Conference Highlights

Angular Momentum Evolution of Young Stars: Toward a Synthesis of Observations, Theory, and Modeling

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The aim of this AAS Topical Session was to update the community on the current state of knowledge about the angular momentum evolution of young stars. For newcomers to the subject, the session was intended to provide an introduction and general overview and to highlight emerging issues. For experienced workers in this field, the session provided an opportunity for synthesizing recent developments in observations, theory, and modeling of rotation of young stars and for identifying promising new research directions.

1. Overview of Angular Momentum Evolution of Young Stars

During the last decade, we have witnessed a tremendous growth in the amount and quality of data on stellar rotation, which now includes samples in ages from T Tauri stars to clusters as old as the Hyades. Along with this has been an increase in the sophistication of theoretical models of the spin-down of stars before and on the main sequence. Many of us in the field now believe we have a good handle on the three principal ingredients of these models:

1. the distribution of initial rotation rates in the pre-main sequence, coupled with the (possible) influence of accretion disks;
2. angular momentum loss from a magnetized solar-like wind, which operates on timescales of tens to hundreds of Myr;
3. prescriptions for the angular momentum distribution in convective regions of the star and angular momentum transport in radiative regions.

The initial conditions for rotation are set during the star formation process. T Tauri stars are logical starting points, as they represent the earliest easily observable phases of evolution at which stars have reached their final mass. These stars are at the beginning of the hydrostatic phase of evolution prior to the ignition of nuclear reactions and typically have modest accretion disks; order 0.01 \( M_\odot \). There are extensive data on rotation rates of T Tauri stars, beginning with the work of S. N. Vogel & L. V. Kuh (1981, ApJ, 245, 960), which shows that there is already a significant range of rotation rates among protostars with ages of 1 Myr or less. Recent surveys in the Orion Nebula Cluster (ONC), which has an age of 1–3 Myr, have provided hundreds of rotation periods as will be reviewed below.

The observation that the youngest stars rotate at a small fraction (10%–20%) of the breakup velocity indicates that they must have had an efficient method for shedding angular momentum. The most common approach to modeling this is to invoke “disk locking,” as introduced by A. Königl (1991, ApJ, 370, L37). In the presence of an accretion disk, a star could maintain a nearly constant surface rotation rate as it contracts (F. Shu et al. 1994, ApJ, 429, 781); this corotation between the star and the accretion disk would govern the stellar rotation rate. Theoretical models of angular momentum evolution have therefore included the accretion disk lifetime as a parameter describing the initial conditions (A. Sills, M. H. Pinsonneault, & D. M. Terndrup 2000, ApJ, 534, 335 and references therein).

Later on, when stars have arrived on the main sequence, the stars experience continuing angular momentum loss, envisioned as resulting from a magnetized stellar wind (E. D. Weber & L. Davis, 1967, ApJ, 148, 217). In all young clusters, most stars are rotating slowly, with \( v \sin i < 20 \) km s\(^{-1}\), but a minority are rotating much faster. The loss mechanism efficiently removes stellar angular momentum; in clusters such as \( \alpha \) Persei (age 50–80 Myr), the fastest rotators have equatorial velocities near 200 km s\(^{-1}\), but these have fallen to below 10 km s\(^{-1}\) by the age of the Hyades (R. R. Radick et al. 1987, ApJ, 321, 459). The existence of rapid rotation at ages of \( \sim 100 \) Myr suggests that the loss rate is saturated or suppressed at high rotation rates. Observations of stellar activity (e.g., A. Krishnamurthi et al. 1998, ApJ, 493, 914) and a variety of theoretical arguments lead to the idea of a saturation threshold (S. D. Kawaler 1988, ApJ, 333, 236). In this picture, the loss rate scales as \( \omega^3 \) for slow rotators (A. Skumanich 1972, ApJ, 171, 565), where \( \omega \) is the angular velocity, but scales as \( \omega_{\text{crit}} \), \( \omega \) for \( \omega > \omega_{\text{crit}} \). The saturation threshold depends on stellar mass, in the sense that it has a lower value for stars of lower mass (A. Krishnamurthi et al. 1997, ApJ, 480, 303).

