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Angular Momentum Evolution of Stars in the Orion Nebula Cluster

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Abstract. We present theoretical models of stellar angular momentum evolution from the Orion Nebula Cluster (ONC) to the Pleiades and the Hyades. The observed periods, masses and ages of ONC stars in the range 0.2–0.5 $M_\odot$, and the loss properties inferred from the Pleiades and Hyades stars, are used as the initial conditions for stellar evolution models. We then use these models to estimate the distribution of rotational velocities for the ONC stars at the age of the Pleiades (120 Myr). The modeled ONC and observed Pleiades distributions of rotation rates are not consistent if only stellar winds are included. In order to reconcile the observed loss of angular momentum between these two clusters, an extrinsic loss mechanism such as protostar-accretion disk interaction is required. Our model, which evolves the ONC stars with a mass dependent saturation threshold normalized such that $\omega_{crit} = 5.4\omega_\odot$ at 0.5 $M_\odot$, and which includes a distribution of disk lifetimes that is uniform over the range 0–6 Myr, is consistent with the Pleiades data. This model for disk-locking lifetimes is also consistent with inferred disk lifetimes from the percentage of stars with infrared excesses observed in young clusters. Different models, using a variety of initial period distributions and different maximum disk lifetimes, are also compared to the Pleiades. For disk-locking models that use the ONC period distribution and a uniform distribution of disk lifetimes over the range 0 to τ_{max}, the acceptable range of the maximum lifetime is $3.5 < \tau_{max} < 8.5$ Myr.

1. Introduction

A fundamental problem in the study of stellar evolution is the loss of angular momentum in stars as they evolve from the birthline to the main-sequence. T Tauri stars generally rotate rapidly, with velocities approaching 150 km s^{-1} (Herbst et al. 2001). Observations of main-sequence stars (Stauffer & Hartmann 1986) and open clusters such as the Hyades (Stauffer et al. 1987; Terndrup et al. 2000) demonstrate that late-type stars are typically slow rotators, with $v \sin i$ < 20 km s^{-1}.

Many theoretical models have been presented to explain the apparent loss in angular momentum in these stars as they evolve along the pre-main-sequence (pre-MS). These models generally involve a magnetic interaction between the star and its cirumstellar disk. While material from the disk is accreted onto

Table 1. Saturation threshold as a function of stellar mass for four different normalizations. The column in bold type is the best-fit normalization from Tinker, Pinsonneault, & Terndrup (2001).

$M_\star$ ($M_\odot$)	ω_{crit} ($\omega_\odot$)	ω_{crit} ($\omega_\odot$)	ω_{crit} ($\omega_\odot$)	ω_{crit} ($\omega_\odot$)
0.5	1.8	3.6	**5.4**	7.2
0.4	1.4	2.7	**4.1**	6.2
0.3	1.0	1.9	**2.9**	4.4
0.2	0.6	1.2	**1.8**	2.7

the surface of the star through magnetic field lines, angular momentum is transported back out. The star and the disk corotate at a period that does not change while the star contracts (Königl 1991; Shu et al. 1994). Significant loss of angular momentum is then a natural consequence of these "disk-locking" models.

Observations of the rotation rates in the ONC are an important test of these theoretical models. Herbst et al. (2000; see also Attridge & Herbst 1992; Choi & Herbst 1999; Herbst et al. 2001) claimed a distribution of rotation periods that was bimodal, peaked at ~ 2 and 8 days. Under the disk-locking hypothesis, the slow rotators are stars that are locked to their disks while the rapid rotators have been released by their disks and allowed to spin up.

Observations by Stassun et al. (1999) challenged this description. They found a period distribution that is statistically uniform and did not find a correlation between accretion and rotation. They also found no correlation between stars with infrared excess and rotation. These data questioned the role of circumstellar disks in the ONC.

