

FOUR NEW EXOPLANETS AND HINTS OF ADDITIONAL SUBSTELLAR COMPANIONS TO EXOPLANET HOST STARS¹

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Received 2006 July 26; accepted 2006 October 28

ABSTRACT

We present four new exoplanets: HIP 14810b and HIP 14810c, HD 154345b, and HD 187123c. The two planets orbiting HIP 14810, from the N2K project, have masses of 3.9 and 0.76 M_J . We have searched the radial velocity time series of 90 known exoplanet systems and found new residual trends due to additional, long period companions. Two stars known to host one exoplanet have sufficient curvature in the residuals to a one planet fit to constrain the minimum mass of the outer companion to be substellar: HD 68988c with $8 M_J < m \sin i < 20 M_J$ and HD 187123c with $3 M_J < m \sin i < 7 M_J$, both with $P > 8$ yr. We have also searched the velocity residuals of known exoplanet systems for prospective low-amplitude exoplanets and present some candidates. We discuss techniques for constraining the mass and period of exoplanets in such cases, and for quantifying the significance of weak RV signals. We also present two substellar companions with incomplete orbits and periods longer than 8 yr: HD 24040b and HD 154345b with $m \sin i < 20 M_J$ and $m \sin i < 10 M_J$, respectively.

Subject headings: planetary systems — techniques: radial velocities

1. INTRODUCTION

Of the 151 nearby stars known to harbor one or more planets, 19 are well-characterized multiple-planet systems, and an additional 24 show radial velocity (RV) residuals indicative of additional companions (Butler et al. 2006). For instance, Vogt et al. (2005) reported additional companions around five stars, including two revealed by incomplete orbits apparent in the RV residuals (HD 50499 and HD 217107) and one as a short-period, low amplitude variation in the residuals of the fit to a long-period outer companion. Rivera et al. (2005) detected a $7.5 M_{\oplus}$ companion to GJ 876 in a 2 day period through analysis of the RV residuals to a two-planet dynamical fit of the more massive, outer exoplanets. Goździewski & Migaszewski (2006) similarly analyzed the RV residuals of four stars to search for Neptune-mass companions.

Very little is known about the frequency or nature of exoplanets with orbital distances greater than 5 AU (Marcy et al. 2005b). Precise radial velocities have only reached the precision required to detect such objects within the last 10 years (Butler et al. 1996), which is less than the orbital period of such objects ($P > 12$ yr for exoplanets orbiting solar mass stars). Thus, the RV curves for

such planets are all necessarily incomplete, and we must obtain many more years of data before our knowledge of their orbits improves significantly.

The ability to put constraints on planets with incomplete orbits, however weak, allows us to peek beyond the 5 AU completeness limit inherent in the 10 year old planet searches. Characterizing incomplete orbits also increases our sample of known multiple exoplanetary systems, which improves our understanding of the frequency of orbital resonances, the growth of multiple planets, and the mechanics of orbital migration. In this work, we present our analysis of the RV data of Butler et al. (2006) in an effort to determine which of those systems have additional, low-amplitude companions.

Many systems known to host one exoplanet show more distant, long-period companions with highly significant but incomplete orbits. In these systems, it can be extremely difficult to constrain the properties of the outer companion: in the case of a simple trend with no curvature, very little can be said about the nature of these companions beyond their existence, but even this informs studies of exoplanet multiplicity and the frequency of exoplanets in binary systems.

In § 2 we discuss a new multiple planet system from the N2K project, HIP 14810. In § 3 we describe how we have employed a false alarm probability statistic to test the significance of trends in the RV data of stars already known to host exoplanets. We find that six stars known to host exoplanets have previously undetected trends, and thus additional companions.

When the RV residuals to a single Keplerian show significant curvature, one may be able to place additional constraints on the maximum $m \sin i$ of the additional companion. In §§ 4–5 we present our analysis of this problem in the cases of HD 24040b and HD 154345b, two substellar companions new to this work with very incomplete orbits. By mapping χ^2 space for Keplerian fits, we show that HD 154345b is almost certainly planetary ($m \sin i < 10 M_J$), and that HD 24040b may be planetary ($5 M_J < m \sin i < 20 M_J$).

In § 6 we describe how we extended this method to the RV residuals of known planet-bearing stars which show trends. We

¹ Based on observations obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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TABLE 1
RV DATA FOR HIP 14810

Time (JD -2,440,000)	Radial Velocity (m s ⁻¹)	Uncertainty (m s ⁻¹)
13,693.760579.....	-130.8	1.3
13,694.831481.....	-473.6	1.2
13,695.909225.....	-226.9	1.2
13,723.786250.....	162.6	1.0
13,724.688484.....	324.9	1.2
13,746.814595.....	2.4	1.3
13,747.852940.....	-435.82	0.94
13,748.734190.....	-433.3	1.2
13,749.739236.....	-71.4	1.2
13,751.898252.....	358.3	1.1
13,752.807431.....	241.05	0.80
13,752.912477.....	211.6	1.7
13,753.691574.....	-79.8	1.1
13,753.810359.....	-137.6	1.2
13,753.901042.....	-180.2	1.2
13,775.836157.....	-240.01	0.97
13,776.812859.....	123.4	1.4
13,777.723102.....	346.7	1.3
13,778.720799.....	416.0	1.3
13,779.744410.....	238.4	1.3
13,841.722049.....	-515.7	1.4
13,961.130301.....	-280.9	1.0
13,962.133333.....	-413.4	1.1
13,969.097315.....	-348.3	1.2
13,981.969815.....	-476.5	1.2
13,982.947431.....	-200.9	1.2
13,983.981470.....	151.5	1.0
13,984.096979.....	187.3	1.2
13,984.985775.....	345.7	1.3
13,985.102106.....	357.6	1.3

find that for two stars we can place sufficiently strong upper limits on $m \sin i$ to suggest that the additional companions are planetary in nature.

2. HIP 14810

HIP 14810 is a metal-rich ($[\text{Fe}/\text{H}] = 0.23$) G5 V, $V = 8.5$ star, which we have observed at Keck Observatory as part of the N2K program (Fischer et al. 2005) since 2005 November. The radial velocity data for this star were initially reduced using the template-free spectral morphing technique of Johnson et al. (2006). When the first five data points showed evidence of a short-period planet, we obtained a template observation and re-reduced the data using standard techniques (Butler et al. 1996).

Table 1 contains the RV data for this star. Its stellar characteristics are listed in Table 2, determined using the same LTE

spectral analysis used for stars in the SPOCS catalog (Valenti & Fischer 2005). We quickly detected a short-period, high-amplitude companion ($P = 6.67$ days, $m \sin i = 3.9 M_J$) and a strong, $\sim 200 \text{ m s}^{-1}$ trend. Further observations revealed evidence for substantial curvature in the residuals to a planet plus trend fit. Figure 1 shows the RV curve for this star decomposed into Keplerian curves for the b and c components, and Table 3 contains the best-fit double Keplerian elements.

A two-planet Keplerian fit yields an outer planet with $m \sin i = 0.95 M_J$, $P = 114$ days, and eccentricity of 0.27. We present the orbital solutions for this two-planet system in Table 3.

3. DETECTING LONG-PERIOD COMPANIONS

Very long period substellar companions appear in radial velocity data first as linear trends (constant accelerations), then as trends with curvature, and finally, as the duration of the observations becomes a substantial fraction of the orbital period, as recognizable portions of a Keplerian velocity curve. It is important, then, to have a statistically robust test for trends in velocity residuals. In this section, we discuss calculating false alarm probabilities (FAPs) for such trends.

3.1. Using FAP to Detect Trends

Marcy et al. (2005b; § 5.2) present a detailed discussion of using false alarm probabilities (FAPs) for determining the significance of a periodic signal in an RV time series. Here our task is similar. We wish to test the hypothesis that a star has an additional companion with a long period, manifest only as a linear trend in the RV series. We compare this hypothesis to the null hypothesis that the data are adequately described only by the best-fit Keplerians and noise.

We first fit the data set with a Keplerian model and compare the χ^2_ν statistic to that of a model employing a Keplerian plus a linear trend. If this statistic improves, that is, if $\Delta\chi^2_\nu = \chi^2_{\nu, \text{trend}} - \chi^2_{\nu, \text{notrend}}$ is negative, then the inclusion of the trend may be justified. To test the significance of the reduction in χ^2_ν , we employ an FAP test.

We first employ a bootstrap method to determine our measurement uncertainties. We subtract the best-fit Keplerian RV curve from the data and assume the null hypothesis—namely that the residuals to this fit are properly characterized as noise and thus approximate the underlying probability distribution function of the noise in the measurements. We then draw from this set of residuals (with replacement) a mock set of residuals with the same temporal spacing as the original set.

