

## FIVE NEW TRANSITS OF THE SUPER-NEPTUNE HD 149026b

JOSHUA N. WINN,<sup>1</sup> GREGORY W. HENRY,<sup>2</sup> GUILLERMO TORRES,<sup>3</sup> AND MATTHEW J. HOLMAN<sup>3</sup>

Received 2007 September 12; accepted 2007 November 12

### ABSTRACT

We present new photometry of HD 149026 spanning five transits of its “super-Neptune” planet. In combination with previous data, we improve on the determination of the planet-to-star radius ratio:  $R_p/R_* = 0.0491^{+0.0018}_{-0.0005}$ . We find the planetary radius to be  $0.71 \pm 0.05 R_{\text{Jup}}$ , in accordance with previous theoretical models invoking a high metal abundance for the planet. The limiting error is the uncertainty in the stellar radius. Although we find agreement among four different ways of estimating the stellar radius, the uncertainty remains at 7%. We also present a refined transit ephemeris and a constraint on the orbital eccentricity and argument of pericenter,  $e \cos \omega = -0.0014 \pm 0.0012$ , based on the measured interval between primary and secondary transits.

*Subject headings:* planetary systems — stars: individual (HD 149026)

*Online material:* machine-readable table

### 1. INTRODUCTION

Many clues about the processes of planet formation and evolution have been discovered by studying the ensemble properties of exoplanets, such as the “brown dwarf desert” (Halbwachs et al. 2000; Marcy & Butler 2000) and the tendency for metal-rich stars to have more detectable planets (Santos et al. 2003; Fischer & Valenti 2005). However, there are also individual exoplanets whose properties bear directly on theories of planet formation and evolution. One of the best examples is the transiting planet HD 149026b (Sato et al. 2005).

Compared to Saturn, HD 149026b has a similar mass but its radius is 15% smaller, despite the intense irradiation from its parent star that should *enlarge* the radius. Sato et al. (2005) modeled HD 149026b as a dense heavy-element core surrounded by a fluid envelope of solar composition. They found a core mass of  $70\text{--}80 M_{\oplus}$ , which is 65%–75% of the total mass of the planet. This is larger than the canonical core mass of  $10\text{--}20 M_{\oplus}$  that is expected from the core accretion theory of planet formation (Mizuno 1980; Pollack et al. 1996). The finding of a highly metal-enriched composition was confirmed in models by Fortney et al. (2006), Ikoma et al. (2006), Broeg & Wuchterl (2007), and Burrows et al. (2007). The latter authors dubbed HD 149026b a “super-Neptune” because the inferred mass fraction of heavy elements is similar to that of an ice giant rather than a gas giant.

Interestingly, the parent star has a rather high metallicity ( $[\text{Fe}/\text{H}] = +0.36$ ; Sato et al. 2005). The observation of a large core in such a metal-rich system would seem to support the core accretion theory as opposed to coreless alternatives such as gravitational instability (Boss 1997). However, the larger than expected core mass raises some questions. Why did the growing protoplanet not accrete gas efficiently? Or if it did, what happened to its envelope of light elements? Many scenarios have been proposed: a collision of two massive protoplanets (Sato et al. 2005; Ikoma et al. 2006), in situ formation in a low-pressure nebula (Broeg & Wuchterl 2007), a viscous and evaporating gas disk

(Ikoma et al. 2006), and a separation of gas from planetesimals at the magnetospheric “X point” (Sato et al. 2005).

More recently, Harrington et al. (2007) found that the  $8 \mu\text{m}$  brightness temperature of HD 149026b exceeds its expected black-body temperature, even if the planet is assumed to absorb all of the incident stellar radiation. In this sense the planet is anomalously hot. The high temperature may result from novel atmospheric or structural properties. Most recently, Torres et al. (2007) announced the discovery of a transiting planet, HAT-P-3b, whose measured mass and radius indicate that it too is highly enriched in heavy elements.

