A Possible Tilted Orbit of the Super-Neptune HAT-P-11b*

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Abstract

We report the detection of the Rossiter-McLaughlin effect for the eccentric, super-Neptune exoplanet HAT-P-11b, based on radial velocity measurements taken with HDS, mounted on the Subaru 8.2m telescope, and simultaneous photometry with the FTN 2.0m telescope, both located in Hawai‘i. The observed radial velocities during a planetary transit of HAT-P-11b show a persistent blue-shift, suggesting a spin-orbit misalignment in the system. The best-fit value for the projected spin-orbit misalignment angle is \( \lambda = 103^{\circ} \pm 23^{\circ} \). Our result supports the notion that eccentric exoplanetary systems are likely to have significant spin-orbit misalignment (e.g., HD 80606, WASP-8, WASP-14, WASP-17, and XO-3). This fact suggests that not only hot-Jupiters but also super-Neptunes like HAT-P-11b had once experienced dynamical processes such as planet-planet scattering or the Kozai migration.

Key words: stars: planetary systems: individual (HAT-P-11) — stars: rotation — techniques: radial velocities — techniques: spectroscopic — techniques: photometric

1. Introduction

Transiting exoplanetary systems provide us a unique probe to investigate the dynamical history of planetary systems discovered today. The Rossiter-McLaughlin effect (hereafter, the RM effect), which was originally discussed for stellar eclipsing binaries (Rossiter 1924; McLaughlin 1924), is an apparent radial velocity (hereafter, RV) anomaly during a planetary transit caused by a partial occultation of the rotating stellar surface (e.g., Queloz et al. 2000; Winn et al. 2005; Ohta et al. 2005; Gaudi & Winn 2007). Through the RM effect, one can estimate the angle between the stellar rotation axis and the planetary orbital axis projected onto the sky plane. This angle, which we denote by \( \lambda \), is strongly related to formation and migration history of close-in exoplanets.

The standard formation theory of close-in gas-giants (hot-Jupiters) suggests they formed outside the so called “snow-line”, which is usually located at a few AU away from the host star, and then migrated inward due to some migration process (e.g., Lin et al. 1996; Chambers 2009; Lubow & Ida 2010). While migration processes such as disk-planet interactions (type I or II migration) predict relatively small values of \( \lambda \), dynamical processes including planet-planet scattering and Kozai cycles might produce a large value of \( \lambda \) (e.g., Wu et al. 2007; Fabrycky & Tremaine 2007; Nagasawa et al. 2008; Chatterjee et al. 2008). The observed distribution of \( \lambda \) and its host star dependence would help reveal the dynamical history of exoplanetary systems.

To this point, the RM effect has been measured for approximately 30 transiting hot-Jupiters (see Table 1 of Winn et al. 2010). The observational results indicate that the spin-orbit axes in some of the systems are well-aligned (at least on the sky), but others show significant misalignment. Eccentric exoplanetary systems, where \( e > 0.1 \), and systems whose central stars are massive (\( M_\star \geq 1.2M_\odot \)) are more likely to show strong misalignment (Winn et al. 2010). Specifically, out of the thirteen eccentric transiting systems (CoRoT-9, CoRoT-10, GJ 436, HAT-P-2, HAT-P-11, HAT-P-14, HAT-P-15, HD 17156, HD 80606, WASP-8, WASP-14, WASP-17, and XO-3), the RM effect has been observed for seven systems (HAT-P-2, HD 17156, HD 80606, WASP-8, WASP-14, WASP-17, and XO-3). Among them, five systems have been reported to have significant spin-orbit misalignment (HD 80606, WASP-8, WASP-14, WASP-17, and XO-3) based on measurements of the RM effect (Hébrard et al. 2008; Winn et al. 2009b; Queloz et al. 2010; Winn et al. 2009a; Triaud et al. 2010). In addition, Schlaufman (2010) reported the possibility of spin-orbit “misalignment along the line-of-sight” in other eccentric systems (e.g., HD 17156 and HAT-P-14) based on an analysis of stellar rotational pe-
periods (note that the sky-projected spin-orbit alignment angle for HD 17156 has been reported as $\lambda = 10.0^\circ \pm 5.1^\circ$ by Narita et al. 2009a).

