KEPLER-4b: A HOT NEPTUNE-LIKE PLANET OF A GO STAR NEAR MAIN-SEQUENCE TURNOFF

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Received 2009 November 16; accepted 2010 January 5; published 2010 March 30

ABSTRACT

Early time-series photometry from NASA’s Kepler spacecraft has revealed a planet transiting the star we term Kepler-4, at R.A. = 19h02m27s68, δ = +50’08’08”.7. The planet has an orbital period of 3.213 days and shows transits with a relative depth of 0.87 × 10−3 and a duration of about 3.95 hr. Radial velocity (RV) measurements from the Keck High Resolution Echelle Spectrometer show a reflex Doppler signal of 9.3+1.1−0.9 m s−1, consistent with a low-eccentricity orbit with the phase expected from the transits. Various tests show no evidence for any companion star near enough to affect the light curve or the RVs for this system. From a transit-based estimate of the host star’s mean density, combined with analysis of high-resolution spectra, we infer that the host star is near turnoff from the main sequence, with estimated mass and radius of 1.223+0.053−0.091 Msun and 1.487+0.071−0.064 Rsun. We estimate the planet mass and radius to be [Mp,Rp] = [24.5 ± 3.8 Msun, 3.99 ± 0.21 Rsun]. The planet’s density is near 1.9 g cm−3; it is thus slightly denser and more massive than Neptune, but about the same size.

Key words: planetary systems – stars: fundamental parameters – stars: individual (Kepler-4, KIC 11853905, 2MASS 19022767+500807)

1. INTRODUCTION

Transiting extrasolar planets provide unparalleled opportunities for detailed study of the physical characteristics of distant solar systems. Since the first transiting planet detection a decade ago, ground-based surveys such as TrES, HAT, and Super-WASP (Alonso et al. 2004; Bakos et al. 2004; Pollacco et al. 2006) and the space-borne telescope CoRoT (Baglin et al. 2007) have located more than 50 transiting planets, spanning a large range in size and mass. With the advent of NASA’s Kepler Mission, we have a new and extraordinarily sensitive tool for studying transiting planets. Kepler has enough sensitivity to detect Earth-size planets orbiting in the habitable zones of Sun-like stars during its planned 3.5-year mission (Koch et al. 2010; Borucki et al. 2010). The first science data to return after Kepler’s launch in 2009 March were time series from a 9.7 day commissioning run, followed after a 1.6 day gap by a 33.5 day science run. Here, we describe the transiting planet Kepler-4b, one of several transiting planets discovered during these first two observing intervals.

2. OBSERVATIONS, ANALYSIS, AND TESTS FOR FALSE POSITIVES

Observations of the Kepler target field commenced 2009 May 1; the data that we describe here are long cadence (LC) photometry, which correspond to integration times of 29.426 minutes. For a full description of the Kepler field of view, observing modes, and data processing pipeline, see Jenkins et al. (2010) and Caldwell et al. (2010). For Kepler target stars brighter than r = 13, the rms photometric precision attained for relative flux time series is typically better than 2 × 10−4 per 29 minutes integration (Gilliland et al. 2010). We detrended photometry from the mission data reduction pipeline and searched it for significant transit-like events using the procedures described by Jenkins et al. (2010) and by Batalha et al. (2010).

One of the transiting planet candidates identified by the process just described was the star that we now term Kepler-4. This star is uncommonly bright by Kepler standards. Its Kepler magnitude (AB magnitude averaged over the Kepler bandpass) is Kepler mag = 12.211. Characteristics of this star are given in Table 1; briefly, it is a somewhat metal-rich ([Fe/H] = +0.17 ± 0.06) star of nearly solar temperature (5857 ± 120 K), evidently seen near the end of its main-sequence lifetime, as explained below.

* Some of the data presented herein were 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.
Table 1

