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TWO SUBSTELLAR COMPANIONS ORBITING HD 168443[1]

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ABSTRACT

Precise Doppler measurements during 4.4 yr from the Keck/HIRES spectrometer reveal two superimposed Keplerian velocity variations for HD 168443 (G6 IV). A simultaneous orbital fit to both companions yields companion masses of $M \sin i = 7.7$ and 17.2 $M_{\rm JUP}$, orbital periods of $P = 58$ days and 4.8 yr, semimajor axes of $a = 0.29$ and 2.9 AU, and eccentricities of $e = 0.53$ and 0.20. An upper limit to the mass of the outer companion of 42 $M_{\rm JUP}$ is derived from the lack of astrometric wobble. The outer companion was not detected with Keck adaptive optics in the near-IR. Dynamical simulations show that the system is remarkably stable for all possible masses of both companions. The two orbiting companions have masses that are probably near and slightly above the upper end of the observed mass distribution of "planets" at 10 $M_{\rm JUP}$. Formation in a protoplanetary disk seems plausible. But these objects present a puzzle about their formation and dynamical history, as well as about their possible kinship with planetary systems and triple-star systems.

Subject headings: planetary systems — stars: individual (HD 168443)

1. INTRODUCTION

Properties of substellar companions within 5 AU of nearby stars have been obtained by precise Doppler measurements that reveal Keplerian reflex motion (see Marcy, Cochran, & Mayor 2000; Mayor et al. 1998; Udry et al. 2000; Halbwachs et al. 2000; Butler et al. 2000; Fischer et al. 2001). Approximately 2000 nearby main-sequence stars have been surveyed, including a majority of the single main-sequence stars in the *Hipparcos* catalog brighter than magnitude $V = 7.5$. The surveys, while ongoing, have already yielded ~ 50 companions that have $M \sin i < 10$ $M_{\rm JUP}$, consistent with the high-mass tail of the planetary mass distribution.

In contrast, only ~ 10 substellar companions have been found that have higher masses, $M \sin i = 10$–80 $M_{\rm JUP}$ (Mayor et al. 1998). Many of these brown dwarf candidates are simply stars, as revealed by *Hipparcos* astrometry (Halbwachs et al. 2000). Thus, the "brown dwarf desert," first revealed around G and M dwarfs (Campbell, Walker, & Yang 1988; Marcy & Benitz 1989), remains characterized by a paucity of companions having masses of 10–80 $M_{\rm JUP}$ within 5 AU (Marcy & Butler 1998; Halbwachs et al. 2000).

A catalog of the "extrasolar planets," including their $M \sin i$ and orbital characteristics, is provided by Butler et al. (2000). The histogram of $M \sin i$ rises rapidly toward the lowest detectable masses, with an observed distribution $dN/dM \propto M^{-0.9 \pm 0.2}$ (Marcy & Butler 2000). This overall mass distribution provides an observable segregation between planets and brown dwarfs.

Nonetheless, the definitions of planets and brown dwarfs remain unclear. Reasonable defining characteristics include formation processes, mass distribution, nuclear reactions, orbital status, and sources of pressure support. Indeed, a few companions defy clear classification, namely those that have $M \sin i = 7$–15 $M_{\rm JUP}$ and reside in eccentric orbits (e.g., 70 Vir, HD 89744; Korzennik et al. 2000). These massive eccentric substellar companions may not represent close kin of the planets, and they may have formed by a variety of mechanisms that do not depend on dust agglomeration (Boss 2000; Armitage & Hansen 1999; Nelson et al. 2000; Kley 2000). Here we present the Doppler measurements for HD 168443, which harbors two companions with masses near the nominal interface between "planets" and "brown dwarfs."

2. STELLAR CHARACTERISTICS AND VELOCITY MEASUREMENTS

2.1. *Stellar Characteristics*

The stellar characteristics of HD 168443 (G6 IV) were described in Marcy et al. (1999). New measurements of the stellar metalicity and mass are now available from spectral synthesis by Gonzalez et al. (2001). They find [Fe/H] = $+0.10 \pm 0.03$, an age of 10 Gyr, and a mass $M = 1.01 \pm 0.05$ $M_\odot$, all of which are consistent with preliminary spectral synthesis by D. Fischer (2000, private communication; [Fe/H] = $+0.09$). Based on available narrowband photometry for HD 168443, we estimate a mass of 1.05 ± 0.05 $M_\odot$, consistent with the measurement by Gonzalez et al. (2001). Therefore we adopt the Gonzalez et al. (2001) mass of 1.01 $M_\odot$ for HD 168443.

Its parallax of 26.4 mas (Perryman et al. 1997) implies an absolute visual magnitude of $M_V = 4.03 \pm 0.07$ and a luminosity $L = 2.1$ $L_\odot$, which places it ~ 1.5 mag above the main sequence. These stellar parameters suggest a subgiant status, in agreement both with its observed spectral type and with its weak chromospheric emission, $S = 0.15$, which

