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A TRANSITING "51 PEG–LIKE" PLANET[1]

GREGORY W. HENRY,[2] GEOFFREY W. MARCY,[3] R. PAUL BUTLER,[4] AND STEVEN S. VOGT[5]

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ABSTRACT

Doppler measurements from Keck exhibit a sinusoidal periodicity in the velocities of the G0 dwarf HD 209458, having a semiamplitude of 81 m s^{-1} and a period of 3.5239 days, which is indicative of a "51 Peg–like" planet with a minimum mass ($M \sin i$) of 0.62 M_{Jup} and a semimajor axis of 0.046 AU. Follow-up photometry reveals a drop of 0.017 mag at the predicted time (within the errors) of transit by the companion based on the velocities. This is the first extrasolar planet observed to transit its star. The radius of the planet derived from the magnitude of the dimming is 1.42 R_{Jup}, which is consistent with models of irradiated Jupiter-mass planets. The transit implies that $\sin i > 0.993$, leading to a true mass of 0.62 M_{Jup} for the planet. The resulting mean density of 0.27 g cm^{-3} implies that the companion is a gas giant.

Subject headings: planetary systems — stars: individual (HD 209458)

1. INTRODUCTION

Five "51 Peg–like" planets have been discovered orbiting nearby solar-type stars (Mayor & Queloz 1995; Butler et al. 1997, 1998; Mayor et al. 1999). These systems are characterized by orbital periods ranging from 3 to 5 days, semimajor axes of 0.04–0.06 AU, and nearly sinusoidal Doppler velocity curves, implying circular orbits. By virtue of their short-period orbits, these planets have ~10% probability of transiting their host stars.

Photometric searches have been carried out for all the announced 51 Peg–like planets, but none have resulted in the detection of a transit (Henry et al. 1997; Baliunas et al. 1997; Henry et al. 1999). Observation of a transiting 51 Peg–like planet would provide the first detection of an extrasolar planet by a technique other than precision Doppler measurements. For a system to transit, the orbital inclination must be nearly 90°, and, thus, $\sin i$ must be very close to 1. The minimum ($M \sin i$) mass derived from precision Doppler measurements would be very close to the true mass for such an object.

During a transit, the fractional reduction in the stellar flux is simply the fraction of the stellar surface that is occulted by the dark companion, excluding the small effects of stellar limb darkening and surface brightness variations. The amount of dimming thus yields the diameter of the companion, given the stellar diameter, which can be derived from spectral type and luminosity class. From the mass and diameter, the mean density of the companion follows. This Letter reports on the solar-type star HD 209458, recently found by the Keck Doppler survey to show a 3.5239 day Doppler-velocity periodicity, which is consistent with a 51 Peg–like planet.

2. STELLAR CHARACTERISTICS OF HD 209458

HD 209458 (HIP 108859, SAO 107623) is a G0 dwarf with $V = 7.65$, $B-V = 0.594$, and a distance of 47 pc from *Hipparcos* (Perryman et al. 1997), yielding $M_V = 4.29$. HD 209458 does not have any known companions. Based on *Hipparcos* data, Prieto & Lambert (1999) estimate the mass, radius, and effective temperature of HD 209458 to be 1.03 $M_{\odot}$, 1.15 $R_{\odot}$, and 6025 K.

Spectroscopically, HD 209458 is similar to the Sun, as demonstrated in Figure 1, which shows a comparison of HD 209458 and the Sun, centered on the Ca II H line. The absorption lines of HD 209458 are slightly broader and shallower than the Sun, indicating rotational broadening, $v \sin i \approx 3 \pm 1$ km s^{-1}. The core of the H line is deeper than in the Sun, indicating low chromospheric activity. The R'_{HK} value measured from our H and K lines is -4.93 as calibrated by Noyes et al. (1984). The intrinsic Doppler jitter for this level of chromospheric activity is less than 3 m s^{-1} (Vogt et al. 1999; Saar, Butler, & Marcy 1998; Butler & Marcy 1997).

3. KECK OBSERVATIONS OF HD 209458

The Keck Doppler survey began in 1996 July with an observing list of 258 stars. The throughput of the Keck/HIRES system has been better than initially expected, allowing us to double our sample size over the last 3 years. As a result, HD 209458 was added in 1999 May.

Spectra were obtained on Keck I with the HIRES echelle spectrometer (Vogt et al. 1994). The resolution for these spectra is $R \sim 80{,}000$, spanning wavelengths from 3900 to 6200 Å. Wavelength calibration is carried out by means of an iodine absorption cell, which superposes a reference iodine spectrum directly on the stellar spectrum (Marcy & Butler 1992; Valenti et al. 1995; Butler et al. 1996). We routinely achieve photon-limited Doppler precision of 3 m s^{-1} with this system (Vogt et al. 1999).

