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WIYN Open Cluster Study: Tidal Interactions in Solar-Type Binaries

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Abstract. We present an ongoing study on tidal interactions in late-type close binary stars. New results on tidal circularization are combined with existing data to test and constrain theoretical predictions of tidal circularization in the pre-main-sequence (PMS) phase and throughout the main-sequence phase of stellar evolution. Current data suggest that tidal circularization during the PMS phase sets the tidal cutoff period for binary populations younger than $\sim$ 1 Gyr. Binary populations older than $\sim$ 1 Gyr show increasing tidal cutoff periods with age, consistent with active main-sequence tidal circularization.

1. The Effects of Tidal Interactions

Recent studies of angular momentum gain and loss in young solar-type stars have primarily been focused on single stars and the interaction with circumstellar disks (e.g. Barnes et al. 2001, Terndrup et al. 2000, and Krishnamurthi et al. 1997). Motivated by the high frequency of late-type binary stars, we will study the effect of close binary companions on stellar angular momentum evolution through tidal interactions.

Tidal deformation of stars in binaries results in a torque component in their gravitational attraction. This torque is responsible for the spin-orbit coupling by which angular momentum is exchanged between the star and the orbit (Zahn 1966,1977, Hut 1981 and references therein). Tidal interactions will continually change the rotation of the binary components and the orbital parameters of the binary system until an equilibrium state is reached. An equilibrium state is characterized by co-planarity of the equatorial planes of the two stars with the orbital plane of the system, circularity of the stellar orbits, and synchronization of the stellar rotation with the orbital revolution of the system.

Figure 1 (Zahn & Bouchet 1989) shows an example of a theoretical model of tidal evolution from the birth-line through the main-sequence phase for a binary system of two 1 $M_{\odot}$ components. In this model, the friction that the tidal bulge experiences as the star rotates is caused by the interaction between convective turbulence and the tidal flow. The turbulent viscosity is reduced when the orbital period becomes shorter than the convective turnover time. The torque (τ) on the tidal bulge is a sensitive function of the ratio of the stellar radius (R) to the distance r between the stars ($\tau \propto (\frac{R}{r})^6$). The timescales for tidal evolution are therefore extremely sensitive to the stellar radius and the depth of the surface convection zone. Thus the rate of tidal circularization and synchronization is higher during pre-main-sequence phase ($t \lesssim 10^6$ yr) than

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during the main-sequence phase. Indeed, Zahn & Bouchet find that the main-sequence rate is so small as to not cause any significant tidal circularization during the main-sequence. The deviation from synchronization after 10^6 yrs is due to conservation of angular momentum as the stars contract before settling on the main-sequence.

