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, leading to an estimate of the tidal Love number and an assessment of the degree of central concentration in the planetary interior. An initial ground-based secondary-eclipse phase reported by López-Morales et al. (0.510 ± 0.002) implied eccentricity at the 4.5σ level. The spectroscopic orbit of Hebb et al. has eccentricity 0.049 ± 0.015, a 3σ result, implying an eclipse phase of 0.509 ± 0.007. However, there is a well-documented tendency of spectroscopic data to overestimate small eccentricities. Our eclipse phases are 0.5010 ± 0.0006 (3.6 and 5.8 μm) and 0.5006 ± 0.0007 (4.5 and 8.0 μm). An unlikely orbital precession scenario invoking an alignment of the orbit during the Spitzer observations could have explained this apparent discrepancy, but the final eclipse phase of López-Morales et al. (0.510 ± 0.007) is consistent with a circular orbit at better than 2σ. An orbit fit to all the available transit, eclipse, and radial-velocity data indicates precession at < 1σ; a non-precessing solution fits better. We also comment on analysis and reporting for Spitzer exoplanet data in light of recent re-analyses.

Key words: planetary systems – stars: individual (WASP-12) – techniques: photometric

Online-only material: color figures, supplemental data file (tar.gz)

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). This allows atmospheric characterization by measurement of planetary flux and constrains orbital eccentricity, e, through timing and duration of the eclipse (Kalnajs & 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 quickly circularize such close-in orbits (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, though this calculation was based on a formalism (Goldreich & Soter 1966) that ignores the influence of stellar tides and the coupling of eccentricity and semimajor axis in the evolution of the system. The influence of stellar tides could prolong the dissipation timescale to well over the age of the system (Jackson et al. 2008). The non-Keplerian gravitational potential may cause apsidal precession, measurable as secondary eclipse and transit timing variations over short time scales. WASP-12b also has an anomalously large radius ($R_p = 1.79 \pm 0.09$ Jupiter radii, $R_j$; 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 López-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 (López-Morales et al. 2010 revised the uncertainty to 0.007). Radial-velocity data (Hebb et al. 2009) find $e = 0.049 \pm 0.015$, 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).
Against an orbit established by transit timings, precession would be apparent in just two eclipses, if sufficiently separated in time. For eccentric orbits, the eclipse-transit interval can differ from the transit-eclipse interval, and for precessing orbits this difference varies sinusoidally over one precession period. If the difference is insignificant, it places an upper limit on \( \cos \omega \), where \( \omega \) is the argument of periapsis. In the case of WASP-12b, which is expected to precess at a rate of 0.05 day\(^{-1}\) (Ragozzine & Wolf 2009), if the orbit is observed when \( \omega \sim \pm 90^\circ \) and the effect on the eclipse timing is maximized, and assuming a timing precision of 0.0007 days, then secondary-eclipse observations situated five months apart could detect precession at the 3 \( \sigma \) level (see Equation (8)). 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 planet and a nearby, eccentric, outer planet, cannot currently be applied to WASP-12b.

Paired with the López-Morales et al. data, our Spitzer Space Telescope (Werner et al. 2004) eclipse observations provide a one-year baseline. Spitzer's high photometric precision also allows an accurate assessment of \( \cos \omega \). One can solve for \( \epsilon \) and \( \omega \) separately given \( \epsilon \sin \omega \) from precise radial-velocity data. The following sections present our observations: photometric analysis, a dynamical model that considers parameters from this work, the original and revised parameters of López-Morales et al. (2009) and Hebb et al. (2009), new transit times from the Wide-Angle Search for Planets (WASP), and transit times from a network of amateur astronomers; and our conclusions.

## 2. OBSERVATIONS

We observed two secondary eclipses of WASP-12b with the Spitzer Infrared Array Camera (IRAC; Fazio et al. 2004) in full-array mode. Observations on 2008 October 29 at 4.5 and 8.0 \( \mu \)m (IRAC channels 2 and 4, respectively) lasted 338 minutes (Program ID 50759); those on 2008 November 3 at 3.6 and 5.8 \( \mu \)m (channels 1 and 3, respectively) lasted 368 minutes (Program ID 50517). The IRAC beam splitter enabled simultaneous observations in the paired channels; all exposures were 12 s, resulting in 1696 frames in each of channels 1 and 3 and 1549 frames in each of channels 2 and 4. 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 (BCD) 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 4\( \sigma \) 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 \( \sim 10 \) pixels above the star. A similar diagonal streak appears \( \sim 10 \) pixels below and left of the star. This artifact, which we masked, resulted from saturation in a prior observation. A two-dimensional Gaussian fit found the photometry center for each image (Stevenson et al. 2010, see the Supplementary Information for discussion of centering methods on Spitzer data). 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 evaluated numerous photometry apertures (see Table 5 in the Appendix), choosing the one with the best final light-curve fit in each channel (see below). Because channel 4 had a higher background flux level, 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.

