Binary Companions of Evolved Stars in APOGEE DR14: Orbital Circularization

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Received 2018 April 18; revised 2018 September 1; accepted 2018 September 16; published 2018 October 25

Abstract

Short-period binary star systems dissipate orbital energy through tidal interactions that lead to tighter, more circular orbits. Using a sample of binaries with subgiant, giant, and red clump star members that is nearly an order of magnitude larger than that of Verbunt & Phinney, we reexamine predictions for tidal circularization of binary stars with evolved members. We confirm that binary star systems in our sample predicted to have circular orbits (using equilibrium tide theory) generally have negligible measured eccentricities. At a fixed stellar mass, the transition period is correlated with the surface gravity (i.e., size) of the evolved member, indicating that the circularization timescale must be shorter than the evolutionary timescale along the giant branch. A few exceptions to the conclusions above are mentioned in the discussion. Some of these exceptions are likely systems in which the spectrum of the secondary biases the radial velocity measurements, but four appear to be genuine, short-period, moderate-eccentricity systems.

Key words: binaries: close – binaries: spectroscopic – stars: evolution – stars: interiors

1. Introduction

From studies of binary star systems in open clusters, it is clear that short-period binaries tend to have smaller eccentricities as compared to longer-period binaries of the same age (e.g., Mathieu 2005). Within a given population of binaries, this manifests as an apparently steep transition from a spread in eccentricities to mainly circularized orbits that occurs around a characteristic value of the orbital period. The value of this transition period or circularization period depends on the age and evolutionary state of the population (see, e.g., Figure 5 in Mathieu 2005). Many studies have measured this transition period, predominantly for main-sequence binaries (e.g., Latham et al. 2002; Meibom et al. 2006; Kjurkchieva et al. 2017), and have found that it tends to be between 5 and 20 days, depending on age (e.g., Mathieu & Mazeh 1988). For binary star systems with giant-star members, the transition period is longer, closer to ≈100 days (e.g., Mayor & Mermilliod 1984; Bluhm et al. 2016), but fewer such systems have been studied. These observed trends are likely a result of binary orbital circularization rather than a manifestation of binary star formation, as the transition period appears to vary with the age of the stellar population (Meibom & Mathieu 2005).

Theoretical predictions for orbital circularization generally explain this phenomenon by assuming that orbital energy is tidally dissipated within each binary star member, with an efficiency and timescale set by the stellar structure of the members (see Mazeh 2008; Zahn 2008 for recent reviews). For stars with deep convective zones (and especially evolved stars), the equilibrium tide theory of orbital circularization (Zahn 1977, 1989) has been shown to predict the eccentricity evolution and therefore transition periods of a small sample of binaries with giant-star members in open clusters of different ages (Verbunt & Phinney 1995, hereafter VP95). In this theory, the tidal bulge induced on the primary (evolved) star will lag the orbital motion of the companion because of coupling of the tidal flow to turbulent eddies driven by convection. These eddies cause an effective viscosity in the convective region of the primary star, and the magnitude of this viscosity affects the amount of lag, which directly relates to the circularization timescale for a given binary system (Zahn 1989). This viscous dissipation of orbital energy acts to synchronize and circularize a binary system, and align the rotational and orbital axes (Zahn 1977, 1989).

In the context of equilibrium tide theory (e.g., Zahn 1989), the time-dependence of the eccentricity, $e$, and semimajor axis, $a$, of a binary star system is given by

$$\frac{1}{t_{\text{circ}}} = f \left( \frac{L_1}{M_{\text{env}} R_1^2} \right)^{1/3} M_{\text{env}} M_1 q (1 + q) \frac{R_1}{a}^8, \quad (1)$$

$$\frac{1}{a} \frac{da}{dt} = - \frac{38}{7} \frac{e^2}{\tau_{\text{circ}}} \frac{1}{a}, \quad (2)$$