In this paper, we focus on the RM effect of the super-Neptune HAT-P-11b. So far, the RM effect has been observed only for hot-Jupiters. In order to obtain a clearer insight into planetary migration processes, we need to measure the RM effect for a wider range of planetary and stellar parameters. The transiting super-Neptune exoplanet HAT-P-11b (Bakos et al. 2010) was detected by the HATNet transit survey (Bakos et al. 2004) and confirmed by subsequent RV measurements at Keck with HIRES. HAT-P-11b orbits a bright K dwarf star ($V \sim 9.6$ mag) with an orbital period of $\sim 4.9$ days. Its planetary radius, $R_p = 0.422 \pm 0.014 R_J$, is one of the smallest among the known transiting exoplanets. Although HAT-P-11b is a difficult target for an RM measurement due to its small size, the significant eccentricity ($e = 0.198 \pm 0.046$) makes it very interesting for attempting the challenging observation. The detection of the RM effect for Neptune-sized planets is of great importance for making further progress in studying migration histories.

The rest of the present paper is organized as follows. In Section 2 we report on new spectroscopic and photometric observations of the HAT-P-11 system using the High Dispersion Spectrograph (HDS) installed on the 8.2m Subaru Telescope, and the LCOGT 2.0m Faulkes Telescope North (FTN). The new observations include simultaneous transit spectroscopy and photometry of HAT-P-11b on UT 2010 May 27 as well as several out-transit RV datasets to determine the orbital (Keplerian) motion of HAT-P-11. Data analysis is presented in Section 3. We combine the new photometric and RV dataset with the published RV data by Bakos et al. (2010) and simultaneously determine the orbital and RM parameters in Section 4. We report that the RV anomaly during the transit shows a possible spin-orbit misalignment in the known transiting exoplanets. Although HAT-P-11b is a difficult target for an RM measurement due to its small size, the significant eccentricity ($e = 0.198 \pm 0.046$) makes it very interesting for attempting the challenging observation. The detection of the RM effect for Neptune-sized planets is of great importance for making further progress in studying migration histories.

2. Observations

2.1. Subaru Spectroscopy

We conducted spectroscopic observations of HAT-P-11 with Subaru/HDS on UT 2010 May 21, 27, and July 1. We employed the Std-12b setup on May 21 and 27, and the Std-12a setup on July 1. Due to the bad seeing during the May observations, we needed to broaden the slit width, which we set to 0.8", yielding a spectral resolution of $R \sim 45000$. We set it to 0.4" for the July observation, corresponding to $R \sim 90000$. We observed the target with the iodine cell for a precise wavelength calibration. Adopting exposure times of 360-420 seconds, we obtained a typical signal-to-noise ratio (S/N) of 150-200.

We reduced the raw data with the standard IRAF procedure, and extracted one-dimensional spectra. We then input the spectra into the RV analysis routine. The RV analysis for Subaru/HDS is described in detail by Sato et al. (2002) and Narita et al. (2007). Specifically, in order to obtain the stellar template spectrum, we adopted the method developed by Butler et al. (1996), which uses a high S/N, high resolution observed spectrum of the host star without the Iodine cell. We took that stellar template spectrum during the July 1 observation, and deconvolve it with the instrumental profiles, which were estimated by the rapid rotator plus $I_2$ spectrum. The output relative RVs are summarized in Table 1. The reported errors based on the RV analysis do not include stellar "jitter", which have been reported to be significant for HAT-P-11. The measured RVs as well as the published Keck data by Bakos et al. (2010) are plotted in Figure 1.

Table 1. Radial velocities measured with Subaru/HDS.

