DISK LOCKING AND THE PRESENCE OF SLOW ROTATORS AMONG SOLAR-TYPE STARS IN YOUNG STAR CLUSTERS

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ABSTRACT

The simultaneous presence of both the so-called ultrafast rotators and slowly rotating stars among the solar-type stars (∼0.6–1.2 \(M_\odot\)) in the same young star clusters has been a puzzle in the field of stellar rotation. No model to date has been able to explain both by a single mechanism intrinsic to the star, and questions about the appropriate initial conditions for models often complicate the problem. In this paper, using the same starting conditions for the models that we used in examining the origin of the ultrafast rotators in young star clusters, we show that the slowest rotators demand an extrinsic mechanism. Assuming that this mechanism is a disk-star interaction, we determine that a disk-locking timescale of a few Myr must operate for this type of star. If, instead of allowing (radial) differential rotation, we enforce solid-body rotation, the models require timescales about 2–3 times as long.

Subject headings: circumstellar matter — stars: evolution — stars: magnetic fields — stars: pre–main-sequence — stars: rotation — Sun: rotation

1. BACKGROUND

During the past decade, the study of rotation in solar-type stars has been one of the more active areas in the field of stellar evolution. Although our ultimate objective is to understand the consequences of rotation, the first step requires that the models reproduce the observed rotation periods/velocities of stars as a function of age.

It has been recognized for a while that the rotational properties of massive stars are quite different from those of solar-type stars (Slettebak 1956; Kraft 1967). The angular momentum evolution of stars more massive than about 1.25 \(M_\odot\), approximately the point at which the surface convection zone that characterizes lower mass stars vanishes, is complicated. Endal & Sofia (1976, 1978, 1979) developed a method, based on work by Kippenhahn & Thomas (1970), to model rotating stars in one dimension, using a series of nested, deformed shells, and initially applied it to massive stars. The most recent work on massive star rotation that the authors are aware of is that by Heger, Langer, & Woosley (2000), again guided by the Endal and Sofia scheme, using a large number of nested shells, with radial angular momentum transfer and consequently radial differential rotation but no latitudinal dependence of rotation, and using a Kawaler-type parameterization for the rate of angular momentum loss through the wind (Kawaler 1988). Observations of rotation rates of these stars, available since the 1970s, have provided a solid observational underpinning to these studies. This is the type of star that we will consider in this paper.

Nowadays, it is possible to study the rotation of even 0.1 and 0.2 \(M_\odot\) stars in the Hyades and Pleiades open clusters (e.g., Terndrup et al. 2000), and models have also been made for the very lowest mass stars, below about 0.5 \(M_\odot\) (Sills et al. 2000, hereafter SPT00), which are fully convective and evolve somewhat differently from the solar-type stars. The hope is that the very simple internal structure of these stars will allow a relatively isolated study of the properties of the processes of angular momentum loss through their winds.

2. INTRODUCTION

Among solar-type stars, a significant problem centers on the necessity of accounting simultaneously for the presence of slow and rapid rotators in young star clusters given the small observed range in rotation rates among their pre–main-sequence precursors. This has proven to be a difficult
The angular momentum evolution of low-mass stars is a function of the initial conditions, angular momentum loss, internal angular momentum transport, and, now, disk interaction; disentangling these effects has not been easy. For an extensive discussion of the observations and theoretical studies see Krishnamurthi et al. (1997), hereafter KPBS97, and for the extension to very low mass stars see SPT00. In a previous paper (Barnes & Sofia 1996, hereafter Paper I), we have presented a scenario whereby one could account for the presence of the ultrafast rotators (UFRs) observed in young star clusters. This involved both starting the evolution at the stellar birth line and changing the prescription for the rate of angular momentum loss. Unlike the Kawaler (1988) formulation of angular momentum loss, we found it necessary to assume that, regardless of the initial stellar rotation rate, the rate of angular momentum loss must saturate at high rotation speeds (e.g., MacGregor & Brenner 1991). In Paper I, we also found that this saturation threshold must be mass dependent to explain the data; KPBS97 reached a similar conclusion in an extensive study that used a single 10 day starting period.