The internal distribution of angular momentum within a star must also be understood in a complete theory of angular momentum evolution. Low-mass stars are initially fully convective. Their surface rotation rates can be used to infer an initial angular momentum if the angular momentum distribution in convective regions is specified, since the convective overturn timescale is much shorter than the evolutionary timescale. Once on the main sequence, however, stars with masses above 0.35 \( M_\odot \) develop radiative cores. Stars with higher masses have much thinner
convective zones: at 1 $M_\odot$, for example, only 10% of the moment of inertia is in the convective envelope. When a radiative core develops, the internal transport of angular momentum in the radiative regions must be accounted for, since the timescales for evolution and for angular momentum transport are comparable. All this means that the models have to begin with assumptions about the (radial) angular momentum profile; obvious limiting cases are to assume initial solid-body rotation or constant specific angular momentum. The models also need to have an adjustable efficiency of internal angular momentum transport.

2. ROTATION OF SOLAR-MASS STARS AT DIFFERENT STAGES OF EVOLUTION: OBSERVATIONS

2.1. Rotation of Protostars—Thomas Greene (NASA Ames) and Charles Lada (CfA)

It is important to determine the angular momenta of embedded protostars to understand better the star formation accretion process and to establish the angular momentum “zero point” from which stars evolve. Unfortunately, the angular momenta of protostars are largely unknown. Very high extinctions ($A_V \geq 40$ mag) make them impossible to observe in visible light with high-resolution spectrographs. Further, these objects are not very bright in the near-IR ($K \sim 10$), and they have very large continuum veiling ($r \sim 3$) at these wavelengths, greatly diluting the strength of their photospheric absorption lines and star spots.

Despite these difficulties, we have recently obtained high-resolution absorption spectra of some protostars using sensitive IR spectrographs on large telescopes. These data show that protostars with flat-spectrum and Class I spectral energy distributions (SEDs) have spectral types, surface gravities, and radii similar to more evolved T Tauri stars (TTSs). However, the embedded protostars observed to date have considerably different $v \sin i$ and angular momenta. These objects appear to be rotating significantly faster than most TTSs; typical protostars have $v \sin i \sim 40$ km s$^{-1}$ (T. P. Greene & C. J. Lada 1997, AJ, 114, 2157; 2002, AJ, 124, 2185). Recent ASCA and Chandra X-ray observations also suggest that these protostars have short rotation periods.

Our Keck NIRSPEC observations of YLW 15 have provided the first measurement of the angular momentum and detailed astrophysics of a Class I protostar (T. P. Greene & C. J. Lada 2002, AJ, 124, 2185). With a projected rotation velocity $v \sin i = 50$ km s$^{-1}$, its corotation radius is about $2R_*$, which is about equal to the magnetic coupling radius predicted by the F. Shu et al. (1994, ApJ, 429, 781) X-wind/magnetospheric accretion model for the observed mass accretion rate of $\dot{M} = 1.6 \times 10^{-6} M_\odot$ yr$^{-1}$. Like other Class I protostars, YLW 15 will evolve into a TTS in $\sim 10^6$ yr. Since TTSs in the same $\rho$ Oph cloud (Fig. 1) rotate only about one-third as fast (e.g., T. P. Greene & C. J. Lada 1997, AJ, 114, 2157), YLW 15 (and other similar protostars) must shed approximately two-thirds of its angular momentum in about this amount of time. Within the framework of magnetic star-disk interactions, this is possible provided that its mass accretion rate drops quickly to $10^{-7} M_\odot$ yr$^{-1}$.

