It has become customary for detection papers to announce these companions as “extrasolar planets”, with this characterization based solely on the assumption that the true masses of these companions are statistically not much different than the minimum masses obtained by the radial velocity studies. This arises from the assumption that the distribution of line-of-sight angles is random. Other authors (Black 1997, Heacox 1999, Stepinski and Black 2000) have noted the similarity in orbital properties between all of these low-mass companions and stellar binaries, and suggest that alternative interpretations to that of planetary bodies must be considered.

In addition to these 46 stars, radial velocity studies have detected similar periodic behavior in 11 stars, where the minimum masses fall in the range of  $\sim 17$  to 60 Jupiter masses. Interestingly, and germane to the results of our study, a subsequent analysis (Halbwachs et al. 2000) of *Hipparcos* data on those 11 stars have shown that the majority of the companions are stellar. That is, the systems that appeared to have companions whose minimum masses were in the brown dwarf mass range have relatively small inclination to our line-of-sight to the star. In many ways the study by Halbwachs and collaborators anticipated the work presented here.

A determination of the true mass of these companions is equivalent to a determination of the inclination of their orbital planes to the line-of-sight. Orbit plane inclinations can be determined by other techniques such as estimating the rotation axis of the primary (e.g., Cochran et al. 1991) and observing the transit by the companion (e.g., Charbonneau et al. 2000, Henry et al. 2000). The latter technique provides a direct assessment of the inclination of the transiting object orbit plane to our line-of-sight, whereas the former requires an assumption as to the orientation of the companion orbit plane to the rotation axis of the star (the assumption typically is that the normal to the plane is parallel to the rotation axis).

Astrometric data can also provide a determination of the inclination. To our knowledge there are only three previous astrometric studies to determine the inclination of systems that are among the 46 stars

asserted to have planetary mass companions. Perryman et al. (1996) utilized the *Hipparcos* IAD to study the stars 51 Peg, 47 UMa, and 70 Vir, while Mazeh et al. (1999), and Zucker and Mazeh (2000) utilized the *Hipparcos* IAD to study Upsilon Andromedae and HD10697 respectively. Virtually all of the suspect primary stars are bright enough to have been included in the *Hipparcos* Catalogue (ESA 1997). The only existing high precision astrometric instrument with the ability to observe these stars and thus extend the *Hipparcos* data set is the Thaw-red-light refractor and its MAP instrument (Gatewood 1987). The Allegheny Observatory began observations of these stars in April of 1999. The program has already resulted in a detection and an associated revised mass for the companion object to the star Rho CrB (Gatewood et al. 2001).

## 2. DATA REDUCTION

The methodology that we used is that given by van Leeuwen & Evans (1998). Our algorithm is similar to, but different than the one described by Mazeh et al.(1999). First we adopt and fix the spectroscopic orbital elements,  $P$ ,  $e$ ,  $T_0$ , and  $\omega$ . We also calculate an astrometric  $a \sin(i)$  using the spectroscopic orbital parameters and the parallax given by IAD in order to facilitate determination of the orbit. In the  $\chi^2$  minimization procedure we fixed  $a \sin(i)$ , from the beginning. (This is similar to the  $K$  constraint described by Zucker and Mazeh, but they apply this after the minimization process.) This results in seven free parameters to be determined. Because the astrometric orbit we are looking for is comparable to the accuracy of IAD, it is virtually impossible to get a satisfactory solution without the  $a \sin(i)$  constraint. We did not take into account the uncertainty of the adopted spectroscopic elements, as the uncertainty of the derived astrometric orbit is dominated by the error of IAD. This procedure often gives two local solutions around  $i = 0$  and  $i = 180$  degree when  $a \sin(i)$  is very small (e.g., Fig. 2 in Mazeh et al.1999 and in Gatewood et al. 2001). We always compared the two local solutions to find the global solution.

The quality of the derived orbital parameters largely depends on the number of data points and their distribution over orbital phase. As *Hipparcos* data are one dimensional, with the angles of measurement not random, we may reasonably suppose that approximately 14 abscissa values are needed to fix 7 free parameters. We found that the solution is generally poor if the number of abscissa values is less than 20. Though IAD gives two abscissa values reduced by FAST and NDAC consortia from the same observation, they are really one data point. We used the abscissa values from both FAST and NDAC consortia by calculating their covariance matrix as described by van Leeuwen & Evans (1998).

