THE DEDICATED MONITOR OF EXOTRANSGITS (DEMONEX): SEVEN TRANSITS OF XO-4b

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Received 2015 November 11; accepted 2016 February 11; published 2016 March 22

ABSTRACT

The DEdicated MONitor of EXotransits (DEMONEX) was a 20-inch robotic and automated telescope to monitor bright stars hosting transiting exoplanets to discover new planets and improve constraints on the properties of known transiting planetary systems. We present results for the misaligned hot Jupiter XO-4b containing seven new transits from the DEMONEX telescope, including three full and four partial transits. We combine these data with archival light curves and archival radial velocity measurements to derive the host star mass $M_*$ = $1.293^{+0.030}_{-0.029}$ $M_\odot$ and radius $R_*$ = $1.554^{+0.042}_{-0.030}$ $R_\odot$, the planet mass $M_p = 1.615^{+0.10}_{-0.099}$ $M_J$ and radius $R_p = 1.317^{+0.040}_{-0.029}$ $R_J$, and a refined ephemeris of $P = 4.1250687 \pm 0.0000024$ days and $T_0 = 2, 4547, 58, 18978 \pm 0.00024$ BJD$_{TDB}$. We include archival Rossiter–McLaughlin measurements of XO-4 to infer the stellar spin–planetary orbit alignment of $\lambda = -40.0^{+3.8}_{-3.5}$ degrees. We test the effects of including various detrend parameters, theoretical and empirical mass–radius relations, and Rossiter–McLaughlin models. We infer that detrending against CCD position and time or airmass can improve data quality but can have significant effects on the inferred values of many parameters—most significantly $R_p/R_*$ and the observed central transit times $T_C$. In the case of $R_p/R_*$ we find that the systematic uncertainty due to detrending can be three times that of the quoted statistical uncertainties. The choice of mass–radius relation has little effect on our inferred values of the system parameters. The choice of Rossiter–McLaughlin models can have significant effects on the inferred values of $v \sin i_*$ and the stellar spin–planet orbit angle $\lambda$.

Key words: methods: data analysis – planetary systems – stars: individual (XO-4) – techniques: photometric – techniques: radial velocities

Supporting material: machine-readable table

1. INTRODUCTION

Hot Jupiters are a unique class of extrasolar planets (exoplanets) known for their proximity to their host stars and their large masses. With the discovery of the first hot Jupiter (Mayor & Queloz 1995), we now know that understanding the physical nature of hot Jupiters can play a large role in constraining our understanding of a variety of theories regarding planetary formation, disk formation, and planet migration (Marcy et al. 2005; Fabrycky & Tremaine 2007; Nagasawa et al. 2008).

Hot Jupiters provide unique observational opportunities relative to exoplanets of other populations. The small semimajor axes of the orbits of hot Jupiters increase the a priori transit probability, which, coupled with a large observational transit signal due to hot Jupiters’ large relative radii and their short periods, provide many observational opportunities to identify hot Jupiters and perform follow-up observations. These observational advantages are not unique to photometric observations, but also appear in radial velocity (RV) measurements, where the large masses of hot Jupiters increase the semiamplitude of the radial velocity signal, as well as Rossiter–McLaughlin (RM) measurements, where the RM signal is proportional to the transit depth.

In general, the transits provide a number of geometric ratios to relate the star and planet (i.e., the depth of the transit is related to the planet/star radius ratio), as well as the density of the star. When combined with another constraint on the mass and radius of the primary (e.g., derived from isochrones using the spectroscopic stellar effective temperature and metallicity) and a measurement of the Doppler amplitude from radial velocity observations, it becomes possible to estimate the masses and radii of both the planet and star. Additional measurements allow for the derivation of a large number of physical parameters, not just the planet and stellar masses and radii (see Winn 2010).

Following the discovery of systems containing hot Jupiters, one generally would like to follow up with observations to better understand the properties of the host star and planet. In general, this requires additional photometric and radial velocity observations. Providing stricter constraints on known hot Jupiters provides predictions for future observations, increasing the efficiency of those observations.

The purpose of this paper is threefold in nature. First, we present new data on XO-4b from the DEdicated MONitor of EXotransits (DEMONEX) telescope. Second, we investigate the effects of choices of detrending variables, mass–radius relations, RM models, and other models or user-defined variables on the derived parameters of the system. Third, we improve the parameters of XO-4 and XO-4b by globally fitting all available data in a homogeneous manner.

2. DATA

The following sections contain summaries of all available data used in our global analysis, as well as information regarding the data reduction process used for the new DEMONEX data.

2.1. DEMONEX Observations of XO-4

New observations of XO-4b were made using DEMONEX (Eastman et al. 2010a). DEMONEX was a low-cost, 0.5 m,
robotic telescope constructed from commercially available parts operated remotely out of Winer Observatory in Sonoita, Arizona. DEMONEX monitored bright stars hosting known transiting planets over a 3 yr period from 2008 to 2011 in order to provide a homogeneous data set of precise relative photometry for over 40 transiting systems. The DEMONEX mount became increasingly unreliable and failed on multiple occasions, requiring both major and minor repairs. After 3 yr of operations, DEMONEX was decommissioned owing to the maintenance costs and resources required to keep the mount operational from its remote location.

There are 20 nights of data from 2008 November to 2010 May taken during primary transits of XO-4b. All observations were made in the Sloan $z$ band. Five nights were lost owing to the mount pointing to the incorrect field. In addition, the DEMONEX observing strategy prioritized full transits of other targets over partial transits of XO-4b. Often, that resulted in small observing windows, which we opted to fill with observations near transit in case they happened to be useful rather than sitting idle. Unfortunately, four nights only got data out of transit and four nights only captured the flat bottom of the transit, neither of which ended up providing useful constraints. Thus, we were left with an unfortunately low yield of 7/20 (35%) usable nights, but we obtain three full transits, two ingresses, and two egresses.

2.2. McCullough et al. (2008)

McCullough et al. (2008, hereafter MC08) report the original discovery of the planet XO-4b detected using the XO telescope (McCullough et al. 2006). Follow-up $BVR$ observations were made by the XO Extended Team (XOET), as well as follow-up $R$-band photometric observations using the Perkins $1.8$ m telescope. Follow-up spectroscopic measurements were made using the Harlan J. Smith $2.7$ m telescope and the $11$ m Hobby–Eberly Telescope. MC08 perform an analysis of the spectra to report the stellar properties of the host star, including stellar effective temperature $T_{\text{eff}}$, surface gravity $\log g_*$, metallicity [Fe/H], projected rotational velocity $v \sin I_*$, and the RV semiamplitude $K$. Combining the stellar parameters with the light curves, MC08 report a planet mass of $M_p = 1.72 \pm 0.20 M_J$, radius of $R_p = 1.34 \pm 0.048 R_J$, orbital period of $P = 4.12502 \pm 0.00002$ days, and heliocentric Julian date at mid-transit of $2,454,859.9322 \pm 0.0004$ for XO-4b.

