THE EFFECT OF BINARITY ON STELLAR ROTATION: BEYOND THE REACH OF TIDES

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ABSTRACT

We present a comparison between the rotation period distributions of solar-type single stars and primary stars in close binaries (0.1 AU ≤ a ≤ 5 AU) in the young (∼150 Myr) open cluster M35 (NGC 2168). We find that the primary stars in the close binaries rotate faster than the single stars, on average. The differences in the means and medians between the period distributions are statistically significant at the 99.9% level or higher. The faster rotation among the primary stars in close binaries is not due to tidal synchronization as tidally evolved stars are excluded from the comparison. We discuss this result in the context of different early-evolution accretion processes and star-disk interactions for single stars and stars in close binaries.

Subject headings: binaries: spectroscopic — open clusters and associations: individual (M35) — stars: late-type — stars: rotation

1. INTRODUCTION

The rotational properties of young low-mass (∼2 \( M_\odot \)) stars challenge our understanding of their angular momentum evolution and specifically of the physical mechanisms, internal and external, that control transport of angular momentum. The importance of determining these processes is underscored by the observed loss of angular momentum during the pre-main-sequence (PMS) phase producing slowly rotating zero-age main-sequence (ZAMS) stars, and by observations of orders of magnitude dispersions and distinct mass dependencies in the rotation period distributions for coeval samples of PMS, ZAMS, and main-sequence (MS) stars (e.g., Barnes 2003; Herbst & Mundt 2005 and references therein).

Inspired by these challenges, a large body of observational and theoretical work on the rotational evolution of low-mass PMS and MS stars was accomplished over past decades. The interpretations and discussions of the results have focused primarily on the roles of stellar magnetic winds and interactions between global stellar magnetic fields and circumstellar (CS) disks in controlling the angular momentum evolution.

In the context of single stars, current models of PMS rotational evolution (e.g., Tink et al. 2002; Bouvier et al. 1997a; Barnes & Sofia 1996) rely on the regulation of stellar angular momentum by CS disks via magnetic disk-braking (e.g., Koenigl 1991; Shu et al. 1994) to recreate the observed rotational properties of ZAMS stars from those of PMS stars. It is generally assumed that the action of magnetic star-disk coupling is to force the star to rotate at constant angular velocity for the lifetime of the disk. It follows from these models that stars with massive long-lived disks will reach the ZAMS rotating more slowly than stars with short-lived disks.

In parallel, models of the evolution of CS disks in PMS binary stars have studied the effect of a close companion on the sizes, masses, and accretion rates, and thereby the lifetimes, of the disks. In binaries with separations ≳100 AU, current models of star-disk interactions predict that a companion star will truncate (Armitage & Clarke 1996; Artymowicz & Lubow 1994; Lin et al. 1993), cause accelerated mass-accretion from (Papaloizou & Terquem 1995; Korycansky & Papaloizou 1995), and potentially disrupt (Pringle 1991; Artymowicz 1992) the CS disks. Accordingly, most models predict that the lifetimes of CS disks are reduced for stars in close binaries as compared to stars in wider binaries and single stars (but see Armitage & Clarke 1996). Such models find support in observational evidence for truncated CS disks and “gaps” in disks cleared by a companion (e.g., Jensen et al. 1996; Jensen & Mathieu 1997 and references therein).

Together, the models suggest that stellar companions may affect one another’s rotational evolution indirectly, by virtue of their disruptive effects on the CS disks that would otherwise act to regulate stellar rotation. To test for a relationship between binarity and rotation, an observational comparison of the rotational evolution between young single and binary primary stars of the same age is needed.

In the closest binary stars, tidal theory (e.g., Zahn 1977; Hut 1981) predicts that stellar rotation is affected by tidal interactions. The timescale for tidal influence on rotation is dominated by the binary separation [\( f_{\text{syn}} \propto (\alpha R)^2 \)]. Thus, tidal theory predicts a (time-dependent) binary separation beyond which rotational evolution due to tides is negligible. Accordingly, in binaries with greater separations, any effect of binarity on stellar rotation must originate from processes other than tidal interactions between the two stars.

Previous searches for a relationship between binarity and rotation among late-type dwarfs were published by Bouvier et al. (1997b) and Patience et al. (2002). Both groups used projected rotational velocities (v sin i) and speckle imaging to identify binaries as close pairs (separations ∼10–1000 AU). Bouvier et al. found no evidence for a relationship between binarity and rotation in the Pleiades. Patience et al. reported higher v sin i values of four binaries with separations between 10 and 60 AU than for 12 wider binaries in \( \alpha \) Persei.

We present an analysis based on coeval samples of spectroscopic single stars and spectroscopic binaries, 83% of which have determined spectroscopic orbits (Meibom & Mathieu 2005). All are members of the 150 Myr open cluster M35, and all single/primary stars have well-determined rotation periods (Meibom et al. 2006; Meibom 2005). The sample of spectroscopic binaries probe a previously unexplored domain of binary separations (∼0.05–5 AU) in which the CS disks are expected to be truncated, disrupted, and accreted onto the stars on short
timescales compared to CS disks of the single stars or stars in wider binaries. Our samples are therefore well suited to search for a relationship between binarity and rotation on the MS, which is the goal of this study.