These observations are in their infancy, but they may prove essential for understanding initial stellar angular momentum and star-disk interactions during the protostellar evolutionary phase. Soon we expect to extract statistically significant results on these issues from our recently completed Keck NIRSPEC observations of a few dozen embedded protostars in nearby star-forming clouds.

2.2. Rotation of Pre–Main-Sequence Stars—William Herbst (Wesleyan University)

Low-mass stars often have large, stable, nonaxisymmetric, cool spots on their surfaces, which makes it possible to measure their rotation periods by photometric monitoring. There is nothing we can determine with as much accuracy for PMS stars as their rotation rates.

Angular velocities accurate to about 1% are currently available for $\sim 1500$ PMS stars (see Fig. 2). Approximately 40% of the stars with $12.5 < I < 15.5$ in the ONC, the best-studied example, now have rotation periods measured for them.

There is no reason to believe that this sample is significantly biased with respect to rotation properties (K. L. Rhode, W. Herbst, & R. D. Mathieu 2001, AJ, 122, 3258; W. Herbst et al. 2002, A&A, 396, 513) or other characteristics, so it provides an excellent means of studying rotation among very young stars. We focus our discussion on angular velocity instead of angular momentum, because the latter requires knowledge of the radii of stars, which are particularly uncertain at PMS ages.

The first surprising fact about PMS rotation rates is the breadth of the distribution—it extends over at least a factor of
30 from $\sim 1$ day to $\sim 20$ days. The second surprising fact is that it is strongly mass dependent. Stars in the range of $\sim 1$ to $1 M_\odot$ have a bimodal distribution (Fig. 3) with peaks near 2 and 8 days, as first shown by J. M. Attridge & W. Herbst (1992, ApJ, 398, L61) and P. I. Choi & W. Herbst (1996, AJ, 111, 283), while lower mass stars have a unimodal distribution and generally spin faster (W. Herbst, C. A. L. Bailer-Jones, & R. Mundt 2001, ApJ, 554, L197). This behavior is not limited to the ONC, but is seen also in NGC 2264 (M. Lamm et al. 2003, in preparation). As NGC 2264 is a somewhat older cluster, the peaks in the higher mass distribution are at 1 and 4 days instead of 2 and 8 days as in the ONC. This is evidence for spin-up of a significant percentage of the PMS stars in NGC 2264. Assuming that it is three times the age of the ONC (i.e., 3 Myr as opposed to 1 Myr), the amount of spin-up (i.e., a factor of 2) is consistent with expectation based on PMS contraction models and conservation of angular momentum.

It is interesting to speculate about how these (mass-dependent) distributions could have arisen during the early PMS or protostar stages. The leading hypothesis is disk locking. One possibly relevant piece of information is that in the ONC, we find a distinct correlation between rotation rate and strength of near-IR excess (indicative of the presence of an inner circumstellar disk). In particular, the $I-K$ excess emission is $0.55 \pm 0.05$ for slowly rotating stars (i.e., those with angular velocities less than 1, corresponding to rotation periods longer than 6.3 days), while it is $0.17 \pm 0.05$ for rapid rotators (with $\omega > 2$ corresponding to $P < 3.1$ days). The first-order interpretation of this is that disks tend to brake stars, as the disk-locking theory predicts. Under some scenarios, however, one expects a correlation in the opposite sense, as K. G. Stassun et al. (2001, AJ, 121, 1003) have discussed. A deeper understanding of the meaning of the near-IR correlation and its relation to disk-locking theory will require further study, particularly aimed at establishing the presence and nature of disks around PMS stars with known rotation rates.

2.3. Rotation of Solar-Type Stars at Zero Age and Beyond—Sydney A. Barnes (University of Wisconsin, Madison)

The most basic and most solidly known result in stellar rotation is that of the solar rotation rate, on the surface, and more recently, in the interior. We know that upper main-sequence (F and earlier) stars spin fast and that lower main-sequence (G, K, and M) stars spin slowly. This is related, respectively, to the absence and presence of surface convection zones and winds on these stars (E. Schatzman. 1962, Ann. d’Astrophys., 25, 18).

