THE ASTROPHYSICAL JOURNAL, 474:L115–L118, 1997 January 10

THREE NEW “51 PEGASI–TYPE” PLANETS[1]

R. PAUL BUTLER,[2] GEOFFREY W. MARCY,[2] ERIC WILLIAMS, HEATHER HAUSER, AND PHIL SHIRTS
Department of Physics and Astronomy, San Franciscso State University, San Francisco, CA, 94132; paul@further.berkeley.edu
Received 1996 August 12; accepted 1996 October 22

ABSTRACT

We report Keplerian Doppler velocity variations, consistent with orbiting “51 Pegasi–type” planets, for the three stars HR 3522 (G8V), HR 5185 (F7V), and HR 458 (F8V). HR 3522 exhibits a velocity semiamplitude of 77 m s^{-1} and a period of 14.65 days, implying a semimajor axis of 0.11 AU and a minimum mass for the companion of $M_2 \sin i = 0.84 M_{\rm JUP}$. For HR 5185, the semiamplitude is 469 m s^{-1}, and the period is 3.3128 days, implying an orbital radius of 0.0462 AU and a minimum mass of $3.87 M_{\rm JUP}$. For HR 458, the semiamplitude is 74 m s^{-1}, and the period is 4.61 days, implying an orbital radius of 0.057 AU and a minimum mass of $0.68 M_{\rm JUP}$. These three companions, along with 51 Peg b, may constitute a heretofore unrecognized class of planets, defined by circular orbits, Jupiter-like masses, and orbital radii less than ~0.2 AU. The relatively large orbital radius for HR 3522 (0.11 AU) precludes tidal circularization, suggesting that the circular orbits are primordial. During the past 9 years, the velocity residuals to the Keplerian fit of HR 3522 exhibit a long-term systematic trend, suggestive of an additional companion. HR 5185 exhibits velocity residuals that fluctuate erratically by ~70 m s^{-1}, which are as yet unaccounted for. HR 5185 has a rotation period very close to the orbital period of the planet, suggesting that the companion may have tidally locked the primary.

Subject headings: planetary systems — planets and satellites: general — stars: low-mass, brown dwarfs

1. INTRODUCTION

Four planet-like companions have now been identified orbiting solar-like stars: 51 Pegasi (Mayor & Queloz 1995; Marcy et al. 1997), 47 UMa (Butler & Marcy 1996), 70 Vir (Marcy & Butler 1996), and HD 114762 (Latham et al. 1989; Williams, Butler, & Marcy 1997). These four companions were all detected by Doppler monitoring of the host star. The four companions have values of $M \sin i$ between 0.5 and $10 M_{\rm JUP}$, suggesting that the actual masses reside within a range associated with extrasolar giant planets, whatever their origin. (Here i is the unknown orbital inclination.) Theoretical models of the interior structures and atmospheres of giant planets have been computed by Burrows et al. (1995), Saumon et al. (1996), and Guillot et al. (1996).

These first “planets” around solar-like stars exhibit a variety of characteristics: 51 Peg is distinguished by an orbital radius of 0.05 AU, closer than expected directly from theory (Boss 1995; Lissauer 1995); 70 Vir and HD 114762 have large masses ($M \sin i = 6.6$ and $9 M_{\rm JUP}$, respectively) and high eccentricities of $e > 0.3$, suggesting a less dissipative formation history; and the companion to 47 UMa resides in a circular orbit of radius 2.1 AU and has a mass of $2.4 M_{\rm JUP}/\sin i$, and thus most closely resembles Jupiter in the solar system.

This array of characteristics of planetary companions challenges current theories of the formation of planetary systems (Lissauer 1995; Wetherill 1996; Boss 1995). Some new disk dynamics have been proposed to explain the small orbital distances and the large eccentricities (Lin, Bodenheimer, & Richardson 1996; Artymowicz et al. 1991). The mass densities, the chemical composition, and the environments of protoplanetary disks may span a wider range than had been included in solar system disk models. These models need to be broadened if 51 Peg–type planets occur commonly. Here we describe Doppler observations of three main-sequence stars, HR 3522, HR 5185, and HR 458, which exhibit Doppler variations reminiscent of the 51 Peg system.

