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A Common Proper Motion Stellar Companion to HAT-P-7

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Abstract

We report that HAT-P-7 has a common proper motion stellar companion. The companion is located at ~ 3.9 arcsec to the east and estimated as an M5.5V dwarf based on its colors. We also confirm the presence of the third companion, which was first reported by Winn et al. (2009), based on long-term radial velocity measurements. We revisit the migration mechanism of HAT-P-7b given the presence of those companions, and propose sequential Kozai migration as a likely scenario in this system. This scenario may explain the reason for an outlier in the discussion of the spin-orbit alignment timescale for HAT-P-7b by Albrecht et al. (2012).

Key words: stars: planetary systems: individual (HAT-P-7) — stars: binaries: general — techniques: high angular resolution — techniques: photometric — techniques: radial velocities

1. Introduction

To uncover formation mechanisms of diverse exoplanetary systems, the (mis)alignment between the planetary orbital axis and the stellar spin axis, which can be measured via the Rossiter-McLaughlin (RM) effect (e.g., Ohta et al. 2005; Hirano et al. 2011) or spot-crossing events (e.g., Sanchis-Ojeda & Winn 2011; Sanchis-Ojeda et al. 2012), has been recognized as an useful clue. Previous observations have revealed that about one third of hot Jupiters have tilted or even retrograde orbits relative to their host star's spin (e.g., Hébrard et al. 2008; Narita et al. 2009; Winn et al. 2009). This indicates that not only disk-planet interaction but also few-body interaction (planet-planet scattering and/or the Kozai mechanism) play an important role in planetary migration processes. Moreover, some studies pointed out the interesting facts that spin-orbit misalignments in planetary orbits are apparently correlated with host star's temperature (Winn et al. 2010) and age (Triaud 2011), while these correlations can be explained by the properties and evolution of the internal structure in host stars (Albrecht et al. 2012). Those correlations are important clues to understand the whole picture of planetary migration.

However, previous discussions often overlooked the possible presence of faint distant companions. In most of the RM measurements, except for some obvious cases (e.g., XO-2, HD80606), observers did not check whether the host star has outer companions. Thus any correlation between the spin-orbit misalignment and the existence of binary companions has not been well investigated. To solve this problem, we have started high-contrast direct imaging observations for known transiting planetary systems in the course of the SEEDS (Strategic Explorations of Exoplanets and Disks with Subaru; Tamura 2009) project.

Narita et al. (2010) reported two candidate companions around HAT-P-7, which was known to have a retrograde hot Jupiter HAT-P-7b (Narita et al. 2009; Winn et al. 2009; Albrecht et al. 2012). In this letter, we present evidence that one of the two candidate companions is indeed a true companion of HAT-P-7, confirmed by the common proper motion and the distance from Earth inferred from its spectral type and apparent magnitude.

2. Observations and Results

For high-contrast direct imaging, we employed IRCS (for J, K, L' bands) and HiCIAO (for H band) with AO188 (Hayano et al. 2008) on the Subaru 8.2m telescope. Our observation logs (observing dates, instruments, filters, exposure times) and properties of the candidate companions are summarized in tables 1 and 2. Magnitudes of the bright companion are derived by relative photometry with the host star using unsaturated images, and then magnitudes of the faint companion are similarly derived by relative photometry with the bright companion using saturated images. Figure 1 shows pictures of HAT-P-7 in different epochs and bands. Figure 2 plots time changes of positions of the candidate companions. Based on the Tycho-2 Catalogue (Høg et al. 2000), HAT-P-7 has a proper motion of -14.8 ± 1.5 mas/yr in right ascension (RA) and 8.7 ± 1.4 mas/yr in declination (Dec). From figure 2, we find that the motion of the western (fainter) candidate is consistent with a background star ($\chi^2 = 4.3$ for a degree of freedom of 6), while the motion of the eastern (brighter) candidate is different from a background star ($\chi^2 = 83.0$ for a degree of freedom of 6) and consistent with a common proper motion with HAT-P-7.

