EXPLORING A “FLOW” OF HIGHLY ECCENTRIC BINARIES WITH KEPLER

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ABSTRACT

With 16-month of Kepler data, 15 long-period (40–265 days) eclipsing binaries on highly eccentric orbits (minimum e between 0.5 and 0.85) are identified from their closely separated primary and secondary eclipses (ΔtH = 3–10 days). These systems confirm the existence of a previously hinted binary population situated near a constant angular momentum track at P(1−e 2)3/2 ≈ 15 days, close to the tidal circularization period P circ. They may be presently migrating due to tidal dissipation and form a steady-state “flow” (~1% of stars) feeding the close-binary population (few % of stars). If so, future Kepler data releases will reveal a growing number (dozens) of systems at longer periods, following dN/d ln P ∝ P1/3 with increasing eccentricities reaching e → 0.98 for P → 1000 days. Radial-velocity follow-up of long-period eclipsing binaries with no secondary eclipses could offer a significantly larger sample. Orders of magnitude more (hundreds) may reveal their presence from periodic “eccentricity pulses,” such as tidal ellipsoidal variations near pericenter passages. Several new few-day-long eccentricity-pulse candidates with long periods (P = 25–80 days) are reported.

Key words: binaries: close – binaries: eclipsing – stars: formation

1. INTRODUCTION

How do close binaries (P ≤ 10 days) form? An intriguing clue comes from a surprisingly high fraction having a tertiary companion, reaching as much as ~96% for systems with P ≤ 3 days (Tokovinin et al. 2006). This lends support to the “Kozai Cycles plus Tidal Friction” (KCTF) formation channel advocated by several authors (Kiseleva et al. 1998; Fabrycky & Tremaine 2007; see also Mazeh & Shaham 1979). In KCTF, a tertiary companion on a highly inclined outer orbit can excite the inner binary orbit (initially having a much longer period than a few days) to very high eccentricity during Kozai–Lidov cycles, which allows efficient tidal dissipation to take place during close pericenter passages, eventually shrinking the orbital period to a few days.

One clear implication of KCTF is that there should exist a population of highly eccentric binaries in the process of migrating to final close-in orbits. Such a prediction was studied in the context of a similar formation process of close-in Jovian-mass companions by Socrates et al. (2012). In this Letter, we explore the observational implications of such a population possibly responsible for close-binary formation.

2. STEADY-STATE DISTRIBUTION

We briefly review the features of a steady-state distribution of migrating binaries due to tidal dissipation similar to migrating Jupiters discussed in Socrates et al. (2012). The star formation rate changes slowly over the age of the Galaxy, therefore one would expect a steady-state source of new distant binaries that constantly migrate to lower periods, “feeding” the close-binary population. Tidal dissipation drains orbital energy but hardly changes the angular momentum of an eccentric binary. While losing energy due to tidal dissipation, eccentric binaries migrate on tracks of constant orbital angular momentum corresponding to constant P(1−e 2)3/2 = P f, P f equals the period of the final circularized close binary (once circular, tidal dissipation ceases to operate in the tidally locked system). The rate of energy dissipation is a strong function of binary separation, and for an eccentric orbit, most of the energy loss occurs during the pericenter passage. At high e, due to the constant angular momentum, the pericenter passages have approximately the same parabolic shape, and the energy lost each orbit, ∆E, is approximately the same. This implies an average energy loss rate E ∝ 1/P, which results in a steady state distribution dN/d ln P ∝ E/E ∝ P1/3, where E ∝ P−2/3. This distribution at high e is relatively independent of tidal dissipation physics. At moderate and low e, the distribution is sensitive to the poorly understood tidal dissipation processes. The distribution obtained for the commonly assumed equilibrium tide model (e.g., Hut 1981) is derived in Socrates et al. (2012). An additional complication is that angular momentum oscillates while the Kozai mechanism operates. As shown in Socrates et al. (2012), this does not significantly affect the resulting distribution as long as we consider narrow bins in angular momentum (or P f) in which most of the dissipation occurs. In this Letter, we focus on the long-period, highly eccentric members in this population, which are simple to analyze theoretically and, as shown below, are easily distinguishable observationally.