By adding these mock residuals to the best-fit Keplerian RV curve we produce a mock data set with the same temporal sampling as the original data set, but with the velocity residuals

TABLE 2
PROPERTIES OF THREE STARS HOSTING NEW SUBSTELLAR COMPANIONS

HD	Hipparcos No.	R.A. (J2000.0)	Decl. (J2000.0)	$B - V$	V	Distance (pc)	T_{eff} (K)	$\log g$ (cm s ⁻²)	[Fe/H]	$v \sin i$ (m s ⁻¹)	Mass (M_\odot)	S	ΔM_V	Jitter (m s ⁻¹)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
24040.....	17960	03 50 22.968	+17 28 34.92	0.65	7.50	46.5(2.2)	5853(44)	4.361(70)	0.206(30)	2.39(50)	1.18	0.15	0.65	5.7
154345.....	83389	17 02 36.404	+47 04 54.77	0.73	6.76	18.06(18)	5468(44)	4.537(70)	-0.105(30)	1.21(50)	0.88	0.18	-0.21	5.7
...	14810	03 11 14.230	+21 05 50.49	0.78	8.52	52.9(4.1)	5485(44)	4.300(70)	0.231(30)	0.50(50)	0.99	0.16	0.64	3.5

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. For succinctness, we express uncertainties using parenthetical notation, where the least significant digit of the uncertainty, in parentheses, and that of the quantity are understood to have the same place value. Thus, “0.100(20)” indicates “ 0.100 ± 0.020 ,” “1.0(2.0)” indicates “ 1.0 ± 2.0 ,” and “1(20)” indicates “ 1 ± 20 .” Data in cols. (3)–(7) and (14) are from *Hipparcos* (Perryman et al. 1997), and col. (15) is derived using the formula in Wright (2005a). ΔM_V refers to the height of a star above the main sequence, as defined in Wright (2005b). Data in cols. (8)–(12) are from the SPOCS catalog (Valenti & Fischer 2005), and col. (13) is from Wright et al. (2004), except for the entries for HIP 14810, which are new to this work and were derived using the same methods used in those works.

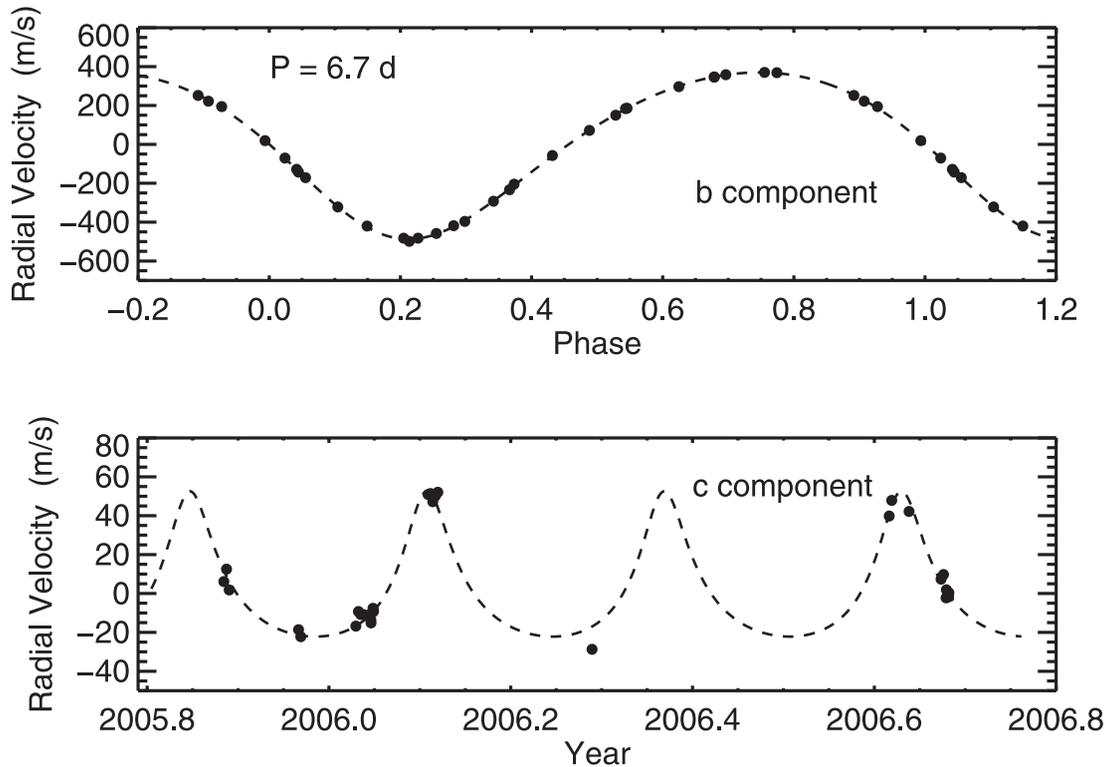


FIG. 1.—RV curve for HIP 14810 with data from Keck, showing the inner planet with $P = 6.67$ days and $m \sin i = 3.9 M_J$ and the outer planet with $P = 95.3$ days and $m \sin i = 0.76 M_J$.

“scrambled” (“redrawn” might be a better term since we have drawn residuals *with* replacement). It is important in this procedure that internal errors remain associated with the scrambled residuals. This ensures that points with error bars so large that they contribute little to the χ^2_ν sum, but nonetheless lie far from the best-fit curve, do not gain significance when “scrambled,” inappropriately increasing χ^2_ν .

We then compare $\Delta\chi^2_\nu$ for our mock data set to that of our genuine data. By repeating this procedure 400 times, we produce 400 mock sets of residuals and 400 values for $\Delta\chi^2_\nu$. If the linear trend is simply an artifact of the noise, then redrawing the residuals should not systematically improve or worsen $\Delta\chi^2_\nu$. Conversely, if a linear trend is significant, then the null hypothesis, that the residuals to a Keplerian are uncorrelated noise, is invalid, and redrawing them should worsen the quality of the Keplerian(s) plus trend fit, since scrambling will remove evidence of the trend. Thus, the fraction of these sets with $\Delta\chi^2_\nu$ less than that of the proper, unscrambled residuals, provides a measurement of the false alarm probability that the residuals to a Keplerian-only fit are correlated.

3.2. Velocity Trends and Additional Companions in Known Exoplanet Systems

The Catalog of Nearby Exoplanets (Butler et al. 2006) contains 172 substellar companions with $m \sin i < 24 M_J$ orbiting 148 stars within 200 pc. Since then, at least three more systems have been announced, including a triple Neptune (Lovis et al. 2006), and two single-planet detections (Johnson et al. 2006; Hatzes et al. 2006). Of these 151 systems, 24 show significant trends in addition to the Keplerian curves of the known exoplanets. We have reanalyzed the radial velocities of Butler et al. (2006) to determine the significance of these trends and to find evidence for additional trends using the FAP test described in § 3.1. Note that we have obtained additional data for some of these systems since Butler et al. (2006) went to press.

We confirm here 21 of the 24 trends in Butler et al. (2006) to have FAPs below 1% (two others are in systems for which we have no data to test, and the third is HD 11964, discussed in § 6.3). We also confirm the trend in the 14 Her system, first announced in Naef et al. (2004) and analyzed more thoroughly in Goździewski et al. (2006) and § 6.2. We confirm the finding of Endl et al. (2006) that the trend reported in Marcy et al. (2005b) for HD 45350b is not significant (FAP = 0.6 and χ^2_ν increases with the introduction of a trend).

We announce here the detection of statistically significant linear trends (FAP < 1%) around four stars already known to harbor a single exoplanet: HD 83443, GJ 436 (=HIP 57087), HD 102117, and HD 195019. GJ 436 will be discussed more thoroughly in an upcoming work (Maness et al. 2007). In one additional case, HD 168443, we detect a radial velocity trend with FAP < 1% in a system already known to have two exoplanets, indicating that a third, long-period companion may exist. We present the updated orbital solutions in Table 3.

HD 49674 has an FAP for an additional trend of $\sim 2\%$, which is of borderline significance when we account for the size of our sample: we should expect that around 2 of our 100 systems will prove to have FAPs $\sim 2\%$ purely by chance, and not because of an additional companion. We include the fit for HD 49674 with a trend in Table 3, but note here the weakness of the detection.

4. CONSTRAINING LONG-PERIOD COMPANIONS

4.1. The Problem of Incomplete Orbits

It is difficult to properly characterize the orbit of an exoplanet when the data do not span at least one complete revolution. After one witnesses a complete orbit of the planet in a single-planet system, subsequent orbits should have exactly the same shape (absent strong planet-planet interactions), and so one can interpret deviations as the effects of an additional companion. Before witnessing one complete orbit, one can easily misinterpret the signature of an

TABLE 3
 UPDATED ORBITAL FITS FOR NINE EXOPLANETS

Planet	Period (days)	K (m s^{-1})	e	ω (deg)	T_p (JD $-2,440,000$)	Trend ($\text{m s}^{-1} \text{ yr}^{-1}$)	$m \sin i$ (M_J)	a (AU)	rms (m s^{-1})	$(\chi^2_\nu)^{1/2}$	N_{obs}
HIP 14810b.....	6.6742(20)	428.3(3.0)	0.1470(60)	158.6(2.0)	13,694.588(40)		3.91(55)	0.0692(40)	5.1	1.4	30
HIP 14810c.....	95.2847(20)	37.4(3.0)	0.4091(60)	354.2(2.0)	13,679.585(40)		0.76(12)	0.407(23)	5.1	1.4	30
HD 49674b.....	4.9437(23)	13.7(2.1)	0.29(15)	283	11,882.90(86)	2.6(1.1)	0.115(16)	0.0580(33)	4.4	0.62	39
HD 83443b.....	2.985625(60)	56.4(1.4)	0.008(25)	24	11,211.04(82)	2.40(79)	0.400(34)	0.0406(23)	8.2	0.93	51
GJ 436b.....	2.643859(74)	18.35(80)	0.145(52)	353(24)	11,551.72(12)	1.42(35)	0.0682(63)	0.0278(16)	4.2	0.93	60
HD 102117b.....	20.8079(55)	11.91(77)	0.106(70)	283	10,942.9(3.0)	$-0.91(26)$	0.172(18)	0.1532(88)	3.3	0.83	45
HD 168443b.....	58.11289(86)	475.9(1.6)	0.5286(32)	172.87(94)	10,047.387(34)		8.02(65)	0.300(17)	4.1	0.97	109
HD 168443c.....	1749.5(2.4)	298.0(1.2)	0.2125(15)	65.07(21)	10,273.0(4.6)		18.1(1.5)	2.91(17)	4.1	0.97	109
HD 195019b.....	18.20163(40)	272.3(1.4)	0.0140(44)	222(20)	11,015.0(1.2)	1.31(51)	3.70(30)	0.1388(80)	16	1.5	154

NOTE.—For succinctness, we express uncertainties using parenthetical notation, where the least significant digit of the uncertainty, in parentheses, and that of the quantity are understood to have the same place value. Thus, “0.100(20)” indicates “ 0.100 ± 0.020 ,” “1.0(2.0)” indicates “ 1.0 ± 2.0 ,” and “1(20)” indicates “ 1 ± 20 .”

