THE TRANSIT LIGHT CURVE PROJECT. IX. EVIDENCE FOR A SMALLER RADIUS OF THE EXOPLANET XO-3b

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ABSTRACT
We present photometry of 13 transits of XO-3b, a massive transiting planet on an eccentric orbit. Previous data led to two inconsistent estimates of the planetary radius. Our data strongly favor the smaller radius, with increased precision: \( R_p = 1.217 \pm 0.073 \) \( R_{\text{Jup}} \). A conflict remains between the mean stellar density determined from the light curve, and the stellar surface gravity determined from the shapes of spectral lines. We argue the light curve should take precedence, and revise the system parameters accordingly. The planetary radius is about 1 \( \sigma \) larger than the theoretical radius for a hydrogen-helium planet of the given mass and insolation. To help in planning future observations, we provide refined transit and occultation ephemerides.

Subject headings: planetary systems — stars: individual (GSC 03727—01064, XO-3)

On-line material: machine-readable table

1. INTRODUCTION

The most intimate details about exoplanets have come from observations of transits and occultations, as recently reviewed by Charbonneau et al. (2007a), Ksanfomality (2007), and Seager (2008). This is the ninth publication of the Transit Light Curve (TLC) project, a series of photometric investigations of transiting exoplanets. The short-term goal of this project is the accurate determination of planetary radii and other system parameters (Holman et al. 2007; Winn et al. 2007a), the intermediate-term goal is detecting reflected light or thermal emission with ground-based observations (Winn et al. 2008), and the longer term goal is seeking evidence for additional planets or satellites in the pattern of measured transit times (Holman & Murray 2005; Agol et al. 2005).

This paper is concerned with the determination of system parameters for XO-3, which was discovered by Johns-Krull et al. (2008, hereafter JK08), as part of the XO Project (McCullough et al. 2005). In this system, a planet with a mass near the deuterium-burning limit of 13 \( M_{\text{Jup}} \) orbits an F5 V star, with a period of 3.19 days and an eccentricity of 0.26. The planet is the most massive transiting planet yet reported. It is also one of only four transiting planets with an obviously noncircular orbit. How such a massive planet formed, how it achieved its tight orbit, and why the orbit is eccentric are interesting unanswered questions, and precise determinations of the basic system parameters may help to answer them.

JK08 found that a key parameter — the planetary radius — was especially uncertain, with an allowed range from 1.17 to 2.10 times the radius of Jupiter. This wide range encompassed the results of two different methods for determining the planetary radius that gave discrepant values. They found that if the true radius is near the low end of this range, it can be accommodated by ordinary models for gas giants of solar composition with the given mass and degree of insolation, while if the radius is near the high end of the allowed range, more complex and interesting models would require consideration (see, e.g., Guillot & Showman 2002; Bodenheimer et al. 2003; Chabrier & Baraffe 2007; Hansen & Barman 2007; Burrows et al. 2007). High-precision photometry of transits is one avenue for improving the precision of the radius measurement. In \( \S \) 2 we describe our observations and the production of the light curves. In \( \S \) 3 we describe the procedure with which we estimated the system parameters from the light curves. In \( \S \) 4 we present the results for the planetary, stellar, and orbital parameters, as well as the transit times and updated transit and occultation ephemerides, which are useful for planning future observations. In \( \S \) 5 we summarize, and revisit the issue of the planetary radius and its theoretical interpretation, in light of the new data.

2. OBSERVATIONS AND DATA REDUCTION

We observed XO-3 on 12 nights when transits were predicted to occur according to the ephemeris of JK08. The observing dates and other pertinent characteristics of the observations are given in Table 1.

On six of those nights, we used the 1.2 m telescope at the Fred L. Whipple Observatory (FLWO) on Mount Hopkins, Arizona. We used KeplerCam (Szentygorygi et al. 2005), which has a monolithic 4096×4096 CCD detector giving a 23.1′×23.1′ field of view. We binned the images 2×2, giving a scale of 0.68″ per binned pixel. We used a Sloan z filter, the reddest broadband filter available, to minimize the effects of stellar limb darkening on the transit light curves. On each night we attempted to observe as much of the transit as possible, preferably starting at least 1 hr prior to ingress and ending at least 1 hr after egress, although this was not always possible. We defocused the telescope slightly to permit exposure times of 10–15 s without saturating...
the brightest star in the field. We also obtained dome flat exposures and bias exposures for calibration purposes.

