Search for Outer Massive Bodies around Transiting Planetary Systems: Candidates of Faint Stellar Companions around HAT-P-7*

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Abstract
We present results of direct imaging observations for HAT-P-7 taken with the Subaru HiCIAO and the Calar Alto AstraLux. Since the close-in transiting planet HAT-P-7b was reported to have a highly tilted orbit, massive bodies such as giant planets, brown dwarfs, and a binary star are expected to exist in the outer region of this system. We show that there are indeed two candidates for distant faint stellar companions around HAT-P-7. We discuss how such companions can play a role on the orbital evolution of HAT-P-7b. We conclude that since there is a third body in the system, as reported by Winn et al. (2009, ApJ, 763, L99), Kozai migration is less likely, while planet–planet scattering is possible.

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

1. Introduction
The discovery of more than 400 extrasolar planets and the diversity of their orbital distributions dramatically changed our perception of planetary systems during the last 15 years. Especially, the existence of exoplanets in very close-in or eccentric orbits stimulated theorists to develop various models for planetary migration during the epoch in the history of planet formation. To explain the orbital distribution of known exoplanets, a number of planetary migration models have been proposed, including disk–planet interaction models (i.e.,
Type I and Type II migration models: e.g., Lin & Papaloizou 1985; Lin et al. 1996; D’Angelo et al. 2002; Ida & Lin 2004), planet–planet scattering models explaining the gravitational interaction among multiple giant planets (i.e., jumping Jupiter models: e.g., Rasio & Ford 1996; Marzari & Weidenschilling 2002; Nagasawa et al. 2008; Chatterjee et al. 2008), and Kozai migration models explaining the perturbation by a distant massive companion and cointaneous tidal evolution (e.g., Wu & Murray 2003; Takeda & Rasio 2005; Fabrycky & Tremaine 2007; Wu et al. 2007).

These planetary migration models can now be tested by observations of the Rossiter–McLaughlin (RM) effect (Rossiter 1924; McLaughlin 1924) for transiting planetary systems, which is an anomalous shift in the observed radial velocities due to the occultation of a rotating star. Measurements of the RM effect enable us to estimate the sky-projection angle of the planetary orbital axis relative to the stellar spin axis (i.e., the spin–orbit alignment angle: Ohta et al. 2005; Gaudi & Winn 2007; Hirano et al. 2010). Information about the spin–orbit alignment angle is very useful for differentiating the planet–planet scattering model and the Kozai migration one from the disk–planet interaction one, because the latter does that migrated planets would have only slight spin–orbit alignment angles. Thus, an observation of a highly tilted orbit for a specific planet gives strong evidence to a planet–planet scattering process or a perturbation by an outer companion during its migration history.

Indeed, very recently has it been reported that several transiting exoplanets show such highly tilted orbits via measurements of the RM effect. These observations lead to an interesting prediction: around these spin–orbit misaligned exoplanets should be other massive bodies (e.g., massive planets, brown dwarfs, a low-mass stellar companion) present. In addition, since migration mechanisms for such exoplanets cannot be distinguished by the spin–orbit alignment angles alone, direct imaging of such massive bodies gives us important additional information on distinctions between the two migration mechanisms of highly tilted orbit planets. Motivated by these facts, we began searching for such outer massive bodies around known transiting planetary systems with the Subaru HiCIAO (High Contrast Instrument for the Subaru next generation Adaptive Optics: Tamura et al. 2006; Hodapp et al. 2008; R. Suzuki in preparation), as part of the SEEDS project (Strategic Explorations of Exoplanets and Disks with Subaru, PI: Motohide Tamura). The Subaru HiCIAO is a powerful instrument used to search for outer faint bodies around stars, proven by the detection of a massive planet or a brown dwarf around GJ 758 (Thalmann et al. 2009).