| Time [BJD (TDB)] | Relative RV [m s$^{-1}$] | Error [m s$^{-1}$] |
|------------------|--------------------------|-------------------|
| 2455338.06263    | 21.81                    | 3.50              |
| 2455338.06814    | 25.54                    | 3.17              |
| 2455343.88425    | 2.48                     | 2.61              |
| 2455343.89527    | 4.69                     | 2.27              |
| 2455343.90078    | -0.64                    | 2.53              |
| 2455343.90629    | 8.59                     | 2.73              |
| 2455343.91180    | -1.56                    | 2.52              |
| 2455343.91731    | -3.65                    | 2.24              |
| 2455343.92282    | 3.52                     | 2.46              |
| 2455343.92833    | -1.20                    | 2.45              |
| 2455343.93384    | -4.11                    | 2.20              |
| 2455343.93935    | -0.79                    | 2.55              |
| 2455343.94487    | -2.32                    | 2.27              |
| 2455343.95038    | -2.89                    | 2.29              |
| 2455343.95590    | -0.98                    | 2.50              |
| 2455343.96142    | -0.79                    | 2.48              |
| 2455343.96694    | -1.78                    | 2.60              |
| 2455343.97245    | 0.94                     | 2.67              |
| 2455343.97797    | 1.69                     | 2.29              |
| 2455343.98349    | 1.83                     | 2.58              |
| 2455343.98901    | 1.82                     | 2.48              |
| 2455343.99453    | -2.05                    | 2.43              |
| 2455344.00004    | 4.62                     | 2.02              |
| 2455344.00556    | 0.70                     | 2.80              |
| 2455344.01108    | -4.27                    | 2.72              |
| 2455344.01659    | -4.03                    | 2.62              |
| 2455344.02211    | -5.10                    | 2.32              |
| 2455344.02762    | 0.28                     | 2.76              |
| 2455378.96572    | -11.69                   | 3.45              |
| 2455378.97054    | -8.31                    | 3.74              |
| 2455378.97553    | -8.92                    | 3.75              |
| 2455378.98035    | -3.12                    | 3.54              |
| 2455378.98517    | -4.25                    | 3.76              |
| 2455379.09717    | -5.42                    | 3.77              |
| 2455379.10198    | -4.86                    | 3.62              |
| 2455379.10683    | -4.84                    | 3.73              |
| 2455379.11165    | 2.36                     | 4.05              |
| 2455379.11648    | -6.53                    | 3.29              |
| 2455379.12133    | -5.33                    | 3.93              |
| 2455379.12615    | 1.63                     | 3.55              |
2.2. Simultaneous FTN Photometry

In order to derive an accurate estimate of the start and end times of the transit, we obtained a photometric light curve of the same transit event on UT 2010 May 27. We observed with FTN and the Spectral Instruments camera with the Pan-STARRS-Z filter. The camera has a back-illuminated Fairchild Imaging CCD and we used the default $2 \times 2$ pixel binning mode, with an effective pixel scale of 0.304 arcsec pixel$^{-1}$. The telescope was defocused and the 10.5 x 10.5 arcmin field of view (FOV) was positioned so the guiding camera FOV will contain a suitable guide star. We used an exposure time of 10 seconds and the median cycle time was 30.6 seconds. FTN observations started at UT 2010 May 27 09:08 and ended at UT 2010 May 27 13:09, an overall duration of 4.0 hours. Photometry was done with aperture photometry and the light curve was calibrated using several non-variable stars in the field. Observing conditions have deteriorated at FTN during the HAT-P-11 transit observation, and only a small amount of sufficient quality exposures were obtained during egress. The dome had to be closed soon after the transit ended. The resultant photometric light curve is shown in Figure 2 (panel b).

3. Analysis

In order to estimate the positions of the planet on the stellar surface based on the observed RM velocity anomaly during the transit, one must know the relation between them. Following the procedure described by Winn et al. (2005) and Hirano et al. (2010), we performed a mock data simulation, by changing the relative decrease in flux $f$ (which is the flux ratio of the occulted portion on the stellar surface to the disk-integrated flux) and the velocity component $v_p$ (which is a line-of-sight component of the rotational velocity of the occulted stellar portion), we generated many simulated spectra during a transit, and put them into the RV analysis procedure as we did for the observed spectra. After fitting the output velocity anomaly $\Delta v$ with input parameters $f$ and $v_p$ we derived the following empirical relation:

$$\Delta v = -f v_p \left[ 1.16 - 0.205 \left( \frac{v_p}{v \sin i_s} \right)^2 \right], \quad (1)$$

where $v \sin i_s$ is the projected stellar rotational velocity of HAT-P-11, which we set here as $v \sin i_s = 1.5 \text{ km s}^{-1}$ (Bakos et al. 2010).

Bakos et al. (2010) reported that the HAT-P-11 system shows a long-term RV drift over one-year of observations of the system. Since our new observations span only about one month we could not determine the long-term RV drift from our new Subaru dataset alone. Instead, we assumed the RV drift as $\dot{\gamma} = 0.029 \pm 0.0050 \text{ m s}^{-1} \text{ day}^{-1}$, as reported by Bakos et al. (2010).