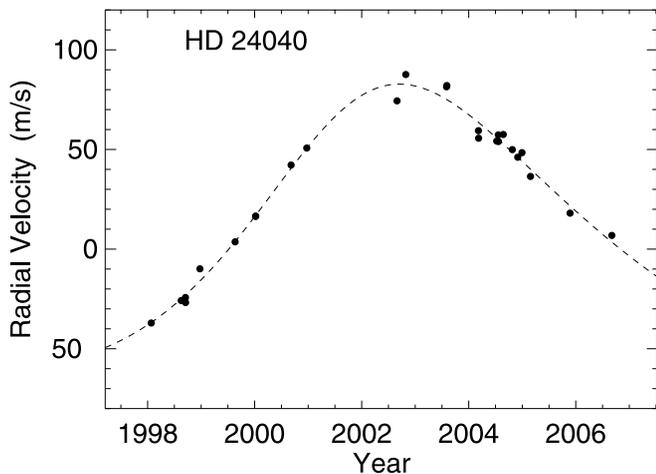


FIG. 2.— RV curve for HD 24040 with data from Keck. The best-fit Keplerian is poorly constrained due to incomplete coverage of the orbit. The fit shown here is for $P = 16.5$ yr and $m \sin i = 6.9 M_J$, one of a family of adequate solutions.

additional companion as it is absorbed into the orbital solution for the primary companion. Even when only one planet is present, small portions of single Keplerian curves can easily mimic portions of other Keplerians with very different orbital elements.

4.2. Constraining $m \sin i$ and P

When an RV curve shows significant curvature, it may be possible to constrain the minimum mass ($m \sin i$) and orbital period of the companion. Brown (2004) discussed the problem extensively, and Wittenmyer et al. (2006) studied the significance of nondetections in the McDonald Observatory planet search without assuming circular orbits by injecting artificial RV signals into program data to determine the strength of a just recoverable signal. Wittenmyer et al. (2006) reasonably assigned a broad range of eccentricities, $0 < e < 0.6$, with an upper limit they justified by the fact that over 90% of all known exoplanets have $e < 0.6$ (Butler et al. 2006). The presence of this upper limit greatly limits the number of pathological solutions to a given RV set. Below, we explore the nature of limits on mass and period implied by a given data set and how constraining e can improve those limits.

Since $m \sin i$, not K , is the astrophysically interesting quantity in exoplanet detection, it is useful to transform into P , e , and $m \sin i$ coordinates when considering constraints. The minimum mass of a companion can be calculated from the *mass function*, $f(m)$, and the stellar mass, according to the relation:

$$f(m) = \frac{m^3 \sin^3 i}{(m + M_*)^2} = \frac{PK^3(1 - e^2)^{3/2}}{2\pi G}, \quad (1)$$

where, in the minimum mass case (where $\sin i = 1$), we set m equal to $m \sin i$. This relation allows us to fit for the minimum mass (which we refer to as $m \sin i$ for brevity) eliminating the orbital parameter K .

Using equation (1), we can find the best-fit Keplerian RV curve across P - $m \sin i$ space, allowing e , ω , and γ (the RV zero point) to vary at many fixed values of P and $m \sin i$ to map χ^2 .

5. TWO NEW SUBSTELLAR COMPANIONS WITH INCOMPLETE ORBITS

Here we consider HD 24040, a metal-rich ($[\text{Fe}/\text{H}] = 0.21$) G0 V star at 46 pc (stellar characteristics summarized in Table 2). This star shows RV variations consistent with a planetary companion

TABLE 4
RV DATA FOR HD 24040

Time (JD -2,440,000)	Radial Velocity (m s^{-1})	Uncertainty (m s^{-1})
10,838.773206.....	-37.1	1.4
11,043.119653.....	-25.8	1.5
11,072.039039.....	-24.3	1.4
11,073.002315.....	-26.8	1.2
11,170.876921.....	-9.9	1.4
11,411.092975.....	3.6	1.6
11,550.824005.....	16.4	1.3
11,551.863449.....	16.5	1.2
11,793.136725.....	42.2	1.2
11,899.945741.....	50.7	1.1
12,516.065405.....	74.4	1.3
12,575.951921.....	87.6	1.5
12,854.115278.....	81.4	1.2
12,856.115671.....	82.1	1.1
13,071.741674.....	59.4	1.2
13,072.799190.....	55.6	1.3
13,196.130000.....	54.2	1.3
13,207.120116.....	57.3	1.3
13,208.125625.....	54.0	1.2
13,241.091852.....	57.5	1.2
13,302.947025.....	49.9	1.3
13,339.945972.....	46.1	1.2
13,368.865139.....	48.4	1.2
13,426.809792.....	36.5	1.1
13,696.904468.....	18.0	1.1
13,982.061586.....	6.8	1.2

with $P \sim 15$ yr and $m \sin i \sim 7 M_J$ (Fig. 2), although longer orbital periods and minimum masses as high as $m \sin i \sim 30$ cannot be ruled out. The RV data for HD 24040 appear in Table 4.

Here and in § 6.2, we use χ^2 as a merit function and infer parameters for acceptable fits from increases of this function by 1, 4, and 9, which correspond to 1, 2, and 3 σ confidence levels for systems with Gaussian noise. Because stellar jitter provides a source of pseudorandom noise which may vary on a stellar rotation timescale, the noise in RV residuals may be non-Gaussian. Thus, to the degree that the RV residuals are non-Gaussian, the translation of these confidence limits into precise probabilities is not straightforward.

In this case, we have enough RV information to put an upper limit on $m \sin i$. Figure 3 shows χ^2 for best-fit orbits in the P - $m \sin i$ plane. Fits with P as low as 10 yr and $m \sin i$ as low as $5 M_J$ are allowed. Interestingly, the data (following the middle, $\chi^2 = \chi_{\text{min}}^2 + 4$ contour) exclude orbits with $m \sin i > 30 M_J$, providing a “maximum minimum mass.” Since without an assumption for the eccentricity (which we will make below) we cannot exclude orbits with $m \sin i$ as high as $30 M_J$, there is a chance that this companion to HD 24040 is a brown dwarf, or even stellar.

A similar case is HD 154345, a G8 V star at 18 pc (stellar characteristics summarized in Table 2). This star shows RV variations remarkably similar to those of HD 24040 (Fig. 4), but with an amplitude about 6 times smaller. In this case, the maximum $m \sin i$ is only around $10 M_J$, giving us confidence that this object is likely a true exoplanet, and masses as low as $1 M_J$ are allowed. The RV data for HD 154345 are in Table 5. We summarize the orbital constraints for these objects in Table 6.

We can put more stringent constraints on these orbits by noting that ninety percent of all known exoplanets have $e < 0.6$ (Butler et al. 2006). For both HD 24040b and HD 154345b, the high-period solutions all have high eccentricities (Figs. 3 and 5,

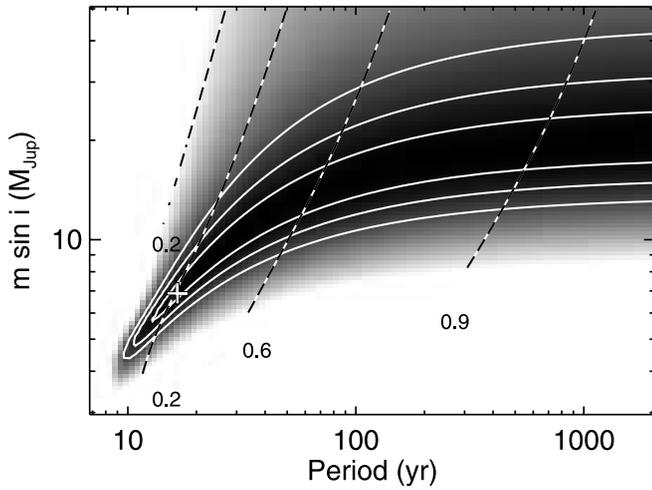


FIG. 3.—Contours of χ^2 and e in P - $m \sin i$ space of best-fit orbits to the RV data of HD 24040 (Fig. 2), with χ^2 in gray scale. The solid contours mark the levels at which χ^2 increases by 1, 4, and 9 from the minimum. The dashed contours mark levels of the eccentricity of 0.2, 0.6, and 0.9. Planets with $e > 0.6$ are rare, implying that this object is unlikely to have a period longer than 100 yr. The orbit is largely unconstrained, but $m \sin i$ has a maximum value around $20 M_J$ for orbits with $e < 0.6$. The position of the cross at 16.5 yr and $6.9 M_J$ represents the solution plotted in Fig. 2, one in a family of adequate orbital solutions.

dashed contours). If, following Wittenmyer et al. (2006), we therefore assume that $e < 0.6$ for these objects and that the true values of $m \sin i$ and P lie within the limits of the middle ($\chi^2 = \chi_{\min}^2 + 4$) contour, then we can constrain $5 M_J < m \sin i < 20 M_J$ and $10 < P < 100$ yr for HD 24040b, and $0.8 M_J < m \sin i < 10 M_J$ and $7 < P < 100$ yr for HD 154345b.

