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THE SPIN-ORBIT ALIGNMENT OF THE HD 17156 TRANSITING ECCENTRIC PLANETARY SYSTEM[1,2]

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ABSTRACT

We present high-precision radial velocity observations of HD 17156 during a transit of its eccentric Jovian planet. In these data, we detect the Rossiter-McLaughlin effect, which is an apparent perturbation in the velocity of the star due to the progressive occultation of part of the rotating stellar photosphere by the transiting planet. This system had previously been reported by Narita et al. in 2008 to exhibit a $\lambda = 62° \pm 25°$ misalignment of the projected planetary orbital axis and the stellar rotation axis. We model our data, along with the Narita et al. data, and obtain $\lambda = 9.4° \pm 9.3°$ for the combined data set. We thus conclude that the planetary orbital axis is actually very well aligned with the stellar rotation axis.

Subject headings: planetary systems — stars: individual (HD 17156)

Online material: color figure

1. INTRODUCTION

Transiting extrasolar planets allow us to perform critical tests of models of planetary system formation and evolution. In our solar system, all of the planets orbit approximately, *but not exactly*, in the solar equatorial plane. Beck & Giles (2005) find that the angle between the plane of the ecliptic and the solar equator is $7.155° \pm 0.002°$. The near coplanarity of the planetary orbits in our solar system has influenced models of planetary system origin from the time of Kant (1755) and Laplace (1796) to essentially all modern models (e.g., Lissauer 1995; Pollack et al. 1996; Boss 2000). Given the level of misalignment in our solar system and the observation of warps in debris disks around nearby stars such as β Pic (e.g., Burrows et al. 1995; Mouillet et al. 1997; Heap et al. 2000), it is obvious that there are common processes that give rise to some small level of spin-orbit misalignment in planetary systems. The degree of misalignment in real planetary systems must depend on the initial conditions (the initial asymmetries of the collapsing cloud), the physics of disk formation and evolution, and the physics of stellar mass and angular momentum loss during the T Tauri phase. Most transiting planets have periods of just a few days and orbits of low eccentricity. Significant exceptions are HD 147506b (HAT-P-2b) (Bakos et al. 2007), with a 5.6 day orbital period and eccentricity of 0.52, HD 17156 (Fischer et al. 2007; Barbieri et al. 2007), which has the longest orbital period (21 days) and the largest eccentricity (0.67) of all of the transiting exoplanets, and XO-3b, a massive (13.25 $M_{\rm Jup}$) planet that has an eccentricity of 0.26 in spite of its short orbital period of 3.192 days (Johns-Krull et al. 2008). Scenarios for the formation of short-period planetary systems do not necessarily deliver those planets to their present semimajor axes with low eccentricity. Type II migration can result in planets with moderate eccentricities (Sari & Goldreich 2004), while dynamical interactions among newly formed planets and planetesimals (Jurić & Tremaine 2008) or the Kozai mechanism (Holman et al. 1997; Wu & Murray 2003) can result in large eccentricities and significant inclination of planetary orbital planes from the plane of the stellar equator (which is presumably close to the plane of the inner portion of the protoplanetary disk). While the shortest period transiting systems have probably been tidally circularized, longer period systems can easily retain large eccentricities over the main-sequence lifetime of the parent star. A planet that has undergone significant gravitational scattering or Kozai excitation would not necessarily retain a low inclination relative to the stellar equator. Thus, the report of a possible spin-orbit misalignment of the HD 17156b transiting planet by Narita et al. (2008) is extremely interesting and calls for further detailed investigation. In this Letter, we report our own spectroscopic observations of a transit of HD 17156 by its planet, using two telescopes at McDonald Observatory.

