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Rotation In Young Stars

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Abstract. The smallest molecular cores observed to date have at least ~6 orders of magnitude greater angular momentum per unit mass than the Sun, suggesting that they would greatly exceed the breakup velocity if no angular momentum was lost during the star formation process. Therefore, an angular momentum regulation mechanism must be at work in the pre-main-sequence phase, and disks are often invoked as the solution to the angular momentum problem. Thanks to large-format CCDs, more than 1000 periods for young stars are now known (with more being presented at this conference), and with the Spitzer Space Telescope, we have the ability to get reliable circumstellar disk indicators for many 1000s of stars at once. Now, for the first time, we may have enough stars to start to constrain the angular momentum loss mechanism in a meaningful fashion. In this contribution, we review the observations made to date of rotation in pre-main-sequence low-mass stars.

1. Introduction

In broad strokes, the evolution of rotation rates as found in young, low-mass pre-main-sequence (PMS) stars seems easy to understand. The clumps within a molecular cloud (or even the entire molecular cloud itself) are initially spinning as a result of turbulence and tidal encounters among clumps within a cloud. A spinning and collapsing clump produces a flattened envelope from which material flows towards the circumstellar disk, then onto the protostellar core. The mass of the central object builds up through accretion, and this material comes from regions that rotate. If there was no way to slow down the rotation rate of the star, it would rotate so rapidly that material would be flung off the equator. Without regulation of the rotation rate, there is no way for the star to actually complete the formation process. Stellar winds, jets, and disks all act in some fashion as regulators of the rotation rate of the young stellar object (YSO) and redistributors of the angular momentum within the system. Of course, planets form in circumstellar disks late in this process. We note that Jupiter has most of the angular momentum in our Solar System, so planet formation is surely important for the angular momentum budget of the system.

However, truly understanding the angular momentum evolution of a YSO and its immediate environs has proven complicated. For more than 10 years (including, e.g., Edwards et al. 1993), observers have attempted to test the hypothesis that disk-related processes account for angular momentum regulation among solar-like PMS stars. The test is seemingly simple: compare the observed rotation periods or projected equatorial rotational velocities of PMS stars surrounded by disks (and thus, by hypothesis, regulated) with those that lack disks and are presumed free to spin up in response to contraction toward the main sequence absent a regulating disk. The results of these tests have, however, been mixed; for example, Rebull (2001) and Makidon et al. (2004) find no clear correlation between disk excess and rotation rate in Orion and NGC 2264, respectively, but Herbst et al. (2002) and Lamm et al. (2004) find such a correlation in these same clusters. Moreover, Herbst et al. (2002) find a weak correlation between the rotation rate and the *size* of the disk excess, which is not found by, e.g., Stassun et al. (1999) or Rebull (2001).

Why should we worry about the evolution of angular momentum in broad strokes, much less in the details? The study of the evolution of stellar angular momenta also sheds light on the evolution of circumstellar disks (and possibly associated disk winds), stellar winds, and stellar interior processes (such as core/envelope rotation and mixing). The observed stellar angular momenta in young stars may provide information regarding initial conditions in that specific star-forming region – the angular momentum distribution and evolution in high-density clusters may be entirely different than that found in lower density star-forming regions (e.g., Wolff et al. 2007).

By the time of the ZAMS, we know from observations in, e.g, the Pleiades, that there are both very fast (>300 km/s) and (many) very slow (<10 km/s) rotators (see, e.g., Prosser 1998 or Terndrup et al. 2002 and references therein). So, a question we seek to answer is how and when does this distribution get established? The early PMS (t<∼5 Myr) is when the stellar radius changes the most and is therefore the best phase of evolution for testing models that predict how stellar angular momentum evolution changes with time. In this contribution, we briefly review the state of observations of rotation in young, low-mass stars.

2. Observations

There are two ways to measure rotation in stars: projected rotational velocity, $v \sin i$, or rotation period, P.

High-resolution spectroscopy yields $v \sin i$, where the stellar rotation gives rise to the Doppler broadening of spectral lines. In order to obtain such a measurement, only one observation per star is needed, ideally of a line region with few blended lines. In practice, the resolution of most spectrographs limits us to >10-12 km/s; at the extremes of fast rotation, the lines are too broad for a $v \sin i$ to be accurately determined. The inclination angle (i) of the rotation axis with respect to the line of sight is a fundamental uncertainty, irreducible without additional data (such as the rotation period). High-resolution spectroscopy will also give an indication of binarity for unresolved binaries, and, potentially, membership from radial velocities, Li abundances, and/or strength of Hα emission/absorption.