The velocities of HD 209458 showed nightly variations of up to 60 m s^{-1}. A total of nine observations were obtained through 1999 September, from which periodogram analysis revealed a periodicity at 3.5239 ± 0.0046 days. The velocities are plotted as a function of time in Figure 2. Measurement error is 3.7 m s^{-1}. The solid line shows the weighted, least-squares sinusoidal fit to the data. This is virtually identical to the best least-squares Keplerian fit obtained with a floating eccentricity,

[1] Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the University of California and the California Institute of Technology, and the automatic photoelectric telescopes at Fairborn Observatory in the Patagonia Mountains of southern Arizona.

[2] Center of Excellence in Information Systems, Tennessee State University, 330 10th Avenue N, Nashville, TN 37203; henry@schwab.tsuniv.edu.

[3] Department of Astronomy, University of California, Berkeley, Berkeley, CA 94720; and Department of Physics and Astronomy, San Francisco State University, San Francisco, CA.

[4] Carnegie Institution of Washington, Department of Terrestrial Magnetism, 5241 Broad Branch Road NW, Washington, DC 20015-1305.

[5] UCO/Lick Observatory, University of California, Santa Cruz, Santa Cruz, CA 95064.

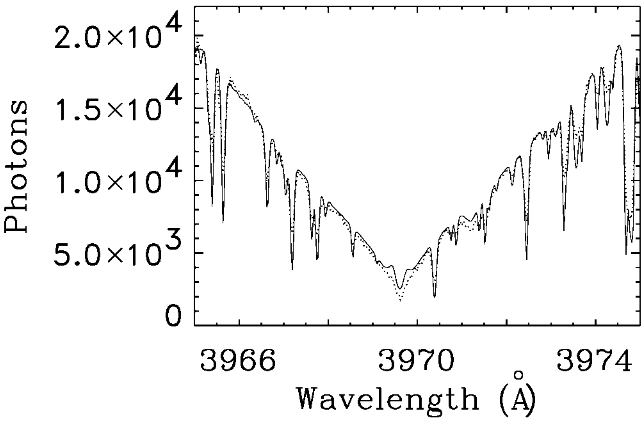

FIG. 1.—Comparison of Ca II H line core for HD 209458 (*dotted line*) with the Sun (*solid line*). The solar spectrum is similar to HD 209458 throughout the visible region. The lack of line core reversal in the H line demonstrates that both stars are chromospherically inactive and slowly rotating.

and the rms to both fits is 2.27 m s^{-1}. The orbital parameters and their uncertainties are listed in Table 1. The resulting minimum mass of the companion is $M \sin i = 0.62\ M_{\rm Jup}$, and its orbital radius is 0.046 AU.

4. PRECISION PHOTOMETRY OF HD 209458

As soon as the orbit was well enough established to predict transit times accurately, we began a photometric search for transits. Observations commenced on 1999 November 7 with the 0.80 m automatic photoelectric telescope (APT), designated "T8," at Fairborn Observatory in southern Arizona. This APT is dedicated to the long-term measurement of luminosity cycles in Sun-like stars that accompany stellar magnetic cycles but is sometimes used to help confirm the detection of new extrasolar planets (Henry et al. 1997; Baliunas et al. 1997; Henry et al. 1999). For each program star, the telescope is programmed to conduct differential photometry in the Strömgren *b* and *y* passbands with respect to three comparison stars. For HD 209458, the comparison stars were HD 210074 ($V = 5.74$, F2 V), HD 209775 ($V = 7.56$, F0), and HD 210957 ($V = 8.01$, A9 IV). The typical external precision of a single differential observation is 0.0011 mag; for seasonal means the external