2. OBSERVATIONS

We observed the transit of HD 17156 by its hot-Jupiter companion on the night of 2007 December 25 UT, using both the 2.7 m Harlan J. Smith Telescope (HJST) and the Hobby-Eberly Telescope (HET) at McDonald Observatory. The HJST observations used the 2d coudé spectrograph (Tull et al. 1995) in its "F3" mode, which gives a spectral resolving power of $R = \lambda/\delta\lambda = 60{,}000$. This mode is referred to as "cs23." A temperature-stabilized I_2 gas absorption cell is used to impose the velocity metric for precise radial velocity measurements of the stellar spectrum. Details of the 2.7 m cs23 observing and data reduction procedures are given by Endl et al. (2004, 2006). Velocity observations were started before the expected beginning of the transit and were continued until after the expected end of the transit. At total of 18 spectra, each 15 minutes in length, were obtained. Table 1 gives the relative radial velocities for the HJST observations of HD 17156.

HET observations were made on the same night (2007 December 25 UT) using the High Resolution Spectrograph (HRS) (Tull 1998) in its $R = 60{,}000$ mode. Due to its fixed-zenith-distance design, we were able to observe HD 17156 only from shortly before the beginning of the transit to just past midtransit. The observations were planned to obtain as many 600 s exposures of HD 17156 as possible during the 2.1 hr track length. The 13th target exposure on the HET was terminated after

[1] Based on observations obtained with the Hobby-Eberly Telescope, which is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig Maximilians Universität München, and Georg August Universität Göttingen.

[2] This Letter includes data taken at the McDonald Observatory of the University of Texas at Austin.

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TABLE 1
McDonald Observatory 2.7 m HJST Relative Velocities for HD 17156

BJD (−2,400,000)	Velocity (m s^{-1})	σ (m s^{-1})
54,459.604759	−7898.41	9.14
54,459.616367	−7905.69	9.79
54,459.627985	−7936.46	9.57
54,459.639520	−7912.68	10.41
54,459.651060	−7913.60	8.61
54,459.663985	−7921.94	12.61
54,459.675520	−7916.51	11.56
54,459.687056	−7936.95	10.14
54,459.698591	−7955.00	11.86
54,459.710170	−7960.05	12.44
54,459.721705	−7985.06	10.98
54,459.733240	−7964.48	12.75
54,459.744778	−8003.38	10.36
54,459.757932	−7977.30	11.57
54,459.769469	−7979.22	11.89
54,459.781004	−7988.41	12.40
54,459.792539	−7990.68	10.82
54,459.804150	−8010.27	10.81

455 s when the fiber-instrument-feed reached the end of track. Details of the instrument configuration and the data reduction and analysis procedures are given by Cochran et al. (2004, 2007). Table 2 gives the relative radial velocities for the HET observations of HD 17156.

For both the HJST and HET data, observation times and velocities have been corrected to the solar system barycenter. The uncertainty σ for each velocity in the table is an *internal* error computed from the variance about the mean of the velocities from each of the ∼2 Å small chunks into which the spectrum is divided for the velocity computation. Thus, it represents the relative uncertainty of one velocity measurement with respect to the others for that instrument, based on the quality and observing conditions of the spectrum. This uncertainty does not include other intrinsic stellar sources of uncertainty, nor any unidentified sources of systematic errors. The two different spectrographs have independent arbitrary velocity zero points, and thus there is some constant offset velocity (determined below and denoted as γ) between the data sets presented in Tables 1 and 2.

3. ROSSITER-MCLAUGHLIN EFFECT MODEL

A variety of different types of models have been used by others to analyze observations of the Rossiter-McLaughlin (RM) (Rossiter 1924; McLaughlin 1924) effect for transiting planets. Queloz et al. (2000) divided a model stellar photosphere into a large number of cells and then used a "Gaussian shape cross-correlation model" with a linear limb-darkening law to compute the radial velocity anomaly. Ohta et al. (2005) developed analytic expressions for the apparent radial velocity perturbation during a transit, in several different approximations. Giménez (2006) developed another set of analytic expressions for the RM effect that utilize a more generalized higher order limb-darkening expression. A more elaborate technique was developed by Winn et al. (2005), who first computed an approximation to the disk-integrated stellar spectrum. They then computed a Doppler-shifted and intensity-scaled spectrum of the portion of the disk that would be blocked by the transiting planet and subtracted this from their disk-integrated spectrum. This spectrum was then multiplied by their high-resolution iodine spectrum, and the result was processed through their radial velocity code to compute model velocities in the same manner as the observed data.

