HAT-P-9b: A LOW-DENSITY PLANET TRANSITING A MODERATELY FAINT F STAR

AVI Sipőcz1, GÁSPÁR Á. BAKOS2,9, FRANCOIS BOUCHY3, FREDERIC PONT4, GÉZA KOVÁCS5, DAVE W. LATHAM2, BRIGITTA SIPÓCZ2,9, GUILLERMO TORRES2, TSEVI MAZEH1, ALBERTA ESQUERDO2,7, ANDRÁS PÁL2,6, ROBERT W. NOYES2, DIMITAR D. SASSELOV2, JÓZSEF LÁZÁR5, ISTVÁN PAPP5, PÁL SÁR4, and GÁBOR KOVÁCS2

1 Wise Observatory, Tel Aviv University, Tel Aviv 69978, Israel; sipocz@wise.tau.ac.il.
2 Harvard-Smithsonian Center for Astrophysics (CfA), 60 Garden Street, Cambridge, MA 02138, USA
3 Institut d’Astrophysique de Paris, 98bis Bd Arago, 75014 Paris, France
4 School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK
5 Konkoly Observatory, P.O. Box 67, H-1125 Budapest, Hungary
6 Department of Astronomy, Eotvos Loránd University, Pf. 32, H-1518 Budapest Hungary
7 Planetary Science Institute, 620 N. 6th Avenue, Tucson, AZ 85705, USA
8 Hungarian Astronomical Association, P.O. Box 219, H-1461 Budapest, Hungary

Received 2008 June 24; accepted 2008 September 11; published 2008 December 12

ABSTRACT

We report the discovery of a planet transiting a moderately faint ($V = 12.3$ mag) late F star, with an orbital period of 3.92289 ± 0.0004 days. From the transit light curve and radial velocity measurements, we determine that the radius of the planet is $R_p = 1.40 ± 0.06 \ R_{\oplus}$ and that the mass is $M_p = 0.78 ± 0.09 \ M_{\oplus}$. The density of the new planet, $\rho_p = 0.35 ± 0.06 \ g \ cm^{-3}$, fits to the low-density tail of the currently known transiting planets. We find that the center of transit is at $T_c = 2454417.9077 ± 0.0003$ (HJD), and the total transit duration is $0.143 ± 0.004$ days.

The host star has $M_* = 1.28 ± 0.13 \ M_{\odot}$ and $R_* = 1.32 ± 0.07 \ R_{\odot}$.

Key words: planetary systems – stars: individual (GSC 02463 − 00281, HAT-P-9)

Online-only material: color figures

1. INTRODUCTION

Transiting extra-solar planets are important astrophysical objects as they allow us to test planetary structure and evolution theory (e.g., Fortney 2008; Burrows et al. 2008; Baraffe et al. 2008), especially because they yield a measurement of the planetary mass and radius. Over the last few years, the sample of known transiting planets has grown substantially, leading to an improved theoretical understanding of their physical nature (e.g., Guillot et al. 2006; Burrows et al. 2007; Fortney et al. 2008; Chabrier & Baraffe 2007). In addition, the increasing sample of transiting planets enabled the discovery of some interesting correlations, such as the mass–period relation (Mazeh et al. 2005; Gaudi et al. 2005). The astrophysics behind these correlations is not fully understood, and a clear way toward progress is the discovery of many more transiting planets.

We report here the discovery of another transiting planet detected by the HATNet project10 (Bakos et al. 2002, 2004), labeled HAT-P-9b, and our determination of its parameters, including mass, radius, density, and surface gravity. In Section 2, we describe our photometric and spectroscopic observations, and in Section 3 we derive the stellar parameters. The orbital solution is performed in Section 4, and a discussion of possible blend scenarios is brought in Section 5. The determination of the light curve parameters and the planet’s physical parameters is described in Section 6, and we bring a discussion in Section 7.

2. OBSERVATIONS AND ANALYSIS

2.1. Detection of the Transit in the HATNet Data

HAT-P-9 is positioned in HATNet’s internally labeled field G176, centered at $\alpha = 07^h28^m$, $\delta = 37^\circ30’$. This field was observed in network mode by the HAT-6 telescope, located at the Fred Lawrence Whipple Observatory (FLWO) of the Smithsonian Astrophysical Observatory (SAO), and the HAT-9 telescope at the Submillimeter Array (SMA) site atop Mauna Kea, HI. In total, 6884 exposures were obtained at a 5.5 min cadence between 2004 November 26 and 2005 October 21 (UT).