3. PAST OBSERVATIONAL HINTS

Making meaningful statistical studies of the binary distribution requires an unbiased sample. Testing the steady-state distribution requires a stellar population with roughly uniformly distributed stellar age (as compared to a coeval population like an open cluster) such as the solar neighborhood. The commonly adopted study on multiplicity of solar-type primaries is from a complete, volume-limited (within 22 pc and spectral type F7-G9) sample of ~164 systems by Duquennoy & Mayor (1991). They identify three period regimes. Binaries with P ≤ 10 days have eccentricities close to zero and are thought to
be circularized by strong tidal dissipation (Duquennoy & Mayor 1991). Those with $P \gtrsim 1000$ days are consistent with an Ambartsumian distribution (Ambartsumian 1937), $dN/dep = 2e$, expected for energy conserving dynamical perturbations. For 10 days $< P < 1000$ days, $e$ distributes as bell shaped with an average of $\bar{e} \sim 0.3$, which has since been widely accepted as reflecting the initial distribution at binary formation. They note that the largest eccentricities in the 10 days $< P < 1000$ days regime seem to be curiously populated by triple systems. They further note that just beyond the selection criterion of their complete sample, there exists some clear outlier to the eccentricity distribution, and interestingly two of them, HD 137763 ($e = 0.975$, $P = 890$ days) and HD 114260 ($e = 0.56$, $P = 19.5$ days), have additional companions.

Raghavan et al. (2010) provide a new volume-limited sample selected using Hipparcos parallaxes ($\sim 25$ pc and stellar type F6-K3) including 454 solar-type stars, a factor of $\sim 3$ more than Duquennoy & Mayor (1991). Figure 1 shows the binary $P$ and $e$ distribution in this sample. Systems with known companions (multiples) are shown by filled circles while those without by crosses. As pointed out by the above authors, the upper envelope of eccentricity for systems with 10 days $< P < 1000$ days appears to consist mostly of multiples, indicative of Kozai oscillations. The five “eccentric envelope” systems, each with eccentricity larger than that of any binary with a shorter period, have the following parameters: $(P, e, P_{\text{ter}}) = (890$ days, $0.975$, $2.4 \times 10^{-4}$ yr), HD 156274: (88 days, 0.81, 700 yr), HD 123: (48 days, 0.61, 100 yr), HD 101177: (24 days, 0.41, 2000 yr), HD 209240: (21 days, 0.25, 260 yr).\footnote{Orbital parameters taken from Tokovinin (1997).} Note that the periastron distances for all these binaries are $\gtrsim 0.05$ AU ($\sim 10 R_\odot$), so they are all well-detached systems with negligible mass transfer and their eccentricities are not limited by the radii of the components.

These envelope multiples, which possibly consist of $\sim 1\%$ of all main-sequence stellar systems, are interesting in the context of KCTF. Figure 1 shows constant angular momentum tracks, as discussed in Section 2, of $P_t = P(1-e^2)^{3/2}$ between 10 days and 30 days, which enclose the envelope. This raises the exciting possibility that these systems may represent a population of highly eccentric binaries in steady-state KCTF migration. If true, the fact that $P_t$ values of these systems are close to the circularization threshold of $P_{\text{circ}}$ $\sim 10$ days is not surprising. Systems with $P_t \ll P_{\text{circ}}$ circularize quickly, while those with $P_t \gg P_{\text{circ}}$ do not significantly migrate. Systems at $P_t \sim P_{\text{circ}}$ migrate on a timescale comparable to the age of the Galaxy, implying that a significant fraction of them should be currently migrating.