Stauffer & Hartmann (1987) first noted that the angular momenta of even the slowest pre-main-sequence stars were much higher than those observed for slow rotators in young clusters. Since the angular momentum loss rate is expected, on theoretical grounds, to be smaller for slower rotators, this posed a serious problem. Of the possible solutions suggested, perhaps the most promising concerns the effect that locking the young star to a surrounding disk would have on the subsequent rotational evolution of the star. The idea of disk locking is suggested by various observations of T Tauri star rotation. Edwards et al. (1993) noted that the classical T Tauri stars (CTTs) all have periods greater than 4 days with a most probable period of about 8.5 days while the naked T Tauri stars (NTTs) have a range of periods from 2 to 16 days and include a significant number with periods shorter than 4 days. Because the CTT stars show evidence that they are surrounded by disks (cf. Attridge & Herbst 1992; Bouvier et al. 1993) and the NTT stars do not, a disk-locking scenario appears attractive. This paradigm suggests that stars start out as CTTs with periods of 4–16 days, perhaps locked to their disks, and that these disks are eventually lost by accretion or otherwise, whereupon they become NTT stars. At the current time, it is not clear that this is true for all stars, and Stassun et al. (1999) have questioned its validity for stars less massive than 0.5 $M_\odot$. However, Herbst et al. (2000) point out that the T Tauri period distributions are mass dependent and reiterate that the one for $M > 0.25 M_\odot$ continues to display the previously noted bimodality. Although the reality may eventually turn out to be considerably more complex, a simple consideration of the effects of and limits on disk locking of young solar-type stars seems necessary.

Some theoretical work has been done along these lines. Königl (1991), Cameron & Campbell (1993), and Armitage & Clarke (1996) have demonstrated that star-disk interaction via a (usually dipole) magnetic field is capable of regulating the rotation rate of the central star and, indeed, of locking the star entirely, for field strengths in the several hundred gauss to 1 kG range and plausible accretion rates and disk masses. Bouvier (1994) and Bouvier & Forestini (1994) considered the effect of disk locking on solid-body models and concluded that disk lifetimes of at least 10–20 Myr would be necessary to make the slow rotators. More recently, Bouvier et al. (1997) lowered the median disk lifetime to 3 Myr but still required 10–20 Myr of disk locking to explain the rotation rates of the slowest stars. This is somewhat large, in view of observational studies (Strom et al. 1989; Strom, Edwards, & Skrutskie 1990) that suggest shorter disk lifetimes. Rotational velocity distributions that seem to reproduce many features of the observed distributions have been calculated by Cameron et al. (1995) and Keppens, MacGregor, & Charbonneau (1995). However, the mass range of the models (only 1 $M_\odot$ models in the former and 0.8 and 1 $M_\odot$ models in the latter) is limited. In addition, comparisons with observations are made via distributions at fixed (open cluster) ages, without supplying tracks of the time evolution of rotation of the stellar models.

KPBS97 explored models with different assumptions about internal angular momentum transport: solid-body (SB) models and differentially rotating (DR) ones with internal angular momentum transport by means of hydrodynamic mechanisms. They also considered different levels for the saturation of angular momentum loss at high rotation rates and a range of disk lifetimes to produce the distribution of initial conditions. Modest disk lifetimes, of order 3 Myr, were needed to produce the slow rotators for the DR models, while, in agreement with previous work, longer disk lifetimes (of order 20 Myr) were needed for the SB models. However, for the SB models, the slow rotators were found to exhibit little change in rotation during the early MS, while the DR models were found to spin down significantly even at early ages. The time dependence of the slow rotator phenomenon is therefore a good diagnostic of core/envelope coupling, and KPBS97 found that the data were more consistent with the DR models than the SB models. Because the pre-main-sequence data indicate that there is an intrinsic range in the initial rotation rates in addition to any possible disk locking (KPBS97 used a single 10 day starting period for all models), this could well influence the results. In addition, KPBS97 did not explicitly address the question of whether the data could be reproduced without disks.

More recently, SPT00 have extended this formalism to very low mass stars, in view of the fact that rotation rates are becoming available now for even the lowest mass stars in the Pleiades and Hyades (e.g., Terndrup et al. 2000). The same general formalism seems to hold for these very low mass, fully convective stars, in the sense that both magnetic saturation and disk locking seem to be necessary to account, respectively, for the fast and slow rotators down to the very lowest stellar masses. The prescription for angular momentum loss can be simplified somewhat in this mass range, but some structural aspects that can be ignored in more massive stars must be considered. As in KPBS97, SPT00 chose to use a single starting period of 10 days rather than a starting period range, in order to keep the parameter space tractable.

The main motivation of this work is to examine the behavior of models that include both a range in initial rotation and a range of disk-locking timescales. The emphasis is on examining the conditions under which the slowly rotat-

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2 We allowed periods ranging from 16 days (the longest) to as short as 2 days at the birth line.
3 The loss rate varies as the rotation rate to a power between 1 and 2; also see § 5 of this paper.
ing T Tauri stars can be made to evolve into the slow rota-
tors observed in young star clusters while, simultaneously,
the fast T Tauri stars evolve into the UFRs. We first show
that models without disks cannot reproduce the open
cluster data and then examine which combinations of disk
lifetime and initial rotation rate can reproduce the rotation
periods seen in open clusters. Our goal is not to elucidate
the nature of the star-disk interaction but to understand
the extent of disk locking that would be necessary to account
for the observed rotation periods of young cluster stars. We
examine the effects of both components of the initial condi-
tions. We do not evolve entire distributions in time because,
in the opinion of the authors, the observations are still
inadequately free of biases to test this level of detail. We
wish to provide rotational evolution calculations for indi-
vidual stars in the 0.6–1.2 $M_\odot$ range (representing solar-
type stars) that extend and merge seamlessly with the
models of Paper I that may be compared directly to obser-
vations, especially those that are expected to become avail-
able soon (cf. Barnes 2000; Mathieu 2000).