2. STELLAR CHARACTERISTICS AND DOPPLER TECHNIQUE

During the past 9 years, we have monitored 120 F, G, K, and M dwarf stars with our precise Doppler technique, as described in Butler et al. (1996) and Marcy & Butler (1996). The 0.6 m coudé auxiliary telescope and 3 m Shane telescope at Lick Observatory are both used to feed the “Hamilton,” a coudé echelle spectrometer (Vogt 1987). The measurement errors had been 10–15 m s^{-1} until 1994 November, when the Hamilton optics were refurbished and the wavelength coverage was doubled. As a result, measurement errors have decreased to 4 m s^{-1}.

The stellar characteristics of HR 3522 (HD 75732, ρ^1 Cnc, G8V), HR 5185 (HD 120136, τ Boo, F7V), and HR 458 (HD 9826, υ And, F8V) are shown in Table 1 and are reviewed in the accompanying Letter by Baliunas et al. (1997). All three stars are the primary component in resolved binary systems. Surface gravity measurements for all three stars indicate that they reside on or just above the main sequence. Photometry of HR 3522 and HR 5185 show them to be constant at a millimagnitude level (Baliunas et al. 1997). Both HR 3522 and HR 5185 are wide binaries with separations of ~1000 AU.

Numerous studies have shown that HR 3522 is extraordinarily metal-rich, with values of [Fe/H] ranging from +0.11 to +0.30 (Cayrel de Strobel et al. 1992; Chavez, Malagnini, & Morossi 1995). A determination that involves UV photometric indices finds [Fe/H] = +0.414 (Taylor 1996), warranting the label “super–metal-rich.” The CN abundance also appears to be high (Eggen 1995). However, a cautionary note about the metallicity of HR 3522 is given in the following Letter (Baliunas et al. 1997). HR 5185 is also metal-rich, with derived [Fe/H] values of +0.28 (Perrin et al. 1977; Tomkin, Lambert,

---

[1] Based on observations obtained at Lick Observatory, which is operated by the University of California.

[2] Also at the Department of Astronomy, University of California, Berkeley, CA 94720.

TABLE 1

STELLAR CHARACTERISTICS

Parameter	HR 3522	HR 5185	HR 458
$T_{\rm eff}$ (K)	5200[a]	6450[a]	6200[b]
M_V	5.38[c]	3.18[c]	2.86[c]
Log gravity (cgs)	4.50[a]	4.3[a]	4.2[d]
Spectral type	G8V[a]	F7V[a]	F8V[a]
$R'_{\rm HK}$	−4.97[e]	−4.73[f]	−4.97[e]
$P_{\rm ROT}$ (days)	44[e]	4[f]	12[e]
$v \sin i$ (km s^{-1})	2.0[g]	14.8[h]	9.2[i]
[Fe/H]	+0.23[a]	+0.28[a]	+0.09[d]
Age (Gyr)	5[g]	2[a]	3[d]
Parallax (mas)	76.8 ± 2.4[b]	54.5 ± 4.8[b]	56.8 ± 4.1[b]

[a] Perrin et al. 1977.
[b] van Altena, Lee, & Hoffleit 1995.
[c] From parallax and V magnitude.
[d] Edvardsson et al. 1993.
[e] Soderblom 1985.
[f] Baliunas et al. 1996.
[g] Baliunas et al. 1997.
[h] Gray 1982.
[i] Soderblom 1982.

