

SPIN-ORBIT ALIGNMENT FOR THE ECCENTRIC EXOPLANET HD 147506b¹

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ABSTRACT

The short-period exoplanet HD 147506b (also known as HAT-P-2b) has an eccentric orbit, raising the possibility that it migrated through planet-planet scattering or Kozai oscillations accompanied by tidal dissipation. Either of these scenarios could have significantly tilted the orbit relative to the host star’s equatorial plane. Here we present spectroscopy of a transit of HD 147506b and assess the spin-orbit alignment via the Rossiter-McLaughlin effect. We find the angle between the sky projections of the stellar spin axis and orbital axis to be aligned within 14°. Thus, we find no corroborating evidence for scattering or Kozai migration, although these scenarios cannot be ruled out with the present data.

Subject headings: planetary systems — planetary systems: formation — stars: individual (HD 147506, HAT-P-2) — stars: rotation

1. INTRODUCTION

Giant planets that orbit Sun-like stars with periods shorter than ~5 days present both a problem and an opportunity. The problem is how they achieved such tight orbits after presumably forming at much larger orbital distances (Lin et al. 1996). The opportunity is that such close-in planets are more likely to transit their parent stars, giving access to many system properties such as the planetary radius, temperature, and atmospheric composition, that are otherwise difficult or impossible to measure (Charbonneau et al. 2007).

In this Letter we describe our attempt to exploit the transiting configuration of the recently discovered exoplanet HD 147506b (Bakos et al. 2007) to investigate the planet’s particular migration history. Interestingly, the orbit has a large eccentricity ($e \approx 0.5$), which is typical of giant planets at larger orbital distances, but atypical of short-period planets. The expected e -folding time for tidal circularization is comparable to the stellar age, making it likely that some circularization has already occurred, and raising the question of how such a high initial eccentricity was generated.

Simulations of inward planet migration via tidal interactions with the protoplanetary disk generally do not predict eccentricities as large as 0.5 (see, e.g., D’Angelo et al. 2006). In contrast, planet-planet scattering naturally excites eccentricities to large values (e.g., Rasio & Ford 1996; Chatterjee et al. 2007). Another possibility is the Kozai mechanism: due to the tide of a third body, the orbit undergoes eccentricity/inclination oscillations and ultimately shrinks in semimajor axis due to tidal

dissipation (e.g., Fabrycky & Tremaine 2007; Wu et al. 2007). A corollary of either scattering or Kozai migration is that the orbit can be tilted considerably with respect to its initial orbital plane, which was presumably close to the stellar equatorial plane.

One can search for such a misalignment by exploiting the Rossiter-McLaughlin (RM) effect, the spectral distortion observed during a transit due to stellar rotation. The planet hides part of the rotational velocity field of the stellar photosphere, resulting in an “anomalous Doppler shift” (see, e.g., Ohta et al. 2005, Giménez 2006, or Gaudi & Winn 2007). The time sequence of anomalous Doppler shifts depends on the angle between the stellar spin axis and the orbital axis, as projected on the sky. This angle has been measured to be small or consistent with zero in several systems, with accuracies ranging from 1° to 30° (Bundy & Marcy 2000; Queloz et al. 2000; Winn et al. 2005, 2007; Wolf et al. 2006; Narita et al. 2007).

Here we present observations of the RM effect for HD 147506, also known as HAT-P-2. As reported by Bakos et al. (2007), this system consists of an F8 star with an unusually massive planet ($8M_{\text{Jup}}$) in a 5.6 day orbit. Our observations are described in § 2, our model in § 3, and our results in § 4, followed by a brief summary and discussion in § 5.

2. OBSERVATIONS

We observed the transit of UT 2007 June 6 with the Keck I 10 m telescope and the High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) following standard procedures of the California-Carnegie planet search, as summarized here. We employed the red cross-disperser and used the I_2 absorption cell to calibrate the instrumental response and the wavelength scale. The slit width was 0.85", and the typical exposure time was 200 s, giving a resolution of 70,000 and a signal-to-noise ratio (S/N) of 200 pixel⁻¹. We obtained 97 spectra over 8.4 hr bracketing the predicted transit midpoint.