An unfortunate characteristic of astrometric orbit determination is that the derived astrometric semi-major axis ( $\alpha$ ) is overestimated. This is serious when  $\alpha$  is small compared to the accuracy of the data. Because we fix  $a \sin(i)$ , overestimation of  $\alpha$  results in underestimation of inclination and overestimation of the companion's mass. Halbwachs et al.(2000) studied the overestimation of  $\alpha$  analytically, pointing out the similarity to that of a Rayleigh distribution. We did Monte Carlo experiments to investigate statistical characteristics of the overestimation of  $\alpha$ . We generated artificial abscissa data using the same configuration, i.e. the same epoch and great circle angles found in the IAD. We also used the same spectroscopic orbital elements and assigned an assumed value of the semi-major axis,  $\alpha$ -actual. Then we added random errors with a standard deviation equal to that given by the IAD to the artificial abscissa data. For each  $\alpha$ -actual, we generated 500 data sets and calculated the semi-major axis,  $\alpha$ , inclination, and node. Table 1 shows the computed  $\alpha$  for each  $\alpha$ -actual.

We have divided the 30 stars into four groups with the stars ordered within each group according to increasing value of the ratio ( $R$ ) of the estimated orbit semi-major axis to its standard error. The characteristics of the four groups are summarized below:

Group 1 (stars 1 - 9): The average  $R$ -value, 1.24, is the lowest among the four groups. That indicates that as a group most of the values given for the companion mass ( $M_2$ ) should be considered as mass caps. Taking the overestimation statistics into consideration, we estimate that the true mass for most of these objects is probably of order or less than 10 -15 Jupiter masses.

Group 2 (stars 10 - 20): The average R-value for this group is 1.77. Based upon the higher R-values it would appear that most of these companions have true masses that fall in the range from roughly 15 to 80 Jupiter masses. That is, the majority of the companions in this group are likely to be brown dwarfs.

Group 3 (stars 21 - 24): This group has the highest average R value (2.73) The resultant values for  $M_2$  suggest that these companions are probably M dwarf stars. We note that the inclinations of this group are extremely small. This small inclination is due to the very small  $a \sin(i)$  adopted from the spectroscopic elements. Because  $a \sin(i)$  is very small, we can only detect an astrometric perturbation if the inclination is very small. Even though we allow for a factor of three underestimation in inclinations, the average inclination is less than one degree. If the inclination of companion orbits is randomly distributed, the probability of finding an inclination less than one degree is only 0.00015. We suspected that the small inclination may be due to the small  $a \sin(i)$  value adopted. However our Monte Carlo experiments shows that the estimated semi-major axis is relatively insensitive to the value  $a \sin(i)$  adopted. Still we cannot exclude the possibility that the detected astrometric perturbation is a statistical artifact. We also point out that the spectroscopic orbits of HD 6434 and HD 38529 do not seem to be well determined (see the references for these objects). Also, the periods of these objects are rather short, and the astrometric orbit determination is very sensitive to the input value of the period. For the objects of this group, another astrometric observation is indispensable to confirm the reality of the astrometric perturbation. In the case of Rho CrB, MAP observations did confirm the reality of the perturbation (Gatewood et al. 2001).

Group 4 (stars 25 - 30): This group has the second lowest average R-value (1.45). Moreover, this group contains objects with a small number of data points, which in turn results in a large standard error of  $\alpha$ . For these reasons, we feel that the estimated astrometric parameters are very uncertain. HD 114762, a member of this group, has been suspected to have low inclination (Marcy et al. 1999 and references therein). It is unfortunate that *Hipparcos* IAD has too few data points to estimate a reliable inclination for this system.

### 3. DISCUSSION AND CONCLUSIONS

As noted in the Introduction, other workers have conducted similar, independent analysis of *Hipparcos* data on some of the stars included here. The star Ups And is in Group 1 and our estimate for  $M_2$  agrees well with the value given by Mazeh et al.(1999). The one member of Group 4 with a relatively high R-value is HD10697. Our estimate for the companion mass for that object is almost identical to that obtained independently by Zucker and Mazeh. Our values for the companion masses for stars 70 Vir and 47 UMa differ from those given by Perryman et al. who used fewer constraints in their analysis.