In short, HD 149026b seems to be the harbinger of an entirely new kind of planet that current models of planet formation, evolution, and structure cannot accommodate without interesting and possibly exotic modifications. Because of this situation, it is desirable to improve the reliability and the precision of estimates of the system parameters, and especially a key parameter that makes this planet unusual: its small radius.

One can measure the planetary radius by gathering photometry during transits, modeling the light curve, and supplementing the model with external information about the stellar radius. Previously, Sato et al. (2005) analyzed three light curves, and Charbonneau et al. (2006) added three light curves. In this paper we present another five light curves of comparable or higher quality to the previously published data, and we simultaneously model all of the data to derive the most precise planetary, stellar, and orbital parameters that are currently available. We present our observations and data reduction procedure in § 2 and the light-curve modeling procedure in § 3. We provide the results in § 4, along with an extended discussion about the limiting error: the uncertainty in the stellar radius. The final section summarizes the results and speculates on future prospects for improvement.

### 2. OBSERVATIONS AND DATA REDUCTION

We used three of the 0.8 m automated photometric telescopes (APTs) at Fairborn Observatory to measure the transits of HD 149026b that occurred on UT 2006 April 26, 2006 May 20, 2007 May 3, 2007 June 18, and 2007 June 21. We observed the first three transits with the T11 APT and observed the last two transits simultaneously with the T8, T10, and T11 APTs. All three telescopes are equipped with two temperature-stabilized EMI 9124QB

<sup>1</sup> Department of Physics, and Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139.

<sup>2</sup> Center of Excellence in Information Systems, Tennessee State University, 3500 John A. Merritt Boulevard, Box 9501, Nashville, TN 37209.

<sup>3</sup> Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.