where $L_1$, $M_1$, $R_1$ are the luminosity, mass, and radius of the primary (evolved) star, $M_{\text{env}}$ is the mass of the convective envelope of the primary, $q = M_2/M_1$ is the binary mass ratio, $a$ is the binary semimajor axis, $f$ is a dimensionless factor of order unity that depends on the convective and dissipative properties of the convective envelope, and $t_{\text{circ}}$ is the characteristic circularization timescale (Zahn 1977, 1989; Verbunt & Phinney 1995). These expressions can be used to solve for the predicted change in eccentricity of a given binary system whose primary stellar parameters (i.e., mass, radius, etc.) and binary mass ratio are known. Loosely following the notation of VP95 for a binary star system of age $\tau$, and by neglecting the semimajor axis evolution, the change in eccentricity is given by the integral

$$\Delta \ln e = \int_0^\tau dt \frac{1}{t_{\text{circ}}} \quad (4)$$

$$\quad = A \int_0^\tau dt \left( \frac{L_1}{R_1} \right)^{1/3} M_{\text{env}}^2 M_1^2 R_1^8 \quad (5)$$
over the lifetime of the primary star, where we have collected all terms that are time-independent into the constant

$$A = f \frac{q (1 + q)}{M_i a^8}$$  \hspace{1cm} (6)

$$= \frac{(2\pi)^{16/3}}{(G M_i)^{8/3}} \frac{q}{(1 + q)^{5/3} M_i} \frac{1}{p^{16/3}}$$  \hspace{1cm} (7)

($P$ is the binary orbital period). Within the context of this theory and following VP95, the predicted transition period of a stellar population can then be estimated by solving for the orbital period, $P$, of a binary system of typical mass and mass ratio for that population at which $\Delta \ln e = -3$ (i.e., the final eccentricity is $1/2$ of the initial eccentricity, as described in VP95).

The steep ($R_i/a^8$) scaling in Equation (1) implies that, for a given binary, even small changes in the radius of the primary results in very large changes to the circularization timescale. For example, for binary stars with periods $P \gtrsim 10$ days, we expect orbital circularization to occur rapidly when the primary begins to evolve. Further, if the circularization timescale (Equation (1)) remains short compared to the evolutionary timescale along the subgiant and giant branches, then the transition period of a sample of binary stars should correlate with the present-day radius or evolutionary state of each primary.

Using a sample of $\geq 200$ binary star systems with at least one evolved member—nearly a factor of 10 larger than previous work (Verbunt & Phinney 1995)—we study the transition period along the giant branch. We show that the inferred transition period is a function of the surface gravity of the primary star, and therefore conclude that, for binary star systems with large convective regions, orbital circularization must occur faster than the timescale of stellar radius and structure evolution of post-main-sequence stars.

In Section 2, we describe the original data source and catalog of binary star systems used in this work. In Section 3, we present period-eccentricity distributions as a function of primary star properties and compare with predictions from the equilibrium tide theory. In Section 4, we produce simulated populations of binary systems using the equilibrium tide theory that qualitatively match the observed distributions. In Section 5, we discuss assumptions and caveats with this work, and highlight a few interesting systems that would benefit from follow-up observations. We conclude in Section 6.

2. Data

To identify binaries, we use sources with repeat radial velocity measurements in data release 14 (DR14) of the APOGEE survey (Abolfathi et al. 2018; Majewski et al. 2017), a component of the Sloan Digital Sky Survey IV (SDSS-IV; Gunn et al. 2006; Blanton et al. 2017). APOGEE is a medium-resolution ($R \sim 22,500$), mid-infrared ($H$-band) spectroscopic survey that uses the SDSS telescope in the northern hemisphere to survey (primarily) red stars throughout the Galaxy. The primary objective of the survey is to determine kinematics and chemical abundances for a large sample of Milky Way stars to study the evolution and dynamical state of the Galaxy (Majewski et al. 2017). For the key components of the survey, targets are selected using simple color and magnitude cuts designed to primarily target bright, distant (i.e., giant) stars (Zasowski et al. 2013). However, to meet signal-to-noise requirements for faint targets, many fields are observed multiple times and therefore measure radial velocity variations (e.g., Nidever et al. 2015). We have used the radial velocity measurements from APOGEE DR14 to search for and characterize binary star systems. A full description of our search methodology and binary star catalogs can be found in a companion work (Price-Whelan et al. 2018a).