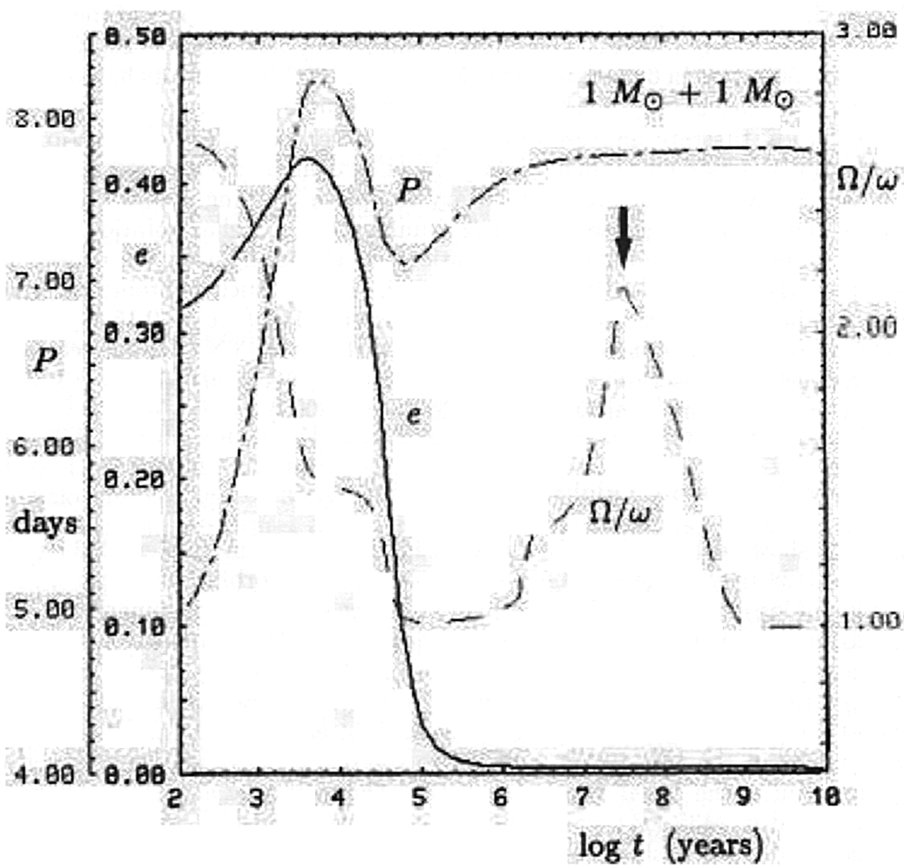

Figure 1. Evolution in time of the eccentricity e, the orbital period P, and of the ratio between the rotational and orbital velocities (Ω/ω), for a system with two components of 1 $M_\odot$. Note that most of the circularization occurs well before the ZAMS (indicated by the arrow) while the stars are still contracting on the Hayashi track. Notice also the synchronism before the ZAMS and the departure from synchronism as the stars approach the ZAMS.

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2. Observing Tidal Evolution

Identification and observations of binary populations of different ages are needed to test the physics of tidal interactions, and constrain and direct models of tidal evolution.

Specifically, to study the the rate and evolution of tidal circularization, observations of orbital eccentricity (e) as a function of orbital period (P) and stellar age are necessary (see Mathieu et al. 1992). For a close binary system determination of the orbital parameters can be obtained through repeated measurements of the radial velocity of one or both stars. Our radial velocity survey of open clusters with ages from $\sim$ 3 Myr to $\sim$ 7 Gyr has been a part of the WIYN Open Cluster Study (WOCS) since 1996. This survey now holds $\sim 20,500$ spectra of $\sim 4,300$ stars in 6 open clusters. More than 100 binary orbits have already resulted from this survey, some of which are presented below.

To study the rate and evolution of tidal synchronization, observations of the rotational periods of stars in binaries must be combined with determinations of binary orbital parameters for a binary sample of varying stellar separation (orbital period) and age (see Claret & Cunha 1997). Stellar rotation periods can be determined from periodic variations in stellar light-curves caused by star-spots (Barnes et al. 1999, Stassun et al. 1999). Such photometric time-series studies are underway for the open clusters M35 (age $\sim$ 0.15 Gyr) and M34 (age $\sim$ 0.25 Gyr) based on observations with the WIYN 0.9m telescope. A comprehensive time-series study of the PMS cluster NGC2264 (age $\sim$ 3-5 Myr) already exists (Lamm et al. 2003, Makidon et al. 2003).

3. New Results on Tidal Circularization

Figure 2 shows orbital data for binaries in the two open clusters M35 (left) and NGC188 (right, age $\sim$ 7 Gyr). The plots present orbital eccentricity as a function of log orbital period for 37 main-sequence spectroscopic binaries in M35 and 28 main-sequence spectroscopic binaries in NGC188. In both clusters the shortest period binaries have circular orbits, while the longest period orbits are all eccentric. The well-defined transition between circular and eccentric orbits was established by the CORAVEL (Mayor 1985) and CfA (Mathieu & Mazeh 1988) teams in the mid 1980's, and led to the definition of the longest period circular orbit as the *"tidal cutoff period"* (P_C, Duquennoy et al. 1992). The tidal cutoff period in M35 (P_C = 10.3 days) and in NGC188 (P_C = 14.9 days) are marked by vertical dashed lines in Fig. 2. The tidal cutoff period is a measure of the tidal circularization rate as a function of binary period integrated over the lifetime of the binary population.

