First Evidence of a Retrograde Orbit of a Transiting Exoplanet HAT-P-7b*

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Abstract

We present the first evidence of a retrograde orbit of a transiting exoplanet HAT-P-7b. The discovery is based on a measurement of the Rossiter–McLaughlin effect with the Subaru HDS during a transit of HAT-P-7b, which occurred on 2008 May 30 UT. Our best-fit model shows that the spin–orbit alignment angle of this planet is \( \lambda = -132^{+7}_{-16} \). The existence of such a retrograde planet has been predicted by recent planetary migration models that consider planet–planet scattering processes, or Kozai migration. Our finding provides an important milestone that supports such dynamic migration theories.

Key words: stars: planetary systems: individual (HAT-P-7) — stars: rotation — techniques: radial velocities — techniques: spectroscopic

1. Introduction

One of the surprising properties of extrasolar planets is their distributions around their host stars. Since many Jovian planets have been found in the vicinity (far inside the snow line) of their host stars, a number of theoretical models have been studied to explain inward planetary migration. Recently, our understanding of planetary migration mechanisms has rapidly progressed through observations of the Rossiter–McLaughlin effect (hereafter, the RM effect: Rossiter 1924; McLaughlin 1924) in transiting exoplanetary systems. The RM effect is an apparent radial-velocity anomaly during binary transits. By measuring this effect, one can learn the sky-projected angle between the stellar spin axis and the planetary orbital axis, denoted by \( \lambda \) (see Ohta et al. 2005; Gaudi & Winn 2007 for theoretical discussion).

So far, spin–orbit alignment angles of about 15 transiting planets have been measured (Fabrycky & Winn 2009; and references therein). Among those RM targets, significant spin–orbit misalignments have been reported for 3 transiting planets: XO-3b (Hébrard et al. 2008; Winn et al. 2009a), HD 80606b (Moutou et al. 2009; Pont et al. 2009; Winn et al. 2009b) and WASP-14b (Johnson et al. 2009). These misaligned planets are considered to have migrated through planet–planet scattering processes (e.g., Rasio & Ford 1996; Marzari & Weidenschilling 2002; Nagasawa et al. 2008; Chatterjee et al. 2008) or Kozai cycles with tidal evolution (e.g., Wu & Murray 2003; Takeda & Rasio 2005; Fabrycky & Tremaine 2007; Wu et al. 2007), rather than the standard Type II migration (e.g., Lin & Papaloizou 1985; Lin et al. 1996; Ida & Lin 2004).

The existence of such misaligned planets has demonstrated the validity of planetary migration models considering planet–planet scattering or Kozai migration. On the other hand, such planetary migration models also predict significant populations of “retrograde” planets. Thus, discoveries of retrograde planets would be an important milestone for confirming the predictions of recent planetary migration models, and also intrinsically interesting.

In this letter, we report on the first evidence of such a retrograde planet in the transiting exoplanetary system HAT-P-7. Section 2 summarizes the target and our Subaru observations, and section 3 describes the analysis procedures for the RM effect. Section 4 presents results and discussion for the derived system parameters. Finally, section 5 summarizes the main findings of this letter.

2. Target and Subaru Observations

HAT-P-7 is an F6 star at a distance of 320 pc, hosting a very hot Jupiter (Pál et al. 2008, hereafter P08). Among transiting-planet host stars, F-type stars are interesting RM targets because they often have a large stellar rotational velocity, which facilitates measurements of the RM effect. However, the rotational velocity of HAT-P-7 is \( V \sin I_\ast = 3.8 \, \text{km s}^{-1} \) (P08), which is unusually slower than expected for an F6 type star. Nevertheless, this system is favorable for RM observations, since the star is relatively bright \( (V = 10.5) \) and the expected amplitude of the RM effect \( [V \sin I_\ast (R_p/R_\star)^2 \sim 20 \, \text{m s}^{-1}] \) is sufficiently detectable with the Subaru telescope.

We observed a full transit of HAT-P-7b with the High Dispersion Spectrograph (HDS: Noguchi et al. 2002) on the Subaru 8.2 m telescope on 2008 May 30 UT. We employed the standard I2a set-up of the HDS, covering the wavelength range 4940 Å < \( \lambda < 6180 \, \text{Å} \), and used an Iodine gas absorption cell for radial-velocity measurements. A slit width of 0.6’ yielded a spectral resolution of \( \approx 60000 \). The seeing on that night was around 0.6’. The exposure time for radial-velocity measurements was 6–8 minutes, yielding a typical...
signal-to-noise ratio (SNR) of approximately 120 per pixel. We processed the observed frames with standard IRAF procedures, and extracted one-dimensional spectra. We computed the relative radial velocities following an algorithm of Butler et al. (1996) and Sato et al. (2002), as described in Narita et al. (2007). We estimated the internal error of each radial velocity as the scatter in the radial-velocity solutions among ~4 Å segments of the spectrum. The typical internal error was ~5 m s$^{-1}$. The radial velocities and uncertainties are summarized in table 1.