TABLE 2
Hobby-Eberly Telescope HRS Relative Velocities for HD 17156

BJD (−2,400,000)	Velocity (m s^{-1})	σ (m s^{-1})
54,459.605807	18.55	8.06
54,459.621927	10.35	8.01
54,459.629827	5.63	7.13
54,459.637718	0.74	8.11
54,459.645611	19.18	6.94
54,459.653504	11.45	6.32
54,459.661400	4.77	7.46
54,459.669293	4.65	7.34
54,459.677194	−4.16	7.34
54,459.685096	−7.11	6.32
54,459.692989	−9.91	7.68
54,459.700887	−18.44	7.99
54,459.707944	−35.93	9.25

We analyzed our data using a model that is a hybrid of these methods. We started by adopting the HD 17156b system parameters from Narita et al. (2008). We then computed the orbit of the planet around the star, as we would view it from Earth. This gave us the apparent offset of the planet from the center of the star as a function of time through the transit. We divided the stellar disk into a 400 × 400 grid of cells, in the manner of Queloz et al. (2000), Snellen (2004), or Winn et al. (2005). For each photospheric cell, we computed a specific intensity using the nonlinear four-parameter limb-darkening law of Claret (2000). Each photospheric cell is also assigned a radial velocity due to both the stellar orbital motion and the stellar rotation, with the stellar $v \sin i$ as a model parameter. For each time step during the transit, from first contact to fourth contact, we compute which stellar photospheric cells are blocked by the transiting planet. We then integrate the unblocked Doppler-shifted and intensity-weighted stellar photospheric cells to compute both the RM radial velocity perturbation during the transit and the transit photometric light curve.

We fully recognize the limitations and approximations inherent in this modeling procedure. First, there is no *a priori* reason to assume that limb darkening should follow any particular law. Also, the limb darkening in photospheric absorption lines is quite different from the limb darkening in the continuum. While this appears to be taken into account by Claret (2000), the limb-darkening parameterization is based on model atmospheres rather than on real stars. More importantly, in our model we compute the specific-intensity–weighted apparent Doppler shift of the visible portion of the photosphere. On the other hand, our spectra record transit-perturbed stellar absorption-line profile shapes from which we measure an apparent Doppler shift using a computer code that assumes an unperturbed line-profile shape. In future improvements to our RM model, we will attempt to improve several of these limitations.

4. DATA ANALYSIS

We used the model described in § 3 to analyze simultaneously the data sets from the HJST cs23, the HET HRS, and the observations published by Narita et al. (2008), which we will refer to as the "OAO/HIDES" data set. Since each data set has its own independent velocity zero point, we allowed the systemic velocity of each data set to be an independent free parameter in the analysis. The values of the fixed parameters for the analysis are given in Table 3. The planetary orbital elements were taken from Irwin et al. (2008). These elements are essentially indistinguishable from the single-planet fit of Short et al. (2008). We note that the conclusions of this work

TABLE 3
Assumed System Parameters

Parameter	Value	Source
M_* ($M_\odot$)	1.2	Fischer et al. 2007
R_* ($R_\odot$)	1.47	Fischer et al. 2007
Claret a1	0.5346	Claret 2000
a2	0.1041	Claret 2000
a3	0.4189	Claret 2000
a4	−0.2584	Claret 2000
R_p ($R_{\rm Jup}$)	1.01	Irwin et al. 2008
P (days)	21.21691	Irwin et al. 2008
T_p (HJD)	2,453,738.605	Irwin et al. 2008
K (m s^{-1})	273.8	Irwin et al. 2008
e	0.670	Irwin et al. 2008
ω (deg)	121.3	Irwin et al. 2008

depend on the particular values of these parameters we adopt. If any of these parameters turn out to be in significant error, those errors will propagate through this analysis.