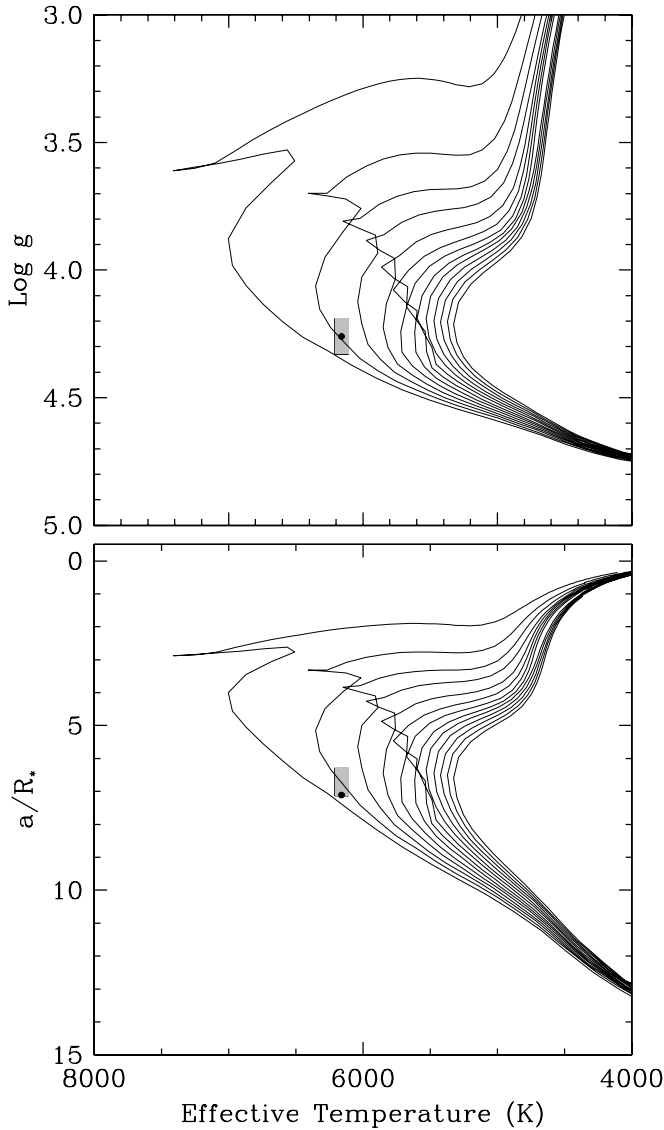


FIG. 3.—Model isochrones from the Yonsei-Yale series by Yi et al. (2001) and Demarque et al. (2004), corresponding to ages of 1–14 Gyr (left to right) for the measured composition of  $[\text{Fe}/\text{H}] = +0.36$ , along with the observational constraints. *Top*: The vertical axis is  $\log g$ , and the shaded box shows the  $1\sigma$  range based on the spectroscopically determined value of  $\log g$ . *Bottom*: The vertical axis is  $a/R_*$ , which is proportional to the cube root of the stellar mean density (see eq. [2]). The shaded box shows the  $1\sigma$  range based on the photometrically determined value of  $a/R_*$ .

treatment of observational errors. The results are all in agreement. Indeed, the differences are smaller than one would expect from Gaussian statistics, given the quoted error bars, although we note that 5 of the 10 light curves that we fitted were taken from those previous works. The precision in  $R_p$  is not improved because the limiting error is the uncertainty in  $R_*$ , which is unchanged.

#### 4.3. Transit Times

For planning future observations of this system it is important to be able to predict transit times as precisely as possible. We used all of the transit times given in Table 3 to calculate a photometric ephemeris for this system,

$$T_c(E) = T_c(0) + EP, \quad (3)$$

where  $T_c$  is the transit midpoint,  $E$  is the integral transit epoch, and  $P$  is the orbital period. The linear fit had  $\chi^2/N_{\text{dof}} = 0.63$  and

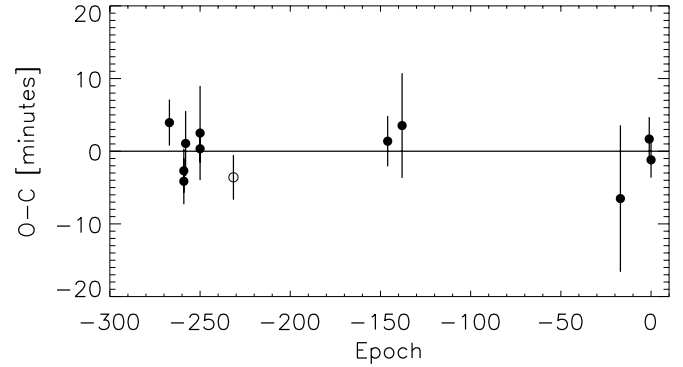


FIG. 4.—Transit timing residuals for HD 149026b. The calculated times, using the ephemeris derived in § 4.3, have been subtracted from the observed times. The filled symbols represent observations of transits. The open symbol represents the observation of the secondary eclipse by Harrington et al. (2007). The secondary eclipse datum was not used in the fit.

$N_{\text{dof}} = 9$ , suggesting that the errors quoted in Table 3 have been somewhat overestimated. The results are

$$T_c(0) = 2,454,272.7301 \pm 0.0013 \text{ (HJD)}, \quad (4)$$

$$P = 2.8758882 \pm 0.0000061 \text{ days}. \quad (5)$$

Our value for the orbital period is in agreement with the previously published values and is about 25 times more precise. Figure 4 is the  $O-C$  (observed minus calculated) diagram for the transit times.

For a circular orbit, successive transits and secondary eclipses should be spaced by exactly half an orbital period. Recently, Harrington et al. (2007) observed a secondary eclipse of HD 149026 with the *Spitzer Space Telescope*, allowing the assumption of a circular orbit to be checked. In the presence of a small but nonzero orbital eccentricity, the time difference between the midpoint of secondary eclipse,  $T_{\text{sec}}$ , and the time of transit,  $T_{\text{tra}}$ , is

$$T_{\text{sec}} - T_{\text{tra}} \approx \frac{P}{2} \left( 1 + \frac{4}{\pi} e \cos \omega \right), \quad (6)$$

where  $\omega$  is the argument of pericenter (Kallrath & Milone 1999, p. 62). Harrington et al. (2007) measured the midpoint of a secondary eclipse to be HJD  $2,453,606.960 \pm 0.001$ , represented by the open circle in Figure 4. The timing offset of equation (6) is  $-3.6 \pm 3.1$  minutes, corresponding to  $e \cos \omega = -0.0014 \pm 0.0012$ . The orbit does indeed appear to be nearly circular, as one would expect from the dissipative effects of stellar and planetary tidal interactions.