We adopt the stellar properties, $T_{\text{eff}}$, $\log g_*$, [Fe/H], and $v \sin I_*$, from MC08 as Gaussian priors for our global analysis as described in Section 4. Additionally, the authors of MC08 kindly provided the original XO light curves, the $BVR$-band XOET follow-up light curves, and the Perkins follow-up light curves, which we use, along with the radial velocity data listed in the MC08 paper in our global analysis.

We convert the times from the MC08 XOET light curves from $\text{HJD}_{\text{UT}}$ to $\text{BJD}_{\text{TDB}}$ using the IDL code $\text{HJD2BJD}$ to maintain uniform time stamps across all available light curves. The average correction is $\sim 94$ s, which is less than the typical uncertainty in the central transit times.

2.3. Narita et al. (2010)

Narita et al. (2010, hereafter N10) report new Sloan $z$-band photometric and radial velocity observations of XO-4 with conducted with the FLWO $1.2$ m telescope (photometric) and the $8.2$ m Subaru Telescope (RV). Based on these new light curves, N10 report a refined transit ephemeris for XO-4b of $P = 4.1250828 \pm 0.0000040$ days and $\tau = 2454485.9323 \pm 0.00039$ $\text{BJD}_{\text{TDB}}$.

N10 also report the first measurements of the RM effect of XO-4b. N10 estimate the sky-projected angle between the stellar spin axis and the planetary orbital axis to be $\lambda = -46.7^{+0.8}_{-0.1}$ degrees. We compare the N10 results from the publicly available N10 light curves and radial velocity data against the results we obtain using the same data set outlined in Section 4.1 to validate our light-curve analysis methods and procedures. We also include the publicly available N10 light curves and radial velocity data in our global analysis.

2.4. Todorov et al. (2012)

Todorov et al. (2012) use the Spitzer Space Telescope (Werner et al. 2004) and Infrared Array Camera (Fazio et al. 2004) to obtain $3.6$ and $4.5 \mu$m observations of the secondary eclipses of three planets, including XO-4b. To better constrain the ephemerides of the planetary transits, Todorov et al. (2012) make additional $I_s$-band ground-based primary transit observations using the Universidad de Monterrey Observatory (UDEM) $0.36$ m telescope. We do not include secondary eclipse data in our data analysis, but we do include the UDEM $I_s$-band ground-based primary transit observations in our global analysis, including the previously unpublished UT 2012-01-07 data, kindly provided by the authors.

We convert the times from the Todorov et al. (2012) UDEM observations from $\text{BJD}_{\text{UT}}$ to $\text{BJD}_{\text{TDB}}$ using the IDL code $\text{JDT2JDTDB}$ to maintain uniform time stamps across all available light curves. While this routine is intended to convert Geocentric Julian Date from UTC to TDB, it is accurate to $30$ ms when using it to convert Barycentric Julian Dates instead (Eastman et al. 2010b), which is more than sufficient for our purposes. The average correction is $\sim 82$ s, which is less than the typical uncertainty in the central transit times.

3. MODELS

3.1. Transits and Radial Velocity

The models used in this paper to fit the transit and orbital radial velocity data are unchanged from the original Eastman et al. (2013) EXOFAST paper. The original EXOFAST paper ignores a number of effects, including RM and transit timing variations (TTVs), which we now include to maintain consistency with work done by the other groups.

3.2. Rossiter–McLaughlin Effect

We also consider the radial velocity data taken during transit, and as such we must consider models for the RM effect (McLaughlin 1924; Rossiter 1924). The precise model used to model the RM effect can have a significant effect on the inferred parameters, and yet this can vary from system to system (Johnson et al. 2008; Hirano et al. 2010). A number of RM models exist, and we investigate two separate models here.

The ambiguity of the proper model of the RM effect that should be used comes from the fact that the RM effect is not, in
fact, due to a change in the radial velocity of the star. The radial velocity measurement is made by estimating some measure of the “centers” of known absorption lines and their change in central wavelength relative to laboratory measurements. If the shape of the absorption features changes in such a way as to change the odd moments of the lines, then this can result in a change in the measured line centers and as a result can be attributed to a change in the radial velocity of the star. The precise relation between the change in the line shape and the inferred change in the line center will depend on many intrinsic properties of the star, such as its effective temperature, surface gravity, and rotation rate, as well as the precise algorithm used to estimate the line centers.

Thus, the RM effect manifests as an anomalous radial velocity measurement $\Delta v_{\text{RM}}$ made during the primary transit, where the anomalous signal is due to a change in the shape of the absorption feature rather than to the motion of the host star. The change in shape is due to the transiting planet preferentially blocking light emitted from the rotating host star. The blocked light, depending on the position of the planet as viewed from the observer, may be red- or blueshifted relative to the center of the star owing to the rotation of the host star. As this light is blocked, it can introduce an asymmetry to the absorption feature (Gaudi & Winn 2007). Because the anomalous signal is dependent on a change in the shape of the absorption feature, the measured $\Delta v_{\text{RM}}$ will depend heavily on the method used to measure the radial velocity signal and whether that method is sensitive to changes in the shape of the absorption features.

The RM anomalous radial velocity shift has a strong dependence on the host star’s rotation $v \sin I_*$ and the axis of the orbit of the planet relative to the sky-projected spin axis of the star $\lambda$. The RM signal is also dependent on the radius of the planet in stellar radii $R_p/R_*$, the limb-darkening parameters $u_1$ and $u_2$, and the path the planet takes over the star, which can be described by the inclination $i$ and orbital distance $a$ or by the impact parameter $b$. Winn (2010) gives an approximation for the maximum amplitude of the RM effect as

$$\Delta v_{\text{RM}} \approx p^2 \sqrt{1 - b^2} (v \sin I_*).$$  

When the effect is observed, it is possible to place constraints on the sky-projected spin axis and planetary orbit axis alignment $\lambda$, sky-projected rotational velocity $v \sin I_*$, and impact parameter $b$. The transit light curves and previous RV studies provide us with independent constraints on $v \sin I_*$ and $b$, and these improve the constraint on $\lambda$.

There are two different RM models we investigate to place these constraints on $\lambda$, those based on the moment method (Ohta et al. 2005, 2009, hereafter OTS) and those based on the cross-correlation method (Queloz et al. 2000; Winn et al. 2005; Narita et al. 2009; Hirano et al. 2010). There are other models available (Giménez 2006; Boué et al. 2013), but we focus on the OTS and cross-correlation methods as the default model in EXOFAST is that based on Ohta et al. (2005) and previous work on XO-4b follows the cross-correlation method. Additional constraints from Doppler tomography (Collier Cameron et al. 2010; Bourrier et al. 2015) could be used to provide an independent check on the accuracy of the two methods.