On the observational side, some confusion has been
created by lumping together the observations of very low
mass stars with those of the solar-type ones. Also, the T
Tauri periods are mostly for stars less massive than solar
type. Because of the paucity of observations of very low
mass stars, this difference could not hitherto be addressed
effectively. With the increase of the observational base, this
distinction is not only possible but also necessary from now
on. Although it is difficult to determine the masses of T
Tauri stars, both Herbst et al. (2000) and Stassun et al.
(1999) have supplied estimated stellar masses with their T
Tauri periods. This added information should improve the
situation considerably. Although complete consistency
between the initial conditions, masses, models, and obser-
vations has not yet been attained, we hope for such consis-
tency soon.

In Paper I (Barnes & Sofia 1996) we have demonstrated
that the UFRs (ultrafast rotators) in young star clusters
cannot be produced if the angular momentum loss scheme
that produces a Skumanich-type slowdown on the main
sequence is also valid on the pre-main sequence. We
demonstrated that they could be produced and, indeed, fit
the overall rotation period observations better, if one
assumed that the magnetic field (and hence angular momen-
tum loss) saturated beyond a threshold angular velocity.
This has also been noted by MacGregor & Brenner (1991),
Cameron & Li (1994), and Keppens et al. (1995). We now
wish to consider whether the slower rotators in these clus-
ters can be explained within the same general framework.
The following section (§ 3) of this paper explains the frame-
work that motivates this and our previous work. Section 4
discusses the observational constraints on the models.
Section 5 describes the stellar models and the evolution
code. Section 6 presents the results, followed by the con-
cluding discussion in § 7.

3. THE FRAMEWORK

The framework we proposed in Paper I involved:

1. Beginning the evolution of solar-type stars at the deute-
rum main sequence as suggested by Palla & Stahler (1991).

This is both observationally justified, since the birth line
delineates the upper envelope of the T Tauri observations in
the H-R diagram, and theoretically appealing since it offers
a uniform initial condition for stars of different masses. This
is important because rotational evolution is rapid on the
Hayashi track. Starting off the models with the observed
rotation periods of T Tauri stars removes a number of uncer-
tainties that would otherwise contaminate the results
and complicate their interpretation.

2. Incorporating some form of saturation of the stellar
magnetic field or, equivalently, of angular momentum loss
beyond a threshold rotation velocity that varies with stellar
mass.—There is some justification for this in the observed
saturation of chromospheric emission (e.g., Stauffer 1994),
which is thought to scale with stellar magnetic fields. The
point of saturation is approximately known to be of order
10$\Omega_\odot$ but has not been precisely constrained as a function
of stellar mass. Angular momentum loss via a stellar wind is
unable to account for the presence of the UFRs in young
star clusters regardless of the starting period unless it
incorporates saturation beyond a threshold angular veloc-
ity (MacGregor & Brenner 1991; Barnes & Sofia 1996).
Furthermore, models that do not incorporate saturation
cannot account for the observed dispersion in stellar rota-
tion periods as a function of time, whereas those that
include saturation can.

Paper I also suggested that the scenario above would not
be sufficient to account for the very slowest rotators
observed in young star clusters and that some additional
ingredient, perhaps disk locking, might have to be invoked
to explain them. Again, there is observational justifi-
cation for this in the T Tauri data, as stated earlier. This has led to
a picture in which young stars are born with disks to which
they seem to be locked in some way (since otherwise they
should spin up as they contract down the Hayashi track). At
some subsequent stage in the evolution (which may vary
from star to star), the disk is lost and the star is now free to
evolve onward as an NTT star. This suggests the following
addition to the framework:

3. Including some form of disk-regulated angular momen-
tum loss for some period on the pre–main sequence to account
for the presence of the slow rotators.

This scenario is compelling in its simplicity. We now wish
to test whether the disk-locking scenario is indeed capable
of explaining the slowest rotators and, if so, what sorts of disk
lifetimes would be necessary. However, before that, we
make a digression to discuss some observational con-
straints.