Preliminary reduction included standard bias, dark and flat-field corrections, followed by an astrometric solution using the code of Pál & Bakos (2006). Photometry was applied using fine-tuned aperture photometry while the raw light curves were processed by our external parameter decorrelation technique. Next, the trend filtering algorithm (TFA; Kovács et al. 2005) was applied to get the final light curves. To search for the signature of a transiting planet in the light curves we used the box least squares (BLS; Kovács et al. 2002) algorithm.

A transit-like signal was identified in the light curve of HAT-P-9 (GSC 02463 – 00281, 2MASS J07204044+3708263), which is a $V = 12.3$ mag star, fainter than most transiting planet host stars detected with small-aperture, wide-field, ground-based campaigns. The HATNet light curve is presented in the top panel of Figure 1, folded on the ephemeris obtained from analyzing the follow-up light curves ($P = 3.92289$ days and $T_c = 2454417.9077$, see Section 2.4), showing a flux decrement of $\sim 1\%$ at phase zero. The figure shows a small shift between phase zero and transit center, suggesting a possible slight difference in the ephemeris for the HATNet data and the photometric follow-up data, obtained $\sim 1000$ days apart (see Section 7 for further discussion). This transiting planet candidate, along with others from the same

---

1 Based on part on radial velocities obtained with the SOPHIE spectrograph mounted on the 1.93 m telescope at the Observatoire de Haute Provence, France (runs 07A.PNP.MAZE, 07B.PNP.MAZE, 08A.PNP.MAZE).
2 NSF Fellow.
9 http://www.hatnet.hu.
field, was selected for follow-up observations to investigate its nature.

2.2. Early Spectroscopy Follow-Up

Initial follow-up observations were made with the CfA Digital Speedometer (DS; Latham 1992) in order to characterize the host star and to reject obvious astrophysical false-positive scenarios that mimic planetary transits. The five radial velocity (RV) measurements obtained over an interval of 62 days showed an rms residual of 1.1 km s$^{-1}$, consistent with no detectable RV variation. Atmospheric parameters for the star (effective temperature $T_{\text{eff}}$, surface gravity $\log g$, and projected rotational velocity $v \sin i$) were derived as described by Torres et al. (2002), initially assuming a fixed metallicity of $[\text{Fe}/\text{H}]=0.0\pm0.2$. We obtained $\log g = 4.05 \pm 0.30$, $T_{\text{eff}} = 6130 \pm 150$ K, and $v \sin i = 12.2 \pm 1.0$ km s$^{-1}$. As the DS results were consistent with a planet orbiting a moderately rotating main sequence star, this target was selected for high-precision spectroscopy follow-up.

2.3. High-Precision Spectroscopy Follow-Up

Observations were carried out at the Haute Provence Observatory (OHP) 1.93 m telescope, with the SOPHIE spectrograph (Bouchy & the Sophie Team 2006). SOPHIE is a multi-order echelle spectrograph fed through two fibers, one of which is used for starlight and the other for sky background or a wavelength calibration lamp. The instrument is entirely computer-controlled and a standard data reduction pipeline automatically processes the data upon CCD readout. RVs are calculated by numerical cross-correlation with a high-resolution observed spectral template of a G2 star.

HAT-P-9 was observed with SOPHIE in the high-efficiency mode ($R \sim 39,000$) during three observing runs, from 2007 May until 2008 May. Due to the relative faintness of this star, exposure times were in the range of 25–75 min, depending on observing conditions. The resulting signal-to-noise ratios were 32–46 per pixel at $\lambda = 5500$ Å. Using the empirical relation of Cameron et al. (2007), we estimated the RV photon-noise uncertainties to be 20–31 m s$^{-1}$. We made 17 RV measurements in total. Two of those were highly contaminated by the Moon and were ignored, leaving 15 RV measurements, listed in Table 1.