| Parameter                              | Value          | Notes |
|----------------------------------------|----------------|-------|
| Transit and orbital parameters         |                |       |
| Orbital period $P$ (d)                  | $3.21346 \pm 0.00022$ | A     |
| Midtransit time $E$ (HJD)               | $2454956.6127 \pm 0.0015$ | A     |
| Scaled semimajor axis $a/R_*$          | $6.47^{+0.26}_{-0.28}$ | A     |
| Scaled planet radius $R_p/R_*$         | $0.02470^{+0.00031}_{-0.00030}$ | A     |
| Impact parameter $b \equiv a \cos i/R_*$ | $0.0222^{+0.0124}_{-0.0022}$ | A     |
| Orbital inclination $i$ (deg)           | $89.76^{+0.24}_{-0.10}$ | A     |
| Orbital semi-amplitude $K$ (m s$^{-1}$) | $9.3^{+1.1}_{-1.9}$ | A, B  |
| Orbital eccentricity $e$               | $0$ (adopted)  | A, B  |
| Center-of-mass velocity $\gamma$ (m s$^{-1}$) | $-1.27 \pm 1.1$ | A, B  |
| Observed stellar parameters            |                |       |
| Effective temperature $T_{\text{eff}}$ (K) | 5857 ± 120   | C     |
| Spectroscopic gravity log $g$ (cgs)    | $4.25 \pm 0.10$ | C     |
| Metallicity [Fe/H]                     | $+0.17 \pm 0.06$ | C     |
| Projected rotation $v \sin i$ (km s$^{-1}$) | $2.2 \pm 1.0$ | C     |
| Mean radial velocity (km s$^{-1}$)     | $-61.0 \pm 0.10$ | B     |
| Derived stellar parameters            |                |       |
| Mass $M_*$ ($M_\odot$)                 | $1.223^{+0.053}_{-0.091}$ | C, D  |
| Radius $R_*$ ($R_\odot$)               | $1.487^{+0.071}_{-0.084}$ | C, D  |
| Surface gravity log $g_*$ (cgs)        | $4.17 \pm 0.04$  | C, D  |
| Luminosity $L_*$ ($L_\odot$)           | $2.26^{+0.06}_{-0.48}$ | C, D  |
| Absolute V magnitude $M_V$ (mag)       | $4.00 \pm 0.28$  | D     |
| Age (Gyr)                              | $4.5 \pm 1.5$   | C, D  |
| Distance (pc)                          | $550 \pm 80$    | D     |
| Planetary parameters                   |                |       |
| Mass $M_P$ ($M_\oplus$)                | $0.077 \pm 0.012$ | A, B, C, D |
| Radius $R_P$ ($R_\oplus$, equatorial)  | $0.357 \pm 0.019$ | A, B, C, D |
| Density $\rho$ (g cm$^{-3}$)           | $1.91^{-0.36}_{-0.47}$ | A, B, C, D |
| Surface gravity log $g_P$ (cgs)        | $3.16^{+0.06}_{-0.10}$ | A, B, C, D |
| Orbital semimajor axis $a$ (AU)        | $0.0456 \pm 0.0009$ | E     |
| Equilibrium temperature $T_{\text{eq}}$ (K) | $1650 \pm 200$ | F     |

Notes: A: based primarily on the photometry. B: based on the RVs. C: based on spectrum analysis (FIES/MOOG or HIRES/SME). D: based on the Yale–Yonsei evolution tracks. E: based on Newton’s version of Kepler’s third law. F: assumes Bond albedo = 0.1 and complete redistribution.

Figure 1 shows the light curve for Kepler-4, folded with a period of 3.21346 days. Since the transit signal was clear, we proceeded with follow-up observations as described in Gautier et al. (2010) and Batalha et al. (2010). Experience with both ground- and space-based transit observations shows that a fairly large fraction of events that resemble planetary transits are actually caused by eclipses involving only stars, or eclipses with properties that are significantly confused by diluting light from one or more stellar companions, either physical or projected. For this reason, we designed our follow-up observations to determine whether the light-curve dips can be ascribed to a transiting planet; if not, what eclipsing star or other process might be responsible for them; and if so, what the properties of the host star and its planet might be.

Ground-based visible-light speckle imaging from the WIYN Telescope, NIR adaptive-optics imaging from the Mt. Palomar 5 m telescope, and also with the NIR2C camera on the Keck telescope all show Kepler-4 as an isolated star, apart from a neighbor that is 3.5 mag fainter at a distance of 11′′9. We estimate that this star contributes 2% ± 2% to the flux we measure for Kepler-4, which dilutes the transit by a factor of 1.02 ± 0.02. We take this dilution and its uncertainty into account in computing the planetary radius $R_p$ and its probable errors. Limits on nearby companions are described by Batalha et al. (2010); the imagery rules out background eclipsing binaries that might simulate the observed transits, up to a magnitude difference of 9.8 in the $H$ band, for companions between 0′′12 and 3′′0 from Kepler-4. We have also searched for motion of the image centroid that is correlated with the transits, finding no such motion with a limit of $4 \times 10^{-4}$ arcsec.