6. MINING VELOCITY RESIDUALS FOR ADDITIONAL EXOPLANETS

6.1. Velocity Residuals Suggesting Additional Companions

For exoplanetary systems in which an additional, low-amplitude signal is not well-characterized by just a linear trend—for instance, where there is significant curvature (e.g., HD 13445 or HD 68988) or even multiple orbits (e.g., GJ 876)—a full, multiplanet fit is needed to properly characterize the system. In this case, we can apply an FAP analysis similar to the one in § 3.1 testing the

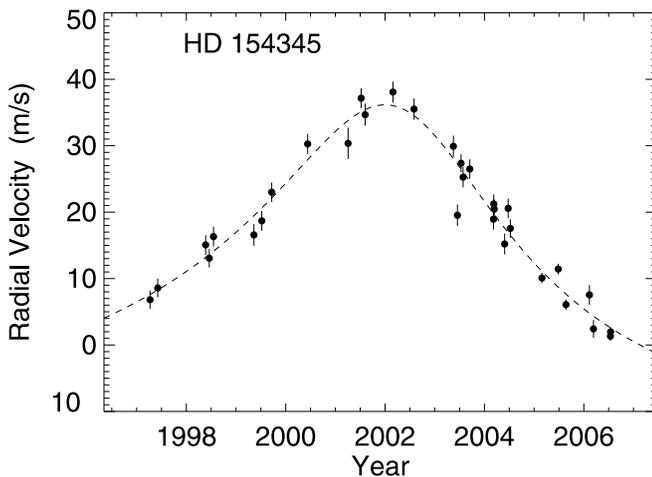


FIG. 4.—RV curve for HD 154345 with data from Keck. The best-fit Keplerian is poorly constrained due to incomplete coverage of the orbit. The fit shown here is for $P = 35.8$ yr and $m \sin i = 2.2 M_J$ (marked in Fig. 5), one in a family of adequate orbital solutions.

TABLE 5
RV DATA FOR HD 154345

Time (JD -2,440,000)	Radial Velocity (m s ⁻¹)	Uncertainty (m s ⁻¹)
10,547.110035.....	6.8	1.4
10,603.955845.....	8.6	1.4
10,956.015625.....	15.1	1.5
10,982.963634.....	13.1	1.4
11,013.868657.....	16.3	1.5
11,311.065486.....	16.6	1.6
11,368.789491.....	18.7	1.5
11,441.713877.....	23.0	1.4
11,705.917836.....	30.3	1.5
12,003.078183.....	30.4	2.3
12,098.916539.....	37.1	1.5
12,128.797813.....	34.7	1.7
12,333.173299.....	38.1	1.6
12,487.860197.....	35.5	1.6
12,776.985463.....	29.9	1.6
12,806.951852.....	19.5	1.6
12,833.801030.....	27.3	1.4
12,848.772037.....	25.3	1.5
12,897.776562.....	26.5	1.5
13,072.046921.....	18.9	1.6
13,074.077766.....	21.2	1.4
13,077.128090.....	20.5	1.4
13,153.943171.....	15.2	1.6
13,179.992454.....	20.6	1.5
13,195.819190.....	17.5	1.4
13,428.162502.....	10.09	0.78
13,547.914433.....	11.44	0.80
13,604.829999.....	6.08	0.78
13,777.155347.....	7.5	1.5
13,807.077257.....	2.4	1.4
13,931.955714.....	1.33	0.72
13,932.913019.....	1.98	0.70

($N + 1$)-planet hypothesis versus the null hypothesis of N planets plus a trend plus noise, where N is the number of previously confirmed planets. This is a much more computationally intensive procedure than that of § 3.1, since we are introducing five new, nonlinear, highly covariant parameters (P , e , ω , T_p , and K), so we have performed only 50–100 trials. In most cases the low-amplitude signal we seek is much weaker than that of the known planet(s). This means we have good initial guesses for the orbital parameters of the established exoplanets, and that those parameters are usually rather insensitive to those of the additional companion, easing the difficulty of the simultaneous 11-parameter fit (16-parameter for existing double systems).

As in § 3.1, we calculate the improvement in the goodness-of-fit parameter, $\Delta\chi_{\nu}^2 = \chi_{\nu, N+1 \text{ planets}}^2 - \chi_{\nu, N \text{ planets} + \text{trend}}^2$ with the

TABLE 6
MASS CONSTRAINTS FOR SOME SUBSTELLAR COMPANIONS WITH INCOMPLETE ORBITS

Object	Period (yr)	$m \sin i$ (M_J)	a (AU)
HD 24040b	10–100	5–20	5–23
HD 68988c.....	11–60	11–20	5–7
HD 154345b.....	7–100	0.8–10	4–25
HD 187123c.....	10–40	2–5	5–12

NOTE.—These constraints correspond to the extrema of the are given by $\chi_{\min}^2 + 4$ contour in P - $m \sin i$ space for orbits with $e < 0.6$.

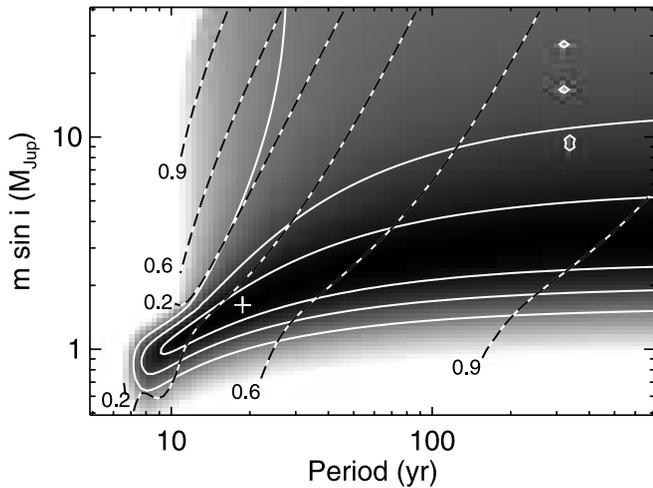


FIG. 5.—Contours of χ^2 and e in P - $m \sin i$ space of best-fit orbits to the RV data of HD 154345 (Fig. 4), with χ^2 in gray scale. The solid contours mark the levels where χ^2 increases by 1, 4, and 9 from the minimum. The dashed contours mark levels of the eccentricity of 0.2, 0.6, and 0.9. Planets with $e > 0.6$ are rare, implying that this exoplanet is unlikely to have a period longer than 100 yr. The orbit is largely unconstrained, but $m \sin i$ has a maximum value around $10 M_J$ for orbits with $e < 0.6$. The white cross at 36 yr and $2.2 M_J$ represents the solution shown in Fig. 4.

introduction of an additional exoplanetary companion compared to a fit including only an additional trend. We compare this reduction to that of mock data sets bootstrapped as the sum of the best-fit solution with a trend, plus noise, drawn, with replacement, from the residuals of the actual data to this fit. We then construct an FAP as the fraction of mock sets that saw a greater

reduction in χ^2 with the introduction of an additional planet than the genuine data set.

A low FAP for the presence of a second planet is not tantamount to the detection of an additional exoplanet. It is only a sign that the null hypothesis is unlikely, i.e., that the distribution of residuals is not representative of the actual noise in the system or that the presumed orbital solution from which the residuals were drawn is in error. This would be the case if, for instance, if the residuals are correlated due to non-Keplerian RV variations (such as systematic errors or astrophysical jitter).

The fits discussed here are purely Keplerian and not dynamical. In particular, fits which produce unstable or unphysical orbits are allowed. More sophisticated, Newtonian fits (e.g., Rivera et al. 2005) would better constrain the orbits of multiple planet systems.

6.2. Long-Period Companions with Incomplete Orbits

We have identified eight other systems in which the FAP for an additional Keplerian vs. a simple trend is below 2%: HD 142, HD 13445, HD 68988, 23 Lib (=HD 134987), 14 Her, τ Boo (=HD 120136), HD 183263, and HD 187123. In addition, we have identified a ninth system, HD 114783, which has a compelling second Keplerian despite a slightly larger FAP (6%). We summarize the orbital constraints for these objects in Table 6.

HD 142.—Most of the RV data for HD 142 (see Fig. 6) show a simple linear trend superposed on the known $K = 34 \text{ m s}^{-1}$, 350 day orbit (Tinney et al. 2002). HD 142 is known to have a stellar companion ($V = 10$; Poveda et al. 1994), which could explain the trend. The first two data points, taken in 1998–1999, are significantly low, producing a low FAP for curvature (<1%). HD 142 has $B - V = 0.52$, indicating it is a late-F or early-G star, suggesting it may have moderate jitter ($\sim 5 \text{ m s}^{-1}$; Wright

