The 20.5th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun
Edited by S. J. Wolk, A. K. Dupree, H. M. Günther

Rotational evolution of young stars: IC 348 and NGC 2362

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Abstract

Evolution of young stars' rotation is investigated by using evolutionary tracks considering conservation of angular momentum and simulations of disk-locking. By assuming that the disk-locking mechanism prevents the expected spin up in the pre-main sequence, we used rotating evolutionary models and observational data to constraint disk lifetimes and locking periods of low-mass stars in the young clusters IC 348 and NGC 2362. We aim at understanding the rotational period distributions of these clusters' stars, which are known to be bimodal and dichotomic. The evolution is assumed to occur with conservation of angular momentum for fast rotators and a constant angular velocity before spinning up to the ZAMS for moderate rotators. We generated sets of evolutionary tracks and estimated a mass and an age for all stars. We found a mean age of 2.5 Myr for IC 348 and 3.3 Myr for NGC 2362. Most of stellar masses were found to be in the ranges of 0.1-0.8 $M_\odot$ for both clusters. In order to investigate the disk-locking effects in these stars, two hypotheses were tested and compared with observational disk indicators available in the literature. In hypothesis 1, we considered that peaks at longer periods in the period distribution are formed by stars with angular velocities locked to a circumstellar disk. Hypothesis 2 considers that rotation period distributions of both clusters were similar to that of Orion Nebula Cluster (ONC) when they had, on average, the same age as the ONC (1 Myr). This scenario implies that some of stars of IC 348 and NGC 2362 were kept locked in their disks during their first million years, and, after that, they evolved conserving their angular momentum. We, then, simulated period distributions for IC 348 and NGC 2362 at about 1 Myr and obtained that they were similar to that of ONC. Our results favor hypothesis 2 and indicate that the disk-locking mechanism seems to operate in young stars with a locking period of about 8 days during a mean disk lifetime of about 1-1.5 Myr.

1 Introduction

The evolution of young stars' angular momentum is still an open problem. Stellar rotation rates are initially set during the star formation process and vary significantly during all evolutionary stages. During the early stages of the pre-main sequence (pre-MS) phase, the star contracts and, in order to conserve angular momentum, its angular velocity increases. However, some stars suffer from mechanisms that prevent the stellar spin up. Disk-locking is one example of such a mechanism. It is due to the magnetic interaction between star and disk, which may occur during the first stages of evolution. From the observational point of view, the range in rotation rates observed for T Tauri stars seems to be narrower than for the main sequence (MS) stars. From pre-MS to the MS several mechanisms act to change the rotational evolution of the star (disk-locking, contraction, accretion, winds). It is well known that rotation periods, $P_{\rm rot}$, of T Tauri stars in young clusters have a very characteristic distribution: they are bimodal and dichotomic. The distribution of periods of stars in the 1 Myr old Orion Nebula Cluster (ONC) has two peaks, one at 2 days and another at 8 days (Attridge & Herbst, 1992; Choi & Herbst, 1996). Another example is the 3.5 Myr old cluster NGC 2264, whose period distribution peaks at 1 and 4-5 days (Lamm *et al.*, 2005). The period distribution depends on mass. Stars less massive than $\sim 0.3\,M_\odot$ show a unimodal distribution formed by fast rotators with a tail of slower rotators, and stars more massive than $\sim 0.3\,M_\odot$ show a bimodal distribution with peaks at 2 (1) days and 8 (4-5) days for ONC (NGC 2264). In a previous work, Landin *et al.* (2016) tested the hypothesis that longer period peaks in ONC and NGC 2264 were due to stars locked into their disks and short period peaks were due to unlocked stars. They used observational data of disk indicators available in the literature and evolutionary tracks considering conservation of angular momentum and simulations of disk-locking to constraint disk lifetimes ($T_{\rm disk}$) and locking periods ($P_{\rm lock}$) of their sample. In this work, we extend the analysis made by Landin *et al.* (2016) to other two young clusters, IC 348 and NGC 2362. We aim at understanding the rotational period distributions of these clusters' stars, which are known to be bimodal and dichotomic, with peaks at 2 and 8 days (for IC 348) and 1.55 and 6.5 days (for NGC 2362), and with transition mass at 0.3 $M_\odot$ (Fig. 1).