On the other six nights, data were obtained with smaller telescopes. On the night of 2008 February 10, we used the 0.5 m telescope at Wise Observatory, in Israel. We used a Santa Barbara SBIG ST-8xe CCD (765 × 510 pixels, 1.31 arcsec pixel−1) and a 0.6 m telescope with an independent light curve. On 2007 September 17, October 18, and November 7, we used a 0.6 m telescope with an SBIG ST-8xe I-band filter on the 0.4 m telescope and an I-band filter was used for the November 7 event. We used standard procedures for the overscan correction, trimming, bias subtraction, and flat-field division. For the FLWO and Wise data, we performed aperture photometry of XO-3 and 15–20 comparison stars. The flux of XO-3 was divided by the sum of the fluxes of the comparison stars, and then divided by a constant to give a unit mean flux outside of transit for each of the two velocity data sets presented by JK08 (from the Hobby-Eberly Telescope and the Harlan J. Smith telescope), we allowed for an arbitrary additive constant velocity. As mentioned in the previous section, we also fitted for a linear function of time describing the OOT flux (two parameters per light curve).

A well-known degeneracy involves both of the bodies’ masses and radii. Only three of those four parameters can be determined independently. Three parameters that can be determined independently are \( R_p/R_s \), \( M_p/R_s^3 \) (Seager & Mallén-Ornelas 2003), and \( M_p/R_p^3 \) (Southworth et al. 2007). Rather than reparameterizing in terms of those variables, we find it more convenient to fix the stellar mass at some fiducial value and then use the scaling relations \( R_s \propto M_s^{1/3}, R_p \propto M_s^{1/3}, \) and \( M_p \propto M_s^{2/3} \) as needed.

To calculate the relative flux as a function of the projected separation of the planet and the star, we employed the analytic formulas of Mandel & Agol (2002) to compute the integral of the intensity over the unobscured portion of the stellar disk. We assumed the limb-darkening law to be quadratic. In some previous studies, including our own, the limb-darkening coefficients have been fixed at the tabulated values based on stellar atmosphere models. A more conservative approach is to fit for the limb-darkening law, since the actual stellar brightness distribution is not known and may differ from the tabulated limb-darkening law. However, it is generally not possible to constrain more than one free parameter in the limb-darkening law. Following the suggestion by Southworth (2008), our approach was to allow the linear coefficient \( a \) to vary freely, and to fix the quadratic coefficient \( b \) at the appropriate value tabulated by Claret (2004). To determine the “theoretical” values of the limb-darkening coefficients, we interpolated the ATLAS tables for the stellar parameters \( T_{\text{eff}} = 6429 \text{ K}, \) \( \log g = 4.244 \text{ (cgs)}, \) [Fe/H] = −0.177, and

### Table 1

| Date (UT) | Telescope | Filter | Cadence \( \Gamma \) (minute\(^{-1}\)) | rms \( \sigma \) | Red Noise Factor \( \beta \) | Effective Noise \( \sigma/\sqrt{\Gamma} \) | Midtransit Time (HJD) |
|-----------|-----------|--------|----------------------------------|----------------|-----------------|---------------------|-----------------|
| 2007 Sep 17 | E. Duran 0.6 m | I | 0.96 | 0.0024 | 2.02 | 0.0049 | 2,454,360.50866 ± 0.00173 |
| 2007 Oct 09 | V. Cliffs 0.4 m | I | 0.54 | 0.0023 | 3.06 | 0.0096 | 2,454,382.84500 ± 0.00265 |
| 2007 Oct 09 | V. Cliffs 0.6 m | R | 1.82 | 0.0022 | 1.58 | 0.0026 | 2,454,382.84523 ± 0.00112 |
| 2007 Oct 18 | E. Duran 0.6 m | I | 0.96 | 0.0027 | 1.18 | 0.0033 | 2,454,392.14999 ± 0.00130 |
| 2007 Oct 22 | E. Duran 0.6 m | I | 0.96 | 0.0022 | 1.93 | 0.0043 | 2,454,395.61179 ± 0.00167 |
| 2007 Oct 25 | FLWO 1.2 m z | 2.08 | 0.0023 | 1.10 | 0.0017 | 2,454,398.80322 ± 0.00066 |
| 2007 Nov 07 | E. Duran 0.6 m | V | 0.96 | 0.0021 | 1.42 | 0.0030 | 2,454,411.56904 ± 0.00161 |
| 2007 Dec 15 | FLWO 1.2 m z | 2.08 | 0.0022 | 1.63 | 0.0023 | 2,454,449.86742 ± 0.00067 |
| 2007 Dec 31 | FLWO 1.2 m z | 2.08 | 0.0011 | 1.00 | 0.0008 | 2,454,465.82610 ± 0.00038a |
| 2008 Jan 13 | FLWO 1.2 m z | 2.50 | 0.0020 | 1.31 | 0.0017 | 2,454,478.59308 ± 0.00119a |
| 2008 Jan 16 | FLWO 1.2 m z | 2.50 | 0.0018 | 1.57 | 0.0018 | 2,454,481.78455 ± 0.00070 |
| 2008 Feb 10 | Wise 0.5 m None | 1.61 | 0.0030 | 1.18 | 0.0028 | 2,454,507.31319 ± 0.00118 |
| 2008 Feb 17 | FLWO 1.2 m z | 2.50 | 0.0022 | 1.69 | 0.0024 | 2,454,513.69768 ± 0.00090 |