4. OBSERVATIONAL CONSTRAINTS

Large samples of spectroscopic $v \sin i$ data have been
collected for solar-type stars in young open clusters for over
a decade now, often in conjunction with measurements of
lithium abundance in stars (e.g., Soderblom et al. 1999,
and references therein; Stauffer et al. 1997a, 1997b, and refer-
ces therein; Queloz et al. 1998). These helped define and
clarify various issues related to the rotation of sun-like stars,
but they were particularly useful with respect to the UFRs
because a star with a very large $v \sin i$ value can have only a
large angular velocity, regardless of the angle of inclination,$i$.
For slow rotators, $v \sin i$ data are less useful. For several
years, only (fairly high) upper limits on $v \sin i$ were avail-
able for many of the slow rotators, and, even if a small
$v \sin i$ value is measured, one cannot tell whether it arises
from a small $v$ or a small $sin i$. Moreover, uncertainties in
stellar radii come into play when one wishes to know the
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$v \sin i$ value is measured, one cannot tell whether it arises
from a small $v$ or a small $sin i$. Moreover, uncertainties in
stellar radii come into play when one wishes to know the
intrinsic angular rotation rate. Thus, for all rotators, and
especially for the slow ones, rotation periods, when available, are preferred.

4.1. Rotation Periods

At present, there exists a modest but rapidly expanding database of rotation periods of stars in young open clusters. Observations exist for T Tauri–type stars (Attridge & Herbst 1992; Edwards et al. 1993; Bouvier et al. 1993, 1995; Choi & Herbst 1996; Stassun et al. 1999; Herbst et al. 2000), IC 2391 (Patten & Simon 1996), IC 2602 (Barnes et al. 1999), IC 4665 (Allain et al. 1996a), Alpha Per (Stauffer et al. 1985; Prosser et al. 1993a, 1993b, 1995; O’Dell & Cameron 1993; Allain et al. 1996b; Prosser & Grankin 1997), the Pleiades (Van Leeuwen & Alphenaar 1982; Van Leeuwen, Alphenaar, & Meys 1987; Prosser et al. 1993a, 1993b, 1995; Krishnamurthi et al. 1998), and the Hyades (Radick et al. 1987; Prosser et al. 1995). Although the data set is incomplete in various respects (see Barnes 2000 for a recent review), several conclusions relevant to this work may already be drawn from it.

1. T Tauri stars in our mass range have periods ranging from \(~1\) to 17 days. The NTT and CTT stars are believed to show a preference for the shorter and longer period ends of the distribution, respectively.

2. The Hyades show a well-defined sequence of lengthening period with increasing color until \(B - V \approx 1.2\). However, in the region beyond, there are some rapid rotators but as yet no evidence of the slow rotators that might be expected just by extending the solar-type observations to lower stellar masses.

3. The young clusters IC 2391, IC 2602, Alpha Per, and the Pleiades have a number of UFRs (periods of 0.2–1 days). However, they also contain a number of slow rotators, including several in the 7–10 day range. This is remarkably long for clusters this young and creates a rotational dispersion that is very difficult to explain simply.

It is this last group of observations of slowly rotating stars that concern us here. These slow rotators will be displayed henceforth in the plots of the stellar models (Figs. 1–5) by the upper boxes whose \(x\)-width represents the age range of 30–120 Myr. The UFRs, which were the subject of Paper I, are represented by the lower boxes in the same figures.

4.2. Initial Periods

It is probably worthwhile to ask whether this paradigm needs to be reconsidered in view of work by Stassun et al. (1999). They have questioned the disk-locking paradigm because they observe no correlation between infrared excess and rotation period. However, we must remember that this data set is almost entirely composed of stars below the mass range considered in this paper. Of the 254 rotation periods reported in that paper, most have masses in the range 0.15–0.4 \(M_\odot\). Of those with both masses and periods tabulated, only nine stars have masses in excess of 0.5 \(M_\odot\). The period range of these eight stars is 1.03–8.26 days (which is the range shown in Figs. 1–5 using gray shading). Herbst et al. (2000) derive similarly short periods but are also sensitive to, and indeed derive, much longer periods. Let us consider the two ends of this distribution.

1. The short-period end: if we take the observations at face value and 1 day is indeed the shortest period for stars in this mass range at 1 Myr ages, this approximately works out to a 4 day initial period for the masses under consideration at the birth line, exactly the value we have chosen in this and the previous paper to use as the starting point for the fast rotators.

2. The long-period end: the longest period in this mass range derived by Stassun et al. (1999) is 8.26 days, but this is due to the fact that they are not sensitive to longer periods. Indeed Herbst et al. (2000) find longer periods (displayed as a cap on the Stassun et al. 1999 observations in Figs. 1–5). Therefore, our choice of a 16 day period to represent the slowest rotators is both reasonable and in agreement with the Herbst et al. (2000) data.

It is remarkable that the range of the actual observations of Stassun et al. (1999) and Herbst et al. (2000) actually match the initial conditions we had chosen in 1996 (see Figs. 1–6) before masses were available for these stars. We conclude that our choices are still the appropriate ones to use for the stars in our mass range.