One of distinctive features of Table 2 is that the inclinations are generally small. Of course we have to take into account that the listed inclinations are underestimated. However, even applying a factor of two correction to the inclination of Group 2, we find the average inclination of that group is 8.4 degrees. If the inclination of the target stars is randomly distributed the probability that we would find an inclination of less than 10 degrees is just 1.5 %. If the small inclinations in Table 2 are real, the orbits of the radial velocity companions are severely biased toward small inclinations. The bias to small inclination differs from the usual tendency, due simply to geometry, to detect high inclinations in spectroscopic binaries, and that may be telling us something about the sample of target stars that have been used in the radial velocity searches for low mass companions.

It is worth repeating that a similar analysis (Halbwachs et al. 2000) of 11 companions detected by radial velocity searches and with minimum masses in the range from roughly 17 to 60 Jupiter masses showed that a very high fraction of those systems have small values of  $\sin i$ . This is consistent with our findings for the companions with lower minimum masses. Possible causes for such a bias in the radial velocity surveys include pre-selection for binary systems (stellar or brown dwarf) seen more pole on as the planet hunters generally focus on stars thought to be "single" based on binary searches with less accurate instruments, as well as the tendency to focus on systems with low "jitter". It is conceivable that this stellar parameter has a latitude dependence on a star, so that stars with low jitter are more likely to be systems viewed pole on. Some support for this can be found in the fact that many of the stars seen here to have

low inclination angles also have remarkably small values of  $v \sin i$ . (Black et al. 2001).

There are independent means of checking our results, particularly the systems where our estimated masses are consistent with low-mass stellar companions. A technique developed by Simon and collaborators (Mazeh et al. 2000) uses both visible and IR observations to turn single line binaries into double line systems. Observations using that methodology could determine whether any of the apparently more massive companions are correctly identified in our analysis. Additional astrometric observations with the Allegheny Observatory MAP system have proved valuable in increasing our understanding of these systems (Gatewood et al. 2001). More accurate observations using either ground-based or space-based interferometers (e.g. FAME and SIM) that are one to two orders of magnitude more accurate than Hipparcos would also either corroborate or refute the inferences drawn in this paper.

In summary we conclude that it appears that the line-of-sight inclinations of the low minimum mass companions detected to date, those generally referred to as “extrasolar planets”, appear to be biased toward small inclination angles. Our results suggest that a significant fraction (Groups 2 and 3 in Table 2) of the 30 companions that we analyzed are brown or M dwarfs, not planetary mass objects. We again emphasize that the finding in this study is preliminary and should be confirmed by further astrometric and other observations.

We thank Joost Kiewiet de Jonge, Tom Stepinski, and the referee for useful comments on the paper. DCB is supported under contract NASW-4574 with the National Aeronautics and Space Administration.