## 5. DISCUSSION AND SUMMARY

We have presented five new transit light curves of the exoplanet HD 149026b and analyzed them along with five previously published light curves. The joint analysis has resulted in much more precise determinations of the orbital period and transit ephemerides and also in a more precise value of the planet-to-star radius ratio. In some cases, this ratio is of primary interest, such as inferring the brightness temperature of the planet from the depth of a secondary eclipse (Harrington et al. 2007), or testing for any wavelength dependence in the radius ratio as a means of identifying planetary atmospheric features (see, e.g., Charbonneau et al. 2002).

However, when it comes to understanding the interior structure of the planet, the quantity of primary interest is  $R_p$  itself, and here we can offer no significant improvement. The limiting error

is the 7% uncertainty in the stellar radius. This error was not reduced by acquiring more light curves, although we did find agreement between the results of four different (and intertwined) methods for estimating the stellar radius using all of the available data. Thus, we leave unchanged the interpretation of this planet as a being unexpectedly small for its mass and likely to be highly enriched in heavy elements (Sato et al. 2005; Fortney et al. 2006; Ikoma et al. 2006; Burrows et al. 2007).

Further improvement will depend on progress in measuring the stellar radius. Baines et al. (2007) recently used optical interferometry to measure the angular diameter of the planet-hosting star HD 189733 and combined it with the *Hipparcos* parallax to measure the stellar radius. For HD 149026, similar observations are not likely to result in a more precise value of the stellar radius, at least not in the near future. This is not only because of the 6% uncertainty in the parallax, but also because the expected angular diameter is only  $\approx 180 \mu\text{as}$ , which is only 7–8 times larger than the measurement error that was achieved for HD 189733.

Supposing the parallax were known with 10  $\mu\text{as}$  precision (as one might hope from a space-based interferometric mission), the error in the Stefan-Boltzmann method for determining  $R_*$  would be reduced to 2.7%. The limiting errors in that case would arise

from the effective temperature and bolometric correction. In the nearer term a possible path forward is the continued acquisition of high-quality transit photometry, in order to improve our measurement of  $a/R_*$  and thereby establish the stellar mean density with greater precision. At fixed mean density,  $R_*$  varies as  $M_*^{1/3}$ , and our application of the Yonsei-Yale models to HD 149026 suggests that the stellar mass has already been pinned down to within 4.6%. If  $a/R_*$  were known exactly, the fractional error in the stellar radius would be approximately 1.5% (i.e., one-third as large as the fractional error in the stellar mass). In effect, transit photometry measures  $M_*/R_*^3$ , and the stellar models generally constrain a different combination of  $M_*$  and  $R_*$  (see, e.g., Cody & Sasselov 2002). We encourage observers to be persistent in gathering additional seasons of ground-based photometry and look forward to the results of space-based photometry for this system.

We are grateful to the anonymous referee for a thorough and helpful review of the manuscript. G. W. H. acknowledges support from NSF grant HRD-9706268 and NASA grant NNX06AC14G. G. T. acknowledges partial support for this work from NASA grant NNG04LG89G.

