ON THE ORBIT OF EXOPLANET WASP-12B

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ABSTRACT

We observed two secondary eclipses of the exoplanet WASP-12b using the Infrared Array Camera on the Spitzer Space Telescope. The close proximity of WASP-12b to its G-type star results in extreme tidal forces capable of inducing apsidal precession with a period as short as a few decades. This precession would be measurable if the orbit had a significant eccentricity. The ground-based secondary eclipse phase reported by Lopez-Morales et al. (0.510 ± 0.002) implies eccentricity at the 4.5σ level, and the spectroscopic orbit of Hebb et al. has eccentricity 0.049 ± 0.015, a 3σ result, and predicts an eclipse phase of 0.509 ± 0.007. Our eclipse phases are 0.5012 ± 0.0006 (3.6 and 5.8 µm) and 0.5007 ± 0.0007 (4.5 and 8.0 µm). These values are inconsistent with the ground-based data, but marginally consistent with the spectroscopic orbit. Considering the unlikely possibility that precession brought the long axis of the orbit into alignment during our observations, a model considering these points and transit times from professional and amateur observers estimates orbital precession at ω = 0.02 ± 0.01°d⁻¹. This implies a tidal Love number, k₂p, of 0.15 ± 0.08, indicating a very centrally condensed planet. However, if the orbit is actually eccentric, we have observed it at a remarkably special time to find eclipse phases consistent with apsidal alignment. Future observations can decide between these possibilities.

Subject headings: planetary systems — stars: individual: WASP-12 — techniques: photometric

1. INTRODUCTION

When exoplanets transit (pass in front of) their parent stars as viewed from Earth, one can constrain their sizes, masses, and orbits (Charbonneau et al. 2007; Winn 2009). Most transiting planets also pass behind their stars (secondary eclipse), which allows atmospheric characterization by measurement of planetary flux and constrains orbital eccentricity, e, through timing and duration of the eclipse (Kaltrath & Milone 1999).

WASP-12b is one of the hottest transiting exoplanets discovered to date, with an equilibrium temperature of 2516 K for zero albedo and uniform redistribution of incident flux (Hebb et al. 2009). It also has a 1.09-day period, making it one of the shortest-period transiting planets. The close proximity to its host star (0.0229 ± 0.0008 AU, Hebb et al. 2009) should induce large tidal bulges on the planet’s surface. Tidal evolution should circularize such close-in orbits quickly (Mardling 2007). Hebb et al. (2009) calculate a circularization time for WASP-12b as short as 3 Myr, much shorter than the estimated 2 Gyr age of WASP-12 or even the circularization times estimated for other hot Jupiters, given similar planetary tidal dissipation. The non-Keplerian gravitational potential may cause apsidal precession, measurable as secondary eclipse and transit timing variations over short time scales. Ragozzine & Wolf (2009) predict a precession period of just 18 yr, which could be measurable in eclipses separated about one year. WASP-12b also has an abnormally large radius (Rₚ = 1.79 ± 0.09 Jupiter radii, Rⱼ, Hebb et al. 2009), compared to those predicted by theoretical models (Bodenheimer et al. 2003; Fortney et al. 2007) and to other short-period planets. Tidal heating models assume non-zero e, and the heating rate can differ substantially for different values of e. WASP-12b’s inflated radius may result from tidal heating, but this is difficult to justify if the orbit is circular (Li et al. 2010).

Ground-based observations by Lopez-Morales et al. (2009) detected a secondary eclipse phase for WASP-12b of 0.510 ± 0.002, implying an eccentric orbit at the 4.5σ level. Radial velocity data (Hebb et al. 2009) find e = 0.049 ± 0.015, a 3σ eccentricity, and predict an eclipse phase of 0.509 ± 0.007. Given an eccentric orbit and the fast predicted precession time scale, WASP-12b makes an excellent candidate for the first direct detection of exoplanetary apsidal precession. Such precession has been detected many times for eclipsing binary stars (Kreiner et al. 2001). (We note that the method of Batygin et al. 2009, based on the work of Mardling 2007 and extended to the three-dimensional case by Mardling 2010, is an indirect assessment of apsidal precession, since no orbital motion is actually observed. The technique, which only applies to multi-planet systems with a tidally affected inner...
2. OBSERVATIONS