For lower main-sequence stars, the spin-down is described by the A. Skumanich (1972, ApJ, 171, 565) relationship: $v \propto t^{-1/2}$, where $v$ and $t$ are the stellar rotation velocity and the age of the star, respectively. This suggests that on the main sequence, the rate of angular momentum ($J$) loss is related to the angular velocity ($\omega$) by $dJ/dt \propto \omega^3$. Apparently, this relationship breaks down among very fast rotators, a phenomenon referred to as magnetic “saturation.”

But there are complications when one deals with young stars.
It appears that in addition to contracting on the PMS, a star can also interact with its circumstellar disk, and this can have profound effects on the rotational evolution. Once on the main sequence, winds dominate the rotational evolution, except that internal transport of angular momentum can also play an important role.

Thus, the present framework for interpreting the observations involves PMS evolution, magnetic saturation, disk interaction, winds, and internal transport. The complexity of these phenomena requires observational guidance to decode. On the PMS, a wealth of data has been provided by Herbst and collaborators, K. G. Stassun et al. (1999, AJ, 117, 2941), and L. M. Rebull (2001, AJ, 121 1676). On the main sequence, two $v \sin i$ data sets have emerged recently, for the open clusters M34 (D. R. Soderblom, B. F. Jones, & D. Fischer 2001, ApJ, 563, 334) and NGC 2516 (D. M. Terndrup et al. 2002, ApJ, 576, 950). With ages of approximately 250 and 150 Myr, respectively, these observations are helping to fill in the gap in the observations between the young clusters (≤100 Myr) and the Hyades (600 Myr).

Today, significant numbers of rotation periods among main-sequence stars are available in IC 2391 (B. M. Patten & T. Simon 1996, ApJS, 106, 489), IC 2602 (S. A. Barnes et al. 1999, ApJ, 516, 263), IC 4665 (S. Allain et al. 1996, A&A, 305, 498), α Per (C. F. Prosser & K. Grankin 1997, CfA preprint 4539; C. F. Prosser et al. 1993, PASP, 105, 1407), the Pleiades (F. van Leeuwen, P. Alphenaar, & J. J. M. Meys 1987, A&AS, 67, 483; A. Krishnamurthi et al. 1998, ApJ, 493, 914), and Hyades/Coma (R. R. Radick et al. 1987, ApJ, 321, 459; R. R. Radick, B. A. Skiff, & G. W. Lockwood, 1990, ApJ, 353, 524), spanning an age range from 30 to 600 Myr. In the immediate future, we can expect the release of data sets in NGC 1039 (M34), NGC 2516, and NGC 3532 (Barnes and collaborators), two of which were displayed in preliminary form at the 2002 June AAS meeting. The author is aware of ongoing studies in M34 and M35 (S. Meibom 2002, private communication). These and other observations will ensure that it is possible to build a time sequence for a range of stellar masses, thus completely removing the ambiguities inherent in $v \sin i$ data.

It is already possible to identify trends in the complete data set. These were pointed out during the meeting and will be published in the immediate future. The color-magnitude diagrams of the newly studied clusters, often generated in conjunction with membership studies of one sort or another, appear to be very promising and enable the identification even of very low mass cluster members. Trends in the amplitudes of rotational variability are slowly emerging, and we are beginning to decode its dependence on stellar mass, age, and rotation rate.

Lest implications on the PMS and during the early main-sequence evolution distract us, it is worth noting that the A. Skumanich (1972, ApJ, 171, 565) relationship is still an excellent description of main-sequence stellar spin-down, once the stars have been binned by stellar mass. This is explained at length in S. A. Barnes (2001, ApJ, 561, 1095), which considered whether and how the rotation rates of the extremely well studied sample of Mount Wilson stars can be connected to those in open clusters and whether the rotation rates of the host stars of extrasolar planets could be distinguished from the others. The result is that, with a few minor exceptions that can be explained, a Skumanich-type spin-down is a perfectly adequate description of the behavior of both the Mount Wilson stars and the planet-host stars. The planet-host stars are not particularly slow rotators, in contrast to expectations from disk-locking scenarios of stellar rotation.

