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# Good Combination of the Rossiter-McLaughlin Measurements and Direct Imaging Observations



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**Abstract.** We introduce a novel methodology to distinguish planetary migration mechanisms by a combination of Rossiter-McLaughlin measurements and direct imaging observations. The methodology is especially useful to specify a planetary migration mechanism one-by-one for an eccentric or tilted planet. We present an example of the application of the methodology for HAT-P-7 based on our observations with the 8.2m Subaru Telescope.

## 1. Introduction

The discovery of about 500 extrasolar planets and the diversity of their orbital distributions dramatically changed our perception of planetary systems. To explain the whole orbital distribution of known exoplanets, a number of planetary migration mechanisms have been proposed, including disk-planet interaction models (e.g., Lin et al. 1996; Ida & Lin 2004), planet-planet scattering models considering gravitational interaction among multiple giant planets (e.g., Nagasawa et al. 2008), or Kozai migration models considering perturbation by a distant companion and coinstantaneous tidal evolution (e.g., Fabrycky & Tremaine 2007). These planetary migration models can now be tested by measurements of the Rossiter-McLaughlin (RM) effect (Rossiter 1924; McLaughlin 1924) for transiting planetary systems, which is an anomalous shift in observed radial velocities due to a partial occultation of a rotating star. Previous measurements of the RM effect have revealed that numbers of transiting planets indeed have highly tilted orbits, which are consistent with predictions of the planet-planet scattering models and the Kozai migration models. The fact is important evidence that a significant part of exoplanets have migrated inward through planet-planet scattering or Kozai migration processes. However, a big problem is that one cannot distinguish the planet-planet scattering models and the Kozai migration models by orbital eccentricities or spin-orbit alignment angles alone. We thus need to obtain more clues to discriminate the two planetary migration models by identifying counterparts of migration processes (i.e., scattered outer planets for the planet-planet scattering models, and a binary companion for the Kozai migration models). For the purpose, direct imaging is very useful to search for outer massive bodies and give us crucially important information to distinguish between the two migration mechanisms of eccentric or tilted exoplanets.

## 2. Methodology

We have devised a novel procedure to discriminate or at least constrain planetary migration models for eccentric or tilted exoplanets by direct imaging observations. The procedure is summarized as follows.

– STEP 1. Check the presence of binary companion candidates.

  If there is no binary companion, then we can exclude the Kozai migration mechanism caused by a binary star. If there is a binary candidate(s), proceed to STEP 2. Note that we can confirm the binary nature by checking (i) common distance inferred by spectral type, (ii) common peculiar velocity by high dispersion spectrocopy, or (iii) common proper motion by additional direct imaging.

– STEP 2. Calculate the restricted region (in mass and semi-major axis space) of additional bodies for the Kozai migration.

  The Kozai migration cannot occur if the timescale of orbital precession due to an additional body ($P_{G,c}$) is shorter than that caused by a binary companion through Kozai mechanism ($P_{K,B}$) (Kozai 1962, Innanen et al. 1997). Using this fact, if a long-term radial velocity trend in the system suggests that an additional body orbits in the restricted region, we can exclude the Kozai migration. If there is no additional body in the restricted region, then proceed to STEP 3.

– STEP 3. Calculate the initial planet-binary configuration for the Kozai migration.

  In this case we cannot exclude the possibility of the Kozai migration completely. Instead, we can constrain the initial mutual inclination angle between the planetary orbital axis and the binary orbital axis based on the angular momentum conservation during the Kozai migration.