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,

\[
V_{IP}(x, y) = p_1 x^2 + p_2 y^2 + p_3 x y + p_4 y + p_5 x + 1,
\]

where \( x \) and \( y \) are the centroid coordinates relative to the pixel center nearest the median position and \( p_1, p_2, p_3, p_4, \) and \( p_5 \) can be 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 light-curve model is

\[
F(x, y, t) = F_0 V_{IP}(x, y) R(t) E(t),
\]

where \( F(x, y, t) \) is the flux measured from interpolated aperture photometry and \( F_0 \) is the (constant) system flux outside of eclipse, including the planet.

To estimate photometric uncertainties, we propagate the values in the Spitzer BCD uncertainty images through the aperture photometry calculation. Since the Spitzer pipeline generally overestimates uncertainties, we fit an initial model with a \( \chi^2 \) minimizer and then scale all uncertainties to give a reduced \( \chi^2 \) of unity (Harrington et al. 2007). We confirm the fit by redoing it with the new uncertainties. The scaling factor is proportional to the standard deviation of the normalized residuals (SDNR) from the models, as reported in Tables 1 and 5. The \( \sim 2\% \) SDNR variation does not significantly affect the fits. To select among models, we must compare fits made to the same data, including uncertainties. Therefore, we use just one
Figure 1. Preflash light curve. These are channel-4 (8 µm) data, analyzed with aperture photometry at the pixel location of the eclipse observations. The preflash source is bright compared to WASP-12, which allows the array sensitivity to “ramp” up before the science observations. Without a preflash, similar observations generally show a steeper and longer ramp in the eclipse observations.

Table 1

| Parameter                      | 3.6 µm | 4.5 µm | 5.7 µm | 8.0 µm |
|-------------------------------|--------|--------|--------|--------|
| Array position (x, pixel)     | 25.20  | 20.24  | 19.35  | 21.45  |
| Array position (y, pixel)     | 26.98  | 27.95  | 27.15  | 25.67  |
| Position consistency (d_x, pixel) | 0.012  | 0.013  | 0.030  | 0.13   |
| Position consistency (d_y, pixel) | 0.012  | 0.013  | 0.018  | 0.14   |
| Aperture size (pixel)         | 3.75   | 4.00   | 2.75   | 2.00   |
| Sky annulus inner radius (pixel) | 7.00   | 7.00   | 7.00   | 12.00  |
| Sky annulus outer radius (pixel) | 12.00  | 12.00  | 12.00  | 30.00  |
| System flux (µJy)             | 25922  | ± 11   | 16614  | ± 3    |
| Eclipse depth (F_p/F_r)       | 0.00379 ± 0.00013 | 0.00382 ± 0.00019 | 0.00629 ± 0.00052 | 0.00636 ± 0.00067 |
| Brightness temperature (K)    | 2794  | 49 ± 271 | 73 ± 3073 | 176 ± 2948 |
| Eclipse mid-time (t_m.sup.1)  | 0.5010 ± 0.0006 | 0.5006 ± 0.0007 | 0.5010 ± 0.0006 | 0.5006 ± 0.0007 |
| Eclipse mid-time (t_m,BJD=2454,000) | 773.6481 ± 0.0006 | 769.2819 ± 0.0008 | 773.6481 ± 0.0006 | 769.2819 ± 0.0008 |
| Eclipse duration (t_e−t_i, s) | 0.0000  | 0.0000  | 0.0000  | 0.0000  |
| Ingress time (t_e−1, s)       | 10.656 ± 102.95 | 10.749 ± 142.72 | 10.615 ± 102.95 | 10.749 ± 142.72 |
| Egress time (t_e−3, s)        | 12.6643 | 12.6643 | 12.6643 | 12.6643 |
| Ramp name                     | Rising exponential | Linear | Linear | Linear |
| Ramp, curvature (r_1)         | 0.0 ± 1.0 | 0.0 ± 0.0 | 0.0 ± 0.0 | 0.0 ± 0.0 |
| Ramp, phase offset (r_2)      | 0.17747 | ± 0.5  | ± 0.5  | ± 0.5  |
| Ramp, linear term (r_3)       | 0.0 ± 0.0102 ± 0.0015 | 0.0 ± 0.016 ± 0.004 | 0.0 ± 0.010 ± 0.005 |
| Intra-pixel, quadratic term in y (p_1) | 0.0 ± 0.09 ± 0.04 | 0.0 ± 0.0 | 0.0 ± 0.0 |
| Intra-pixel, quadratic term in x (p_2) | −0.140 ± 0.011 | 0.0 ± 0.0 | 0.0 ± 0.0 |
| Intra-pixel, cross term (p_3) | 0.0 ± 0.0 | 0.0 ± 0.0 | 0.0 ± 0.0 |
| Intra-pixel, linear term in y (p_4) | 0.086 ± 0.004 | 0.0 ± 0.0 | 0.0 ± 0.0 |
| Intra-pixel, linear term in x (p_5) | 0.0 ± 0.0 | 0.0 ± 0.0 | 0.0 ± 0.0 |
| Total frames                  | 1697   | 1560   | 1697   | 1560   |
| Good frames (%)               | 1532   | 1457   | 1543   | 1467   |
| Rejected frames (%)           | 9.0    | 6.0    | 9.0    | 5.0    |
| Free parameters               | 10.0   | 9.0    | 10.0   | 9.0    |
| Number of data points in fit  | 3075   | 2924   | 3075   | 2924   |
| BIC                          | 3155.5 | 2996.0 | 3155.5 | 2996.0 |
| AIC                          | 3095.7 | 2942.2 | 3095.7 | 2942.2 |
| Standard deviation of normalized residuals | 0.00228716 | 0.00324027 | 0.01058880 | 0.01222100 |
| Uncertainty scaling factor    | 0.31248 | 0.44500 | 0.91832 | 0.62475 |

