THE SUB-SATURN MASS TRANSITING PLANET HAT-P-12b

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ABSTRACT

We present new photometric data of the transiting planet HAT-P-12b observed in 2011. Our three transit curves are modeled using the JKTEBOP code and adopting the quadratic limb-darkening law. Including our measurements, 18 transit times spanning about 4.2 yr were used to determine the improved ephemeris with a transit epoch of 2,454,187.85506 ± 0.00011 BJD and an orbital period of 3.2130596 ± 0.0000035 days. The physical properties of the star–planet system are computed using empirical calibrations from eclipsing binary stars and stellar evolutionary models, combined with both our transit parameters and previously known spectroscopic results. We found that the absolute dimensions of the host star are $M_A = 0.73 ± 0.02 M_\odot$, $R_A = 0.70 ± 0.01 R_\odot$, log $g_A = 4.61 ± 0.02$, $\rho_A = 2.10 ± 0.09 \rho_\odot$, and $L_A = 0.21 ± 0.01 L_\odot$. The planetary companion has $M_b = 0.21 ± 0.01 M_{\text{Jup}}$, $R_b = 0.94 ± 0.01 R_{\text{Jup}}$, log $g_b = 2.77 ± 0.02$, $\rho_b = 0.24 ± 0.01 \rho_{\text{Jup}}$, and $T_{eq} = 960 ± 14$ K. Our results agree well with standard models of irradiated gas giants with a core mass of $11.3 M_\odot$.

Key words: planetary systems – stars: individual (HAT-P-12) – techniques: photometric

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

Transiting exoplanets are interesting objects to study because the coupling of radial velocity and photometric measurements allows a determination of stellar and planetary parameters and thus gives us an important constraint on fundamental models of planet formation and evolution. For that purpose, we need to precisely measure the physical properties of both the stars and planets in these systems from a detailed analysis of transit curves obtained with high-precision photometry. Basically, it is possible to regard the star–planet systems as detached eclipsing binaries with extremely low-mass ratios ($<0.001$). Therefore, the methods and tools that are used to model the binary stars could be applied to analyze the light curves of transiting exoplanets and then to determine their physical parameters (Southworth 2008, 2009; Lee et al. 2011).

The transiting nature of HAT-P-12b was detected with the HAT-5 telescope of the Hungarian-made Automated Telescope Network (Bakos et al. 2004) in 2006. Hartman et al. (2009) conducted follow-up photometry of four transits together with spectroscopic observations and reported that the transit features come from a Saturn mass planet with a mass of 0.21 ± 0.01 $M_{\text{Jup}}$ and a radius of 0.94 ± 0.01 $R_{\text{Jup}}$ in a 3.2 day circular orbit. Its host star is a K4 dwarf GSC 3033-706 (2MASS J13573347+4329367; $V = +12.84$) with $M_A = 0.73 ± 0.02 M_\odot$, $R_A = 0.70 ± 0.01 R_\odot$, and [Fe/H] = −0.29 ± 0.05. Since HAT-P-12b is one of the lowest-density planets orbiting metal-poor host stars, the physical properties of the system are important for irradiation models. In this work, we report and analyze three new high-precision transits of HAT-P-12 and refine the physical parameters of the transiting planetary system.

2. NEW OBSERVATIONS

We obtained new photometric data from observing three transits of HAT-P-12b. Observations were carried out between 2011 March and May, using an ARC 4K CCD camera and a Cousins R filter attached to the 1.0 m reflector at the Mt. Lemmon Optical Astronomy Observatory (LOAO) in Arizona, USA. The telescope was significantly defocused, because it is expected to minimize random and flat-fielding errors (see, e.g., Southworth et al. 2009). The e2v CCD chip has 4096 × 4096 pixels and a pixel size of 15.28 arcmin$^2$ at the f/7.5 Cassegrain focus of the telescope. A summary of the observations is given in Table 1, where we present observing interval, filter, binning mode, exposure time, numbers of observed points, and weather condition. During the first run, a gap before the transit ingress was caused by technical problems. With the customary IRAF package, we processed the CCD frames to correct for bias level, dark noise, and pixel-to-pixel inhomogeneities of quantum efficiency (flat-field correction). We applied simple aperture photometry to obtain instrumental magnitudes.