## 3. The Case for HAT-P-7

### 3.1 Target Properties

We selected the transiting planetary system HAT-P-7 as the first target. HAT-P-7 (also known as Kepler-2) is an F8 star, hosting a very hot Jupiter HAT-P-7b (Pál et al. 2009). The stellar distance was estimated as $320^{+50}_{-40}$ pc. This star is in the field of view of the NASA Kepler mission (Borucki et al. 2009). The planet HAT-P-7b has a mass of $1.82 \pm 0.03 M_{\rm Jup}$, with the orbital period of $2.204733 \pm 0.000010$ days and the semi-major axis of $a = 0.0386 \pm 0.0001$ AU (Welsh et al. 2010). The orbit of HAT-P-7b does not have a significant eccentricity. Nevertheless, Narita et al. (2009) and Winn et al. (2009) found that the planet has an extremely tilted orbit relative to the stellar rotation axis. In addition, Winn et al. (2009) reported an additional long term RV trend, implying a massive third body in the planetary system.

### 3.2 Direct Imaging Observations

We conducted direct imaging observations with the Subaru HiCIAO (High Contrast Instrument for the Subaru next generation Adaptive Optics; Suzuki et al. 2009), as part of the SEEDS project (Strategic Explorations of Exoplanets and Disks with Subaru, PI: Motohide Tamura; Tamura 2009). We observed HAT-P-7 in the $H$ band combined with the AO188 (188-element curvature sensor adaptive optics system; Hayano et al. 2008), mounted on the Subaru Telescope on UT 2009 August 6. The result image is shown in figure 1 (north is up and east is left, and the field of view is 12×12 arcsec, as a subset of the full 20×20 arcsec frame). Two faint sources at about 3-4 arcsec away are clearly detected. The apparent $H$ band magnitude, separation angle, and position angle of each companion star from HAT-P-7 are presented in Narita et al. (2010). We estimate that projected separation distances of these candidate companion stars from HAT-P-7 are about 1000 AU. HAT-P-7 was also observed in SDSS $i'$ and $z'$ filter with the AstraLux Norte Lucky Imaging camera (Hormuth et al. 2008) at the 2.2 m telescope at Calar Alto on UT 2009 October 30. Assuming that the candidate companions are main sequence stars associated with HAT-P-7, we estimate that the candidate companions are late M stars, based on a comparison of the colors of the candidate companions with the spectral energy distribution (SED) standard stars (Kraus & Hillenbrand 2007; Covey et al. 2007).