1 The Image Reduction and Analysis Facility (IRAF) is distributed by the US National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

### Table 1. Radial velocities obtained with the Subaru/HDS.

| Time (HJD) | Value (m s$^{-1}$) | Error (m s$^{-1}$) |
|-----------|-------------------|-------------------|
| 2454616.89606 | 65.07 | 5.02 |
| 2454616.90384 | 56.63 | 5.00 |
| 2454616.91160 | 55.84 | 4.98 |
| 2454616.91936 | 52.22 | 5.03 |
| 2454616.92712 | 43.55 | 5.00 |
| 2454616.93489 | 45.98 | 4.98 |
| 2454616.94264 | 42.45 | 4.94 |
| 2454616.95039 | 37.97 | 4.94 |
| 2454616.95678 | 28.22 | 5.20 |
| 2454616.96176 | 26.60 | 5.17 |
| 2454616.96674 | 26.32 | 5.15 |
| 2454616.97172 | 14.40 | 5.17 |
| 2454616.97670 | 18.77 | 5.11 |
| 2454616.98167 | 15.30 | 5.15 |
| 2454616.98666 | 12.88 | 5.21 |
| 2454616.99165 | –2.53 | 5.18 |
| 2454616.99663 | 2.91 | 5.16 |
| 2454617.00161 | 9.84 | 5.17 |
| 2454617.00661 | 4.34 | 5.19 |
| 2454617.01159 | 1.23 | 5.19 |
| 2454617.01657 | –9.81 | 5.16 |
| 2454617.02156 | –10.32 | 5.16 |
| 2454617.02655 | –7.47 | 5.13 |
| 2454617.03154 | –11.00 | 5.15 |
| 2454617.03652 | –4.53 | 5.17 |
| 2454617.04151 | –16.47 | 5.16 |
| 2454617.04650 | –15.68 | 5.23 |
| 2454617.05147 | –19.28 | 5.16 |
| 2454617.05645 | –20.31 | 5.21 |
| 2454617.06142 | –18.94 | 5.17 |
| 2454617.06640 | –28.10 | 5.21 |
| 2454617.07206 | –23.85 | 5.16 |
| 2454617.07842 | –28.44 | 5.18 |
| 2454617.08479 | –39.88 | 5.13 |
| 2454617.09115 | –35.41 | 5.09 |
| 2454617.09751 | –38.90 | 5.13 |
| 2454617.10389 | –51.68 | 5.15 |
| 2454617.11026 | –51.74 | 5.16 |
| 2454617.11664 | –61.71 | 5.12 |
| 2454617.12301 | –75.20 | 5.14 |

### Table 2. Adopted stellar and planetary parameters.

| Parameter | Value | Source |
|-----------|-------|--------|
| $M_\star$ ($M_\odot$) | 1.47 | P08 |
| $R_\star$ ($R_\odot$) | 1.84 | P08 |
| $R_p/R_\star$ | 0.0763 | P08 |
| $i$ (°) | 85.7 | P08 |
| $a/R_\star$ | 4.35 | P08 |
| $u_1$ | 0.45 | Claret (2004) |
| $u_2$ | 0.31 | Claret (2004) |
| $T_c$ (HJD) | 2453790.2593 | P08 |
| $P$ (d) | 2.2047299 | P08 |

### 3. Analyses

We modeled the RM effect of HAT-P-7 following a procedure of Winn et al. (2005), as described in Narita et al. (2009) and T. Hirano et al. (2009 in preparation). We started with a synthetic template spectrum, which matches for the stellar property of HAT-P-7 described in P08, using a synthetic model by Coelho et al. (2005). To model the disk-integrated spectrum of HAT-P-7, we applied a rotational broadening kernel of $V \sin I_*$ = 3.8 km s$^{-1}$, and assumed limb-darkening parameters for the spectroscopic band as $u_1 = 0.45$ and $u_2 = 0.31$, based on a model by Claret (2004). We then subtracted a scaled copy of the original unbroadened spectrum with a velocity shift to simulate the spectra during a transit. We created numbers of such simulated spectra using different values of the scaling factor, $f$, and the velocity shift, $v_p$, and computed the apparent radial velocity of each spectrum. We thereby determined an empirical formula that describes the radial velocity anomaly, $\Delta v$, in HAT-P-7 due to the RM effect, and found

$$\Delta v = -f v_p \left[ 1.444 - 0.623 \left( \frac{v_p}{V \sin I_*} \right)^2 \right].$$

