Rotational evolution of young stars: IC 348 and NGC 2362

N.R. Landin [1,2] J.K.L. Chaves [3,1] T.S.M. Souza [1] L.T.S. Mendes [4,2] L.P.R. Vaz [2] S.H.P. Alencar [2]
[1]Universidade Federal de Viçosa - UFV Florestal - Brazil (nlandin@ufv.br) [2]Departamento de Física, Universidade Federal de Minas Gerais - Brazil [3]Instituto de Física, Universidade de São Paulo - Brazil
[4]Departamento de Eng. Eletrônica - Universidade Federal de Minas Gerais - Brazil

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 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, what is problematic if the T Tauri phase velocity distribution is to evolve into to that seen on the MS. It is well known that rotation periods, $\mathbf{P_{rot}}$, 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 1Myr 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 3.5Myr old cluster NGC 2264, whose period distribution peaks at 1 and 4-5 days (Lamm et al., 2005). Stars less massive than $\sim 0.3\mathrm{M}_\odot$ show a unimodal distribution formed by fast rotators with a tail of slower rotators and stars more massive than $\sim 0.3\mathrm{M}_\odot$ 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 ($\mathbf{T_{disk}}$) and locking periods ($\mathbf{P_{lock}}$) 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 $0.3\mathrm{M}_\odot$ (Fig. 1).

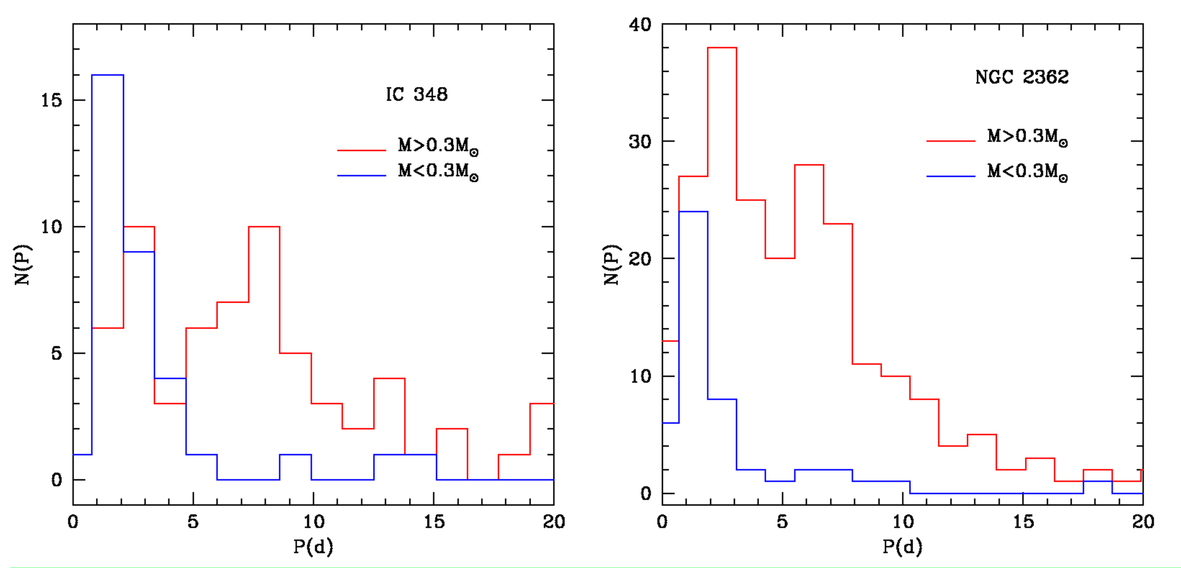

Figure 1: Period distribution of IC 348 (left) and NGC 2362 (right) separated in stars more massive and less massive than $\mathrm{M_{trans}} = 0.3\mathrm{M}_\odot$. Periods were taken from Cieza & Baliber (2006) for IC 3348 and Irwin et al. (2008) for NGC 2362.

MODELS

The version of **ATON** code we use in this work is briefly described bellow. For more details, see Landin et al. (2016). In our models, convection is treated according to the Mixing Length Theory (α=2.0) and 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. Our models were generated by considering rigid body rotation (Mendes et al., 1999). For models conserving angular momentum, the initial angular momentum of each model was obtained according to the Kawaler (1987) relation

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

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 $\mathbf{T_{disk}}$ of 0.2, 1, 3 and 10Myr.

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 2.5Myr while for NGC 2362 stars it was 3.3Myr. Most ($\sim 89\%$) of IC 348 objects and the majority ($\sim 85\%$) of NGC 2362 stars 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 $\mathbf{P > P_{thresh}}$ (8 days for IC 348 and 6.5 days for NGC 2362) are still locked;
- for stars with $\mathbf{P < P_{thresh}}$ (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.

So, 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 $\mathbf{P < P_{thresh}}$ and ages $> 10^5$yr.

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

The evolution of the early fast rotators is consistent with conservation of angular momentum from the beginning (Fig. 2).