Two reconnaissance spectra obtained with the TRES spectrograph on the 1.5 m Tillinghast Reflector at the Whipple Observatory showed a velocity variation of less than 150 m s$^{-1}$ over 5 days. Accordingly, we obtained RV measurements with the High Resolution Echelle Spectrometer (HIRES) on the Keck I telescope (Vogt et al. 1994). Figure 2 shows the RV data for Kepler-4, folded with the transit period and shifted so that transit center occurs at zero phase. Assuming zero eccentricity, we obtained a RV variation with phase that is consistent with the observed light curve, with a reflex velocity amplitude $K$ of $9.3^{+1.1}_{-1.9}$ m s$^{-1}$ and velocity residuals of only 3.6 m s$^{-1}$. We also performed a fit in which we allowed the eccentricity $e$ to float. This gave $e = 0.22 \pm 0.08$ and $K = 10.0$ m s$^{-1}$; the reduced $\chi^2$ improved only slightly. Finally, a Monte Carlo bootstrap (described below) that simultaneously fits all photometry and RV values, and that is consistent with stellar evolution models, gives $e \sin \omega = -0.003 \pm 0.058$ and $e \cos \omega = -0.005 \pm 0.057$. There is thus only marginal evidence for a noncircular orbit. In the analysis below, we do however account throughout for the possible range of $e$ and $\omega$ in our estimates of stellar and planetary parameters and their uncertainties. Given the integration

13 Time series of the photometry and of radial velocity (RV) data presented here may be retrieved from the MAST/HLSP data archive at http://archive.stsci.edu/prepds/kepler_hlsp.
times of the spectra and Kepler-4’s brightness, $T_{\text{eff}}$, and slow rotation ($v\sin i = 2.2 \pm 1.0 \text{ km s}^{-1}$), the residuals are consistent with expectations. We also used the HIRES spectra to search for variations in the shapes of line bisectors; the component of the bisector span that is in phase with the orbital period has amplitude $-1.2 \pm 4.2 \text{ m s}^{-1}$ (with uncertainty estimated from the bisector scatter), offering no support for the presence of a blended eclipsing binary star.

We can reject many photometric blend scenarios, but not all. Kepler-4b’s long transit duration rules out hierarchical triple systems in which the primary of the eclipsing pair contributes less than about 25% of the system luminosity. Near-twin star systems permitted by this constraint would lead to errors in the planet radius and mass by factors of a few—these would be serious, but not large enough that transits by stars could be confused with those by planets. Moreover, virtually all transiting planet parameter estimates are vulnerable to confusion of this sort. An unresolved background eclipsing binary star might accurately simulate the transit light curve, but such a system would not likely produce the very small observed RV variation, nor the small line bisector variation. The most plausible remaining blend scenario involves an unresolved background transiting Jupiter-size planet. Such a blend could be consistent with all current observations, though the required coincidence in apparent position is very unlikely a priori.

Thus, although some kinds of confusing photometric blends are possible, there is no evidence for them. In what follows, we assume that the observed light curve results from transits by a rather small extrasolar planet across the face of a normal, single, Sun-like star.
Moreover, in the light-curve analysis, the estimated $\rho_*$ depends somewhat on the initial guess for $M_*$ (Koch et al. 2010) and on the range of orbital eccentricity allowed by the observations. To account for the different information supplied by these two kinds of model fitting, we iterated the solution by putting the MCMC probability distributions back into the light-curve analysis. The most likely parameter values and uncertainty distributions we report below are the result of this once-iterated fit.

Brown (2010) has tested the $\rho_*$ method against a sample of 169 stars (mostly members of eclipsing binaries taken from the compilation by Torres et al. 2009) that have accurately known masses and radii. This comparison shows that method’s systematic errors do not exceed 2%–3% in radius, and about 6%–9% in mass. Random errors appear to arise about equally from uncertainties in the estimated stellar $T_{\text{eff}}$ and metallicity, and from uncertainties in the masses and radii inferred for the eclipsing binary components using traditional (but largely model-independent) techniques. Systematic errors arise mostly because rapidly rotating and hence magnetically active stars are seen to have larger radii than slowly rotating stars with otherwise similar properties (e.g., Torres et al. 2006; López-Morales 2007; Morales et al. 2008). The sample of eclipsing binary stars consists almost entirely of such fast rotators; this causes an excess of up to several percent in the actual radii of stars of sub-solar mass, relative to the YY models. On the other hand, the host stars of confirmed transiting planets found by Kepler are mostly slow rotators (if only because it is difficult to measure precise RVs of rapidly rotating stars). Errors in these estimates should therefore be dominated by measurement errors, especially in $[Z]$ and in $\rho_*$.