In this paper, we target the transiting planetary system HAT-P-7, which was reported to have a planet (HAT-P-7b) on an orbit highly inclined relative to the stellar equatorial plane (Narita et al. 2009, hereafter NSH09; Winn et al. 2009, hereafter WJA09). Consequently, we report 2 candidates for faint stellar companions of HAT-P-7 based on the Subaru HiCIAO and the Calar Alto AstraLux data. Although it is impossible from our data alone to determine whether or not the candidates for companion stars are physically associated with HAT-P-7 at this point in time, the findings are useful for constraining the mechanism of planetary migration in this system. We summarize the properties of our target in section 2, and report our observations, analyses, and results in section 3. We present theoretical discussions of the migration mechanism of HAT-P-7b in section 4. Finally, in section 5 summarize we the findings in this paper.

2. Target Properties

HAT-P-7 (also known as Kepler-2) is an F8 star, hosting a very hot Jupiter HAT-P-7b (Pál et al. 2008, hereafter PBT08). The stellar distance was estimated to be 320 ± 50 pc (PBT08). According to the 2MASS catalog (Skrutskie et al. 2006), the H-band magnitude of HAT-P-7 is 9.34 ± 0.02. This star is in the field of view of the NASA Kepler mission (Burucki et al. 2009), and detailed stellar parameters that were reported through a Kepler astroseismology research are as follows: the mass $M_*$ = 1.520 ± 0.036 $M_\odot$, the radius $R_*$ = 1.991 ± 0.018 $R_\odot$, and the age 2.14 ± 0.26 Gyr (Christensen-Dalsgaard et al. 2010, hereafter CKB10). The planet HAT-P-7b has a very close-in orbit with an orbital period of 2.204733 ± 0.000010 d and a semimajor axis $a$ = 0.0386 ± 0.0001 AU (Welsh et al. 2010, hereafter WOS10). The mass, radius, and orbital inclination of HAT-P-7b are 1.82 ± 0.03 $M_{\text{Jup}}$, 1.50 ± 0.02 $R_{\text{Jup}}$, and 83.1 ± 0.5, respectively (WOS10). These properties are summarized in table 1.

The orbit of HAT-P-7b does not have a significant eccentricity (PBT08; NSH09; WJA09; WOS10). Nevertheless, NSH09 and WJA09 found that HAT-P-7b has an extremely tilted orbital axis relative to the stellar rotation axis. In addition, WJA09 reported an additional long-term radial velocity trend, implying a third body in the planetary system. Thus, this system is a very fascinating target of direct imaging to search for outer massive bodies.

Table 1. Summary of stellar and planetary parameters.

| Parameter | Value | Error | Source |
|-----------|-------|-------|--------|
| Star      |       |       |        |
| $M_*$ [$M_\odot$] | 1.520 | 0.036 | CKB10  |
| $R_*$ [$R_\odot$] | 1.991 | 0.018 | CKB10  |
| Age [Gyr] | 2.14  | 0.26  | CKB10  |
| Distance [pc] | 320  | ±50   | PBT08  |
| App. $H$ mag. | 9.344 | 0.029 | 2MASS2 |
| Planet    |       |       |        |
| $M_{\text{p}}$ [$M_{\text{Jup}}$] | 1.82  | 0.03  | WOS10  |
| $R_{\text{p}}$ [$R_{\text{Jup}}$] | 1.50  | 0.02  | WOS10  |
| $i$ [°]  | 83.1  | 0.5   | WOS10  |
| $a$ [AU] | 0.0386 | 0.0001 | WOS10  |
| $P$ [d] | 2.204733 | 0.000010 | WOS10  |

1 There is a slight uncertainty in the spectral subclass of HAT-P-7, and the uncertainty would have a slight effect on apparent $i^\prime$ and $z^\prime$-band magnitudes quoted in table 2. However, subsequent discussions and conclusion of this paper would remain unchanged.