Section 2 outlines the spectroscopic and photometric observations, and § 3 describes the identification of single and close binary stars and the exclusion of tidally synchronized binaries. We present and compare the distributions of rotation periods for single and close binary stars in § 4 and summarize and discuss our results in § 5.

2. OBSERVATIONS

We have conducted two parallel observational programs of late-type stars in the open cluster M35: (1) high precision ($\sim 0.5$ km s$^{-1}$; Meibom et al. 2001; A. Geller & R. D. Mathieu 2007, in preparation) radial-velocity surveys to identify single and binary cluster members and determine orbital parameters for the closest binaries and (2) comprehensive photometric time series surveys to determine stellar rotation periods from light modulation by star-spots.

All spectroscopic data were obtained over a $1^\circ$ field centered on M35 using the WIYN 3.5 m telescope\(^5\) with the Hydra Multi-Object Spectrograph. Approximately 125 spectroscopic binary members have been identified from the radial-velocity survey, including 32 with orbital periods between 2.25 and 3112 days (0.04 AU $\leq a \leq 5$ AU, assuming $M_p = 1 M_\odot$ and $M_* = 0.75 M_\odot$; Meibom & Mathieu 2005). Radial-velocity membership probabilities were calculated based on the formalism by Vasilevskis et al. (1958) and Gaussian fits to the distinct peaks in the radial-velocity distributions of the cluster ($\sim 8.1$ km s$^{-1}$) and field stars (see Meibom et al. 2006; Meibom et al. 2007).

The photometric data were obtained within the $1^\circ$ field of the spectroscopic survey using the WIYN 0.9 m telescope.\(^6\) Photometric members were selected based on their location in the color-magnitude diagram (CMD) within or above the main sequence (allowing for inclusion of equal-mass binaries). A relative photometric precision of $\sim 0.5\%$ was obtained for the brightest stars (1.2 $\leq V \leq 15$). We have determined stellar rotation periods for 196 photometric and radial-velocity members of M35 (Meibom 2005; S. Meibom et al. 2007, in preparation). The periodic variability detected in the light curves of single-lined spectroscopic binaries is caused by spots on the primary stars and is therefore a reliable measure of their rotation periods (see Meibom et al. 2006 for a detailed discussion).

3. DEFINING binary- and single-star samples

Of the 196 photometric and spectroscopic members of M35 with rotation periods, 118 have three or more radial-velocity measurements, allowing us to test for variability indicative of a close companion star. Specifically, we can distinguish between binaries with $a \leq 5$ AU and single stars or primary stars in wider binaries (both of which are hereafter called single).

We apply the following criteria for determining whether a star is single or a member of a close binary system:

Single star.—$N_{RV} \geq 3$, $\sigma_{RV} \leq 0.5$ km s$^{-1}$, and photometrically single.

Binary star.—$N_{RV} \geq 3$ and $\sigma_{RV} \geq 1.5$ km s$^{-1}$.

$N_{RV}$ denotes the number of radial-velocity measurements, $\sigma_{RV}$ is the standard deviation of these measurements, and “photometrically single” refers to a location on the “single” star cluster sequence in the M35 CMD, thereby excluding equal brightness binaries.

These criteria ensure that single stars are not variable above the 1 $\sigma$ level, and binary stars vary above the 3 $\sigma$ level in radial velocity. Stars in the gray-zone between single and binary (0.5 km s$^{-1} \leq \sigma_{RV} \leq 1.5$ km s$^{-1}$) were not considered. The radial-velocity thresholds are independent of stellar rotation as we find no correlation between stellar rotation period and $\sigma_{RV}$ for either the single stars or stars in the gray zone.

We find 53 single stars and 18 binary stars with measured rotation periods. Of the 18 binary stars, 15 have determined spectroscopic orbits (Meibom & Mathieu 2005). Of the three remaining binaries without spectroscopic orbits, two have $\sigma_{RV}$ values of 8.3 and 5.9 km s$^{-1}$, based on $N_{RV} = 24$ and 12, respectively, significantly above the 1.5 km s$^{-1}$ threshold. The lack of satisfactory orbital solutions for these two binaries is due in part to the blending of the primary and secondary components, preventing accurate determination of the velocities, and to insufficient sampling of the orbits near periastron passage in moderate to high eccentricity orbits. Preliminary orbits have been found for both, but additional measurements are needed to confirm and constrain the solutions. The last binary without an orbit has a $\sigma_{RV}$ of 1.6 km s$^{-1}$ based on four velocities. Inspection of each individual spectrum and cross-correlation function leaves no reason to doubt the quality of the derived radial velocities for this star, and we keep it in the binary sample.

