The architecture of the hierarchical triple star KOI 928 from eclipse timing variations seen in Kepler photometry

J. H. Steffen, S. N. Quinn, W. J. Borucki, E. Brugamyer, S. T. Bryson, L. A. Buchhave, W. D. Cochran, M. Endl, D. C. Fabrycky, E. B. Ford, M. J. Holman, J. Jenkins, D. Koch, D. W. Latham, P. MacQueen, F. Mullally, A. Prša, D. Ragozzine, J. F. Rowe, D. T. Sanderfer, S. E. Seader, D. Short, A. Shporer, S. E. Thompson, G. Torres, J. D. Twicken, W. F. Welsh and G. Windmiller

1 Fermilab Center for Particle Astrophysics, PO Box 500, Batavia, IL 60510, USA
2 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
3 NASA Ames Research Center, Moffett Field, CA 94035, USA
4 McDonald Observatory, The University of Texas, Austin, TX 78712-2059, USA
5 Niels Bohr Institute, Copenhagen University, DK-2100 Copenhagen, Denmark
6 Department of Astronomy and Astrophysics, University of California, Santa Cruz, Santa Cruz, CA 95064, USA
7 Department of Astronomy, University of Florida, 211 Bryant Space Science Center, Gainesville, FL 32611-2055, USA
8 SETI Institute, 515 North Whisman Road, Mountain View, CA 94043, USA
9 Department of Astronomy and Astrophysics, Villanova University, 800 East Lancaster Avenue, Villanova, PA 19085, USA
10 San Diego State University, 5500 Campanile Drive, San Diego, CA 92182, USA
11 Las Cumbres Observatory Global Telescope, Goleta, CA 93117, USA

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ABSTRACT
We present a hierarchical triple star system (KIC 9140402) where a low-mass eclipsing binary orbits a more massive third star. The orbital period of the binary (4.988 29 d) is determined by the eclipse times seen in photometry from NASA’s Kepler spacecraft. The periodically changing tidal field, due to the eccentric orbit of the binary about the tertiary, causes a change in the orbital period of the binary. The resulting eclipse timing variations provide insight into the dynamics and architecture of this system and allow the inference of the total mass of the binary (0.424 ± 0.017 M⊙) and the orbital parameters of the binary about the central star.

Key words: binaries: eclipsing.

1 INTRODUCTION
The timings of transit or eclipse events in multibody astronomical systems provide a high-precision measurement of the phase of the orbits of the transiting bodies – typically a few parts in 10^4 or better. Such high-precision measurements allow for detailed studies of the dynamics of these systems through eclipse timing variations [ETVs; or transit timing variations (TTVs) for planetary systems] (Borkovits et al. 2003; Agol et al. 2005; Holman & Murray 2005). A variety of mechanisms can cause the eclipse times to deviate from a linear ephemeris including the Roemer effect [light travelt ime (LTT)], transverse displacements of the star with respect to the system barycentre, resonance interactions among the bodies and effects that correspond to the synodic periods of the objects. A detailed discussion of these cases is found in Agol et al. (2005).

One notable cause of ETVs is the effect of a changing tidal field on a binary pair due to a perturber on a hierarchical, eccentric orbit. This scenario was derived analytically in Borkovits et al. (2003), and a simplified derivation is shown in Agol et al. (2005). Basically, when the perturbing third object is far from its short-period binary companions, the period of the binary is largely unmodified. However, when the perturbing object is near the binary and near the binary’s orbital plane, its presence slows the orbital period of the binary. The result is a periodic TTV signal with a period equal to the orbit time of the perturbing body. The more eccentric the orbit, the larger and more asymmetric the TTV signal appears because the slowing of the binary’s orbital period at the perturber’s per centre passage takes a smaller fraction of its orbital period and the large change in proximity from the high eccentricity exaggerates the change in the binary’s period. The nature of this signal is such
that it is virtually independent of the azimuthal orientation of the
apse of the orbit of the perturbing body, though it does depend upon
the mutual inclination of the two relevant orbital planes.