4. Tidal Circularization on the Main-Sequence

The tidal cutoff periods for several populations of solar-type binaries has been established over the last two decades. The distribution of tidal cutoff periods with age enables us to study the evolution of tidal circularization from the PMS phase (Melo et al. 2001) and through the main-sequence (Mathieu et al. 1992) and beyond (Verbunt & Phinney 1995). Figure 3 shows our newly derived tidal

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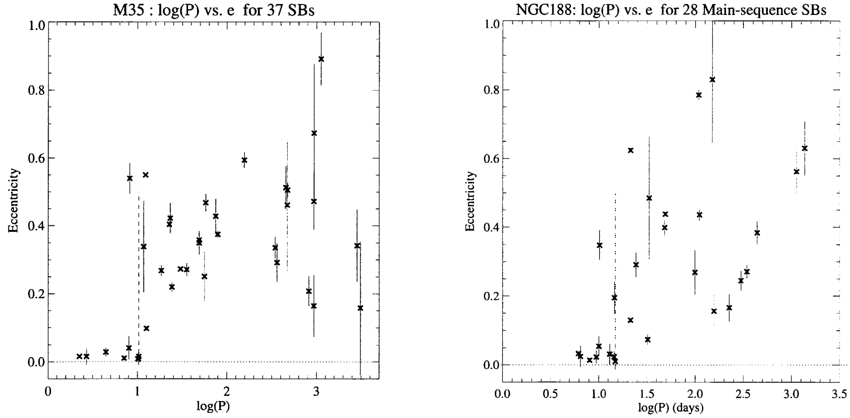

Figure 2. Period (log P) vs. eccentricity for 37 main-sequence spectroscopic binaries in M35 (left) and 28 main-sequence spectroscopic binaries in NGC188 (right). The vertical dashed lines mark the tidal cutoff periods of 10.3 days in M35 and 14.9 days in NGC188, respectively

cutoff periods for M35 and NGC188 (black circles) combined with previously determined cutoff periods (grey circles: 7.7 days among PMS binaries (age $\sim$ 1 Myr, Melo et al. 2001), 7.0 days in the Pleiades (age $\sim$ 0.1 Gyr, Duquennoy et al. 1992), 8.5 days in the Hyades/Praesepe (age $\sim$ 0.6 Gyr, Duquennoy et al. 1992), 12.4 days in M67 (age $\sim$ 4 Gyr, Latham et al. 1992a), and 18.7 days for the halo sample (age $\sim$ 13 Gyr, Latham et al. 1992b).

Concurrent with these observations of binary populations, different scenarios have been proposed for the evolution of tidal circularization through the main-sequence:

"No main-sequence tidal circularization": This model by Zahn & Bouchet (1989) (cf. Fig. 1, horizontal dashed line in Fig. 3) suggests that PMS tidal circularization sets a tidal cutoff period of $\sim$ 7-8 days and that there is little further circularization throughout the main-sequence phase. Existing data for PMS binaries support a tidal cutoff period of $\sim$ 7-8 days. However, data for binary populations older than $\sim$ 1 Gyr clearly show an increase in the tidal cutoff period with age, suggesting significant active main-sequence tidal circularization.

"Hybrid scenario": While the distribution of tidal cutoff periods continue to suggest active main-sequence circularization beyond $\sim$ 1 Gyr, they do not exclude the idea that PMS circularization sets the tidal cutoff period for populations younger than $\sim$ 1 Gyr. The hybrid scenario suggest that the cutoff period of binary populations younger than $\sim$ 1 Gyr derive from PMS tidal circularization, and that after the passage of $\sim$ 1 Gyr the integrated main-sequence tidal circularization begins to circularize binaries with orbital periods of $\sim$ 7-8 days (Mathieu et al. 1992).

The observed tidal cutoff periods for PMS binaries and binaries in the Pleiades and Hyades/Praesepe are in agreement with the hybrid scenario, while the most recent cutoff period in M35 is curiously high by 2-3 days. The significance of this result is not yet clear. While the tidal cutoff periods for M35