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TABLE 1

VELOCITIES FOR HD 168443

JD (−2,450,000)	V_{rad} (m s^{-1})	Error (m s^{-1})
276.9089	−335.83	4.2
603.0118	−65.37	2.4
665.8678	−93.92	2.5
713.7377	−97.65	2.5
714.7665	−99.56	2.6
955.0104	−31.80	2.5
955.9586	−30.36	2.3
957.0711	−35.77	2.4
981.8801	−593.02	2.5
982.8913	−516.37	2.7
983.0769	−496.48	2.5
983.8223	−442.21	2.9
984.0614	−432.76	3.0
1009.8701......	−0.74	2.9
1010.0599......	−2.84	2.3
1010.8498......	−5.17	2.8
1011.8608......	1.58	2.9
1012.9541......	−9.25	2.5
1013.0674......	−8.78	2.0
1013.8279......	−4.99	2.5
1013.9298......	−11.81	3.0
1042.9556......	−355.40	2.3
1043.9560......	−307.18	2.8
1050.8141......	−101.88	2.7
1068.7704......	28.01	2.6
1069.7860......	31.02	2.3
1070.7981......	27.43	2.4
1071.7700......	26.23	2.6
1072.7627......	20.00	2.8
1074.7851......	11.73	2.6
1228.1611......	62.43	2.2
1229.1494......	71.31	3.2
1311.0417......	128.64	2.8
1312.0776......	110.37	2.6
1313.0759......	99.27	2.6
1314.0870......	77.13	3.0
1341.0266......	84.10	2.9
1341.9059......	102.48	2.3
1342.9714......	114.29	2.5
1367.8606......	184.79	3.2
1368.8431......	176.80	3.2
1370.0115......	157.90	2.7
1370.9187......	137.55	1.6
1371.9102......	123.66	2.6
1372.8781......	103.61	3.2
1373.7950......	81.58	3.2
1409.8500......	244.62	2.7
1410.8458......	246.91	2.7
1411.8464......	258.66	2.7
1438.7381......	−309.30	2.7
1439.7306......	−439.87	2.6
1440.7183......	−554.04	2.9
1441.7400......	−639.05	2.7
1679.0480......	−136.29	2.7
1680.0718......	−45.38	3.1
1703.0176......	459.47	2.6
1703.9884......	455.20	2.8
1705.0390......	462.67	2.7
1705.9585......	463.57	2.7
1707.0812......	471.48	2.3
1754.8588......	425.23	4.0
1755.9099......	457.83	2.5
1792.7476......	−362.98	2.3
1793.8001......	−251.52	2.9
1882.6831......	471.99	2.4
1883.6818......	469.65	2.4

indicates an age of ∼8 Gyr and an equatorial rotation velocity under 3 km s^{-1}. The known characteristics of HD 168443 are similar to those of 70 Vir (Marcy & Butler 1996).

2.2. *Velocity Observations*

We are surveying ∼600 FGKM dwarfs on the Keck I telescope for Doppler variability using repeated, high-resolution spectra, $R \sim 80{,}000$, obtained with the HIRES echelle spectrometer (Vogt et al. 1994). The spectra span the wavelength range 3900–6200 Å, and an iodine absorption cell provides wavelength calibration and the instrumental profile from 5000 to 6000 Å (Marcy & Butler 1992; Butler et al. 1996). Typical signal-to-noise ratios are 200–300 pixel^{-1}. We routinely obtain Doppler precision of 3 m s^{-1} for FGKM dwarfs brighter than $V = 8.5$ in 5 minutes (Vogt et al. 2000). The Ca II H and K lines provide simultaneous chromospheric diagnostic (Saar et al. 1998).

We reported previous Doppler measurements of HD 168443 which revealed a companion with semimajor axis of 0.3 AU having $M \sin i = 5\ M_{JUP}$ (Marcy et al. 1999). Our best Keplerian fit gave velocity residuals that exhibited a trend with curvature, suggesting the presence of an additional companion having greater orbital period. We reported the minimum period to be ∼4 yr which led to a mass estimate: "For the shortest possible period of 4 yr, the companion mass would be at least 15 M_{JUP}" (Marcy et al. 1999).

Since that discovery paper, we have continued to obtain velocity measurements which now span 4.5 yr. Table 1 lists all 64 Doppler measurements of HD 168443 obtained to date. These new velocities were obtained with improvements to our spectroscopic Doppler analysis which now yields a precision of 3–5 m s^{-1} (Vogt et al. 2000), instead of the previous errors of ∼6–7 m s^{-1}. We reanalyzed all of the old spectra with the new algorithms.

3. ORBITAL SOLUTIONS

We attempted to fit the new velocities with a single orbiting companion. Such a fit is extremely poor with residuals exceeding 70 m s^{-1}, despite measurement uncertainties of 3–5 m s^{-1}. We further attempted to fit the velocities with a Keplerian and a simple linear trend, shown in Figure 1. The residuals have rms = 56 m s^{-1} and a reduced $\chi^2 = 55$, indicating residuals that are much greater than the uncertainties. Moreover, the residuals are not random in time,

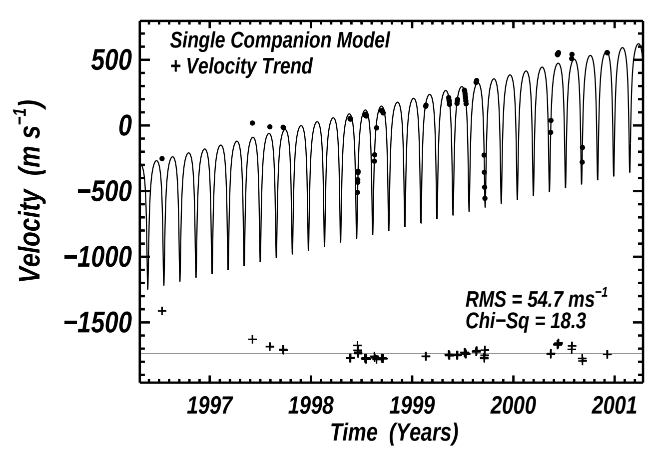

FIG. 1.—Velocities for HD 168443 (*points*) fit with a model (*solid line*) of a single companion in a Keplerian orbit with an additional free velocity trend. The residuals (*crosses*) have rms = 56 m s^{-1}, much larger than Doppler errors of 3 m s^{-1}. The single-companion model is inadequate.