2 (http://irsa.ipac.caltech.edu/applications/Gator/).
3. Analyses

3.1. Subaru / HiCIAO

We first observed HAT-P-7 in the $H$ band with the HiCIAO combined with the AO188 (188-element curvature sensor adaptive optics system: Hayano et al. 2008), mounted on the 8.2 m Subaru Telescope on 2009 August 6 UT. The field of view was $20'' \times 20''$, and the typical seeing was $\approx 0.5''$ on that night. We used the target star, itself, as natural guiding for AO188. We took 30 object frames with an exposure of 19.50 s (i.e., the total exposure was 9.75 min). The observations were conducted in the pupil tracking mode to use the angular differential imaging (ADI: Marois et al. 2006) technique. The gain of the detector was $1.66 \, e^-/ADU$, the readout noise was $15 \, e^-$, and the zero point magnitude (the magnitude of an object that would yield 1 ADU/s) of the image was $H = 24.654 \pm 0.036\,\text{mag}$. Our Subaru HiCIAO reduction procedures were as follows. We first removed a characteristic stripe bias pattern arising from the Subaru HiCIAO detector. Then, flat fielding was done by using dome flat frames, and bad/hot pixels were removed. Note that we did not subtract dark frames, since the dark current of Subaru HiCIAO is sufficiently low for the exposure time. We made corrections for any distortion of the field of view by comparing an M15 image taken by Subaru HiCIAO on 2009 August 5 UT with that taken by HST/ACS. The measured pixel scale of Subaru HiCIAO was $9.44 \pm 0.10\,\text{mas per pixel}$. We shifted frames to match the stellar centroid, and used the ADI technique to combine the object frames. Field rotation during our exposures was $7''023 \pm 0''007$.

The median combined object frame is shown in the left panel of figure 1 (north is up and east is to the left, and the field of view is $12'' \times 12''$, as a subset of the full $20'' \times 20''$ frame). Two faint sources on both sides $\approx 3''$ away were clearly detected. The FWHM of the PSF was $6.1\,\text{pixel}$ ($0''.058$). We determined the positions of the candidates for companion stars using the imexam task in IRAF, and conducted aperture photometry using the phot task. We used the photometric standard star FS151 ($H = 11.946 \pm 0.008\,\text{mag}$) to determine the apparent $H$-band magnitudes of the candidates for companion stars, since HAT-P-7 in the image was saturated. The apparent $H$-band magnitude, separation angle, and position angle of each companion star from HAT-P-7 are listed in the second column of table 2. Combining our result for the separation angle with the PBT08's result for the stellar distance, we estimate that projected separation distances between these candidates for companion stars and HAT-P-7 are $\approx 1000\,\text{AU}$.

In addition, we used the locally optimized combination of...
images algorithm (LOCI: Lafrenière et al. 2007) to maximize the efficiency of the ADI technique and to search for fainter objects in the inner region around HAT-P-7. The upper-right panel of figure 1 shows an LOCI-reduced image around HAT-P-7 (north is up and east is to the left, and the field of view is $6'' \times 6''$ centered on HAT-P-7, as a subset of the full $20'' \times 20''$ frame). Clearly, the bright halo in the inner region seen in the left panel is significantly suppressed. The upper panel of figure 2 plots the $5\sigma$ contrast ratio around HAT-P-7 achieved by the Subaru HiCIAO observation, and the lower panel of figure 2 shows the corresponding detectable mass of companions, based on an age of 2.14 Gyr and the COND model by Baraffe et al. (2003). We achieved the post-LOCI contrast ratio around HAT-P-7 achieved by the Subaru HiCIAO observation, and the lower panel of figure 2 shows the corresponding detectable mass of companions, based on an age of 2.14 Gyr and the COND model by Baraffe et al. (2003). We achieved the post-LOCI $5\sigma$ contrast sensitivity for $H$ bands of $\sim 7 \times 10^{-4}$ at 0''3, $\sim 2 \times 10^{-4}$ at 0''5, and $\sim 6 \times 10^{-5}$ at 1''0, which correspond to $\sim 110\ M_{\text{Jup}}$, $\sim 80\ M_{\text{Jup}}$, and $\sim 70\ M_{\text{Jup}}$ companions, respectively. As a result, we exclude the presence of a stellar companion (more massive than $80\ M_{\text{Jup}}$ within the $6'' \times 6''$ field of view) separated 0''5 or farther at the 5$\sigma$ level. At this point in time, we have not yet put a stringent constraint on inner massive bodies. For instance, an M star ($\sim 100\ M_{\text{Jup}}$) within 0''3 ($\sim 100\ AU$) is not ruled out.

