The Astrophysical Journal, 531:L67–L69, 2000 March 1

ANALYSIS OF THE *HIPPARCOS* MEASUREMENTS OF HD 10697: A MASS DETERMINATION OF A BROWN DWARF SECONDARY

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Received 1999 November 22; accepted 2000 January 3; published 2000 February 4

ABSTRACT

HD 10697 is a nearby main-sequence star around which a planet candidate has recently been discovered by means of radial velocity measurements (Vogt et al.). The stellar orbit has a period of about 3 yr, the secondary minimum mass is 6.35 Jupiter masses (M_J), and the minimum semimajor axis is 0.36 mas. Using the *Hipparcos* data of HD 10697 *together* with the spectroscopic elements of Vogt et al., we found a semimajor axis of 2.1 ± 0.7 mas, implying a mass of 38 ± 13 M_J for the unseen companion. We therefore suggest that the secondary of HD 10697 is probably a brown dwarf, orbiting around its parent star at a distance of 2 AU.

Subject headings: astrometry — planetary systems — stars: individual (HD 10697)

1. INTRODUCTION

More than 20 candidates for extrasolar planets have been announced over the past 4 years (e.g., Mayor & Queloz 1995; Noyes et al. 1997; Marcy & Butler 1998; Marcy, Cochran, & Mayor 2000). In each case, very precise stellar radial velocity measurements, with a precision of 10 m s^{-1} or better, indicated the presence of a low-mass unseen companion orbiting a nearby solar-type star. These high-precision discoveries came almost a decade after the first "planet candidate" around HD 114762 was discovered (Latham et al. 1989; Mazeh, Latham, & Stefanik 1996) with much lower precision. In most cases, the individual masses of the companions are not known because the inclination angles of their orbital planes relative to our line of sight cannot be derived from the spectroscopic data. The minimum masses for all candidates, attained for an inclination angle of 90°, are in the range 0.5–10 Jupiter masses (M_J).

To derive the actual mass we need additional information, like precise astrometry of the orbit, from which we can derive the inclination and therefore the secondary mass. This can be done at least for the cases in which the primary mass can be estimated from its spectral type. At present, the astronomical community has at hand the accurate astrometric *Hipparcos* data, which have already yielded numerous orbits with small semimajor axes (Perryman 1997; Söderhjelm 1999), down to a few milliarcseconds. Perryman et al. (1996) indeed used the *Hipparcos* data to constrain the orbits of some planet candidates.

The *Hipparcos* data, which span about 3 yr, can be most effective for systems with periods comparable to the lifetime of the satellite mission. Since the time base of the precise radial velocity surveys is getting longer, we expect more such planets to be discovered. Such an example was the outermost planet of υ And, whose period was found to be close to 3 yr. Mazeh et al. (1999) used the *Hipparcos* data *together* with the spectroscopic data of υ And to get a mass of $10.1^{+4.7}_{-4.6}$ M_J for the outermost known planet of that system. That work has shown the great potential of the combination of spectroscopic data and *Hipparcos* measurements to derive masses for planet candidates.

Very recently Vogt et al. (2000) detected radial velocity evidence of six new planet candidates. One of these stars is HD 10697, with a period of 1072 ± 10 days and a companion lower mass estimate of 6.35 M_J. The minimum semimajor axis of the stellar orbit was found to be 0.36 mas. In this Letter, we follow Mazeh et al. (1999) and combine the spectroscopic elements with the *Hipparcos* data to find that the unseen companion has a mass of about 40 M_J. We therefore suggest that the secondary is probably a brown dwarf in close orbit, of about 2 AU, around its parent star.

2. THE *HIPPARCOS* ASTROMETRY

HD 10697 (109 Psc, HIP 8159; $\alpha = 01^h44^m55^s.82$, $\delta = +20°04'59''.34$ [J2000]; $V = 6.3$) is a G5 IV star whose mass is estimated by Vogt et al. (2000) to be 1.10 $M_\odot$. The *Hipparcos* data of HD 10697 included 33 independent abscissa measurements, which are the results of work of FAST and NDAC—the two consortia involved in reduction of the raw *Hipparcos* data. These 33 measurements represent data from 17 orbits of the satellite, analyzed separately by the two consortia and then decorrelated to produce two independent measurements out of each orbit (van Leeuwen 1997; van Leeuwen & Evans 1998; Perryman et al. 1997). In orbit number 614, only the NDAC consortium produced a measurement of HD 10697.

The present analysis used the spectroscopic elements of HD 10697 as given by Vogt et al. (2000). These included the spectroscopic period $P = 1072 \pm 10$ day, the periastron passage $T_0 = 2451482 \pm 39$, the radial velocity amplitude $K = 119 \pm 3$ m s^{-1}, the eccentricity $e = 0.12 \pm 0.02$, and the longitude of the periastron $\omega = 113 \pm 14$. The orbital astrometric elements include P, T_0, e, ω, and three additional elements—the semimajor axis a_1, the inclination i, and the longitude of the nodes Ω. In addition, the astrometric solution includes the five regular astrometric parameters: the parallax, the position (in right ascension and declination), and the proper motion (in right ascension and declination). All together we had a 12-parameter model to fit to the astrometric data, four of which are common with the spectroscopic orbit.