Briefly, we use a custom-built Monte Carlo sampler (The Joker; Price-Whelan et al. 2017) to generate posterior samples over binary orbital parameters (period, eccentricity, etc.) for all stars with $\geq 3$ radial velocity measurements in APOGEE DR14 that pass a series of quality cuts. By making cuts on our posterior belief about the amplitude of radial velocity variations, we identified $\sim 5000$ binary star systems with at least one evolved member that dominates the luminosity of each system. However, the majority of these systems have too few radial velocity measurements to uniquely determine the binary orbital parameters.

Here, we consider only 320 binary systems for which the period and eccentricity have been uniquely determined from the radial velocity data alone (the “high-$K$, unimodal” sample of Price-Whelan et al. 2018a). We further subselect the 234 primary stars with log $g > 2$ that pass visual inspection (from previous work, clean_flag==0; see Section 5.2 in Price-Whelan et al. 2018a). We note that because of the sparse time sampling of the APOGEE survey, we expect that our detection efficiency for high-eccentricity systems is poor, but do not expect biases for low-eccentricity systems. The left panel of Figure 1 shows the stellar parameters (surface gravity, log $g$, and effective temperature, $T_{\text{eff}}$) for all 234 primary stars in the sample used in this work, the middle panel shows the distribution of primary masses for the 68 systems with masses from Ness et al. (2016), and the right panel shows the minimum mass ratios for the 68 systems.

3. Orbital Circularization of APOGEE Binaries

Our sample of binaries contains primary stars with a range of stellar parameters (Figure 1), and therefore a range of expected transition periods. Figure 2 shows the orbital period and eccentricity for all of the systems in bins of primary surface gravity. From top left to bottom right shows bins of decreasing surface gravity, i.e., from subgiants to giant branch stars. Vertical dashed lines at 10 days and 100 days are meant as reference lines. Note the steadily increasing transition period from top left to bottom right as the typical size of the primary increases.

To remove the dependence on the size of the primary, Figure 3 (left) shows period and eccentricity but now with periods normalized by the orbital period at which the minimum separation of the centers of mass of the binary star components is equal to the surface size of the primary star,

$$P_{\text{surface}} = 2\pi \left( \frac{G (M_1 + M_2)}{R_1^3} \right)^{-1/2} (1 - e)^{-3/2}. \hspace{1cm} (8)$$

We compute $P_{\text{surface}}$ for all systems under the following assumptions.

Primary/companion masses. Only a small fraction of the systems in our sample have measured primary masses (Figure 1) and therefore have measured (minimum) mass ratios. We make the simplifying assumption that all primary
stars have masses equal to the median mass over all stars with prior mass measurements in this sample, \( \text{med}(M_i) = 1.36 \, M_\odot \), and all companions have masses equal to the median over minimum companion masses, \( \text{med}(M_{2,\text{min}}) = 0.5 \, M_\odot \).

**Primary evolved first.** We assume that the primary star (i.e., the observed star) is the first member of the binary to evolve off the main sequence.

**First ascent.** We assume that all primary stars are on their first ascent up the giant branch. This is motivated by the small fraction of red clump stars in our sample. Only seven of the primaries were confidently identified as red clump stars in a recent study of APOGEE DR14 evolved stars (Ting et al. 2018).

Assuming that the semimajor axes of the APOGEE binaries have remained constant, and with the assumptions above, we can also compute the expected change in eccentricity, \( \Delta \ln e \), for each binary (see also Figure 4 in Verbunt & Phinney 1995).

As noted in Verbunt & Phinney (1995), the assumption of a constant binary semimajor axis is technically incorrect, but the typical change to the semimajor axis is only between 1% and 10%, i.e., smaller than the uncertainty introduced in the inferred semimajor axes for our systems due to unknown inclination.