3. ROTATIONAL EVOLUTION OF SOLAR-MASS STARS: THEORY

3.1. Internal Angular Momentum Transport Processes—Marc Pinsonneault (Ohio State University)

Hydrodynamic mechanisms (meridional circulation, shear, and Goldreich-Schubert-Fricke instabilities) can cause mixing, and they are effective in rapidly rotating stars. However, these mechanisms occur over a long timescale in slowly rotating stars. Turbulence in convective regions can excite waves where the restoring force is variations in the potential ($g$-modes); such waves can effectively transport angular momentum throughout the radiative cores of stars. Significant mixing would occur only near the edges of convection zones. However, the impact of this mechanism upon stellar models has been controversial, and the overall impact on the behavior of stars is not clear. Finally, if there exists a magnetic field in the radiative core of a star, it will tend to enforce corotation along field lines without inducing significant mixing. The impact upon stellar properties, however, depends significantly upon the overall morphology of the field.

We have two important constraints on the timescale for angular momentum transport in stars. Helioseismic data provide a measurement of the internal solar rotation as a function of radius and latitude. There is a shear layer located beneath the convection zone with a characteristic width of less than 0.05 solar radii, and the radiative core below the shear layer appears to rotate as a solid body. This indicates that angular momentum transport in the solar interior was highly effective, but it does not directly provide an indication of the relevant timescale. The second constraint is the spin-down of slowly rotating stars. Because only a fraction of the total moment of inertia is contained in the outer convection zone, there will be a difference in the time evolution of the surface rotation rates between models where the timescale for internal angular momentum transport is short (e.g., the whole star must be spun down by the wind) and models where the timescale for internal angular momentum transport is long (e.g., initially only the convection zone is spun down, and the core is coupled at a later epoch).
Models that include only angular momentum transport from hydrodynamic mechanisms predict that as stars lose angular momentum from a magnetized wind, there will be an initial phase where the envelope spins down with respect to the core. At later ages, the models will reach a rough equilibrium where the core is rotating significantly faster than the surface. The observed spin-down of the slow-rotator population in young open clusters is consistent with the early core-envelope decoupling predicted by such models, but the flat solar rotation profile is inconsistent with the strong internal angular velocity gradients predicted by such models. This combination of evidence suggests that there is an additional angular momentum transport mechanism that operates over timescales longer than 100 Myr but shorter than the lifetime of the Sun. Possible methods for distinguishing between waves and magnetic fields were also briefly discussed.

3.2. Magnetic Star-Disk Coupling Mechanisms—Frank Shu (Tsing Hua University)3

The idea of magnetic “disk locking” in some sense originates with the theory developed by P. Ghosh & F. K. Lamb (1979, ApJ, 234, 296) in the context of neutron stars. In their model, a stellar dipole field $B$ everywhere threads a circumstellar disk, which is truncated at an inner radius $R_c$, where magnetic and ram pressures balance. In this picture, if $R_c$ is within the corotation radius $R_d$ (the radius in the disk that rotates with Keplerian angular velocity equal to the stellar angular velocity), then gas interior to $R_c$ spins the star while gas exterior to $R_c$ spins it down.

But the Ghosh & Lamb picture presents some problems in the context of young, low-mass stars. By construction, the magnetic field is strong enough marginally to compete with centrifugal forces in the funnel flow. Thus, since the disk must be much more dense than the funnel flow, the field threading the disk cannot resist wrapping except at the single radius $R_c$. Continuous wrapping of the field would lead to magnetic reconnection, but the observed X-ray activity of classical T Tauri stars (those with disks) is similar to that of weak-lined T Tauri stars.