In this sample, the primaries are solar-type stars with mass $M_1 \sim 1 M_\odot$, and the secondary mass $M_2$ ranges from $\sim 0.1$ to $1 M_\odot$. The tidal dissipation timescale for equilibrium tide $t_D \propto M_1 a_f^3 / M_2^2$ (where $a_f = (1-e^2) \propto P_t^2$; see Socrates et al. 2012) has a strong dependency on $a_f$ ($P_t$) while a much weaker dependency on the secondary mass. Therefore, for these binaries, $a_f$ (and $P_t$) for the binaries on the envelope is expected to vary by factor of $\sim 2$ by changing mass ratio by factor of 10.

Curiously, the tertiary companions of the above five systems all share very long, $P_{\text{ter}} \sim 1000$ yr, orbital periods. A more detailed examination of their orbital parameters indicate that due to the large perturber separations, the amplitude of the Kozai oscillations (if present) is suppressed by relativistic precession (see the discussions on “quenched” Kozai oscillation in Socrates et al. 2012 and Figure 1 of Fabrycky & Tremaine 2007 for an example), which would naturally explain why they form an upper eccentric envelope.

Unfortunately, the small-number ($\sim 5$) statistics makes it difficult to robustly establish the existence of an eccentric envelope population.

4. **KEPLER PROBES**

*Kepler* mission has great potential to provide a complete sample that is orders of magnitude larger than Raghavan et al. (2010) to probe the above-mentioned population between 20 days and 1000 days that consists of possibly $\sim 1\%$ of main-sequence stellar systems. *Kepler* is a high-cadence, high-precision mission that aims to find habitable Earth-size planets. It has been monitoring $\sim 150,000$ FGK stars continuously with high cadence and high photometric precision since 2009 (Borucki et al. 2011; Batalha et al. 2010), and is designed to operate for 3.5 yr with the possibility of an extension of several more years. The public release available on 2012 January 10 includes 16 month long light curves.\footnote{During review, a new release was available on 2012 October 28, which corrected occasional distortion of astrophysical signals.} There are potentially $\sim 1500$ *Kepler* systems belonging to the eccentric envelope population.
4.1. Eclipsing Binaries

A straightforward method to detect binary stars is to look for eclipses, i.e., eclipsing binaries (EBs). For an isotropic distribution of orbital orientations, the chance of seeing an EB can be obtained by integrating over the true anomaly \( f \) and all inclinations, \( P = \frac{R_{\text{tot}}}{2\pi} \int_0^{\frac{1}{2}} r \text{d}f \), where \( R_{\text{tot}} \) is the radius sum and \( r \) is the orbital separation. The probability of at least one of the stars being eclipsed is \( P_{\text{EB}} = R_{\text{tot}}(1-e^2)^{-1}(1+2e/\pi) \) if \( R_{\text{tot}} \ll r \). This geometrical probability is roughly constant for a given orbital angular momentum \( J \propto \sqrt{1-e^2} \) [1/2] and, for a track with \( P_f = 15 \) days and high \( e \), is approximately \( P_{\text{EB}} = 0.06(R_{\text{tot}}/R_0)(M_{\text{tot}}/M_0)^{-1/3} \), where \( M_{\text{tot}} \) is the total binary mass. We therefore expect to find of the order of \( \sim 100 \) EBs within the eccentric envelope population with 20 days \( < P < 1000 \) days.

While the period is a direct observable of an EB light curve, the eccentricity is not. One way to accurately determine \( e \) is to make radial velocity (RV) observations. Alternatively, with well-characterized stellar parameters, a reasonable \( e \) estimate can be made from carefully modeling the EB light curve. We follow a third path by focusing on a subsample of EBs with both primary and secondary eclipses observed, upon which one can place strict lower limits on the eccentricity by measuring the timing separation between the two eclipses. We show that a robust selection of highly eccentric binaries can be made by searching for long-period eclipses with short primary–secondary separations.