TABLE 2

ORBITAL PARAMETERS

Parameter	HR 3522	HR 5185	HR 458
P (days)	14.648 (0.0009)	3.3128 (0.0002)	4.611 (0.005)
$T_{\rm max}$ (JD)[a]	2450231.94 (0.8)	2450235.41 (0.2)	2450088.64 (0.3)
e	0.051 (0.013)	0.018 (0.016)	0.109 (0.04)
ω (deg)[b]	41	254	314
K_1 (m s^{-1})	77.1 (0.9)	469 (5)	74.1 (4)
$a_1 \sin i$ (AU)	0.00010	0.00014	0.000032
f_1(m) ($M_\odot$)	7.04×10^{-10}	3.54×10^{-8}	2.18×10^{-10}
N[c]	45	19	18
$O-C$ (m s^{-1})	12.0	13.9	12.1

[a] Time of velocity maximum.
[b] ω is poorly constrained for these circular orbits.
[c] Number of consecutive observations used at end of data string.

& Balachandran 1985) and +0.30 (Boesgaard & Lavery 1986). There is some confusion about the [Fe/H] value for HR 458. Based on high-resolution spectroscopy and spectral synthesis, Edvardsson et al. (1993) report that the [Fe/H] value of HR 458 is +0.09. Taylor (1996) reviews [Fe/H] values, including some lower values.

Based on Ca II H and K measurements, the rotation period of HR 5185 is estimated to be 3.5–4 days (Baliunas, Sokoloff, & Soon 1996; Baliunas et al. 1997). This implies an equatorial velocity of 15–20 km s^{-1} that is similar to the measured values of $v \sin i$, 14–17 km s^{-1}, suggesting that we view the star nearly equator-on. The rotation period of HR 3522 is estimated to be 42–44 days (Soderblom 1985; Baliunas et al. 1997). This rotation period implies an equatorial velocity of about 1 km s^{-1}, consistent with its $v \sin i$ of 1–2 km s^{-1}. HR 3522 has kinematics that suggest an age of ~1 Gyr (Eggen 1995), but its slow rotation period suggests an age closer to 5 Gyr (Baliunas et al. 1997). The age of HR 5185 is estimated to be ~2 Gyr (Perrin et al. 1977; Baliunas et al. 1997), while υ And has a similarly estimated age of 5 Gyr.

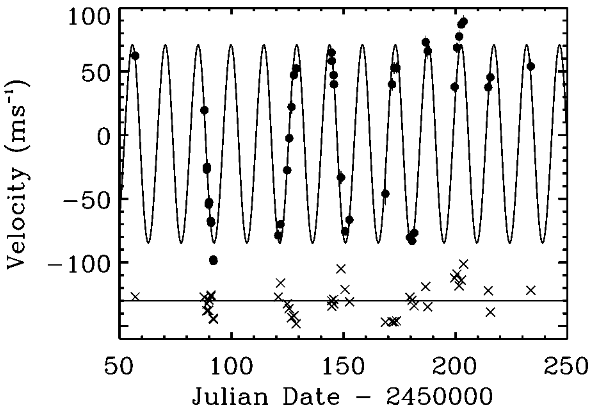

FIG. 1.—Doppler Velocities for HR 3522 (ρ^1 55 Cnc) from 1995 December through 1996 June. A Keplerian fit yields the orbital parameters P = 14.64 days and K = 77.5 m s^{-1}, indicating a companion having $m \sin i$ = 0.84$M_{\rm JUP}$ at 0.11 AU. The error bars are about the size of the points.

3. DOPPLER VELOCITIES AND ORBITAL SOLUTIONS

A total of 60 observations of HR 3522 have been obtained spanning 7 years, from 1989 February through 1996 May. Beginning in early 1996, intense monitoring took place, permitting assessment of the short timescale variability that was evident. The 41 measured Doppler velocities from this latest observing season are shown in Figure 1. Periodic velocity variations are clearly evident with a semiamplitude of 77 m s^{-1}, much greater than the errors of 4 m s^{-1} (Butler et al. 1996).