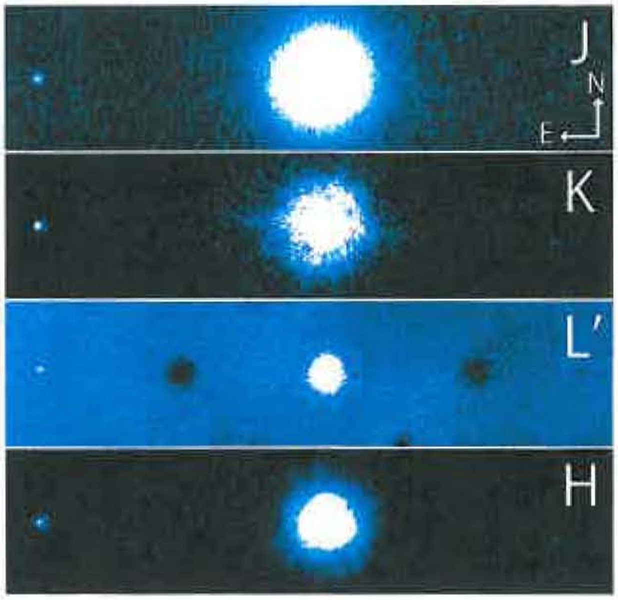

Fig. 1. High-contrast images around HAT-P-7 taken with the Subaru IRCS (J, K, L') in 2011 and HiCIAO (H) in 2012 (see table 1). The field of view of each panel is 8 arcsec (horizontal) × 2 arcsec (vertical). Black circle regions in the L' band image are vestiges of dithering pattern. North is up and east is left for all panels. Note that only unsaturated images are used in this figure to highlight the eastern companion. The western companion is not detected in the J and L' band images.

In addition to the common proper motion, the spectral type of the eastern candidate supports a consistent distance with HAT-P-7, as follows. The distance to HAT-P-7 was estimated as 320^{+50}_{-40} pc by Pál et al. (2008), based on the Yonsei-Yale stellar evolution models (Yi et al. 2001) and SME (Spectroscopy Made Easy: Valenti & Piskunov 1996) analysis. On the other hand, using the available colors (i', z', J, H, K), we confirm that the eastern companion is an M5.5V dwarf (see figure 3). Based on the absolute magnitude of an M5.5V dwarf in H band (Kraus & Hillenbrand 2007), we estimate a distance modulus of ~ 6.15, which corresponds to ~ 300 pc. Thus the spectrophotometric distance to the eastern companion is in good agreement with the distance to HAT-P-7 from Earth.

We thus conclude that HAT-P-7 has a common proper motion stellar (M5.5V) companion at a projected separation of ~ 3.9 arcsec (1240^{+190}_{-160} AU). Note that assuming a random distribution for the companion orbit, the expected unprojected separation is $4/\pi$ times larger than the projected separation (see also table 6 of Dupuy & Liu

Table 1. Observation logs and magnitudes of candidate companions

UT Dates	Inst.	Band	Exp. Time [s]	Mag.(East)	Mag.(West)	Ref.
2009Aug06	HiCIAO	H	585^a	15.12 ± 0.04	16.64 ± 0.06^b	this work^b
2009Oct30	AstraLux	i'	30	18.50 ± 0.21	non-detection	Narita et al. (2010)
2009Oct30	AstraLux	z'	30	17.43 ± 0.09	non-detection	Narita et al. (2010)
2009Nov02	HiCIAO	H	100^c	15.07 ± 0.04	16.56 ± 0.07	this work
2011Aug12	IRCS	J	560.6^d	15.81 ± 0.19	17.48 ± 0.25	this work
2011Aug12	IRCS	K	560.6^d	14.81 ± 0.07	16.38 ± 0.09	this work
2011Aug12	IRCS	L'	396^e	14.45 ± 0.41	non-detection	this work
2012Jul07	HiCIAO	H	1810^f	15.18 ± 0.07	16.66 ± 0.07	this work

[a] 19.5 s (saturated) × 30 images. [b] The previous value in Narita et al. (2010) is turned out to be false, and here we present the corrected value. [c] 4.18 s (unsaturated) × 24 images. [d] 180 s (saturated) × 3 images and 4.12 s (unsaturated) × 5 images. [e] 12 s (unsaturated) × 33 images. [f] 20 s (saturated) × 89 images and 1.5 s (unsaturated) × 20 images.

Table 2. Separation angles (SA) and position angles (PA) of candidate companions

UT Dates	Inst.	SA(East) ["]	PA(East) [°]	SA(West) ["]	PA(West) [°]	Ref.
2009Aug06	HiCIAO	3.875 ± 0.005	89.81 ± 0.30	3.139 ± 0.005	266.30 ± 0.37	Narita et al. (2010)
2009Nov02	HiCIAO	3.861 ± 0.006	89.82 ± 0.08	3.137 ± 0.006	266.14 ± 0.09	this work
2011Aug12	IRCS	3.871 ± 0.006	89.68 ± 0.10	3.103 ± 0.011	266.23 ± 0.24	this work
2012Jul07	HiCIAO	3.860 ± 0.004	89.83 ± 0.05	3.095 ± 0.004	265.73 ± 0.08	this work