### 3.2.1. Moment Method

Ohta et al. (2005) describe their derivation of the RM effect as an approximate but accurate analytic formula for the anomaly in the radial velocity curves. Their method approximates the velocity anomaly as the change in the first moment of the absorption-line profile and uses only linear stellar limb darkening. This work is followed by Ohta et al. (2009), where the authors present theoretical predictions for the photometric and spectroscopic signatures of rings around transiting extrasolar planets that now include quadratic limb darkening and terms for ringed extrasolar planets. These new expressions supersede the work in Ohta et al. (2005).

OTS define the flux of the star as a function of the position of the planet

$$F = \int \frac{I(x, z)dx dz}{\int I_0(x, z)dx dz},$$  

where $x$ and $z$ are the position of the center of the planet perpendicular to and parallel to, respectively, the projected rotation axis of the star, and they integrate over the surface brightness of the unocculted stellar disk $I_0$, and $I$ is the surface brightness of the occulted star, such that $I = 0$ in the region occulted by the planet. OTS assume rigid rotation in the star, i.e., no differential rotation such that the projected velocity is constant along lines of constant $x$.

When we use these expressions, we ignore the effects of planetary rings as they are not expected around hot Jupiters (Gaudi et al. 2003). Under this assumption, the anomalous radial velocity can be reduced to the following expression:

$$\Delta v_{\text{RM}} = x_p v \sin I_* F$$  

(3)

where $x_p$ is the $x$ component of the planet’s position in units of stellar radii and $F$ is the relative flux from Equation (2). The details of these expressions are included in Ohta et al. (2009), including detailed expressions for integrating the flux in Equation (2).

### 3.2.2. Cross-correlation Method

An alternative method to measure the RM effect is to compare the anomalous radial velocity by cross-correlation with a stellar template spectrum. This method was used by Queloz et al. (2000), Winn et al. (2005), and Narita et al. (2009), among others, and is described in detail by Hirano et al. (2010). Hirano et al. (2010) cover in detail the choice of absorption-line profile (Gaussian, Voigt, etc.) and eventually settle on a form inspired by their Gaussian approximation:

$$\Delta v_{\text{RM}} = -F v_p (p - q v_p^2).$$  

(4)

Here $F$ is the flux ratio and uses the same expression as that of Equation (2). For rigidly rotating stars $v(x, y) \sin I_*$ is a constant along lines of constant $x$ and the expression reduces to

$$v_p(x, y) = x v \sin I_*$$  

(5)

and reproduces the OTS result as noted by Hirano et al. (2010).

The parameters $p$ and $q$ are each functions of thermal broadening, microturbulent broadening, and the stellar rotation width that describe the shape of the line. The parameters $p$ and $q$ are empirically fit for each individual planetary system the method is applied to. As a result, to first order, for which $p = 1$
and \( q = 0 \), Equation (4) reduces to Equation (3) and the two methods are identical. For reference, in the case of XO-4b, N10 derive and report \( p = 1.6159 \) and \( q = 0.83778 \), but do not quote errors or uncertainties for these values.

Because \( p \) and \( q \) depend on precisely how the algorithm used to estimate the radial velocity measures the shape of the absorption profiles and the line-spread function of the spectrograph, it is possible to cause a change in line shape as instrumental and not due to the RM effect. If ignored, this can lead to a misinterpretation of the RM effect, and as such this method must be applied to each system as outlined above to distinguish between the two effects. There are cases when the moment method and cross-correlation methods produce the same results (Johnson et al. 2008; Winn et al. 2008). However, discrepancies in the derived parameters can arise between the two methods, particularly for systems with small impact parameters (Winn et al. 2005; Hirano et al. 2011).

4. DATA ANALYSIS

To analyze the XO-4b data, we use a custom version of the publicly available EXOFAST suite of IDL programs described in Eastman et al. (2013). This is a continuation of the same code used to fit the KELT discoveries (e.g., Siverd et al. 2012) and includes the ability to simultaneously fit multiple transit light curves, both on the same telescope from different nights and from different telescopes, as well as the ability to include multiple radial velocity data sets. Additional modifications were made by us to update the default RM models, include alternative RM models, and to change how the estimated errors are scaled on the RM data.

We adopt Gaussian priors from MC08 on the stellar parameters \( T_{\text{eff}} \), \( \log g_s \), [Fe/H], and \( v \sin I_c \) and use the reported values of \( p = 1.6159 \) and \( q = 0.83778 \) from N10 when using the Hirano et al. (2010) based RM models. We do ignore secondary eclipse data from Todorov et al. (2012) and assume \( e = 0 \) as this is consistent with all of the other groups (McCullough et al. 2008; N10; Todorov et al. 2012).

4.1. Narita Data versus Narita et al. (2010)

As a confirmation of our light-curve analysis, we make many of the same assumptions used in the N10 paper and compare the output from EXOFAST using the N10 data to the published results of the N10 paper. It should be noted that N10 include the same Gaussian priors we adopt and additionally include a Gaussian prior on the period and \( T_0 \) from MC08. N10 also fix the limb-darkening parameter \( u_1 \) and treat the second limb-darkening parameter \( u_2 \) as a free parameter. In EXOFAST both \( u_1 \) and \( u_2 \) are calculated from \( \log g_s \), \( T_{\text{eff}} \), [Fe/H], and the observed bandpass by Claret & Bloemen (2011). During this exercise, we do not create a new free parameter for \( u_2 \), nor do we fix \( u_1 \), but we do include the Gaussian priors on period and \( T_0 \). Thus, our results are not precisely comparable, although we expect any differences to be relatively minor.

Table 1 contains the same parameters published in N10 (Narita, \( \chi^2 \)) along with those produced by EXOFAST (EXOFASTMCMC). The values are consistent within the errors for all parameters. It should be noted that N10 use the minima in \( \chi^2 \) and \( \Delta \chi^2 = 1 \) to quote their best value and errors, where we typically quote the median values of the parameters and the 68% confidence intervals from the MCMC chains. In order to more precisely compare our results with those of N10, we also fit a multidimensional hyperboloid to the output MCMC chains in order to infer the values of the parameters with the minimum \( \chi^2 \) and the values where \( \Delta \chi^2 = 1 \) (EXOFAST, \( \chi^2 \)).