To find the best astrometric orbit, we used the values of P, T_0, e, and ω as given by the spectroscopic orbit and solved for the other parameters. To do that, we considered a dense grid on the (a_1,i)-plane and found the values of the five regular astrometric parameters and Ω that minimized the χ^2 statistics for each value of (a_1, i). The result of this search is a χ^2 *function*,

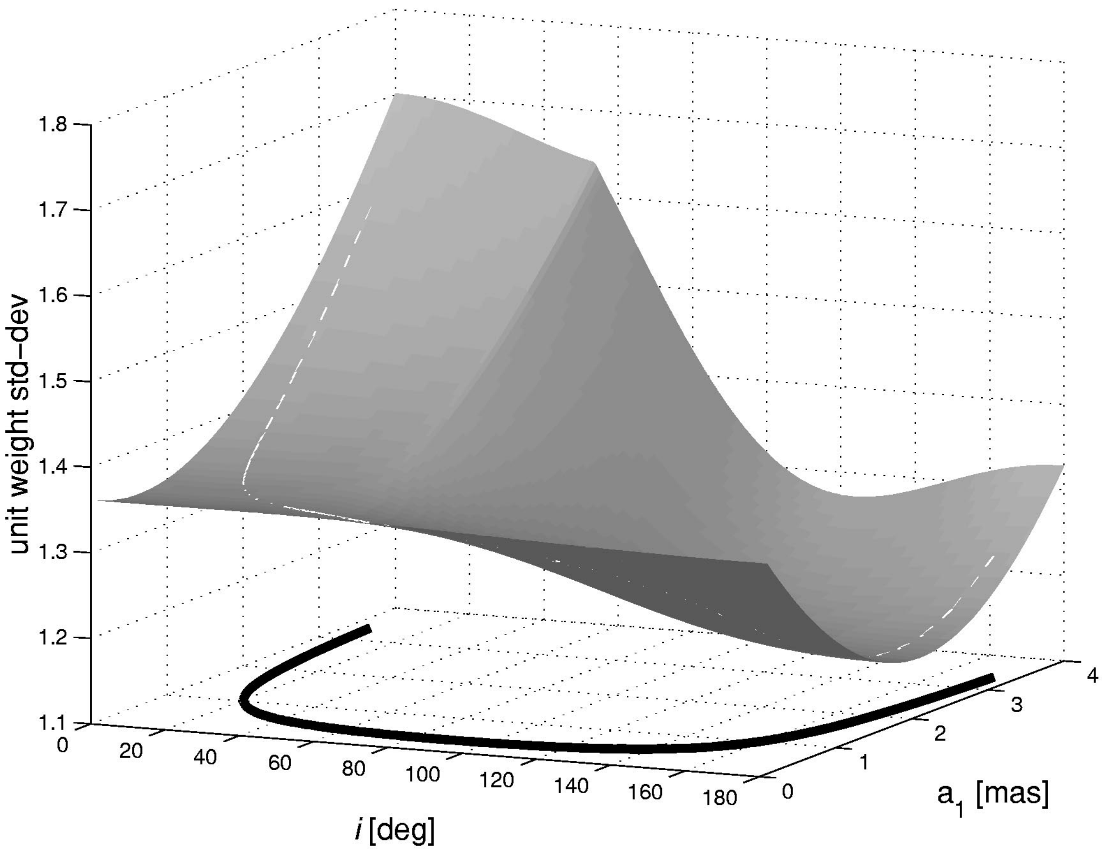

FIG. 1.—Minimum square-root–normalized χ^2 statistics as a function of a_1 and i. The line is the $a_1 \sin i = 0.36$ mas constraint.

which depends on a_1 and i. The square-root–normalized χ^2 is plotted in Figure 1 as a two-dimensional function.

The figure shows a very pronounced "valley" at about $a_1 = 2$ mas and $i = 160°$, indicating a detection of an astrometric motion. To derive the best semimajor axis and inclination for the system, we used another spectroscopic element—the radial velocity amplitude K, which has not been used so far in the analysis. This element induces a constraint on the product of a_1 and $\sin i$, which for the HD 10697 case results in

$$a_1 \sin i = 0.36 \pm 0.01 \left(\frac{P}{1072\ \mathrm{days}}\right)\left(\frac{K}{119\ \mathrm{m\ s^{-1}}}\right) \times \left(\frac{\sqrt{1-e^2}}{0.993}\right)\left(\frac{\pi}{30.71\ \mathrm{mas}}\right)\ \mathrm{mas}, \quad (1)$$

where we have used here the *Hipparcos* catalog parallax, $\pi = 30.71 \pm 0.81$ mas. This constraint is plotted in Figure 1 as a solid line both on the (a_1, i)-plane and on the square-root–normalized χ^2 surface. The product was calculated assuming the best-fit value of π: 30.3 mas. Using the catalog value yielded very similar results. In Figure 2 we collapsed the two-dimensional function onto the line of equation (1). We can see a clear minimum at 170°. This corresponds to a semimajor axis of 2.1 mas and a mass of 38 M_J. Detailed χ^2 analysis resulted in

$$a_1 = 2.1 \pm 0.7\ \mathrm{mas}, \quad M_{\mathrm{sec}} = 38 \pm 13\ M_J, \quad (2)$$

where M_{sec} is the mass of the unseen companion.