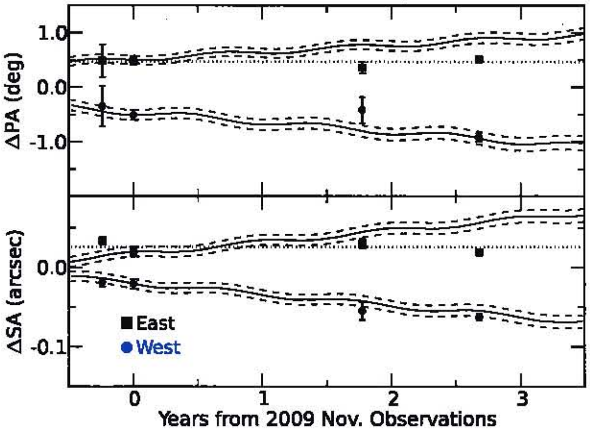

Fig. 2. The panels illustrate the variations of position angles (top) and separation angles (bottom) of the both candidates over the course of three years. The solid trajectories show the variations expected from an assumption that the candidates are background stars: the dashed lines show the 1σ errors. Note that we add offsets to all the values for clarify. The dotted lines indicate the averages of observed separation angles and position angles for the east candidate. As shown in this figure, the east one is inconsistent with a background source, while the west object is in good agreement with the background hypothesis.

2011 for a conversion factor from the projected separation to the semi-major axis). Here we name the eastern companion as "HAT-P-7B" (hereafter, just "B").

3. Discussions

3.1. Further Evidence of the Third Companion

Winn et al. (2009) reported the possible existence of a third (different from HAT-P-7b and HAT-P-7B) companion from a long-term radial velocity (RV) trend observed with the Keck HIRES between 2007 and 2009. We confirm the long-term trend based on RVs measured with the Subaru HDS in 2008 and 2010 (the RVs are available upon request). Figure 4 shows the RVs taken with the Subaru HDS and residuals from the best-fit one-planet model with and without a long-term linear RV trend $\dot{\gamma}$ (see Narita et al. 2011, for the fitting procedure). We find $\dot{\gamma} = 20.3 \pm 1.8$ m s^{-1} yr^{-1}, which agrees well with Winn et al. (2009) ($\dot{\gamma} = 21.5 \pm 2.6$ m s^{-1} yr^{-1}). Note that "B"

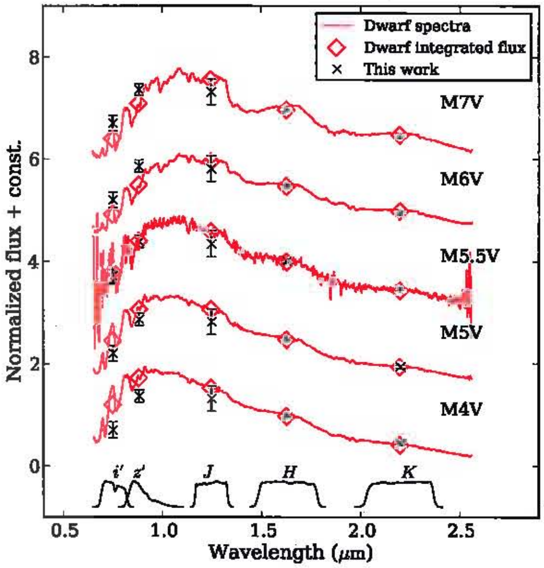

Fig. 3. Comparions of the observed colors with template spectra of known M4V-M7V dwarfs (Burgasser et al. 2004; Burgasser et al. 2008) taken with IRTF/SpeX. We find the M5.5V dwarf template gives a minimum χ^2.

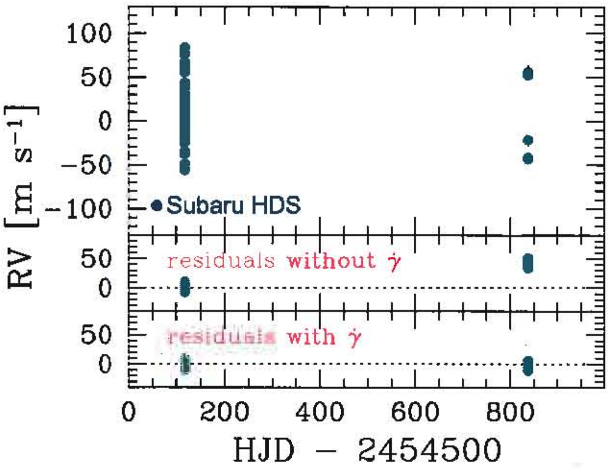

Fig. 4. Top panel: RVs of HAT-P-7 observed with the Subaru HDS. Middel panel: Residuals of RVs from the best-fit one-planet model without subtracting the long-term RV trend. Bottom panel: Same as the middle panel but with subtracting the RV trend.

cannot explain the observed long-term RV trend. Thus we conclude that there is the third companion in this system. Here we name the long-term RV companion as "HAT-P-7c" (hereafter, just "c").