Notes.

A RMS frame-to-frame position difference.
B Based on the transit ephemeris time given by Hebb et al. (2009).
C MCMC jump parameter.
D Uncorrected for light-travel time in the exoplanetary system (see the dynamics section).
E We reject frames during instrument/telescope settling and with bad pixels in the photometry aperture.

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Figure 1. Preflash light curve. These are channel-4 (8 µm) data, analyzed with aperture photometry at the pixel location of the eclipse observations. The preflash source is bright compared to WASP-12, which allows the array sensitivity to “ramp” up before the science observations. Without a preflash, similar observations generally show a steeper and longer ramp in the eclipse observations.

Sivia & Skilling (2006) provide an accessible tutorial to the Bayesian approach of our subsequent analysis. MacKay (2003, chap. 29, and especially Section 4) introduces Markov Chain Monte Carlo (MCMC) and discusses its practicalities. Briefly, the MCMC algorithm calculates $\chi^2$ at random locations near the $\chi^2$ minimum in the parameter phase space, accepting only some of these steps for later analysis. The density of these accepted points is proportional to the probability of a model at that location, given the data. The attraction of MCMC is that histograms and scatter plots of subsets of interesting parameters from the accepted points display parameter uncertainties and correlations in a way that fully accounts for the uncertainties in and correlations with the uninteresting parameters. These are called marginal distributions.

We fit Equation (4) with a $\chi^2$ minimizer and assess parameter uncertainties with a Metropolis random-walk (MRW) MCMC algorithm. Our MRW used independent Gaussian proposal distributions for each parameter with widths chosen to give an acceptance rate of 20%–60% of the steps. See Figures 4–7 for marginal distribution figures for our final models.
Figure 2. Raw (left), binned (center), and systematics-corrected (right) secondary-eclipse light curves of WASP-12b in the four IRAC channels, normalized to the mean system flux within the fitted data. Colored lines are the best-fit models; black curves omit their eclipse model elements. A few initial points in all channels are not fit, as indicated, to allow the telescope pointing and instrument to stabilize.

(A color version of this figure is available in the online journal.)