The first system known to exhibit this effect, also found with
Kepler photometric data, is the triple star system KOI 646 (KIC 5384802; Fabrycky 2010). Here we present and discuss a second stellar system that shows a periodic ETV signal consistent with this same model, KOI 928 (KIC 9140402) (Latham et al. 2005). Two other Kepler systems that show similar orbital architecture are KOI 126 (KIC 5897826; Carter et al. 2011), which is viewed in a different orientation and thus does not show the same ETV signal, and HD 181068 (KIC 5952403; Derekas et al. 2011), which has a low-mass binary orbiting a red giant. Additional star systems that show trends indicative of dynamical interactions were reported in Slawson et al. (2011). This Letter is organized as follows. In Section 2, we present the Kepler photometry and transit times. In Section 3, we outline the spectroscopically derived stellar parameters and radial velocity (RV) measurements of the target star. Section 4 gives the dynamical analysis of the transit times and RV measurements of the system. Concluding remarks are in Section 5. We note that the true orbital structure of these systems is a bright central star orbited by an eclipsing binary of low-mass stars. However, for the purposes of our discussion we will label the eclipsing binary as the ‘inner binary’ of objects one and two, and the third star, which perturbs the orbital period of the inner binary, as the third or ‘outer’ object.

2 KEPLER PHOTOMETRY

KOI 928 (KIC 9140402) has Kepler magnitude $K_p = 15.251$, making it quite dim among Kepler targets. It is located at RA 18°59′02.26 and Dec. 45°35′56″86 (J2000). For our study, we use data from the first six quarters of Kepler operations (BJD 245 4968–245 5650) corresponding to nearly 700 d of observation. Information about the Kepler spacecraft and its performance can be found in Koch et al. (2010). The period of the eclipse events is 4.988 29 d, and the eclipse depths are 0.06 per cent of the nominal flux. A binned light curve and representative model (generated using the PHOEBE software from Pása & Zwitter 2005) are shown in Fig. 1.

This system was initially identified as a planetary candidate through the Transiting Planet Search and the Data Validation pipelines (Jenkins et al. 2010; Wu et al. 2010) which identify significant transit-like features and conduct a battery of statistical tests on those transit events in an effort to rule out false-positive transit signals. As data for KOI 928 were being analysed, the interpretation of the system quickly grew complicated. The transit times showed a sizeable, roughly sinusoidal timing variations with nearly a 2-h peak-to-peak amplitude (consistent with a near-resonant two-planet system). However, initial RV measurements (described in the next section) differed significantly from the predictions of a two-planet model.

A point spread function fit to the difference image formed by subtracting averaged in-transit pixels from averaged out-of-transit pixels (see Torres et al. 2011) indicated no significant centroid motion. This fact effectively eliminates the possibility of the transits being on a star that is more distant than 0.3 pixels (1.2 arcsec) from KOI 928. Taken together, with a few additional RV data, the information suggests a model of a bright star being orbited by a low-mass binary pair.

Attempts to model the eclipse times of this system suffer both from the lack of photons (given the dimness of the target) as well as additional systematic errors. In particular, some estimates of the eclipse times show multiple local minima, while others have unusually large error bars. Consequently, we derived the eclipse times and their uncertainties using two different methods (described below). We then adopt one set of times as ‘nominal’, but eliminate eclipses at certain epochs based upon the estimated errors and the differences between the two methods. Times from the second method are not analysed in the dynamical model.

To estimate the nominal eclipse times for both the members of the eclipsing binary, we fit standard fourth-order non-linear limb-darkened eclipse models (Mandel & Agol 2002) to the Kepler light curve. For each primary or secondary eclipse, the model allowed for independent values of the primary-to-secondary radius ratio, eclipse duration and impact parameter. For each eclipse, we fit for the flux normalization and a local linear slope in the flux, and we numerically averaged the model over the 30-min integration duration.

The first step to determine the eclipse times is to fit a single model to the set of all eclipses for each individual star assuming a constant orbital period. Secondly, we hold the radius ratio, eclipse duration and impact parameter fixed, and we fit a small segment of the light curve around each eclipse for the remaining parameters. Thirdly, we phase the light curve using each measured eclipse and refit for the eclipse parameters (aside from period and epoch). The second and third steps are iterated to converge on a final model. This model also includes a nuisance parameter which estimates the ‘contamination’ light from stars in the Kepler aperture (excluding the star being eclipsed) as a fixed parameter. We verified that our results for eclipse times are not sensitive to the value of this nuisance parameter.