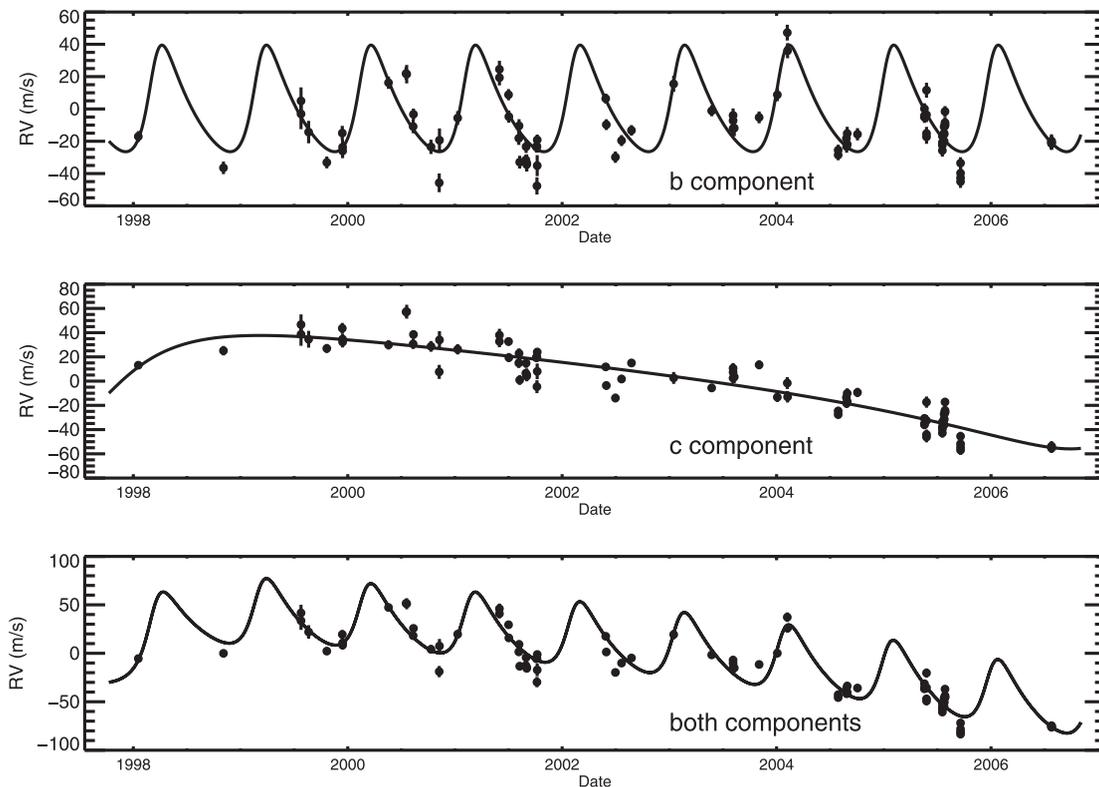


FIG. 6.—RV curve for HD 142, a multiple companion system, with data from AAT. The previously known inner planet has $P = 350$ days, and the outer companion is poorly constrained but consistent with the known stellar companion. The data are inconsistent with a linear trend, mostly because of the first two data points.

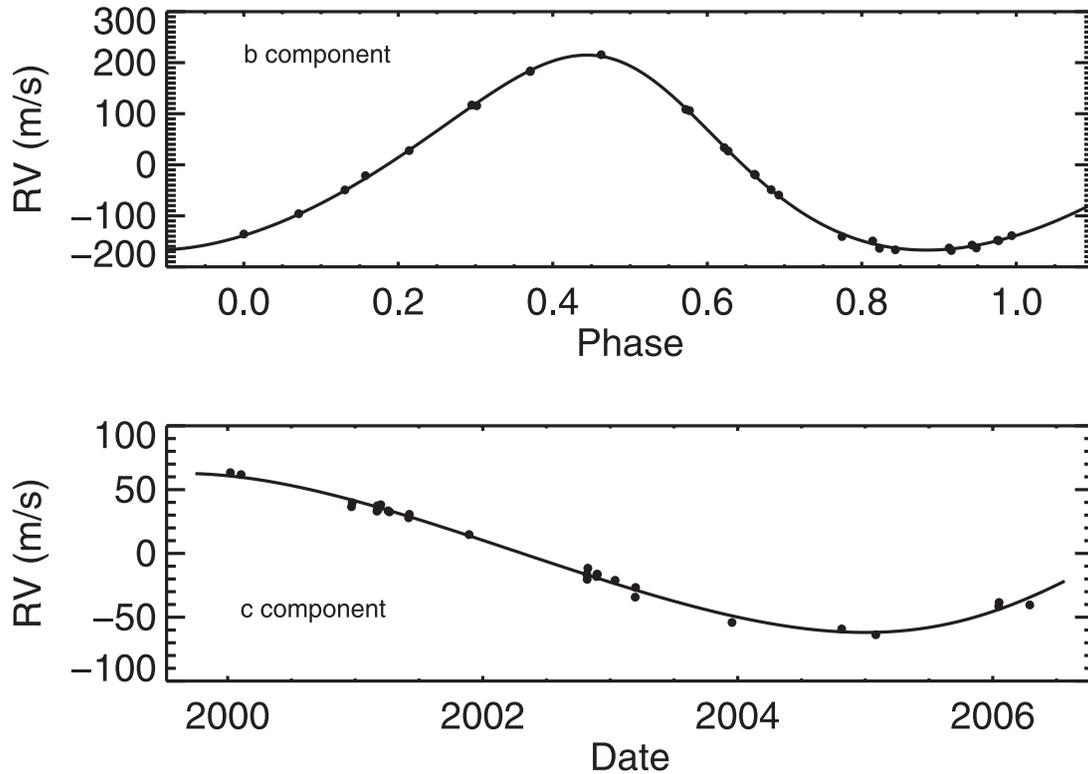


Fig. 7.—RV curve for HD 68988, a multiple-companion system, with data from Keck. The previously known inner planet has $P = 6.28$ days, and the outer companion is poorly constrained but likely has $m \sin i < 20 M_J$ and $P < 60$ yr.

2005a), so we therefore view the low FAP for curvature, apparently based on only two low points, with suspicion. If the curvature is real, it is consistent with an exoplanet with period longer than the span of the observations ($P > 10$ yr) with a minimum mass of at least $4 M_J$.

HD 13445 (=GL 86).—Has a known planet with $P = 15.76$ days (Queloz et al. 2000; Butler et al. 2006). Superposed on that Keplerian velocity curve is a velocity trend of roughly $-94 \text{ m s}^{-1} \text{ yr}^{-1}$ during the past 9 years, apparently consistent with the brown dwarf companion previously reported by Els et al. (2001), Chauvin et al. (2006), and Queloz et al. (2000). There is a hint of curvature in these residuals to the inner planet, but not enough to put meaningful constraints on this outer object beyond that fact that its period is longer than the span of the observations (~ 10 yr) and $m \sin i > 22 M_J$.

HD 68988.—Shows definite signs of curvature in the residuals to the $1.8 M_J$ inner planet (as Fig. 7 shows). Figure 8 shows the outer companion has $m \sin i < 30 M_J$, and the assumption of $e < 0.6$, using the middle contour, further restricts $m \sin i < 20 M_J$, and $P < 60$ yr.

HD 114783.—Shows curvature in its residuals, and may have experienced both an RV minimum (in 2000) and maximum (in 2006) as the RV curve in Figure 9 shows. The data are only moderately inconsistent with a linear trend, however (FAP = 6%), indicating that the outer companion's orbit is still underconstrained.

23 Lib (=HD 134987).—Shows signs of curvature in the residuals to the known inner planet. The signal appears as a change in the level of otherwise flat residuals between 2000 and 2002 of 15 m s^{-1} (see Fig. 10). This suggests an outer planet on a rather eccentric orbit which reached periastron in 2001. The small magnitude of this change in RV suggests a low-mass object, but the incomplete nature of this orbit makes us less than certain that it is due to an exoplanet.

14 Her (=HD 145645).—This star has a known trend (Naef et al. 2004) and has been analyzed by Goździewski et al. (2006) as a possible resonant multiple system and by Wittenmyer et al. (2007). The previously-known planet has $m \sin i = 4.9 M_J$ and $P = 4.8$ yr, but the character of the second companion is uncertain. Combining our data with the published ELODIE data from the Geneva Planet Search (Naef et al. 2004) (Fig. 11) provides a good picture of the system. The character of the orbit of the outer planet is unconstrained, and several equally acceptable but qualitatively distinct solutions exist. One is a long period, nearly circular orbit

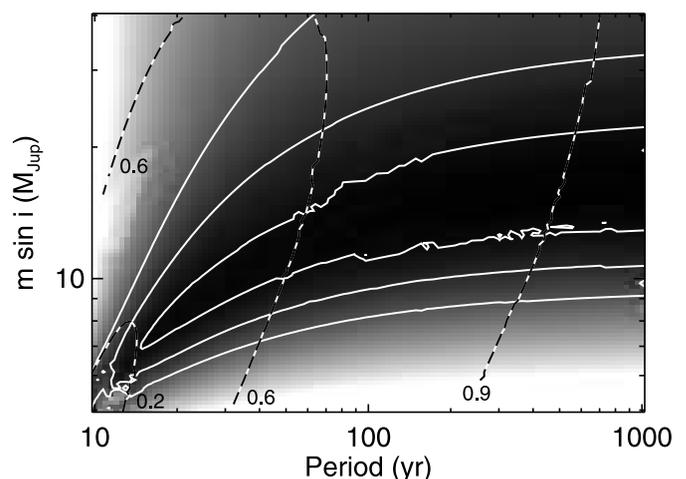


Fig. 8.—Contours of χ^2 and e_c in $P_c - (m \sin i)_c$ space for the best double-Keplerian fits to the RV data of HD 68988 (Fig. 7), with χ^2 in gray scale. The solid contours mark the levels where χ^2 increases by 1, 4, and 9 from the minimum. The dashed contours mark levels of the eccentricity of 0.2, 0.6, and 0.9. Assuming $e < 0.6$, we can constrain $6 M_J < m \sin i < 20 M_J$ and $11 < P < 60$ yr.