We determined the relative Doppler shifts with the algorithm of Butler et al. (1996). We estimated the measurement uncertainties based on the scatter in the solutions for each 2 Å section of the spectrum. The data are given in Table 1 and plotted in Figure 1. Also shown in Figure 1 are data obtained previously by Bakos et al. (2007), consisting of 10 velocities measured

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TABLE 1
SYSTEM PARAMETERS OF HD 147506

Parameter	Value	Uncertainty
M_* (M_\odot)	1.32	0.08
M_p (M_{Jup})	8.04	0.40
R_* (R_\odot)	1.48	0.05
R_p (R_{Jup})	0.98	0.04
Orbital period (days) ^a	5.63341	0.00013
e	0.501	0.007
ω (deg)	-172.6	1.6
i (deg)	>86.8	(95% conf.)
Impact parameter ^b	<0.41	(95% conf.)
T_c (HJD)	2454212.8561	0.0006
$v \sin i_*$ (km s^{-1})	19.6	1.0
λ (deg)	1.2	13.4
γ (m s^{-1})	399	10
$\Delta\gamma$ (m s^{-1})	45	18

^a From Bakos et al. (2007).

^b See eq. (3).

with Keck/HIRES¹⁰ and a z-band transit light curve obtained with the Fred L. Whipple Observatory 1.2 m telescope. All of these data were incorporated into our model.

3. THE MODEL

We fitted the photometry and radial velocities with a parameterized model based on a star and planet in a Keplerian orbit about the center of mass. To calculate the relative flux as a function of the projected separation of the planet and the star, we assumed the limb-darkening law to be quadratic and employed the formulas of Mandel & Agol (2002). We fixed the z-band limb-darkening coefficients at the values $a = 0.14$, $b = 0.36$, based on interpolation of the tables by Claret (2004) for a star with the observed effective temperature, surface gravity, and metallicity.

To calculate the anomalous Doppler shift, we used the technique of Winn et al. (2005): we simulated RM spectra with the same data format and noise characteristics as the actual data and determined the Doppler shifts using the same algorithm used on the actual data. The simulations rely on a template spectrum (described below) that is meant to mimic the emergent spectrum from a small portion of the photosphere. We scaled the template spectrum in flux by ϵ and shifted it in velocity by v_p , representing the spectrum of the occulted portion of the stellar disk. We subtracted the scaled and shifted spectrum from a rotationally broadened version of the template spectrum (broadened to 20 km s^{-1} to mimic the disk-integrated spectrum of HD 147506) and then “measured” the anomalous Doppler shift Δv . This was repeated for a grid of $\{\epsilon, v_p\}$, and a polynomial function was fitted to the resulting surface.

The template spectrum should be similar to that of HD 147506 but with narrower lines because of the lack of rotational broadening. We tried both an empirical template and a theoretical template. The empirical template was a spectrum of HD 3861 (F5, $v \sin i_* = 2.8 \text{ km s}^{-1}$; Valenti & Fischer 2005) that was observed immediately following the transit, with an S/N of 500 and a resolution of 70,000. The theoretical template had a resolution of 200,000 and was taken from the model library of Coelho et al. (2005) for a nonrotating star with $T_{\text{eff}} =$

¹⁰ Bakos et al. (2007) reported 13 Keck/HIRES velocities measured on 10 different nights. For convenience, we binned the data that were obtained on the same night. We did not use the less precise Lick velocities, to avoid the introduction of another free parameter for the Lick/Keck velocity offset.