In this paper we will present results of models that use the observed rotation rates of low-mass stars (0.2–0.5 $M_\odot$) in the ONC and predict the rotational distribution of these stars at the age of the Pleiades (120 Myr). In §2 we describe the theoretical framework for these models and how observational data are incorporated in them. In §3 we apply these models to ONC data. In §4 we discuss the implications of these results.

2. Theoretical Framework and Observational Data

Theoretical models of low-mass stars were constructed using the Yale Rotational Evolution Code (YREC, Guenther et al. 1992). YREC is a Henyey code which solves the equations of stellar structure in one dimension. YREC uses the nuclear reaction rates of Gruzinov & Bahcall (1998) and the equation of state from Saumon, Chabrier & van Horn (1995). Our models have a metallicity of $Z = 0.0176$ and a mixing length of $\alpha = 1.845$, calibrated such that a 1.0 $M_\odot$ model will reproduce the solar radius and luminosity at the solar age. The input physics for these models is discussed in Sills et al. (2000). A more complete treatment of the method employed in this paper is found in Tinker, Pinsonneault, & Terndrup (2001, hereafter TPT). Here we will give a brief description of the necessary elements in our analysis.

Solid-body rotation is enforced in all our models. This is appropriate for this analysis since low-mass stars ($M < 0.5$ $M_\odot$) are nearly fully convective up until the the age of the Pleiades. This condition also makes the implementation of disk-locking simple; when the model star is disk-locked, its period is held constant over the lifetime of the disk, τ_{disk}, and the change in angular momentum is a function of the star's moment of inertia.

When the star's age becomes greater than the disk-locking lifetime, the rotation period of the star is free the evolve under the influence of stellar winds only. To quantify this angular momentum loss rate, we use a prescription adopted from Kawaler (1988) and described in Krishnamurthi et al. (1997). We write

$$\frac{d\omega}{dt} = K_\omega \omega^3 \left(\frac{M}{M_\odot}\right)^{-0.5} \left(\frac{R}{R_\odot}\right)^{0.5}, \omega \leq \omega_{crit}, \tag{1}$$

$$\frac{d\omega}{dt} = K_\omega \omega \omega_{crit}^2 \left(\frac{M}{M_\odot}\right)^{-0.5} \left(\frac{R}{R_\odot}\right)^{0.5}, \omega > \omega_{crit}, \tag{2}$$

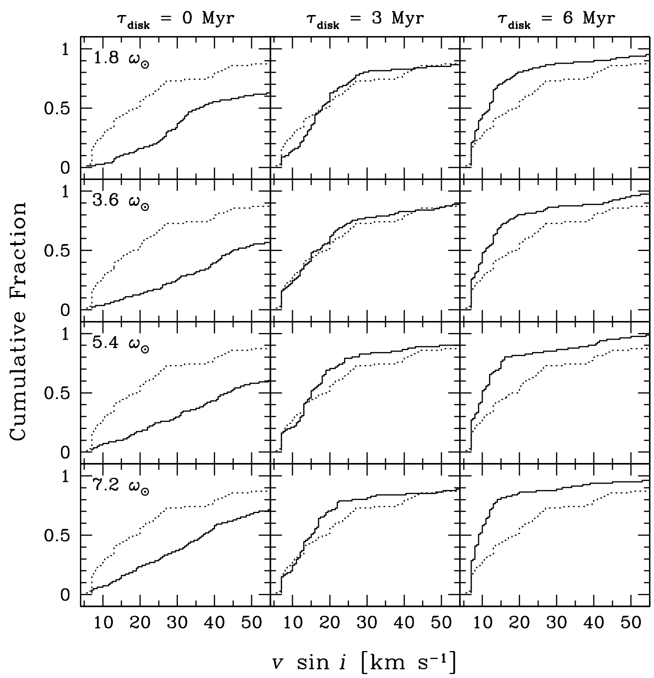
where ω is the angular rotation rate of the star, K_ω is a normalization parameter fixed such that a solar model rotates at the observed solar period at the age of the Sun, and ω_{crit} is the threshold at which the angular momentum loss rate saturates (i.e., $\dot{\omega} \propto \omega$ rather than ω^3, for $\omega > \omega_{crit}$). The constant K_ω is calculated from Kawaler (1988) to be -2.83×10^{47} s.