3.2. Calar Alto / AstraLux Norte Lucky Imaging

HAT-P-7 was observed in SDSS $i''$ and $z''$ filters with the AstraLux Norte Lucky Imaging camera (Hormuth et al. 2008) on the 2.2 m telescope at Calar Alto on 2009 October 30 UT. The observations were part of a large-scale high-resolution imaging in the search for close stellar companions to all known exoplanet hosts brighter than $i'' = 16$ mag (see Daemgen et al. 2009 for the first results). The survey employs the Lucky Imaging technique, which provides almost diffraction-limited images by a shift-and-add drizzle combination of only the best few percent of a series of $\sim 10000$ very short exposures ($\sim 10\ ms$), selected by the Strehl ratio. For a photometric analysis of HAT-P-7 and its companion candidates, the best 10% of a total 20000 integrations of 15 ms exposures were used, yielding a total integration time of 30 s. The combined $z''$ band image is presented in the lower right panel of figure 1 (north is up and east is to the left, and the field of view is $12'' \times 12''$).

Table 2. Magnitudes, positions, estimated* spectral type and masses of candidates for companion stars.

| Parameter | HiCIAO ($H$) | AstraLux ($i''$) | AstraLux ($z''$) |
|-----------|--------------|-----------------|-----------------|
| West (fainter) | 2009 August 6 | 2009 October 30 | 2009 October 30 |
| Apparent magnitude [mag] | Value | Error | Value | Error | Value | Error |
| Separation angle [''] | 16.92 | 0.06 | > 18.65 | — | > 18.55 | — |
| Position angle [''] | 3.14 | 0.01 | — | — | — | — |
| Estimated spectral type and mass [$M_\odot$] | M9V-L0V (0.078–0.088) |
| East (brighter) | 2009 October 30 | 2009 October 30 |
| Apparent magnitude [mag] | Value | Error | Value | Error | Value | Error |
| Separation angle [''] | 15.12 | 0.04 | 18.50 | 0.21 | 17.43 | 0.09 |
| Position angle [''] | 3.88 | 0.01 | — | — | 3.82 | 0.01 |
| Estimated spectral type and mass [$M_\odot$] | M5V-M6V (0.17–0.20) |

* Assuming that the candidate companions are main sequence stars and at the same distance as HAT-P-7.

† Assuming that HAT-P-7 is an F8 star.
The IRAF phot task was used for relative aperture photometry of HAT-P-7 and the eastern companion candidate. The western companion could not be seen in the AstraLux images. Combining the relative photometry with the $JHK$ magnitudes of HAT-P-7 (2MASS) and with the absolute magnitudes of an F8 main-sequence star (Kraus & Hillenbrand 2007), we found the apparent $i'$- and $z'$-band magnitudes to be $i' = 18.50 \pm 0.21$ mag and $z' = 17.43 \pm 0.09$ mag for the eastern companion candidate and upper limits of $i' > 18.65$ mag and $z' > 18.55$ mag for the western one. In the astrometric calibration we followed the procedures outlined by Köhler et al. (2008) based on observations of stars with well-defined astrometry in the Orion Nebula Cluster. The derived image scale of AstraLux Norte for this observing run was $23.43 \pm 0.06$ mas per pixel. For the eastern companion candidate, we determined a separation of $3.82 \pm 0.01$ and a position angle of $90^\circ 39 \pm 0^\circ 11$. These results are summarized in table 2.