### Table 1

| BJD−2,400,000 (days) | RV$^a$ (m s$^{-1}$) | $\sigma_{\text{RV}}$ (m s$^{-1}$) | BS$^b$ (m s$^{-1}$) | S/N$^c$ |
|----------------------|-------------------|-----------------|-----------------|-------|
| 54233.3347           | 22667             | 24              | −62             | 43    |
| 54379.6357           | 22586             | 20              | 5               | 44    |
| 54380.6213           | 22672             | 24              | −93             | 38    |
| 54381.5815           | 22749             | 23              | −148            | 40    |
| 54413.6292           | 22727             | 21              | 3               | 43    |
| 54414.6084           | 22610             | 24              | −31             | 38    |
| 54415.6457           | 22675             | 27              | −45             | 34    |
| 54416.6392           | 22749             | 21              | −13             | 42    |
| 54421.6701           | 22659             | 31              | −11             | 32    |
| 54422.6651           | 22595             | 20              | −59             | 46    |
| 54587.3543           | 22536             | 21              | 10              | 44    |
| 54588.3571           | 22650             | 23              | 30              | 41    |
| 54589.3525           | 22730             | 23              | −2              | 40    |
| 54590.3425           | 22699             | 25              | −45             | 38    |
| 54591.3647           | 22564             | 30              | 10              | 32    |

Notes.

$^a$ The RVs include the barycentric correction.

$^b$ Bisector span.

$^c$ Signal-to-noise ratio per pixel at $\lambda = 5500$ Å.

In order to better characterize the transit parameters and to derive a better ephemeris, we performed photometric follow-up observations with 1 m class telescopes. We obtained a total of four transit light curves of HAT-P-9b, shown in Figure 3.
Two events were observed by the KeplerCam detector on the FLWO 1.2 m telescope (see Holman et al. 2007) on UT 2007 November 13 and UT 2008 January 11, in the Sloan z band. We refer to the 2007 November 13 event as having a transit number $N_t = 0$, so the 2008 January 11 transit number is $N_t = 15$. In addition, two light curves were obtained at the Wise Observatory. On UT 2007 December 6 the $N_t = 6$ transit event was observed by the Wise 0.46 m telescope (Brosch et al. 2008), with no filter. The following event, with $N_t = 7$, was observed on UT 2007 December 10 by the Wise 1 m telescope in the Cousins $R$ band. An additional light curve, obtained with the FLWO 1.2 m telescope, was of poor quality and is not included here. Table 2 lists for each light curve its $N_t$ number, UT date, observatory, telescope, filter used, limb-darkening coefficients used in its analysis, mean cadence, the correlated noise factor $\beta^a$ (see below), and the rms residuals from the fitted light curve model.

Data were reduced in a similar manner to the HATNet data, using aperture photometry and an ensemble of $\sim 100$ comparison stars in the field. An analytic model was fitted to these data, as described below in Section 6, and yielded a period of 3.92289 $\pm$ 0.00004 d and a reference epoch of mid-transit $T_c = 2454417.9077 \pm 0.0003$ d (HJD). The length of the transit as determined from this joint fit is 0.143 $\pm$ 0.004 d (3 h 26 min), the length of ingress is 0.019 $\pm$ 0.003 d (27 min), and the central transit depth is 1.17 $\pm$ 0.01%. The latter value is simply the square of the radius ratio (see Table 4) if one ignores the limb-darkening effect. This effect increases the depth by about 0.1% in the bands used here.

### Table 2

| $N_t$ | Start Date UT | Observatory + Telescope | Filter | $u_1$ | $u_2$ | Cadence min$^{-1}$ | $\beta^a$ | RMS % |
|------|---------------|-------------------------|--------|-------|-------|-------------------|----------|-------|
| 0    | 2007 Nov 13   | FLWO 1.2 m              | $\gamma$ | 0.1313 | 0.3664 | 1.0               | 1.1      | 0.17  |
| 6    | 2007 Dec 6    | Wise 0.46 m             | clear  | 0.2403 | 0.3810 | 1.1               | 1.0      | 0.21  |
| 7    | 2007 Dec 10   | Wise 1.0 m              | $R$     | 0.2403 | 0.3816 | 0.4               | 1.2      | 0.22  |
| 15   | 2008 Jan 11   | FLWO 1.2 m              | $\gamma$ | 0.1513 | 0.3664 | 1.0               | 1.6      | 0.18  |

#### Note.

$^a$ The correlated noise factor, by which the errors of each light curve are multiplied (see Section 2.4).