Our own X-wind model avoids these difficulties by bringing the dipole field in the disk together at the X-point, $R_c \approx R_d$. All of the unperturbed dipole exterior to $R_c$ is brought in by disk accretion to $R_d$, and half of the interior field is brought to $R_c$. This pinch toward $R_c$ is caused by back-reaction to the funnel flow and X-wind. This pinch distorts the dipole configuration near $R_d \approx R_c$, so that differential rotation of the disk no longer wraps the field, even though the disk is much denser than the gas in the flow/X-wind, making a steady state configuration possible.

The “dipole” assumption has problems when confronted by observation, however. For example, the results of polarization studies are inconsistent with well-organized fields at the stellar surface, and the hot spots that have been observed on classical T Tauri stars have much smaller areas than implied by the dipole assumption. Furthermore, completely convective stars are not expected to have dipole field geometries near the surface.

Fortunately, X-wind theory is not dependent on the (unperturbed) magnetic field being dipolar. The critical invariant in the theory is the assumption of “trapped magnetic flux” at the X-point, $R_c$. Relaxing the dipole assumption, we find that disk locking in the X-wind model is only very slightly modified in the “multipole” case, but the model now allows for the smaller hot spots and polarization levels that are observed.

We make two critical assumptions:

1. disk locking: $\Omega_d = \Omega_c$, and
2. flux trapping: $\Phi_p = \alpha(GM_\star\dot{M}_D/\Omega_c)^{1/2}$,

where $\Phi_p$ is the magnetic flux at the truncation radius and $\alpha$ is an order unity coefficient that depends on details of X-wind theory.

In the X-wind model, the trapped flux is $\frac{1}{7}$ in the outflowing X-wind, $\frac{1}{3}$ in the “dead zone” (static coronal gas), and $\frac{1}{7}$ in the funnel flow. Since the $\frac{1}{7}$ of the trapped flux in the funnel flow is anchored in the stellar surface, we have the prediction that

$$B(f4\pi R_c^2) = \frac{1}{7}\Phi_p,$$

where $B$ is the field strength in the footprint on the stellar surface and $f$ is the surface covering fraction of that footprint. Assuming that $B$ does not vary much from star to star, this leads to the testable prediction that

$$fR_c^2 \propto (M_c\dot{M}_D\dot{P}_{rot})^{1/2},$$

where $\dot{P}_{rot} = 2\pi/\Omega_c$.

Recently, C. M. Johns-Krull & A. D. Gafford (2002, ApJ, 573, 685) compared observations of T Tauri stars in Taurus-Auriga to the disk-locking prediction of this generalized, multipole X-wind model. Their results, shown in Figure 4, seem to verify this prediction.

We close by commenting on the eventual breakdown of disk locking. At some point, as $\dot{M}_D$ decreases in time, disk locking must break down because the star has too much inertia for the then-meager funnel flow to force the star to rotate at $\Omega_d = \Omega_c$. However, unlike the situation where the stellar field is a fixed dipole, disk locking may have some flexibility built into it from the ability of corotating multipole fields to accommodate even fairly low disk accretion rates. Because of this complication, and because we do not know how stellar dynamos work in the presence of interactions with a surrounding accretion disk, we have no first-principles, quantitative theory of disk locking.

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3 Written by K. Stassun from notes provided by F. Shu.
4. PANEL DISCUSSION: OBSERVATIONS AND THEORY VIS-À-VIS MODELING

The session included a panel discussion that focused on a set of guiding questions posed by Keivan Stassun (University of Wisconsin), who moderated the discussion. The aim of the panel discussion was for the observers, theorists, and modelers to begin synthesizing work from one another’s domains, to confront areas of uncertainty, and to identify future research directions. The specific questions discussed by the panel were as follows:

Disks:

1. How can we understand the observed relationship between rotation and infrared excesses (among PMS stars in Orion) in the context of star-disk coupling?