5. THE STELLAR MODELS AND THE EVOLUTION CODE

All the stellar models used in this work begin at the deuterium main sequence, at which point they are assigned zero age. These models were originally generated from polystropic ones higher up on the Hayashi track, which were allowed to evolve downward in the H-R diagram (during which time their internal structure stabilized), until they satisfied the mass-radius relationship of Palla & Stahler (1991). This step is important because, otherwise, the change in the moment of inertia of the star as the internal structure stabilizes will influence the rotational evolution.

As in previous work, the code was calibrated (helium abundance and mixing length adjusted) such that a 1 \(M_\odot\) model would reproduce the solar radius and luminosity at the solar age. We have chosen this age to be 4.54 Gyr, adding 40 Myr to the canonical value to account for pre-main-sequence evolution. A choice of \(Z = 0.01895\) then leads to an \(H\) mass fraction of 0.708 and a mixing-length parameter of 1.758. These are identical to the parameters used in Paper I.

We have evolved all the stellar models using the Yale Rotating Stellar Evolution Code (YREC). This code models the rotating stars using a series of nested, deformed shells. It accounts for transport and redistribution of chemical species and of angular momentum within a star as a result of various rotationally induced instabilities (cf. Pinsonneault et al. 1989, 1990). Convection zones are assumed to be fully mixed and to rotate as solid bodies, so that instabilities are effective only in radiative regions of the star.
Angular momentum loss via a magnetic stellar wind is modeled by draining it from the outer convection zone via the parameterization

\[
\frac{dJ}{dt} = \begin{cases} 
-K\Omega^1 + 4N/3\left(\frac{R}{R_\odot}\right)^2 N - \frac{M}{10^{-14}}\left(\frac{M}{M_\odot}\right)^{1 - 2N/3} \left(\frac{M}{M_\odot}\right)^{-N/3}, & \text{when } \Omega < \Omega_c, \\
-K(\Omega_c^4 N/3)\left(\frac{R}{R_\odot}\right)^2 N - \frac{M}{10^{-14}}\left(\frac{M}{M_\odot}\right)^{1 - 2N/3} \left(\frac{M}{M_\odot}\right)^{-N/3}, & \text{when } \Omega \geq \Omega_c, 
\end{cases}
\]

\hspace{1cm} (1)

where \( \Omega, R, \) and \( M \) represent the surface rotation rate, radius, and the mass of the star, respectively, and the wind index, \( N_c \) is set to 1.5. This includes magnetic saturation beyond a threshold rotation rate \( \Omega_c \) (constant for a star of particular mass). The rationale for this expression is explained extensively in Paper I, but, essentially, it is necessary to explain the presence of the ultrafast rotators in young star clusters. The actual values of the thresholds used are given later in this section.

In addition, the present version allows us to lock the rotation rate of a young star on the Hayashi track for a specified time. This is done to mimic the effect of disk locking on the pre-main sequence. Solid-body rotation is enforced during the time that disk locking is in effect. This is not an unreasonable condition because YREC enforces solid-body rotation in the surface convection zone and because stars are almost entirely convective on the Hayashi track anyway. Although this prescription does not model the interaction between the star and the disk, its simplicity is attractive. We do not (yet) wish to complicate the interpretation of the rotation period data with arguments about the exact shape and magnitude of the required magnetic fields or the nature of the star-disk interaction. These issues have been addressed, for instance, by K"{o}nigl (1991) and Cameron et al. (1995). We merely wish to lock the rotation of the star for a while and examine whether the same models that generated the fast rotators can also make the slow rotators with this one additional modification. This is one of the first steps, and doubtless improvements can and will be made.

Apart from the enforcement of disk locking, the version of the code used in this paper is identical to the one used in Paper I. In addition to the solar radius and luminosity calibration at 4.54 Gyr as mentioned above, the constant \( K \) in equation (1) above was chosen such that the 1 \( M_\odot \) model with 10 day starting period and no disk locking reproduces the solar rotation rate at the same age. The saturation thresholds, \( \Omega_c \), have been set to 2, 5, 8, and 12 for the 0.6, 0.8, 1.0, and 1.2 \( M_\odot \) models, respectively. These are the same values as were used in Paper I except that here we have also included a 1.2 \( M_\odot \) model.

For the solid-body models, it is necessary to modify the saturation thresholds. The thresholds are kept identical to the differentially rotating ones, these models become unreasonably fast on the pre-main sequence and the inferred disk lifetimes would be even longer than the ones we quote here. We have chosen instead to adjust the saturation thresholds for these models so that the fastest ones account for the ultrafast rotators, in symmetry with the differentially rotating models. This threshold is then used for all the solid-body models (of the same mass). The saturation thresholds used for the solid-body models in this work are 5, 12.5, 20, and 30 \( M_\odot \), respectively, for the 0.6, 0.8, 1.0, and 1.2 \( M_\odot \) models. We remind readers that the difference between the differentially rotating and solid-body models is that the former include redistribution of internal angular momentum via hydrodynamical instabilities in radiative zones. Dynamical instabilities are treated by instantaneous readjustment, while secular instabilities are treated through diffusion equations.