The MCMC routine ran an initial “burn in” of a least $10^5$ iterations to forget the initial starting conditions and then used two million iterations to sample the phase space near the fit solution. To test for adequate sampling, we ran four independent MCMC chains, three started away from the initial minimizer location and calculated the Gelman & Rubin (1992) statistic for each parameter. These were all within 1% of unity, indicating the chains converged. We initially fit each channel separately with all free model parameters as MCMC jump parameters (see Table 5). Then we pair the channels observed together, fitting a common eclipse phase and duration (see Table 1). Due to high correlations, the MCMC sampling becomes very inefficient with all the parameters free in the joint fit. Estimates of the interesting parameters (eclipse depth, time, and duration) are unaffected if we freeze $r_2$ and the ingress and egress times at several different values. We set $r_2$ from the independent light-curve fits and the ingress and egress times as predicted by the Hebb et al. (2009) orbit.

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 $\chi^2$ minima in different parts of phase space. These minima may change their relative depths given different systematic models (e.g., exponential versus log-plus-linear ramps), resulting in different conclusions. To control for this, we fit data from a range of photometry apertures with many combinations of analytic model components (see Table 5) before choosing Equations (1)–(3). The models included quadratic and logarithmic-plus-linear ramps and a variety of polynomial intra-pixel models. Additionally, we drop a small number of initial points to allow the pointing and instrument to stabilize, which vastly improved the fits.

Choices among photometry apertures and numbers of dropped points are choices between different data sets fit with the same models, so we minimize the SDNR, removing the fewest points consistent with low SDNR. The model lines in Figure 2 show the included points.
specific goals and assumptions, so none is perfectly general, but two have broad application. The Akaike Information Criterion,

\[ AIC = \chi^2 + 2k, \]

where \( k \) is the number of free parameters, applies when the goal is accurate prediction of future data; its derivation is valid even when the candidate models might not include the theoretically correct one (as is the case, so far, for Spitzer intra-pixel and ramp modeling). The Bayesian Information Criterion,

\[ BIC = \chi^2 + k \ln N, \]

where \( N \) is the number of data points, applies when the goal is identifying the theoretically correct model, which is known to be one of those being considered. The best model minimizes the chosen information criterion. The ratio of probabilities favoring one model over another is \( \exp(\Delta BIC/2) \), where \( \Delta BIC \) is the difference in BIC between models, but the difference in AIC between models has no simple calibration to a probability or significance level.

These goals give different answers for finite data sets. If the right model is a candidate, the BIC will do better than AIC as the number of points increases; if not, which is better depends on the sample size and on how close the candidate models are to the (absent) correct model. Other information criteria exist, but are either tailored to specific circumstances or are still being developed. The goal of a multi-model analysis is not always easily classified as solely predictive or explanatory, so there is some elasticity between models has no simple calibration to a probability or significance level.

Differences in interesting parameter values (eclipse depth, time, and duration) for such near-optimal alternatives are \( \lesssim 1\sigma \).

Given the questions raised by re-analyses of certain Spitzer exoplanet data sets (Knutson et al. 2009; Beaulieu et al. 2010), we consider it critical that investigators disclose the details of their analyses both so that readers can assess the quality of the analysis and so that others may make meaningful comparisons in subsequent analyses of the same data (e.g., did they find a better \( \chi^2 \)?). It is important to include a full description of the centering, photometry, uncertainty assessment, model fitting, correlation tests, phase-space exploration, and convergence tests. A listing of alternative model fits and their quality may build confidence that there is not a much better model than those tried. One must identify the particular \( \chi^2 \) minimum explored by reporting even the less-correlated models with insignificantly poorer AIC or BIC (e.g., channel 1).

### 4. DYNAMICS

Hebb et al. (2009) detect a non-zero eccentricity for WASP-12b that should be observable in the timing of the secondary