Our single transit light curve could not refine the light curve parameters determined by Bakos et al. (2010), based on several transit light curves. We thus adopt the system parameters of Bakos et al. (2010) for the semi-major axis scaled by the stellar radius, $a/R_s = 15.58^{+0.17}_{-0.82}$, the radii ratio, $R_p/R_s = 0.0576 \pm 0.0009$, the orbital period, $P = 4.8878162 \pm 0.0000071$ days, and the orbital inclination, $i_o = 88.5^\circ \pm 0.6^\circ$. We fix each parameter above at the central value and use the light curve model by Ohta et al. (2009). Assuming a quadratic limb-darkening law, we fix the limb-darkening coefficients for the transit light curve as $u_1 = 0.35$ and $u_2 = 0.26$ (Claret 2004). The remaining free parameters are as follows: the midtransit time $T_C$ determined by the simultaneous photometry, the RV semi-amplitude $K$, the orbital eccentricity $e$, the argument of periastron $\omega$, the spin-orbit misalignment angle $\lambda$, the projected stellar rotational velocity $v \sin i_s$, and the RV offset between the Subaru and Keck datasets. The $\chi^2$ statistic in this case is expressed as

$$\chi^2 = \sum_i \left[ \frac{v_i^{(1)}_{\text{obs}} - v_i^{(1)}_{\text{model}}}{\sigma_i^{(1)}} \right]^2 \sum_j \left[ \frac{v_j^{(2)}_{\text{obs}} - v_j^{(2)}_{\text{model}}}{\sigma_j^{(2)}} \right]^2 ,$$

where $v_i^{(1)}_{\text{obs}}$ and $v_i^{(1)}_{\text{model}}$ are the RV values, and $v_j^{(2)}_{\text{obs}}$ and $v_j^{(2)}_{\text{model}}$ are the relative flux values, obtained by the observations and model calculations, respectively. The RV and flux errors are represented by $\sigma_i^{(1)}$ and $\sigma_j^{(2)}$, respectively. Note that we adopt a “stellar jitter” of $\sigma_{\text{jitter}} = 4.1 \text{ m s}^{-1}$ so that the resultant reduced $\chi^2$ for the observed RVs becomes unity, and compute modified RV errors $\sigma_i^{(1)}$ by

$$\sigma_i^{(1)} = \sqrt{\sigma_{0,i}^2 + \sigma_{\text{jitter}}^2}, \quad (3)$$

where $\sigma_{0,i}$ are the reported errors by the RV analysis. We used the modified RV errors $\sigma_i^{(1)}$ for estimating errors of the free parameters.

4. Results and Discussion

We determine the model parameters so that the $\chi^2$ statistic takes its minimum value by the AMOEBA algorithm (see Narita et al. 2008; Narita et al. 2010). Figure 1 presents the phase-folded RVs obtained by Subaru and Keck, along with the best-fit RV curve. In this figure, we subtract the long-term RV variation $\dot{\gamma}$ from the observed values. In Figure 2, we also show the RVs around the transit (phase $\sim 0$), as well as the simultaneous photometry with FTN. The observed RVs show a persistent blue-shift throughout the transit, suggesting a spin-orbit misalignment. The best-fit values for the six parameters are summarized in Table 2. The 1$\sigma$ uncertainty for each parameter is estimated by the criterion of $\Delta \chi^2 = 1.0$. The spin-orbit misalignment angle $\lambda$ is estimated as $\lambda = 103^{\circ} \pm 23^{\circ}$. Since the Keck RV dataset covers most of the orbital phase outside of the transit, the estimated values for $K$, $e$, and $\omega$ are in good agreement with the reported values by Bakos et al. (2010).

The estimated stellar rotational velocity $v \sin i_s = 2.09^{+0.98}_{-0.93} \text{ km s}^{-1}$ by our RM analysis agrees with the spectroscopically measured value within 1$\sigma$. In order to confirm the robustness of the estimated spin-orbit misalignment angle $\lambda$, we test the following two cases. First,
Table 2. The best-fit parameters

| Parameter | Best-fit value |
|-----------|---------------|
| $T_C$ [HJD] | 2455343.95000$^{+0.00173}_{-0.00227}$ |
| $K$ | $11.8 \pm 0.9$ [m s$^{-1}$] |
| $e$ | $0.205 \pm 0.036$ |
| $\omega$ | $351^{+16}_{-12}$ [$^\circ$] |
| $\lambda$ | $103^{+13}_{-20}$ [$^\circ$] |
| $v \sin i_s$ | $2.09^{+0.98}_{-0.93}$ [km s$^{-1}$] |

instead of letting $v \sin i_s$ be a free parameter, we fix it as $v \sin i_s = 1.5$ km s$^{-1}$ (the spectroscopically measured value) and fit the other five parameters. As a result, we obtain $\lambda = 106^{+25}_{-23}$, in good agreement with the main result described above. Second, we changed the planet to star radius ratio to the value determined by Dittmann et al. (2009), of $R_p/R_s = 0.0621 \pm 0.0011$, based on a photometric follow-up observation of the system. Adopting their results we obtain $\lambda = 100^{+24}_{-21}$, which is also consistent with the main result within 1$\sigma$. As expected in this case, we obtain a slightly smaller rotational velocity ($v \sin i_s = 1.73^{+0.83}_{-0.86}$ km s$^{-1}$) than the main result. In both cases above, we find no significant difference in the other fitted parameters ($K$, $e$, $\omega$) from the main result.