3. DISCUSSION

All 29 planet candidates discovered so far have $M \sin i$ in the range of 0.5–10 M_J. No report has been published yet about any precise radial velocity detection of a secondary with minimum masses in the range of 10–80 M_J. The large radial velocity survey of K and G stars with lower precision of Mayor et al. (1997) also yielded only a few binaries with minimum secondary mass in the range of 10–80 M_J, most of which are actually main-sequence secondaries with low inclination (Halbwachs et al. 2000; Udry et al. 2000). These studies attest to the paucity of secondaries in the range of 10–80 M_J and suggest a distinction between the population of stellar secondaries and planets (Vogt et el. 2000; Mazeh 1999). This distinction might also help to find the mass upper limit for planetary companions.

An upper limit of the planetary mass at about 10–20 M_J is consistent with the accumulated distribution of planetary masses (Mazeh 1999). It is also consistent with the mass of the outermost known companion of υ And: $10 \pm 5\ M_J$ (Mazeh et al. 1999). It therefore seems that the mass of the secondary of HD 10697 is probably too large for a planetary mass. We therefore suggest that the secondary of HD 10697 is a brown dwarf orbiting around its parent star at a distance of 2 AU.

The paradigm behind the distinction between brown dwarfs and planets assumes that binaries, even with small-mass secondaries, are formed by a different mechanism than that of planets (e.g., Boss 1996). Brown dwarf secondaries are therefore at the low-mass end of the distribution of secondaries that

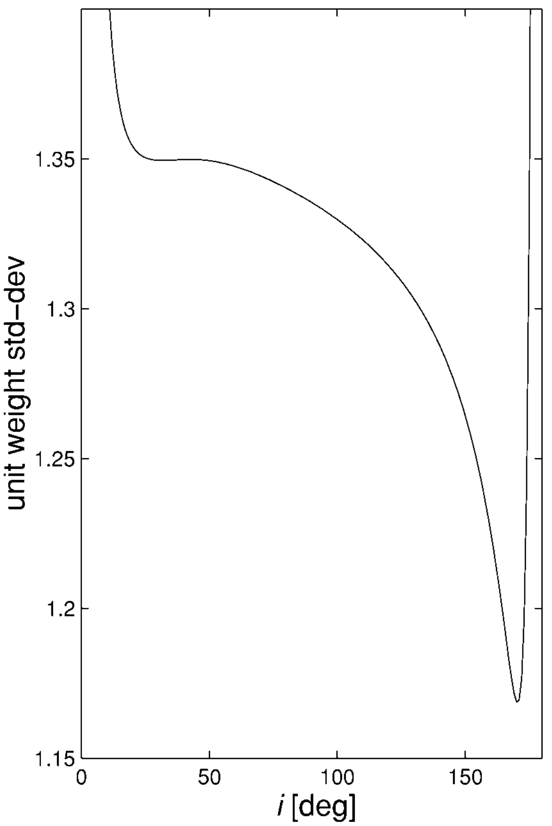

FIG. 2.—Minimum square-root–normalized χ^2 statistics as a function of i, given the constraint $a_1 \sin i = 0.36$ mas.

were formed as binaries and not as planets. The study of the lower end of the mass distribution has great importance to our understanding of binary formation, especially if we compare them to the emerging population of brown dwarf field stars (e.g., Bèjar, Zapatero Osorio, & Rebolo 1999; Binney 1999; Tinney 1999, and references therein). Until now the paucity of brown dwarf secondaries in short-period binaries could give the impression that such objects do not exist. This work suggests that there are such secondaries, even though they are rare, in this range of masses.

As usual, objects in binaries with short enough periods supply the precious opportunity of dynamical mass determination. The combination of astrometry and radial velocity work yields here a first mass determination of a brown dwarf that is model independent. The separation between the two components of HD 10697 is about 70 mas (Vogt et al. 2000). Ground-based interferometry might be able to resolve the two objects despite the huge brightness difference between them and supply for the first time brightness measurements of a brown dwarf with dynamical mass determination. In addition, time-dependent spectroscopy might help to obtain a spectrum of the faint companion, enabling us to confront the theory of brown dwarf evolutionary models (e.g., Burrows & Sharp 1999) with the observations.

This work was supported by the US-Israel Binational Science Foundation through grant 97-00460 and the Israeli Science Foundation.

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