Notes.—Col. (1): UT date at midtransit. Col. (4): \( \Gamma \), the median number of data points per minute. Col. (5): \( \sigma \), the rms relative flux after subtracting the best-fitting model. Col. (6): Scaling factor \( \beta \) that was applied to the single-point flux uncertainties to account for red noise (see § 3). Col. (7): Effective noise per minute, defined as \( \sigma/\sqrt{\Gamma} \).

### 3. Determination of System Parameters

In order to determine the stellar, planetary, and orbital parameters, we fitted a parametric model to the 13 photometric time series, as well as the 21 radial velocity measurements of JK08. Our model and fitting method were similar to those described in previous TLC papers (see, e.g., Holman et al. 2006; Winn et al. 2007a). It is based on a Keplerian orbit of two spherical bodies. The physical parameters were the stellar mass and radius (\( M_s, R_s \)); the planetary mass and radius (\( M_p, R_p \)); the orbital period, inclination, eccentricity, and argument of pericenter (\( P, i, e, \omega \)); and a particular midtransit time (\( T_c \)). In addition, for each of the two velocity data sets presented by JK08 (from the Hobby-Eberly Telescope and the Harlan J. Smith telescope), we allowed for an arbitrary additive constant velocity. As mentioned in the previous section, we also fitted for a linear function of time describing the OOT flux (two parameters per light curve).

A well-known degeneracy involves both of the bodies’ masses and radii. Only three of those four parameters can be determined independently. Three parameters that can be determined independently are \( R_p/R_s \), \( M_p/R_s^3 \) (Seager & Mallén-Ornelas 2003), and \( M_p/R_p^3 \) (Southworth et al. 2007). Rather than reparameterizing in terms of those variables, we find it more convenient to fix the stellar mass at some fiducial value and then use the scaling relations \( R_s \propto M_s^{1/3}, R_p \propto M_s^{1/3}, \) and \( M_p \propto M_s^{2/3} \) as needed.
The interpolated values are given in Table 4, as well as the results for the fitted linear coefficient. The fitting statistic was

$$\chi^2 = \sum_{j=1}^{21} \left[ \frac{v_j^{(\text{obs})} - v_j^{(\text{calc})}}{\sigma_{v,j}} \right]^2 + \sum_{j=1}^{104} \left[ \frac{f_j^{(\text{obs})} - f_j^{(\text{calc})}}{\sigma_{f,j}} \right]^2,$$

where $v_j^{(\text{obs})}$ is the radial velocity observed at time $j$, $\sigma_{v,j}$ is the corresponding uncertainty, and $v_j^{(\text{calc})}$ is the calculated radial velocity. A similar notation applies to the fluxes $f_j$. For the velocity uncertainties, we used the values reported by JK08. For the flux uncertainties, we used a procedure that attempts to account for time-correlated (“red”) noise, at least approximately. For each of the 13 observed transits, we set the uncertainty of each data point equal to the rms relative flux observed out of transit, multiplied by a factor $\beta \geq 1$. The factor $\beta$ was determined using two different methods (described at the end of this section), and the larger of the two results was used in our final analysis.

We found the “best-fitting” values of the model parameters, and their uncertainties, using a Markov Chain Monte Carlo (MCMC) algorithm (see Tegmark et al. [2004] for applications to cosmological data, Ford [2005] for radial velocity data, Holman et al. [2006] or Winn et al. [2007a] for our particular implementation, and Burke et al. [2007] for a similar approach). This algorithm creates a chain of points in parameter space by iterating a jump function, which in our case was the addition of a Gaussian random deviate to a randomly selected single parameter. If the new point has a lower $\chi^2$ than the previous point, the jump is executed; if not, the jump is executed with probability $\exp \left( -\Delta \chi^2/2 \right)$. We set the sizes of the random deviates such that 40% of jumps are executed. We create a number of chains from different starting conditions to verify that they all converge to the same basin in parameter space, and then we merge them for our final results. The phase-space density of points in the chain is an estimate of the joint a posteriori probability distribution of all the parameters, from which may be calculated the probability distribution for an individual parameter by marginalizing over all of the others.