## REFERENCES

- Black, D.C., 1997, ApJ, 490, L171
- Black, D.C., Stepinski, T., Kiewiet de Jonge, J., Han, I. & Gatewood, G.D., 2001, In preparation
- Butler, R. P. & Marcy, G. W., 1996, ApJ, 464, L153
- 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., Williams, E., Hauser, H. & Shirts, P., 1997, ApJ., 474, L115
- Butler, R. P., Vogt, S. S., Marcy, G. W., Fischer, D. A., Henry, G. W. & Apps, K., 2000, ApJ submitted
- Charbonneau, D. Brown, T.M., Latham, D.W., & Mayor, M., 2000, ApJ, 529, L45.
- Cochran, W. D., Hatzes, A. P., & Hancock, T. J., 1991, ApJ, 380, L35
- Cochran, W. D., Hatzes, A. P., Butler, R. P. & Marcy, G. W., 1997, ApJ, 483, 457
- ESA 1997, The *Hipparcos* and Tycho Catalogs, ESA SP-1200 Noordwijk:ESA
- Extrasolar Planets Encyclopedia, Home Page <http://www.obspm.fr/encycl/encycl.html>
- Extrasolar Planet Search, Home Page <http://exoplanets.org/>
- Fisher, D., Marcy, G.W., Butler, R.P., Vogt, S.S., & Apps, K. 1999, PASP 111, 50
- Fischer, D. A., Marcy, G. W., Butler, R. P., Vogt, S. S., Frint, S. & Apps, K., 2000, ApJ submitted
- Geneva Extrasolar Planet Search Programs, Home page <http://obswww.unige.ch/~udry/planet/planet.html>
- Gatewood, G. 1987, AJ 94, 213
- Gatewood, G., Stein, J., Kiewiet de Jonge, J., Persinger, T., Reiland, T., & Stephenson, B. 1992, A.J. 104, 1237.
- Gatewood, G., Han, I. & Black, D.C., 2001, To appear in Ap. J
- Halbwachs, J.L., Arenou, F., Mayor, M., Udry, S., & Queloz, D. 2000, A.&A. 355, 581
- Heacox, W.D., 1999, ApJ, 526, 928
- Heintz, W.D. 1978, Double Stars, D.Reidel Pub. Co., London
- Henry, G.W., Marcy, G.W., Butler, P. R., & Vogt, S.S., 2000, ApJ, 529, L41.
- Kurster, M., End, M., Els, S., Hatzes, A.P., Cochran, W.D., Dobereiner, S., & Dennerl, K., 2000, A&A 353, L33
- Korzennik, S. J., Brown, T. M., Fisher, D. A., Nisenson, P. & Noyes, W., 2000, ApJ, 533, L147
- van Leeuwen, F., & Evans, D.W. 1998, A&AS, 130, 157
- Marcy, G. W. & Butler, R. P., 1996, ApJ, 464, L147
- Marcy, G. W., Butler, R. P. & Vogt, S. S., 2000, ApJ, 536, L43
- Marcy, G. W., Butler, R. P., Vogt, S. S., Fischer, D., & Lissauer, J. J., 1998, ApJ, 505, L147
- Marcy, W. M., Butler, R. P., Vogt, S. S., Fischer, D. and Liu, M. C., 1999, ApJ 520, 239
- Mazeh, T., Zucker, S., Torre, A. D., & van Leeuwen, F. 1999, ApJ, 522, L149
- Mazeh, T., Prato, L. and Simon, M., 2000, IAU Coll. 200 in Birth and Evolution of Binary Stars, Poster Papers, B. Reipurth and H Zinnecker, eds., pg 22
- Noyes, R.W., Contos, A.R., Korzennik, S.G., Nisenson, P., Brown, T.M., & Horner, S.D. 1998, IAU Colloquim #170.
- Noyes, R.W., Jha, S., Korzennik, S.G., Krockenberger, M., Nisenson, P., Brown, T.M., Kennelly, E.J. & Horner, S.D. 1997, ApJ. L 483, L111.
- 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., Froeschle, M., Grenon, M., Hering, R., Hoeg, E., Kovalevsky, J., Mignard, F., Murray, C.A., Penston, C.S., Le Polle, R.S., Söderhjelm, S., & Turon, 1996, A&A, 310, L21
- Queloz, D., 2000, A&A, 354, 99
- Stepinski, T. & Black, D.C., 2000, A&A, 356, 903
- Vogt, S. S., Marcy, G. W., Butler, R. P. and Apps, K., 2000, ApJ, 536, 902
- Zucker, S., & Mazeh, T., 2000, ApJ, 531, L67

Table 1  
 $\alpha$  for different actual  $\alpha$  values

$\alpha$ -actual	$\alpha$ -mean	SD	SE
0.2	0.79	0.46	0.69
0.3	0.81	0.42	0.69
0.4	0.88	0.48	0.69
0.5	0.98	0.52	0.69
0.6	1.03	0.48	0.70
0.7	1.08	0.53	0.70
0.8	1.16	0.56	0.71
0.9	1.23	0.58	0.71
1.0	1.31	0.59	0.71
1.5	1.70	0.62	0.73
2.0	2.16	0.71	0.73
2.5	2.63	0.70	0.74
3.0	3.14	0.67	0.72

Notes:  $\alpha$ -actual is the input value. All units are mas (milli arcsecond). The adopted  $a*\sin(i) = 0.137$ .  $\alpha$ -mean and SD are the mean and standard deviation of the calculated  $\alpha$  from 500 simulated data sets. SE is the mean of the standard error of  $\alpha$  given by least squares method. The orbit configuration of the simulation is from HD190228 of IAD.

Table 1 clearly shows the overestimation tendency of the calculated semi-major axis. The percentage of over estimation, however, decreases rapidly for larger  $\alpha$ actual. For  $\alpha$ -actual = 1.0, the overestimation is about 30 %. To a good degree of precision, one can calculate the actual value of  $\alpha$  from the formula  $\alpha$ -actual =  $(\alpha^2 - 1.3 SE^2)^{1/2}$ .