In contrast, P is obtained from multi-night photometric observations, watching surface blemishes on the star rotate into and out of view. In order to do this, one needs many observations over many nights, over at least enough time to observe at least two periods of the modulation. If enough stars are in the field of view along with the target stars, relative photometry against other stars in the field can be used to obtain milli-magnitude accuracy. In practice, limits are set by the observing cadence and length – observations only once per day are insensitive to rotation rates faster than a day, and an observing run of a week's length is unable to reliably determine periods longer than at the very most 4-5 days. By using the standard methodology for finding a periodic signal in unevenly sampled data as described by Scargle (1982), Horne & Baliunas (1986), Gilliland & Baliunas (1987), and more generally by Press et al. (1992), the signal modulation period can be very precisely determined (<1%). While the modulation period can be well-known, if the star has exactly evenly spaced spots (or spot groups), this method will not be able to distinguish the rotation rate of the star from the modulation of the light curve. So, paradoxically, the P measured is either right to a fairly high precision, or wrong by a lot. Periods can be the thing we know the most precisely of all possible characteristics of the studied stars.

Both of these methodologies have special considerations when working with young stars. Young stars may have circumstellar disks providing emission lines and motions (e.g., from accreting matter) that may artificially broaden spectral lines. In comparison to main sequence stars, young stars generally have larger spots (and spot groups), so they produce larger amplitude variability, making them easier to observe. Young stars have both accretion, producing hot spots, and starspots, producing cool spots, and the spots can be stable on timescales of years. However, strong accretion or flare events can create stochastic variability that masks periodic variability due to stellar rotation. (A high level of variability, due either to accretion or stellar flares, can be an indicator of cluster membership, so monitoring can be useful even if no periodic signal is obtained.) For both $v \sin i$ and P, we need a clear view of the photosphere, so edge-on stars with disks (even weak disks) will not work well with either method, but exactly pole-on objects will not work well either (because little to no variation or Doppler line broadening will be obseved). For these reasons, most of the data that exist are for classical and weak-lined T Tauris (C/WTTS), as opposed to still younger objects.

3. Rotation in the Youngest Objects

Measuring rotation in the earliest phases is difficult because the YSO is deeply embedded in natal material (obscuring views of the photosphere), but is important because significant accretion of mass and angular momentum go on during these earliest phases. The best observations to date have used $v \sin i$ from infrared spectra, and they only exist for a relative handful of objects (<50); see Covey et al. (2005) and references therein. Covey et al. (2005) find that IR-selected Class I/flat spectrum objects rotate significantly faster (∼20 km/s) than T Tauri objects. There is no correlation with mass accretion indicators found, but they do find a weak possible correlation with mass.

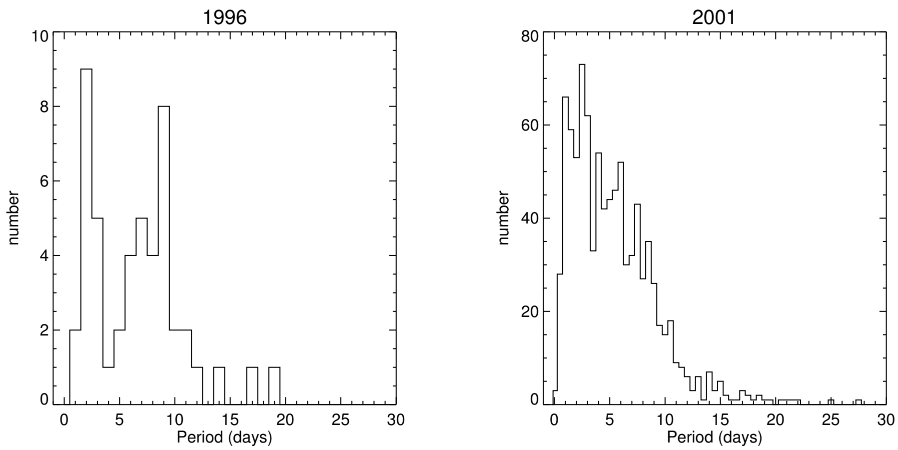

Figure 1. Histograms of periods found in Orion. LEFT: results from the mid 90s for the ONC, e.g., Choi and Herbst (1996). The bimodal nature of this histogram was a striking result. RIGHT: results from all of the periods found in Orion over the subsequent 5 years, including the far reaches of the cluster and stars of all masses. The bimodality of the distribution is not nearly so obvious.