We observed two secondary eclipses of WASP-12b with the Spitzer (Werner et al. 2004) Infrared Array Camera (IRAC, Fazio et al. 2004). Observations on 2008 October 29 at 4.5 and 8.0 μm (IRAC channels 2 and 4) lasted 338 minutes (program ID 50759); those on 2008 November 3 at 3.6 and 5.8 μm (channels 1 and 3) lasted 368 minutes (Program ID 50517). The IRAC beam splitter enabled simultaneous observations in the paired channels; all exposures were for 12 seconds, resulting in 1696 frames per channel for channels 1 and 3 and 1549 frames per channel in channels 2 and 4. Exoplanet characterization requires photometric stability well beyond Spitzer’s design criteria. To minimize inter-pixel variability in all channels and the known intra-pixel variability in channels 1 and 2 (Reach et al. 2005; Charbonneau et al. 2005; Harrington et al. 2007; Stevenson et al. 2010), each target had fixed pointing. Prior to the science observations in channels 2 and 4, we observed a 57-frame preflash, exposing the array to a relatively bright source to reduce the time-dependent sensitivity (“ramp”) effect in channel 4 (Charbonneau et al. 2005; Harrington et al. 2007; Knutson et al. 2008, see Figure 1). Each observation ended with a 10-frame, post-eclipse observation of blank sky in the same array position as the science observations to check for warm pixels in the photometric aperture.

3. DATA ANALYSIS

Spitzer’s data pipeline (version S18.7.0) applied both standard and IRAC-specific corrections, producing the Basic Calibrated Data we analyzed. Our analysis pipeline masks pixels according to Spitzer’s permanent bad pixel masks. It masks additional bad pixels (e.g., from cosmic-ray strikes), by grouping frames into sets of 64 and doing a two-iteration outlier rejection at each pixel location. Within each array position in each set, this routine calculates the standard deviation from the median, masks any pixels with greater than 3σ deviation, and repeats this procedure once. Masked pixels do not participate in the analysis.

The channel 4 data show a horizontal streak of pixels with low fluxes located ~10 pixels above the star. A similar diagonal streak appears ~10 pixels below and left of the star. This artifact could result from saturation in a prior observation. The streak pixels were masked. A two-dimensional Gaussian fit found the photometry center for each image. The pipeline uses interpolated aperture photometry (Harrington et al. 2007), ignoring frames with masked pixels in the photometry aperture and not using masked pixels in sky level averages. Table 1 presents photometry parameters. We ran photometry apertures in 0.25-pixel increments, choosing the one with the best final lightcurve fit (see below). Because channel 4 had a high background, the best sky annulus was larger and the photometry aperture was smaller than in the other channels. The channel-4 aperture contained 63% of the point-spread function; the others contained 89% or more.

We fit an analytic lightcurve model, assessing parameter uncertainties with a Metropolis-Hastings Markov-Chain Monte Carlo (MCMC) algorithm. The model includes terms that correct the systematic effects mentioned above. The intra-pixel variation only affects channels 1 and 2, and was only substantial in channel 1 (see Table 1 and Figure 2). We model the intra-pixel effect with a second-order, two-dimensional polynomial,

\[ V_{IP}(x,y) = p_{1}y^{2} + p_{2}x^{2} + p_{3}xy + p_{4}y + p_{5}x + p_{6}, \]

where \( x \) and \( y \) are the centroid coordinates relative to the pixel center nearest the median position and \( p_{1}, p_{2}, p_{3}, p_{4}, p_{5}, \) and \( p_{6} \) are free parameters. We model the ramp for channel 1 with the rising exponential

\[ R(t) = 1 - \exp(-r_{1}(t - r_{2})), \]

where \( t \) is orbital phase and \( r_{1} \) and \( r_{2} \) are free parameters. The remaining channels used a linear model,

\[ R(t) = r_{3}(t - 0.5) + 1, \]

where \( r_{3} \) is a free parameter. The eclipse, \( E(t) \), is a Mandel & Agol (2002) model, assuming no limb darkening. The final lightcurve model is

\[ F(x,y,t) = F_{c}V_{IP}(x,y)R(t)E(t), \]

where \( F(x,y,t) \) is the flux measured from interpolated aperture photometry and \( F_{c} \) is the (constant) system flux outside of eclipse, including the planet.

The final fits pair the channels observed together, fitting a common eclipse phase. To remove correlations (see below) and increase signal-to-noise ratio on parameters of interest,
we fix the eclipse duration to the mean duration found for each channel separately. These are consistent with each other and with the transit duration of Hebb et al. (2009) to well within 1σ. A subsequent report will present atmospheric results, including eclipse depths; signal-to-noise ratios for these range from 9 to 29.