2 Clusters

IC 348 is a young (2-3 Myr), nearby (315 pc), relatively compact and rich open cluster, with about 400 stars (Lada *et al.*, 2006; Luhman *et al.*, 2003). It is embedded in the Perseus Molecular cloud and, despite having low extinction (A_V<4), it is not uniform across the region. IC 348 has been very well characterized by using optical and infrared photometry and spectroscopy (Lada & Lada, 1995). NGC 2362 is a young open cluster, located in the constellation Canis Major, with 100-150 stellar members. According to Moitinho *et al.* (2001),

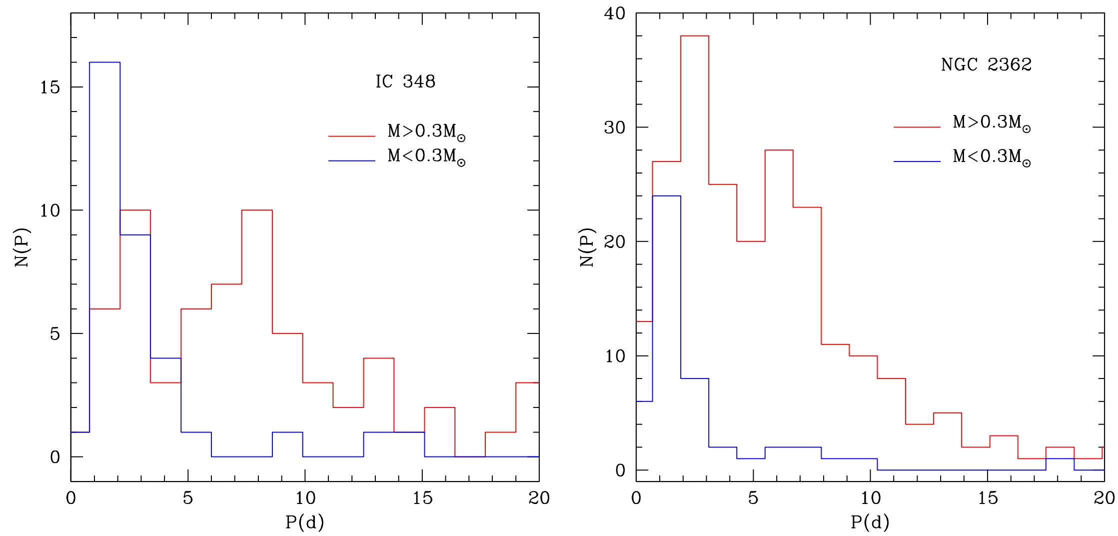

Figure 1: Period distribution of IC 348 (left) and NGC 2362 (right) separated in stars more massive and less massive than $\mathrm{M_{trans}} = 0.3\,\mathrm{M_\odot}$. Periods were taken from Cieza & Baliber (2006) for IC 3348 and Irwin *et al.* (2008) for NGC 2362.

the cluster is about 1480 pc away from the Sun and its age is estimated in 5 Myr. The cluster is practically free from dust extinction and exhibits no signs of nebular emission.

3 Models

The version of the ATON stellar evolution code we use in this work is briefly described below; further details can be seen in Landin *et al.* (2016). In our models, convection is treated according to the Mixing Length Theory (α=2.0) and Allard *et al.* (2000) non-grey surface boundary conditions are used. Here, we assume the solar chemical composition (X=0.7125 and Z=0.0175) and that the elements are mixed instantaneously. Rotating models in ATON code can be generated under three different rotation laws: rigid body rotation, local conservation of angular momentum over the whole star, and local conservation of angular momentum in radiative zones and rigid body rotation in convective regions (Mendes *et al.*, 1999).