The trend corresponds to the mass constraint of "c" as,

$$M_{\rm c} \sin i_{\rm c} / a_{\rm c}^2 \sim 0.12 \pm 0.01\ M_{\rm Jup}\ {\rm AU}^{-2}. \qquad (1)$$

The orbital period of "c" is presumably longer than 10 yr, since the trend is still approximately linear. Thus "c" is likely to be more massive than Jupiter. We do not detect "c" in high-contrast direct images, because it is too close to the host star.

3.2. *Migration Mechanism of HAT-P-7b Revisited*

Narita et al. (2010) pointed out that HAT-P-7b (hereafter, just "b") cannot be migrated by the Kozai mechanism caused by "B" in the presence of "c" in the system. However, they also pointed out that there is another possibility of "sequential" Kozai migration (see e.g., Takeda et al. 2008; Kita et al. 2010) in this system. Namely, an inclined outer stellar companion "B" causes the Kozai mechanism for the outer "c" first, and then the inclined "c" induces the Kozai mechanism for the inner "b". Such an initial inclined configuration can be formed by planet-planet scattering of "b" and "c" (and other possible undetected massive planets).

Recently, Albrecht et al. (2012) pointed out the interesting fact that the spin-orbit alignment timescale of HAT-P-7 due to the tidal effect is much shorter than the star's age (see figure 25 of Albrecht et al. 2012). Namely, the retrograde orbit of HAT-P-7b appears to be a strong outlier which should be aligned at the age of HAT-P-7. However, they did not consider the existence of the outer companions "B" and "c". Here we propose an alternative reason of the outlier: if the Kozai oscillation of "b" caused by "c" had once happened, the tidal timescale for spin-orbit alignment can be much longer. Based on equation (1) and the timescale of the Kozai oscillation as,

$$P_{\rm Kozai} \sim \frac{M_s}{M_{\rm c}} \frac{P_{\rm c}^2}{P_{\rm b}} (1 - e_{\rm c}^2)^{3/2}, \qquad (2)$$

where $M_{\rm s}$ is the host star's mass, $M_{\rm c}$, $P_{\rm c}$, and $e_{\rm c}$ are the mass, orbital period, and eccentricity of "c", and $P_{\rm b}$ is the orbital period of "b" (Wu et al. 2007), we estimate that the timescale of Kozai oscillation of "b" caused by "c" is comparable to the age of HAT-P-7 (2.14 ± 0.26 Gyr). Thus a possible slowly-changing orbital inclination due to the Kozai oscillation might have prevented HAT-P-7b from achieving a spin-orbit alignment. We note that, however, the above discussion may be still optimistic, as the Kozai oscillation is easily suppressed by other effects such as general relativity, tides, stellar distortion, or extra bodies (see e.g., Fabrycky & Tremaine 2007). At the current position of "b", the timescale of general relativity is indeed shorter than the timescale of Kozai oscillation of "b" caused by "c". This means the Kozai oscillation does not extend the timescale of spin-orbit alignment any more, although it might have once happened. We thus note that we may still overlook other special conditions that inhibit the spin-orbit alignment in this system.

3.3. *Suggestion to Further Discussions on Planetary Migration*

Thus far, the existence of possible faint outer companions around planetary systems has not been checked and is often overlooked, even though the Kozai migration models assume the presence of an outer companion. To further discuss planetary migration using the information of the RM effect / spot-crossing events as well as significant orbital eccentricities, it is important to incorporate information regarding the possible or known existence of binary companions. This is also because a large fraction of the stars in the universe form binary systems (Ghez et al. 1993). Thus it would be important to check the presence of faint binary companions by high-contrast direct imaging. In addition, if any outer binary companion is found, it is also necessary to consider the possibility of sequential Kozai migration in the system, since planet-planet scattering, if it occurs, is likely to form the initial condition of such planetary migration.

4. Summary

We present evidence that HAT-P-7 has a common proper motion stellar companion by high-contrast direct imaging with Subaru HiCIAO and IRCS. The companion is located at ∼ 3.9 arcsec to the east and estimated as an M5.5V star based on its colors. We also confirm the presence of the third companion HAT-P-7c by RV measurements with the Subaru HDS.

Our finding that HAT-P-7 is a wide binary system increase the potential that the sequential Kozai migration had once occured in this system. This scenario may be favorable to explain the discrepancy between the spin-orbit alignment timescale for HAT-P-7b and the stellar age noted by Albrecht et al. (2012).

In recent years, a number of RM and spot-crossing observations have provided useful information on the spin-orbit (mis)alignment, which is an important clue to understand the variety of planetary migration mechanisms. The same holds for eccentric planetary systems, since the eccentricity is another important clue to discuss planetary migration by few-body interactions. We thus propose that high-contrast direct imaging observations should be made for known planetary systems to check the presence of outer faint companions. Since the dependence of the spin-orbit (mis)alignment or significant eccentricity on the existence of outer companions is still unclear, it is important to conduct such observations to understand the entire picture of planetary migration.

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