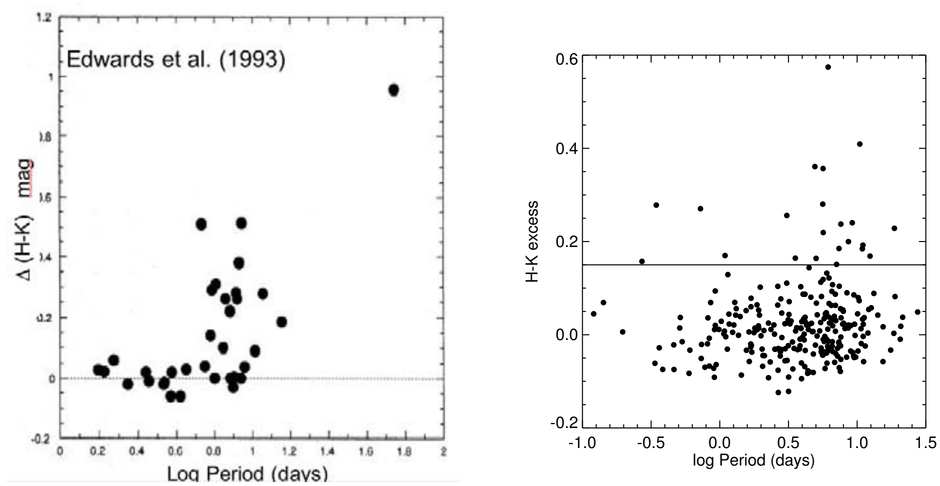

Figure 2. Plot of disk indicator vs. period. LEFT: results from the mid 90s, e.g., Edwards et al. (1993). This striking result suggests that slowly rotating stars have infrared excesses, e.g., disks. RIGHT: results from 2001, e.g., Rebull (2001). Clearly there are large numbers of slowly rotating stars that do not have disks.

4. Rotation in the T Tauri Phase

Measurements of rotation of objects in the T Tauri phase are comparatively easy, because of the accessibility of the photosphere of most T Tauri objects. Choi and Herbst (1996) found a striking result for T Tauri stars in the core of the Orion Nebula Cluster (ONC); see Figure 1 (left). They found two populations of stars – fast and slow rotators. However, over the subsequent ∼5 years, many hundreds of additional periods were found for stars in Orion. As can be seen in Figure 1 (right), the bimodality was no longer nearly so clear and obvious. However, this Figure includes stars of all masses, and from both the core of the ONC and the outer reaches of the cluster.

Now, in 2006, the community seems to be agreeing that the period distribution in the heart of the ONC is bimodal for stars $>0.25\ M_{\odot}$, but it is not necessarily bimodal elsewhere in Orion. Mass needs to be considered when working with rotation distributions.

In 1993, Edwards et al. found another striking result, seen in Figure 2 (left). Working in Taurus-Auriga, they found that slowly rotating stars have near-infrared excesses, e.g., they are the ones with circumstellar disks. Rebull (2001) did not find so obvious a correlation in Orion, despite using three different disk indicators and many more periods; Figure 2 (right) shows the results for one of the disk indicators used.

All recent theories about angular momentum transfer suggest mechanisms intimately related to the accretion process itself. These include (a) transfer of stellar angular momentum to a spreading accretion disk (e.g., Königl 1991, Königl & Pudritz 2000), and (b) transfer of angular momentum to an accretion-driven wind, launched either at the disk/magnetosphere boundary (e.g., Shu et al. 2000) or elsewhere in the star-accretion disk system (Matt & Pudritz 2005a,b). All of the above disk-related regulation mechanisms posit that an accretion disk is present, and that the central star is 'locked' (or nearly so) to a constant angular velocity fixed by the Keplerian speed at the radius at which the stellar magnetosphere and disk are linked (co-rotation radius) even as the PMS stars contract.

The predictions of the observational manifestations of the angular momentum regulation are relatively simple. If the star is locked, e.g., stellar *angular velocity* is conserved, then as the stars contract, they rotate at the same rate (P ∼constant, independent of stellar R, or equatorial velocity $v \sim R$). If, on the other hand, stellar *angular momentum* is conserved, as the stars contract, they spin up; taking stellar angular momentum $J \sim MvR$ to be constant, then $P \sim R^2$, or $v \sim 1/R$. In both cases, we can obtain R from the star's position in a dereddened color-magnitude diagram.