The fitting procedure had four basic steps. First, we performed a joint fit of all the light curves along with the radial velocities, to determine provisional values of the orbital period and physical parameters. Second, we measured individual midtransit times, by performing a MCMC analysis of each light curve with only three free parameters: the zero point and slope of the linear function describing the OOT flux, and the midtransit time. We fixed $R_p$, $R_*$, and $i$ at the best-fitting values determined from the ensemble. There is no need to fit the midtransit times simultaneously with $\{R_p, R_*, i\}$, because the errors in those parameters are uncorrelated with the error in the midtransit time. Third, we recomputed the transit ephemeris using the newly measured

$\nu_j = 2.0 \text{ km s}^{-1}$. The interpolated values are given in Table 4, as well as the results for the fitted linear coefficient.
midtransit times (see § 4.2 for more details on this step). Fourth, we fixed the orbital period and midtransit times at the values just determined, and performed another joint fit of all the radial velocity and photometric data, to obtain final estimates of the model parameters and their uncertainties. The results from this final computation did not differ significantly from the results of the initial joint fit.

As mentioned previously, we used two different methods to estimate the factor $\beta$ by which time-correlated noise effectively increases the flux uncertainties. We refer to the first method as the “time-averaging” method, which has been described previously by Winn et al. (2007b) and is closely related to a method used by Gillon et al. (2006). For each light curve we found the best-fitting model and calculated $\sigma_1$, the standard deviation of the unbinned residuals between the observed and calculated fluxes. Next we averaged the residuals into $M$ bins of $N$ points and calculated the standard deviation $\sigma_N$ of the binned residuals. In the absence of red noise, we would have expected

$$\sigma_N = \frac{\sigma_1}{\sqrt{N}} \sqrt{M - 1},$$

but often $\sigma_N$ is larger than this by a factor $\beta$. We found that $\beta$ depends only weakly on the choice of averaging time $\tau$, generally

\[ \text{Fig. 2.—Relative photometry of XO-3, based on observations with 0.4–0.6 m telescopes.} \]

We thank G. Kovacs for pointing out that we erroneously neglected the factor $[M/(M - 1)]^{1/2}$ in previous analyses. Typically $M > 5$, and this factor is smaller than 1.12.
rising to an asymptotic value at \( \tau \approx 10 \) minutes. We denote by \( \beta_1 \) the median of these factors when using averaging times ranging from 15 to 30 minutes (the approximate duration of ingress or egress).

We refer to the second method as the “rosary-bead” method, which has been used previously by many investigators (e.g., Bouchy et al. 2005; Southworth 2008). For each light curve, we found the best-fitting model and computed the time series of midtransit times. For each of the 13 light curves we computed the error bar in the median of these factors when using averaging times ranging from 15 to 30 minutes (the approximate duration of ingress or egress). For our final results, we assigned each light curve a larger error estimate. For our final results, we assigned each light curve an error estimate assuming uncorrelated errors.

In general, \( \beta_1 \) and \( \beta_2 \) are specific to each parameter of the model, but for simplicity we assumed they are the same for all parameters, and to calculate them we focused on the determination of midtransit times. For each of the 13 light curves we obtained the error bar in \( T_c \) as obtained through the time-averaging method, and as obtained with the rosary-bead method. For the 13 light curves, \( \beta_2/\beta_1 \) varied from 0.86 to 1.47, with a mean of 1.13 and a standard deviation of 0.21. Thus, the two methods gave similar results, and the rosary-bead method tended to produce larger error estimates. For our final results, we assigned each light curve the value \( \beta = \max(\beta_1, \beta_2) \). These choices of \( \beta \) are given in Table 1. All of these procedures may be fairly criticized for lacking statistical rigor, but experience has shown that the more common procedure of setting \( \sigma_{\beta} = \sigma_1 \) results in underestimated uncertainties in the model parameters, as demonstrated by a lack of agreement between the results of different but presumably equivalent data sets.

4. RESULTS

Table 1 gives all of the newly measured transit times. Table 3 gives the results for the planetary, stellar, and orbital parameters, as well as many other quantities of intrinsic interest or importance for planning follow-up observations. As an example of the latter, the quantity \( (R_p/a)^2 \) is the planet-to-star flux ratio at opposition, for a geometric albedo of unity, and as such it is relevant to pursuing observations of reflected light from the planet. Another example is the amplitude of the Rossiter-McLaughlin effect, given by \( (R_p/R_*)^2(v \sin i_*) \), where \( v \sin i_* \) is the projected rotation rate of the star (see, e.g., Gaudi & Winn 2007). The labels A–E, explained in the table caption, are an attempt to clarify which quantities are determined independently from our analysis, which quantities are functions of those independent parameters, and which quantities depend on our isochrone analysis to break the fitting degeneracy between the stellar mass and radius. Table 4 gives the results for the limb-darkening coefficients.