### 3. STELLAR PARAMETERS

The mass ($M_\star$) and radius ($R_\star$) of a transiting planet, determined from transit photometry and RV data, are dependent also on those of the parent star. In order to determine the stellar properties needed to place $M_p$ and $R_p$ on an absolute scale, we made use of stellar evolution models along with the observational constraints from spectroscopy and photometry, as described in Torres et al. (2008). Because of its relative faintness, the host star does not have a parallax measurement from *Hipparcos*, and thus a direct estimate of the absolute magnitude is not available for use as a constraint. An alternative approach is to use the surface gravity of the star, which is a measure of the evolutionary state of the star and therefore has a very strong influence on the radius. However, $\log g$ is a difficult quantity to measure spectroscopically and is often strongly correlated with other spectroscopic parameters (see Section 2.2). It has been pointed out by Sozzetti et al. (2007) that the normalized separation of the planet, $a/R_\star$, can provide a much better constraint for stellar parameter determination than the spectroscopic $\log g$. The $a/R_\star$ quantity can be determined directly from the photometric observations with no additional assumptions (other than the values of the parameters describing limb darkening, which is a second-order effect), and it is related to the mean density of the host star. As discussed later in Section 6, an analytic fit to the light curve yields $a/R_\star = 8.6 \pm 0.2$. This value, along with $T_c$ from Section 2.2, and assuming $[\text{Fe}/H] = 0.0 \pm 0.2$, was compared with the *Yonsei–Yale* stellar evolution models of Yi et al. (2001). This resulted in values for the stellar mass and radius of $M_\star = 1.16^{+0.12}_{-0.13}$ $M_\odot$ and $R_\star = 1.28 \pm 0.08 R_\odot$, and an estimated age of $3.6^{+1.3}_{-2.7}$ Gyr. The result for $\log g$ was $4.29^{+0.03}_{-0.04}$ consistent with the value derived from the DS spectra.

Moreover, in order to verify the overall consistency of our results and refine the stellar parameters, we carried out a new iteration. We imposed this latter value of $\log g$ (coming from stellar evolution modeling), and analyzed the DS spectra by allowing the metallicity, $\sin i$, and $T_{\text{eff}}$ to vary. The new results were $[\text{Fe}/H] = 0.12 \pm 0.20$, $\sin i = 11.9 \pm 1.0$ km s$^{-1}$, and $T_{\text{eff}} = 6350 \pm 150$ K. Repeating the stellar evolution modeling resulted in $M_\star = 1.12^{+0.11}_{-0.10} M_\odot$ and $R_\star = 1.32 \pm 0.07 R_\odot$, and an age of $1.6^{+1.3}_{-1.4}$ Gyr. The stellar properties are summarized in Table 3 and they correspond to a late F star.

| Parameter | Value | Source |
|-----------|-------|--------|
| R.A. | 07h 20m 40s 44 | 2MASS |
| Decl. | +37° 08′ 26” 3 | 2MASS |
| $m_v$ (mag) | 12.297 $\pm$ 0.063 | TASS |
| $T_{\text{eff}}$ (K) | 6350 $\pm$ 150 | DS + *Yonsei–Yale* |
| $\sin i$ (km s$^{-1}$) | 11.9 $\pm$ 1.0 | DS + *Yonsei–Yale* |
| log $g$ | 4.29 $^{+0.03}_{-0.04}$ | DS + *Yonsei–Yale* + light curve shape |
| $[\text{Fe}/H]$ (dex) | 0.12 $\pm$ 0.20 | DS + *Yonsei–Yale* |
| Mass ($M_\star$) | 1.28 $\pm$ 0.13 | *Yonsei–Yale* + light curve shape |
| Radius ($R_\star$) | 1.32 $\pm$ 0.07 | *Yonsei–Yale* + light curve shape |
| log($L_\star/L_\odot$) | 0.41 $^{+0.08}_{-0.09}$ | *Yonsei–Yale* |
| $M_v$ (mag) | 3.7 $^{+0.2}_{-0.2}$ | *Yonsei–Yale* |
| Age (Gyr) | 1.6 $^{+0.3}_{-0.2}$ | *Yonsei–Yale* + light curve shape |
| $B-V$ (mag) | 0.50 $^{+0.06}_{-0.05}$ | *Yonsei–Yale* |
| Distance (pc)$^a$ | 480 $\pm$ 60 | *Yonsei–Yale* |

#### Note.

$^a$ Assuming extinction of $A(V) = 0.15$ mag (see Section 3).
calibrations of Ramírez & Meléndez (2005) and Casagrande et al. (2006) to derive independent temperature estimates, using the [Fe/H] value found above in these calibrations. We adjusted the reddening until the photometric temperature matched the spectroscopic temperature, yielding $E(B - V) = 0.053$ (Ramírez & Meléndez 2005) and $E(B - V) = 0.043$ (Casagrande et al. 2006). We adopted the mean value of 0.048 as reddening, implying an extinction of $A(V) = 0.15$ mag. Note that the Burstein & Heiles (1982) reddening maps for this celestial position ($l, b = 181.1, 21.4$) give $E(B - V) = 0.072$ and the Schlegel et al. (1998) maps yield $E(B - V) = 0.065$, broadly consistent with our findings, especially if we take into account that these latter methods measure the total reddening along the line of sight.