As we did not create a new free parameter for \( u_2 \), the constraint on the second limb-darkening parameter is calculated from the parameters \( \log g_s \), \( T_{\text{eff}} \), [Fe/H], and the band. Thus, the uncertainty on \( u_2 \) is simply a reflection on the covariance of \( u_2 \) with these parameters. We generally find values and uncertainties that are in good agreement with those of N10, verifying that the methods used in N10 are comparable to those used in EXOFAST. The final column of Table 1 shows the differences in the two minimum \( \chi^2 \) values divided by the uncertainties in quadrature for reference. The differences between methods are less than \( 1 \sigma \), and any differences may be attributable to our slightly different methods of estimating the values for the minimum \( \chi^2 \) and \( \Delta \chi^2 = 1 \).

4.2. DEMONEX Data

We converted all times in the DEMONEX data to Barycentric Julian Date in the barycentric dynamical time (BJDTDB) as advocated in Eastman et al. (2010b). We performed standard data reduction procedures for the raw DEMONEX XO-4 data. These include bias correction, dark subtraction, and flat fielding, and owing to our Sloan \( z \)-band observations, we additionally perform fringe corrections. To
perform the fringe corrections, a master fringe image is created by
taking the median of the nearest 100 images separated by a
minimum time step, where the stars are masked out in each
image. The background and amplitude of the master fringe
image are

divided by the sum of the
an initial set of comparison stars based on their similar counts
in the image and normalized to unity. We then select
the result of various red noise sources
example, Collins

Time (BJD$_{TDB}$) | Normalized Flux | Flux Error | $x$ (pixels) | $y$ (pixels)
--- | --- | --- | --- | ---
20081111: | | | | |
2,454,782.762028 | 1.001644 | 0.002393 | 866.200393 | 1219.753505
2,454,782.762820 | 1.008380 | 0.002104 | 870.227406 | 1220.639406
2,454,782.763614 | 1.016223 | 0.001979 | 873.242392 | 1220.334975
2,454,782.764407 | 1.004863 | 0.001808 | 875.858008 | 1220.666278
2,454,782.765201 | 1.005626 | 0.001758 | 877.882314 | 1219.812195
2,454,782.765994 | 1.005393 | 0.001807 | 879.948887 | 1218.680215
2,454,782.766786 | 1.010737 | 0.001784 | 881.385388 | 1218.341993
2,454,782.767579 | 1.006882 | 0.001733 | 881.728714 | 1218.411449
2,454,782.768372 | 1.002178 | 0.001764 | 883.499507 | 1216.778263
2,454,782.769167 | 1.007074 | 0.001747 | 883.487292 | 1216.278131

(This table is available in its entirety in machine-readable form.)

significant trends in all four detrend parameters when fitted
individually. Once all of the parameters are included, the
derived parameters converge to within 1σ of values previously
published in the literature, as well as the values derived when we
use only the N10 data in EXOFAST from Section 4.1. This
suggests that including all available detrend parameters
improves our analysis, at the expense of more computational
time and creating the potential of a new local minima in the
χ$^2$

EXOFAST can take trends in the photometric data and
remove them to improve the quality of data. We investigate
which, if any, detrend parameters in the DEMONEX data are
significantly affecting the data quality and thus should be
removed. We consider the position on the star on the CCD, $x$ and
$y$, the time (BJD$_{TDB}$), and airmass $sec z$ as these are typical
detrend parameters used in other studies (e.g., Collins
et al. 2014). We take the case of no detrending and compare
the results when the light curves were detrended against a
single parameter. We then began adding in additional detrend
parameters to detrend simultaneously. We notice that there are

5 http://www.astro.louisville.edu/software/astroimagej/
of systematic uncertainties that exist in addition to the quoted statistical uncertainties. It is still the case that even when using detrending parameters, multiple nights have an O–C that implies a significant TTV.

It is not clear to the authors which detrend parameters, or combinations of detrend parameters, are the “correct” parameters to detrend against. Including detrend parameters has significant implications on the derived parameters, especially $R_P/R_*$, but we do not yet have an objective way to determine which set of parameters is “correct.” We consider some metric involving $\chi^2$ minimization, but note that this assumes uncorrelated data that we know not to be the case. We understand that our data contain systematics, and detrending is one such effort to reduce the effects of these systematics. We also note that including all of the available parameters produces inferred values consistent with previous measurements, but this which set of parameters is “correct.” We consider some metric involving $\chi^2$ minimization, but note that this assumes uncorrelated data that we know not to be the case. We understand that our data contain systematics, and detrending is one such effort to reduce the effects of these systematics. We also note that including all of the available parameters produces inferred values consistent with previous measurements, but this

| Parameter                        | Value            |
|----------------------------------|------------------|
| $R_P/R_*$                        | $0.0893 \pm 0.0012$ |
| $a/R_*$                          | $7.70^{+0.21}_{-0.21}$ |
| $i$ (deg)                        | $88.47^{+0.58}_{-0.53}$ |
| $b$                              | $0.205^{+0.10}_{-0.08}$ |
| $\delta$                         | $0.00797^{+0.00022}_{-0.00021}$ |
| $T_{\text{FWHM}}$ (days)         | $0.1672 \pm 0.0011$ |
| $\tau$ (days)                    | $0.01569^{+0.00096}_{-0.00050}$ |
| $f_{14}$ (days)                   | $0.1831^{+0.0016}_{-0.0033}$ |
| $\psi_f$                         | $0.1183^{+0.0017}_{-0.0017}$ |
| $\psi_f,g$                       | $0.1414^{+0.0040}_{-0.0021}$ |
| $u_{\text{Sloanz}}$              | $0.1745 \pm 0.0059$ |
| $u_{2\text{Sloanz}}$             | $0.3019^{+0.0021}_{-0.0022}$ |

Figure 1. Top: each of the seven DEMONEX light curves with an arbitrary offset fitted using only DEMONEX data and detrended against the $x$ and $y$ position of the star on the chip, and the time (BJD$_{\text{TDB}}$). The error bars are plotted in gray, and the best-fit model is overplotted in red. Bottom: binned data and the best-fit model are shown at the bottom with residuals. Binned data are not used in the analysis but shown to better display the overall quality of the data and the statistical power of the DEMONEX data.

Figure 2. Various derived parameters in the DEMONEX light curves as a function of the chosen detrend parameters: the position of the star on the CCD ($x$, $y$), time $t$, and airmass sec $z$. The $x$-axis containing the detrend parameters is the same for each plot and lists which detrend parameters were used, i.e., no detrending, detrending in $x$ only, $y$ only, etc. including detrending against multiple parameters simultaneously. The solid and dashed lines represent the published Narita results and their error bars. In most cases the inferred value is still consistent, i.e., within 1$\sigma$, with previous results when no detrending parameters are chosen, but the answers tend to converge to more consistent values when a larger number of detrend parameters are included. It should be noted that for the parameter $R_P/R_*$ the change in the detrend parameter can change the inferred value by over 3$\sigma$ and the systematic uncertainty due to the selection of detrend parameters is far greater than the statistical uncertainty estimated from the data themselves. We did not apply an additional Gaussian prior on $T_0$ (see Section 4.1), which explains the difference in our inferred value for the period relative to the published Narita value.
can vary at the 3σ level to the inferred value when detrend parameters are not used. We therefore conclude that detrended data inherently contain additional systematic uncertainties, typically not quoted, and detrending must be applied carefully in order to avoid biasing the inferred parameters. Additionally, readers should be cautious when trusting the inferred values of these parameters in this and other papers. We have made efforts to quantify and reduce these systematic uncertainties, but do not yet have an ideal way in which to eliminate them altogether. Our study of these effects is, however, a step in the right direction.