For a radial-velocity fitting, including the Keplerian motion and the RM effect, we adopted stellar and planetary parameters based on P08, as follows: stellar mass, $M_\star = 1.47 M_\odot$; stellar radius, $R_\star = 1.84 R_\odot$; radial ratio, $R_p/R_\star = 0.0763$; orbital inclination, $i = 85.7^\circ$; and the semi-major axis in units of the stellar radius, $a/R_\star = 4.35$. We assess possible systematic errors due to uncertainties in the fixed parameters in section 4. We also included a stellar jitter of 3.8 m s$^{-1}$ for the P08 Keck data as systematic errors of radial velocities by a quadrature sum. It enforced the ratio of $\chi^2$ contribution and the degree of freedom for the Keck data to be unity. We did not include additional radial velocity errors for the Subaru data, because we found that the ratio for the Subaru dataset is already smaller than unity (as described in section 4).

In addition, we adopted the transit ephemeris, $T_c = 2453790.2593$ (HJD), and the orbital period, $P = 2.2047299$ d, based on P08. Note that this ephemeris has an uncertainty of 3 minutes for the observed transit; however, this uncertainty is well within our time-resolution (exposure time of 6–8 minutes and readout time of 1 minute) and is negligible for our purpose. The adopted parameters above are summarized in table 2.
Our model had 3 free parameters describing the HAT-P-7 system: the radial velocity semi-amplitude \( K \), the sky-projected stellar rotational velocity \( V \sin I_\ast \), and the sky-projected angle between the stellar spin axis and the planetary orbital axis \( \lambda \). We fixed the eccentricity, \( e \), to zero, and the argument of periastron, \( \omega \), was not considered. Finally, we added two offset velocity parameters for the respective radial velocity datasets \((v_1, \text{our Subaru dataset}; v_2, \text{Keck dataset in P08})\).

We then calculated the \( \chi^2 \) statistic (hereafter “main-case”),
\[
\chi^2 = \sum_i \left[ \frac{v_{i,\text{obs}} - v_{i,\text{calc}}}{\sigma_i} \right]^2,
\]
where \( v_{i,\text{obs}} \) and \( \sigma_i \) are the observed radial velocities and the uncertainties, and \( v_{i,\text{calc}} \) are the radial velocity values calculated based on a Keplerian motion and on the empirical RM formula given above.

We determined the optimal orbital parameters by minimizing the \( \chi^2 \) statistic using the AMOEBA algorithm (Press et al. 1992). We estimated the 1σ uncertainty of each free parameter based on the criterion \( \Delta \chi^2 = 1.0 \) when a parameter was stepped away from the best-fit value and the other parameters were re-optimized.

We also fitted the radial velocities using another statistic function for a reference (hereafter “test-case”),
\[
\chi^2 = \sum_i \left[ \frac{v_{i,\text{obs}} - v_{i,\text{calc}}}{\sigma_i} \right]^2 + \left[ \frac{V \sin I_\ast - 3.8}{0.5} \right]^2.
\]
The last term is an a priori constraint for \( V \sin I_\ast \) to match the independent spectroscopic analysis by P08.

4. Results and Discussion

Figure 1 shows the observed radial velocities and the best-fit model curve for the main-case. Figure 2 illustrates the RM effect of HAT-P-7b with the best-fit model, and also shows a comparison with the case of \( \lambda = 0^\circ \) and \( V \sin I_\ast = 3.8 \text{ km s}^{-1} \) model. The upper panel of figure 3 plots a \( \chi^2 \) contour in \((\lambda, V \sin I_\ast)\) space. As a result, we found the key parameters, \( \lambda = -132.6^\circ (+10.5^\circ, -16.3^\circ) \), implying a retrograde orbit of HAT-P-7b. The stellar rotational velocity is \( V \sin I_\ast = 2.3 \pm 0.6, -0.5 \) km s\(^{-1}\), which is marginally consistent with the P08 spectroscopic result \((V \sin I_\ast = 3.8 \pm 0.5 \text{ km s}^{-1})\). Residuals from the best-fit model indicate an rms of 4.14 m s\(^{-1}\) for the Subaru dataset and 4.09 m s\(^{-1}\) for the P08 Keck dataset. The rms of the Subaru residuals is well within our internal radial velocity errors, and that of the Keck residuals is in good agreement with the assumed jitter level of 3.8 m s\(^{-1}\). One may wonder how a smaller \( V \sin I_\ast \) allowed in the main-case would weaken the detection-significance of the RM effect. However, since \( V \sin I_\ast = 0 \text{ km s}^{-1} \) is excluded by \( \Delta \chi^2 = 36.49 \), there is very little chance that a true \( V \sin I_\ast \) is actually nearly zero, and the spin–orbit alignment angle, \( \lambda \), is very small. The lower panel of figure 3 plots a similar \( \chi^2 \) contour, but for the test-case. In this case, we find \( \lambda = -122.5^\circ (+6.7^\circ, -7.7^\circ) \) and \( V \sin I_\ast = 3.1 \pm 0.4 \text{ km s}^{-1} \). Thus, our two results (main and test cases) are very consistent with each other. In addition, we tested the fitting with the eccentricity, \( e \), and the argument of periastron, \( \omega \), as free parameters. As a result, we did not find any significant (nonzero) eccentricity for this planet. The best-fit parameters and uncertainties are summarized in table 3.