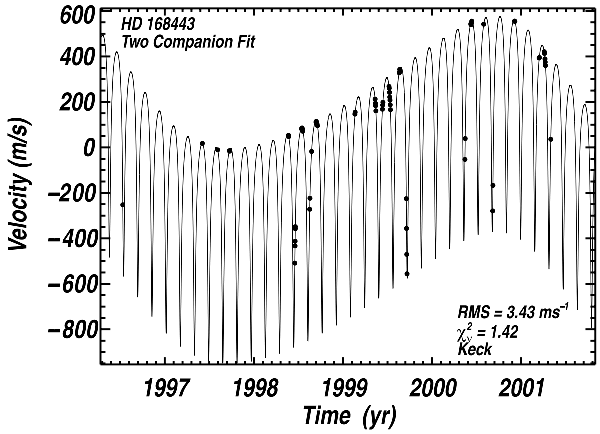

FIG. 2.—Velocities for HD 168443 (*points*) fit with two companions in Keplerian orbits (*solid line*). The rms of the residuals is 4 m s^{-1}, consistent with Doppler errors.

exhibiting a clear curvature which indicates an inadequacy in this model that consists only of a single companion with an additional long-term trend. This inadequacy is consistent with, but more pronounced than, the curvature in the residuals noted in Marcy et al. (1999).

Here we attempt to fit the observed velocities with two orbiting companions. Such a fit is shown in Figure 2. This two companion model yields velocity residuals with an rms = 4.2 m s^{-1}, a significant drop from 56 m s^{-1}. The reduced $\chi^2 = 1.6$, which indicates residuals that are just slightly larger than measurement errors. As the addition of only five new free parameters (with 66 velocity measurements) reduced the rms of the residuals from 56 to 4.2 m s^{-1}, this two-companion model is compelling. Indeed, the rms of 4.2 m s^{-1} and the $\chi^2 = 1.6$ indicate that photospheric kinematics contribute very little to the residuals beyond with the measurement errors. Further embellishments to the two-companion model are not warranted.

The best-fit orbital parameters for the two companions are listed in Table 2. The periods and semimajor axes are 58.1 and 1770 days, and 0.29 and 2.9 AU, respectively. The values of $M \sin i$ are 7.7 and 17.15 $M_{\rm JUP}$. The inclusion of the outer companion has changed the best-fit orbital values for the inner companion, notably of $M \sin i$ from 5.0 to 7.7 $M_{\rm JUP}$. The old orbital values for the inner companion were contaminated by the reflex velocity induced by the outer companion. The apsides of the orbits of the two companions are not aligned ($\omega_b = 173°$; $\omega_c = 63°$), nor would significant dynamical resonances be expected for such widely separated planets. In this respect the system of companions to HD 168443 differs from the υ Andromedae system for which apsidal alignment is found.

TABLE 2

ORBITAL PARAMETERS

Parameter	Inner	Outer
Orbital period P (days)	58.10 (0.006)	1770 (25)
Velocity amplitude K (m s^{-1})......	472.7 (1.8)	289 (3.8)
Eccentricity (e)	0.53 (0.003)	0.20 (0.01)
ω (deg)	172.9 (0.4)	62.9 (3.2)
Periastron time (JD)	2,450,047.58 (0.2)	2,450,250.6 (18)
$M \sin i$ ($M_{\rm JUP}$)	7.73	17.15
a (AU)	0.295	2.87

Udry et al. (2001) have taken the velocities from Marcy et al. (1999) which span 800 days and, at the suggestion of an additional companion, have added new precise velocities that span an additional 550 days. The combined velocities show the same clear signature of the second companion with nearly identical properties. The agreement is not surprising as the first 800 days of velocities are the same.

The minimum masses ($M \sin i$) are unprecedented in this system. The inner companion with $M \sin i = 7.7$ $M_{\rm JUP}$ is among the highest $M \sin i$ values ever discovered with precise velocities. The outer companion with $M \sin i = 17.15 M_{\rm JUP}$ has the second largest value of $M \sin i$ ever found with precise velocities, the largest being $M \sin i = 46 M_{\rm JUP}$ for HD 164427 reported by Tinney et al. (2001). The present $M \sin i$ of 17.15 $M_{\rm JUP}$ for the outer companion to HD 168443 lies above the maximum mass often adopted for "planets," namely, 8–13 $M_{\rm JUP}$ (see § 5). Thus HD 168443 apparently contains two companions having minimum masses near and above the nominal upper end of the planet mass distribution.

4. COMPANION MASS LIMITS: ASTROMETRY, DYNAMICS, ADAPTIVE OPTICS

Both companions could have masses arbitrarily higher than their values of $M \sin i$. For randomly oriented orbits, the probability that the inclination, i, is smaller (more face-on) than i' is $P(i > i') = 1 - \cos i$. Thus, the probability that either companion has a mass greater than 3 times their $M \sin i$ is 0.057. Here we examine other limits to the masses of the companions from three approaches.

4.1. *Astrometry*

The Keplerian fit to the velocities implies that the orbit of the star has a semimajor axis of $a_1 \sin i = 0.045$ AU. For its parallax of 26.4 mas (Perryman et al. 1997), the angular semimajor axis is $\alpha_1 \sin i = 1.19$ mas. If the true mass of the outer companion were much larger than its $M \sin i$ of 17.15 $M_{\rm JUP}$, the *Hipparcos* astrometry could plausibly detect the stellar wobble.

The 4.8 yr period of the outer companion is longer than the 3.0 yr duration of the *Hipparcos* measurements for HD 168443. Any astrometric wobble would thus be partially absorbed into the solution for proper motion and parallax of the star. Nonetheless, because *Hipparcos* observed the star during 64% of the orbit of the outer companion, some curvature or acceleration could have been detected (see Fig. 3), especially if the outer companion's mass were considerably greater than $M \sin i$.