4.3. Combined Data Set

Having demonstrated that the DEMONEX data (when properly detrended) are consistent with the results from previous analyses, we now combine the light-curve data from the detrended DEMONEX data, MC08 XO Extended Team data (XOET), N10 data (FLWO), and Todorov et al. (2012) optical data (UDEM) to create our combined primary transit data set. Additionally, we detrend each of the non-DEMONEX data sets against time as we noticed trends in the XOET data. This final data set includes 24 primary transit light curves of XO-4b, covering 21 different nights, in five different bands. There are seven transits taken from the 0.5 m DEMONEX telescope, four transits taken with the FLWO telescope from the N10 data set, nine transits from the XO Extended Team MC08 data set, and four transits from the UDEM telescope in the Todorov et al. (2012) data set. These are shown binned by telescope in Figure 4 and binned together in Figure 5. Combined there are 17 full transits containing both ingress and egress with multiple transits covered in multiple wavelengths or by different telescopes. The remaining light curves include seven partials, with four containing only the ingress and three containing only the egress.

Figure 3. Various derived offsets from the calculated central transit time to the measured Tc as a function of the various combinations of detrending parameters used for the seven DEMONEX nights. For some nights the changes in O–C are consistent within the errors, while for others the inferred O–C is dependent on the choice of detrend parameters. It should be noted that most of the inferred O–C values are still inconsistent with zero and suggest the presence of a TTV independent of the choice of detrend parameter. We believe that these TTVs are unlikely to be real, but rather are the result of as-yet-unrecognized systematics.

Figure 4. Binned light curves from each telescope to show relative quality of data from each data source. The best-fit global model is plotted in red. Each set of data is binned in the same way. The DEMONEX data are detrended against x, y, and t, while all others are detrended against t. Binned data are not used in the analysis but shown to better display the overall quality of the data.

Figure 5. All of the data globally fit by EXOFAST from the four different telescopes (XOET having nine nights, FLWO four nights, UDEM four nights, and DEMONEX seven nights), phased and binned. Overplotted in red is the best-fit model for the global analysis, and the residuals of the binned data are shown at the bottom. Binned data are not used in the analysis but shown to better display the overall quality of the data and the statistical power of the total data set.
4.3.1. Data Diagnostics

To look at the overall quality of our data, we look at the rms of the residuals of the combined light curves shown in the bottom inset of Figure 5. We find that the weighted rms of the \( \sim6700 \) data points within 4 hr of the central transit to have a fractional rms in the residuals of the normalized flux of 0.00221, or a factor of 3.4 smaller than the transit depth. To test the quality of our data, we also verify that the rms decreases as \( \sqrt{1} \) as expected if the errors are uncorrelated. When the data are binned at 5-minute intervals, as shown in Figure 5, the fractional rms in the residuals of the normalized flux decreases to 0.000276, or a factor of 27 smaller than transit depth.

The most natural interpretation of the uncertainties we quote on the derived parameters assumes that the photometric uncertainties in the data are both uncorrelated and Gaussian distributed. In Figure 7 we plot the distribution of the residuals in the light curves from all of the data sets normalized by their uncertainties. We find that the distribution is not perfectly Gaussian, with a larger number of points with values of \((O-C)/\sigma \) near zero than expected. This implies that our process of scaling the uncertainties by a constant factor is not entirely capturing the true nature of the systematic errors.

4.3.2. Mass–Radius

In addition, we test the effects of using two methods to resolve the mass–radius degeneracy. The default relation for EXOFAST is based on the Torres relation, while the updated EXOFAST uses the Yale-Yonsei (YY2) isochrones. The Torres relation is based on Torres et al. (2010), who provide empirical estimates of stars with precise mass and radius measurements to derive simple polynomial functions of \( T_{\text{eff}} \), \( \log g_{\star} \), and \([\text{Fe/H}]\) that yield \( M_{\star} \) and \( R_{\star} \) with scatter within the relations of 6% and 3%, respectively. As an alternative, we also use isochrones based on Yi et al. (2001) and Demarque et al. (2004), which provide sets of isochrones over a wide range of metallicities and ages scaled to the solar mixture. The update to the EXOFAST code and implementation is described in Eastman et al. (2015) and combines the spectroscopic constraint on \( T_{\text{eff}} \) and an additional penalty when \( T_{\text{eff}} \) differs from the YY2 isochrones with a model uncertainty of 50 K.

We use both relations in our analysis and find that the constraints are tighter for \( M_{\star} \) and \( R_{\star} \) when using the YY2 isochrones. In the cases of the mass and radius of the star (and therefore the planet) the constraints are tighter by 50%–95%. We adopt the results from the YY2 over those derived from the Torres relations as they provide increased precision. The two models provide consistent results, providing confidence that the parameters we infer are accurate to within the precision with which we can measure them given the quality of the data.

4.3.3. Eccentricity

While other groups report that the eccentricity of the system is consistent with zero (McCullough et al. 2008; Narita et al. 2010; Todorov et al. 2012), we verify this by performing an additional run where we allow \( e \cos \omega_{\phi} \) and \( e \sin \omega_{\phi} \) to be free parameters. We find that \( e \cos \omega_{\phi} = 0.0026^{+0.012}_{-0.0066} \) and \( e \sin \omega_{\phi} = -0.0072^{+0.0089}_{-0.028} \), such that the eccentricity is small, \( e = 0.014^{+0.025}_{-0.010} \) and \( \omega_{\phi} = -62^{+110}_{-41} \) is largely unconstrained. These results are consistent with Todorov et al. (2012), who
find $|e \cos \omega| < 0.004$ at the $3\sigma$ level. Therefore, we furthermore adopt the constraint that $e = 0$.