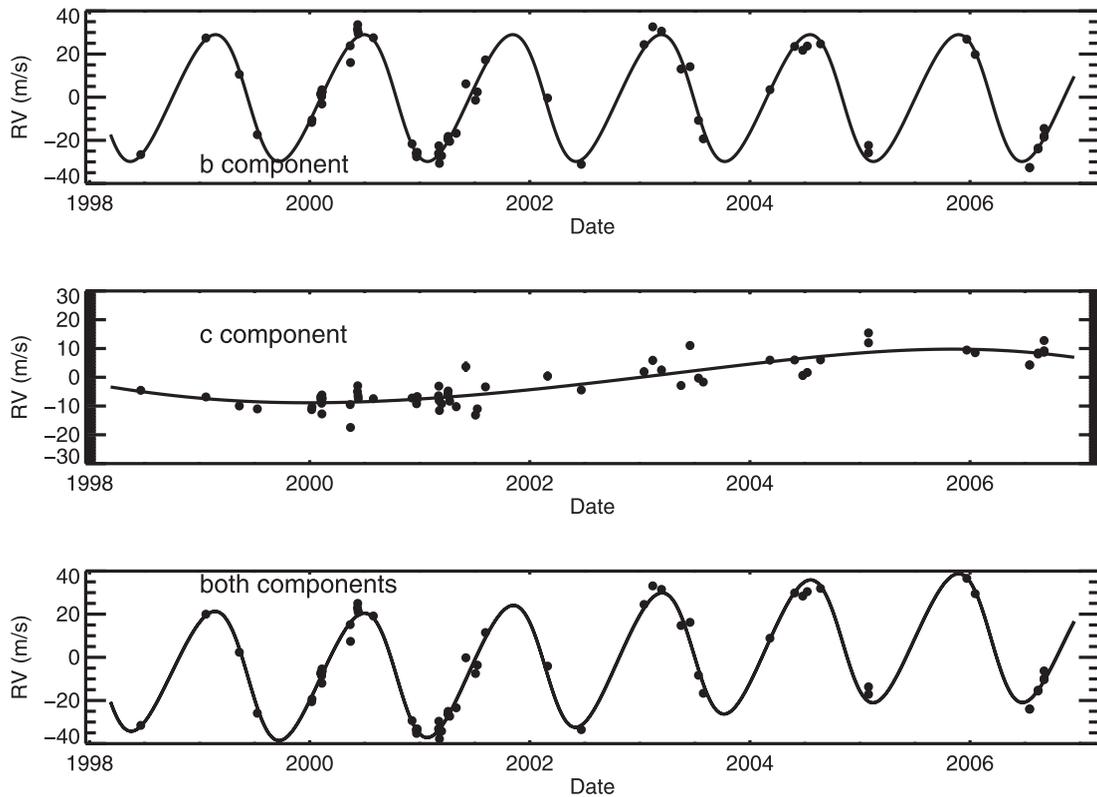


FIG. 9.—RV curve for HD 114783, a multiple-companion system, with data from Keck. The previously known inner planet has $P = 495$ days and $m \sin i = 1.1 M_J$. The residuals are only moderately inconsistent with a linear trend (FAP = 6%), indicating that the outer companion is poorly constrained.

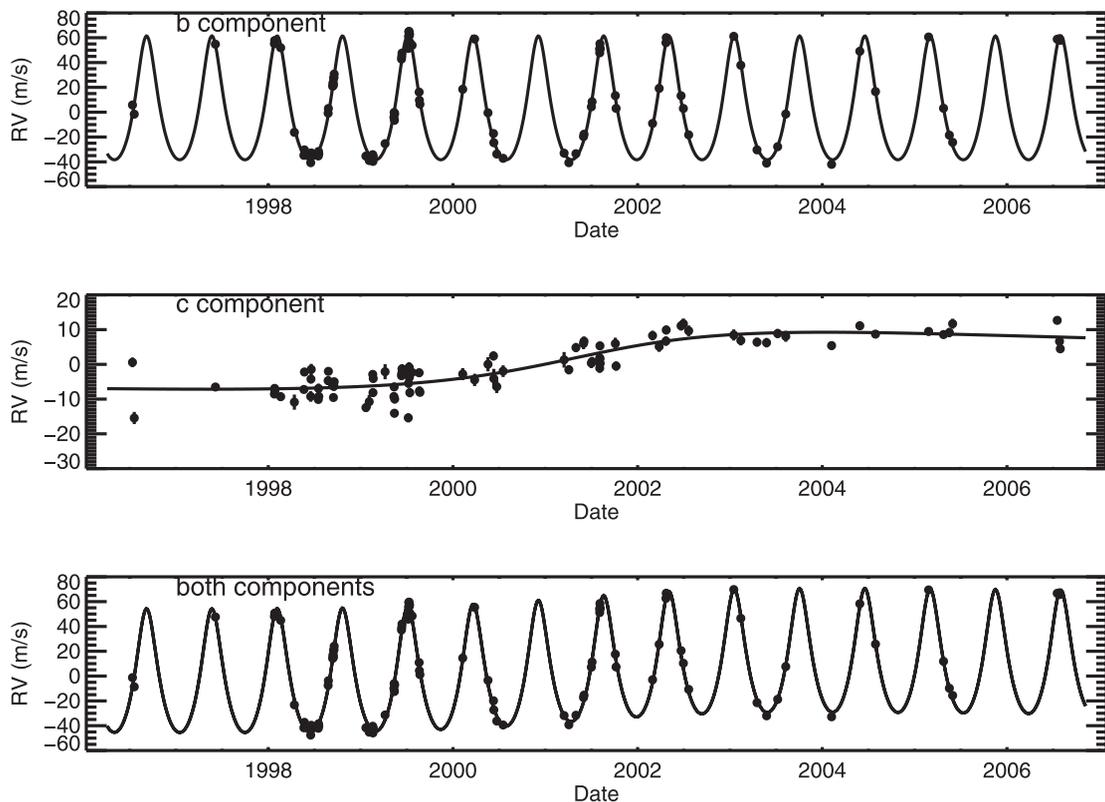


FIG. 10.—RV curve for 23 Lib (=HD 134987), a multiple-companion system, with data from Keck and AAT. The previously known inner planet has $P = 258$ days and $m \sin i = 1.62$. The outer companion is poorly constrained. The orbital parameters of the inner planet are not significantly changed with a two-parameter fit.

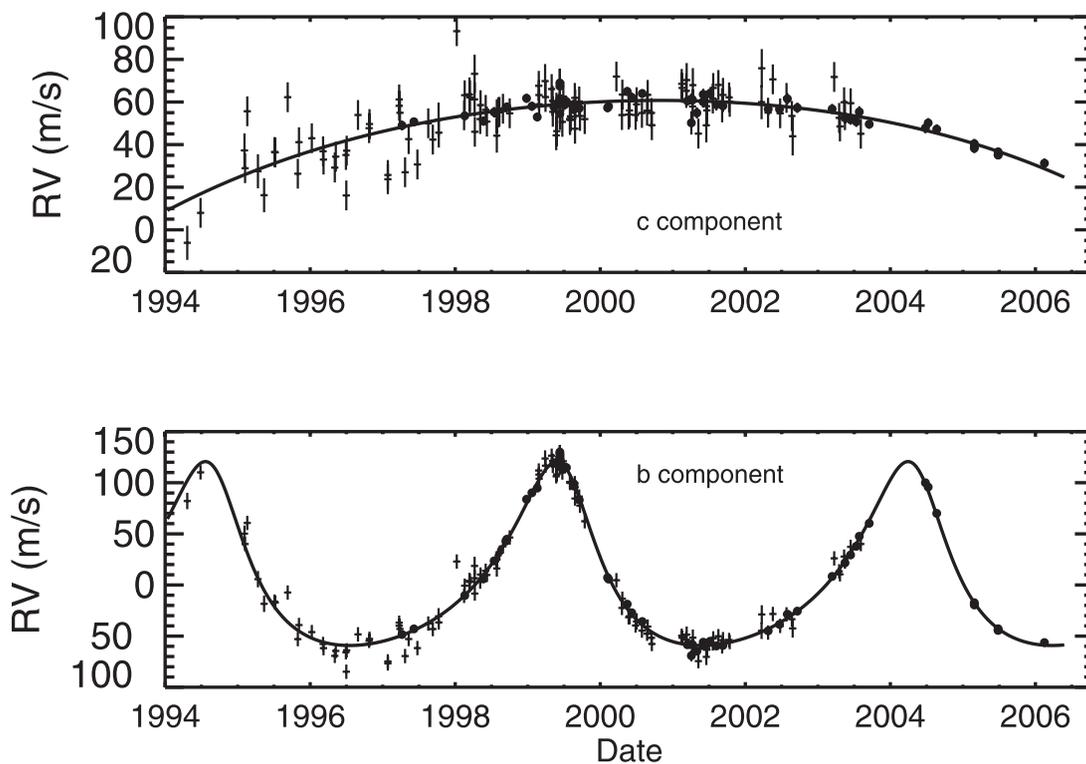


FIG. 11.—RV curve for 14 Her (=HD 145675), a system with multiple companions. Crosses represent data from the ELODIE instrument operated by the Geneva Planet Search (taken from Naef et al. 2004), and large filled circles represent data taken at Keck Observatory by the California and Carnegie Planet Search (Butler et al. 2006). Error bars represent quoted errors on individual velocities; for some points the error bars are smaller than the plotted points. The combined data set shows a long-period companion with $P > 12$ yr and $m \sin i > 5 M_J$. The previously known inner planet has $P = 4.8$ yr and $m \sin i = 4.9 M_J$.

like the one shown in Fig. 10 and a mass near $2 M_J$. Other solutions include a 3:1 resonance with the inner planet. The next few years of observation should break this degeneracy. The degeneracy may also be broken by high contrast, high resolution imaging, and we suggest that such attempts be made on this interesting system.