We simulated the astrometric motion of HD 168443 for two cases: $\sin i = 1$ and $\sin i = 0.4$, as shown in Figure 3. We considered the two-body problem consisting of the star and the outer companion, and we adopted the known orbital parameters from Table 2, namely, P, e, K, ω, and T_0, as well as the mass of the star, $M = 1.01$ $M_\odot$. We calculated the position of the star relative to the center of mass, evaluated at the times of actual *Hipparcos* observations of HD 168443 during 3 yr. Figure 3 shows that for $\sin i = 1.0$ ($M_c = 17$ $M_{\rm JUP}$), the edge-on reflex orbit of the star has a semimajor axis of only 1 mas. For $\sin i = 0.4$ ($M_c = 42$ $M_{\rm JUP}$) the stellar wobble would have an angular semimajor axis of $\alpha > 3$ mas, which is larger than *Hipparcos* measurement errors.

We have examined the *Hipparcos* astrometry of HD 168443 for evidence of a wobble by several approaches. The

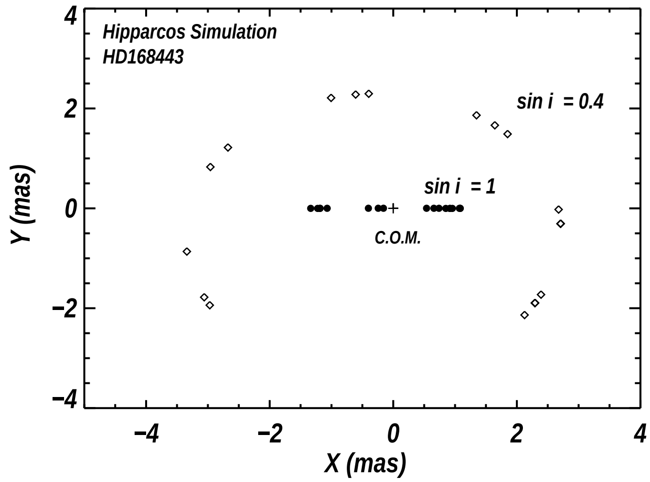

FIG. 3.—Predicted astrometric position of HD 168443, at the actual times of *Hipparcos* observations, for two possible orbital inclinations of the outer companion, sin $i = 1$ (*filled circles*) and sin $i = 0.4$ (*diamonds*). For sin $i = 0.4$, the wobble of the star has an amplitude of $\sim \pm 3$ mas which would be detectable by *Hipparcos*. But no such motion was seen. Thus the actual value of sin i is between 0.4 and 1.0, which implies that the mass of the outer companion is between 42 and 17 $M_{\rm JUP}$.

standard deviation of the residuals to the fit for parallax and proper motion is 2.1 mas, consistent with the median error of 2.22 mas. A periodogram reveals no significant peaks at any periods from 3 to 2000 days, and no trends are seen in the residuals. The *Hipparcos* solution listed in the "Double and Multiple Star Annex" shows no indication of acceleration (i.e., label "G" is absent). Thus, an approximate measure of the maximum astrometric wobble is 2.1 mas.

A more detailed search for a wobble in *Hipparcos* astrometry can be carried out by adopting the orbital parameters from our velocities and searching for the remaining orbital parameters by χ^2 minimization (Halbwachs et al. 2000). However, such an orbital search requires extensive Monte Carlo investigation of the subtle error distribution both in the *Hipparcos* measurements and in the resulting orbital parameters, as done by Halbwachs et al. (2000). The stated *Hipparcos* uncertainties are themselves in error by some small amount which remains unknown to us. This uncertain behavior of *Hipparcos* errors suggests that one should exercise caution in extracting low-amplitude astrometric wobbles or in setting upper limits. A large ensemble of single (null) stars must be studied extensively to assess the systematic behavior of *Hipparcos* measurements in the detection of small wobbles.

Therefore, we use previous careful *Hipparcos* analyses of two comparison stars which are astrometrically similar to HD 168443, namely, 47 UMa and HIP 21832 (Perryman et al. 1996; Halbwachs et al. 2000). These two comparison stars have V magnitudes of $V = 5.05$ and 7.28, respectively, thereby bracketing that of HD 168443, $V = 6.92$. These two comparison stars were observed 29 and 12 times, respectively, by *Hipparcos*, again bracketing HD 168443, which was observed 16 times. For all three stars, the uncertainty in the *Hipparcos* parallax is less than 1.1 mas, and all three stars have derived uncertainties in proper motion under 1 mas yr^{-1}. These small uncertainties indicate that a simple single-star model (with no companion) fits the astrometric data within its errors of $\sim$2 mas per observation. Moreover, none of these three stars exhibits any astrometric acceleration or curvature. Thus, these three stars had astrometry of comparable quality carried out by *Hipparcos*, within a factor of $\sim$2.

From velocities of 47 UMa and HIP 21832, the orbital periods are $P = 1100$ days and $P = 1474$ days, respectively (Butler et al. 1996; Halbwachs et al. 2000), not unlike that for HD 168443c, which has $P = 1738$ days. From the velocities, these two comparison stars have derived values of α_1 sin i of 0.334 and 3.4 mas, respectively, which bracket the value, 1.2 mas, for HD 168443c. The value of sin i remains unknown. Careful orbital analyses of the *Hipparcos* data provide an upper limit of $\alpha_1 < 3.0$ mas (90% confidence limit) for 47 UMa, and for HIP 21832 the uncertainty in α_1 is 2.4 mas (Perryman et al. 1997; Halbwachs et al. 2000). As there is no qualitative astrometric distinction between HD 168443 and these two comparison stars, the upper limits to the angular wobbles of all three stars should be similar. We therefore deduce that that HD 168443 has no astrometric wobble (due to its companions) greater than 3.0 mas, i.e., $\alpha_1 < 3.0$ mas (1 σ). This limit is consistent with the standard deviation of the *Hipparcos* residuals of 2.1 mas, mentioned above.