By design, our spectroscopic observing program targets the closest binary stars and gives lowest priority to stars with no or low-amplitude velocity variations. Accordingly, the 53 stars identified as single have only between three and six velocity measurements separated in time by $\sim 0.5$–1.5 years. We cannot rule out the possibility of long-period low brightness ratio binaries among the single stars. However, we find from Monte Carlo analysis based on 30,000 binary orbits, assuming an overall binary fraction of two-thirds for solar-type stars (e.g., Mermilliod et al. 1992; Duquennoy & Mayor 1991), that of the 53 stars in the single sample, none will be binaries with semimajor axes less than 10 AU, and at most seven (13%) will be binaries with separations less than 100 AU. We sampled each binary orbit with a frequency similar to our actual observing pattern.

Excluding tidally evolved binary stars.—Because we are interested in effects on stellar rotation in close binaries other than those imposed by tidal interactions, we evaluate the degree of tidal evolution in the closest binaries and exclude from our sample those likely affected by tidal synchronization at the age of M35 ($\sim 150$ Myr).

Five binaries have orbital periods similar to or shortward of the tidal circularization period for M35 ($P_{circ} = 10.1$ days, $a = 0.12$ AU; Meibom & Mathieu 2005). Considering theoretical predictions that the rate of tidal synchronization exceeds that of tidal circularization by a factor $\sim 10^3$ for constant stellar interior structure (Zahn 1989; Hut 1981), tidally synchronized or pseudosynchronized stellar spins are expected for all five primary stars. However, time series spectroscopic and photometric observations of the five binaries reveal that only two have synchronized primary stars and circular orbits (Meibom et al. 2006). The primary stars in the remaining three binaries,
only one of which has circularized, are rotating either highly super- or subsynchronously.

Theoretical tidal synchronization times for the five binaries can be estimated from the prescription by Hut (1981). The synchronization times for the five binaries range from \(\leq 10\) Myr to several Gyr due to their differences in orbital period and eccentricity, and in the mass of the primary star. At this time there is no consistent agreement between the expectations and predictions of tidal theory and the observed levels of tidal synchronization and circularization in the five closest binaries in M35. Therefore, in the analysis that follows we will exclude all five. In the resulting sample of 13 binaries the shortest orbital period is 30.13 days, and the influence of tidal interactions at the age of M35 can safely be ignored.

4. THE SINGLE- AND BINARY-STAR ROTATION PERIOD DISTRIBUTIONS

Figure 1 shows the rotation period distribution of the single star sample (gray histogram) and for the sample of binary primary stars (solid histogram). The mean and median rotation periods of the sample of binary primary stars fall 1.7 and 1.9 days, respectively, short of the mean and median of the single star sample. The significance of the differences in the mean and median rotation periods of the single star and the binary star samples can be formally evaluated by the Student’s t-test and the Mann-Whitney \(\mu\)-test (Press et al. 1992). These two statistical tests are parametric and nonparametric tests of the null hypothesis that two populations derive from the same parent population, or equivalently, that the differences in the means or medians between two distributions are not statistically significant. We performed both tests on the single star period distribution against the binary primary star period distribution. Both tests result in less than 0.1% probability that the difference in the means/medians is by chance and thus that the two distributions derive from the same parent distribution.

5. SUMMARY AND DISCUSSION

We compare the rotation period distributions of solar-type single stars and primary stars in close \((a \leq 5\) AU) binaries in the 150 Myr open cluster M35. We find that the primary stars rotate faster than the single stars or primary stars in wider binaries, on average. This relationship between binarity and rotation is not due to tidal synchronization, and we find no correlations between stellar rotation and orbital period or eccentricity among the close binaries.

The observed effect of on average faster rotation in close binaries is consistent with a model scenario involving truncation of the CS disk lifetime by a close companion and consequently a shortened phase of magnetic disk-braking of the stellar rotation during the early PMS phase. Whether magnetic disk-braking is the dominant process setting stellar rotation at 150 Myr remains uncertain on both observational and theoretical grounds.

Conceivably, the observed difference in rotation at 150 Myr may reflect differences between single and close binary stars in the amount and distribution of angular momentum at their formation and very early evolution. The formation of the closest binaries, in particular, may differ significantly from the formation of single stars or stars in wide binaries (Larson 2003 and references therein). For example, highly variable accretion rates are frequently associated with the presence of a close companion, and observations of jetlike outflows (Herbig-Haro and FU Orionis stars) have been linked to episodic accretion caused by tidal interactions between protostars and their disks in close binaries (Reipurth 2001; Hartmann & Kenyon 1996; Bonnell & Bastien 1992). A radically different circumstellar environment between single stars and stars in close binaries is carried through to the PMS phase where single stars accrete from extensive CS disks while stars in close binaries may accrete through different processes such as accretion streams (Artymowicz & Lubow 1996; Mathieu et al. 1997; Jensen et al. 2007). Whether these different accretion processes also lead to different depositions of angular momentum remains to be seen.

If indeed the observed rotational difference between single and primary stars in M35 derive from differences in the protostellar environment or from star-disk interactions in the early PMS phase, it should be more pronounced in younger stellar populations and gradually disappear for older populations as magnetic winds spin down all stars not tidally locked. If, on the other hand, the rotational difference is persistent over stellar age, then it may be caused by an as-yet-unknown effect of a close companion. Further observational study of the single- and binary-star rotation periods in younger and older populations will probe any dependency on stellar age.

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