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Pre-main sequence stellar models simulating the disk-locking mechanism applied to NGC 6530

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Abstract. Rotational evolution in young stars is described with pre–main sequence evolutionary tracks including non-gray boundary conditions, rotation and simulations of disk-locking. Our rotating models assume that stars either evolve by conserving angular momentum since the beginning of their evolution or that the disk-locking is the regulation mechanism for the stellar angular velocity during the early stages of evolution. Observational data are used to constraint disk lifetimes of low-mass stars by means of their representative sample present in the young cluster NGC 6530. In order to mimic the disk-locking effect in the stellar evolution, we generated rotating evolutionary tracks from fully convective configuration with low central temperatures and kept the angular velocity constant during a given disk lifetime. The resulting mass distribution for the bulk of NGC 6530 population is in the range of 0.4-0.8 $M_\odot$ and the average age of the stars in the cluster is around 2 Myr. The rotational period distribution of NGC 6530 stars is bimodal, with a peak at 2 days and a less pronounced secondary peak at 9 days, and vary slightly with mass. Among the low-mass stars (M<0.5 $M_\odot$), about 31% appear to be fast rotators (P<2 days), while in the high-mass regime, the fast rotators represent 21% of the NGC 6530 objects. In order to follow the rotational history of slow and fast rotators, we consider evolution with constant angular momentum and with constant angular velocity, allowing a range of initial angular momentum and disk lifetimes. We tested the hypotheses that (1) the secondary peak is composed by locked stars and that (2) at about 1Myr the NGC 6530 stars had the same period distribution as ONC (Orion Nebula Cluster) evolving after that by conserving angular momentum.

Resumo. A evolução rotacional de estrelas jovens é descrita por meio de trilhas evolutivas na pré-sequência principal que incluem condições de contorno não-cinza, rotação e simulação de *disk-locking*. Nossos modelos com rotação supõem que as estrelas evoluem conservando o momento angular desde o início de suas evoluções ou que o *disk-locking* é um mecanismo de regulação para a velocidade angular estelar durante os estágios evolutivos iniciais. Dados observacionais são usados para vincular o tempo de vida dos discos de estrelas de baixa massa por meio de uma amostra representativa presente no aglomerado jovem NGC 6530. A fim de reproduzir o efeito do *disk-locking* na evolução estelar, geramos trilhas evolutivas com rotação partindo de uma configuração completamente convectiva com baixa temperatura central e mantivemos a velocidade angular constante durante um dado tempo de vida do disco. A distribuição de massas resultante para a maior parte da população de NGC 6530 está no intervalo de 0,4-0,8 $M_\odot$ e a média das idades das estrelas deste aglomerado está em torno de 2 Ma. A distribuição de períodos de rotação das estrelas de NGC 6530 é bimodal, com um pico em 2 dias e um pico secundário menos pronunciado em 9 dias, e varia ligeiramente com a massa. Entre as estrelas de baixa massa (M<0.5 $M_\odot$), cerca de 31% parece girar rapidamente (P<2 days), enquanto no regime de alta massa, os rotores rápidos representam 21% dos objetos de NGC 6530. Para seguir a história rotacional dos rotores lentos e rápidos, consideramos evolução com momento angular constante e com velocidade angular constante, permitindo intervalos de momento angular inicial e de tempos de vida dos discos. Testamos as hipóteses que (1) o pico secundário seja composto de estrelas travadas em seus discos e que (2) em torno de 1 Ma as estrelas de NGC 6530 tinham a mesma distribuição de períodos que ONC (Aglomerado da Nebulosa de Órion) evoluindo posteriormente conservando o momento angular.

Keywords. stars: rotation – stars: pre-main sequence – circumstellar disks – angular momentum evolution – disk-locking models

1. Introduction

The angular momentum evolution of pre-Main Sequence (pre-MS) stars is an important open issue in star formation. Gravitational contraction of stars and marginal loss of angular momentum can explain the spin up of star from the pre-MS to the zero-age main-sequence (ZAMS) and the presence of rapidly rotating stars on the ZAMS. In order to explain the existence of slow rotators on the ZAMS it is necessary to consider a significant loss of angular momentum during early phases of evolution. In addition, to explain the broad period distribution of ZAMS stars these angular momentum loss should be rather different from star to star (Lamm et al. 2005). It is well known that rotational periods of T Tauri stars show a very characteristic distribution. The rotational periods of Weak-lined T Tauri stars (WTTS) are lower than those of Classical T Tauri stars (CTTS) by a factor of 4. These observations suggest that T Tauri stars in accretion disk systems (CTTS) are subjected to a regulation of their angular velocities. Attridge & Herbst (1992) suggested that the disk-locking mechanism, due to the magnetic coupling between star and disk is the responsible for this behavior. Observational data from NGC 6530 stars, a massive star forming region composed by a rich population of more than 1100 members (from OB-type to very-low mass stars, Henderson et al. 2012), are used to constraint disk lifetimes of low-mass stars. This young cluster is located in the Lagoon Nebula, distancing 1336 pc from Earth (Jia et al. 2024).

2. Models

By using the ATON code, we model non-grey, rotating evolutionary tracks from 0.15 to 2.3 $M_\odot$ adopting solar abundances (Y=0.27, Z=0.0142). Convection is treated according to the Mixing Length Theory ($\alpha = 2$) and rotation is modelled as rigid body. We use our theoretical predictions to analyze the rotational properties of NGC 6530 stars, which were found to vary with mass. We generated models which conserve angular momentum during all evolution and whose initial values of an-

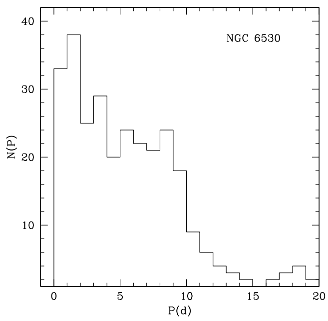

Figure 1. Period distribution of NGC 6530 stars (left) and period distribution divided into two mass populations (right).