To compute \( \Delta \ln e \), we use a model stellar evolution track to integrate Equation (2) up to the measured \( \log g \) of each primary star. In detail, we use MESA (Paxton et al. 2011) to follow the stellar evolution of a \( M_1 = 1.4 \, M_\odot \) star with solar metallicity from the pre-main-sequence (PMS) phase to the asymptotic giant branch (AGB) phase (we stop the models when they first reach \( \log g = 0 \)). The output evolutionary track contains the luminosity, \( L_1 \), radius, \( R_1 \), and convective envelope mass, \( M_{\text{env}} \), at each of the \( \sim 10^5 \) time steps between the PMS and AGB phase. For each APOGEE star, we then use linear interpolation with the output of this evolutionary model to solve for the eccentricity change starting from the time the star leaves the main sequence up to the phase at which the model has the same surface gravity as is measured. We use 10,000 steps evenly spaced between these two phases and use Simpson’s rule to compute the integral.

Following Verbunt & Phinney (1995), Figure 4 shows the expected change in eccentricity plotted against the observed eccentricity for all of the APOGEE binaries used in this work. With the exception of a few outliers with unexpectedly large eccentricities (discussed further in Sections 5.2–5.3), systems that are predicted to have large negative changes to the log-eccentricity have circular orbits. This overall agreement confirms the conclusions of previous work based on a much smaller sample of giant-star binaries (Verbunt & Phinney 1995); the theory of equilibrium tides successfully explains the observed eccentricities of close binaries with member stars that have large convective envelopes.

**4. Population Synthesis**

To compare with the data, we generate a simulated population of binary star systems with primary stars that have similar stellar parameters (by the end of their evolution) to our sample of APOGEE system primaries. We assume simple initial binary orbital parameter distributions (i.e., in period and eccentricity) and compute the change in eccentricity and separation of the companion orbit as the primary star evolves off the main sequence.

In detail, we sample primary stellar masses, companion masses, and primary surface gravities by fitting two-component Gaussian mixture models (GMMs) to the stars in our sample with measurements of each, then resample using the fitted distributions. As described in previous work (Price-Whelan et al. 2018a), primary mass measurements come from Ness et al. (2016), secondary (minimum) masses come from the posterior samplings over orbital parameters using APOGEE radial velocity data, and surface gravities come from the APOGEE (DR14) data reduction pipeline (García Pérez et al. 2016). In our sample, the median primary mass, companion mass, and surface gravity are \( \text{med}(M_1) = 1.4 \, M_\odot \), \( \text{med}(M_{2,\text{min}}) = 0.4 \, M_\odot \), and \( \text{med}(\log g) = 3.1 \). We assume \( M_2 = M_{2,\text{min}} \) when generating companion masses.

We generate eccentricity \( e \) by sampling from a truncated normal distribution with mean and standard deviation, \((\mu, \sigma) = (0.4, 0.3)\), truncated to the domain \([0, 1]\). We note that a thermalized (i.e., uniform in phase space) eccentricity distribution would be \( p(e) = 2e \) (Jeans 1919), but the observed eccentricity distributions of main-sequence binary star systems with periods of \( 10 < P < 1000 \) days is broadly consistent with being flat for moderate eccentricities, with fewer very low and high eccentricities (Duchêne & Kraus 2013). Our comparison with this simulated population does not depend strongly on this choice of initial eccentricity distribution.

We generate initial binary orbital periods, \( P \), by assuming a distribution that is uniform in \( \ln P \) between \((P_{\text{surface}} = 8192) \) days. Figure 5 (left) shows the initial periods and eccentricities of the
simulated systems. Markers are colored by the mass of the primary, $M_1$, and the size of the marker indicates the log-surface gravity, log $g$.