The second, comparative set of eclipse time estimates was calculated using an iterative process starting with an initial linear ephemeris and eclipse width. Eclipses in the ‘raw’ data were masked, then the light curve was piecewise detrended and normalized locally (0.5 d) using a cubic polynomial. All the eclipses were then folded on the ephemeris, and a piecewise cubic Hermite spline was fitted using least squares to the folded eclipse using observations that fell within a window of width 1.4 times the eclipse width +1 cadence on each side. The cubic Hermite spline was fitted using nine evenly spaced points across the window and the $\chi^2$ of the fit recorded. The cubic Hermite was refitted 25 more times using odd numbers (11–35) of spline knots. The best fit from these 26 cases defined the eclipse template, and the eclipse width estimate was updated using this template.

Figure 1. Binned and folded light curve for KOI 928. Also shown is a representative model which has equal size ($R = 0.238 R_{\odot}$) and mass ($M = 0.21 M_{\odot}$) members of the binary.
The light curve was again detrended locally using a cubic polynomial but now using three different out-of-eclipse lengths: 7.5, 15 and 20h. For each of the three out-of-eclipse lengths, the template was correlated with the eclipse at 1000 time-steps, spanning 115 min. The estimate for the mid-eclipse time is that which gave the minimum χ² value over the three different out-of-eclipse lengths.

This entire process was iterated using the new eclipse time estimates, but those eclipses with a reduced χ² > 2.0 were eliminated from the template building step, and the correlation time-step length was reduced by a factor of 8. Once the second iteration was completed, the uncertainties in eclipse times were estimated using the χ² curve of the fits.

To select the eclipse times from the nominal (first) method to used in our analysis, we rejected those epochs where either of the two methods had large uncertainties (greater than 0.045 d) and the epochs where the two methods disagreed by more than 3σ. The epochs that survived these cuts were analysed. These two criteria were determined by analysing the distribution of the differences in the eclipse times of the two models and the distribution of the uncertainties in the eclipse times. In both cases (the cut on uncertainty and the cut on difference), there is an obvious gap where the outlier population dominates over the nominal distribution and the chosen cuts reflect those transitions.

3 Stellar Properties, Imaging and Spectroscopic Observations

We obtained seven high-resolution spectra of KOI 928 in order to measure improved stellar properties of the bright, outer star and to place RV constraints on its orbit. Six spectra were taken with the Tull Coudé Spectrograph on the 2.7-m Harlan J. Smith Telescope at the McDonald Observatory in West Texas, which has a resolving power of R ≈ 60 000 and wavelength coverage of 3750–10 000 Å. One additional spectrum was taken with the Fibre-fed Echelle Spectrograph (FIES) on the 2.5-m Nordic Optical Telescope at La Palma, Spain (Djupvik & Andersen 2010). The FIES spectrum was taken with the medium-resolution fibre, which has resolving power of R ≈ 46 000 and wavelength coverage of 3600–7400 Å.

In order to determine the effective temperature (T_eff), projected rotational velocity (v sin i), surface gravity (log g) and metallicity ([Fe/H]) of the bright star in the system, we cross-correlated the strongest spectrum — the only one with signal-to-noise ratio (S/N) greater than 20 per resolution element — against a grid of synthetic stellar spectra computed from Kurucz models (Kurucz 1992). A new set of tools (Buchhave et al., in preparation) was then used to derive more precise stellar parameters from the normalized cross-correlation peaks. Formally, the value of log g = 4.56 places the star below the isochrones in an unphysical part of the Hertzsprung–Russell diagram. This is most likely due to errors in the measured quantities, and given the relatively low S/N of our spectrum and the strong spectroscopic correlations between T_eff, log g and [Fe/H], this is not surprising. However, the formal error in log g is large enough that there are valid solutions that do fall on the isochrones. The results from this analysis, with conservative uncertainties, are given in Table 1.

To obtain radial velocities, we performed a multi-order cross-correlation of the six McDonald spectra following the procedure outlined in Buchhave et al. (2010). For the FIES spectrum, we adopt the RV derived from cross-correlation against the best matched synthetic template. The velocities are shifted on to the IAU absolute scale as defined by the velocity of the IAU RV standard HD 182488 (Nidever et al. 2002). The errors have been inflated to include an instrumental component corresponding to the long-term rms velocity residuals of HD 182488 as observed by each instrument. The RV measurements derived from this analysis are given in Table 2.