A recent re-analysis of older data by Knutson et al. (2009) demonstrates that the complex models required to fit Spitzer’s systematics can have multiple, comparable χ² minima in different parts of phase space. These minima may change their relative depths given different systematics models (e.g., exponential vs. log-plus-linear ramps), resulting in different conclusions. To control for this, we fit many combinations of analytic model components. To compare models with different numbers of free parameters, we apply the Bayesian Information Criterion,

$$\text{BIC} = \chi^2 + k \ln N,$$

where $k$ is the number of free parameters and $N$ is the number of data points (Liddle 2007). For example, we also tested quadratic and logarithmic-plus-linear ramps and a variety of polynomial intrapixel models before choosing Eq. 1 – Eq. 3. To pare down the possible combinations of models and free parameters, we seek unimodal parameter histograms and minimal parameter correlations.

Additionally, we drop a small number of initial points to allow the telescope and instrument to stabilize. To assist those who may subsequently work with these datasets, Table 1 gives the values and uncertainties of all parameters. The histograms and correlation plots for the final models, and data files containing the lightcurves, best-fit models, centering data, etc., are electronic supplements to this article. We encourage all investigators to make similar disclosure in future reports of exoplanetary transits and eclipses.

4. DYNAMICS

Hebb et al. (2009) detect a non-zero eccentricity for WASP-12b that should be observable in the timing of the secondary eclipse. Our two secondary eclipse phases (Table 1) are within 2σ of $\phi = 0.5$ for the Hebb et al. (2009) ephemeris, and taken together imply $e \cos \omega = 0.0016 \pm 0.0007$. This indicates that if the planet’s orbit is eccentric, then its argument of periapsis ($\omega$) is closely aligned with our line of sight. Recognizing the unlikelihood of this configuration (which implicitly questions the ground-based eclipse phase), this section nonetheless considers the possibility of significant eccentricity, and precession between the ground-based eclipse phase and Spitzer’s.

We use a MCMC routine to fit a Keplerian model of the planet’s orbit to our secondary eclipse times, radial velocity data (Hebb et al. 2009), transit timing data (Table 2) provided by the WASP team and amateur observers, and a recent ground-based secondary-eclipse measurement (Lopez-Morales et al. 2009). Because the Lopez-Morales et al. secondary-eclipse phase was determined by folding 1.5 complete eclipses, we represent their point as a single observation taken during an orbit halfway between their observations (HJD 2455002.8560 ± 0.0024). We remove three in-transit radial velocity points due to the possibility of the Rossiter-
McLaughlin effect affecting our results.

In our model,

$$\chi^2 = \sum \left( \frac{V_{rv,s} - V_{rv,m}}{\sigma_{rv}} \right)^2 + \sum \left( \frac{t_{tr,s} - t_{tr,m}}{\sigma_{tr}} \right)^2 + \sum \left( \frac{t_{ecl,s} - t_{ecl,m}}{\sigma_{ecl}} \right)^2, \quad (6)$$

where $V_{rv,s}, t_{tr,s}, t_{ecl,s}$ are the observed radial velocities, transit times, and eclipse times, respectively; $\sigma_{rv}, \sigma_{tr}, \sigma_{ecl}$ are their respective errors, and $V_{rv,m}, t_{tr,m}, t_{ecl,m}$ are the calculated model outputs.

Table 3 gives our best-fit results. The eccentricity of $e = 0.063 \pm 0.014$ may be high due to poor constraints on $e \sin \omega$. It is worth noting that our dynamical fits considered only the transit and eclipse times and did not fit the lightcurves, which could additionally have modeled variable eclipse and transit durations.

A significantly positive eccentricity implies either extremely low tidal dissipation (e.g., $Q_0 \gtrsim 10^8$; a tidal evolution model could give a better limit, Mandling 2007; Levrard et al. 2009) or a perturber such as another planet. In the latter case, coupling between the two planets could potentially drain energy and angular momentum from the outer orbit to the point where it is not able to maintain a large eccentricity for WASP-12b (e.g., Mandling 2007). Tidal dissipation of a non-zero eccentricity could account for the inflated radius of WASP-12b. If the orbit is actually circular, the bloated size (Hebb et al. 2009) requires either an energy source or new interior models.

The planet’s proximity to its star must raise huge tidal bulges (Ragozzine & Wolf 2009) that significantly contribute to an aspherical planetary gravitational potential, which would induce apsidal precession measurable over short timescales through transit and eclipse timing variations. The rate of precession is proportional to the tidal Love number, $k_2$, which describes the concentration of the planet’s interior mass (Ragozzine & Wolf 2009). A lower $k_2$ implies more central condensation, but $k_2$ alone does not define a unique density profile (Batygin et al. 2009). A nominal value of $k_2 = 0.3$ yields precession of $\sim 0.05^\circ$ d$^{-1}$ for the orbit of WASP-12b. A precise measurement of the precession rate will therefore constrain the planet’s internal structure, as long as the eccentricity is significantly non-zero (Ragozzine & Wolf 2009). Conversely, the absence of observable precession limits the eccentricity.