Thus *Hipparcos* reveals no wobble and sets an upper limit of $\alpha_1 < 3.0$ mas. This maximum value corresponds to a 68% confidence limit. Indeed, the *Hipparcos* astrometry is strongly inconsistent with a wobble twice as great, 6 mas, indicating that 6 mas represents at least a 2 σ upper limit.

Given the value of α_1 sin $i = 1.19$ mas from the velocities, one finds that sin $i > 1.19/3.0 = 0.40$. This restriction on sin i implies an upper limit to the mass of companion "c" of $M < 17.15/0.40 = 42.8 M_{\rm JUP}$. Thus, HD 168443c is likely to be substellar, and has a mass between 17 $M_{\rm JUP}$ and 42.8 $M_{\rm JUP}$.

4.2. *Dynamical Stability*

The large masses, significant eccentricities, and the modest separations of the two companions in the HD 168443 system indicate the possibility of ongoing dynamical interactions between them. Gladman (1993) has derived the minimum separation that two companions on initially circular orbits require for stability,

$$\Delta_{\rm min} = 2.4(\mu_1 + \mu_2)^{1/3} ,$$

where μ_1 and μ_2 are the ratios of the planet masses to the stellar mass and $\Delta = (a_c - a_b)/a_b$ is the actual fractional orbital separation of the two planets. For the nominal masses of the planets orbiting HD 168443, $\Delta = 9$, which is much larger than the minimum separation, $\Delta_{\rm min} = 0.7$, required for stability. One may choose a more conservative value for Δ for closest approach, namely, $\Delta = [a_c(1 + e) - a_b(1 + e)]/a_b = 6.2$, which is still much greater than $\Delta_{\rm min} = 0.7$.

Thus this criterion suggests that the system is stable. The two companions here, however, have large orbital eccentricities, and so the Gladman criterion is not strictly valid. Orbital integrations of the system can serve to investigate the degree of stability. In particular, as was the case with the planetary system surrounding υ Andromedae, numerical experiments can be used to constrain the unknown inclination angles of the planets in the system (see, e.g., Laughlin & Adams 1999; Rivera & Lissauer 2000).

We have used two numerical methods to study the HD 168443 system. The first method uses the Burlirsch-Stoer technique (Press et al. 1992) to directly integrate the equations of motion. The second method uses the symplectic N-body map of Wisdom & Holman (1991), as implemented by Laughlin & Adams (1999). The symplectic technique is faster, but is not well suited to handling close approaches between the planets.

The Doppler measurements yield estimates of five orbital parameters for each companion (e, K, P, $T_{\rm peri}$, and ω), as given in Table 2. The inclination angles for the orbits remain unknown. If we assume a value of sin i for each companion, then the semimajor axis, a, and the mass of each companion, $M_{\rm pl}$, can be derived using

$$a = \left[\frac{P^2 G(M_* + M_{\rm pl})}{4\pi^2}\right]^{1/3},$$

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_{\rm pl} \sin i}{(M_* + M_{\rm pl})^{2/3}} \frac{1}{\sqrt{1-e^2}}.$$

For $\sin i = 1$, we find $a_{\rm b} = 0.29$ AU, $a_{\rm c} = 2.9$ AU, $M_{\rm b} = 7.7\ M_{\rm JUP}$, and $M_{\rm c} = 17.15\ M_{\rm JUP}$.

Using the symplectic N-body map with a 1 day timestep, we have made a number of long-term integrations of the HD 168443 system (see runs 1–8 of Table 3). For initially coplanar simulations, a small perpendicular velocity, $v_z = 0.001 v_{\rm Kepler}$, was given to the inner planet in order to give the integrator access to all three spatial dimensions. When the orbits are initially nearly coplanar, the system is very stable, even for values of $\sin i < 0.25$. This is shown by the near-constant value of the maximum eccentricity achieved by the inner companion ($e_{\rm max,b}$ in Table 3).

The factor of 10 difference in the orbital periods of the two planets causes them to be dynamically well separated, even when the mass of the outer planet exceeds the 0.075 $M_\odot$ substellar cutoff. Indeed, even for sin i as small as 0.02, rendering HD 168443 a hierarchical triple-star system, the system appears initially stable. In that light, it is interesting that no such triple-star system is known.

Figure 4 shows the inner and outer radial excursions for the two planets, $a(1 \pm e)$ (as computed from osculating orbital elements) for a nearly coplanar system with $\sin i = 0.5$. Over 500 million yr, the two planets never develop more than 1° of mutual inclination, and the orbits remain well separated.

The system is dynamically much more active, however, when the two planets are given a mutual inclination. For example, Figure 5 shows the results of an integration of duration, 5.0×10^4 yr, using the Burlirsch-Stoer integrator, in which the outer companion starts from the current epoch

TABLE 3

NUMERICAL INTEGRATIONS OF THE HD 168443 SYSTEM

Run	$\sin i_{\rm b}$	$\sin i_{\rm c}$	Time (Myr)	$e_{\rm max,b}$
1	0.90	0.90	735	0.593
2	0.80	0.80	444	0.594
3	0.70	0.70	821	0.591
4	0.50	0.50	1027	0.593
5	0.333	0.333	402	0.588
6	0.25	0.25	82	0.591
7	0.20	0.20	322	0.586
8	0.15	0.15	322	0.587
9	1.00	0.75	1	0.757
10......	1.00	0.50	1	0.780
11......	1.00	0.333	1	0.903
12......	1.00	0.25	1	0.945