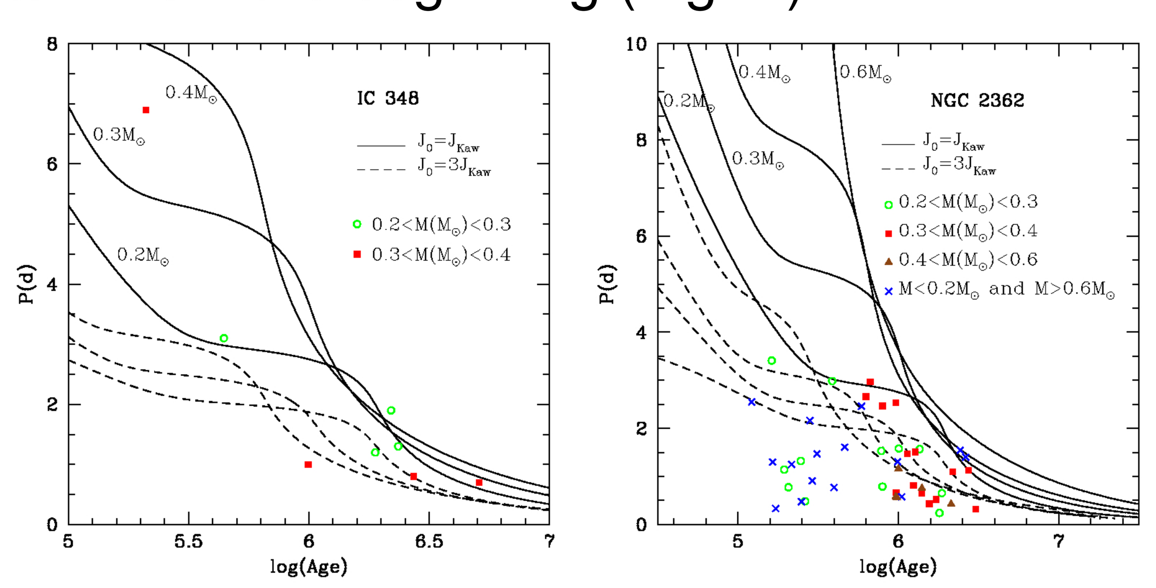

Figure 2: Period evolution of the early fast rotators of IC 348 and NGC 2362.

To fully bracket the observed periods it is necessary to assume a distribution of initial angular momenta $\mathbf{J_{in}}$, at least, in the range $\mathbf{J_{Kaw} < J_{in} < 3J_{Kaw}}$.

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 $\mathbf{P_{lock}}$ of 6.5 and 8 days and $\mathbf{T_{disk}}$ of 0.2, 1, 3 and 10Myr. However, a $\mathbf{T_{disk}}$ of 10Myr is not expected, once almost all stars have already lost their disks at this age. As hypothesis 1 requires odd assumptions about $\mathbf{T_{disk}}$ and our criterion of disk presence do not fully agree with observations, we tested hypothesis 2.

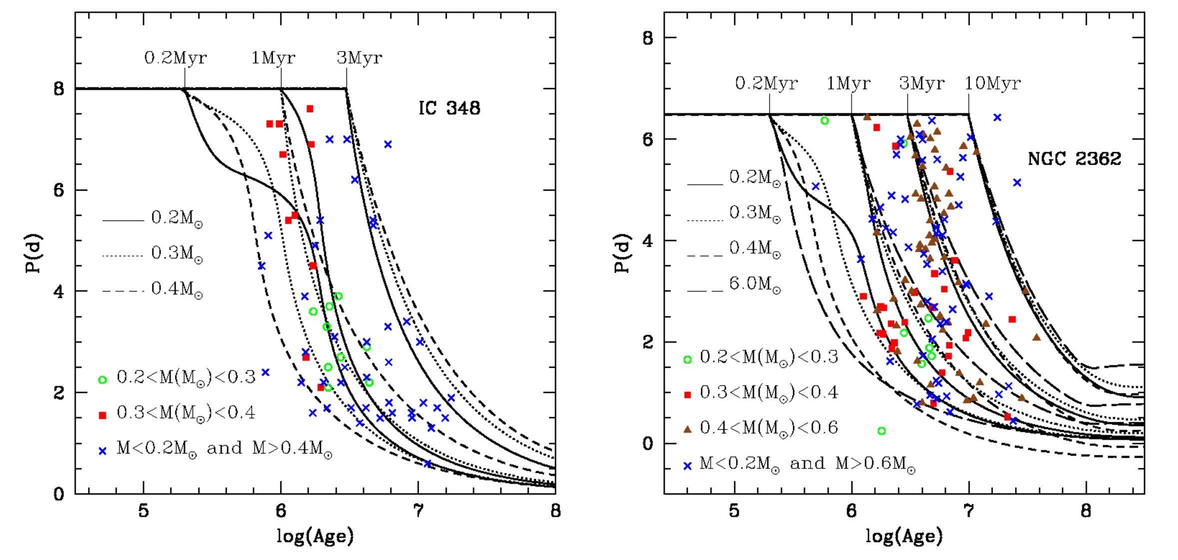

Figure 3: Period evolution of the moderate rotators of IC 348 and NGC 2362.