For each transit event, we constructed an artificial comparison star by monitoring field stars imaged on the chip. Following the method described in Lee et al. (2011), we selected and followed field stars from a set of artificial reference stars. Then, the differential magnitudes from the artificial reference were normalized by fitting a linear function to the out-of-transit data to remove time-varying atmospheric effects (detrending). Resultant transit curves are plotted in Figure 1 and listed in Table 2, where times are Barycentric Julian Dates (BJD) in the Barycentric Dynamical Time (TDB) system (Eastman et al. 2010).

3. LIGHT CURVE ANALYSIS AND TRANSIT TIMES

To determine the planetary and orbital parameters, three LOAO transits of HAT-P-12 were analyzed simultaneously in a manner almost identical to that for the transiting planetary system TrES-3 (Lee et al. 2011) using the JKTEBOP code (Southworth et al. 2004a, 2004b), which is a code for modeling the light curves of detached eclipsing binary stars using biaxial spheroids. The main parameters of the model are the orbital period ($P$), the ephemeris epoch ($T_0$), the fractional radii of the star ($r_A = R_A/a$, where $a$ is the orbital semimajor axis).
and planet ($r_b = R_b/a$), the orbital inclination ($i$), and the limb-darkening coefficients (LDCs). Actually, $r_A$ and $r_b$ are incorporated as their sum ($r_A + r_b$) and ratio ($k = r_b/r_A$). Throughout this paper, we refer to the star and planet with the subscripts “A” and “b,” respectively.

In the transit analysis, we used $r_A + r_b$ and $k$ as the fitting parameters, because these parameters are more weakly correlated than $r_A$ and $r_b$ (Southworth 2008). Initial quadratic LDCs were taken from the tables of Claret (2000), using the atmospheric parameters of $T_A = 4650 \pm 60$ K, $\log g_A = 4.61 \pm 0.01$, and $[\text{Fe/H}] = -0.29 \pm 0.05$ (Hartman et al. 2009). Final results are obtained from fitting the linear LDC ($u_A$) but fixing the nonlinear LDC ($v_A$), because the two LDCs suffer from strong correlations between them (Southworth 2008; Johnson et al. 2008). These are summarized in Table 3, together with the stellar density ($\rho_A$) and the planetary surface gravity ($g_b$) and zero-albedo equilibrium temperature defined as $T_{\text{eq}} = T_A \sqrt{R_A / R}$ (Southworth 2010). The lower three values were directly calculated from those transit parameters and the stellar velocity amplitude ($K_A = 35.8 \pm 1.9 \text{ m s}^{-1}$) of Hartman et al. (2009). In order to assess the uncertainties of the fitted parameters, we ran 10,000 Monte Carlo simulations and a residual permutation algorithm (Jenkins et al. 2002) implemented into JKTEBOP, respectively. On these occasions, the nonlinear LDC was perturbed by $\pm 0.1$ around the fixed value. The error estimates presented in Table 3 are the 1σ values adopted from the larger of the two results. Figure 2 displays the light curves with our best-fitting model and residuals.

Table 1: Observing Log of HAT-P-12

| Transit | UT Date | Observing Interval (BJD+2,455,000) | Filter | Binning Mode | Exposure Time (s) | $N_{\text{obs}}$ | Weather Condition |
|---------|---------|-----------------------------------|--------|--------------|-------------------|-----------------|-------------------|
| 1       | 2011 Mar 29 | 649.67–649.95 | RC | 2 × 2 | 50–70 | 224 | Clear |
| 2       | 2011 Apr 14 | 665.74–665.97 | RC | 2 × 2 | 50–70 | 273 | Partly cloudy |
| 3       | 2011 May 13 | 694.65–694.93 | RC | 2 × 2 | 40–60 | 314 | Clear |

Table 2: $R_C$-band Photometry of HAT-P-12

| BJD     | Diff. Mag | $\sigma_{\text{mag}}$ | Relative Flux |
|---------|-----------|------------------------|---------------|
| 2455649.67120 | +0.0005 | 0.0021 | 0.9995 |
| 2455649.67207 | -0.0043 | 0.0021 | 1.0039 |
| 2455649.67293 | -0.0004 | 0.0021 | 1.0003 |
| 2455649.67380 | +0.0009 | 0.0021 | 0.9991 |
| 2455649.67467 | +0.0019 | 0.0021 | 0.9982 |
| 2455649.67554 | +0.0011 | 0.0021 | 0.9990 |
| 2455649.67641 | +0.0011 | 0.0021 | 0.9990 |
| 2455649.67729 | -0.0038 | 0.0021 | 1.0035 |
| 2455649.67815 | -0.0001 | 0.0021 | 1.0001 |
| 2455649.67902 | +0.0001 | 0.0021 | 0.9999 |

Notes.

a BJD 2,455,000 is suppressed.
b rms scatter of residuals.