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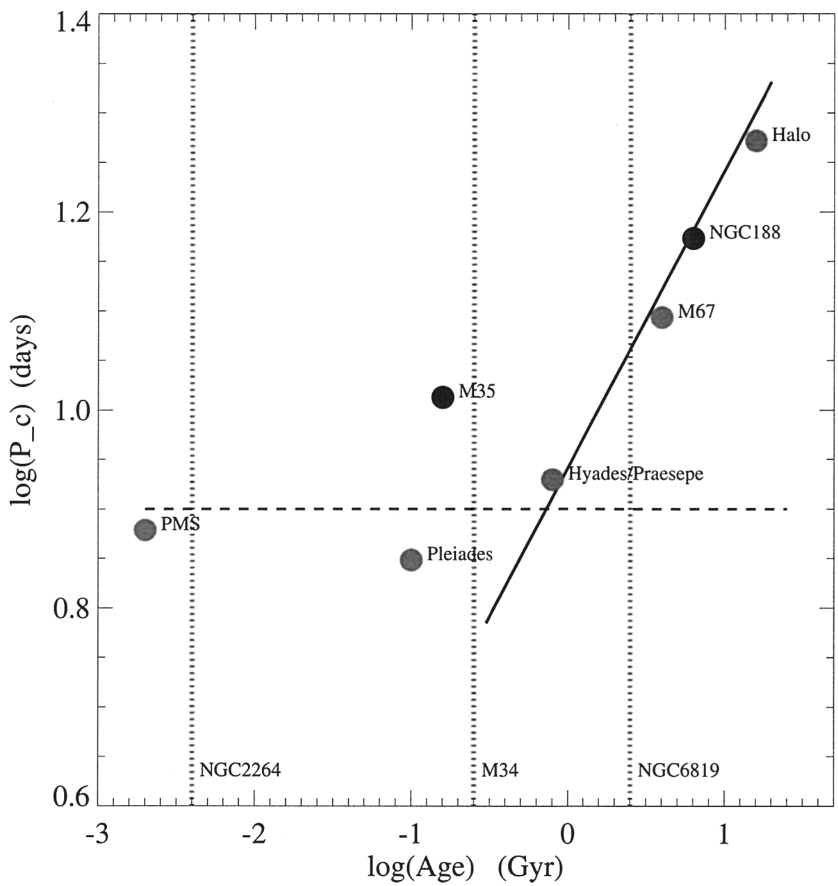

Figure 3. Newly derived tidal cutoff periods (black circles) combined with previously determined cutoff periods (grey circles). The horizontal dashed line represent the model by Zahn & Bouchet (1989). The solid black power-law is a fit to the tidal cutoff periods for binary populations with ages larger than $\sim$ 1 Gyr, representing a main-sequence tidal circularization rate proportional to the binary period to the power of 10/3 (Goldman & Mazeh 1991). The 3 vertical dashed lines indicate the location (in age) of cutoff periods that will be derived in the near future from the open clusters NGC2264, M34, and NGC6819.

and the Hyades/Praesepe are well defined, the cutoff periods for the PMS and Pleiades binary populations are likely lower limits. The cutoff periods for M35 and Hyades/Praesepe might be showing a scatter among tidal cutoff periods due to astrophysical differences in the two binary populations.

New models for the tidal evolution in eccentric late-type main-sequence binaries was recently published by Witte & Savonije (2002) and Savonije & Witte (2002). The tidal dissipation in these models is calculated in the framework of resonant interactions between the harmonic oscillations created by the perturbing potential of the companion star and the stellar eigenmode oscillations. PMS tidal evolution was not considered in these models. At the time of writing this paper we have have not compared these models to the current set of observed tidal cutoff periods.

Tidal cutoff periods for binary populations at ages: $\sim$ 3-5 Myr (NGC2264), $\sim$ 250 Myr (M34), and $\sim$ 2.5 Gyr (NGC6819) will be derived in the near future from ongoing radial velocity surveys on these clusters. The location (in age) of these future cutoff periods are indicated by vertical grey dashed lines in Fig. 3.

5. Tidal Synchronization

The amount of observational data suitable for testing the rate of synchronization in main-sequence late-type close binaries is sparse. Claret & Cunha (1997a,b) analyzed the validity of the theories of Zahn (1977,1989) and Tassoul & Tassoul (1990,1992) using the binary data from Andersen 1991. Most of the work on synchronization in close binaries has concentrated on early type stars with radiative envelopes where the proposed mechanism for tidal dissipation is significantly different (Witte & Savonije 2001,1999, Giuricin et al. 1984a,b).

Our immediate goal is to study synchronization during the PMS and early main-sequence (age $\lesssim$ 300 Myr) phases by comparing the rotational periods of stars in binary systems with their orbital velocity.

6. Conclusions

Binary populations younger than $\sim$ 1 Gyr have tidal circularization cutoff periods between $\sim$ 7-10 days suggesting that a 7-10 day tidal cutoff period is set during PMS phase. After the passage of $\sim$ 1 Gyr tidal cutoff periods increase with increasing age suggesting active main-sequence circularization. This distribution of tidal cutoff periods with age is in agreement with the hybrid scenario proposed by Mathieu et al. (1992). However, there are currently no theoretical model for tidal circularization that can account for both the observed PMS and main-sequence evolution of tidal cutoff periods.

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