The scaling of ω_{crit} with stellar mass for low-mass stars was empirically measured by Sills et al. (2000). TPT used this scaling to determine the normalization of $\omega_{crit}(\mathrm{M}_\star)$ by evolving the Pleiades open cluster forward to the age of the Hyades (600 Myr) and comparing the observed rotational distribution in the Hyades to the projected Pleiades distribution for different normalizations. Table 1 shows the values of ω_{crit} as a function of mass used by TPT. Different normalizations will be referred to in this paper by their value at 0.5 $\mathrm{M}_\odot$.

The initial conditions for our models are the masses, ages, and periods of the stars in the ONC, combined with values of τ_{disk} and ω_{crit}. We used the photometric periods listed in Herbst et al. (2000) (see TPT for a discussion on this choice). The masses and ages for these stars were taken from Hillenbrand (1997). This gave us a sample of 81 stars in the mass range 0.2–0.5 $\mathrm{M}_\odot$. Once a value of ω_{crit} and τ_{disk} were chosen, the rotation rate of an ONC star could be calculated at any future time. When the projected rotation rate at 120 Myr was calculated, it was converted to an equatorial velocity and multiplied by a random sin$i$. This allowed for statistical comparison between the theoretical model and the observations of the Pleiades taken from Terndrup et al. (2000).

For the choice of τ_{disk} we used both a constant value for all stars and distribution of ages, $f(\tau_{disk})$. The distribution $f(\tau_{disk})$ was motivated by the observations of Haisch, Lada, & Lada (2001), which reported results of $JHKL$ photometry of young star-forming regions to measure the fraction of stars with the infrared excess indicative of circumstellar disks against the age of the cluster. Their observations show an initial disk fraction that is very high ($\geq 80\%$) and decreases linearly with age to a maximum disk lifetime of $\tau_{max} \sim 6$ Myr. Their results imply that all stars are born with accretion disks around them and that the spectrum of disk lifetimes is flat in the range of 0–6 Myr.

Figure 1. The cumulative distribution of $v \sin i$ of our sample of ONC stars theoretically evolved with 12 different loss laws. The columns are models in which τ_{disk} is 0, 3, and 6 Myr respectively. The rows are four different normalizations of ω_{crit}. The theoretical ONC distribution is the solid line and the observed Pleiades distribution is the dotted line.

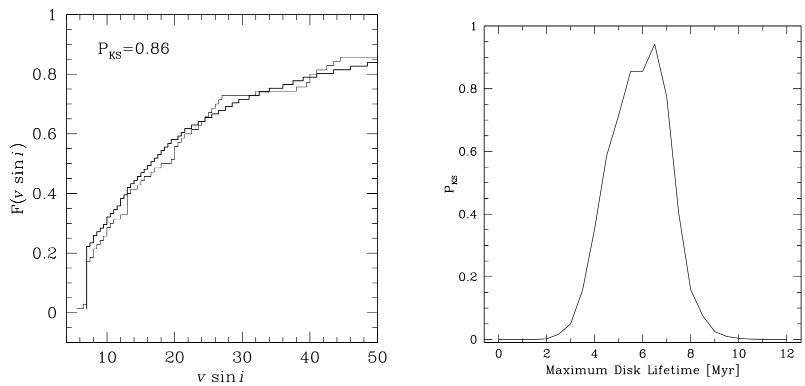


3. Evolving the ONC

In our ONC models, we examined the effect of changing both ω_{crit} and τ_{disk}. Even though TPT found a best-fit normalization of ω_{crit} it is still important to explore the effect of different stellar wind loss rates with the same τ_{disk}. For our initial models, we chose the four normalizations listed in Table 1 and disk-locking lifetimes of 0, 3, and 6 Myr. The choice of $\tau_{disk} = 0$ Myr was motivated to test the idea that disks do not play a significant role in the ONC and that all angular momentum loss is caused by stellar winds. The choice of τ_{disk}= 6 Myr was chosen becuase observations of circumstellar disks suggest that these disks do not normally exist beyond this age. The combination of these two parameters gave us 12 models.