To follow the stellar evolution of the primary stars, we run stellar evolution models using MESA (Paxton et al. 2011) for stars with $M = [0.8, 1, 1.2, 1.4, 1.6, 1.8, 2, 2.5, 3] M_{\odot}$ and solar metallicity. Figure 6 shows the evolutionary tracks in surface gravity and the effective temperature for each of these models. We follow the evolution from the PMS phase until the AGB phase, but again only use the post-main-sequence evolution when evolving the orbit of the binary. At each timestep during the evolution, we output and store all stellar evolution when evolving the orbit of the binary. At each transition period for higher log $g$ assuming $M_1 = 1.36 M_{\odot}$ and $M_2 = 0.5 M_{\odot}$ for all systems (the median values). Intermediate bins show steadily increasing transition periods with decreasing log $g$.

We assume that the equilibrium tides dominate the circularization process for all systems and therefore ignore the effect of dynamical tides (e.g., Goodman & Dickson 1998) during the main-sequence phase. Finally, we assume that all of our systems are detached binaries.

Figure 5 (middle panel) shows the final periods and eccentricities of the simulated systems. As expected, the transition period for higher log $g$ systems (i.e., smaller radii, lighter markers) appears to be close to $\sim 10$ days, but the transition period for stars with lower log $g$ (i.e., larger radii, darker markers) is closer to $\sim 100$ days. In the right panel we normalize the orbital period by $P_{\text{surface}}$. This rescaling removes the dependence on primary size or log $g$ and predicts that circularization should occur around $P/P_{\text{surface}} \approx 10$. The simulated systems that remain very eccentric, $e \approx 0.6$, with periods of $P/P_{\text{surface}} < 10$ are likely a relic of the fact that Equations (2)–(3) break down when $e \sim 1$ (e.g., Hut 1981).

The sharp transition in eccentricity around $P/P_{\text{surface}} \approx 10$ or $a/R_1 \approx 4–5$ observed in the sample of APOGEE binaries (Figure 3, left panel) is therefore qualitatively consistent with predictions from this simulated population (Figure 5, right panel).

5. Discussion

5.1. Assumptions

Here we return to the assumptions made above and assess their applicability.
that the circularization timescale is much more sensitive to the primary star’s radius—which changes considerably after the main sequence—than to its mass. The small spread in primary masses can therefore be neglected, and variations in the mass ratio by typical factors of ~2 (Figure 1) still lead to circularization timescales that are much shorter than the giant branch lifetime. For the sample of binaries considered here, the simple assumptions about primary and companion masses are therefore reasonable.

Primary evolved first. All of the binaries in our sample appear to be single-lined (from visual inspection of the APOGEE spectra). Therefore, if the companion evolved first, it would now be a stellar remnant, and its evolution as a giant would have contributed significantly to the orbital circularization. Only four of the systems with measured masses have minimum mass ratios above 1, indicating a possible neutron star or black hole companion. However, an unknown fraction could have white dwarf companions. Still, the majority of systems in the subset with measured masses are consistent with low-mass main-sequence companions.

First ascent. As mentioned above, only seven of the primary stars in our sample are likely red clump stars (Ting et al. 2018), and these systems all have periods between 120 and 1000 days. This is possibly because shorter period companions would have been common-envelope when the evolved star reached the tip of the red giant branch. During this phase, rapid orbit evolution with timescales of months to years will cause engulfment and possible destruction of the companion (e.g., Nordhaus et al. 2010). We therefore consider this to be a reasonable assumption.

5.2. Exceptional Systems

There are 10 systems with $e > 0.1$ and $P/P_{\text{surface}} < 6$ apparent in Figures 3 and 4. These binaries have short periods and large eccentricities that appear to be discrepant with our conclusions made about tidal circularization. Of these 10 systems, 6 have the warning flag SUSPECT_BROAD_LINES from the APOGEE pipeline, which suggest that these primary...
stars are either fast rotators or may contain blended light from the companion star; the inferred eccentricities for these systems may therefore be biased. In total, 39 systems distributed over the full range of periods have this warning flag. The remaining four systems are listed in Table 1 and warrant further study to understand why they have not circularized. One possibility is that these are actually triple systems with misaligned, long-period companions; the outer body could drive the eccentricity of the inner companion through Kozai-Lidov oscillations (Kozai 1962; Lidov 1962). Verifying this would require long-term radial velocity monitoring of these systems.