Further details about the code may be obtained in Pinsonneault et al. (1989), Pinsonneault, Kawa
er, & Demarque (1990), Chaboyer (1993), Chaboyer et al. (1995), Krishnamurthi et al. (1997), and M. H. Pinsonneault & S. Sofia (2001, in preparation). In summary, these models (1) begin at the birth line and include pre-main-sequence evolution, (2) use a parameterization of angular momentum loss that includes saturation, and (3) hold the rotation rate of the star constant for a specified period on the pre-main sequence, mimicking the effect of disk locking.

6. RESULTS

As stated earlier, we have generated a grid of stellar models of masses 0.6, 0.8, 1.0, and 1.2 \( M_\odot \). The first set has been evolved without any disk locking, and the others have been locked for 0.3, 1, 3, and 10 Myr in turn. All the models begin their (pre-main-sequence) evolution at the stellar birth line of Palla & Stahler (1991) with initial rotation periods of 4, 8.5, and 16 days. The models have then all been evolved to solar age (4.54 Gyr) under the various conditions detailed hereinafter. All of these models incorporate a saturation of angular momentum loss with the thresholds as indicated in the previous section. We have also evolved an equivalent set of solid-body models of which only an illustrative selection are displayed here. However, all models are available in electronic form from the first author.

6.1. Disk-free Models

The rotational evolution of (differentially rotating) models without disk locking is displayed in Figure 1. Except for the 1.2 \( M_\odot \) models, which were not displayed there, these are the same models that we presented in Barnes & Sofia (1996). The lower and upper boxes at 30–120 Myr represent observations of UFRs and slow rotators, respectively, in young open clusters (IC 2391, IC 2602, Alpha Per, and the Pleiades). Given the current state of the observations, no attempt has been made to display the mass dependence, if any, of rotation in these observations. We also show, using gray bars at 1 Myr, the recent rotation period measurements in Orion in this mass range from Stassun et al. (1999), capped by the longer periods from Herbst et al. (2000).

The figure shows that the range of periods we have used at the stellar birth line is generally adequate to understand the origin of the UFRs in young open clusters in the context of models incorporating magnetic saturation (as shown in Barnes & Sofia 1996). Furthermore, these are also consistent with the fast rotators among the T Tauri stars in this mass range. The way in which the faster rotators at earlier ages evolve into the UFRs among young open clusters (and, as shown later, the faster rotators among older clusters) is highly satisfactory, especially because the relevant period data are probably not biased against fast rotators.

The principal point we wish to make with this figure is that the stars rotating slowest at the birth line, with a start-
The lower and upper boxes represent the UFRs and the slow rotators, respectively, in Alpha Per and the Pleiades. The letters “sp” indicate the starting period of the models. The gray bar at 1 Myr represents the rotation period measurements available in this mass range from work by Stassun et al. (1999) capped by longer periods from Herbst et al. (2000). Note that their fastest rotators are matched well by these disk-free models.

This effect is primarily a consequence of the structural evolution of single stars on the pre-main sequence.

The upshot of this is that the models are incapable of reproducing simultaneously the UFRs and the slow rotators. However, the T Tauri observations, as indicated earlier, suggest that many of the Orion stars display circumstellar disk signatures and evidence that disk interaction acts to brake the central star. Thus, the following section considers the rotational consequences on these stars of varying amounts of disk locking.

There is another significant way in which these models are inadequate. The rotational dispersion of the models beyond 1 Gyr is nonexistent. Observations of nearby solar-type stars contradict this, as stars of similar mass are found to have a range of rotation rates (e.g., Baliunas, Sokoloff, & Soon 1996). This has its origin in the Ω dependence of the angular momentum loss rate and suggests that the dispersion observed may not entirely come from phenomena intrinsic to the star.

6.2. Disk-locked Models

Figure 2 displays the rotational evolution of models that are disk locked for 0.3 (dashed lines) and 1 Myr (solid lines). By “disk locked,” we mean that the rotation periods of the models are held constant for the indicated times. The disk itself is not explicitly modeled in any way. Beyond the indicated time, the models are allowed to evolve freely as detailed in § 5. As expected, these models all rotate more slowly than the models without disks because, unlike the previous models, these have not been allowed to spin up during contraction on the pre-main sequence.

The T Tauri data of Stassun et al. (1999) can be accounted for using only 0.3 Myr of disk locking, while the longer periods of Herbst et al. (2000) suggest that at least some of the slow rotators require the enforcement of 1 Myr of disk locking, i.e., locking from the birth line to Orion age. As regards the slow rotators in young clusters, many of them (but perhaps not the slowest ones) can be accounted for using 1 Myr of disk locking. This suggests even longer disk-locking times for some of these stars. In passing, we note that the models are able to retain some rotational dispersion beyond 1 Gyr.