3.3. Combined Results

We discovered two candidates of faint stellar companions around HAT-P-7. The $i'$ and $z'$ colors for the eastern companion suggest a main-sequence spectral type of M5–M6V, corresponding to $0.17–0.20 M_\odot$ (Kraus & Hillenbrand 2007; Covey et al. 2007). For this luminosity class, its apparent brightness in the $i'$- and $z'$-band yields as a distance modulus of $10.03$ mag for spectral type M6V, corresponding to a distance of $\sim 300$ pc. This is in agreement with the distance estimate for HAT-P-7 of $320^{+30}_{-50}$ pc (PBT08). We note that the magnitude and color of the companion candidate would also be explained by a background M5III–M6III star at a distance of 126 kpc or more (Covey et al. 2007). As to the western companion, the AstraLux Norte observations only provide an upper limit on the $i'$- and $z'$-band brightnesses; we can just derive a lower limit on its $i' - H$ and $z' - H$ colors. On the assumption that the western companion candidate is a main-sequence star associated with HAT-P-7, its $H$-band magnitude suggests M9V–L0V, corresponding to a mass in the range of $0.078–0.088 M_\odot$ (see Kraus & Hillenbrand 2007).

We note that, however, it is unrealistic that both stars are true companions of HAT-P-7, because such a wide separation of the triple system is likely to be physically unstable, and it is known that triple or quadruple stars discovered so far are hierarchial (Duquennoy & Mayor 1991). High spectral resolution observations of the candidates for companion stars would be useful for constraining their peculiar radial velocities, and thereby for discriminating their binarity. In addition, follow-up direct imaging observations, in the near future, will allow us to show via common proper motion whether the objects are true companions of HAT-P-7, whose proper motion is $18.60 \pm 3.25$ mas per year in the TYCHO reference catalogue (Høg et al. 1998). We note, however, that there exists more than a $3\sigma$ inconsistency between the Subaru HiCIAO result and the Calar Alto AstraLux one (epoch difference of less than 3 months) for the separation angle of the eastern companion. However, at this point in time we do not conclude that the eastern companion is not associated with HAT-P-7, because the separation angle might be affected by the errors of the pixel scale, and also because the errors of the separation angle might be underestimated due to systematic errors caused by saturation or a non-Gaussian PSF shape. Thus, further follow-up observations would be needed to decide whether the two stars are truly associated with HAT-P-7 or not.

4. Discussion

In this section, we discuss realizable migration mechanisms of the highly tilted orbit planet HAT-P-7b. First of all, as a simple case, if neither of the companion candidates we discovered is physically associated with HAT-P-7, only planet–planet scattering can explain the tilted orbit of HAT-P-7b. We thus examine a Kozai migration scenario for HAT-P-7b first, based on the assumption that either of the candidates for companion stars is a true binary of HAT-P-7. We present the conditions required for the Kozai migration of HAT-P-7b with a binary companion in subsection 4.1. We show a restricted area of a third body for the Kozai migration in this system in subsection 4.2., and describe the impact of a possible third body (HAT-P-7c) reported by WJAO9 in subsection 4.3.

4.1. Required Condition for the Kozai Migration of HAT-P-7b

According to Kozai (1962), the angular momentum, $L_Z \equiv G (M_p + M_s) a \cos \Psi m$, should be conserved in a planetary system with a binary star during the Kozai mechanism, where $G$ is the gravitational constant, $M_s$ and $M_p$ the masses of the planet and its host star, $a$ and $e$ the semimajor axis and the orbital eccentricity of the planet, and $\Psi_m$ (domain: $[0^\circ, 180^\circ]$) the mutual inclination between the orbital planes of the planet and the binary star. In addition, given that the angular momentum is also conserved during the tidal orbital evolution, $a (1 - e^2) \cos^2 \Psi_m$ should be conserved through the Kozai migration.