## REFERENCES

- Agol, E., Steffen, J., Sari, R., & Clarkson, W. 2005, MNRAS, 359, 567  
 Baines, E. K., van Belle, G. T., ten Brummelaar, T. A., McAlister, H. A., Swain, M., Turner, N. H., Sturmann, L., & Sturmann, J. 2007, ApJ, 661, L195  
 Boss, A. P. 1997, Science, 276, 1836  
 Broeg, C., & Wuchterl, G. 2007, MNRAS, 376, L62  
 Burrows, A., Hubeny, I., Budaj, J., & Hubbard, W. B. 2007, ApJ, 661, 502  
 Charbonneau, D., Brown, T. M., Noyes, R. W., & Gilliland, R. L. 2002, ApJ, 568, 377  
 Charbonneau, D., et al. 2006, ApJ, 636, 445  
 Claret, A. 2000, A&A, 363, 1081  
 Cody, A. M., & Sasselov, D. D. 2002, ApJ, 569, 451  
 Demarque, P., Woo, J.-H., Kim, Y.-C., & Yi, S. K. 2004, ApJS, 155, 667  
 Eaton, J. A., Henry, G. W., & Fekel, F. C. 2003, in The Future of Small Telescopes in the New Millennium, Vol. II-The Telescopes We Use, ed. T. D. Oswalt (Dordrecht: Kluwer), 189  
 Fischer, D. A., & Valenti, J. 2005, ApJ, 622, 1102  
 Flower, P. J. 1996, ApJ, 469, 355  
 Fortney, J. J., Saumon, D., Marley, M. S., Lodders, K., & Freedman, R. S. 2006, ApJ, 642, 495  
 Gillon, M., Pont, F., Moutou, C., Bouchy, F., Courbin, F., Sohy, S., & Magain, P. 2006, A&A, 459, 249  
 Gillon, M., et al. 2007, A&A, 472, L13  
 Halbwachs, J. L., Arenou, F., Mayor, M., Udry, S., & Queloz, D. 2000, A&A, 355, 581  
 Harrington, J., Luszcz, S., Seager, S., Deming, D., & Richardson, L. J. 2007, Nature, 447, 691  
 Henry, G. W. 1999, PASP, 111, 845  
 Holman, M. J., & Murray, N. W. 2005, Science, 307, 1288  
 Holman, M. J., et al. 2006, ApJ, 652, 1715  
 ———. 2007, ApJ, 664, 1185  
 Ikoma, M., Guillot, T., Genda, H., Tanigawa, T., & Ida, S. 2006, ApJ, 650, 1150  
 Kallrath, J., & Milone, E. F. 1999, Eclipsing Binary Stars: Modeling and Analysis (New York: Springer)  
 Mandel, K., & Agol, E. 2002, ApJ, 580, L171  
 Marcy, G. W., & Butler, R. P. 2000, PASP, 112, 137  
 Masana, E., Jordi, C., & Ribas, I. 2006, A&A, 450, 735  
 Mizuno, H. 1980, Prog. Theor. Phys., 64, 544  
 Perryman, M. A. C., et al. 1997, A&A, 323, L49  
 Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., & Greenzweig, Y. 1996, Icarus, 124, 62  
 Santos, N. C., Israelian, G., Mayor, M., Rebolo, R., & Udry, S. 2003, A&A, 398, 363  
 Sato, B., et al. 2005, ApJ, 633, 465  
 Seager, S., & Mallén-Ornelas, G. 2003, ApJ, 585, 1038  
 Southworth, J., Wheatley, P. J., & Sams, G. 2007, MNRAS, 379, L11  
 Sozzetti, A., Torres, G., Charbonneau, D., Latham, D. W., Holman, M. J., Winn, J. N., Laird, J. B., & O'Donovan, F. T. 2007, ApJ, 664, 1190  
 Torres, G., Winn, J. N., & Holman, M. J. 2008, ApJ, in press  
 Torres, G., et al. 2007, ApJ, 666, L121  
 Winn, J. N., et al. 2007, AJ, 133, 1828  
 Yi, S., Demarque, P., Kim, Y.-C., Lee, Y.-W., Ree, C. H., Lejeune, T., & Barnes, S. 2001, ApJS, 136, 417