3.2. The Star Kepler-4

Simultaneous fits to the transits of Kepler-4b and to the RV data (allowing nonzero eccentricity) yield the ratio of orbital semimajor axis $a$ to stellar radius $R_*$, namely $a/R_* = 6.47^{+0.26}_{-0.28}$, which with the orbital period gives $\rho_* = 0.50 \pm 0.16$ g cm$^{-3}$. This is a low value, roughly 1/3 that of the Sun, suggesting that Kepler-4 must have evolved considerably away from the zero-age main sequence. Applying the $\rho_*$ method confirms this conclusion, and in fact finds a range of model parameters, all of which fit the observations almost equally well, but which imply distinct evolutionary states for the star. Figure 3 shows evolution tracks for three models having masses between $1.13 \, M_\odot$ and $1.28 \, M_\odot$. In this mass range, old main-sequence stars have small convective cores. Because of efficient mixing, these cores suffer hydrogen exhaustion all at once, following which the entire star must compress and heat until the central temperature rises enough to start shell hydrogen burning. The blue-going hook at main-sequence turnoff is a result of this compression. In the case of Kepler-4, the observed $\rho_*$ and $T_{\text{eff}}$ (indicated by the error box in Figure 3) are closely matched by each of the evolution tracks, albeit at different ages and with models occupying different evolutionary states. Thus, for the lowest-mass star to fit the observations, it must have just finished its core-contraction phase, and be on its way to becoming a shell-burning subgiant. The highest-mass star to fit the same observations must still be on the main sequence but nearing hydrogen exhaustion in its core, just poised to begin core contraction.

It is not possible to distinguish among these possibilities using existing observations. Although the masses of acceptable models differ by as much as 13%, the radii differ by only 1/3 as much (in order to give the same observed mean density). This radius difference would cause a difference in $\log(g)$ that is too small to measure with current methods. Likewise, the luminosity difference of about 8% implies a parallax difference of only 4%, also too small to discern at this star’s likely distance of about 550 ± 80 pc. Asteroseismology may however offer a way out of this quandary. Because of the star’s relatively large luminosity and apparent brightness, it may be possible to measure the frequencies of its pulsation modes, and hence distinguish among the feasible evolution scenarios. Kepler-4 is now being observed with Kepler’s short (60 s) cadence; the mission will report pulsation properties estimated from these data if and when the pulsation signals rise above the noise.

We list the inferred properties of Kepler-4 in Table 1. For the quantities $M_*$ and $R_*$ we give uncertainties that include the effects of observational uncertainties, of uncertainty in orbital eccentricity, and of uncertainty in the host star’s evolutionary state.

3.3. The Planet Kepler-4b

Given the properties of its host star, the depth of transits due to Kepler-4b implies a planetary radius of $0.357 \pm 0.019 \, R_\oplus$, and a mass of $0.077 \pm 0.012 \, M_\oplus = 24.5 \pm 3.8 \, M_\oplus$. As with $M_*$ and $R_*$, these values and uncertainties should be interpreted as describing the centers and 68% probability points of the marginal probability distributions, accounting for all of the uncertainties. Kepler-4b is therefore slightly more massive than Neptune, and about the same size. Its mean density is about $1.9 \, g \, \text{cm}^{-3}$, greater than that of Jupiter and considerably larger than that of Saturn. Assuming a 10% Bond albedo and efficient heat redistribution to the planet’s night side, its equilibrium temperature is $1650 \pm 200 \, \text{K}$ (Koch et al. 2010). Radial velocity data provide no evidence for other massive planets in small orbits. Because of the limited time span and precision of the extant RV observations, it is however impossible to rule out such planetary companions.

4. DISCUSSION

Figure 4 shows Kepler-4 in a mass–radius diagram that spans the range so far occupied by small transiting exoplanets. Kepler-4b is the third known transiting Neptune-like planet,
Figure 4. Kepler-4b is shown in a mass–radius plot, along with other hot Neptunes, the hot super-Earths CoRoT-7b (Léger et al. 2009) and GJ1214b (Charbonneau et al. 2009), and model curves by Baraffe et al. (2008) and by Valencia et al. (2007), showing increasing heavy-element fractions toward the bottom of the figure. Multiple dashed and solid curves show model results for differing ages; “I” indicates irradiated and “NI” non-irradiated models. Kepler-4b appears to be denser than HAT-P-11b but similar to GJ436b, less dense than is expected for a water or rocky planet. Nevertheless, we can state with a measure of confidence that the rock-to-water ratio in the interior of Kepler 4b is unusually high (i.e., significantly higher than in Neptune or Uranus). Nevertheless, we can state with a measure of confidence that there are no possible interior models for Kepler-4b with no H/He envelope and neither it nor GJ436b is compact enough to be a water-rich super-Earth.

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The slightly eccentric orbits of the two previously known transiting Neptune-like planets, in similar potentials and at similar ages, suggest that their interiors are somewhat less dissipative to stellar tides than the giants in our solar system. Therefore, it would be very interesting to resolve whether the orbit of Kepler-4b has comparable eccentricity or is circular; the current observations are still inconclusive.

Funding for this Discovery mission is provided by NASA’s Science Mission Directorate. We are grateful first to the entire Kepler team, past and present. Their tireless efforts were all essential to the success of the mission. For special advice and assistance, we thank Lars Buchhave, David Ciardi, Megan Crane, Willie Torres, Mike Haas, and Riley Duran.

Facilities: Kepler