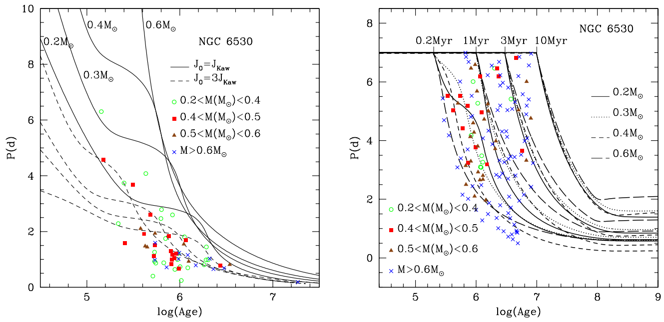

Figure 2. Time evolution of periods of our models and the stars classified as early-fast rotators (left) and moderate rotators (right).

gular momentum are given by Kawaler (1987), according to the relation $J_{\rm Kaw}=1.566\times10^{50}\ (M/{\rm M}_\odot)^{0.985}\,{\rm g\,cm^2s^{-1}}$.

We also generated disk-locking models for a locking period, $P_{\rm lock}$, of 7 days and different disk lifetimes, $T_{\rm disk}$ = 0.2, 1, 3 and 10 Myr. In these cases, $P_{\rm lock}$ defines the initial angular momentum of the track. For more details about the code and input parameters of the models see Landin et al. (2006).

3. Results and discussions

To study angular momentum evolution in the pre-MS phase, we compare our evolutionary tracks with observational data of 290 stars from NGC 6530. With our tracks we estimated a mass and an age for each star of NGC 6530. Masses are distributed from 0.2 to 1.0 $\rm M_\odot$ and the mean age of the stars in the cluster is 2.17 Myr.

The period distribution of NGC 6530 presents two main related characteristics: bimodality (two peaks in the period distribution) and dichotomy (mass dependent rotation properties). Stars with masses larger than a threshold value (transition mass, $M_{\rm tr}$=0.50 $\rm M_\odot$) have a clear bimodal period distribution with peaks at 2 and 7 days. The less massive sample contains a peak at 2 days and a tail of slow rotators. (Fig. 1).

Assuming that disk-locking is the responsible for the long period peak, we defined $P_{\rm lock}$=7 days for NGC 6530. Then, we investigate the role of disk lifetimes on the rotational evolution of these stars. Following Landin et al. (2006), the observed periods of NGC 6530 stars were used to establish a criterion of presence of disk: stars with P>7 days are considered to be still locked and stars with P<7 days are considered unlocked objects. For them, we determined the epoch at which their period was equal to 7 days. This would be the time at which the stars would have lost their disks. We, then, identified three distinct populations: (1) early-fast rotators: 59 stars that were locked only for ages <10^5yr, (2) slow rotators: 98 stars that are probably still disk embedded, and (3) moderate rotators: 128 stars that have lost their disks at ages >10^5yr. Besides, 5 stars were found to be younger than 10^5 yr and did not enter in our analysis.

By comparing our period based criterion of disk presence with the reddening-free index of NIR excess, $Q_{\rm VIJK} = (J-K) - E(J-K)/E(V-I)\times(V-I)$ (Damiani et al. 2006), we can notice that it is in agreement with observed NIR excesses 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 since the beginning of the evolution (left panel of Fig. 2). To fully bracket their periods it is necessary to assume a distribution of initial angular momenta $J_{\rm in}$, at least, in the range $J_{\rm Kaw}<J_{\rm in}<3J_{\rm Kaw}$. On the other hand, the evolution of the moderate rotators can be modelled considering the disk-locking mechanism with different disk lifetimes (right panel of Fig. 2). We tested the hypothesis that there exists a mechanism preventing the stellar spin-up. To accomplish this goal, we used the objects classified as moderate rotators. In the right panel of Fig. 2 we show them in the $P\times$ age plane. These objects had a disk during an earlier evolutionary stage. In a given epoch they lost their disks and, after that, began a constant angular momentum evolution. We note from this figure that our theoretical curves reproduce the observed loci of NGC 6530 stars. The full distribution is reproduced by using a range of disk lifetimes of 0.2–10 Myr. However, observational data indicate that a disk lifetime of 10 Myr seems not to be a good estimate (Bouvier 2007). This analysis has 2 problems: (i) unlike disk lifetime of 10 Myr; (ii) our criterion for presence of disk has poor agreement with observations.

Following Lamm et al. (2005), we present another hypothesis: when NGC 6530 had the age of ONC (1 Myr), it had a period distribution similar to that ONC presents today, with the same locking period, i.e., $P_{\rm lock}$=8 days. Approximately at this age, NGC 6530 stars would have lost their disks and would have began an evolution conserving angular momentum. We, then, simulated the NGC 6530 period distribution at 1 Myr. For stars with $Q_{\rm QVJK}$ index indicating no disk presence, we estimated the rotation period when they aged 1 Myr. For stars with $Q_{\rm QVJK}$ index indicating disk presence, we assumed that their rotation periods have not changed since they were 1 Myr old. The simulated period distribution of NGC 6530 stars preserves bimodality, but not dichotomy, at the same transition mass, $M_{\rm tr}$=0.5 $\rm M_\odot$. The most likely reason is that our simulated distribution has only 56.5% of the stars present in the original sample. The more promising explanation for period distribution of NGC 6530 is an evolution with $P_{\rm lock}$=8 days during the first 1 Myr followed by an evolution conserving angular momentum.

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