4.1. The Stellar and Planetary Radii

As discussed in the previous section, the joint analysis of the light curves and velocities cannot independently determine the masses and radii of both bodies. Some external information about the star or the planet must be introduced to break the fitting degeneracies \( M_p \propto M_*^{2/3} \) and \( R_p \propto R_* \propto M_*^{1/3} \). Our approach was to seek consistency between the observed spectroscopic properties of the star, the stellar mean density that is derived from the transit light curves, and theoretical models of stellar evolution. This is the same approach (and uses the same software) that was described in detail by Sozzetti et al. (2007) and Torres et al. (2008). Here we summarize the procedure, and refer the reader to those papers for more details.

There were two sets of inputs. First, we used the values of the effective temperature \( T_{\text{eff}} \), surface gravity \( \log g \), and metallicity \([\text{Fe/H}]\) of the host star, as reported by JK08, based on a parametric fit to the optical spectrum of XO-3 using the Spectroscopy Made Easy (SME) program (Valenti & Piskunov 1996; Valenti & Fischer 2005). Second, we used the scaled semimajor axis \( a/R_* \), and the orbital parameters from our joint analysis of the photometry and radial velocity data. Given \( a/R_* \), and the orbital parameters, it is possible to derive the mean stellar density, using Kepler’s law (Seager & Malleón-Ornelas 2003). We use the symbol \( \rho_* \) to refer to the mean density determined in this fashion.

We used the Yonsei-Yale (Y2) stellar evolution models by Yi et al. (2001) and Demarque et al. (2004). We computed isochrones for the full range of metallicities allowed by the data, and for stellar ages ranging from 0.1 to 14 Gyr, seeking points that gave agreement with the observed \( T_{\text{eff}} \) and one of the two gravity indicators (\( \log g \) and \( \rho_* \)). For each stellar property (mass, radius, and age), we took a weighted average of the points on each isochrone. The weights were based on the agreement with the observed temperature, metallicity, and gravity indicator, and a factor taking into account the number density of stars along each isochrone (assuming a Salpeter mass function).

In almost all of the 23 cases examined by Torres et al. (2008), the results when using either \( \log g \) or \( \rho_* \) as the gravity indicator were in agreement, and greater precision was obtained with \( \rho_* \),...
TABLE 3
SYSTEM PARAMETERS OF XO-3

| Parameter                        | Value       | 68.3% Conf. Limits | Comment |
|----------------------------------|-------------|--------------------|---------|
| **Transit Parameters**           |             |                    |         |
| Orbital period, $P$ (days)       | 3.1915239   | ±0.0000068         | A       |
| Midtransit time (HJD)            | 2,454,449.86816 | ±0.00023         | A       |
| Planet-to-star radius ratio, $R_p/R_*$ | 0.09057 | ±0.00057            | A       |
| Orbital inclination, $i$ (deg)   | 84.20       | ±0.54              | A       |
| Scaled semimajor axis, $a/R_*$   | 7.07        | ±0.31              | A       |
| Transit impact parameter        | 0.705       | ±0.023             | B       |
| Transit duration (hr)            | 2.989       | ±0.029             | B       |
| Transit ingress or egress duration (hr) | 0.466   | ±0.033             | B       |
| RM figure of merit ($R_p/a^2$)   | 152.2       | ±2.3               | B, C    |
| **Occultation Parameters (Predicted)** |           |                    |         |
| Midoccultation time (HJD)        | 2,454,451.977 | ±0.034          | B       |
| Occultation duration (hr)        | 2.86        | –0.014, +0.080     | B       |
| Occultation ingress or egress duration (hr) | 0.355   | –0.027, +0.067     | B       |
| Occultation impact parameter     | 0.614       | ±0.050             | B       |
| Reflected light figure of merit ($R_p/a^2$) | 0.000164 | ±0.00015           | B       |
| **Other Orbital Parameters**     |             |                    |         |
| Orbital eccentricity, $e$        | 0.260       | ±0.017             | A       |
| Argument of pericenter, $\omega$ (deg) | 345.8   | ±7.3               | A       |
| Velocity semi-amplitude, $K$ (m s\(^{-1}\)) | 1463    | ±53                | A       |
| Planet-to-star mass ratio, $M_p/M_*$ | 0.00927 | ±0.00036           | D       |
| Semimajor axis (AU)             | 0.0454      | ±0.00082           | D       |
| **Stellar Parameters**           |             |                    |         |
| Mass, $M_*$ ($M_\odot$)          | 1.213       | ±0.066             | D       |
| Radius, $R_*$ ($R_\odot$)        | 1.377       | ±0.083             | D       |
| Mean density, $\rho_*$ (g cm\(^{-3}\)) | 0.650    | ±0.086             | B       |
| Effective temperature, $T_{\text{eff}}$ (K) | 6429    | ±100               | E       |
| Surface gravity, log $g_*$ (cgs) | 4.244       | ±0.041             | D       |
| Projected rotation rate, $v \sin i_*$ (km s\(^{-1}\)) | 18.54  | ±0.17              | C       |
| Metallicity (Fe/H)               | –0.177      | ±0.080             | E       |
| Luminosity ($L_*$)               | 2.92        | –0.48, +0.59       | D       |
| Age (Gyr)                        | 2.82        | –0.82, +0.58       | D       |
| Distance (pc)                    | 174         | ±18                | D       |
| **Planetary Parameters**         |             |                    |         |
| $M_p$ ($M_\text{Jup}$)           | 11.79       | ±0.59              | D       |
| $R_p$ ($R_\text{Jup}$)           | 1.217       | ±0.073             | D       |
| Surface gravity, log $g_p$ (cgs) | 4.295       | ±0.042             | B       |
| Mean density, $\rho_p$ (g cm\(^{-3}\)) | 8.1       | –1.3, +1.7         | D       |
| Equilibrium temperature, $T_{\text{eff}} (R_p/a)^{1/2}$ (K) | 1710  | ±46               | D       |