HD 183263.—Shows definite signs of curvature in the residuals to the known inner planet (as Fig. 12 shows), but too little to constrain the mass of the distant companion. Figure 13 shows that there is little meaningful constraint on the orbit beyond $P > 7$ yr and $m \sin i > 4 M_J$. Even the assumption of $e < 0.6$ allows for $m \sin i > 13$, so the planetary nature of the companion is very uncertain.

τ Boo (=HD 120136).—Has residuals to the fit for the known inner planet which show evidence of a long-period companion which have been discussed elsewhere (Butler et al. 2006). Analysis of the distant companion is complicated by the lower quality of the data during the apparent periastron in 1990. The current best fit suggests a period greater than 15 years, but is otherwise unconstrained. Poveda et al. (1994) report that *τ Boo* has a faint ($V = 10.3$) companion (separation of $5.4''$), which may be the source of the RV residuals.

HD 187123.—Known to host a $0.5 M_J$ “hot Jupiter” in a 3 day orbit (Butler et al. 1998). Observations over the subsequent 8 years have revealed a trend of -7.3 m s^{-1} in the residuals to a one planet fit (Butler et al. 2006). In 2001, the trend began to show signs of curvature, and in 2006 it became clear that the residuals had passed through an RV minimum (see Fig. 14). Figure 15 shows the χ^2 and e contours in P - $m \sin i$ space. In this case the $e = 0.6$ contour and middle χ^2 contour provide the following constraints: $2 M_J < m \sin i < 5 M_J$ and $10 < P < 40$ yr.

6.3. Short-Period Companions to Stars with Known Planets

We now consider known single-planet systems with low FAPs for second planets whose best-fit solutions have periods shorter than the span of observations. We have identified eight such systems, and we discuss them below.

Five stars appear to exhibit coherent residuals (FAP $< 2\%$) to a one planet fit, but in all cases the best two-Keplerian fits are not compelling (as noted in § 3.2, in a sample of 100 known planet-bearing stars, we expect around 2 to exhibit residuals coherent at this level purely by chance). These possible companions do not appear in Table 3 because the tentative nature of these signals do not warrant publication of a full orbital solution with errors.

HD 11964.—Announced in Butler et al. (2006) as having a planet with a 5.5 yr orbital period and a linear trend. We find an FAP for a linear trend to be 6%, suggesting that while the inner planet is real, the trend is not. We find an FAP for a second planet to be $< 2\%$, and a best-fit solution finds an inner planet with $P = 37.9$ days. This star sits 2 mag above the main sequence, and the residuals to the known planet are consistent with the typical jitter for subgiants of 5.7 m s^{-1} (Wright 2005a), so this signal could represent some sort of correlated noise. This very low amplitude signal ($K = 5.6 \text{ m s}^{-1}$) will thus require much more data for confirmation.

HD 177830.—Already known to have a Jupiter-mass object in a nearly circular, 1.12 yr orbit. This remarkable system has a low FAP $< 1\%$ for a second planet versus a trend. Two good two-planet solutions exist for this system: the first has $P = 111$ days and $m \sin i = 0.19 M_J$, the second has $P = 46.8$ days and $m \sin i = 0.16 M_J$. This star sits more than 3.5 mag above the main sequence, and the residuals to the known planet are consistent with the typical

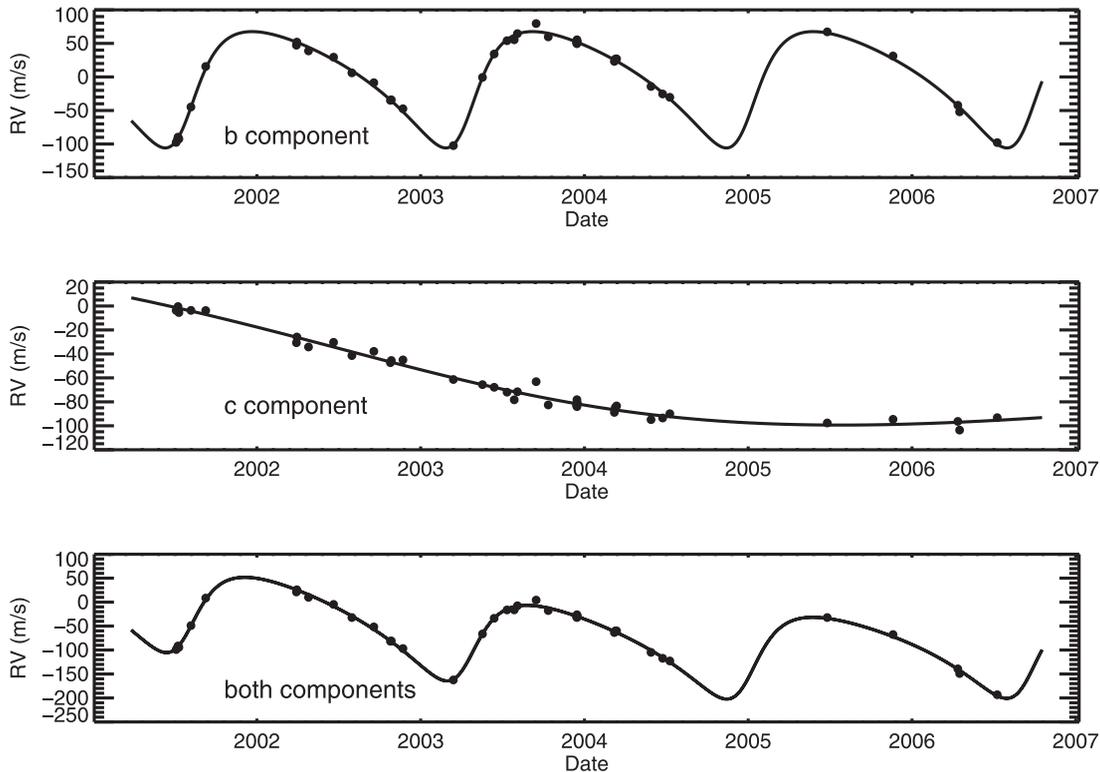


FIG. 12.—RV curve for HD 183263, a multiple-companion system, with data from Keck. The previously known inner planet has $P = 635$ days and $m \sin i = 3.8 M_J$, and the outer companion is poorly constrained.

jitter for subgiants of 5.7 m s^{-1} (Wright 2005a), so this signal could represent some sort of correlated noise.

70 Vir (=HD 117176).—Subgiant with a massive, 116.6 day planet on an eccentric orbit ($e = 0.39$). The FAP for a second planet is 2%, but the best-fit second planet is not persuasive: $P = 9.58$ days and $K = 7 \text{ m s}^{-1}$. The typical internal errors for this target are 5.4 m s^{-1} , making a bona fide detection of a 7 m s^{-1} planet very difficult. We suspect that this signal is an artifact of stellar jitter, possibly due to the advanced evolution of the star.

HD 164922.—Has a known planet with a 3.1 yr orbital period. For this star, the FAP for a second planet is $<1\%$. The best fit for this second planet has $P = 75.8$ days and $m \sin i = 0.06 M_J$. The amplitude of this signal is extremely low—only $K = 3 \text{ m s}^{-1}$ —making this an intriguing but marginal detection.

HD 210277.—Already known to host a planet with a 1.2 yr orbit. The FAP for a second planet is 2%, and the best-fit second Keplerian has $K = 3 \text{ m s}^{-1}$ signal and $P = 3.14$ days, and a 2% FAP. The best-fit orbit has $e = 0.5$, which is unlikely given that nearly all known hot Jupiters have $e < 0.1$ (although the presence of the 1.2 yr, $e = 0.5$ outer planet could be responsible, in principle, for pumping an inner planet's eccentricity). The extremely low amplitude of this planet makes the exoplanetary nature of this signal very uncertain.

Three additional stars with low FAPs are of a very early spectral type (F7–8): HD 89744 (Korzennik et al. 2000), HD 108147 (Pepe et al. 2002), and HD 208487 (Tinney et al. 2005). Their low activity yields a low jitter in the estimation of Wright (2005a) but this is likely underestimated due to poor statistics: the California and Carnegie Planet Search has very few stars of this spectral type from which to estimate the jitter. For HD 89744 and HD 108147 we suspect that, the low FAP of $<2\%$ is an artifact of coherent noise, since in our judgment neither case shows a compelling evidence of a second Keplerian of any period.

HD 208487 has a very low FAP ($<1\%$) despite the modest rms of the residuals to a one-planet fit of 8 m s^{-1} (consistent with stellar jitter). This star was discussed by Gregory (2006), who applied a Bayesian analysis to the published RV data, concluding that a second planet was likely, having $P = 909^{+82}_{-92}$ days and $m \sin i \sim 0.4 M_J$. Goździewski & Migaszewski (2006) also studied the published data, and suggested a planet with $P = 14.5$ days. We note here two plausible solutions apparent in our data. The

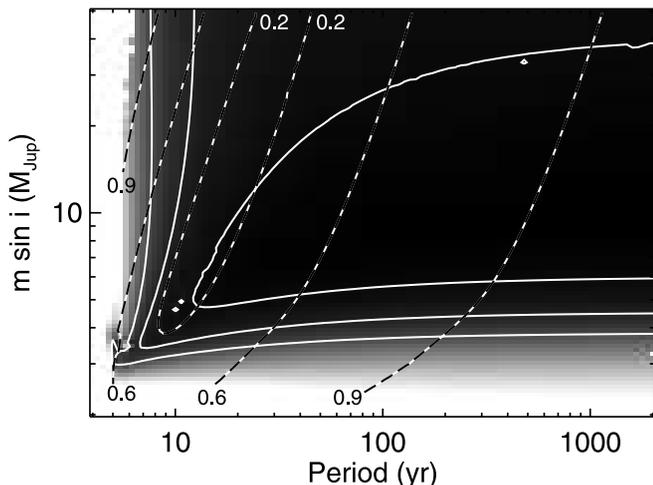


FIG. 13.—Contours of χ^2 and e_c in $P_c-(m \sin i)_c$ space for the best double-Keplerian fits to the RV data of HD 183263 (Fig. 12), with χ^2 in gray scale. The solid contours mark the levels where χ^2 increases by 1, 4, and 9 from the minimum. The dashed contours mark levels of the eccentricity of 0.2, 0.6, and 0.9. P and $m \sin i$ for this companion are poorly constrained.