Another interesting set of systems have negligible measured eccentricities with periods between 10 < P < 100 days (see top middle and right panels of Figure 2). Analogs of these systems are also seen in the simulated population in the middle panel of Figure 5. In the simulated population, these are simply systems that started with lower eccentricities and thus can evolve faster to e ≈ 0. In the observed systems, we expect the spur of low-eccentricity systems at periods longer than the transition period to be a mix of systems that started with lower eccentricity, systems in which the companion has already evolved, and a minority of red clump stars that circularized when the primary was at the tip of the giant branch.

5.3. Applicability of the Equilibrium Tide Theory

The expressions derived from the equilibrium tide theory (i.e., Equations (1)–(3)) and used to predict the circularization of binary systems in this work are linearized in eccentricity, e, and are therefore only strictly correct for small initial eccentricities (e.g., Zahn 1989; Mazeh 2008). When the eccentricity is not negligible, several harmonics of the orbital frequency contribute to the tide, which may cause qualitative differences in the evolution of eccentric orbits (e.g., Hut 1981; Ivanov & Papaloizou 2004). However, given the small fraction of very eccentric (e > 0.5) orbits in observed populations of binary stars, the equilibrium tide theory has been shown to explain the observed binary period-eccentricity distributions in several stellar clusters over a range of ages (<10 Myr–10 Gyr; Meibom & Mathieu 2005), and for binary systems with giant-star members (Verbunt & Phinney 1995). In addition, this theory successfully predicts the upper envelope of the eccentricity distribution as a function of period even for very high-eccentricity “heartbeat” star systems (Shporer et al. 2016). Since the majority of our sample consists of systems with e < 0.5, it is therefore likely safe to use this theory to compare predictions with the observed bulk properties of our sample.

Still, a few outlier systems appear in the figures throughout this work, especially with short periods and high eccentricities (see Section 5.2). For systems with large initial eccentricity, circularization is expected to be less efficient because the equilibrium tide dissipates less efficiently when the tidal period is short compared to the convective friction time, t_f ≈ (M_{env}R^2/L)^{1/3}, in Equation (1),

$$ t_f \approx 0.5 \left( \frac{M_{env}}{M_\odot} \right)^{1/3} \left( \frac{T_{eff}}{5000 \text{ K}} \right)^{-4/3} \text{years}. $$

The median orbital period of our sample is comparable to this friction time, and the unmodified circularization time, t_{circ} (Equation (1)), appears to explain most of our data, as well as
those of VP95. As the exceptional systems highlighted in Table 1 have relatively short orbital periods, however, it is natural to ask whether their persistent eccentricities might be explained in this way. The nominal $t_{\text{circ}}$ implied by Equation (1) for, e.g., the first system listed in Table 1, is only $t_{\text{circ}} \sim 100$ years (assuming $M_1 = 1.4 M_\odot$ and $M_2 = 0.5 M_\odot$), so an extreme suppression of the tidal dissipation rate predicted from the equilibrium tide would be required.

There are two schools of thought regarding the degree to which the turbulent viscosity ($\nu_T$) depends upon the tidal period, which sets the dissipation rate. Zahn (1989) supposes that $\nu_T$ is linear in the ratio $P/t_f$ when this is sufficiently small, while Goldreich & Nicholson (1977), hereafter GN77 argue for a quadratic suppression (the underlying physical arguments for each are reviewed in Goodman & Oh 1997). Penoy (2009) used numerical simulations to try to decide between the two prescriptions, with somewhat ambiguous results. Here we consider the more severe prescription of GN77, following the approach described in Section 4 of Goodman & Oh (1997) for treating the variation of the convective properties with radius. Applying this prescription to a MESA model of a subgiant star to represent the first system in Table 1 (with $M_1 = 1.4 M_\odot$, and solar metallicity), we find that the predicted circularization time exceeds that predicted from the equilibrium tide (i.e., Equation (1)) by a factor of $\approx(t_f/P)^{1.84}$ when the orbital period is increased from $P < t_f$. In particular, the circularization time at $P = 1.053$ days increases from $t_{\text{circ}} \sim 100$ years to $\sim 2$ Myr. This is still very short compared to the age of the star ($\sim 3$ Gyr, implied by the MESA model), and is even shorter compared to the timescale on which the factor $(R_t/a)^6$ in Equation (1) grows (57 Myr).