Using the conservation relation above, we constrain the initial mutual inclination to initiate the Kozai migration in this system. First we assume that HAT-P-7b was born in the snow line with the initial eccentricity, $e_0$, and the initial mutual inclination, $\Psi_{m,0}$. The distance of the snow line from the host star is roughly estimated to be $a_0 = 2.7 (M_s/M_\odot)^2 = 6.24$ AU (i.e., 20 mas). We note that although the position of the snow line is somewhat uncertain, this has little impact on the following discussions. Then, using the conservation relation rewritten as

$$a_0 (1 - e_0^2) \cos^2 \Psi_{m,0} = a_n (1 - e_n^2) \cos^2 \Psi_{m,n},$$

(2)

where the indices 0 and n indicate the values of the initial state and those as of now, respectively, we obtain

$$|\cos \Psi_{m,n}| \leq \sqrt{\frac{0.0386}{6.24}} \frac{1}{1 - e_0^2} |\cos \Psi_{m,0}|$$

(3)

as a necessary initial condition for the orbit of HAT-P-7b. If this condition is satisfied, the eccentricity would be excited over the critical value $\sqrt{[1 - (0.0386/6.24)]} = 0.997$, and the planet would initiate tidal evolution.

We note that the timescale of the Kozai migration under consideration is approximated as (Wu et al. 2007)

$$P_k \sim \frac{M_s}{M_p} \frac{P_0}{P_2} (1 - e_0^2)^{3/2},$$

(4)
where $M_B$, $P_B$, and $e_B$ are the mass, orbital period, and eccentricity of the binary star, and $P_0$ is the orbital period of HAT-P-7b at the initial position. Assuming that $M_B = 0.20M_\odot$ (as a typical mass of M star) and $e_B = 0$, we obtain $P_{\text{Kozai}} \sim 300$ Myr, which is sufficiently short relative to the age of this system (~2 Gyr). In addition, the timescale of general relativity is estimated to be (Wu & Murray 2003)

$$P_{\text{GR}} \sim \frac{2\pi c^2}{3(GM_\odot)^{1/2}} \sim 2\text{Gyr},$$

where $c$ is the speed of light. Thus, general relativity would not disturb the Kozai migration of HAT-P-7b at an early stage.

Based on equation (3), if HAT-P-7b was born with $e_0 = 0$ and if $\Psi_{m,n} = 0^\circ$, namely if HAT-P-7b and the binary star are coplanar now, the initial mutual inclination, $\Psi_{m,0}$, needs to be within $85.5^\circ$–$94.5^\circ$ to initiate Kozai migration. Even if we assume that the initial eccentricity is large (e.g., $e_0 = 0.8$) and the current mutual inclination is zero, $\Psi_{m,0}$ needs to be within $82.5^\circ$–$97.5^\circ$. This is a very optimistic case; if the eccentricity is lower and $\Psi_{m,0}$ is not zero, the required condition becomes more stringent. These required conditions are very tight, but still possible (a few suggestive circumstellar disk observations of nonzero $\Psi_{m,0}$ for young binary stars were reported: e.g., Akeson et al. 1998; Duchêne et al. 2005; Hioki et al. 2009).

### 4.2. Restricted Area of a Third Body for the Kozai Migration Scenario

As discussed by Wu and Murray (2003) for HD 80606b, a hypothetical additional body HAT-P-7c in the HAT-P-7 system could destroy the Kozai migration process (Innanen et al. 1997), if the timescale of orbital precession of HAT-P-7b caused by the gravitational perturbation from HAT-P-7c, $P_{\text{Ko},c}$, is shorter than that caused by the Kozai mechanism due to the binary companion, $P_{\text{Ko},B}$. We calculated that a conditional equation for a restricted area of an outer third body at the initial stage is

$$M_c > \frac{3}{2} \frac{M}{a_B^2} \frac{a}{b_{3/2}},$$

where $a_c$ and $M_c$ are the semimajor axis and the mass of the additional planet, $a_B$ the semimajor axis of the binary star, and $b_{3/2}$ the Laplace coefficient (see, e.g., Murray & Dermott 2000; Wu & Murray 2003).