For models conserving angular momentum, the initial angular momentum of each model was obtained according to the Kawaler (1987) relation

$$J_{\mathrm{kaw}} = 1.566 \times 10^{50} \left(\frac{M}{M_\odot}\right)^{0.985} \quad \mathrm{cgs.} \tag{1}$$

For models simulating disk-locking, the initial angular momentum corresponds to the long period peak of each cluster, 8 days for IC 348 and 6.5 days for NGC 2362. We considered values of $\mathrm{T_{disk}}$ of 0.2, 1, 3 and 10 Myr.

In Table 1, we highlight some of models' features and give some input parameters.

Table 1: Main physical parameters of the models.

Parameter	Input
Mass range	0.09–3.8 $M_\odot$
Convection model	MLT (α=2.0)
Rotation	rigid body rotation
Opacities	IR93[1] and AF94[2]
Equation of state	R96[3] and M88[4]
Boundary conditions	AHS00[5] (τ=10)
Chemistry	(X,Z)=(0.7125, 0.0175)

1.Iglesias & Rogers (1993), 2.Alexander & Ferguson (1994), 3.Rogers *et al.* (1996), 4.Mihalas *et al.* (1988) and 5.Allard *et al.* (2000).

4 Results

We generated sets of pre-MS evolutionary tracks with masses between 0.09 and 3.8 $\mathrm{M_\odot}$. We estimated a mass and an age for all stars of our sample. The average age found for IC 348 stars was 2.5 Myr while for NGC 2362 stars it was 3.3 Myr. There is an apparent age spread in both clusters, with the bulk of the populations (70-80%) in the interval of 1-10 Myr. Most of IC 348 and NGC 2362 stars ($\sim 89\%$ and $\sim 85\%$, respectively) have masses in the range of 0.1-0.8 $\mathrm{M_\odot}$.

In order to investigate the disk-locking effects in these stars, two hypotheses, taken from Landin *et al.* (2016), were tested and compared with observational indicators of disk presence available in the literature.

Hypothesis 1 uses observed periods to establish a criterion of disk presence:

- stars with $\mathrm{P} > \mathrm{P_{thresh}}$ (8 days for IC 348 and 6.5 days for NGC 2362) are still locked;
- for stars with $\mathrm{P} < \mathrm{P_{thresh}}$ (unlocked) we determined the epoch at which their period were equal to 8 days. These would be the times at which the stars would have lost their disks.

In this way, three distinct populations were identified:

1. early fast rotators – stars locked only for ages $< 10^5$ yr;
2. slow rotators – stars probably still disk embedded;

3. moderate rotators – unlocked stars with $P < P_{thresh}$ and ages $> 10^5$ yr.

This criterion was compared to mid-infrared indicators of disk presence from Cieza & Baliber (2006) for IC 348 and Irwin *et al.* (2008) and Currie *et al.* (2009) for NGC 2362. Both criteria are in agreement only for early fast rotators and moderate rotators, but not for slow rotators.

In this work, the more rapidly rotating stars were assumed to evolve by conserving angular momentum during all stages of evolution, while stars which rotate with moderate rotation rates were assumed to experience an evolution with constant angular velocity before spinning up to the zero-age main sequence.

The evolution of the early fast rotators is relatively consistent with conservation of angular momentum from the beginning (Fig. 2). To fully bracket the observed periods it is necessary to assume a distribution of initial angular momenta J_{in}, at least in the range $J_{Kaw} < J_{in} < 3\,J_{Kaw}$.