Figure 1 shows the the cumulative distributions of $v \sin i$ for these twelve models. The observed Pleiades distribution is plotted in each panel for comparison. As can be seen in this figure, for $\tau_{disk} = 0$ Myr the predicted distributions of the ONC at 120 Myr do not match the observed Pleiades distribution even when ω_{crit} is varied. The timescale is not long enough for stellar winds to move significant amounts of angular momentum. The resulting distribution is dominated by rapid rotators. Conversely, the models with $\tau_{disk} = 6$ Myr have too many slow rotators as a result of their extended disk-locking lifetimes. From Figure

Figure 2. *Right panel*– The cumulative distribution of rotation rates for the model ONC (*thick line*) and the observations of the Pleiades (*thin line*). The model is the average of 1000 Monte Carlo simulations that sample disk lifetimes for stars uniformly in the range 0–6 Myr. *Left panel*– The results of multiple simulations in which the value of τ_{max} is changed. The horizontal axis is the value of τ_{max} for each simulation. The vertical axis is the K-S probability that the rotation rates produced by the simulation are consistent with the observed rotational distribution in the Pleiades.



1 it is clear that stellar winds alone cannot account for the angular momentum loss between the ages of these two clusters.

The distribution of disk lifetimes discussed in §2, where $f(\tau_{disk})$ is a constant in the range 0-τ_{max}, was implemented by randomly sampling a disk lifetime for each star from $f(\tau_{disk})$ by Monte Carlo method and then averaging the results of 1000 such simulations. The left panel in Figure 2 shows the results for the τ_{max} = 6 Myr, as motivated by observations. The cumulative distribution of rotation rates from the model are plotted along with the Pleiades observations. These two distributions are statistically identical by K-S test. Figure 2 also shows the results of a series of simulations in which the value of τ_{max} was changed from 0 to 12 Myr. For each simulation, the resulting distribution of rotation rates was compared to the observational distribution of the Pleiades by K-S test, which is plotted in the left panel of Figure 2. At the 90% confidence level, we exclude values of τ_{max} less than 3 Myr and greater than 9 Myr. The region of accepted values is centered on 6 Myr, in good agreement with observations.

4. Discussion

In this paper we have placed limits on the angular momentum loss of pre-MS stars through the disk-locking mechanism. We have presented a method that uses observational data as the initial conditions for theoretical models in order to predict the rotation rates of stars at later times. With this method, we have tested the effect of different disk-locking lifetimes on the rotational evolution of low-mass stars in the ONC and compared the resulting distribution of rotation rates to those observed in the Pleiades for the same mass range.

We conclude that disk-locking is necessary to reconcile the observed rotation rates in the ONC and the Pleiades. Stellar winds alone cannot account for the loss in angular momentum. As seen in the left-hand column Figure 1, all the models are inconsistent with the Pleiades no matter what loss rate from stellar winds is used. The value of ω_{crit} has little effect on resulting distribution. The models shown in the right-hand column of this figure are also inconsistent with the Pleiades, thereby demonstrating that we can place limits on τ_{disk} and $f(\tau_{disk})$.

The effectiveness of this method will be enhanced greatly by an increase in statistics, both a larger sample of stars in the ONC and a higher number of young clusters, especially clusters in the pre-main-sequence. Greater statistics in the ONC will place stronger constraints on disk lifetimes. When observations of multiple clusters along the pre-MS are available, the degeneracy between different forms of $f(\tau_{disk})$ can be broken.

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