In the above analyses, we fixed several parameters, as summarized in table 2, which were based on P08 and Claret (2004). In order to estimate the level of possible systematic errors, we retried the fitting for the following four cases: (1) \( a/\hat{R}_s = 4.63, i = 89^\circ \) (corresponding to the 1σ lower limit of the impact parameter in P08); (2) \( a/R_\ast = 3.97, i = 82^\circ \) (corresponding to the 1σ upper limit of the impact parameter in P08); (3) \( u_1 = 0.65 \) (a greater limb-darkening case); and (4) \( u_1 = 0.25 \) (a smaller limb-darkening case).

Consequently, we found that respective results for \( \lambda \) and \( V \sin I_\ast \) are: (1) \( \lambda = 151.8^\circ (-13^\circ, -128^\circ) \) and \( V \sin I_\ast = 2.1 \pm 0.4 \text{ km s}^{-1} \); (2) \( \lambda = -99.5^\circ (+33^\circ, -62^\circ) \) and \( V \sin I_\ast = 7.6 \pm 2.9 \text{ km s}^{-1} \); (3) \( \lambda = -135.9^\circ (+13^\circ, -167^\circ) \) and \( V \sin I_\ast = 2.2 \pm 0.5 \text{ km s}^{-1} \); and (4) \( \lambda = -119.8^\circ (+15^\circ, -151^\circ) \) and \( V \sin I_\ast = 2.4 \pm 0.6 \text{ km s}^{-1} \). Thus, \( \lambda = 164^\circ -96.5^\circ \) and \( V \sin I_\ast = 1.7 -10.5 \text{ km s}^{-1} \) can still be probable if the uncertainties for the fixed parameters (especially for the impact parameter) are taken into account. These systematic errors would be significantly reduced when the Kepler photometric data for HAT-P-7 are available (Borucki et al. 2009).

The derived value of \( \lambda \) seems to indicate a retrograde orbit by itself. However, since the true spin–orbit angle, \( |\Psi| \), also depends on the inclination of the stellar spin axis, \( I_\ast \), \( |\Psi| \) is not necessarily greater than 90° (corresponding to a retrograde
Table 3. Best-fit values and uncertainties of the free parameters.

| Parameter          | Value   | Uncertainty | Value   | Uncertainty |
|--------------------|---------|-------------|---------|-------------|
| $K$ (m s$^{-1}$)   | 212.6   | $\pm$ 1.9   | 213.3   | $\pm$ 1.9   |
| $V \sin I_s$ (km s$^{-1}$) | 2.3 $^{+0.6}_{-0.5}$ | $^{+1.0}_{-1.8}$ | 3.1   | $\pm$ 0.4   |
| $\lambda$ (°)     | $-132.6^{+10.5}_{-16.3}$ | $-122.5^{+6.4}_{-7.7}$ |
| $v_1$ (m s$^{-1}$) | $-14.7^{+1.6}_{-1.6}$ | $-16.6^{+1.3}_{-1.3}$ |
| rms (Subaru) (m s$^{-1}$) | 4.14 | 4.32 |
| $v_2$ (m s$^{-1}$) | $-37.4^{+1.6}_{-1.6}$ | $-37.5^{+1.6}_{-1.6}$ |
| rms (Keck) (m s$^{-1}$) | 4.09 | 4.09 |

* Systematic errors are not included in the uncertainties (see text).