Table 2  
Summary of Parameters

#	R	OBJECT	MSINI	ASINI	N	$\alpha$	SE	i	M2	Ref	note
1	0.4	Gliese86	4.00	0.050	34	0.18	0.47	164.0	15	17	a
2	0.9	HD1237	3.32	0.099	40	0.48	0.51	11.8	16	1	
3	0.9	HD134987	1.58	0.045	17	0.95	1.09	2.7	34	4	
4	1.0	47UMA	2.60	0.339	28	0.38	0.39	63.1	2.9	3	b
5	1.1	70Vir	7.44	0.171	28	0.61	0.55	16.1	27	11	
6	1.5	16CygB	1.68	0.125	37	1.06	0.69	173.0	14	5	
7	1.5	HD210277	1.28	0.069	25	0.95	0.63	175.8	18	6	
8	1.7	14Her	5.44	0.579	39	1.39	0.84	155.3	13	1	
9	2.2	UpsAndd	4.29	0.574	26	1.38	0.64	155.5	10	2	c
10	1.6	HD82943	2.24	0.086	24	1.37	0.88	176.4	36	1	
11	1.6	HD12661	2.83	0.054	26	1.08	0.66	2.9	56	7	
12	1.6	HD169830	2.96	0.029	21	1.01	0.63	178.3	102	1	
13	1.6	55Cnc	0.88	0.008	24	1.15	0.72	179.6	126	16	
14	1.7	HD222582	5.29	0.164	21	1.83	1.08	5.1	59	4	
15	1.7	HD202206	14.7	0.258	35	1.34	0.79	11.1	76	1	
16	1.8	HD177830	1.22	0.019	48	0.86	0.49	1.3	55	4	
17	1.8	HD89744	7.17	0.111	25	1.50	0.85	175.8	97	9	
18	1.9	HD92788	3.86	0.104	18	1.44	0.75	176.0	54	7	
19	2.1	IotaHor	2.26	0.113	38	1.18	0.57	5.5	24	8	
20	2.1	HD190228	5.00	0.137	56	1.25	0.60	6.3	45	1	
21	1.6	HD38529	0.77	0.002	24	1.12	0.69	0.1	435	7	e
22	1.9	HD6434	0.48	0.002	39	1.24	0.67	179.9	296	1	
23	3.6	RhoCrB	0.99	0.014	40	1.60	0.44	0.5	115	14	f
24	3.8	HD195019	3.47	0.012	23	2.50	0.66	0.3	713	15	
25	1.0	HD16141	0.22	0.002	16	1.01	1.02	0.1	111	12	
26	1.0	HD192263	0.81	0.007	24	0.74	0.76	179.5	82	4	
27	1.1	HD52265	1.07	0.017	24	0.65	0.57	178.5	41	10	
28	1.2	HD37124	1.04	0.018	18	2.06	1.74	179.5	119	4	
29	1.2	HD114762	11.0	0.111	15	1.47	1.22	4.3	145	6	
30	2.9	HD10697	6.35	0.358	16	2.12	0.73	170.3	38	4	d

Table 2 Notes: If possible, we used updated orbital elements from the Web pages of the primary institutions of the discoveries. R is the ratio of the estimated semi-major axis and its standard error. ASINI is calculated from the spectroscopic orbital elements and parallax. MSINI is given by each reference. N is the number of observations in IAD.  $\alpha$  is the estimated value of semi-major axis in mas. SE is the estimated standard error of  $\alpha$ . M2 is the estimated mass (in units of Jupiter mass) of the companion calculated from MSINI/sin(i).

Notes:

- (a) Changing P to 15.946 days results in  $a = 1.28 \pm 0.27$  mas;
- (b) IAD shows large residuals, may have an unmodeled perturbation,
- (c) see also Mazeh et al. (1999),
- (d) see also Zucker et al. (2000),
- (e) acceleration solution for proper motion
- (f) published by Gatewood, Han and Black 2000.

References.- (1) The Geneva EPSP Home page; (2) Butler et al. 1999; (3) Butler and Marcy 1996; (4) Vogt et al. 2000; (5) Cochran et al. 1997; (6)

Marcy et al. 1999; (7) Fischer et al. 2000; (8) Kurster et al. 2000; (9) Korzennik et al.2000; (10) Butler et al. 2000; (11) Marcy and Butler 1996; (12) Marcy et al. 2000; (13) Marcy et al. 1998; (14) Noyes et al. 1997; (15) Fischer et al.