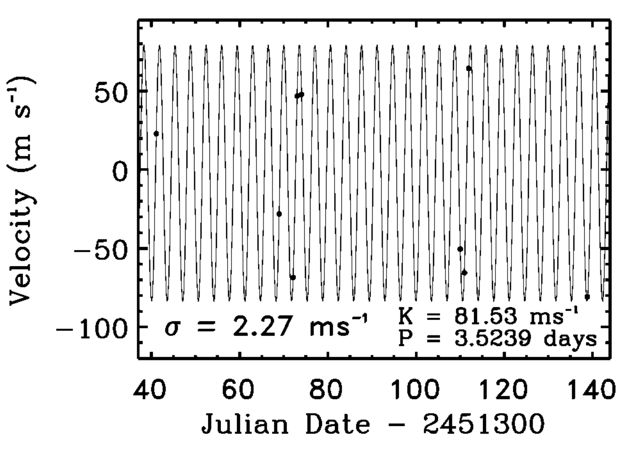

FIG. 2.—Velocities for HD 209458 (G0 dwarf). The solid line is a sinusoidal fit with a period of 3.5239 days and a semiamplitude of 81 m s^{-1}, yielding a minimum mass $M \sin i = 0.62\ M_{\rm Jup}$ for the companion. The rms of the sinusoidal fit is 2.27 m s^{-1} , smaller than expected errors of 3.7 m s^{-1} .

TABLE 1
ORBITAL SOLUTION FOR HD 209458

Parameter	Value	Uncertainty
Orbital period P (days)	3.5239	0.0046
Velocity semiamplitude K (m s^{-1})	81.5	5.5
Eccentricity e	0.00 (adopted)	0.04
Time of max velocity T_0 (JD)	2,451,412.3085	0.013
Number of observations	9	…
RMS to sinusodial fit (m s^{-1})	2.27	…

precision is 0.0001–0.0002 mag. Complete details on the operation of the telescope, the specific observing sequences, data reduction, and the precision of the data can be found in Henry (1999).

Because the radial velocities predicted a time of inferior conjunction (planet between the star and the earth) on the first night of photometric observations (at JD 2,451,490.715 ± 0.04), the APT was programmed to make repeated observations that night of HD 209458 and its three comparison stars until they became too low in the sky to observe. The resulting differential magnitudes are shown in Figure 3. Each plotted observation is the mean of three successive differential observations taken over a time interval of about 13 minutes. In addition, the differential magnitudes from the Strömgren *b* and *y* bands are averaged into a single $(b + y)/2$ passband to increase precision since the air mass of the observations was rather high (up to ∼1.75) toward the end of the night's observations. Finally, to increase precision even further, the differential magnitudes are computed with respect to the mean of the first and third comparison stars. The second comparison (HD 209775) was not used because we found it to be variable with an amplitude of ∼0.01 mag and a period of ∼1.4 hr, suggesting it to be a δ Scuti star.

A decrease in the brightness of HD 209458 is seen in Figure 3 near the time of inferior conjunction predicted from the radial velocities, confirming that the planet transits the star. Since the entire transit event was not observed, we estimated the time of mid-transit from the ingress branch of the light curve and the predicted duration of the transit (3.1 hr or 0.13 days). This predicted duration was computed from the stellar radius, the orbital radius, and the orbital period. Comparison of our observed time of mid-transit with the predicted time of inferior conjunction shows that the two times agree within their respective errors (Table 2). If the first seven observations in the figure are taken to represent the unobstructed brightness of HD 209458 (before first contact) and the last four observations

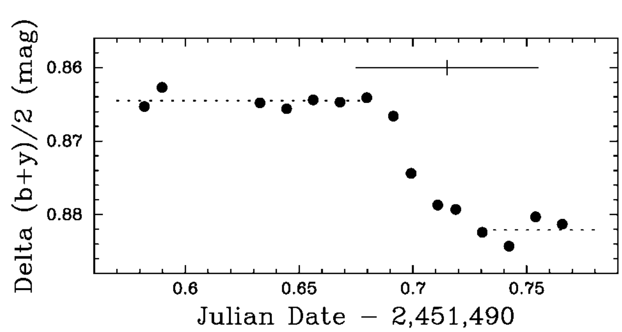

FIG. 3.—Photometric observations of HD 209458 from the night of 1999 November 7 UT showing ingress of the planetary transit. The measured transit depth is 0.017 ± 0.002 mag or 1.58% ± 0.18%. The error bar shows the time of inferior conjunction and its uncertainty predicted from the radial velocities in this Letter.

TABLE 2
PHOTOMETRIC TRANSIT RESULTS

Parameter	Value	Uncertainty
Predicted time of midtransit (JD)	2,451,490.715	0.040
Observed time of midtransit (JD)	2,451,490.765	0.02
Photometric transit depth (mag)	0.017	0.002
Photometric transit depth (%)	1.58	0.18

lie between second and third contacts, then the overall drop in brightness is 0.017 mag with a formal uncertainty of 0.002 mag. This corresponds to a drop in light intensity of 1.58% $\pm$ 0.18%. The time resolution of our observatons in Figure 3 is not sufficient to measure the time of first and second contacts accurately. The apparent slowness of ingress implies a grazing incidence angle so that the planet transits along a rather short chord of the stellar disk. Table 2 summarizes the photometric observations of the 1999 November 7 transit. Additional observations of the transit are needed to refine the transit depth and the detailed shape of the light curve.