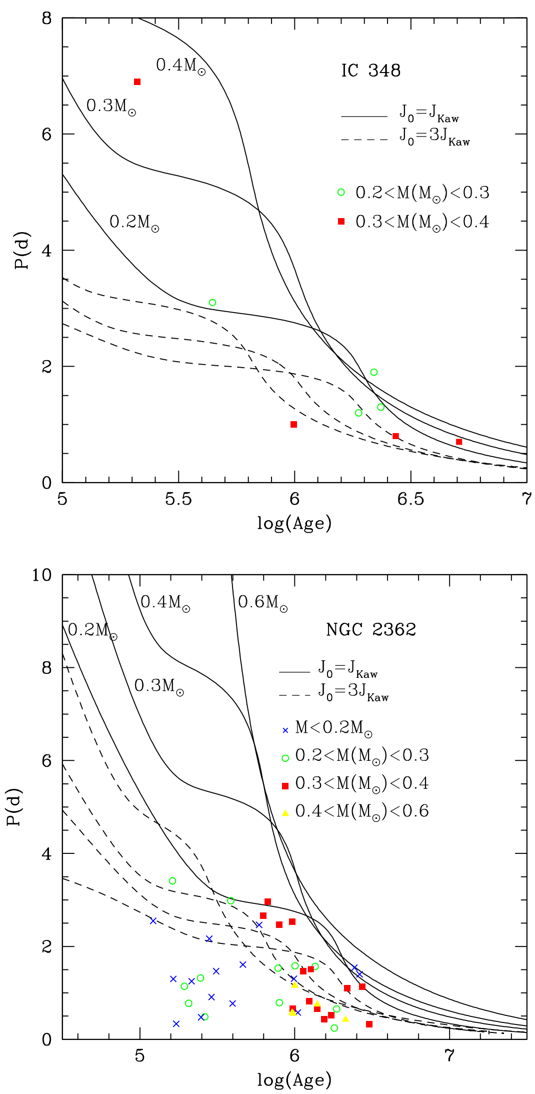

Figure 2: Period evolution of the early fast rotators of IC 348 (top) and NGC 2362 (bottom).

The evolution of the moderate rotators is consistent with a disk-locking phase, with constant angular velocity, before spinning up to the zero-age main sequence (Fig. 3). In order to reproduce the stars' positions in the period-age plane, we used values of P_{lock} of 8 days and T_{disk} of 0.2, 1 and 3 Myr for IC 348 and, for NGC 2362, we used P_{lock}=6.5 days and T_{disk} values of 0.2, 1, 3 and 10 Myr. However, a T_{disk} of 10 Myr is not expected, since almost all stars should have already lost their disks at this age. As hypothesis 1 requires odd assumptions about T_{disk} and our criterion of disk presence do not fully agree with observations, we tested hypothesis 2.

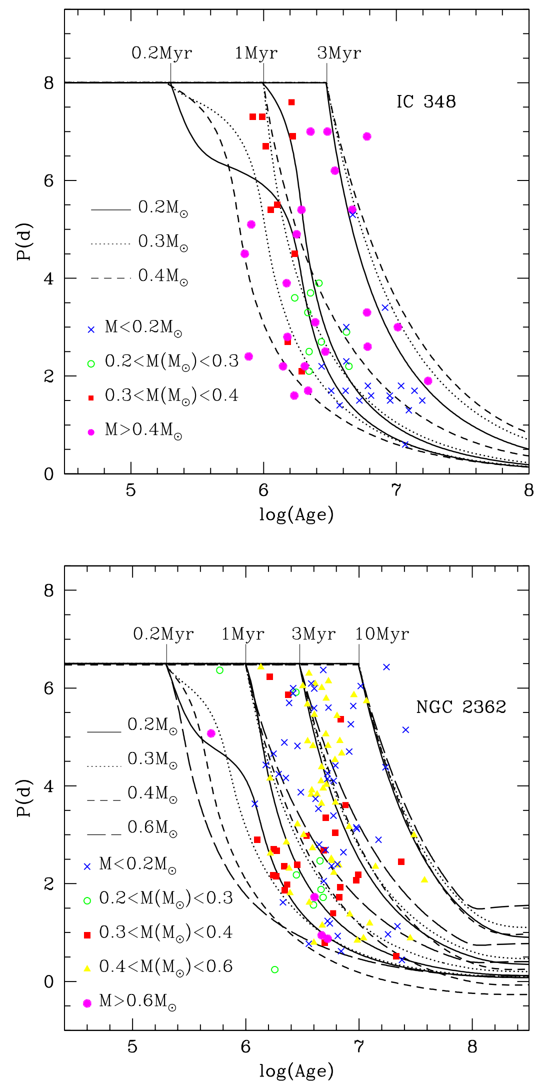

Figure 3: Period evolution of the moderate rotators of IC 348 (top) and NGC 2362 (bottom).