The spin-orbit misalignment angle $\lambda$ is very sensitive to the RVs taken out-of-transit, which determine the Keplerian motion of HAT-P-11b. Our new dataset contains two, nine, and twelve out-of-transit RVs taken on UT 2010 May 21, 27, and July 1, respectively. However, the number of RVs might not be sufficient in systems as
HAT-P-11, where the planet is small and its host star is active. In addition, since the observations in May and July are separated by roughly a month, the long-term RV drift reported by Bakos et al. (2010) might have affected the result. If the long-term RV drift is actually caused by a secondary planet lurking in the HAT-P-11 system, the RV drift should modulate with time. In order to test the effect of a RV drift variation, we artificially increased the RV drift from $\dot{\gamma} = 0.0297$ m s$^{-1}$ day$^{-1}$ to $\dot{\gamma} = 0.10$ m s$^{-1}$ day$^{-1}$. This treatment resulted in a slightly larger value for the spin-orbit misalignment angle ($\lambda = 103^\circ_{+23}^{-26}$) and a smaller value for the projected stellar rotational velocity ($\upsilon \sin i_s = 1.68_{-0.94}^{+1.12}$ km s$^{-1}$), both of which are consistent with the main result shown in Table 2. This result indicates that the long-term RV drift has less impact on estimating $\lambda$, as long as $\dot{\gamma}$ does not exceed 0.10 m s$^{-1}$ day$^{-1}$.

Although the measurement of the RM effect in the HAT-P-11 system seems challenging due to the small size of the planet and large stellar jitter, our result suggests a significant spin-orbit misalignment of the system. As we have described in Section 1, five out of the seven eccentric hot-Jupiters where the RM effect has been observed have significant spin-orbit misalignment. Our result suggests that the super-Neptune HAT-P-11b migrated to its present location by dynamical scattering or a long-term perturbation by an outer body, similarly to other eccentric hot-Jupiters. By contrast, the fraction of misaligned systems with circular orbits is significantly smaller (e.g., CoRoT-1, HAT-P-7, WASP-15; Pont et al. 2010; Narita et al. 2009b; Winn et al. 2009b; Triaud et al. 2010).

Winn et al. (2010) suggested the interesting possibility that hot-Jupiters have large initial spin-orbit misalignment caused by dynamical processes, but the host stars’ obliquity could decline due to tidal interactions between hot-Jupiters and the stellar convective zone. Since convective zones are particularly well-developed in cooler and less massive stars, we are likely to observe spin-orbit alignment around cool host stars. Although HAT-P-11 is a very cool star ($T_{\text{eff}} = 4780 \pm 50$ K), this hypothesis also claims that the decay timescale of host star’s obliquity is larger when the planet has a lower mass and a distant orbit from the host star (see eq. 2 of Winn et al. 2010). According to their criteria, the HAT-P-11 system can show a spin-orbit misalignment mainly because of the lower mass of HAT-P-11b.

Comparison of the spin-orbit misalignment angle for HAT-P-11b with those of other transiting hot-Neptunes (e.g., GJ 436b and Kepler-4b) is quite interesting, because their host stars are of different spectral types (Kepler-4 is a G0 star and GJ 436 is an M2.5 star), while HAT-P-11b, GJ 436b, and Kepler-4b have similar planetary radii and masses (e.g., Butler et al. 2004; Shporer 2009; Borucki et al. 2010). Further observational investigations of formation and migration history of hot-Neptunes will be an interesting topic in the next decade.

5. Summary

We have measured the RM effect for one of the smallest transiting exoplanets known to date, HAT-P-11b. The exoplanet has a significant eccentricity and is an interesting target for the RM effect. The observed RV anomaly during the transit suggests a significant spin-orbit misalignment of the system, of $\lambda = 103^\circ_{+23}^{-26}$. To confirm the spin-orbit misalignment decisively, however, it is necessary to measure even more RVs of the system during and outside transits, as well as to better characterize the long-term RV variation. Although challenging, the measurement of the RM effect for Neptune-sized exoplanets will extend the parameter space where planetary formation and migration theories will be studied in the near future.

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