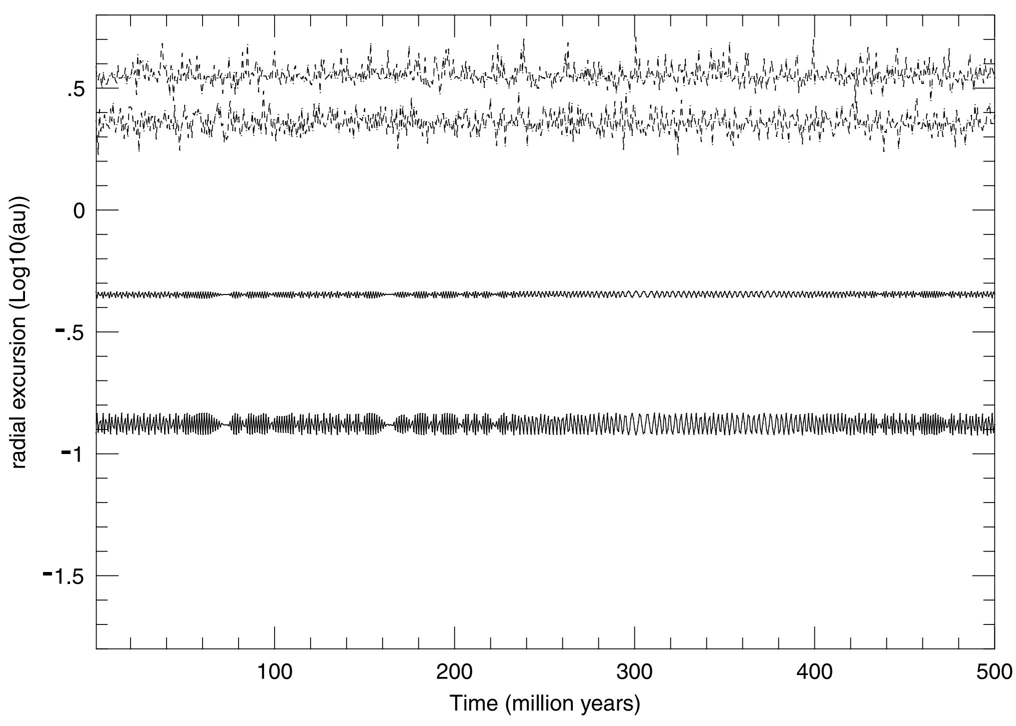

FIG. 4.—Periastron and apastron distances of both companions, $a(1 - e)$ and $a(1 + e)$, as a function of time. The lower pair of curves represents the inner companion, and the upper pair represents the outer companion. This shows the evolution of the radial excursions for both companions during 500 Myr. In this simulation, $\sin i = 0.5$ and the orbits are initially coplanar. The system is evidently stable against dynamical destruction.

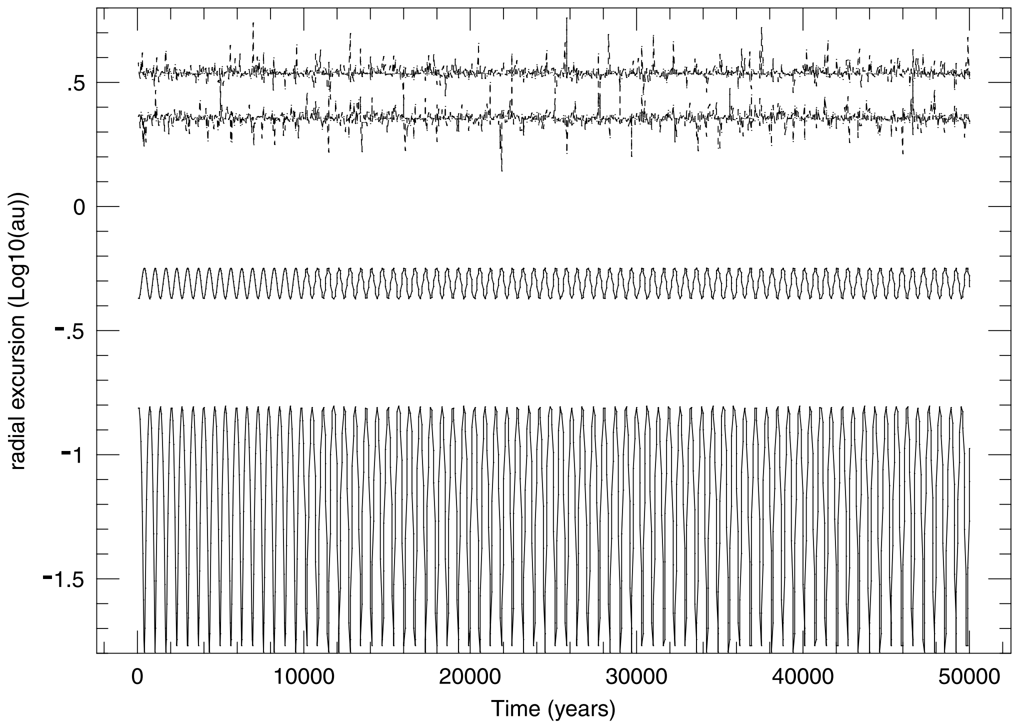

FIG. 5.—Same as Fig. 4, showing the time dependence of the radial excursions $r_{in} = a(1 \pm e)$ for both companions during 50,000 yr of evolution. In this simulation, sin $i = 1$ for the inner companion and sin $i = 0.25$ for the outer companion at the beginning of the simulation.

with sin $i = 0.25$, and the inner companion is started with sin $i = 1.00$. In all of our mutually inclined simulations, the longitude of the ascending node is the same as the longitude of pericenter. In this case, the orbital inclination of the inner companion undergoes periodic oscillations of nearly 150, and the orbital eccentricity oscillates between $e = 0.46$ and $e = 0.95$. Both oscillations have a period of 650 yr. In this calculation, the inner companion regularly approaches within 0.02 AU of the central star. Such an orbit would likely be rapidly tidally circularized, and is thus incompatible with the presently observed orbital elements of the system (unless another companion exists).