In modeling the data, we allowed the orbital plane inclination i, the projected angle λ between the planetary orbital axis and the stellar rotation axis, the projected stellar rotational velocity $v \sin i$, as well as the systemic velocity of each separate data set to be free parameters. We then minimized the χ^2 of the model fit to the data.

For the combined data sets, we obtained $\lambda = 9.4° \pm 9.3°$ at $v \sin i = 6.3 \pm 1.1$ km s^{-1} and $i = 85.9° \pm 0.4°$. This indicates that the planet is orbiting near the stellar equatorial plane, to within the uncertainty of our determination. Our derived $v \sin i$ is somewhat larger than the value of 4.7 m s^{-1} found by Narita et al. (2008) and the 2.6 km s^{-1} given by Fischer et al. (2007). Our inclination is within 1 σ of the Narita et al. value of 85.65°. However, our value for λ from the combined data differs significantly from that of Narita et al. (2008), who found $\lambda = 62° \pm 25°$.

In order to understand the reason for this difference, we then modeled each of the three data sets separately. The derived λ and i for the combined fit, as well as for each individual data set, are given in Table 4. We also give γ_c, the systemic velocity for each data set in the combined fit, as well as γ_i, the systemic velocity for each individual data set fit. From the OAO/HIDES data set alone, we computed $\lambda = 59.4° \pm 19.7°$ at $i = 86.2° \pm 0.8°$. If we fix the inclination at the $i = 85.65°$ value of Narita et al. (2008), we get $\lambda = 61.4° \pm 28.5°$. The surprisingly excellent agreement of all of these values for the OAO/HIDES data set thus validates the modeling process of Narita et al. We note that the results from the HJST data alone are in very good agreement with the combined results. Due to the design limitations of the HET, the HET/HRS data covered only the first half of the transit. Thus, the code could trade off λ versus the systemic velocity for the data set and derived a slightly lower χ^2 with $\lambda = -32.4° \pm 25.2°$ for the HET data alone.

The model fit to the data is shown in Figure 1. We also computed a model with no RM effect by setting $v \sin i = 0$. This removes the stellar rotation, and thus there is no apparent

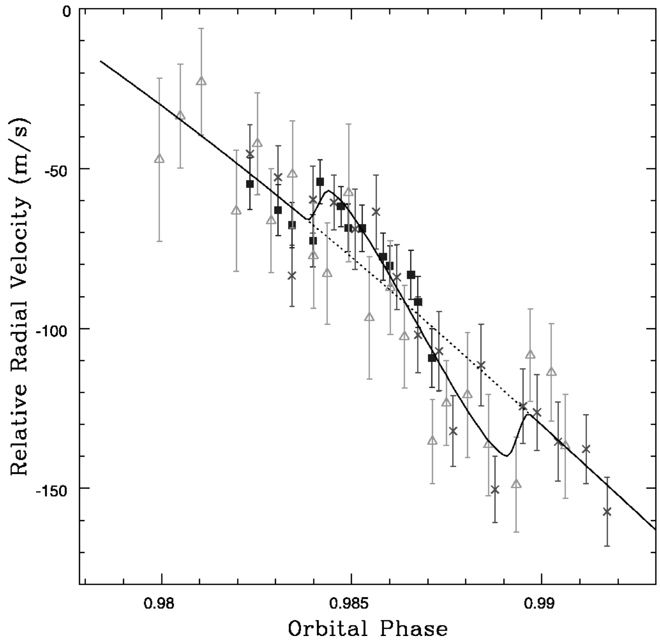

Fig. 1.—The fit of our Rossiter-McLaughlin effect model (*solid black line*) to the observational data sets. The HJST cs23 data are shown as the (*red*) crosses, the HET HRS data are (*blue*) solid squares, and the OAO/HIDES data are (*green*) open triangles. The dashed black line is the orbital velocity of the star in the absence of any Rossiter-McLaughlin velocity perturbation. [*See the electronic edition of the Journal for a color version of this figure.*]