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**Table 2**

| Mid-transit Time (HJD) | Uncertainty | Source |
|------------------------|-------------|--------|
| 2453264.7594           | 0.0048      | WASP Team |
| 2454120.4290           | 0.0070      | WASP Team |
| 2454129.1600           | 0.0017      | WASP Team |
| 2454508.9761           | 0.0002      | Hebb et al. (2009) |
| 2454515.5246           | 0.00016     | WASP Team |
| 2454552.6218           | 0.0034      | WASP Team |
| 2454836.4026           | 0.0006      | Veli-Pekka Hentunen, AXA |
| 2454837.4955           | 0.0013      | Alessandro Marchini, AXA |
| 2454840.7704           | 0.001      | Bruce Gary, AXA |
| 2454848.41003          | 0.00213     | Frantisek Lomza, TRESCA |
| 2454860.41473          | 0.0023      | Yenal Oghmen, TRESCA |
| 2454860.4176           | 0.00132     | Jaroslav Trnka, TRESCA |
| 2454883.33312          | 0.0056      | Alessandro Marchini, AXA |
| 2454908.4372           | 0.001      | Ramon Naves, AXA |
| 2454931.35739          | 0.00098     | Lubos Brat, TRESCA |
| 2455136.54322          | 0.00066     | Leonard Kornos and Peter Veres, TRESCA |
| 2455151.82129          | 0.00141     | Stan Shadick, TRESCA |
| 2455164.92317          | 0.00149     | Stan Shadick, TRESCA |
| 2455172.5620           | 0.00014     | Mikael Ingemry, TRESCA |
| 2455197.6628           | 0.00203     | Brian Tieman, TRESCA |
| 2455198.75595          | 0.00141     | Brian Tieman, TRESCA |
| 2455219.48996          | 0.00131     | Lubos Brat, TRESCA |

Notes.

4 The Amateur Exoplanet Archive (AXA, http://brucegary.net/AXA/x.htm) and TRansiting ExoplanetS and CAndidates group (TRESCA, http://var2.astro.cz/EN/tresca/index.php) supply their data to the Exoplanet Transit Database (ETD, http://var2.astro.cz/ETD/), which performs the uniform transit analysis described by Podda et al. (2010). The ETD Web site provided the AXA and TRESCA numbers in this table.
Our two secondary-eclipse phases (Table 1) are within 2σ of φ = 0.5 for the Hebb et al. (2009) ephemeris, and taken together imply e \cos ω = 0.0016 ± 0.0007. This indicates that if the planet’s orbit is eccentric, then ω is closely aligned with our line of sight. Recognizing the unlikelihood of this configuration (which implicitly questions the López-Morales et al. 2009 eclipse phase), this section nonetheless considers the possibility of significant eccentricity, with precession between the López-Morales et al. (2009) eclipse phase and Spitzer’s. Subsequent to the initial submission of this paper, López-Morales et al. (2010) increased their uncertainty by a factor of three. Since the arXiv postings of both López-Morales et al. (2009) and the submitted version of this paper raised some community discussion, we now treat both cases to explain how this adjustment changes our conclusions.

We use an 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 provided by the WASP team and amateur observers (Table 2), and the ground-based secondary-eclipse measurement of López-Morales et al. (2009, 2010). Because López-Morales et al. folded 1.5 complete eclipses, we represent their point as a single observation taken during an orbit halfway between their eclipses (HJD 2455002.8560 ± 0.0024). We remove three in-transit radial-velocity points due to Rossiter–McLaughlin contamination and correct the times of mid-eclipse given in Table 1 and by López-Morales et al. (2009, 2010) for light travel across the orbit by subtracting 22.8 s. We note that eclipse observers should report uncorrected times, as the correction depends on the orbit model and, in the future, measurements may be uncertain at the level of model uncertainty.

The amateur observers synchronize their clocks to within 1 s of UTC by means such as Network Time Protocol (NTP) or radio signals from atomic clocks. In pre-publication discussions with Eastman et al. (2010), we determined that the amateurs’ observing software, MaximDL, did not account for leap seconds,
nor did the software of most of our professional contributors. We thus made the adjustment ourselves as needed.

In our model,

\[
\chi^2 = \sum \left( \frac{v_{\text{rv},o} - v_{\text{rv},m}}{\sigma_{\text{rv}}} \right)^2 + \sum \left( \frac{t_{\text{tr},o} - t_{\text{tr},m}}{\sigma_{\text{tr}}} \right)^2 + \sum \left( \frac{t_{\text{ecl},o} - t_{\text{ecl},m}}{\sigma_{\text{ecl}}} \right)^2,
\]

where \( v_{\text{rv},o}, t_{\text{tr},o}, \) and \( t_{\text{ecl},o} \) are the observed radial velocities, transit times, and eclipse times, respectively; \( \sigma_{\text{rv}}, \sigma_{\text{tr}}, \) and \( \sigma_{\text{ecl}} \) are their respective uncertainties, and \( v_{\text{rv},m}, t_{\text{tr},m}, \) and \( t_{\text{ecl},m} \) are the respective model calculations.