Using the V magnitude from the TASS survey (Droege et al. 2006), $V = 12.297 \pm 0.063$ mag, the absolute $V$ magnitude from the stellar evolution model, and the $A(V) = 0.15$ mag value determined above, the distance to HAT-P-9 is 480 ± 60 pc.

4. SPECTROSCOPIC ORBITAL SOLUTION

Our 15 RV measurements from SOPHIE were fitted with a Keplerian orbit model solving for the velocity semi-amplitude $K$ and the center-of-mass velocity $\gamma$, holding the period and transit epoch fixed at the well-determined values from photometry (see Table 4). The eccentricity was set to zero. The fit yields $K = 84.7 \pm 7.9$ m s$^{-1}$ and $\gamma = 22.665 \pm 0.006$ km s$^{-1}$. The observations and fitted RV curve are displayed in the top panel of Figure 2. The residuals are presented in the bottom panel of the same figure. RMS residuals are 22.1 m s$^{-1}$, consistent with the RV uncertainties. The value of $\chi^2$ is 12.4 for 13 degrees of freedom.

5. EXCLUDING BLEND SCENARIOS

We tested the reality of the velocity variations by examining the spectral line bisector spans (BSs) of the star using our SOPHIE data. If the measured velocity changes are due only to distortions in the line profiles arising from contamination of the spectrum by the presence of a binary with a period of 3.92 days,
we would expect the BSs (which measure line asymmetry) to vary with this period, resulting in a correlation between BS and RV (see, e.g., Queloz et al. 2001; Torres et al. 2005). As shown in Figure 4, the BSs show no significant variations, except one or two outliers. The correlation coefficient between BS and RV for all 15 measurements is $-0.38$. Ignoring the extreme point reduces the correlation to $-0.18$.

In order to estimate the statistical significance of a correlation between BS and RV we define the following statistics:

$$ r_\sigma = \frac{\sigma_{\text{BS, fit}}}{\sigma_{\text{BS}}} \equiv \frac{\sigma_{\text{BS, fit}}}{\sigma_{\text{BS}}} $$

where $\sigma_{\text{BS}}$ is the standard deviation of the BS values and $\sigma_{\text{BS, fit}}$ the standard deviation of the residuals of a BS fit to the RVs. Both standard deviations are the unbiased estimators. For pure noise $r_\sigma$ will equal 1.0. When fitting the BSs to the RVs of all 15 measurements, using polynomials of degrees 1–3 we got $r_\sigma$ in the range 0.984–1.043, consistent with no significant correlation.

Another sign of a binary would be a dependence between the RV amplitude and the template used. This may happen when the components of the blended binary are of a different spectral type than the primary target. We re-calculated the RVs using F0 and K5 templates, and got an amplitude consistent with our original value, within $1\sigma$ (not shown).

These analyses indicate that the orbiting body is a planet with high significance.

6. PLANETARY PARAMETERS

To determine the light curve parameters of HAT-P-9b we fitted the four available transit light curves simultaneously, as described in Shporer et al. (2008). A circular orbit was assumed. We adopted a quadratic limb-darkening law for the star, and determined the appropriate coefficients, $u_1$ and $u_2$, by interpolating on the Claret (2000, 2004) grids for the atmospheric model described above. For the Wise 0.46 m light curve, observed with no filter, we adopted the Cousins R-band limb-darkening coefficients as the CCD response resembles a “wide-R” filter (Brosch et al. 2008). The values of the limb-darkening coefficients used for each light curve are listed in Table 2.

The drop in flux in the light curves was modeled with the formalism of Mandel & Agol (2002). The five adjusted parameters in the fit were (1) the period $P$, (2) the mid-transit time of the $N_0 = 0$ transit event, $T_{C0}$, denoted simply as $T_c$, (3) the relative planetary radius, $r \equiv R_p/R_\ast$, (4) the orbital semimajor axis scaled by the stellar radius, $a/R_\ast$, and (5) the impact parameter, $b \equiv a \cos(i)/R_\ast$, where $i$ is the orbital inclination angle.