Table 3: Transit Parameters of HAT-P-12

| Parameter | Value |
|-----------|-------|
| $r_A + r_b$ | 0.0969 ± 0.0012 |
| $k (=r_b/r_A)$ | 0.1370 ± 0.0019 |
| $i$ (deg) | 89.915 ± 0.098 |
| $u_A$ | 0.739 ± 0.069 |
| $v_A$ | 0.177 perturbed |
| $T_0$ (BJD) | 649.79751 ± 0.00036 |
| $P$ (days) | 3.213089 ± 0.000037 |
| $r_A$ | 0.0852 ± 0.0012 |
| $r_b$ | 0.01168 ± 0.00005 |
| $\sigma$ (mmag) | 2.1269 |
| $K_{\text{rad}}$ | 0.9920 |
| $\rho_A$ ($\rho_{\odot}$) | 2.100 ± 0.089 |
| $g_b$ ($g_{\text{eq}}$) | 0.257 ± 0.014 |
| $T_{\text{eq}}$ (K) | 960 ± 14 |

Figure 1. Transit light curves of HAT-P-12 observed between 2011 March and May.
Figure 2. Phased light curves of HAT-P-12. The continuous curves represent the solutions obtained with the best-fit parameters listed in Table 3. The residuals from the fit are offset from zero and plotted at the bottom in the same order as the transit curves.

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

**Table 4**

| BJD           | Uncertainty | $E$ | $O - C_{tr}$ | References$^a$ |
|---------------|-------------|-----|--------------|----------------|
| (2,450,000+)  | ±0.00020    | 0   | 0.00095      | Hartman et al. (2009) |
| 4,187.85655$^b$ | ±0.00014    | 9   | −0.00049     | Hartman et al. (2009) |
| 4,216.77265$^b$ | ±0.00017    | 212 | −0.00027     | Hartman et al. (2009) |
| 4,897.94225$^b$ | ±0.00024    | 221 | 0.00048      | Hartman et al. (2009) |
| 4,952.56398    | ±0.00080    | 238 | 0.00019      | Gregorio (AXA) |
| 4,965.41639    | ±0.00046    | 242 | 0.00036      | Kucakova (TRESCA) |
| 4,965.41748    | ±0.00090    | 242 | 0.00145      | Ayoimanitis (AXA) |
| 4,984.69368    | ±0.00060    | 248 | −0.00070     | Gary (AXA) |
| 5,312.42673    | ±0.00032    | 350 | 0.00027      | Vilagi & Gajdos (TRESCA) |
| 5,630.51896    | ±0.00049    | 449 | −0.00040     | Ivanov & Sokov (TRESCA) |
| 5,646.58477    | ±0.00059    | 454 | 0.00011      | Nicolas (TRESCA) |
| 5,646.58486    | ±0.00040    | 454 | 0.00020      | Gajdos & Vilagi (TRESCA) |
| 5,649.79769    | ±0.00020    | 455 | −0.00003     | Salas (TRESCA) |
| 5,659.43563    | ±0.00038    | 458 | −0.00127     | Ruiz (TRESCA) |
| 5,665.86234    | ±0.00031    | 460 | −0.00068     | This paper (LOAO) |
| 5,675.49947    | ±0.00064    | 463 | −0.00273     | Zinoviev & Sokov (TRESCA) |
| 5,694.78089    | ±0.00024    | 469 | 0.00033      | This paper (LOAO) |
| 5,704.42185    | ±0.00038    | 472 | 0.00211      | Salas (TRESCA) |

Notes.

$^a$ AXA (Amateur eXoplanet Archive), TRESCA (TRansiting ExoplanetS and Candidates).

$^b$ Newly determined by us from the individual measurements.

4. RESULTS AND DISCUSSION

We can compute the absolute dimensions of transiting planetary systems by combining photometric and spectroscopic results. Currently, there are two main methods of obtaining stellar and planetary parameters from the observed quantities. The first method is to use the empirical relations from eclipsing binary stars and the second is to apply the isochrones from stellar evolutionary models. For this procedure, we used the planet velocity amplitude $K_0$ as a key parameter governing the solution process to find the best match between the observations and predictions, which is the same approach as in Southworth (2009) and Lee et al. (2011).