Observations in Orion show a positive correlation between rotation period and magnitude of near-IR excess. This would seem to suggest that the inner edges of the circumstellar disks in these stars know something about the rotation rate of the star. This is puzzling because near-IR emission probes the dust in the disk, not the gas that is thought to magnetically couple to the star. And, if any correlation might be expected, it is in the opposite sense of what is seen. The panel was not able to put closure on this issue, and it remains unclear what this observational result might imply for the physics of magnetic star-disk interaction.

2. Does star-disk coupling always act to remove angular momentum from a star?

Models of PMS angular momentum evolution typically invoke disk locking as a way of extracting angular momentum from the star. However, strictly speaking, accretion torques can act positively on the star as well as negatively, depending on the balance between stellar magnetic field strength and the accretion rate in the disk. Panelist Frank Shu confirmed that in some cases stellar spin-up can result from star-disk interaction.

Winds:

1. What do we know (or wish we knew) about solar-analog winds from young stars and their role in early angular momentum evolution?

Panelist Marc Pinsonneault suggested that more quantitative observations of stellar magnetic field strengths and of mass outflow rates would be extremely helpful in more rigorously constraining models. Indeed, there is some uncertainty about the basic relationship between stellar rotation, dynamo-generated field strength, and mass outflow rates. In addition, observations that probe the internal rotation profiles of young stars are needed, specifically to test the prediction that young stars are strong differential rotators internally.

With respect to future research directions, the following were presented as key areas of observational focus:

1. obtain rotation measurements prior to 1 Myr;
2. obtain rotation measurements in the “age gaps” (primarily between 1 and 100 Myr); connect rotation period distributions at various ages;
3. better assess the biases in measured rotation rates at various ages;
4. ascertain the role of stellar multiplicity on the angular momentum evolution of single PMS stars.

5. NEW FRONTIERS AT OTHER MASSES: INTERMEDIATE-MASS STARS AND BROWN DWARFS

5.1. Intermediate-Mass Stars: From the Birth Line to the Main Sequence—Sidney C. Wolff (NOAO), S. Strom (NOAO), and L. Hillenbrand (Caltech)

We have measured projected rotational velocities ($v \sin i$) for a sample of 145 stars located in the Orion star-forming complex with masses ($M$) between 0.41 and 15 $M_\odot$. These measurements establish, as nearly as direct observations can, the initial values of specific angular momentum ($j = J/M$) for stars in this mass range. The goal of this work is to try to account for the initial values of $j$ in terms of theories of star formation and angular momentum regulation. We then map the initial values of $j$ onto the zero-age main sequence (ZAMS) and discuss the processes that affect the evolution of angular momentum from the birth line to the ZAMS.

Our data (see Fig. 5) show that there is a continuous power-law relationship between $j$ and $M$ for stars on convective tracks with masses in the range $\sim 0.5$ (and probably less) to 2–3 $M_\odot$, and that this power law merges smoothly with the relationship...
for more massive stars, which are already on the ZAMS. This power law can be compared with the predictions of models that posit that stars are “locked” to circumstellar accretion disks until they are released at the birth line. If we assume that the accretion rate is \(10^{-3} M_\odot \text{yr}^{-1}\) for 1 \(M_\odot\) stars and that mass accretion rates are proportional to stellar mass, we can account for the observed slope and zero point of the upper envelope of the observed power-law relationship between \(j\) and \(M\).

If we compare the initial values of \(j\) with those of stars on PMS radiative tracks or on the main sequence, we find the primary difference to be a break in the power law for stars with \(M < 2 M_\odot\) that have completed the convective phase of evolution. This sharp decrease in \(j\) has been known for a long time for field stars, but the decrease is seen already in the Orion stars, which are less than 1 Myr old and are still on PMS radiative tracks. We show that the break in the power law is a consequence of core-envelope decoupling at the time of the transition from the convective to radiative tracks. The difference in rotation rates seen for stars on either side of this transition is consistent with conservation of angular momentum in shells and inconsistent with solid-body rotation.