Accounting for correlated noise in the photometric data (Pont et al. 2006) was done similarly to the “time-averaging” method of Winn et al. (2008; see also Shporer et al. 2008). After a preliminary analysis we binned the residual light curves using bin sizes close to the duration of ingress and egress, which is 27 min. The presence of correlated noise in the data was quantified as the ratio between the standard deviation of the binned residual light curve and the expected standard deviation assuming pure white noise. This ratio is calculated separately for each bin size and we defined $\beta$ to be the largest ratio among the bin sizes we used. For each light curve we multiplied the relative flux errors by $\beta$ and repeated the analysis. The $\beta$ value of each light curve is listed in Table 2.

We used the Markov Chain Monte Carlo algorithm (MCMC; see, e.g., Holman et al. 2007) to derive the best-fit parameters and their uncertainties. The MCMC algorithm results in a distribution of each of the fitted parameters. We took the distribution median to be the best-fit value and the values at 84.13 and 15.87 percentiles to be the $+1\sigma$ and $-1\sigma$ confidence limits, respectively.

Our four follow-up light curves are presented in Figure 3, where the fitted model is overplotted and the residuals are also shown. The result for the radius ratio is $R_p/R_\ast = 0.1083 \pm 0.0005$, and the normalized separation is $a/R_\ast = 8.6 \pm 0.2$. From the mass of the star (Table 3), the orbital parameters (Section 4), and the light curve parameters, the physical planetary parameters (such as mass and radius) are calculated in a straightforward way, and are summarized in Table 4. We note that $a/R_\ast$, as derived from the light curve fit, is an important constraint for the stellar parameter determination (Section 3), which in turn defines the limb-darkening coefficients that are used in the light curve analytic fit. Thus, after the initial analytic fit to the light curves and the stellar parameter determination, we performed another iteration of the light curve fit. We found that the change in parameters was imperceptible.

7. DISCUSSION

We present here the discovery of a new transiting extra-solar planet, HAT – P – 9b, with a mass of $0.78 \pm 0.09 M_{Jup}$, radius of $1.40 \pm 0.06 R_{Jup}$, and orbital period of $3.92289 \pm 0.00004$ days. The $V = 12.3$ mag host star is among the faintest planet host stars identified with small-aperture, wide-field, ground-based campaigns. In fact, together with WASP-5 (Anderson et al. 2008), they are currently the faintest planet host stars discovered with such campaigns, where the transit depth is below 2%.

To show the main characteristics of the new planet relative to the currently known transiting planets, we plot in Figure 5 the position of the latter on the radius–mass diagram on the top panel, and the mass–period diagram on the bottom panel. In both panels HAT-P-9b position is marked by an open circle.

The radius–mass diagram, presented here in log–log scale, visually shows that the new planet has a low density, of $\rho_p = 0.35 \pm 0.06$ g cm$^{-3}$, similar to that of HD 209458b (e.g., Knutson et al. 2007; Mazeh et al. 2000), WASP-1b (Cameron et al. 2007; Shporer et al. 2007; Charbonneau et al. 2007), HAT-P-1b (Bakos et al. 2007; Winn et al. 2007b), and CoRoT-Eexo-1b (Barge et al. 2008).

Comparing the measured radius to the modeled radius of Burrows et al. (2007), for the same stellar luminosity, semi-major axis, and (core-less) planet mass as the HAT-P-9 system, shows that the measured value is larger than the modeled one by $1–2\sigma$. In this comparison we assumed solar opacity for the planetary atmosphere. As shown by Burrows et al. (2007), the transit radius effect together with enhanced planetary atmospheric opacities, relative to solar opacity, can be responsible for inflating the planetary radius. Since atmospheric opacities are related to the host star metallicity, and HAT-P-9 metallicity seems to be super-solar, it is likely that these two effects account for the radius difference, as is the case for WASP-1b (Burrows et al. 2007; see their Figure 7). Other mechanisms that may explain the increased radius involve downward transport and dissipation of kinetic energy (Showman & Guillot 2002), and layered convection (Chabrier & Baraffe 2007).