Further photometric observations of HD 209458 were made with the 0.80 m APT on eight subsequent nights. These are plotted in Figure 4 along with the observations from the first night. The differential magnitudes were computed in the same way as for Figure 3. The dotted line represents the mean of all the observations, excluding the observations within transit. The standard deviation about the mean is 0.0017 mag. This is somewhat larger than the nominal precision of 0.0011 mag for this telescope and is probably the result of the higher-than-normal air mass of the observations (see Fig. 8 of Henry 1999 for the effect of air mass on the precision of the observations). Therefore, we can conclude that the two comparison stars as well as HD 209458 are constant to better than 0.002 mag over a timescale of days and that, to the limit of our precision, the only variation we can detect in the three stars is the dimming of HD 209458 at the predicted time of transit on JD 2,451,490.

The predicted times of all three transits within the date range of our observations are also shown in Figure 4. The second transit was unobservable from our longitude, and the third was obscured by clouds.

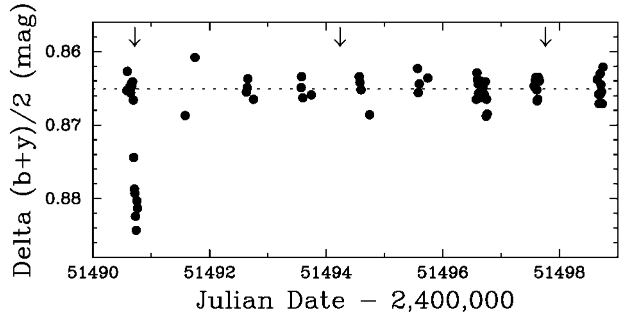

FIG. 4.—Complete photometric data set for HD 209458, consisting of 71 mean differential magnitudes over nine nights. The standard deviation of the data outside of transit shows that HD 209458 and its comparison stars are constant to better than 0.002 mag. The arrows indicate the three predicted times of transit within the date range of our observations. The second transit was unobservable from the longitude of the APT, and the third was obscured by clouds.

5. DISCUSSION

As with the previous 28 known extrasolar planets, HD 209458b was found from a precision Doppler survey. Like the other 51 Peg–like planets, HD 209458b is in a circular orbit, perhaps enforced by tidal circularization (Rasio et al. 1996; Marcy et al. 1997; Ford, Rasio, & Sills 1999). The follow-up photometric detection of the transit represents the first planet detection by a completely independent technique and confirms the existence of HD 209458's planet and, by implication, the other planets discovered by Doppler-velocity techniques. Since the probability of a transit by a 51 Peg–like planet is about 10%, it was expected that a transit would be found among the first 10 discovered examples. HD 209458b is the sixth such object to be found.

The semimajor axis is 8.9 times larger than the stellar radius, implying an 11% chance of a transit, assuming random orbital orientations. For HD 209458b to transit, $\sin i$ must be larger than 0.993. Since a transit is observed, the $\sin i$ ambiguity is removed and the minimum mass for this planet derived from the Doppler velocities is very close to the true mass, 0.62 $M_{\rm Jup}$.

The 1.58% $\pm$ 0.18% photometric drop, along with stellar radius of 1.15 $\pm$ 0.05 $R_\odot$, gives a planetary radius of R = 1.42 $\pm$ 0.10 $R_{\rm Jup}$. However, given that the shape of the light curve is not yet well defined, the uncertainty in the radius may be somewhat larger than this. In addition, given our incomplete transit light curve, we do not attempt to account for the effects of limb darkening on our determination of the planetary radius. This small correction, though, would be within our quoted errors for the radius. After submission of this Letter, Charbonneau et al. (2000) reported detection of two complete transits for this same star, yielding results similar to those presented here, albeit a slightly smaller radius of 1.27 $R_{\rm Jup}$. A bloated planet was predicted for 51 Peg–like planets due to stellar insolation (Guillot et al. 1996; Saumon et al. 1996; Burrows et al. 1998). The radius for a 1 $M_{\rm Jup}$ planet at 0.05 AU is predicted to be about 1.5 $R_{\rm Jup}$ (Saumon et al. 1996; D. Saumon 1999, private communication), in close agreement with the observed radius. The mass and radius lead to a mean density of 0.27 g cm^{-3}, compared to that of Saturn, which is 0.69 g cm^{-1}. The planet is therefore inferred to be a gas giant and not a rocky body like the inner planets of the solar system. The derived planetary properties are summarized in Table 3.