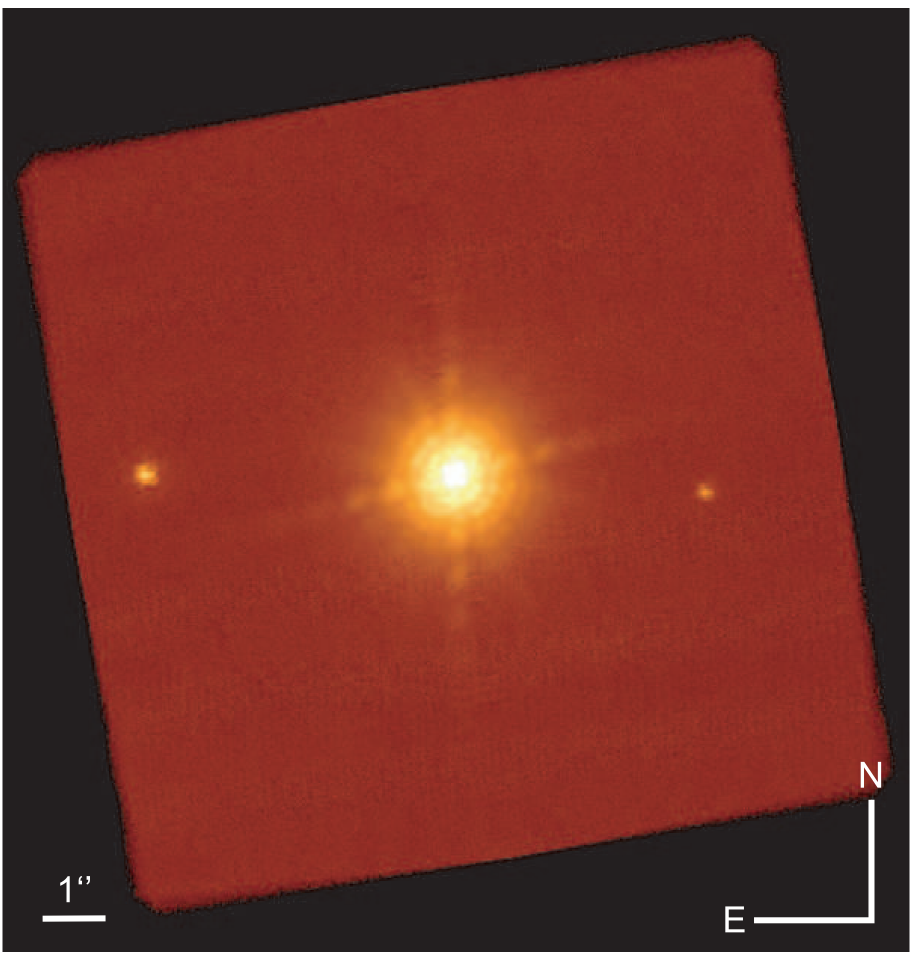


Figure 1: *A combined image of HAT-P-7 in H band taken with the Subaru HiCIAO on UT 2009 August 6. North is up and east is left. The field of view is 12×12 arcsec.*

### 3.3 The planetary migration mechanism of HAT-P-7b

As discussed by Wu & 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 ($P_{\mathrm{G},c}$) is shorter than that caused by the Kozai mechanism due to the binary companion ($P_{\mathrm{K},B}$). A conditional equation for a restricted area of an outer third body at the initial stage is:

$$M_c > \frac{3}{2} M_s \frac{a_c^2 a}{a_B^3} \frac{1}{b_{3/2}^{(1)}}, \tag{1}$$

where $a_c$ and $M_c$ are the semi-major axis and mass of the additional planet, $a_B$ is the semi-major axis of the binary star, and $b_{3/2}^{(1)}$ is the Laplace coefficient (see Wu & Murray 2003). If the above condition is met, the Kozai migration of HAT-P-7b due to the candidate companions cannot occur. On the other hand, Winn et al. (2009) reported that there is indeed a possible third body HAT-P-7c in the HAT-P-7 system. As a constraint on the mass and semi-major axis of the additional body, they reported the following relation:

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

where $i_c$ is the orbital inclination of HAT-P-7c relative to the line of sight. As a result, we have found that HAT-P-7c is in the restricted region. Thus in the presence of HAT-P-7c, it is impossible to explain the tilted orbit of HAT-P-7b by the Kozai migration caused by the possible binary companions. Thus we conclude that the Kozai migration is less likely while planet-planet scattering is possible for the migration mechanism of HAT-P-7b (see Narita et al. 2010 for details).

## 4. Summary and Future Prospects

We have devised a novel procedure to discriminate or at least constrain planetary migration models by a combination of the Rossiter-McLaughlin effect and direct imaging observations. We have applied the methodology to HAT-P-7b, which was reported to have a highly tilted or even retrograde orbit based on the Rossiter-McLaughlin measurements (Narita et al. 2009; Winn et al. 2009). Based on additional direct imaging observations, two candidates of distant stellar companions have been found around HAT-P-7. We have shown that the Kozai migration of HAT-P-7b due to the candidate companions is impossible in the presence of HAT-P-7c reported by Winn et al. (2009). As a result, we conclude that planet-planet scattering is the most likely migration mechanism for HAT-P-7b. Through the experience for the HAT-P-7 system, we have demonstrated that the methodology is especially useful to specify planetary migration mechanisms for eccentric or tilted planets. In addition, we note that direct imaging observations are also important for non-eccentric and aligned planetary systems to constrain populations of the Kozai migration. Planetary migration mechanisms for large numbers of exoplanets can be constrained one-by-one via the combination of the Rossiter-McLaughlin effect and direct imaging, and thereby we would be able to specify a dominant mechanism of planetary migration statistically in the near future.

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