This revised estimate of the circularization time for this system could still be an overestimate; for one, the correction would be smaller with the Zahn (1989) prescription for the frequency dependence, and also dynamical tides may significantly add to the rate of tidal dissipation, especially in stars (such as these) that have surface convection zones and entirely extensive cores (Goodman & Dickson 1998; Terquem et al. 1998; Ogilvie & Lin 2007; Barker & Ogilvie 2011; Weinberg et al. 2017). In summary, larger samples of binary star systems with evolved members may probe the frequency dependence of the equilibrium tide, but no proposed or plausible dependence seems able to account for the persistence of the eccentric orbits in Table 1.

6. Conclusions

We selected binary star systems with well-determined orbital properties from a catalog of binaries identified using repeat radial velocity measurements from the APOGEE survey (Price-Whelan et al. 2018a). Because of the selection function for APOGEE, the majority of these systems contain an evolved primary star that dominates the luminosity of the system, and thus these systems are predominantly single-lined spectroscopic binaries. The systems have a range of orbital periods and the primaries have a range of surface gravities, indicating that they are a mix of subgiant, giant branch, and red clump stars (Figure 1).

As has been seen in many other samples of binary star systems, we find that the short-period systems have small or zero eccentricities, but above a characteristic transition period the systems have a range of eccentricities. This transition period depends on the stellar parameters of the primary (evolved) star in the system (Figure 2). If we normalize the orbital periods by the orbital period of the system with a hypothetical companion whose orbit just grazes the surface of the primary star (i.e., to remove the dependence on the primary star size), we find a steep transition from eccentric to circular orbits that occurs around $P/P_{\text{surface}} \approx 10$. This dimensionless transition period is consistent with theoretical predictions (Figure 5). We find that the eccentricities and observed transition periods of binary star systems with evolved members can be explained using a standard tidal circularization theory for stars with significant convective envelopes (Zahn 1977, 1989; Verbunt & Phinney 1995).

The APOGEE survey was not designed to do binary star science (Majewski et al. 2017), but has enabled a number of stellar companion studies because it returns to fields as a part of its survey strategy (Troup et al. 2016; Badenes et al. 2018; Price-Whelan et al. 2018a). Future data releases from APOGEE will provide more visits for current stars and nearly twice as many sources, which will allow more detailed studies of tidal circularization and other binary star phenomena. However, for bright stars, the end-of-mission data release of the Gaia mission will revolutionize binary star science by providing time-series radial velocity information for nearly 100 million stars.

It is a pleasure to thank Matteo Cantiello (Flatiron), David W. Hogg (NYU/Flatiron/MPIA), Hans-Walter Rix (MPIA), and Joshua Winn (Princeton). We additionally thank the anonymous referee for constructive feedback that improved the quality of this article.

The authors are pleased to acknowledge that the work reported on in this paper was substantially performed at the TIGRESS high performance computer center at Princeton University which is jointly supported by the Princeton Institute for Computational Science and Engineering and the Princeton University Office of Information Technology’s Research Computing department.

Astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018b), IPython (Pérez & Granger 2007), matplotlib (Hunter 2007), numpy (Van der Walt et al. 2011), scipy (https://www.scipy.org/).

Facilities: Sloan.
The Astrophysical Journal, 867:5 (8pp), 2018 November 1

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