According to its $T_{eq}$ and Safronov number, listed in Table 4, HAT-P-9b is likely a Class II planet, as defined by Hansen & Barman (2007). This classification is in accordance with its low density, since members of this class usually have smaller masses and larger radii than those of Class I.
Follow-up light curves of HAT-P-9. The four light curves are shown at the top of the figure, with the fitted model overplotted. The label next to each light curve gives the transit event number, observatory, telescope, and filter used. Residuals are presented at the bottom of the figure, with the same top to bottom order as the actual light curves.

(A color version of this figure is available in the online journal.)

The stellar incident flux at the planet is $f_p = 1.3_{-0.3}^{+0.3} \times 10^9$ erg cm$^{-2}$ s$^{-1}$, which is at the lower end of the $f_p$ range for pM planets, according to the pL/pM planet classification of Fortney et al. (2008). Since it is positioned near the transition region in $f_p$ between these two classes of planets it may be used to further characterize them.
In the mass–period diagram the new planet is positioned near XO-1b (McCullough et al. 2006; Holman et al. 2006), OGLE-TR-182b (Pont et al. 2008), OGLE-TR-111b (Pont et al. 2004; Winn et al. 2007a), and HAT-P-6b (Noyes et al. 2008). The position of HAT-P-9b along with that of neighboring planets suggests that the mass–period relation (Mazeh et al. 2005; Gaudi et al. 2005), i.e., the decrease of planetary mass with increasing orbital period, levels off at periods \( \gtrsim 3 \) days.

The ephemeris obtained here is based on the four follow-up light curves. We compared it to the mid-transit time of the HATNet light curve, obtained some 1000 days earlier, by propagating the error on the period. The result shows a difference of about 1.5\( \sigma \) between the mid-transit times of the follow-up light curves and that of the HATNet light curve. Future follow-up light curves will be able to study more thoroughly this possible discrepancy.

Finally, we note that due to the line-of-sight stellar rotation velocity of 11.9 \( \pm \) 1.0 km s\(^{-1}\) and the non-zero impact parameter 0.52 \( \pm \) 0.03, this planet is a good candidate for the measurement of the Rossiter–McLaughlin effect (e.g., Winn et al. 2005). Equation (6) of Gaudi & Winn (2007) gives an expected amplitude for the effect of more than 100 m s\(^{-1}\), which is larger than the orbital amplitude. However, since this is a relatively faint star, with \( V = 12.3 \) mag, such a measurement will be challenging.

Figure 5. Top panel: the radius–mass diagram for the known transiting planets, in log–log scale, with HAT-P-9b marked by an open circle. Constant density lines are overplotted. The diagram visually shows that the new planet has a relatively low density. The Neptune-mass planet GJ 436b, orbiting an M star, is positioned beyond the lower-left corner of this diagram. Bottom panel: the mass–period diagram for the known transiting planets, in linear scale, with HAT-P-9b marked by an open circle. Three planets are positioned outside the boundaries of this diagram: the long-period planet HD 17156b, and the massive planets HAT-P-2b (a.k.a. HD 147506b) and XO-3b. The planet with the lowest mass in this diagram is GJ 436b, orbiting an M star, and the one with the largest mass is CoRoT-Exo-2b. This figure is based on data taken from http://www.inscience.ch/transits/ on 2008 June 1.

(A color version of this figure is available in the online journal.)
Fund (OTKA) support through grant K-60750. G.T. acknowledges partial support for this work from NASA Origins grant NNG04L89b.