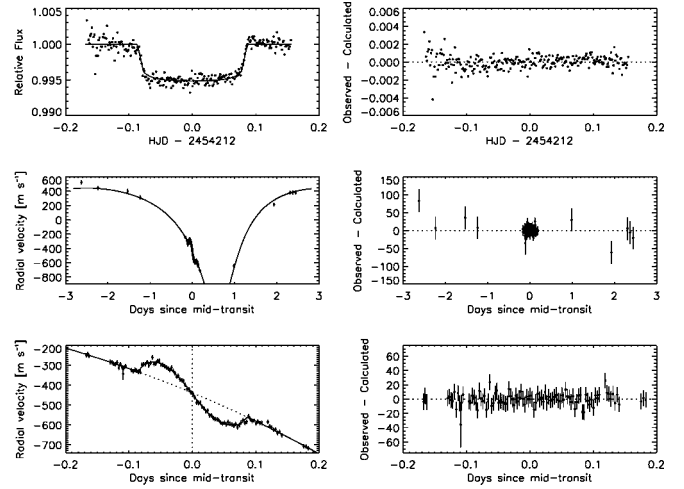


FIG. 1.—Photometry and spectroscopy of HD 147506. *Top*: The z-band photometry of Bakos et al. (2007), binned into groups of 4 points to reduce visual clutter. The solid line is our best-fitting model. *Middle*: Radial velocities, from this work and from Bakos et al. (2007), as a function of the time modulo the orbital period. The solid line is our best-fitting model. *Bottom*: Close-up of the radial velocities near the midtransit time.

6250 K, $\log g = 4.0$, and $[\text{Fe}/\text{H}] = 0.10$. The final results for the system parameters did not vary significantly with the choice of template, but the calibration based on the empirical template provided a better fit to the data. Hence, in our final results we used the following relation based on the empirical template:

$$\Delta v = -\epsilon v_p \left[2.16 - 2.47 \left(\frac{v_p}{20 \text{ km s}^{-1}} \right)^2 + 0.98 \left(\frac{v_p}{20 \text{ km s}^{-1}} \right)^4 \right]. \quad (1)$$

With this formula, the anomalous Doppler shift $\Delta v(t)$ can be related to the flux decrement ϵ and the subplanet velocity v_p at that time. The subplanet velocity is the projected rotation velocity of the portion of the star hidden by the planet. When fitting the model to the data, v_p was computed as a function of the relative position of the star and planet under the assumption of uniform rotation of the photosphere.

The fitting statistic was

$$\chi^2 = \sum_{j=1}^{962} \left[\frac{f_j(\text{obs}) - f_j(\text{calc})}{\sigma_{f,j}} \right]^2 + \sum_{j=1}^{111} \left[\frac{v_j(\text{obs}) - v_j(\text{calc})}{\sigma_{v,j}} \right]^2 + \left(\frac{v \sin i_* - 19.8 \text{ km s}^{-1}}{1.6 \text{ km s}^{-1}} \right)^2 + \left(\frac{M_*/M_\odot - 1.32}{0.08} \right)^2 + \left(\frac{R_*/R_\odot - 1.53}{0.10} \right)^2 + \left(\frac{\Delta\gamma}{31 \text{ m s}^{-1}} \right)^2, \quad (2)$$

where $f_j(\text{obs})$ is the flux observed at time j , $\sigma_{f,j}$ is the corresponding uncertainty, and $f_j(\text{calc})$ is the calculated value. A similar notation applies to the velocities. The last four terms are a priori constraints. The first three of these constraints enforce the spectroscopic parameters derived by Bakos et al. (2007). The last constraint is explained below.

It is important for the data weights $\sigma_{f,j}$ and $\sigma_{v,j}$ to account for unmodeled systematic errors in addition to measurement

errors. We assessed systematic errors in the photometry by examining the out-of-transit (OOT) measurements. We compared the standard deviation of the unbinned OOT data (σ_1) with the standard deviation of the binned OOT data (σ_N , where $N = 40$ data points or 20 minutes). We chose the bin size to be the approximate ingress or egress duration, since those phases provide much of the leverage on the model parameters. With independent Gaussian noise, we would find $\sigma_N = \sigma_1/\sqrt{40}$, but in fact σ_N was larger by a factor of 1.25, representing a level of “red noise” that is commonly seen in ground-based photometry. For this reason, we set $\sigma_{f,j} = 1.25\sigma_1$ before computing our final results. With this choice, the minimum value of χ^2/N_{dof} was less than unity, which is appropriate because the data points are not truly independent.