Table 1. Stellar parameters for the bright star in KOI 928.

| Parameter      | Value      | Uncertainty |
|----------------|------------|-------------|
| T_eff (K)      | 5506       | 150         |
| log g          | 4.56       | 0.23        |
| [Fe/H]         | 0.08       | 0.29        |
| V sin i (km s⁻¹)| 3.3        | 1.7         |
| M₂ (M☉)        | 0.97       | 0.1         |
| R₂ (R☉)        | 0.89       | 0.1         |

Table 2. RV measurements.

| Date (BJD – 245 4900) | RV (km s⁻¹) | Error (km s⁻¹) | Instrument |
|-----------------------|-------------|----------------|------------|
| 445.8325              | −8.039      | 0.339          | MCD        |
| 523.5395              | 10.322      | 0.400          | FIES       |
| 570.6033              | −14.269     | 0.319          | MCD        |
| 596.6075              | −4.859      | 0.343          | MCD        |
| 599.6062              | −2.119      | 0.340          | MCD        |
| 627.5932              | 11.821      | 0.319          | MCD        |
| 732.9574              | 9.697       | 0.520          | MCD        |

4 Dynamical Model

As discussed above, in the case of a hierarchical triple system where the distant third body is on an eccentric orbit, the changing tidal field produced by the perturbing third body causes a change in the period of the binary that cycles with its orbit about the perturber. For our investigation, we use the coplanar approximation as model fits with mutually inclined orbits did not produce a sufficient improvement to justify the additional parameters. Thus, our model is given by (equation 25 in Agol et al. 2005):

$$\delta t = \xi \left( \frac{P_3}{1 - e_3^2} \right) \left[ f_3 - \frac{2 \pi (t - \tau_3)}{P_3} + e_3 \sin f_3 \right],$$

(1)

where

$$\xi \equiv \frac{1}{2 \pi} \left( \frac{m_3}{m_1 + m_2} \right) \left( \frac{P_{12}}{P_3} \right)^2,$$

(2)

where m₁ and m₂ are the masses of the two objects in the binary and P₁₂ is the period of the binary. The parameters for the third body are its mass m₃, period P₃, eccentricity e₃, time of pericentre passage τ₃ and true anomaly f₃ (we change notation from Agol et al. 2005 to use the subscript ‘3’ to denote the third body). The ETV effect for this coplanar case is independent of the orientation of the orbit of the third body with respect to the observer (i.e. the longitude of pericentre θ₃). This orientation can be measured through the LTT effect and with the RV data. For KOI 928, the timing uncertainties are too large to provide meaningful constraints from LTT alone and require the inclusion of RV measurements in the analysis to identify the value of this parameter.

The seven model parameters for our analysis include the mass ratio M = m₃/(m₁ + m₂), P₁₂, P₃, τ₃, e₃, m₃, and the ephemeris epoch T₀ in BJD – 245 4900. The mass ratio is not well constrained by the transit data without an estimate for one of the masses (either the mass of the perturber or the mass of the binary). Consequently,
we fix the mass of the perturber to the value determined from the spectroscopy.

The RV data and timing data were fitted to the ETV model in equation (1), with additional terms for the geometric LTT effect and the RV signal, using a Markov chain Monte Carlo (MCMC). We assume that the measurement uncertainties are Gaussian and uncorrelated. The model parameters corresponding to the maximum likelihood model and the 68.3 per cent credible intervals are given in Table 3, as well as the median value among a posterior sample for each model parameter. (Note that this set of median values does not correspond to any specific model.)

The uncertainties in the model parameters are found using the corresponding posterior distributions from the MCMC. After rejecting the first ~20 per cent of the chain, the values for each of the model parameters were sorted and the smallest and largest 15.9 per cent of the values were rejected. The mean difference between the median of the remaining values for each parameter and the largest and smallest values is our estimate for the uncertainty in that parameter. There is some small asymmetry in the distributions, but it has a sufficiently small effect that we do not report two-sided error bars. In addition, we study the autocorrelation of the chains in the model parameters to determine the uncertainty in our error estimates. The correlation lengths of each parameter indicates a worst case uncertainty of 10 per cent in the error estimate, while several parameters are much better. The best-fitting model and the residuals are shown in Figs 2 and 3 for the eclipse times and RV measurements, respectively.