4.3. *Adaptive Optics*

The new outer companion, HD 168443c, has a semimajor axis of 2.87 AU, implying an angular separation from the primary of 0″.076, given the parallax of 26.4 mas. Such a separation is comparable to the spatial resolution offered by adaptive optics imaging. If HD 168443c were a low-mass H-burning star, it might be detectable with near IR AO imaging.

High-resolution H-band imaging with the Keck adaptive optics system (Wizinowich et al. 2000) was carried out using the KCam near-infrared camera. Two of us (K. L. L. and R. J.) obtained deep images of HD 168443 on 2000 May 11 UT and shallow, unsaturated images on 2000 September 17 UT. The images have a resolution FWHM of 0″.044.

The H-band flux ratio limit we derive for a possible companion is shown in Figure 6 as a function of separation from the primary. At a separation of 0″.076, our photometric observations rule out any object earlier than spectral type K5 V. At twice the separation, the brightness limit for a companion corresponds to M2 V. On both dates of observation, companion " c " is predicted to reside 0″.065 from the primary, based on the orbit derived from the velocities. Thus, only stars considerably more massive than K5 V stars, or more distant stellar companions, would have been detected.

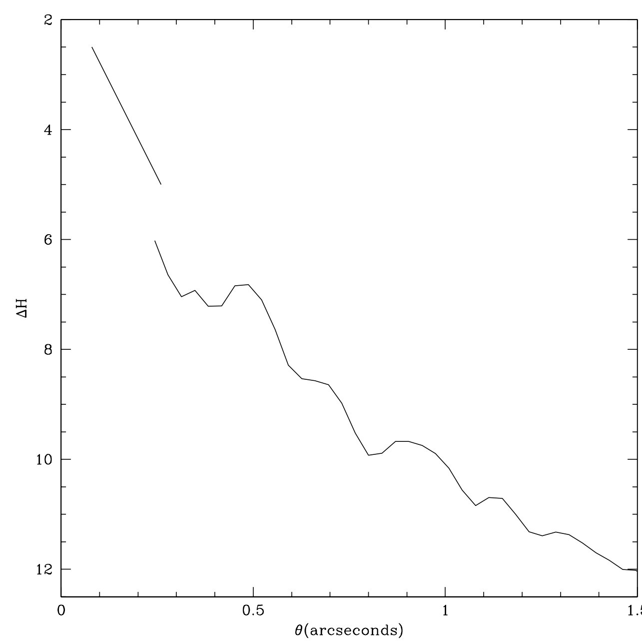

FIG. 6.—Sensitivity vs. separation for companions, obtained with adaptive optics images of HD 168443 at H band. No companions were detected within 1″.5 of the primary, despite a sensitivity to companions brighter than $\Delta H = 2.5$ (K5 V) at 0″.075. Thus the outer companion found from velocities must be fainter than this limit. The inner data are from the 2000 September observing run (unsaturated images), and the outer data are from the 2000 May run.

That no such stellar companions were detected suggests that the dynamics of this unusual system must be explained without recourse to more distant stellar companions. Outside of the "seeing disk," the images achieve much higher sensitivities; for example, outside 0″.5, we are able to detect L dwarf companions, if they exist. The brown dwarf companion Gl 229B would appear at $\Delta H = 13.1$ if placed at the distance of HD 168443.

Three other members of our team (M. C. Liu, J. R. Graham, and J. Lloyd) independently carried out Keck AO observations of HD 168443 on 2000 August 18 UT, using the NIRSPEC "SCAM" camera. The resulting images have a resolution FWHM of 0″.04. We were unable to obtain photometric calibrations during that observing night. However, we had already obtained photometry of this star using the Lick adaptive optics system (Max et al. 1997) with the near-IR camera IRCAL (Lloyd et al. 2000). At a separation of 0″.075, these Keck AO images set an H-band flux ratio limit of 10 for any companion. Scaling from the Lick AO photometry of the primary implies a brightness upper limit for a companion of spectral type K5 V at 0″.076 and M2 V at 0″.15, entirely consistent with the above results. Thus, adaptive optics can rule out a dwarf more massive than 0.4 $M_\odot$ as the outer companion, a limit that is weaker than, but consistent with, that imposed by the astrometry.

5. DISCUSSION

The two companions orbiting HD 168443 have semimajor axes of 0.29 and 2.9 AU, and minimum masses of 7.7 and 17.15 M_{JUP}, respectively. The outer companion has a mass less than 42 M_{JUP}, as imposed by lack of astrometric wobble, thus rendering it certainly substellar. The inner companion has no such mass constraint, but the probability that its true mass is more than 75 M_{JUP} is 1 in 200, for randomly oriented orbital planes. The constraint that the system be dynamically stable favors a substellar status for both companions only for the case of noncoplanar geometries. These issues taken as a whole imply that both companions are likely substellar with masses of roughly 15 and 30 M_{JUP}, within factors of 2.

The unknown value of sin i permits the outer companion mass to reside anywhere between its minimum value, M sin i, and the astrometrically imposed maximum mass of 42 M_{JUP}. However, the average value of sin i for randomly oriented orbital planes is $\pi/4$, implying that the true companion mass is likely within a factor of 2 of its M sin i value.

For a representative inclination, sin $i \approx 0.5$, the masses would be 15 and 32 M_{JUP}. These masses reside above the high-mass tail of the planet mass distribution (Marcy et al. 2000; Vogt et al. 2000). The planet mass distribution can be represented by a power law, $dN/dM \propto M^{-0.9}$ (Marcy & Butler 2000). It remains to be determined whether the companion mass distribution has a characteristic mass scale, such as from an exponential tail. Notably, there are approximately a factor of 10 more companions known with M sin i between 1 and 10 M_{JUP} than between 10 and 100 M_{JUP}, thus suggesting a mass scale to the planetary mass distribution near $10 M_{JUP}$. Nonetheless, the power-law distribution can be normalized from the observation that 7% of the stars in our target list have observed planets within the mass range M sin i = 0.5–8 M_{JUP}, within 3 AU. Thus, the power-law representation demonstrates the extremely rare occurrence of "planet" companions of 15–32 M_{JUP}, within 3 AU, as found around HD 168443.