First of all, we calculated the physical properties of the HAT-P-12 system using the new calibrations of stellar masses and radii expressed as $T_A$, $\log m_A$, and $[\text{Fe/H}]$ (Enoch et al. 2010, hereafter ECPH), which are originally defined by Torres et al. (2010) from 95 well-studied eclipsing binaries and replaced $\log R_A$ with $\log m_A$. The process is to look for $K_0$ satisfying simultaneously the stellar mass and radius from the two relations. The calibrated mass and radius of $M_{A,\text{ECPH}} = 0.765 \pm 0.012 M_\odot$ and $R_{A,\text{ECPH}} = 0.686 \pm 0.012 R_\odot$ were used
to minimize the $\chi^2$ expressed as

$$\chi^2 = \left[ \frac{M_{A,\text{ECPH}} - M_{A,\text{pred}}}{\sigma_{M_{A,\text{ECPH}}}} \right]^2 + \left[ \frac{R_{A,\text{ECPH}} - R_{A,\text{pred}}}{\sigma_{R_{A,\text{ECPH}}}} \right]^2,$$

where $M_{A,\text{pred}}$ and $R_{A,\text{pred}}$ are the relation-predicted mass and radius from the observations and the $K_s$ values. The results are given in the second column of Table 5. The quantity $\Theta$ denotes the Safronov (1972) number.

By considering both the metallicities allowed by the observational errors in $[\text{Fe}/\text{H}]$ and the ages for each metallicity, we use three different sets of the stellar evolutionary models: Yongse–Yale (Demarque et al. 2004), Padova (Girardi et al. 2000), and Baraffe et al. (1998), hereafter BCAH. This method also aims to find the velocity amplitude $K_s$ for which the measured values $[\text{Fe}/\text{H}]$, $r_A$, and $T_A$ are best fitted to the radius $R_{A,\text{pred}}$ and temperature $T_{A,\text{pred}}$ predicted from the model isochrones for each metallicity. This consists of calculating the $\chi^2$ fitting statistic,

$$\chi^2 = \left[ \frac{[\text{Fe}/\text{H}] - [\text{Fe}/\text{H}]_{\text{model}}}{\sigma_{[\text{Fe}/\text{H}]}} \right]^2 + \left[ \frac{r_A - (R_{A,\text{pred}}/a)}{\sigma_{r_A}} \right]^2 + \left[ \frac{T_A - T_{A,\text{pred}}}{\sigma_{T_A}} \right]^2,$$

where $\sigma_{[\text{Fe}/\text{H}]}, \sigma_{r_A}$, and $\sigma_{T_A}$ are the uncertainties corresponding to the measurements. Our process obtained a best-fit model when the BCAH isochrones with $[\text{Fe}/\text{H}] = -0.25$ were used; both the Yongse–Yale and Padova isochrones cannot constrain the age of the planetary system and favor the metal-rich stellar models.

The isochrones from the BCAH models are plotted in Figure 4 along with the position of HAT-P-12A and the results are listed in the third column of Table 5. The mass and radius from BCAH are somewhat smaller than those derived from the empirical calibration of eclipsing binary stars, although the physical parameters between the two methods agree with each other within their uncertainties. Similar situations are found for WASP-21 (Bouchy et al. 2010; Barros et al. 2011), WASP-37 (Simpson et al. 2011), and WASP-39 (Faedi et al. 2011). As is the case for HAT-P-12, the three planet host stars are metal-poor with metallicities $[\text{Fe}/\text{H}]$ of $-0.46 \pm 0.11$, $-0.40 \pm 0.12$, and $-0.12 \pm 0.10$, respectively. On the other hand, 11 eclipsing binaries sampled by Torres et al. (2010) are low-metallicity systems ($[\text{Fe}/\text{H}] < 0.0$). Among these only one component star (V636 CenB) is smaller than $1 M_{\odot}$. From this it follows that the physical properties from the BCAH model for metal-poor low-mass stars seem to be more reliable than those from the empirical calibrations. We chose the BCAH solutions as our final results of HAT-P-12.