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 at which our stars were released from their disks ($\mathbf{Age_{rel}} \gtrsim$1Myr). We assumed that the current $\mathbf{P_{rot}}$ of stars with observational disk indications were kept constant since the mean age of the clusters were $\mathbf{Age_{rel}}$. For stars without observational disk indications, we estimated their $\mathbf{P_{rot}}$ at $\mathbf{Age_{rel}}$ by considering conservation of angular momentum. We, then, simulated the period distribution of IC 348 and NGC 2362 at $\mathbf{Age_{rel}}$ (1 and 1.5Myr, respectively). We realized that, even with few stars remaining in the simulated distributions, both features, bimodality and dichotomy, 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 noted that these simulated distributions are similar to that of ONC and that dichotomies are observed at about the same transition mass, $\mathbf{M_{trans}} = 0.25\mathrm{M}_\odot$ for IC 348 and $\mathbf{M_{trans}} = 0.35\mathrm{M}_\odot$ for NGC 2362 (Fig. 4). Similar results were found in a previous work by Landin et al. (2016) for NGC 2264.

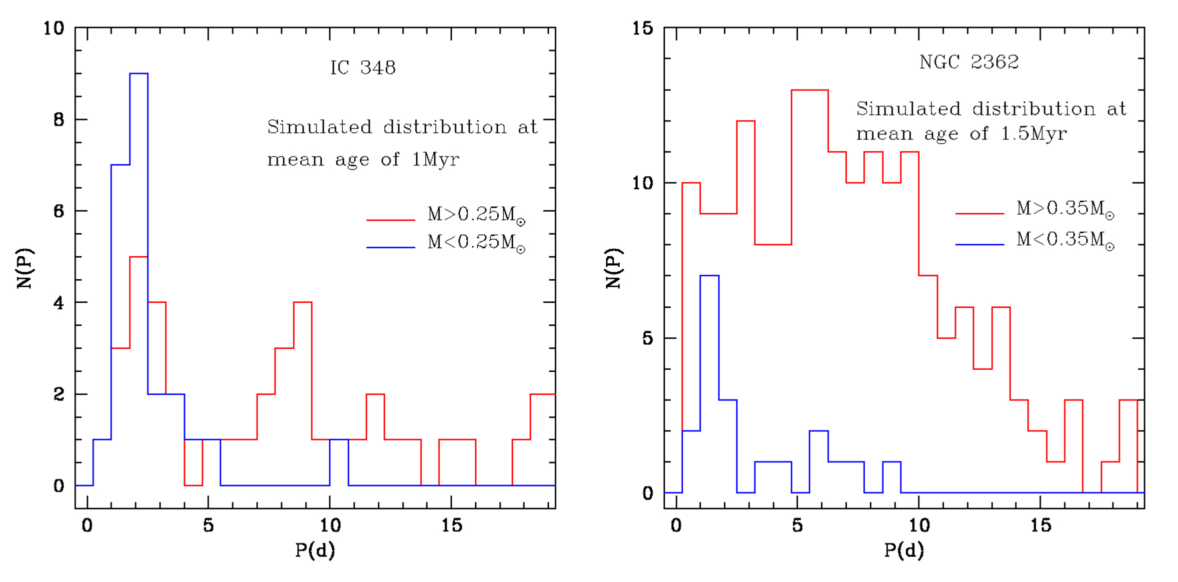

Figure 4: Same as Fig. 1 for the simulated distributions.

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 $\mathbf{P_{lock}}$ of 8 days during a mean $\mathbf{T_{disk}}$ of about 1 - 1.5Myr. 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.

References

Attridge, J.M., Herbst, W., 1992, ApJ, 398, 61.
Choi, P.I., Herbst, W., 1996, AJ, 111, 283.
Cieza, L., Baliber, N., 2006, ApJ, 649, 862.
Currie, T., Lada, C.J., Plavchan, P., Robitaille, T.P., Irwin, J., Kenyon, S.J., 2009, ApJ, 698, 1.
Irwin, J., Hodgkin, S., Aigrain, S., Bouvier, J., Hebb, L., Irwin, M., Moraux, E., 2008, MNRAS, 384, 675.
Kawaler, S.D. 1987, PASP, 99, 1322.
Lamm, M.H., Mundt, R., Bailer-Jones, C.A.L., Herbst, W., 2005, A&A, 430, 1005.
Landin, N.R., Mendes, L.T.M., Vaz, L.P.R., Alencar, S.H.P., 2016, A&A, 586, 96.
Mendes, L.T.S., D'Antona, F., Mazzitelli, I., 1999, A&A, 341, 174.