4.3.4. Spin–Orbit $\lambda$

We simultaneously fit radial velocity data taken by MC08 and N10. The N10 radial velocity measurements also contain RM measurements taken during the transit, and the RM data are fit as well. We separate the RM data to fit independent zero points and to scale the errors of the two data sets independently as we do not expect the night-to-night stellar variability and the stellar jitter to have the same magnitude in the N10 RV and N10 RM data sets. The radial velocity and RM fits are shown in Figures 8 and 9, respectively. Because we scale the individual data sets, we find that both models have a similar global fit with only a $\Delta \chi^2 = 0.6$ between the two, with the Hirano model having the lower $\chi^2$ value. However, if we look at only the RM data and use the Hirano scaled error bars on both data sets, we find that there is a $\Delta \chi^2_{\text{RM}} = 2.5$, again with the Hirano model having the lower $\chi^2$ value.

We find a significant difference between the inferred value of the spin–orbit misalignment angle $\lambda$ for the two RM models we consider. As shown in Figure 9, both models fit the data, but do so with different values of $\lambda$ and $v \sin I_e$. The two values derived for the spin–orbit alignment, $\lambda_{\text{Hirano}} = -40.0^{+1.4}_{-1.2}$ and $\lambda_{\text{OTS}} = -20.6^{+0.0}_{-0.2}$, disagree at the $1\sigma$ level. There is evidence that the OTS method can systematically miscalculate the amplitude of the anomalous radial velocity measurement $\Delta v_{\text{RM}}$, but that the method still correctly recovers $\lambda$ (Benomar et al. 2014).

Gaudi & Winn (2007) have shown that there is strong degeneracy between $v \sin I_e$ and $\lambda$ for systems with central transits, i.e., low-impact parameters. In this case, placing a Gaussian prior on $v \sin I_e$ and misestimating $\Delta v_{\text{RM}}$ will lead to a misestimation of $\lambda$. This is likely the case with XO-4b with an impact parameter of $b = 0.230^{+0.077}_{-0.078}$. To constrain $\lambda$, we apply a Gaussian prior on $v \sin I_e = 8800 \pm 500$ (m s$^{-1}$) taken from MC08. However, the OTS model requires a higher $v \sin I_e$ of $8680^{+340}_{-440}$ and lower $\lambda_{\text{OTS}} = -20.6^{+0.0}_{-0.2}$ to fit the data. The Hirano model is closer to the stellar prior with $v \sin I_e^{\text{Hirano}} = 8680^{+340}_{-440}$ and prefers a higher spin–orbit misalignment of $\lambda_{\text{Hirano}} = -40.0^{+8.8}_{-7.5}$. Figure 10 illustrates the $v \sin I_e$–$\lambda$ degeneracy and where the two models lie in this parameter space. We note that, although the two models agree at nearly $1\sigma$, the implications are very different. In one case, one could infer that the system is almost consistent with being

![Figure 8](image-url) Phased radial velocity curves for the two data sets used. The best-fit model is overplotted in red with residuals below. The N10 data set is split into data during transit (N10 RM) and data out of transit (N10 RV). This is done to get a more accurate estimate of the error scaling on the RM data.

![Figure 9](image-url) N10 RM data set and the two best-fit models. Residuals relative to the Hirano model are shown below. The two models fit the data with two different values of $\lambda$ that vary at the $1\sigma$ level. There is a $\Delta \chi^2_{\text{RM}} = 2.5$ between the two RM data sets using the two RM models, with the Hirano model having the lower $\chi^2$ value.

![Figure 10](image-url) The 68%, 95%, and 99% contours for the $v \sin I_e$ and $\lambda$ for the two RM models derived using the YY2 isochrones. These are equivalent to $1\sigma$, $2\sigma$, and $3\sigma$ error contours. Overplotted is the stellar prior on $v \sin I_e$ from McCullough et al. (2008). The two models prefer values of $\lambda$ that differ at the $1\sigma$ level. The Ohta model is consistent with $\lambda = 0$ at the $2\sigma$ level.
aligned ($\lambda_{\text{OTS}}$ is consistent with zero at $\sim 2\sigma$), whereas this is much less likely for the other model. So, the difference due to the choice of models is not simply quantitative, but is also qualitative. Given the effective temperature of the host star of $T_{\text{eff}} \sim 6400 \, \text{K}$, the inference that XO-4b’s orbit is misaligned with its host star would be consistent with the observed trend that hot Jupiters orbiting hot ($T_{\text{eff}} > 6250 \, \text{K}$) stars tend to have high obliquities (Winn et al. 2010; Albrecht et al. 2012). There are cases where the two methods are consistent (Johnson et al. 2008; Winn et al. 2008), and these are typically systems with large impact parameters, i.e., $b > 0.6$.

Ultimately, we believe the Hirano et al. (2010) model and inferences to be more reliable given the low-impact parameter of XO-4b. This poses a potential complication for future modeling. While the updated Ohta et al. (2009) models can be generally applied to RM measurements, the Hirano et al. (2010) model requires estimating the model parameters $p$ and $q$, which in turn requires performing the cross-correlation analysis and ultimately having access to the RV data themselves or relying on other groups to perform this analysis and publish their results. Without access to the RV data or to the derived values of $p$ and $q$, one must adopt a general model, such as the Ohta model, which may lead to biased and/or incorrect inferences.

### 4.3.5. Transit Timing Variations

We also fit for the mid-transit times of each observed transit, in order to investigate the presence of TTVs. During this, we are also able to refine the orbital period by fitting the observed mid-transit times shown in Table 4 with a linear function

$$T_{c}(E) = T_{c}(0) + EP,$$

where $E$ is the epoch.

For the night of UT 2007-11-03 (XOET), the best-fit mid-transit time results in an O–C of $\sim 2000 \, \text{s}$. Upon further investigation, this outlier is likely the result of the noisy photometry from the beginning of the night. UT 2007-11-03 contains no clear ingress and a feature that could be the egress. After detrending the light curve against time, as no other detrend variables are available, the $\sim 2000 \, \text{s}$ variation is preferred by EXOFAST when allowing for TTVs. In Figure 11 we show the light curve for the TTV and no-TTV cases. When we allow the central transit time to vary, we find that the rms of the residuals decreases from 0.0047 to 0.0044 and that the $\chi^2$ decreases from 404 to 349.

The data suggest that the 2000 s TTV solution is the better fit, but after a visual inspection of Figure 11, both cases appear to be plausible solutions. We do, however, have a strong prior against 2000 s TTVs, and we believe that the variation is not astrophysical in nature and is perhaps due to a false minimum in the $\chi^2$ fit. Little statistical power is contained in any single light curve, and to improve the stellar and planetary constraints, we omit this night so as not to bias the refined transit ephemeris. Omitting this night gives a refined transit ephemeris for XO-4b of

$$P = 4.1250687 \pm 0.0000024 \, \text{days} \quad (7)$$

$$T_{c}(0) = 2454758.18978 \pm 0.00024 \, \text{[BJD$_{\text{TDB}}$]} \quad (8)$$

with a reduced fit of $\chi^2/\text{dof} = 3.89$. These values supersede the ephemeris values constrained by the RV data alone during the global fit and appear in Table 5, while the RV data appear as footnotes.