Continuing in the same vein, Figure 3 displays the results of evolving models with disk locking enforced for longer periods: 3 (dashed lines) and 10 Myr (solid lines). As is obvious from the figure, these models have no trouble accounting for all the slow rotators. In fact, if one takes into account the mass dependence of rotation (not displayed in these figures), 3 Myr of locking may be sufficient.

Finally, Figure 4 displays the entire range of rotation periods that can presently be produced by these (differentially rotating) models. The lower and upper solid curves represent, respectively, the rotational evolution of disk-free stars with 4 day initial periods and of stars disk locked for 10 Myr with 16 day initial periods. The dashed curve is for models with 3 Myr of disk locking. They account reasonably well for both the UFRs and the slow rotators in young star clusters, with equivalent models for the intermediate cases.

In this figure we have also displayed the available rotation periods in the 250 Myr old NGC 3532 (Barnes 1998) and the 600 Myr old Hyades clusters (Radick et al. 1987). These show the limitations of these models in accounting

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7 To generate the slowest T Tauri this way would require ~80 day periods on the birth line!
for the fast rotators in older clusters, especially for the more massive stars. Biases against slow rotators in the observations do not presently allow us to use them effectively to constrain disk lifetimes, but it seems unlikely that disk lifetimes greater than 3 Myr would be necessary in any event.

These models also show that disk interaction is an effective means of retaining rotational dispersion among stars of similar mass beyond say, 1 Gyr, as observed among old solar-type stars. Although we do not wish to test this aspect of the models yet, given the limitations of both the models and the observations, it is quite possible that the dispersion observed among old stars owes its origin to disk interaction in the first few Myr of its existence. In summary, these models, although not completely consistent with all the observations, reproduce the major features reasonably, and the periods of young cluster stars in some detail.

6.3. Solid-Body Models

We have also evolved an equivalent grid of solid-body models. Some of these are displayed in Figure 5 for illustra-

![Figure 2](image2.png)

**Fig. 2.**—Rotational evolution of stellar models with disk locking enforced for 0.3 (dashed lines) and 1 Myr (solid lines). The observations plotted are the same as in Fig. 1. Note that modest disk locking can account for many but perhaps not all of the slow rotators in young star clusters.

![Figure 3](image3.png)

**Fig. 3.**—Rotational evolution of stellar models with disk locking enforced for 3 (dashed lines) and 10 Myr (solid lines). The observations plotted are the same as in Figs. 1 and 2. Note that these models can account for all the slow rotators observed in young star clusters.
F. G. 4. Range in stellar rotation period produced by differentially rotating models without disks and those disks locked for 3 and 10 Myr. Note that these models can explain essentially the entire range of rotation period observations among solar-type stars in young star clusters. In addition to the T Tauri and young open cluster data, we have added observations in NGC 3532 (Barnes 1998) and the Hyades (Radick et al. 1987).

As mentioned earlier, we have adjusted the saturation thresholds for the individual masses to ensure that, as in the case of the differentially rotating models, the ones with initial periods of 4 days reproduce the ultrafast rotator observations. Thus, by design, the faster rotating models are almost equivalent to the corresponding differentially rotating models.

The difference between the two sets of models (Figs. 4 and 5) is striking for the disk-locked models. Whereas \( \sim 3-10 \) Myr of disk locking sufficed to explain all of the slow rotators in the young clusters in the differentially rotating case, in the solid-body case disk lifetimes of \( \sim 10-20 \) Myr are necessary, suggesting disk lifetimes 2-3 times longer than those for the corresponding differentially rotating models.

In Figure 5, we have plotted the rotational evolution of disk-free solid-body models with 4 day initial periods (lower solid line) and of two SB models with initial periods of 16 days disk locked for 10 and 20 Myr (dashed and solid lines, respectively). This is the solid-body equivalent of Figure 4. Apart from requiring longer disk lifetimes, these models are generally equivalent to the DR ones, and neither are very...

* All models are available in electronic form from the first author.
satisfactory in reproducing the observations in older clusters.

There is another difference between the solid-body and the differentially rotating models. We draw attention to this difference in Figure 6, which displays the behavior of the two kinds of models past 100 Myr. The solid curves represent the later evolution of solid-body models with 16 day initial periods that have been disk locked for 20 Myr. If one agrees that this is a reasonable upper limit for disk locking, then the region above the solid line is inaccessible to such models and the discovery of slow rotators in this region among older star clusters will be a problem for them. The differentially rotating models, on the other hand, do populate this zone, as the dashed lines (representing differentially rotating models with an initial period of 16 days and disk locking enforced for 3 and 10 Myr) show. We have also plotted the measured rotation periods in the Hyades (from Radick et al. 1987 and Prosser et al. 1995) and NGC 3532 (from Barnes 1998). The Hyades observations are consistent with both sets of models, but the observations of NGC 3532 seem to be a bit troublesome for the solid-body models to accommodate. They also raise some questions about the lack of slow rotators in the Hyades, an observational issue beyond the scope of this paper.