The probability of observing both eclipses is given by \( P_{\text{EB},2} = (\pi - 2e)/(\pi + 2e)P_{\text{EB}} \), which amounts to about \( \sim 20\% \) of all EBs at high \( e \). We thus expect to find about two dozen systems from the eccentric envelope population. The timing difference between the eclipses, \( \Delta t = t_1 - t_2 \) can be found easily (e.g., in Devor 2008),

\[
\Delta t(P, e, \omega) = \frac{P}{\pi} \left[ \arccos \left( \frac{e \cos \omega}{\sqrt{1 - e^2 \sin^2 \omega}} \right) - \sqrt{1 - e^2} \right],
\]

(1)

where \( \omega \) is the argument of pericenter. At high \( e \) the eclipses are most likely to occur near pericenter and the separation between the two eclipses is of order the pericenter passage time \( \sim P(1-e)^{3/2}/2 \). The separation reaches minimum at \( \omega = 0 \) and is given by

\[
\Delta t_{\text{min}}(P, e) = \frac{P}{\pi} \left[ \arccos \left( e - e \sqrt{1 - e^2} \right) - \sqrt{1 - e^2} \right] \rightarrow 2P_f/3\pi,
\]

(2)

and is approximated by \( P(1-e)^{3/2}/2 \) to an accuracy of better than 20%.

We search for EBs with periods longer than \( P_{\text{cut}} = 40 \) days with secondary eclipses separated by less than \( \Delta t_{\text{min}} \) = 10 days from the primary eclipses. Any EBs that survive, the latter cut must have an eccentricity larger than \( e_{\text{cut}} \), which satisfies \( \Delta t_{\text{min}}(e_{\text{cut}}) = \Delta t_{\text{min}} \). The resulting minimal eccentricity at \( \Delta t_{\text{min}}(e_{\text{cut}}) = 10 \) days as a function of \( P \) is shown in a curved dash line in Figure 1. The period cut \( P_{\text{cut}} = 40 \) days is also shown as a dash line. Any observed EB that satisfies these observational cuts must reside in the \((P, e)\) domain defined by these two lines, which allows for a robust selection of the eccentric envelope population. Moreover, \( \sim 80\% \) of systems with \( P_f = 15 \) days and \( P > P_{\text{cut}} = 40 \) days that show two eclipses satisfy \( \Delta t_{\text{II}} < \Delta t_{\text{II, cut}} = 10 \) days, implying that this cut does not significantly affect systems in the eccentric envelope population.

Kepler is perfectly suited in finding long-period EBs. We search for EBs in the 2012 January release of Kepler data, with all long-cadence (29.4 minutes), pre-search data conditioning light curves from quarters Q1–Q6 (spanning 16 months in total). First, we identify eclipse candidates using a simple criterion that at least three consecutive points are above 3\( \sigma \) deviations from the local median (determined with a window of 200 points). Then candidate light curves are selected by requiring pairs of candidate eclipses to repeat with periods longer than 40 days and that at least one eclipse be deeper than 1\% (larger than the noise present in the vast majority of Kepler light curves). By visually inspecting each of the selected light curves, we identified 14 binary systems with double eclipses having timing separations smaller than 10 days (and periods greater than 40 days). Six out of these are listed in the Kepler EB catalog (Slawson et al. 2011), which is based on the Kepler Q0–Q2 data (with a total time span of 125 days). Among the binaries in the catalog, we found an additional system that survives our period and eclipse separation cuts, but for which both eclipses have depths smaller than 1\%. Therefore, our selection appears to be efficient. The parameters of the 15 systems are listed in Table 1 and plotted as red arrows in Figure 1 showing their periods and minimal eccentricities derived from Equation (2), based on their measured \( \Delta t_{\text{II}} \). The light curves of the three systems with the longest periods are shown in Figure 2. The search is incomplete at long periods, \( P \gtrsim 160 \) days, at which fewer than three primary eclipses occur during the observation time span. Our detections establish that at least \( \sim 1\% \) of stellar systems are binaries (with additional possible companions) in the selected region in the \((P, e)\) plane.

4.2. Eccentric Ellipsoidal Pulses

Kepler’s exquisite photometric precision opens up a venue of binary star detections with ellipsoidal, reflection/irradiation, and relativistic beaming modulations (e.g., Loeb & Gaudi 2003). For very eccentric binaries, these modulations show up as short “pulses” that reach maximum amplitude near pericenter and last
Figure 2. Light curves for the three longest-period eclipsing binaries in our sample. The primary and secondary eclipses can be readily recognized. The timing difference between the two eclipses places a robust lower limit to the orbital eccentricity, as discussed in Section 4.1.