Doppler shift of the portion of the stellar photosphere eclipsed by the planet. The $v \sin i = 0$ model gave $\chi^2 = 71.56$ ($\chi^2_r = 1.43$) as opposed to $\chi^2 = 40.53$ ($\chi^2_r = 0.83$) for the best-fitting RM model for the combined data set. Thus, we conclude that the RM effect was indeed convincingly detected in spite of the apparent noise in the data. Examining the χ^2 of each individual data set in the full model and the $v \sin i = 0$ model showed that even in the noisiest case of the OAO/HIDES data, the RM effect reduced the total χ^2 by 13.1.

Due to the symmetric signature of the RM effect in the $\lambda \approx 0$ case, it is critically important to sample the entire transit. This is evidenced by the fit to the HET/HRS data alone, in which despite the high quality of the data, only the first half of the transit was observable, and therefore erroneous parameters are derived.

In order to successfully calibrate the baseline radial velocity variation, observations well before and after the transit are required. If the radial velocity can be well calibrated by observations before and after transit, the influence of uncertainty in the zero-point velocity offset (γ) will be negligible on the RM effect parameters.

5. DISCUSSION

We have reanalyzed the data of Narita et al. (2008) along with our own independent observations of the spectroscopic transit of the eccentric exoplanet HD 17156b, and we find that

TABLE 4
Rossiter-McLaughlin Model Results

Data Set	λ (deg)	i (deg)	$v \sin i$ (km s^{-1})	χ^2	dof	γ_c (m s^{-1})	γ_i (m s^{-1})
Combined	9.4 ± 9.3	85.9 ± 0.4	6.3 ± 1.1	40.53	49		
HJST cs23	4.5 ± 15.6	86.1 ± 0.6	7.1 ± 2.1	13.19	14	−7853.0	−7854.0
HET HRS	−32.4 ± 25.2	86.3 ± 0.5	4.8 ± 1.5	3.71	9	73.3	65.6
OAO/HIDES	59.4 ± 19.7	86.2 ± 0.8	8.6 ± 1.9	14.25	21	142.1	146.5

$\lambda = 9.4° \pm 9.3°$. We conclude that this exoplanetary system is similar to almost all of the other short-period transiting exoplanetary systems studied using the RM effect so far, in that it shows that the projected planetary orbital axis appears to be aligned with the projected stellar rotation axis, to within our measurement precision. The only remaining notable exception is XO-3b, which was reported by Hebrard et al. (2008) to show a very significant misalignment of $\lambda = 70° \pm 15°$.

The HD 17156b system is extremely interesting because it has a very high eccentricity ($e = 0.67$) for such a short orbital period of 21.2 days. Most other transiting systems have much shorter orbital periods and eccentricities near zero. Many of the interesting ways of getting a planet into this type of orbit might well result in the possibility of an orbital plane significantly inclined to the stellar equatorial plane. Dynamical interactions with another nearby planet could result in ejection of the other body and a large orbital inclination of the surviving body.

The presence of a third planet in the system, as suggested by Short et al. (2008), would have some effect on the orbital elements of HD 17156b. However, as Short et al. (2008) discussed, the primary effects are a small oscillation of the eccentricity and a secular advance of the argument of periastron. As long as the two planets are approximately coplanar, there would be no induced change in the orbital inclination. Thus, it appears that the dynamical process that placed HD 17156b into a short-period highly eccentric orbit did not significantly affect the orbital inclination of the system with respect to the stellar equatorial plane.

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Facilities: HET, McD:2.7m.

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