Table 3 gives our best-fit results using the original López-Morales et al. (2009); differences from our arXiv posting are due to the time corrections and the use of a minimizer to find the true \( \chi^2 \) minimum. The eccentricity of \( e = 0.065 \pm 0.014 \) may be high due to poor constraints on \( e \sin \omega \). Our dynamical fits considered only the transit and eclipse times and did not directly fit the light curves, which could additionally have modeled variable eclipse and transit durations.

A significantly positive eccentricity implies either extremely low tidal dissipation (e.g., \( Q_p > 10^8 \); a tidal evolution model

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**Table 3**

| Parameter | No Precession | With Precession |
|-----------|---------------|-----------------|
| \( e \sin \omega \) | -0.065 ± 0.014 | -0.065 ± 0.014 |
| \( e \cos \omega \) | 0.0014 ± 0.0007 | -0.0058 ± 0.0027 |
| \( e \) | 0.065 ± 0.014 | 0.065 ± 0.014 |
| \( \omega \) (°) | -88.8 ± 0.9 | -95.1 ± 2.3 |
| \( \dot{\omega} \) (day\(^{-1}\)) | \( 0 \pm 0 \) | 0.026 ± 0.009 |
| \( P_s \) (days)\(^a\) | 1.0914240 ± 3 \times 10^{-7} | 1.091436 ± 4 \times 10^{-6} |
| \( P_a \) (days) | 1.0914240 ± 3 \times 10^{-7} | 1.091521 ± 3 \times 10^{-5} |
| \( T_0 \) (MJD)\(^b\) | 508.97686 ± 0.00012 | 508.97686 ± 0.00012 |
| \( K \) (ms\(^{-1}\)) | 224 ± 4 | 224 ± 4 |
| \( \gamma \) (ms\(^{-1}\)) | 19087 ± 3 | 19088 ± 3 |
| BIC | 101.0 | 97.6 |

Notes.

\(^a\) MCMC jump parameter.

\(^b\) MJD = JD−2,454,000.
could give a better limit; Mardling 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., Mardling 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.

As noted above, the planet’s proximity to its star must raise huge tidal bulges (Ragozzine & Wolf 2009) that significantly contribute to an aspherical planetary gravitational potential. This 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, $k_{2p}$, which describes the concentration of the planet’s interior mass (Ragozzine & Wolf 2009). A lower $k_{2p}$ implies more central condensation, but $k_{2p}$ alone does not define a unique density profile (Batygin et al. 2009). A nominal value of $k_{2p} = 0.3$ yields precession of $\sim 0:05$ day$^{-1}$ 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 Equation (15) of Giménez & Bastero (1995) such that

$$ T_{tr} = T_0 + P_s E - \frac{e P_a}{\pi} (\cos \omega_{tr} - \cos \omega_0), $$

where $T_{tr}$ is the time of mid-transit, $T_0$ is the transit time at orbit zero, $P_s$ is the sidereal period, and $P_a$ is the anomalistic period, or time between successive periastron passages. The right bracket indicates truncation of a series. Furthermore, $P_s$ is related to $P_a$.
Figure 7. Parameter histograms for 4.5 and 8.0 μm. To decorrelate the Markov chains, the histograms come from every 100th MCMC step.

(A color version of this figure is available in the online journal.)

\[ P_a = \frac{P_e}{1 - P_e \cos \frac{\omega}{2}}. \]  

(9)

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

Fitting this model to the data with the López-Morales et al. (2009) point, we found that \( \dot{\omega} = 0.026 \pm 0.009 \text{ day}^{-1} \), a 3σ result (Figure 8). This corresponds to a precession period of 33 ± 13 years and implies that \( k_{2p} = 0.15 \pm 0.08 \) (see Table 3). This result depended on an unlikely alignment of the orbit with our line of sight during the Spitzer observations. The revised López-Morales et al. (2010) uncertainty dashed hopes for detecting precession, however, as the model fit with that point