Figure 3 shows the folded light curve of the EB KIC 6864859 with detection of pulses with amplitude of $\delta F_{\text{pulse}} = 0.00025$. The pulse shape (bottom panel) is well described by the linear-perturbation model of ellipsoidal variations $\delta F \propto [1 - 3 \sin^2 \iota \sin^2 (f - \omega)]/r^3$ (Kumar et al. 1995), for parameters $e = 0.63$, $\omega = 88^\circ$, and $i = 90^\circ$ (solid line). These parameters agree with the timings of the primary and secondary eclipses (dashed lines). Since the geometric bias can be well estimated, one could make consistency checks between the systems detected among EBs and the ones without the eclipses. The light curves of a few other candidates (KIC 4459068: $\delta F_{\text{pulse}} = 0.0005$, KIC 5790807: $\delta F_{\text{pulse}} = 0.002$, KIC 4949194: $\delta F_{\text{pulse}} = 0.001$) with periods ranging from 25 to 80 days are shown in Figure 4. KIC 4459068 and KIC 5790807 are associated with single eclipses (both included in the EB catalog by Slawson et al. 2011) while KIC 4949194 does not exhibit any eclipses. Some other probable candidates include KIC 9172506 and 9028474, which show possible pulses with amplitudes similar to those of other variability in the light curve. Note that the eccentricity pulse signals have relatively large amplitude for early-type stars, raising the interesting possibility of studying the possible eccentric migrating binaries for those stars.

5. DISCUSSION

The presence of more than a dozen highly eccentric, long-period Kepler EBs confirm that $\sim 1\%$ of stellar systems reside in the $P-e$ plane near $P(1 - e^2)^{3/2} = P_f \sim 15$ days, as hinted by the Raghavan et al. (2010) sample. The binaries in this flow...
Figure 3. Folded light curves of KIC 6864859, a 41-day eclipsing binary that exhibits “eccentricity pulses” with amplitude $\delta F_{\text{pulse}} \sim 2.5 \times 10^{-4}$ between the two eclipses. The points with different colors represent observations in different period folds. The upper panel shows the portion of the light curve with two eclipses. The lower panel plots the same portion of the light curve zoomed by factor of $\sim 1000$ to show the eccentric pulses which are well described by the linear-perturbation model of ellipsoidal variations (Kumar et al. 1995) plotted in solid blue line with $e = 0.63$. The dashed lines indicate the eclipse timings required by the ellipsoidal variation model, which match well with the observed values.

Figure 4. Examples of systems exhibiting eccentricity pulses (see Section 4.2). The upper panel shows a folded light curve (KIC 4459068, $P = 25$ days, $\delta F_{\text{pulse}} = 0.0005$) while the light curves shown in the middle and lower panels are not folded (KIC 5790807, $P = 80$ days, $\delta F_{\text{pulse}} = 0.002$ and KIC 4949194, $P = 41$ days, $\delta F_{\text{pulse}} = 0.001$).
may be excited to high eccentricity in Kozai cycles and experience tidal migration in the process of forming close binaries. This interpretation has multiple implications that can be tested in the near future. (1) A growing population at increasing periods is expected from the steady-state distribution, following $dN/d\log P \propto P^{1/3}$. This can be tested by future releases of Kepler data, which will enable the exploration of longer period regimes. One interesting possibility is the identification of the initial semimajor axes from which these binaries began their migration. Larger samples can be obtained by using RV follow-up of EBs or by searching for eccentricity pulses in the Kepler data. (2) If affected by Kozai, these systems should have additional companions which can be searched for using high-resolution imaging. (3) Direct tests of Kozai oscillations can be achieved by performing differential astrometry measurements of mutual inclinations between the inner binary and the companion (e.g., Muterspaugh et al. 2006) for the nearby multiples in the flow.

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