The location of HAT-P-12b in the mass–radius diagram is shown in Figure 5, together with 10 known Saturn mass transiting exoplanets with masses in the range $0.15 M_{\text{Saturn}} < M < 0.4 M_{\text{Saturn}}$, wherein Kepler-16b is a circumbinary transiting planet on a nearly circular 229 day orbit around its two parent stars (Doyle et al. 2011). In the same figure, we show constant density contours for 0.1, 0.25, 0.5, and 1.0 $\rho_{\text{Saturn}}$. The physical properties obtained in this study indicate that HAT-P-12b is a low-density sub-Saturn mass planet with a mass of $0.21 M_{\text{Saturn}}$, a radius of $0.94 R_{\text{Saturn}}$, and a mean density of $0.24 \rho_{\text{Saturn}}$. The results are most similar to those $(M_b = 0.20 M_{\text{Saturn}}, R_b = 1.00 R_{\text{Saturn}}, \rho_b = 0.19 \rho_{\text{Saturn}})$ of the transiting exoplanet HAT-P-18b (Hartman et al. 2011). However, HAT-P-12 is younger and more metal-poor than HAT-P-18 with an age of 12.4 Gyr and a metallicity of $[\text{Fe}/\text{H}] = +0.10$. Furthermore, a classification of transiting close-in planets has recently been suggested by Hansen & Barman (2007). The derived equilibrium temperature of $T_{\text{eq}} = 960 K$ and Safronov number of 0.023 would classify HAT-P-12b to be of class II. However, it was recently shown by Southworth (2010) that a correlation between $T_{\text{eq}}$ and $\Theta$ appears to have little statistical significance. Therefore, this classification seems to be of little importance. In addition, future observations of secondary transits (or occultations) of HAT-P-12b might prove to be difficult due to the planet’s low equilibrium temperature.

We compared our mass and radius to the predicted values from theoretical models of Fortney et al. (2007) with various core masses. For these, their models were interpolated to the age of 3.2 Gyr and the solar equivalent semimajor axis of $0.0843 \pm 0.0029$ AU calculated from $a = \sqrt{T_A}$ and were plotted in Figure 5 as solid curves. We conclude that HAT-P-12b is a H/He-dominated gas giant planet with a core mass of $11.3^{+2.6}_{-1.0} M_{\oplus}$ and is moderately irradiated by its low-metallicity host star. Of the 10 circumsolar transiting planets, 8 exoplanets including HAT-P-12b follow a suggestive correlation between the inferred core mass and host star’s metallicity (Guillot et al. 2006; Burrows et al. 2007), while the recently discovered planets HAT-P-18b and HAT-P-19b (Hartman et al. 2011) with

| Parameter | ECPH Model | BCAH Model |
|-----------|------------|------------|
| $K_s$ (km s$^{-1}$) | 131.5 ± 3.0 | 129.7 ± 1.5 |
| $M_A$ ($M_{\odot}$) | 0.757 ± 0.038 | 0.727 ± 0.019 |
| $R_A$ ($R_{\odot}$) | 0.711 ± 0.019 | 0.702 ± 0.013 |
| log $A$ (mag) | 4.613 ± 0.032 | 4.607 ± 0.020 |
| $L_A$ ($L_{\odot}$) | 0.212 ± 0.016 | 0.206 ± 0.013 |
| $M\text{S,
A (mag)}$ | 6.434 ± 0.080 | 6.463 ± 0.069 |
| $M_B$ ($M_{\text{Jup}}$) | 0.216 ± 0.015 | 0.210 ± 0.012 |
| $R_B$ ($R_{\text{Jup}}$) | 0.949 ± 0.022 | 0.936 ± 0.012 |
| $\rho_B$ ($\rho_{\text{Jup}}$) | 0.236 ± 0.016 | 0.240 ± 0.012 |
| $a$ (AU) | 0.03887 ± 0.00088 | 0.03829 ± 0.00046 |
| Age (Gyr) | 3.2 ± 3.8 |

Figure 4. Isochrones from the BCAH models for log ages = 8.0 (bottom), 8.3, 8.7, 9.0, 9.3, 9.5, 9.6, 9.7, 9.8, and 9.9 yr (top). The observed values of $\chi^2$ and $a/R_b$ for HAT-P-12A are shown together with their error bars. (A color version of this figure is available in the online journal.)
negligible core masses but super-solar metalicities disagree with the prediction. Further discoveries will help to identify and understand the possible correlation between planetary parameters such as metallicity, core mass, radius, and equilibrium temperature.

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