A note about the internal rotation rate of the Sun is perhaps in order. The inconsistency of the Yale rotational models with the internal rotational profile of the Sun remains. The solar models rotate 5–20 times faster near the center at solar age than they do on the surface. This is at odds with the rotation profile of the Sun as determined by helioseismology (e.g., Antia, Basu, & Chitre 1998). To a certain extent, this is a problem. However, we are dealing here with very young stars, and it is likely that additional physics will have to be invoked to flatten the profile (see MacGregor 2000 for a recent review of possible solutions to this problem). It is also true that just because the Sun is presently spinning close to solid body does not necessarily imply that it was always spinning as a solid body. In fact, it seems that stars must rotate differentially early on in their evolution to match the early rotational data and to be consistent with the disk lifetime calculations. The twin constraints of early differential rotation and later solid-body–type rotation suggest the existence of an angular momentum transport mechanism that operates on timescales of hundreds of Myr (also see SPT00). This mechanism would bring the models into better agreement with the Hyades data and also might explain the flat solar rotation profile. Additional observations in older clusters would help clarify the situation considerably.

7. CONCLUSION AND DISCUSSION

We have demonstrated the relative impossibility of generating the slow rotators in young open clusters through a mechanism intrinsic to the star within the framework that explains the origin of the ultrafast rotators. The slow rotators cannot be generated from the slow-spinning T Tauri stars unless one takes recourse to some extrinsic mechanism. Assuming that star-disk interaction is responsible for the slow rotators, we find that disk lifetimes ~3 Myr (for differentially rotating models) are required.

Thus, we need to do two separate things to explain the large observed dispersion in rotation rates of stars in young open clusters: both decrease the angular momentum loss rate for fast rotators to make them even faster and couple the central star quite strongly for a few Myr to circumstellar material in order to produce the slow rotators. This effectively splits young solar-type stars into two groups, depriving us of a single, simple, uniformly applicable way of treating young solar-type stars. If we allow this, then why not also allow young stars to have different magnetic field

![Fig. 6.—Comparison of the behavior of slow rotators in the solid-body and differentially rotating cases. The solid lines represent solid-body models with initial periods of 16 days and 20 Myr of disk locking. The dashed lines represent differentially rotating models with the same initial period but 3 and 10 Myr of disk locking. Note that the rotation period is plotted here on a linear scale. The shaded boxes in each panel represent the available observations in young clusters, NGC 3532 and the Hyades (Radick et al. 1987). If stars always rotate as solid bodies, we should not expect to find any objects above the solid lines in the figures.](image)
configurations? Although this is possible in principle, there is no corroborating data in support of this idea. Thus, generating the rotational dispersion using disks is presently preferable to resorting to differing magnetic field configurations.

We find that for the differentially rotating models disk locking for ~3 Myr can account for almost all the presently available observations, with perhaps only a star or two requiring a longer locking period, but less than 10 Myr. Solid-body models require longer disk-locking times, 10–20 Myr. These latter timescales seem to be rather long. Even a 3 Myr timescale is somewhat long, given that the T Tauri data suggest 1 Myr disk lifetimes. However, it is notoriously difficult to place T Tauri stars in an H-R diagram in order to date them, and the difference between 1 and 3 Myr might not be significant.

Although solid-body models seem to require unreasonably long disk lifetimes, it might not be appropriate to reject them entirely because helioseismic inferences suggest a solar interior rotation rate closer to solid body than to the fast interiors of the differentially rotating models (see previous section). A way to reconcile these problems might be just to postulate a radial angular momentum transfer rate of, say, a few hundred Myr between the SB and DR cases. Indeed, detailed observations in a sequence of open clusters might help to find this timescale empirically.

Lastly, we note that, although the young open cluster rotation rates look as if they could be generated from the T Tauri rates, there might be difficulties in explaining the rates in older clusters such as the Hyades and even in the younger cluster NGC 3532. In particular, our models are probably not treating the mass dependence of the rotation rate correctly since, for example, the 1.2 M☉ models are rotating more slowly than the observations in the Hyades. The observations themselves are not consistent. There are slower rotators in the younger NGC 3532 cluster than there are in the Hyades, raising the issue of whether the Hyades data are biased and how much so. Perhaps a more complete period census of the Hyades is needed and maybe one of Praesepe as well. These issues, both observational and theoretical, will, we hope, be addressed and understood in the near future.

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