There are still many nights where the observed mid-transit time is consistent with the presence of TTVs, as seen in Figure 12. As shown from our detrending analysis, it is possible that there are still systematic errors, in addition to our

### Table 4

| Epoch | $T_c$ (BJD$_{\text{TDB}}$) | Error (s) | O–C (s) | D–C Time Group$^a$ |
|-------|---------------------------|-----------|---------|---------------------|
| –77   | 2.454,407.55574           | 266       | −917.90 | −7.40               | X       |
| –76   | 2.454,411.686963          | 268       | 287.14  | 1.07               | X       |
| –74   | 2.454,419.936177          | 100       | 207.01  | 2.06               | X       |
| –61   | 2.454,473.554962          | 140       | −409.37 | −2.92               | X       |
| –60   | 2.454,477.685305          | 105       | 46.15   | 0.44               | X       |
| –58   | 2.454,485.932467          | 175       | −211.27 | −1.21               | X       |
| –58   | 2.454,485.938725          | 201       | 329.42  | 1.64               | X       |
| –58   | 2.454,485.933786          | 176       | −97.31  | −0.55               | X       |
| –53   | 2.454,506.560261          | 77        | −0.41   | −0.01               | X       |
| 5     | 2.454,745.815586          | 59        | 105.39  | 1.77               | F       |
| 6     | 2.454,749.939938          | 63        | 43.29   | 0.69               | F       |
| 14    | 2.454,782.941958          | 102       | 168.95  | 1.65               | D       |
| 21    | 2.454,811.815800          | 97        | 26.14   | 0.27               | U       |
| 28    | 2.454,840.692756          | 104       | 152.38  | 1.45               | U       |
| 29    | 2.454,844.814164          | 95        | −164.08 | −1.72               | U       |
| 30    | 2.454,848.938339          | 240       | −241.46 | −1.00               | D       |
| 36    | 2.454,873.688662          | 102       | −250.21 | −2.44               | D       |
| 86    | 2.455,079.947141          | 91        | 176.96  | 1.94               | D       |
| 102   | 2.455,145.946277          | 89        | 4.57    | 0.55               | D       |
| 108   | 2.455,170.692531          | 129       | −355.73 | −2.75               | D       |
| 124   | 2.455,226.695540          | 63        | −193.49 | −3.04               | D       |
| 124   | 2.455,226.698073          | 32        | 25.36   | 0.78               | F       |
| 133   | 2.455,273.825430          | 102       | 174.03  | 1.69               | D       |
| 293   | 2.455,933.834816          | 79        | 7.64    | 0.10               | U       |

Note. $^a$ X = XOET, F = FLWO, D = DEMONEX, U = UDEM.
### Table 5

| Parameter                        | Units           | Value                                           |
|----------------------------------|-----------------|-------------------------------------------------|
| **Stellar Parameters:**          |                 |                                                 |
| $M_\text{st}$                    | Mass ($M_\odot$) | $1.293^{+0.030}_{-0.029}$                      |
| $R_\text{st}$                    | Radius ($R_\odot$) | $1.554^{+0.040}_{-0.036}$                      |
| $L_\text{st}$                    | Luminosity ($L_\odot$) | $3.63^{+0.25}_{-0.24}$                        |
| $\rho_\text{st}$                | Density (g cm$^{-3}$) | $0.486^{+0.023}_{-0.021}$                      |
| $\log g_\text{st}$              | Surface gravity (g cm$^{-2}$) | $4.166^{+0.013}_{-0.014}$                 |
| $T_{\text{eff}}$                 | Effective temperature (K) | $6390^{+20}_{-20}$                           |
| [Fe/H]                           | Metallicity     | $-0.040^{+0.030}_{-0.030}$                     |
| $v \sin I_a$                    | Rotational velocity (m s$^{-1}$) | $8680^{+160}_{-140}$                          |
| $\lambda$                       | Spin-orbit alignment (deg) | $-40.0^{+8.3}_{-8.3}$                          |
| **Planetary Parameters:**        |                 |                                                 |
| $e$                              | Eccentricity    | 0 (assumed)                                     |
| $P$                              | Period (days)   | $4.1250687^{+0.0000024}_{-0.0000024}$           |
| $a$                              | Semimajor axis (au) | $0.05485^{+0.00042}_{-0.00042}$               |
| $M_p$                            | Mass ($M_\oplus$) | $1.615^{+0.100}_{-0.099}$                      |
| $R_p$                            | Radius ($R_\oplus$) | $1.31^{+0.040}_{-0.029}$                      |
| $\rho_p$                        | Density (g cm$^{-3}$) | $0.873^{+0.041}_{-0.034}$                     |
| $\log g_p$                      | Surface gravity | $3.361^{+0.032}_{-0.034}$                      |
| $T_{\text{eq}}$                  | Equilibrium temperature (K) | $1641^{+25}_{-23}$                            |
| $\Theta$                        | Safronov number | $0.1036^{+0.0070}_{-0.0068}$                  |
| $(F)$                            | Incident flux ($10^9$ erg s$^{-1}$ cm$^{-2}$) | $1.646^{+0.0080}_{-0.0070}$                   |
| **RV Parameters:**               |                 |                                                 |
| $T_C$                            | Time of inferior conjunction (BJD$_{TDB}$) | $2454758.18978^{+0.000024}_{-0.000024}$ |
| $K$                              | RV semiamplitude (m s$^{-1}$) | $172.0^{+10}_{-10}$                           |
| $K_p$                            | RM amplitude (m s$^{-1}$) | $66.4^{+7.5}_{-7.4}$                           |
| $M_p \sin i$                    | Minimum mass ($M_\oplus$) | $1.615^{+0.100}_{-0.099}$                      |
| $M_p/M_\text{st}$                | Mass ratio      | $0.001192^{+0.000073}_{-0.000071}$             |
| $u_1$                            | RM linear limb darkening | $0.3601^{+0.0071}_{-0.0069}$                  |
| $u_2$                            | RM quadratic limb darkening | $0.3097^{+0.0026}_{-0.0026}$                  |
| $g_1$                            | Systemic velocity (m s$^{-1}$) | $-4.3^{+3.5}_{-3.5}$                          |
| $g_2$                            | Systemic velocity (m s$^{-1}$) | $0.2^{+2.5}_{-2.5}$                           |
| $g_3$                            | Systemic velocity (m s$^{-1}$) | $-1^{+16}_{-16}$                              |
| $f(m_1, m_2)$                    | Mass function ($M_\oplus$) | $0.00000029^{+0.0000044}_{-0.0000044}$          |
| **Primary Transit Parameters:**  |                 |                                                 |
| $R_p/R_\text{st}$                | Radius of the planet in stellar radii | $0.08712^{+0.00050}_{-0.00048}$                |
| $a/R_\text{st}$                  | Semimajor axis in stellar radii | $7.50^{+0.12}_{-0.17}$                        |
| $i$                              | Inclination (deg) | $88.20^{+0.61}_{-0.63}$                        |
| $b$                              | Impact parameter | $0.230^{+0.077}_{-0.076}$                      |
| $\delta$                        | Transit depth   | $0.007589^{+0.000087}_{-0.000083}$              |
| $T_{\text{FWHM}}$                | FWHM duration (days) | $0.16880^{+0.00051}_{-0.00051}$                |
| $\tau$                          | Ingress/egress duration (days) | $0.01562^{+0.00078}_{-0.00053}$               |
| $T_{14}$                         | Total duration (days) | $0.18448^{+0.00092}_{-0.00079}$                |
| $P_T$                           | A priori nongrazing transit probability | $0.1203^{+0.0027}_{-0.0018}$                  |
| $P_{T, G}$                       | A priori transit probability | $0.1432^{+0.0033}_{-0.0022}$                  |
| $u_{1G}$                         | Linear limb darkening | $0.514^{+0.012}_{-0.012}$                      |
| $u_{2G}$                         | Quadratic limb darkening | $0.2544^{+0.0079}_{-0.0080}$                  |
| $u_{1I}$                         | Linear limb darkening | $0.2064^{+0.0063}_{-0.0066}$                  |
| $u_{2I}$                         | Quadratic limb darkening | $0.3091^{+0.0021}_{-0.0021}$                  |
| $u_{1L}$                         | Linear limb darkening | $0.2762^{+0.0067}_{-0.0066}$                  |
| $u_{2L}$                         | Quadratic limb darkening | $0.3200^{+0.0022}_{-0.0022}$                  |
| $u_{1Sloant}$                    | Linear limb darkening | $0.1744^{+0.0060}_{-0.0059}$                  |
| $u_{2Sloant}$                    | Quadratic limb darkening | $0.3020^{+0.0021}_{-0.0022}$                  |
| $u_{1V}$                         | Linear limb darkening | $0.3601^{+0.0071}_{-0.0069}$                  |
| $u_{2V}$                         | Quadratic limb darkening | $0.3097^{+0.0026}_{-0.0026}$                  |
| **Secondary Eclipse Parameters:**|                 |                                                 |
| $T_S$                            | Time of eclipse (BJD$_{TDB}$) | $2454483.931^{+0.0183}_{-0.011}$               |