The best-fit Keplerian orbit yields the following parameters: P = 14.65 days, K = 77 m s^{-1}, and e = 0.05. All orbital parameters are listed in Table 2. Assuming the mass of the primary is 0.85 $M_\odot$, the inferred minimum mass of the companion is $M_{\rm comp} \sin i = 0.84 M_{\rm JUP}$, and the semimajor axis is 0.11 AU. The orbital fit is only fair, since the residuals exhibit an rms scatter of 12 m s^{-1}, significantly greater than the expected errors of 5 m s^{-1} (Butler et al. 1996). Indeed, the reduced χ^2 is 3.0, in excess of the 1.0 expected for a good fit. Thus, the Keplerian model of a single companion does not completely describe the observed velocity variations.

To further explore this inadequacy, Figure 2 shows the residuals to the Keplerian fit for all 7 years of data. These residuals exhibit a long-term trend, starting at −80 m s^{-1} in 1989 and climbing to +10 m s^{-1} by 1994 (the velocity zero point is arbitrary). The velocities appeared to decline toward 0 m s^{-1} during the past year, although at least another year of data will be required for confirmation. This trend and the possible curvature in the velocity residuals are consistent with

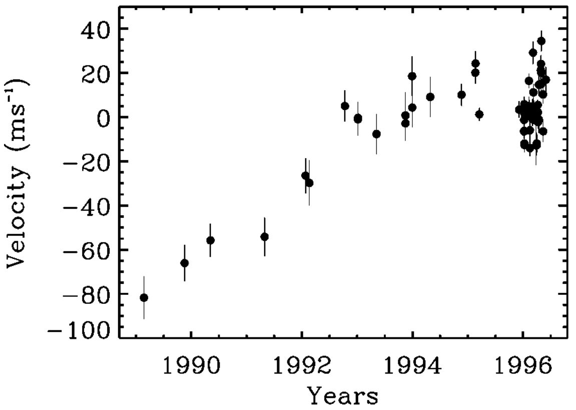

FIG. 2.—Residuals of the velocities for HR 3522 after subtracting the best-fit Keplerian orbit. The residuals trend upward by ~80 m s^{-1} from 1989 through 1994, suggesting a possible second companion.

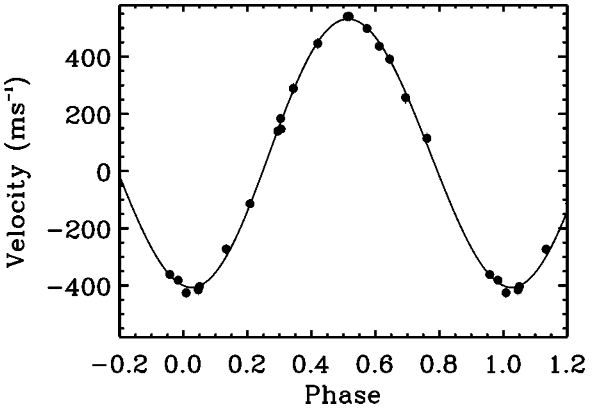

FIG. 3.—Phased Doppler velocities for HR 5185 (τ Boo) for 19 observations obtained since 1994 November. The solid line is the best-fit Keplerian orbit, with $P = 3.3128$ days, $K = 469$ m s^{-1}, and $e = 0.016$, yielding a mass of $m \sin i = 3.9M_{\rm JUP}$.

a second companion orbiting HR 3522 with a period $P > 8$ yr and $M \sin i > 5M_{\rm JUP}$.