| Parameter                  | No Precession | With Precession |
|----------------------------|---------------|-----------------|
| \( e \sin \omega_0 \)      | \(-0.063 \pm 0.014\) | \(-0.065 \pm 0.015\) |
| \( e \cos \omega_0 \)      | \(0.0011 \pm 0.00072\) | \(-0.0036 \pm 0.0045\) |
| \( \omega_0 \) (°)         | \(-89.0 \pm 0.8\) | \(-93 \pm 5\) |
| \( \dot{\omega} \) (°/day) | \(0 \pm 0\) | \(0.017 \pm 0.019\) |
| \( P_e \) (days)           | \(1.0914240 \pm 3 \times 10^{-7}\) | \(1.0914315 \pm 7 \times 10^{-6}\) |
| \( P_T \) (days)           | \(1.0914240 \pm 3 \times 10^{-7}\) | \(1.0914872 \pm 7 \times 10^{-5}\) |
| \( T_0 \) (MJD)            | \(508.97683 \pm 0.00012\) | \(508.97685 \pm 0.00012\) |
| \( K \) (ms^{-1})          | \(225 \pm 4\) | \(224 \pm 4\) |
| \( \gamma \) (ms^{-1})     | \(19087 \pm 3\) | \(19088 \pm 3\) |
| BIC                        | 90.1          | 92.8            |

Notes.

\(^a\) MCMC jump parameter.

\(^b\) MJD = JD − 2,454,000.
Although the L´opez-Morales et al. (2010) eclipse phase is not marginally consistent with zero eccentricity, we note that this 0.9 μm observation could be affected by a wavelength-dependent asymmetry in the planet’s surface-brightness distribution that manifests itself as a timing offset (Knutson et al. 2007). This offset has a maximum possible value of \( R_p/v_p \approx 9 \) minutes, where \( v_p \) is the planet’s orbital velocity. This is somewhat smaller than the observed variation in eclipse timing between López-Morales et al. (2010) and Spitzer.

While we have not yet measured precession, 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 another constraint on interior structure, one that does not depend on an elliptical orbit.

5. CONCLUSIONS

The timing of the Spitzer eclipses is consistent with a circular orbit, and our best fit, including RV data and transit and eclipse times, does not detect precession.

Although the L´opez-Morales et al. (2010) eclipse phase is now marginally consistent with zero eccentricity, we note that 0.9 μm observation could be affected by a wavelength-dependent asymmetry in the planet’s surface-brightness distribution that manifests itself as a timing offset (Knutson et al. 2007). This offset has a maximum possible value of \( R_p/v_p \approx 9 \) minutes, where \( v_p \) is the planet’s orbital velocity. This is somewhat smaller than the observed variation in eclipse timing between López-Morales et al. (2010) and Spitzer.