The boundary of the restricted area is plotted in figure 3 by solid (for $a_B = 1000$ AU) and dotted (for $a_B = 2000$ AU) lines. The horizontal axis and the vertical one represent $a_c$ and $M_c$, respectively. More specifically, the upper region of the solid (dotted) line is the restricted area where HAT-P-7c cannot exist initially for the Kozai migration caused by the binary companion. This constraint is very stringent, and even analogies of Saturn ($a_c = 9.6$ AU, $M_c = 0.3 M_{\text{Jup}}$) and Uranus ($a_c = 19.2$ AU, $M_c = 0.05 M_{\text{Jup}}$) cannot exist.

#### 4.3. Impact of HAT-P-7c Reported by Winn et al. (2009)

On the other hand, WJA09 reported that there is indeed a possible third body, HAT-P-7c, in the HAT-P-7 system (hereafter, just “c”). As a constraint on the mass and the semimajor axis of the additional body, WJA09 reported the following equation:

$$\frac{M_c \sin i_c}{a_c^2} \sim (0.121 \pm 0.014) M_{\text{Jup}} \text{AU}^{-2},$$

where $i_c$ is the orbital inclination of “c” relative to the line of sight. We plot equation (7) (assuming that $\sin i_c = 0$ for the sake of simplicity) in figure 3 using a dashed-dotted line as a reference. Obviously, the Kozai migration scenario is totally excluded if “c” existed in the outer region (beyond the snow line) at the initial stage. Thus, in the presence of “c”, it is impossible to explain the tilted orbit of HAT-P-7b by the Kozai migration caused by only the distant binary companion.

However, there is another chance of a “sequential” Kozai migration scenario for a 2-body system with a binary star, as introduced by Takeda, Kita, and Rasio (2008) and Kita, Rasio, and Takeda (2010). Namely, an inclined binary companion induces the Kozai mechanism for an outer body first, and then the inclined outer body leads the Kozai mechanism for an inner body. In this case, “c” could play an important role for the migration of HAT-P-7b. If this is the case, “c” could have a tilted orbital axis relative to both the stellar spin axis and the orbital axis of HAT-P-7b. We cannot discuss this possibility in detail at this point in time, because the orbital parameters of “c” have not yet been determined. If orbital parameters of “c” are firmly determined, it would be interesting to discuss the possibility of a sequential Kozai migration scenario. We also note that if the semimajor axis of “c” turns out to be large, further direct imaging of this inner body would be also interesting in the future (for example, with TMT or E-ELT).

Through the above discussions, we found that the Kozai migration scenario caused by a distant binary star could be realized only in a very limited situation. In addition, if “c” existed,
the Kozai migration of HAT-P-7b caused directly by the binary star could not have occurred, although we could not rule out the possibility of a sequential Kozai migration for HAT-P-7b at this point in time. In addition, if neither of the candidate stars is a physical companion of HAT-P-7, only planet–planet scattering could explain the tilted orbit of HAT-P-7b. Thus, with a few exceptions, as mentioned above, we conclude that planet–planet scattering is a more plausible explanation for the migration mechanism of HAT-P-7b.

5. Summary

We conducted direct imaging observations of HAT-P-7 with the Subaru HiCIAO and the Calar Alto AstraLux. The system was reported to have a highly tilted transiting planet HAT-P-7b, and massive bodies were expected to exist in the outer region based on planetary migration theories. We discovered two companion candidates around HAT-P-7. We modeled and constrained the Kozai migration scenario for HAT-P-7b under the existence of a binary star, and found that the Kozai migration scenario was realizable only in a very limited condition, and was not favored if the additional body HAT-P-7c existed, as reported by WJA09. As a result, we conclude that planet–planet scattering is particularly plausible for the migration mechanism of HAT-P-7b. To complement our conclusion of the migration mechanism of HAT-P-7b, further radial velocity measurements of HAT-P-7 are earnestly desired to constrain orbital parameters of HAT-P-7c. In addition, further direct imaging and high spectral resolution observations of the candidates for companion stars would be very useful for constraining common proper motions and peculiar radial velocities of the stars, and thereby for discriminating their binarity.

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