A total of 19 observations of HR 5185 have been obtained since the upgrade of the Hamilton spectrometer, from 1995 February through 1996 July. Figure 3 shows these observations phased with a period of 3.3128 days and spanning 150 orbits. The solid line is a Keplerian fit. The velocity semiamplitude is 469 m s^{-1}, and the eccentricity is 0.018. The rms scatter to the orbital fit is 13.9 m s^{-1}, consistent with the internal errors of 16 m s^{-1}. This large internal error is a result of the fast rotation ($v \sin i = 14$ km s^{-1}) and early spectral type of the primary star. Assuming the primary is 1.2 $M_\odot$, the inferred minimum mass of the companion, $M_{\rm comp} \sin i$, is $3.87M_{\rm JUP}$, and the semimajor axis is 0.0462 AU. The full 9 years of velocities for HR 5185 exhibit phase coherence, maintaining the period of 3.3125 days.

HR 5185 had previously been observed by Duquennoy & Mayor (1991) with CORAVEL. A total of 17 observations taken over 9 years exhibited a scatter of 730 m s^{-1}, leading them to categorize the star as a possible spectroscopic binary. Those velocities, along with more recent CORAVEL work, clearly exhibit a periodicity with a period of 3.312 days (M. Mayor 1996, private communication), confirming the velocity variations for HR 5185.

A total of 18 Doppler measurements have been obtained for HR 458 during the past year (see Fig. 4). They exhibit nearly sinusoidal variations with an amplitude of 74.1 m s^{-1} and a period of 4.611 days. The inferred companion mass, $M_{\rm comp} \sin i$, is $0.68M_{\rm JUP}$ (assuming a primary mass of 1.2 $M_\odot$), and it orbits with a semimajor axis of 0.057 AU. During the past 9 years, a total of 36 observations were obtained, with 18 of them spread from 1988 to 1995. The 36 velocities show evidence for variability in the "gamma velocity" of the sine wave on a timescale of about 2 yr with amplitude of ~50 m s^{-1}.

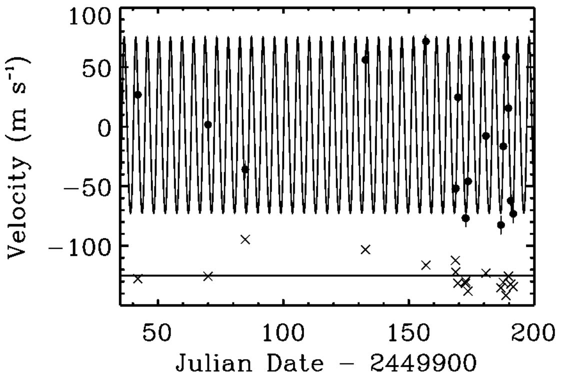

FIG. 4.—Doppler Velocities for HR 458 (υ And) from 1995 August through 1996 January. A Keplerian fit to the measured velocities (*solid line*) yield the following parameters: $P = 4.61$ days, $e = 0.11$, and $K = 74$ m s^{-1}, yielding a companion mass, $m \sin i = 0.68M_{\rm JUP}$, orbiting with semimajor axis of 0.057 AU.

There are two alternative explanations that could, in principle, explain the observed radial velocity signal, namely, spots and pulsation. A large stellar spot would cause a net apparent Doppler shift if it were on the limb of the star. The period of such a Doppler signal would be the rotation period of the star. HR 3522 has an estimated rotation period of 44 days, significantly longer than the "orbital" period of 14.6 days, thus ruling out the spot explanation. Because the rotation period for HR 5185 is ~3.5 days, the spot explanation cannot be so lightly dismissed. If the velocity variations are the result of spots, the area of the star covered by spots must be about 4%, to explain the apparent velocity amplitude of 469 m s^{-1}, given that $v \sin i = 15$ km s^{-1}. Such spot coverage would induce a detectable photometric variation of several percent, which is not observed (Baliunas et al. 1997). For HR 458, the orbital period of 4.6 days is quite different from the calculated rotation period of 12 days (Baliunas et al. 1997), thus ruling out spots as the cause of the velocity variations.