Hypothesis 2 considers that the rotation period distributions of both clusters were similar to that of ONC when they were, on average, similar in age to ONC and that this would be the age, Age_{rel}, at which our stars were released from their disks ($Age_{rel} \gtrsim 1$ Myr). We assumed that the current P_{rot} of stars with observational disk indications were kept constant from the moment that the cluster's mean age reached

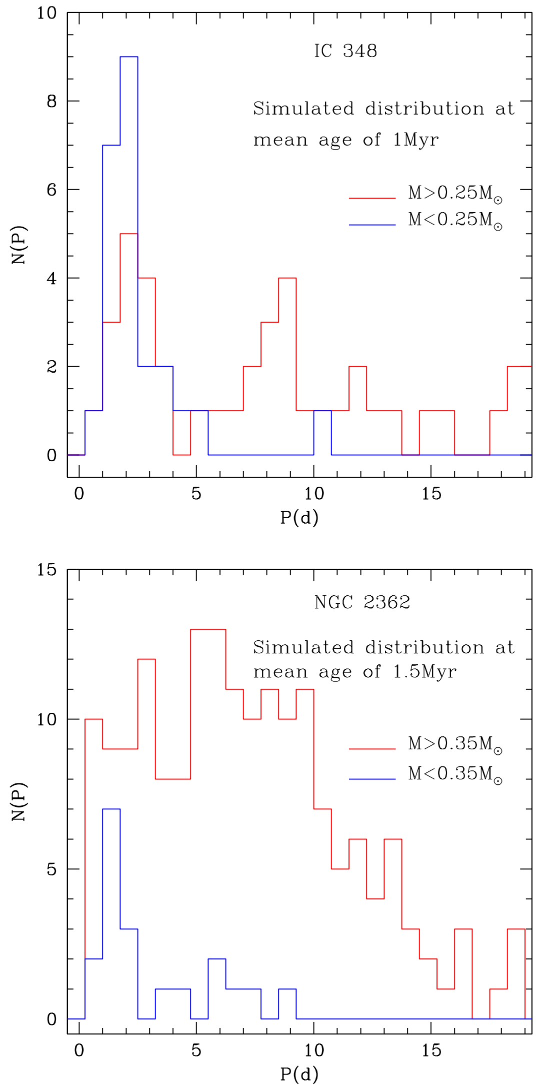

Figure 4: Same as Fig. 1 for the simulated distributions, with $M_{trans} = 0.25\,M_\odot$ for IC 348 (top) and $M_{trans} = 0.35\,M_\odot$ for NGC 2362 (bottom).

Age_{rel}. For stars without observational disk indications, we estimated their P_{rot} at Age_{rel} by considering conservation of angular momentum. We, then, simulated the period distribution of IC 348 and NGC 2362 at Age_{rel} (1 and 1.5 Myr respectively). We realized that, even with few stars remaining in the simulated distributions, both bimodality and dichotomy features have been preserved. The simulated period distributions present peaks at 2 and 8-9 days for IC 348 and at 2 and 7.5 days for NGC 2362. We noticed that these simulated distributions are similar to that of ONC and that dichotomies are observed at about the same transition mass, $M_{trans} = 0.25\,M_\odot$ for IC 348 and $M_{trans} = 0.35\,M_\odot$ for NGC 2362 (Fig. 4). Similar results were found in a previous work by Landin *et al.* (2016) for NGC 2264.

5 Conclusions

Our results indicates that the hypothesis 2 is the most plausible one to explain the analyzed period distributions. Such results indicate that the disk-locking mechanism seems to operate in the clusters' stars with a P_{lock} of 8 days during a mean T_{disk} of about 1 - 1.5 Myr. In addition, the period distributions of IC 348, NGC 3262 and also NGC 2264 seems to represent a later evolutionary stage relative to ONC.

Acknowledgments

The authors thank F. D'Antona and I. Mazzitelli for allowing them to use and improve their ATON code. The Brazilian agencies CAPES, CNPq and FAPEMIG are acknowledged for financial support.

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