Notes.—A = Determined independently from our joint analysis of the photometric and radial velocity data. B = Functions of group A parameters. C = From JK08. D = Functions of group A parameters, supplemented by results of the isochrone analysis (see § 4.1) to break the degeneracies $M_p \propto M_*^{2/3}$, $R_p \propto R_* \propto M_*^{1/3}$. E = From JK08, with enlarged error bars (see § 4.1).

TABLE 4
LIMB-DARKENING PARAMETERS FOR XO-3

| Bandpass | Linear Coefficient | Quadratic Coefficient | Fitted Value of Linear Coefficient |
|----------|--------------------|-----------------------|-----------------------------------|
| (1)      | (2)                | (3)                   | (4)                               |
| z        | 0.13               | 0.35                  | 0.11 ± 0.07                       |
| I        | 0.16               | 0.36                  | 0.06 ± 0.15                       |
| R        | 0.23               | 0.37                  | 0.16 ± 0.14                       |
| V        | 0.31               | 0.36                  | 0.47 ± 0.14                       |
| Clear    | . . .              | 0.33                  | 0.47 ± 0.13                       |

Notes.—The assumed limb-darkening law was $I_i/I_0 = 1 - a(1 - \mu) - b(1 - \mu)^2$. The tabulated coefficients inCols. (2) and (3) are based on interpolation the ATLAS tables of Claret (2000, 2004), for the stellar parameters $T_{\text{eff}} = 6429$ K, $\log g = 4.244$ (cgs), $[\text{Fe/H}] = -0.177$, and $v_\text{t} = 2.0$ km s\(^{-1}\). Col. (4): Results of fitting for the linear coefficient when the quadratic coefficient is fixed at the tabulated value.

This entry refers to the (unfiltered) Wise data, for which we used the tabulated quadratic coefficient $b = 0.33$ appropriate for the SDSS $g$ band.
often by a factor of 2 or more. Torres et al. (2008) did not consider the case of XO-3, but using the same technique we find poor agreement between the results of using the two independent gravity indicators. Using \( C_26 \) results in a less massive and smaller star, with a higher mean density and a stronger surface gravity. This in turn gives a less massive and smaller planet. One way to frame the discrepancy is that by using \( C_26 \) as the gravity indicator, the isochrone analysis gives a stellar surface gravity of \( \log g = 4.244 \pm 0.041 \), as compared to the SME-derived value of \( \log g = 3.950 \pm 0.062 \). The difference is \( 0.294 \pm 0.074 \), which is inconsistent with zero at the 4 \( \sigma \) level. Clearly something is amiss with either our interpretation of the light curve, or the SME determination of \( \log g \), or both. The same conflict was already apparent between the light-curve analysis and the isochrone analysis of JK08. We have improved the precision of the light-curve parameters by factors of 3 or more, and the conflict with the spectroscopic determination of \( \log g \) has been sharpened.