We added a constant precession term $\dot{\omega}$ to our model, and took the inclination to be $\sim 90^\circ$, as the timing effects due to inclination should be negligible and the available timing data cannot directly constrain this quantity. With these assumptions we modified Eq. 15 of Giménez & Bastero (1995) such that

$$T_0 = T_{0,s} + P_s E - \frac{P_s^3}{\pi} (\cos \omega_{tr} - \cos \omega_0), \quad (7)$$

where $T_0$ is the time of mid-transit, $T_{0,s}$ is the transit time at orbit zero, $P_s$ is the sidereal period, and $P_s$ is the anomalous period, or time between successive periastron passages. Furthermore, $P_s$ is related to $P$ by

$$P_s = \frac{P}{1 - P \frac{P}{2}}, \quad (8)$$

$E$ is the number of elapsed sidereal periods since $T_0$ and $\omega_{tr} = \omega(T_{tr} - T_0) + \omega_0$, where $\omega_0$ is $\omega$ at $T_0$. We expand the equation...
to fifth order in $e$ and solve iteratively for $T_{tr}$. We compute the
eclipse time as a function of $e$, $\omega_0$, $P_1$, and $T_{tr}$; radial velocity
is computed as a function of $\omega(t)$.

Fitting this model to the data, we find that $\dot{\omega} = 0.02 \pm
0.01 \text{d}^{-1}$, a $2\sigma$ result, albeit one dependent on the
accuracy of the ground-based point. This corresponds to a precession
period of $40 \pm 17$ years and implies that $k_{2p} = 0.15 \pm 0.08$.

5. CONCLUSIONS

Taken alone, the Spitzer eclipses suggest a small eccentricity,
consistent with that found by Hebb et al. (2009), but also not inconsistent
with zero. To make our eclipse phases consistent with that of Lopez-Morales et al. (2009) requires
a precession term that differs from zero by over $2\sigma$ when fit

with all the available data including the Hebb et al. (2009) radial
velocity points and new transit times from ground-based
observers. On its own this suggests, but does not confirm,
the precession of WASP-12b. Assuming a precession rate of
$0.02 \text{d}^{-1}$ and an eccentricity of 0.065, the secondary eclipse
offset from phase 0.5 would peak at $\sim 32$ minutes in 2019.

If the ground-based eclipse phase is accurate, our fits prefer
the precessing solution (see BIC values in Table 3). The
precession rate yields a $k_{2p}$ that suggests a highly centrally
condensed planet with a light envelope. This is the expected
configuration for bloated hot Jupiters (Bodenheimer et al. 2001).

But there is still a shadow over the precession interpretation:
The required precession just happens to align the orbit
during our eclipse observations, making it indistinguishable
from a circular orbit by transit and eclipse timings. Could there
be problems with some of the data? Given that the
Spitzer observations were taken with four arrays during two
separate eclipses, and that all four channels gave consistent
eclipse times even when analyzed separately, we are confident
in the values reported herein.

Another possibility is a wavelength-dependent asymmetry
in the planet’s surface-brightness distribution that manifests
itself as a timing offset in the wavelengths used during
the Lopez-Morales et al. (2009) observations (Knutson et al.
2007). This offset has a maximum possible value ($R_p/v_p$,
where $v_p$ is the planet’s orbital velocity) of $\sim 9$ minutes, which