Likewise, the weights for the velocities should account for intrinsic velocity noise (“photospheric jitter”). We assessed the amplitude and timescale of the noise as follows. First, we fitted only the 10 velocities obtained by Bakos et al. (2007) on different nights. We fixed the orbital period and transit time and optimized the velocity semiamplitude, eccentricity, argument of pericenter, and velocity zero point. The rms residual was 32 m s^{-1} . This is consistent with the quadrature sum of the typical measurement error of 7 m s^{-1} and an intrinsic noise term of 31 m s^{-1} , and the latter is in agreement with the empirical noise estimators of Wright (2005) for an F8 star with the observed rotation velocity. Therefore, for fitting purposes, we took the weights $\sigma_{v,j}$ of the Bakos et al. (2007) velocities to be the quadrature sum of the measurement error and 31 km s^{-1} . Second, we fitted only 31 OOT velocities observed on 2007 June 6, finding the rms residual to be 11 m s^{-1} , which is consistent with the quadrature sum of the measurement error and an intrinsic noise term of 10 m s^{-1} . Therefore, for the data taken on 2007 June 6, we calculated $\sigma_{v,j}$ by adding the measurement error and 10 m s^{-1} in quadrature. Apparently, most of the intrinsic velocity noise occurs on a timescale longer than one night, as we also found for HD 189733 (Winn et al. 2006).

The model parameters were the two bodies’ masses and radii (M_* , M_p , R_* , and R_p); the orbital inclination (i); the midtransit time (T_c); the line-of-sight stellar rotation velocity ($v \sin i_*$); the angle between the projected stellar spin axis and orbit normal (λ); the velocity zero point (γ); and a velocity offset specific to the night of 2007 June 6 ($\Delta\gamma$). This last parameter is needed because of the photospheric jitter; the last term in equation (2) enforces a reasonable level of noise. We fixed the orbital period to be 5.63341 days (Bakos et al. 2007). We used a Markov Chain Monte Carlo algorithm to solve for the model parameters and their 68% confidence limits.¹¹

4. RESULTS

The results are given in Table 1. Our results for both R_p and R_* are in agreement with the values determined by Bakos et al. (2007), which is not surprising, given that those parameters depend chiefly on the photometry and we have used precisely the same photometry.¹² The impact parameter b of a transit is

the minimum projected star-planet distance, expressed in units of the stellar radius. For an eccentric orbit it is given approximately by

$$b = \frac{1 - e^2}{1 + e \sin \omega} \frac{a \cos i}{R_*}. \quad (3)$$

We find that the HD 147506 transit occurs at a small impact parameter: $b < 0.41$ with 95% confidence. This follows from the short durations of ingress and egress relative to the total duration of the transit. This upper limit on the impact parameter is more constraining than the upper limit that was obtained by Bakos et al. (2007), indicating that our transit velocities are providing most of the leverage on the impact parameter.

As for the key spin-orbit parameter, we found $\lambda = 1.2^\circ \pm 13.4^\circ$, i.e., consistent with perfect alignment. The 95% confidence upper limit on $|\lambda|$ is 29.6° . There is a strong covariance between λ and $v \sin i_*$, which is a consequence of the small impact parameter (Gaudi & Winn 2007). For this reason, we investigated the dependence of our results on the a priori constraint on $v \sin i_*$, by either abandoning the constraint or by strengthening it. The conclusion that λ is consistent with zero is unchanged by modifying the constraint; only the dispersion in λ changes. If we drop the constraint completely, the 1σ error in λ grows to 23° , and the result for $v \sin i_*$ is $22 \pm 4 \text{ km s}^{-1}$. However, if we assume $v \sin i_* = 22 \text{ km s}^{-1}$ exactly, then the error in λ shrinks to 9° .