Fig. 2. Upper figure: RM effect of HAT-P-7b. The upper panel shows the difference radial velocities (namely, the Keplerian motion is subtracted from the original radial velocities). The solid line indicates the best-fit RM model. The lower panel plots residuals from the best-fit model. Lower figure: The case for $\lambda = 0°$ and $V \sin I_s = 3.8$ km s$^{-1}$ model, for reference.

Fig. 3. Plots of $(\lambda, V \sin I_s)$ contours of HAT-P-7 based on our Subaru dataset and the P08 Keck dataset without (upper) and with (lower) the a priori constraint on $V \sin I_s$. The solid lines show $\Delta \chi^2 = 1.0, 4.0, 9.0$ (from inner to outer), respectively.
We note that $|\Psi|$ is always larger than 85.7° (the adopted value of $i_0$, in the case of $I_0 = 0°$). Those estimates favor a retrograde orbit of HAT-P-7b.

On the other hand, it is important to point out that the stellar rotational velocity, $V \sin I_0 = 3.8 \text{ km s}^{-1}$, determined by the spectroscopic analysis (P08) is exceptionally slow for an F6 star. For example, HAT-P-2 and TrES-4, which are other known planetary host stars of a similar spectral type, have larger stellar rotational velocities: $V \sin I_0 = 19.8 \text{ km s}^{-1}$ (HAT-P-2, Bakos et al. 2007; we also confirmed this from the RM effect by Winn et al. 2007) and $V \sin I_0 = 8.5 \text{ km s}^{-1}$ (TrES-4, Sozzetti et al. 2009; and from the RM effect by N. Narita et al. 2009 in preparation). The small $V \sin I_0$ may suggest a smaller inclination angle of the stellar spin axis. In that case, it is highly possible that the planet is in a nearly polar retrograde orbit.

We note that a too small $I_0$ can be constrained by the facts that a faster stellar rotation of HAT-P-7 than 500 km s$^{-1}$ would be physically unlikely, due to stellar break-up, and that a faster rotation than 100 km s$^{-1}$ would be empirically unlikely for an F6 star (Gray 2005). Translating the constraints into $\cos I_0$, we find that the probability of such unrealistic cases is only $\sim 0.03\%$, which has a very small impact on the probability estimations for a retrograde orbit. In any case, it would be important to directly constrain $I_0$ by other observational methods (e.g., Henry & Winn 2008 or asteroseismology with the Kepler motion) in order to estimate a true spin–orbit angle of HAT-P-7b.

We previously experienced a false positive of a spin–orbit misalignment in HD 17156b, due to lower precision radial velocity data (Narita et al. 2008, 2009). The problem for the HD 17156 case (Narita et al. 2008) was that the radial-velocity uncertainties were comparable to the predicted RM amplitude, and also due to a poor number of radial-velocity samples. Based on this lesson, we estimated the significance of our RM detection using equation (26) in Gaudi and Winn (2007). As a result, the SNR of our RM detection is over 10, and thus we conclude to have obtained radial velocities of a sufficient number and precision to model the RM effect of HAT-P-7b.

Nevertheless, we finally note that we should care about possible systematic errors in $\lambda$. Since the RM amplitude of HAT-P-7b is only $\sim 15 \text{ m s}^{-1}$, any systematic shift as much as several meters per second due to stellar jitter, or other reasons at the ingress or egress phase would cause a large systematic difference in $\lambda$. Thus, further radial-velocity measurements for this interesting system are desired to confirm a retrograde orbit of HAT-P-7b more decisively.

5. Summary

We observed a full transit of HAT-P-7b with the Subaru 8.2 m telescope on 2008 May 30 UT, and measured the RM effect of this planet. Based on RM modeling, we discovered the first evidence of a retrograde orbit of HAT-P-7b. This is the first discovery of a retrograde extrasolar planet. The existence of such planets have been indeed predicted in some recent planetary migration models considering planet–planet scattering and/or the Kozai migration (e.g., Fabrycky & Tremaine 2007; Wu et al. 2007; Nagasawa et al. 2008; Chatterjee et al. 2008). In addition, it is interesting to point out that HAT-P-7b is the first spin–orbit misaligned planet having no significant eccentricity. This discovery may suggest that other hot Jupiters in circular orbits also have significant spin–orbit misalignments, or even retrograde orbits. Thus, further RM observations for transiting planets, including not only eccentric or binary system planets, but also close-in circular planets, would be encouraged in order to understand populations of aligned/misaligned/retrograde planets.

Note added in proof (2009 August 28):

Winn et al. (2009c) reported independent evidence for a retrograde orbit of HAT-P-7b, based on independent Subaru HDS observations conducted in 2009 June/July.

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