**Notes.**

a From RV only: $P = 4.12474^{+0.00061}_{-0.00070}$ days.

b From RV only: $T_C = 2454485.993^{+0.082}_{-0.11}$ BJD$_{TDB}$.
statistical errors, that we have not yet accounted for that could explain the nights that are still consistent with the presence of TTVs. We also note that these are present in all four data sets, not just DEMONEX data.

5. RESULTS

In a series of tables we present the median values of the MCMC chains and their 68% intervals for the stellar parameters, planetary parameters, radial velocity parameters, primary transit parameters, limb-darkening parameters, and secondary eclipse parameters in Table 5. The ephemeris listed in Table 5 is constrained from the mid-transit times, but we do include the ephemeris constrained by the RV data alone as footnotes. Using the YY2 mass–radius models and the Hirano-based RM models, we find a refined stellar mass of $1.293^{+0.030}_{-0.029} \ M_\odot$ and stellar radius of $1.554^{+0.042}_{-0.030} \ R_\odot$ with a companion planet mass of $1.615^{+0.10}_{-0.090} \ M_J$ and planet radius of $1.317^{+0.040}_{-0.025} \ R_J$. Additionally, we find a refined ephemeris of $T_0 = 2454758.18978 \pm 0.00024 \ [BJD_{TDB}]$ and $P = 4.1250687 \pm 0.0000024 \ days$.

In general, we find an improved or comparable statistical precision for all available parameters. We note that the improved precision on $R_p/R_*$ and other correlated parameters (e.g., $i$ and $a/R_*$) are subject to additional systematic uncertainties. There is significant disagreement between the inferred period (20σ) compared to the results published by MC08 and a 6σ difference between the inferred period and the N10 published value. This is similar to the 16σ disagreement between the N10 and MC08 periods.

6. DISCUSSION

We provide seven new nights of observations of the misaligned hot Jupiter XO-4b from the DEMONEX telescope and combine those data with previously released data to produce refined stellar and planetary parameters for the XO-4 system analyzed in a homogeneous manner. We investigate a number of possible combinations of detrend parameters and find that the quality of DEMONEX data is significantly improved when detrended against XO-4’s position on the CCD and against time. We also note that there is a 3σ difference in the inferred value of the parameter $R_p/R_*$ depending on the choice of detrend parameters, and as such, caution should be exercised when detrending data as to not bias results with incorrect inferences.

After investigating both the Torres relation and the Yale-Yonsei isochrones, we are not yet sensitive to the choice of method to resolve the mass–radius degeneracy. We are sensitive to the choice of RM model used to infer the projected stellar spin–planet orbit angle $\lambda$. We believe the Hirano et al. (2010) model and inferences to be more reliable; however, the Ohta et al. (2009) models can be generally applied to RM measurements. The Hirano et al. (2010) model requires having access to the radial velocity data, or a previous estimate of $p$ and $q$ from the cross-correlation analysis. Without such access, one must adopt a general model, such as that based on Ohta et al. (2009), which we have shown may lead to biased and/or incorrect inferences.

We would like to thank all of the authors who provided their data to us both publicly (McCullough et al., Narita et al.) and privately (P. McCullough, K. Todorov, and P.V. Sada). Thank you to R. Siverd and K. Collins for their work upgrading and maintaining the custom version of EXOFAST used here. Thanks to B.J. Fulton for his comments on coding the Hirano-based RM models. Thanks to K. Collins for her help and guidance with AstroImageJ. We would also like to thank our anonymous referee for their useful comments and feedback.

S.V. is supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1343012. B.S.G. is supported by National Science Foundation CAREER Grant AST-1056524.

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Figure 12. O–C diagram for the calculated vs. measured central transit times; the epochs are taken relative to the RV data. Nights with zero TTVs will lie on the dashed line. Even with the exception of UT 2007-11-03 (Epoch –74), there are still a few significant outliers and nights consistent with the presence of a TTV. The ~2000 s outlier is the result of poor photometry and the fitting procedure and is omitted in our analysis. The refined transit ephemeris is $T_0 = 2454758.18978 \pm 0.00024 \ [BJD_{TDB}]$ and $P = 4.1250687 \pm 0.0000024 \ days$. 
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