We also argue that the systematic variations seen in \(\langle v \sin i \rangle\) along the ZAMS for stars with masses greater than 2–3 \(M_\odot\), i.e., a maximum in \(\langle v \sin i \rangle\) in the late B-type stars, lower \(\langle v \sin i \rangle\) in the early B-type stars, and a large fraction of B2–B4 stars rotating at less than 100 km s\(^{-1}\), can be accounted for by variations in the predicted mass-radius relationship along the birth line, primarily associated with deuterium-shell burn-

\[ v \sin i \approx 60 \text{ km s}^{-1} \] (G. Basri et al. 2000, ApJ, 538, 363), do not have strong emission, in contrast to hotter rapidly rotating stars, which are typically the most active.

When they are young, however, brown dwarfs are apparently not as extreme in their rotation velocities. V. Joergens & E. Guenther (2001, A&A, 379, 9) have shown that substellar objects in Cha I rotate as rapidly as their T Tauri counterparts. G. Basri (2003, in IAU Symp. 211, Brown Dwarfs, ed. E. L. Martin [San Francisco: ASP], in press) has proposed that the absence of magnetic activity, and hence magnetic braking, allows brown dwarfs to retain their angular momentum as they contract. However, this appealing hypothesis is complicated by the detection of disks around young brown dwarf candidates (A. A. Muench et al. 2001, ApJ, 558, L51; L. Testi et al. 2002, ApJ, 571, L155) and the presence of magnetic flares even in the L dwarfs (P. B. Hall 2002, ApJ, 564, L89). Investigations of rotation velocities in young cluster brown dwarfs are currently underway to clarify this picture (G. Basri 2002, private communication). Theoretical studies of disk braking in these cool, low-mass systems are desperately needed.

Photometric variability studies have also begun to measure rotation periods in ultracool dwarfs, but results have been somewhat confusing. Work by C. A. L. Bailer-Jones & R. Mundt (1999, A&A, 348, 800; 2001, A&A, 367, 218), E. L. Martín, R. Z. Zapatero Osorio, & H. J. Lehto (2001, ApJ, 557, 822), F. J. Clarke, C. G. Tinney, & K. R. Covey (2002, MNRAS,
332, 361), and C. R. Gelino et al. 2002, ApJ, 577, 433) have found photometric variations in late-M and L dwarfs on order 0.01–0.1 mag with aperiodic or periodic (timescales of a few hours) modulations. However, periods have been difficult to characterize in general, as some objects show multiple and equally significant periods (E. L. Martín, M. R. Zapatero Osorio, & H. J. Lehto 2001, ApJ, 557, 822), while others exhibit evolution in the photometric periods (C. A. L. Bailer-Jones & R. Mundt 2001, A&A, 367, 218; C. R. Gelino et al. 2002, ApJ, 577, 433).

The difficulty in obtaining robust rotational periods for these objects is likely related to the presence of condensate clouds in their atmospheres (A. S. Ackerman & M. S. Marley 2001, ApJ, 556, 872), which may produce rotationally modulated features that evolve over a similar timescale (C. R. Gelino et al. 2002, ApJ, 577, 433). Indeed, the transition from L dwarfs to T dwarfs (A. J. Burgasser et al. 2002, ApJ, 564, 421; T. R. Geballe et al. 2002, ApJ, 564, 466) may be driven by the sudden disruption of cloud layers by convective cells (A. J. Burgasser et al. 2002, ApJ, 571, L151), obscuring any rotational modulation. Various studies of photometric variability are currently underway, however, because of the feasibility of such projects on small (1–4 m) telescopes, in contrast to the high sensitivity required to measure $v \sin i$ in these faint dwarfs.

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