Based on the sample sizes from which the five previous detected 51 Peg–like planets have been drawn, Vogt et al. (1999) estimate that 0.5% of late F and G dwarfs have 51 Peg–like companions. Along with HD 187123 (Butler et al. 1998), this is the second 51 Peg–like planet found from our Keck Doppler survey of 530 stars. All of the previous 51 Peg–like systems have metal-rich primary stars (Gonzalez 1999). The metallicity of HD 209458 has not been determined precisely but is estimated to be roughly solar (K. Apps 1999, private communication) from Strömgren *uvby* photometry.

A transiting planet could cause two small changes in the spectrum of the star. As the planet crosses the "blue edge" of the star, the red edge of the star will contribute about 1.5% more light, leading to a small asymmetry in the spectral line. The asymmetry would reverse when the planet transits the "red edge." In addition, a small fraction of the starlight will "leak" around the planet, passing through the outer atmosphere of the

TABLE 3
DERIVED PLANETARY PROPERTIES

Parameter	Value	Uncertainty
Radius ($R_{\rm Jup}$)	1.42	0.10
Mass ($M_{\rm Jup}$)	0.62	0.05
Mean density (g cm^{-3})	0.27	0.04
Semimajor axis (AU)	0.046	0.001

planet, thus recording the absorption spectrum of the planet. By comparing extremely high signal-to-noise spectra of the star taken on and off transit, it might be possible to recover the spectrum of the planet. Emission lines from the planetary atmosphere may also be produced.

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REFERENCES

Baliunas, S., Henry, G. W., Donahue, R. A., Fekel, F. C., & Soon,W. H. 1997, ApJ, 474, L119
Burrows, A., et al. 1998, in ASP Conf. Ser. 134, Brown Dwarfs and Extrasolar Planets, ed. R. Rebolo, E. Martin, & M. R. Zapatero-Osorio (San Francisco: ASP), 354
Butler, R. P., & Marcy, G. W. 1997, in ASP Conf. Ser. 134, Brown Dwarfs and Extrasolar Planets, ed. R. Rebolo, E. Martin, & M. R. Zapatero-Osorio (San Francisco: ASP), 162
Butler, R. P., Marcy, G. W., Vogt, S. S., & Apps, K. 1998, PASP, 110, 1389
Butler, R. P., Marcy, G. W., Williams, E., Hauser, H., & Shirts, P. 1997, ApJ, 474, L115
Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., & Vogt, S. S. 1996, PASP, 108, 500
Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJ, 529, L45
Ford, E. B., Rasio, F. A., & Sills, A. 1999, ApJ, 514, 411
Gonzalez, G. 1999, MNRAS, 308, 447
Guillot, R., Burrow, A., Hubbard, W. B., Lunine, J. I., & Saumon, D. 1996, ApJ, 459, L35
Henry, G. W. 1999, PASP, 111, 845
Henry, G. W., Baliunas, S. L., Donahue, R. A., Fekel, F. C., & Soon, W. H. 1999, ApJ, in press
Henry, G. W., Baliunas, S. L., Donahue, R. A., Soon, W. H., & Saar, S. H. 1997, ApJ, 474, 503
Marcy, G. W., & Butler, R. P. 1992, PASP, 104, 270
Marcy, G. W., Butler, R. P., Williams, E., Bildsten, L., Graham, J. R., Ghez, A., & Jernigan, G. 1997, ApJ, 481, 926
Mayor, M., Naef, D., Udry, S., Santos, N., Queloz, D., Melo, C., & Confino, B. 1999, A&A, submitted
Mayor, M., & Queloz, D. 1995, Nature, 378, 355
Noyes, R. W., Hartmann, L., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Prieto, C. A., & Lambert, D. L. 1999, A&A, in press
Rasio, F. A., Tout, C. A., Lubow, S. H., & Livio, M. 1996, ApJ, 470, 1187
Saar, S. H., Butler, R. P., & Marcy, G. W. 1998, ApJ, 498, L153
Saumon, D., Hubbard, W. B., Burrows, A., Guillot, T., Lunine, J. I., & Chabrier, G. 1996, ApJ, 460, 993
Valenti, J., Butler, R. P., & Marcy G. W. 1995, PASP, 107, 966
Vogt, S. S., et al. 1994, Proc. Soc. Photo-Opt. Instrum. Eng., 2198, 362
Vogt, S. S., Marcy, G. W., Butler, R. P., & Apps, K. 1999, ApJ, submitted