We caution against interpreting the two companions as merely independent "planets." The probability seems minute that two such "planet tail" companions would independently form around one star, given our Keck target size of only 600 stars. Instead, the existence of two such companions suggests that they formed by some process that is distinct from that which formed the majority of the sub-$8 M_{JUP}$ extrasolar planets. If pairs of massive companions were common, we would have found other examples in our sample of 1100 stars surveyed at Keck, Lick, and the Anglo-Australian Telescope. We therefore suggest that the outer companion, and probably both companions, formed by some qualitatively different process than did the bulk of the extrasolar planets having modest masses, $M < 8\ M_{JUP}$.

We propose an upper limit for "planets" dictated by the characteristics of the planets themselves. The mass distribution of companions to nearby stars rises with decreasing mass, for masses less than 5 M_{JUP} (Marcy & Butler 2000; Udry et al. 2001). Less than 1% of the area of the distribution resides above $10 M_{JUP}$, though a mass scale is not yet convincing. Thus an empirical upper mass limit for planets is sensibly positioned at $\sim 10\ M_{JUP}$. This mass limit resides coincidentally (we presume) just below the deuterium-burning limit of $12 M_{JUP}$ (Burrows et al. 1998). The number of planets rises so rapidly with decreasing mass below $5 M_{JUP}$ that deuterium burning apparently plays no role in planet formation. Nonetheless, given the value to set some upper bound on planetary mass, we adopt the deuterium burning limit, both because of its proximity to the empirical end of the mass distribution and also for its mnemonic symmetry with the H-burning limit at the substellar boundary.

While the lower end of the mass distribution plays little role in the current discussion, we adopt the mass of Pluto as the lower limit, for historical reasons. Moreover, planets are commonly thought to bear a formational history that involves orbiting a massive star or brown dwarf. Thus we adopt the following definition of a "planet." A "planet" is an object that has a mass between that of Pluto and the Deuterium-burning threshold and which forms in orbit around an object that can generate energy by nuclear reactions. A thorough discussion of the parameters and considerations that bear on planet status is given by Basri (2001). Therefore, HD 168443 harbors at most one planet by this definition, and possibly none.

Semantics aside, the formation mechanisms of the two companions to HD 168443 remain unknown. One possibility is that the two companions formed "as binary stars do." Unfortunately, there is no widely accepted theory for the formation of close binaries. Such a "stellar" perspective for these two companions within 3 AU renders it a hierarchical "triple-star system." Indeed, a few hierarchical triple-star systems are known that are contained within 3 AU, e.g., HD 109648 (Jha et al. 2000; Tokovinin 1997). Clearly such close triple systems are dynamically stable (§ 4.2; and see Ford, Kozinsky, & Rasio 2000). As the formation of such close triple-star systems remains unkown, one wonders about the possibility of a common set of formation processes. Perhaps formation of all of these systems occurs in a disk, rendering close triple stars kin of planetary systems.

New formation scenarios are required to explain these two companions. Their proximity to the star suggests that they either formed surprisingly within a few AU or were dynamically brought to their present positions. The masses of protoplanetary disks are thought too low within 3 AU to provide the necessary material to form either one of the companions (Beckwith & Sargent 1996). Thus in situ formation requires a more massive disk than those reported for T Tauri stars of age 10^6 yr. Perhaps more massive, young disks of age $\sim 10^5$ yr could form particularly massive "planets" by the conventional set of processes (e.g., Lissauer 1995). Formation of massive companions within young, massive disks should be pursued theoretically, and indeed suggestive models have been constructed by Armitage & Hansen (1999), Kley (2000), and Nelson et al. (2000).

Instabilities within, or collisions between, protoplanetary disks may produce objects with masses of 5–30 M_{JUP} (Lin et al. 1998; Boss 2000; Bryden et al. 2000). Such processes within disks could lead to hybrid objects between planets and brown dwarfs in the sense that formation occurs in the disk but is triggered by a stochastic perturbation imposed by another planet, star, shock wave, or passing disk. Such orbiting objects would have masses constrained by the disk mass, as with conventional planets and would orbit in the disk plane. Indeed, systems of such objects could form around one star, yielding multiple "hybrid planets" that superficially resemble the architecture of a conventional planetary system. Such disk instabilities or collisions could lead to larger orbiting bodies than normally occur with more deterministic, conventional planet formation.

Independent of formation, the two companions could have been dynamically scattered inward to their present location (Weidenschiling & Marzari 1996; Lin et al. 1996; Rasio & Ford 1996; Levison, Lissauer, & Duncan 1998). No stellar companions to HD 168443 are known, and our IR adaptive optics search found none. Energy conservation implies that the present small semimajor axes can only come at the expense of some other massive companion (or disk material) which is farther out or ejected. Our adaptive optics nondetection seems to rule out any stellar companions between 5 and 150 AU.

We are left with two companions, one of which is too massive to be consistent with the empirical mass distribution of planets (Marcy & Butler 2000; Halbwachs et al. 2000). Their masses reside suspiciously near the 13 M_{JUP} interface between planets and "brown dwarfs," and they both reside within 3 AU of a star. These properties suggest that they formed in an environment with a scale size of order ~ 3 AU. A plausible environment for formation is the protoplanetary disk. Thus, these two companions have masses and orbits consistent with formation in a disk, but with masses somewhat larger than is found among extrasolar planets. Taxonomy aside, these two companions may have formed by hybrid processes normally associated with both planets and brown dwarfs, namely gas instabilities in a protoplanetary disk.

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