5. SUMMARY AND DISCUSSION

We have monitored the apparent Doppler shift of HD 147506 during a transit of its giant planet and have modeled the available photometric and spectroscopic data. By modeling the RM effect, we find that the stellar spin axis and the orbit normal are aligned on the sky to within 14° . This is unlikely to be a coincidence. If the spin axis were randomly oriented, the probability of observing $|\lambda|$ smaller than 14° would be $\approx 14/180 = 7.7\%$. It is also reasonable to suppose that the other component of the stellar spin vector (that which is directed toward or away from the Earth) is of the same order of magnitude as λ , because our viewing perspective is random and because the observed value of $v \sin i_*$ is typical of a main-sequence F8 star (Cox 2000, p. 389).

To interpret this result, we first calculate the expected timescale for tidal interactions to cause the stellar obliquity to decay, within the framework of the Hut (1981) analytic model of equilibrium tides. Assuming a stellar tidal quality factor $Q' \sim 10^6$, we find¹³ $\tau \sim 10^{10} \text{ yr}$, which is longer than the estimated stellar age of $3 \times 10^9 \text{ yr}$ (Bakos et al. 2007). This suggests that the alignment we observe today was the outcome of the planet migration process, rather than an aftereffect of tidal interactions.¹⁴ Thus, HD 147506b is in the same category of well-aligned planetary orbits as the other measured systems, despite its uniquely eccentric orbit.

Had the outcome of this experiment been a significant misalignment, it would have argued against quiescent migration due to tidal interaction with a protoplanetary disk and invited an interpretation as either the outcome of a planet-planet scattering

¹¹ For the background on this method, see Tegmark et al. (2004), Ford (2005) or Burke et al. (2007); for more detail on our particular implementation, see Holman et al. (2006) or Winn et al. (2007).

¹² To forestall possible confusion, we note that an early version of the manuscript by Bakos et al. (2007) that was distributed on arxiv.org quoted significantly larger values for R_p and R_* . This is because those authors had not yet made use of the measured transit duration in determining the system parameters, as their original model did not account for the nonuniform speed of the planet.

¹³ This is estimated from eqs. (12), (22), (49), and (53) of Hut (1981).

¹⁴ Likewise, the stellar spin is apparently not yet synchronized with the orbit. Assuming $\sin i_* = 1$, the stellar rotation period is $2\pi R_*/v = 3.8$ days, which is in between the orbital period of 5.6 days and the pseudosynchronization period of 1.9 days for $e = 0.5$ (see Hut 1981, eq. [42]).

event or Kozai oscillations accompanied by tidal dissipation. However, the actual outcome does not rule out the latter scenarios. Planet-planet scattering does enhance any initial misalignments between an initial planetary orbit and other orbits, as well as the stellar spin axis. Indeed, Chatterjee et al. (2007) have predicted a broad range of inclinations ranging up to 45° for hot Jupiters produced in this manner. However, it is possible that the particular impulse that threw HD 147506b inward had only a small vertical component. The same simulations by Chatterjee et al. (2007) found that about half of the planets scattered inward experience misalignments smaller than 15° . Likewise, Fabrycky & Tremaine (2007) have predicted the distribution of stellar obliquities that should result from Kozai migration due to isotropically placed stellar companions. There is a broad distribution ranging out to 140° , but the final obliquity is smaller than 20° approximately 20% of the time.¹⁵ It should be noted that neither Chatterjee et al. (2007) nor Fabrycky & Tremaine (2007) intended their calculations for direct comparison for observations,

¹⁵ The Kozai scenario may be more strongly disfavored than this simple comparison suggests, because those systems with small final obliquities also tended to have final eccentricities much smaller than the observed eccentricity of 0.5 (D. Fabrycky 2007, private communication).

but such calculations now seem warranted, given the increasing number of accurate Rossiter-McLaughlin measurements such as the one presented here.

In this case, the accuracy with which λ can be measured is hampered by the small impact parameter of the transit. Further improvement is possible if the impact parameter can be measured with greater precision and shown to be inconsistent with zero. However, transits with impact parameters near 0.5 offer much greater sensitivity to λ and a cleaner separation from $v \sin i_*$ (Gaudi & Winn 2007). For this reason, the discovery of additional transiting eccentric planets are eagerly anticipated and seem bound to happen soon, given the rapidity with which new transiting systems are being announced.

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