Stellar pulsation can also cause Doppler periodicities. If the velocity variations reported here for HR 3522, HR 5185, and HR 458 were due to radial pulsation, the stellar radii of these stars would be changing by 7.3%, 6.9%, and 2%, respectively. The expected photometric changes of the stars would be detectable, but such is not the case (Baliunas et al. 1997). A search for nonradial pulsation should be carried out by high-resolution spectroscopy (Hatzes, Cochran, & Johns-Krull 1997).

4. DISCUSSION

All three stars exhibit velocity variations that remain phase coherent during the entire 9 years of observations. Periodograms of all three stars show principle peaks at the given orbital periods. The interpretation of orbiting planet-like companions explains all the data for these stars, and no other explanation seems plausible (but see Hatzes et al. 1997). These three companions all orbit within 0.11 AU of their star, and all have nearly circular orbits. Their minimum masses, $m \sin i$, range from 0.6 to $3.8M_{\rm JUP}$. It is tempting to associate these companions with the planet around 51 Peg that also traces a circular orbit with comparable radius of 0.05 AU and $m \sin i = 0.45M_{\rm JUP}$. Taken together, these four companions seem to constitute an unexpected class of "51 Peg planets" characterized by masses less than $\sim 5M_{\rm JUP}$ in orbits smaller than ~ 0.15 AU. Remarkably, all four of these "51 Peg–like" stars are metal-rich (although spectroscopic confirmation is required for HR 3522 and HR 458). Apparently, this class of planets occurs relatively commonly; as within our sample of 120 stars, three such companions have emerged, suggesting a frequency of occurrence of approximately 3% for $M > 0.4M_{\rm JUP}$.

The near coincidence of the rotational period of HR 5185 and the orbital period of its companion suggests that the companion may have tidally spun up the primary, as discussed by Rasio et al. (1996) and Marcy et al. (1997). In contrast, the stars 51 Peg, HR 3522, and HR 458 have not been spun up by their planetary companions because of the small companion mass (Lin et al. 1996; Rasio et al. 1996).

During two stints of 1000 days (JD = 2,447,000–2,448,000 and JD = 2,449,000–2,450,000), HR 5185 exhibits velocity residuals to the Keplerian fit that have a standard deviation of $\sim$30 m s^{-1}, slightly larger than the errors. But from 2,448,000 to 2,449,000, the residuals exhibit wild velocity swings with a standard deviation of $\sim$80 m s^{-1}, much larger than the errors. These erratic fluctuations are not due to instrumental drift since stable stars observed at the same time do not show any excess scatter, as shown in Figure 1 of Marcy & Butler (1996) and Figure 2 of Butler & Marcy (1996). The residuals cannot be explained simply as due to an additional companion as they vary erratically. Two other F dwarfs on our program exhibit similar behavior in their velocity variations, namely, HR 7061 and HR 5933, both of which exhibit relative quiescence for several years but also exhibit erratic fluctuations of $\sim$100 m s^{-1} during timescales of years. These F stars all rotate somewhat rapidly, which suggests a possible physical connection in their erratic velocity behavior. Starspots seem unlikely as the simple explanation because the photometry of Baliunas et al. (1997) shows no variation at a level of 0.002 mag, and the rotation periods of HR 458 and HR 3522 are quite different from the orbital periods. Perhaps "patches" of enhanced turbulence on the stellar surface distort the line profiles on timescales of days. Odd velocity fluctuations have also been found in chromospherically active stars (Irwin, Yang, & Walker 1996; Walker et al. 1995).

Theoretical models of gas giant planets at small orbital distances have been computed by Burrows et al. (1995), Saumon et al. (1996), and Guillot et al. (1996). Assuming a Jupiter-like composition, the radii of the companions to HR 3522, HR 5185, and HR 458 are all about $1.2R_{\mathrm{JUP}}$, enlarged relative to Jupiter because of the absorbed stellar radiation, which also controls the effective temperatures of the planets. The derived temperature for HR 3522b is 700 K, for HR 5185b it is 1400 K, and for HR 458b it is 1300 K (Burrows et al. 1995; Guillot et al. 1996).