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**TABLE 2**

<table>
<thead>
<tr>
<th>Mid-Transit Time (HJD)</th>
<th>Uncertainty</th>
<th>Sourcea</th>
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<td>2455264.7594</td>
<td>0.0048</td>
<td>WASP Team</td>
</tr>
<tr>
<td>2454120.4290</td>
<td>0.0070</td>
<td>WASP Team</td>
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<tr>
<td>2454129.1600</td>
<td>0.0017</td>
<td>WASP Team</td>
</tr>
<tr>
<td>2454508.9761</td>
<td>0.0002</td>
<td>Hebb et al. (2009)</td>
</tr>
<tr>
<td>2454515.52464</td>
<td>0.00016</td>
<td>WASP Team</td>
</tr>
<tr>
<td>2454552.6218</td>
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<tr>
<td>245436.0426</td>
<td>0.0006</td>
<td>Veli-Pekka Hentunen, AXA</td>
</tr>
<tr>
<td>2454287.4955</td>
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<td>Alessandro Marchini, AXA</td>
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<td>0.001</td>
<td>Bruce Gary, AXA</td>
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<td>2454848.41003</td>
<td>0.00213</td>
<td>František Lomoz, TRESCA</td>
</tr>
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<td>2454560.41473</td>
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<td>Jaroslav Trnka, TRESCA</td>
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<td>Ramon Naves, AXA</td>
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<td>2455116.54322</td>
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<td>2455151.82129</td>
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<td>2455172.5620</td>
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<td>Mikael Ingemyr, TRESCA</td>
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<td>2455197.6628</td>
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<td>Brian Tieman, TRESCA</td>
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<td>2455219.48996</td>
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**TABLE 3**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No Precession</th>
<th>With Precession</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e \sin \omega_0$</td>
<td>$-0.063 \pm 0.014$</td>
<td>$-0.065 \pm 0.014$</td>
</tr>
<tr>
<td>$e \cos \omega_0$</td>
<td>$0.00190 \pm 0.00067$</td>
<td>$-0.0054 \pm 0.0030$</td>
</tr>
<tr>
<td>$e$</td>
<td>$0.063 \pm 0.014$</td>
<td>$0.065 \pm 0.014$</td>
</tr>
<tr>
<td>$\omega_0$ ($\text{d}^{-1}$)</td>
<td>$-88.3 \pm 0.8$</td>
<td>$-95 \pm 3$</td>
</tr>
<tr>
<td>$\dot{\omega}$ ($\text{d}^{-1}$)</td>
<td>$0 \pm 0$</td>
<td>$0.02 \pm 0.01$</td>
</tr>
<tr>
<td>$P_1$ (days)</td>
<td>$1.0914240 \pm 4 \times 10^{-7}$</td>
<td>$1.091415 \pm 4 \times 10^{-6}$</td>
</tr>
<tr>
<td>$P_2$ (days)</td>
<td>$1.0914240 \pm 4 \times 10^{-7}$</td>
<td>$1.09151 \pm 4 \times 10^{-6}$</td>
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<tr>
<td>$T_{tr}$ ($\text{ms}^{-1}$)</td>
<td>$508.97606 \pm 0.00012$</td>
<td>$508.97606 \pm 0.00012$</td>
</tr>
<tr>
<td>$K$ ($\text{ms}^{-1}$)</td>
<td>$225 \pm 4$</td>
<td>$224 \pm 4$</td>
</tr>
<tr>
<td>$\gamma$ ($\text{ms}^{-1}$)</td>
<td>$19087 \pm 3$</td>
<td>$19088 \pm 3$</td>
</tr>
<tr>
<td>BIC</td>
<td>97.0</td>
<td>94.8</td>
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</table>

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The Amateur Exoplanet Archive (AXA, http://brucegary.net/AXA/x.htm) and TRAnsitng ExoplanetS and Candidates
supply their data to the Exoplanet Transit Database (ETD,
http://var2.astro.cz/ETD/), which performs the uniform transit analysis
described by Podlany et al. (2010). The ETD web site provided the
AXA and TRESCA numbers in this table.
is somewhat smaller than the observed variation in eclipse timing between Lopez-Morales et al. (2009) and the Spitzer eclipses.

Additional observations are necessary to decide the question of WASP-12b’s precession. Another set of radial velocities like that of Hebb et al. 2009 could determine if apsidal precession is present, as could additional transit and eclipse times, if spaced over the next few years. Additionally, the possible prolateness should be measurable in high-accuracy, infrared transits and eclipses (Ragozzine & Wolf 2009), such as we expect will be available from the James Webb Space Telescope. This would provide a complimentary constraint on interior structure to measurements of precession.

We thank the observers listed in Table 2 for allowing us to use their results, and the organizers of the Exoplanet Transit Database for coordinating the collection and uniform analysis of these data. The IRAC data are based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech. The point of M. Ingemry is based on observations made with the Nordic Optical Telescope (NOT), operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos Instituto Astrofisica de Canarias, and ALFOSC, which is owned by the Instituto Astrofisica de Andalucia (IAA) and operated at the NOT under agreement between IAA and NBIfAFG of the Astronomical Observatory of Copenhagen. We thank contributors to SciPy, Matplotlib, and the Python Programming Language, W. Landsman and other contributors to the Interactive Data Language Astronomy Library, the free and open-source community, the NASA Astrophysics Data System, and the JPL Solar System Dynamics group for free software and services.

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