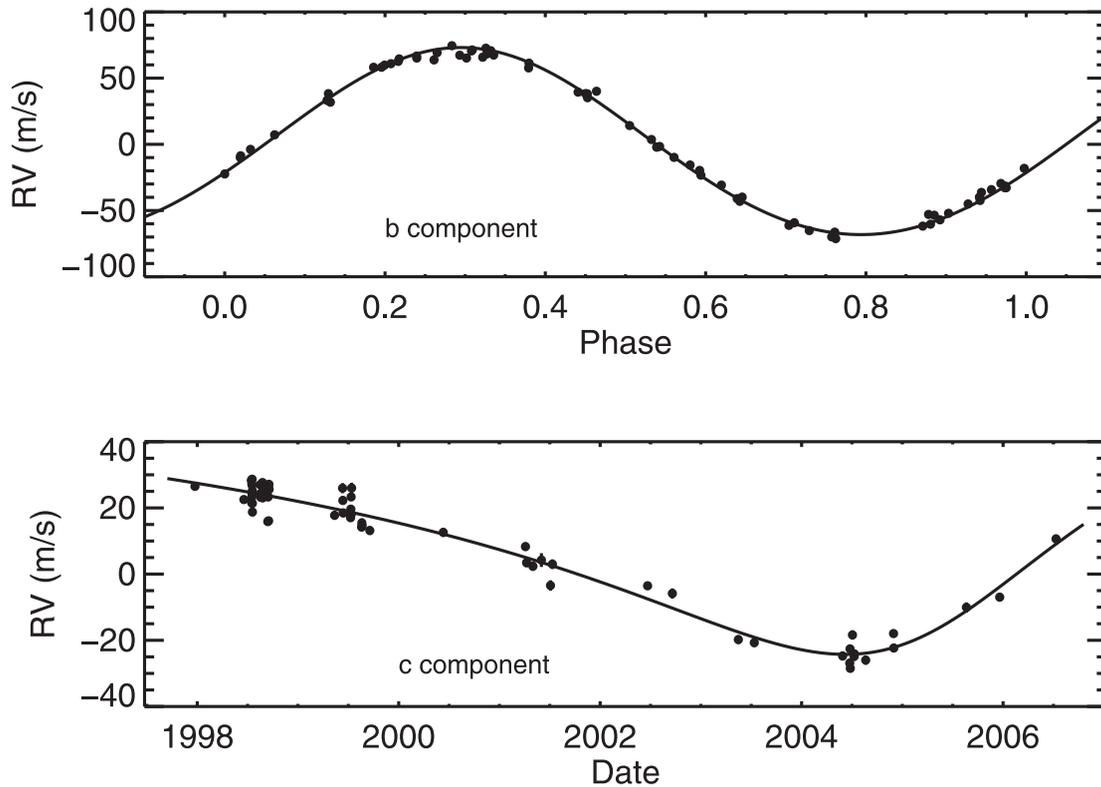


FIG. 14.—RV curve for HD 187123, with data from Keck, showing the $0.5 M_J$ “hot Jupiter” and the outer companion of uncertain period and mass.

first, with $P \sim 1000$ days and $m \sin i \sim 0.5$, is consistent with the solution of Gregory (2006). We also find, however, an additional solution of equal quality with $P = 28.6$ days (double the period of Goździewski & Migaszewski 2006) and $m \sin i = 0.14 M_J$. This second solution has a period uncomfortably close to that of the lunar cycle (we often see this period in the window function of our observations due to our tendency to observe during bright time). For both solutions $K = 10 \text{ m s}^{-1}$. We note that this star’s early spectral type may account for the observed RV residuals.

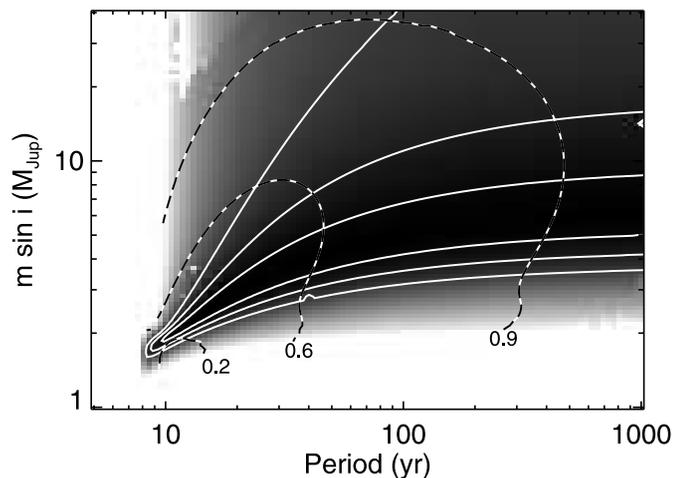


FIG. 15.—Contours of χ^2 and e_c in $P_e - (m \sin i)_e$ space for the best two-planet fits to the RV data of HD 187123 (Fig. 14), with χ^2 in gray scale. The solid contours mark the levels where χ^2 increases by 1, 4, and 9 from the minimum. The dashed contours mark levels of the eccentricity of 0.2, 0.6, and 0.9. Planets with $e > 0.6$ are rare, implying that this object is unlikely to have a period longer than 40 yr or $m \sin i$ greater than $5 M_J$.

Goździewski & Migaszewski (2006) analyzed our published RV data and found a low FAP for the existence of a second planet in orbit around HD 188015. Their FAP, however, is measured against a null hypothesis of a single Keplerian plus noise, thus ignoring the linear trend. We find that $\Delta\chi^2$, the improvement of the goodness-of-fit parameter with the introduction of a second Keplerian versus a trend to be very small—in fact 60% of our mock data sets showed greater improvement. We therefore find no motivation to hypothesize the existence of an additional, short-period planet; the single planet and trend announced in Marcy et al. (2005b) are sufficient to explain the data.

Goździewski & Migaszewski (2006) also found a low FAP for a second planet in orbit about HD 114729, with a period of 13.8 days. Using the data set from Butler et al. (2006) which contains three recent RV measurements taken since the publication of Butler et al. (2003) (their source of RV data), we find no such signal, and a large FAP for a second planet. We suspect our results may differ because the additional data provide for a slightly better fit to the known exoplanet, changing the character of the residuals and destroying the coherence of the spurious 13.8 day signal.

7. HD 150706

HD 150706b, a purported $1.0 M_J$ eccentric planet at 0.8 AU, was announced by the Geneva Extrasolar Planet Search Team (Udry et al. 2003) and appears in Butler et al. (2006); however, there is no refereed discovery paper giving details.

We have made eight radial velocity measurements at Keck observatory from 2002 through 2006. These velocities show an rms scatter of 12.1 m s^{-1} , inconsistent with the reported 33 m s^{-1} semiamplitude of HD 150706b. The rms to a linear fit is 8 m s^{-1} , which is adequately explained by the expected jitter for a young ($700 \pm 300 \text{ Myr}$) and active star like HD 150706. We therefore doubt the existence of a $1.0 M_J$ eccentric planet orbiting HD 150706 at 0.8 AU.

8. DISCUSSION

As noted in § 3.2, prior to this work 24 of the 150 nearby stars known to host exoplanets (including 14 Her and excluding HD 150706) show significant trends in their residuals and 19 host well-characterized multiple planet systems. One of these trends is likely spurious (HD 11964), and at least three others may be due to stellar or brown dwarf companions (HD 142, HD 13445, and τ Boo). We have announced here the detection of an additional five trends for known planet-bearing stars, two new single systems, and one new multiple system (HIP 14810, which appears as a single-planet system in Butler et al. 2006). We have also confirmed that the previously announced trends for HD 68988 and HD 187123 are likely due to planetary-mass objects. This brings the total number of stars with RV trends possibly due to planets to 22, the number of known multiple-planet systems to 22, and the number of nearby planet-bearing stars to 152. This means that 30% of known exoplanet systems show significant evidence of multiplicity. Considering that the mass distribution of planets increases steeply toward lower masses (Marcy et al. 2005a), our incompleteness must be considerable between 1.0 and 0.1 M_J . Thus, the actual occurrence of multiple planets among stars having one known planet must be considerably greater than 30%.

From an anthropocentric perspective, this frequency of multiplicity suggests that in some respects, the solar system is not

such an aberration. Our Sun has four giant planets, and it appears that such multiplicity is not uncommon, although circular orbits are.

From a planet-hunting perspective this result is quite welcome as well, since it means that the immediate future of RV planet searches looks bright. As our temporal baseline expands, we will become sensitive to longer period planets. Our search is just becoming sensitive to true Jupiter analogs with 12 yr orbits and 12 $m s^{-1}$ amplitudes. A true Saturn analog would require 15 more years of observation. As our precision improves we will become sensitive to lower mass planets, which may be the richest domain for planets yet.

The authors would like to thank Kathryn Peek for obtaining the crucial 2006 April 16 RV measurement of HIP 14810, and Simon O'Toole and Alan Penny for their assistance. The authors also thank the anonymous referee for a thorough and constructive report. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France, and of NASA's Astrophysics Data System Bibliographic Services, and is made possible by the generous support of Sun Microsystems, NASA, and the National Science Foundation.

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