We thank Michel Mayor, Lars Bildsten, Bob Donahue, Frank Fekel, Sallie Baliunas, and Greg Henry for helpful discussions. We acknowledge generous support from NASA (NAGW 3182), NSF (AST 9520443), and SUN Microsystems. R. P. B. wishes to acknowledge the passing of Ella Fitzgerald, whose songs helped enliven many a late night at the telescope.

REFERENCES

Artymowicz, P., Clarke, C. J., Lubow, S. H., & Pringle, J.E. 1991, ApJ, 370, L35
Baliunas, S., Henry, G. W., Donahue, R. A., Fekel, F. C., & Soon, W. H. 1997, ApJL, submitted
Baliunas, S., Sokoloff, D., & Soon, W. 1996, ApJ, 457, L99
Boesgaard, A. M., & Lavery, R.J. 1986, ApJ, 309, 762
Boss, A.P. 1995, Science, 267, 360
Burrows, A., Saumon, D., Guillot, T., Hubbard, W. B., & Lunine, J. I. 1995, Nature, 375, 299
Butler, R. P., & Marcy, G. W. 1996, ApJ, 464, L153
Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., & Vogt, S. S. 1996, PASP, 108, 500
Cayrel de Strobel, G., Hauck, B., Francois, P., Thevinen, F., Friel, E., Mermilliod, M., & Borde, S. 1992, A&AS, 95, 273
Chavez, M., Malagnini, M. L., & Morossi, C. 1995, ApJ, 440, 210
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Edvardsson, B., Anderson, J., Gustafasson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101
Eggen, O. J. 1995, AJ, 109, 1327
Gray, D. E. 1982, ApJ, 258, 201
Guillot, T., Burrows, A., Hubbard, W. B., Lunine, J. I., & Saumon, D. 1996, ApJ, 459, L35
Hatzes, A. P., Cochran, W. D., & Johns-Krull, C. M. 1997, ApJ, in press
Irwin, A. W., Yang, S. L. S., & Walker, G. A. H. 1996, PASP, 108, 580
Latham, D. W., Mazeh, T., Stefanik, R. P., Mayor, M., & Burki, G. 1989, Nature, 339, 38
Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, Nature, 380, 606
Lissauer, J. J. 1995, Icarus, 114, 217
Marcy, G. W., & Butler R. P. 1996, ApJ, 464, L151
Marcy, G. W., Butler, R. P., Williams, E., Bildsten, L., & Graham, J. 1997, ApJ, submitted
Mayor, M., & Queloz, D. 1995, Nature, 378, 355
Perrin, M. N., Hejlesen, P. M., Cayrel de Strobel, G., & Cayrel, R. 1977, A&A, 54, 779
Rasio, F. A., Tout, C. A., Lubow, S. H., & Livio, M. 1996, ApJ, 470, 1187
Saumon, D., Hubbard, W. B., Burrows, A., Guillot, T., Lunine, J. I., & Chabrier, G. 1996, ApJ, 460, 993
Soderblom, D. R. 1982, ApJ, 263, 239
———. 1985, AJ, 90, 2103
Taylor, B. J. 1996, ApJS, 102, 105
Tomkin, J., Lambert, D. L., & Balachandran, S. 1985, ApJ, 290, 289
van Altena, W. F., Lee, J. T., & Hoffleit, E. D. 1995, The General Catalogue of Trigonometric Parallaxes (4th ed.; New Haven: Yale Univ. Obs.)
Vogt, S. S. 1987, PASP, 99, 1214
Walker, G. A. H., Walker, A. R., Irwin, A. W., Larson, A. M., Yang, S. L. S., & Richardson, D. C. 1995, Icarus, 116, 359
Wetherill, G. W. 1996, Icarus, 119, 219
Williams, E., Marcy, G. W., & Butler, R. P. 1997, preprint