Some further thoughts on the tension between \( \rho_\star \) and \( \log g \) are given in § 5. For the results given in Table 3, we proceeded under the assumption that the error in the spectroscopic determination of \( \log g \) was greatly underestimated. We disregarded the spectroscopic \( \log g \) while performing the isochrone analysis, and we also increased the error bars on \( T_{\text{eff}} \) and \([Fe/H]\), since the errors in those three quantities are highly correlated when fitting models to the features observed in optical spectra. We increased the error in \( T_{\text{eff}} \) from 50 to 100 K, and in \([Fe/H]\) from 0.023 to 0.08 dex, which we believe to be conservative choices, and are consistent with similar judgments made by Torres et al. (2008) in their homogeneous analysis of transiting systems.

### 4.2. The Transit and Occultation Ephemerides

We calculated a photometric ephemeris for the transits of XO-3 using the 13 midtransit times given in Table 1 and the 16 midtransit times measured by the XO Extended Team and reported previously by JK08. We fitted a linear function of transit epoch \( E \),

\[
T_c(E) = T_c(0) + EP.
\]

The fit had \( \chi^2 = 29.6 \) with 27 degrees of freedom (dof), or \( \chi^2/N_{\text{dof}} = 1.10 \). The results were \( T_c(0) = 2.454, 449.86816 \pm 0.00023 \) (HJD) and \( P = 3.1915239 \pm 0.0000068 \) days. Our derived period agrees with the value 3.19154 \( \pm 0.00014 \) days determined by JK08 and is about 20 times more precise. Figure 4 is the \( O-C \) (observed minus calculated) diagram for the transit times. In this calculation, we did not use the four midtransit times that were based on data from the XO survey instrument, because those data had unquantified and apparently large uncertainties. Nevertheless, all of the observed times are plotted in Figure 3, and are seen to be at least roughly consistent with the new ephemeris.

To help in planning observations of occultations (secondary eclipses) of XO-3b, we have also used our model results to predict the timing, duration, and impact parameter of the occultations. Because of the eccentric orbit, occultations and transits are not separated by exactly one-half of the orbital period, and do not have the same duration or impact parameter. Based on our model of the system, we expect occultations to occur 2.109 \( \pm 0.034 \) days after transits. The predicted occultation ephemeris is given in Table 3.

![Fig. 4.—Transit timing residuals for XO-3b. The calculated times, using the ephemeris derived in § 4.2, have been subtracted from the observed times. The filled circles are the data from this work and from the XO Extended Team observations reported by JK08. Those data were used to calculate the transit ephemeris. The unfilled circles are the data from the XO Survey instruments, which were not used to calculate the transit ephemeris.](image-url)
5. SUMMARY AND DISCUSSION

We have presented new photometry spanning transits of the exoplanet XO-3. The photometry greatly improves the precision with which the light-curve parameters are known. In particular, the planet-to-star radius ratio is known to within 0.6%, an improvement by a factor of 6. The inclination angle is now known to within 0.54°, an improvement by a factor of 2.5. A third light-curve parameter, the scaled semimajor axis (a/Rs), has also been refined by a factor of a few, and was used (along with the orbital period and Kepler’s law) to calculate ρs, the stellar mean density. We found that the photometric result for ρs is incompatible (at the 4 σ level) with the previous spectroscopic determination of log g, in the sense that theoretical stellar evolution models cannot accommodate both values along with the observed effective temperature and metallicity of the star.

Because of this conflict, it is worth reviewing how ρs and log g were determined. The photometric determination of ρs is based on a fit to the light curve with three relevant free parameters, and the application of Kepler’s law (Seager & Mallén-Ornelas 2003). The spectroscopic determination of log g is based on the interpretation of pressure-sensitive features of the stellar spectrum, especially the widths of the wings of selected absorption lines. The interpretation is performed by comparison to theoretical models of stellar atmospheres. For XO-3 this comparison was performed with SME (Valenti & Piskunov 1996; Valenti & Fischer 2005), an automated analysis program that fits a model to an optical spectrum by adjusting many free parameters, of which the most relevant are the effective temperature, surface gravity, projected rotation rate, and metal abundances. The model is based on plane-parallel stellar atmosphere models in local thermodynamic equilibrium, and reasonable assumptions regarding instrumental broadening and turbulent broadening mechanisms. Empirical corrections are applied to the parameters based on an SME analysis of the solar spectrum.