Given the parameter values obtained from the dynamical model, an additional analysis was conducted on the light curve in order to determine the sizes of the stars in the binary. Given that the eclipse depths are almost indistinguishable, we assumed that the two stars are identical in size and mass (with masses equal to 0.212 M⊙). The result of this analysis (also shown in Table 3) is that the radii of the two binary members are 0.28 ± 0.05 R⊙. These radii estimates are somewhat larger than the isochrone models for low-mass stars given in Baraffe et al. (1998); however, the discrepancy is not significant. Moreover, the rather large uncertainty in these sizes makes them less useful for comparison to other measured systems. Additional photometric data from Kepler should lessen the uncertainty in this parameter and consequently provide more valuable insight into the physical properties of such stars and our modelling of them.

### Table 3. Parameter values for the KOI 928 system.

| Parameter | Value        | Error | Best fitting |
|-----------|--------------|-------|--------------|
| M₁       | 0.97 (M⊙)   | 0.1a  | 0.97         |
| M₂       | 0.424 (M⊙)  | 0.01b | 0.423 808    |
| P₁₂      | 4.988 287 (d)| 0.00015 | 4.988 284 |
| P₃       | 116.03 (d)  | 0.35  | 115.986 209 |
| e₃       | 0.262       | 0.013 | 0.263 156    |
| τ₃       | 121.21 (d)  | 0.83  | 121.192 538  |
| σ₃       | 5.195 (rad) | 0.075 | 5.175 702    |
| T₀       | 66.4219 (d) | 0.0016| 66.422 127   |
| vₑffect  | −560 (m s⁻¹) | 240  | −612.095 406 |
| R₁(= R₂) | 0.28 (R⊙)   | 0.05  | —            |

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*This quantity was held fixed during the dynamical analysis, and the stated error comes from a separate analysis of the stellar spectrum.

*bThis is the formal uncertainty from the MCMC analysis. The true uncertainty would be much larger due to the uncertainty in the mass of the tertiary.

*cThis quantity is not part of the dynamical model.

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**Figure 2.** Top panel: plot of the timing data and the best-fitting model. A second (barely visible) red curve shows the LTT effect which is the only means to measure the orbital orientation σ₃ without RV measurements. Bottom panel: residuals after subtracting the model transit times.

5 DISCUSSION

Eclipse time measurements and their counterparts in the field of transiting exoplanets provide very precise measurements of the orbital phase of the various bodies. Consequently, eclipse and transit times can be used to make similarly precise measurements of the various mass ratios and orbital parameters in multi-object systems. In many cases, the values of some parameters derived from timing measurements are significantly more precise than corresponding values from RV measurements (the orbital period, for example). Similarly, some parameters are more difficult to determine from timing measurements – depending upon the orbital configuration – such as the argument of pericentre σ₃.

Regardless, with the high-precision photometry enabled by the Kepler spacecraft, dynamical studies of multi-object systems through timing variations have proven extremely useful as a tool to measure the orbital properties of these systems and the masses of the objects within them. Striking examples include the planetary systems Kepler-9 (Holman et al. 2010) and Kepler-11 (Lissauer et al. 2011) as well the hierarchical triple star KOI 126 (Carter et al. 2011) and now KOI 928.

For both KOI 928 and KOI 126, the very small masses determined by the dynamical analysis provide important guidance to stellar models at the low-mass end of the main sequence. The masses in both KOI 928 and in KOI 126 are among the smallest masses

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1. The relevant quantity being the number of correlation lengths in a Markov chain rather than the number of links in the chain.
Eclipse timing variations in KOI 928

observed in binary systems. For KOI 928, the orbital period, $P_3 = 116$ d, of the perturber is quite short compared to the known hierarchical triples, and the mass ratio of $M_3/M_{12} \simeq 2.5$ is exceptionally large (Tokovinin 2008). The same statements are true both for KOI 126 at $P_3 = 34$ d and $M_3/M_{12} \simeq 3$ and for HD 181068 at 45 d and 2.1. Future investigations of multiple star systems through ETVs, especially with Kepler photometry, are likely to yield an important sample of these rare (or difficult to detect) systems with configurations and masses heretofore unexplored.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1. Primary eclipse times used in the analysis of this system. The uncertainties are in days and date is BJD $-245.4900$.
Table S2. Secondary eclipse times used in the analysis of this system. The uncertainties are in days and date is BJD $-245.4900$.

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