While we have not yet measured precession, 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 another constraint on interior structure, one that does not depend on an elliptical orbit.
| Model   | Ap | NFP | BIC  | AIC  | SDNR  |
|---------|----|-----|------|------|-------|
| 1457 points, uncertainties multiplied by 0.44875 |
| No ramp | 4.00 | 9 | 1513.6 | 1466.0 | 0.00326355 |
| Linear | 4.00 | 10 | 1492.6 | 1439.7 | 0.00223181 |
| Quadratic | 4.00 | 11 | 1497.7 | 1436.9 | 0.0022873 |
| Falling exp | 4.00 | 11 | 1500.8 | 1442.7 | 0.00323302 |
| 1449 points, uncertainties multiplied by 0.45211 |
| No ramp | 4.25 | 9 | 1505.5 | 1458.0 | 0.0027075 |
| Linear | 4.25 | 10 | 1483.7 | 1430.9 | 0.0023780 |
| Quadratic | 4.25 | 11 | 1488.5 | 1430.4 | 0.0023425 |
| Falling exp | 4.25 | 11 | 1492.0 | 1434.0 | 0.0032913 |
| 1435 points, uncertainties multiplied by 0.45715 |
| No ramp | 4.50 | 9 | 1491.4 | 1444.0 | 0.0029102 |
| Linear | 4.50 | 10 | 1470.1 | 1417.4 | 0.0025808 |
| Quadratic | 4.50 | 11 | 1474.8 | 1416.9 | 0.0025441 |
| Falling exp | 4.50 | 11 | 1478.4 | 1420.5 | 0.00325944 |
| Channel 2, intra-pixel with only y² free: 1465 points, uncertainties multiplied by 0.44695 |
| No ramp | 3.50 | 5 | 1496.4 | 1470.0 | 0.00228991 |
| Linear | 3.50 | 6 | 1496.4 | 1432.6 | 0.00224507 |
| Quadratic | 3.50 | 7 | 1470.0 | 1433.0 | 0.00234266 |
| Falling exp | 3.50 | 7 | 1472.6 | 1435.6 | 0.0023466 |
| 1460 points, uncertainties multiplied by 0.44969 |
| No ramp | 3.75 | 5 | 1491.4 | 1465.0 | 0.0029263 |
| Linear | 3.75 | 6 | 1455.3 | 1423.6 | 0.0024297 |
| Quadratic | 3.75 | 7 | 1461.2 | 1424.2 | 0.0024081 |
| Falling exp | 3.75 | 7 | 1463.5 | 1426.5 | 0.0024417 |
| 1457 points, uncertainties multiplied by 0.45194 |
| No ramp | 4.00 | 5 | 1488.4 | 1462.0 | 0.0029209 |
| Linear | 4.00 | 6 | 1450.5 | 1418.8 | 0.0024027 |
| Quadratic | 4.00 | 7 | 1456.2 | 1419.2 | 0.0023791 |
| Falling exp | 4.00 | 7 | 1458.7 | 1421.8 | 0.0024155 |
| 1449 points, uncertainties multiplied by 0.45480 |
| No ramp | 4.25 | 5 | 1480.4 | 1454.0 | 0.0029562 |
| Linear | 4.25 | 6 | 1444.5 | 1412.9 | 0.0024584 |
| Quadratic | 4.25 | 7 | 1449.8 | 1412.9 | 0.0024293 |
| Falling exp | 4.25 | 7 | 1452.9 | 1415.9 | 0.0024720 |
| 1435 points, uncertainties multiplied by 0.45965 |
| No ramp | 4.50 | 5 | 1466.3 | 1440.0 | 0.0031453 |
| Linear | 4.50 | 6 | 1432.7 | 1401.1 | 0.0026654 |
| Quadratic | 4.50 | 7 | 1437.9 | 1401.0 | 0.0026347 |
| Falling exp | 4.50 | 7 | 1441.0 | 1404.1 | 0.0026791 |
| Channel 3: 1544 points, uncertainties multiplied by 0.91447 |
| No ramp | 2.50 | 2 | 1556.7 | 1546.0 | 0.01066331 |
| Linear | 2.50 | 3 | 1553.7 | 1537.6 | 0.01062468 |
| Falling exp | 2.50 | 4 | 1563.2 | 1541.9 | 0.01063552 |
| 1543 points, uncertainties multiplied by 0.92247 |
| No ramp | 2.75 | 2 | 1555.7 | 1545.0 | 0.01063659 |
| Linear | 2.75 | 3 | 1549.9 | 1533.9 | 0.01058879 |
| Falling exp | 2.75 | 4 | 1558.7 | 1537.4 | 0.01059726 |
| 1535 points, uncertainties multiplied by 0.93860 |
| No ramp | 3.00 | 2 | 1547.7 | 1537.0 | 0.01080979 |
| Linear | 3.00 | 3 | 1543.1 | 1527.1 | 0.01076529 |
| Falling exp | 3.00 | 4 | 1551.7 | 1530.4 | 0.01077319 |
| 1529 points, uncertainties multiplied by 0.95222 |
| No ramp | 3.25 | 2 | 1541.7 | 1531.0 | 0.01103641 |
| Linear | 3.25 | 3 | 1538.6 | 1522.6 | 0.01109631 |
| Falling exp | 3.25 | 4 | 1547.6 | 1526.2 | 0.01100564 |
| 1524 points, uncertainties multiplied by 0.96551 |
| No ramp | 3.50 | 2 | 1536.7 | 1526.0 | 0.01132113 |
| Linear | 3.50 | 3 | 1535.2 | 1519.2 | 0.01128630 |
| Falling exp | 3.50 | 4 | 1544.0 | 1522.7 | 0.01129501 |

**Notes.**

*Aperture radius in pixels.*

*Number of free parameters (k in the text).*

*Compare between the aperture sizes, for the same model, by SDNR. Compare within the aperture sizes by BIC and AIC.*
As this paper was in late stages of revision, Croll et al. (2011) published three ground-based secondary eclipses and Husnoo et al. (2010) produced additional radial-velocity data. These data sets are consistent with a circular orbit for WASP-12b.

As the quality of these data attests (the signal-to-noise ratio of the eclipse depth in channel 1 is over 29, second only to that for HD 189733b), WASP-12b has emerged as a highly observable exoplanet. Madhusudhan et al. (2011) report our analysis of the planet’s atmospheric composition. Its phase curves, already in Spitzer’s queue, will enable the first observational discussion of atmospheric dynamics on a prolate planet.

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APPENDIX

In this appendix, we present the data for the candidate models (see Table 5).

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