The spectroscopic method for determining log g is more complex than the photometric method for determining ρs. In addition, it is important to recognize that the quoted error in the spectroscopic determination of JK08 (log g = 3.950 ± 0.062) represents the standard error of the mean of the results of fitting 10 independent spectra of XO-3. Thus, the error bar refers to the repeatability or precision of the result, and not its accuracy. Valenti & Fischer (2005) assessed the accuracy of SME by comparing two methods of determining surface gravity: (1) the purely spectroscopic method described in the previous paragraph; and (2) the surface gravity that follows from the observed stellar luminosity (for stars with measured parallaxes), effective temperature, and metallicity, by requiring consistency with theoretical isochrones of stellar evolution models. They found a systematic offset of 0.1 dex and a large scatter (see § 7.4 of that work). JK08 repeated this comparison for stars with similar temperatures to XO-3, finding a scatter of about 0.1 dex and some cases in which the discrepancy is ≈0.3 dex. Valenti & Fischer (2005) also compared the SME results for log g with spectroscopic results that have been obtained by other authors, finding a scatter of about 0.15 dex, and discrepancies as large as 0.3 dex. These general comparisons cannot speak to the specific case of XO-3, but they suggest that the 4 σ discrepancy between the spectroscopic and photometric methods in the present study is not as serious as it may seem. The true error in the spectroscopic determination of log g is probably larger than 0.062.

An upward revision of the stellar log g corresponds to a downward revision of the planetary radius, to 1.217 ± 0.073 RJup. How does this result compare to the radius that is expected on theoretical grounds? Fortney et al. (2007) have computed models for planets over a wide range of masses, compositions, ages, and irradiation levels, and provided the results in a convenient tabular form. Interpolation of those tables for a coreless, pure hydrogen-helium planet with properties appropriate for the XO-3 system (Mp = 11.8 MJup, a = 0.045 AU, Ls = 2.9 L☉, age 2.82 Gyr) gives a theoretical radius of 1.14 RJup.

Adding as much as ~100 MJup of heavy elements would decrease the theoretical radius by a few percent. On the other hand, the models of Forney et al. (2007) define the planetary surface as the 1 bar pressure level, whereas a much lower pressure is appropriate for comparison to transit observations. This “transit radius effect” will increase the theoretical radius by a few percent (Burrows et al. 2007). Assuming the combination of these effects to be small, the observed radius is 1.3 σ larger than the theoretical radius. Thus, the photometric analysis leads to a planetary radius that is only a little larger than the models of Fortney et al. (2007) would predict, similar to the case of HAT-P-1b (Winn et al. 2007b), and not nearly as “inflated” as some other examples in the literature such as HD 209458b (Charbonneau et al. 2000; Henry et al. 2000), WASP-1b (Collier Cameron et al. 2007; Charbonneau et al. 2007b), and TrES-4b (Mandushev et al. 2007).

Although we have argued that the photometric determination of ρs should take precedence over the spectroscopic determination of log g, it would be more definitive to settle the issue by measuring the trigonometric parallax of XO-3, as suggested by JK08. Our photometric analysis predicts that the distance will be found to be 174 ± 18 pc, based on the stellar luminosity inferred from theoretical isochrones, the V magnitude of 9.80 ± 0.03, and the assumption of negligible extinction. The spectroscopic analysis of JK08 predicted a greater distance, 260 ± 23 pc. An interesting but more challenging prospect for determining the stellar mass (and hence its radius) is to measure the general relativistic periastron precession of 2 arcmin yr−1 by precise long-term timing of transits and occultations (Heyl & Gladman 2007).

In addition to pinning down the correct value of the radius, there are other reasons to pursue further observations of XO-3, of which many are related to its sizable orbital eccentricity. One consequence of the eccentricity is that the planet experiences significant variations in stellar insolation over the 3.2 day orbital period. The time-variable response of the planet’s atmosphere may be detectable through mid-infrared photometry (Langton & Laughlin 2008). Whatever mechanism produced the large eccentricity may also have produced a large inclination angle relative to the stellar equatorial plane, an angle that can be measured through observations of the Rossiter-McLaughlin effect. Narita et al. (2008) have presented this type of evidence for a significant orbital tilt in the HD 17156 system.

If, on the other hand, the stellar rotation axis is well aligned with the orbital axis, then the combination of the measurements of sin i, i, and Rs gives a stellar rotation period of Prot = 3.73 ± 0.23 days. This is not too far from the orbital period of 3.19 days, suggesting that spin-orbit interactions may be unusually strong, perhaps even strong enough to excite the orbital eccentricity to the observed value.

Another way to produce an eccentricity is through stable long-term gravitational interactions with another planet. Although the midtransit times we have recorded are nearly consistent with a constant period, and hence do not provide prima facie evidence...
for any additional bodies in the system, we have achieved a precision of 1–2 minutes using relatively small telescopes. After a few more seasons, a pattern may yet emerge.

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