REFERENCES

Anderson, D. R., et al. 2008, MNRAS, 387, L4
Bakos, G. A., Lázár, J., Papp, I., Sári, P., & Green, E. M. 2002, PASP, 114, 974
Bakos, G. A., Noyes, R. W., Kovács, G., Stanek, K. Z., Sasselov, D. D., & Domuš, I. 2004, PASP, 116, 266
Bakos, G. Á., et al. 2007, ApJ, 656, 552
Baraffe, I., Chabrier, G., & Barman, T. 2008, A&A, 482, 315
Barge, P., et al. 2008, A&A, 482, L17
Bouchy, F., & The Sophie Team 2006, in 10th Anniversary of 51 Peg-b: Status of and Prospects for Hot Jupiter studies, ed. L. Arnold, F. Bouchy, & C. Moutou (Paris: Frontier Group), 319
Brosch, N., Polishook, D., Shporer, A., Kaspi, S., Berwald, A., & Manulis, I. 2008, Ap&SS, 314, 163
Burrows, A., Budaj, J., & Hubeny, I. 2008, ApJ, 678, 1436
Burrows, A., Hubeny, I., Budaj, J., & Hubbard, W. B. 2007, ApJ, 661, 502
Burstein, D., & Heiles, C. 1982, AJ, 87, 1165
Cameron, A. C., et al. 2007, MNRAS, 375, 951
Casagrande, L., Portinari, L., & Flynn, C. 2006, MNRAS, 373, 13
Chabrier, G., & Baraffe, I. 2007, ApJ, 661, L81
Charbonneau, D., Winn, J. N., Everett, M. E., Latham, D. W., Holman, M. J., Esquerdo, G. A., & O’Donovan, F. T. 2007, ApJ, 658, 1322
Claret, A. 2000, A&A, 363, 1081
Claret, A. 2004, A&A, 428, 1001
Droge, T. F., Richmond, M. W., Sallman, M. P., & Creager, R. P. 2006, PASP, 118, 1666
Fortney, J. J. 2008, arXiv:0801.4943
Fortney, J. J., Lodders, K., Marley, M. S., & Freedman, R. S. 2008, ApJ, 678, 1419
Gaudi, B. S., Seager, S., & Mallen-Ornelas, G. 2005, ApJ, 623, 472
Gaudi, B. S., & Winn, J. N. 2007, ApJ, 655, 550
Guillot, T., Santos, N. C., Pont, F., Iro, N., Melo, C., & Ribas, I. 2006, A&A, 453, L21

Hansen, B. M. S., & Barman, T. 2007, ApJ, 671, 861
Holman, M. J., et al. 2006, ApJ, 652, 1715
Holman, M. J., et al. 2007, ApJ, 664, 1185
Knutson, H. A., Charbonneau, D., Noyes, R. W., Brown, T. M., & Gilliland, R. L. 2007, ApJ, 655, 564
Kovács, G., Bakos, G. Á., & Noyes, R. W. 2005, MNRAS, 356, 557
Kovács, G., Zucker, S., & Mazeh, T. 2002, A&A, 391, 369
Latham, D. W. 1992, in ASP Conf. Ser. 32: IAU Colloq. 135: Complementary Approaches to Double and Multiple Star Research (San Francisco, CA: ASP), 110
Mandel, K., & Agol, E. 2002, ApJ, 580, L171
Mazeh, T., Zucker, S., & Pont, F. 2005, MNRAS, 356, 955
Mazeh, T., et al. 2000, ApJ, 532, L55
McCullough, P. R., et al. 2006, ApJ, 648, 1228
Noyes, R. W., et al. 2008, ApJ, 673, L79
Páli, A., & Bakos, G. Á. 2006, PASP, 118, 1474
Pont, F., Bouchy, F., Queloz, D., Santos, N. C., Melo, C., Mayor, M., & Udry, S. 2004, A&A, 426, L15
Pont, F., Zucker, S., & Queloz, D. 2006, MNRAS, 373, 231
Pont, F., et al. 2008, A&A, 487, 749
Queloz, D., et al. 2001, A&A, 379, 279
Ramírez, I., & Meléndez, J. 2005, ApJ, 626, 465
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Showman, A. P., & Guillot, T. 2002, A&A, 385, 166
Shporer, A., Mazeh, T., Winn, J. N., Holman, M. J., Latham, D. W., Pont, F., & Esquerdo, G. A. 2008, ApJ, submitted (arXiv:0805.3915)
Shporer, A., Tamuz, O., Zucker, S., & Mazeh, T. 2007, MNRAS, 376, 1296
Southworth, J., Wheatley, P. J., & Sams, G. 2007, MNRAS, 379, L11
Sozzetti, A., et al. 2007, ApJ, 664, 1190
Torres, G., Konacki, M., Sasselov, D. D., & Jha, S. 2005, ApJ, 619, 558
Torres, G., Neuhauser, R., & Guenther, E. W. 2002, AJ, 123, 1701
Torres, G., Winn, J. N., & Holman, M. J. 2008, ApJ, 677, 1324
Winn, J. N., Holman, M. J., & Fuentes, C. I. 2007a, AJ, 133, 11
Winn, J. N., et al. 2007b, AJ, 134, 1707
Winn, J. N., et al. 2005, ApJ, 631, 1215
Winn, J. N., et al. 2008, ApJ, 683, 1076
Yi, S. K., et al. 2001, ApJS, 136, 417