Rebull et al. (2002, 2004) applied this test (and discuss the analysis in much more detail than can be provided here). We obtained from the literature P or $v \sin i$, magnitudes (V and I), and spectral types for >1000 stars in Orion, TW Hya, Cha, ρ Oph, NGC 2264, Tau-Aur, Lupus, and η Cha. We limited the stars in our database to be types K5-M2 (effectively a cut in mass) to limit mass and age effects when considering the evolution of angular momentum across ages. Figure 3 shows the results for the average $v \sin i$ from many different clusters as a function of stellar R. The slope of the best-fitting line shown there is consistent within errors to the value expected for evolution with constant angular velocity, and inconsistent with the value expected for conservation of angular momentum. Similar results are obtained for the relationship between P and R; P is found to be essentially constant as a function of R, again consistent with the value expected for evolution with constant angular velocity.

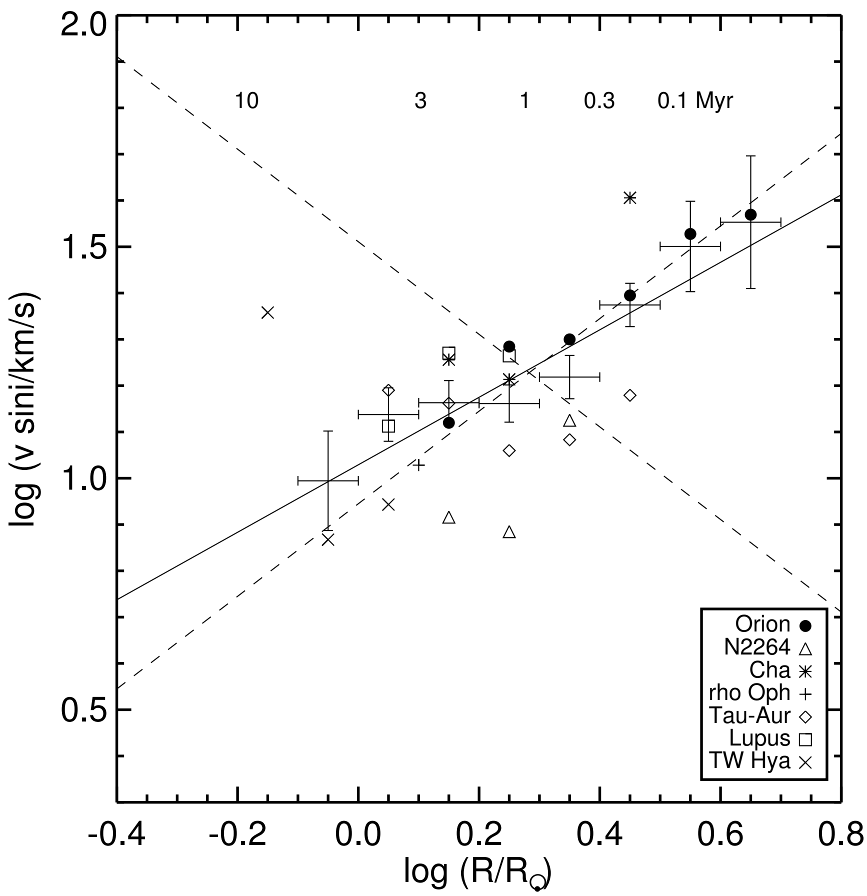

Figure 3. Plot of average $v \sin i$ from many different clusters as a function of stellar R. The points with error bars in both directions are the average log $v \sin i$ calculated for all the cluster stars within the specified range in log R, and the horizontal error bars show the size of the bin. The log $v \sin i$ values for each individual cluster are also plotted, provided there are at least two stars within the bin. Approximate ages (from D'Antona and Mazzitelli 1998 for 0.7 $M_\odot$) as a function of R are indicated. The best-fitting slope is 0.7($\pm$0.2) (dropping the last point from TW Hya, which may indicate the first tantalizing hints of spin-up; see Rebull et al. 2004). The dashed lines are the relationships expected for evolution with constant angular velocity (slope of 1), and conservation of angular momentum (slope of -1). The slope of the best-fitting line shown here is consistent with that expected for evolution with constant angular velocity, and inconsistent with the value expected for conservation of angular momentum. Similar results are obtained for the relationship between P and R.

Clearly, something is tightly regulating the stellar angular momentum in the early PMS to at least ages of $\sim$3-5 Myr. In our work, we found that at least 60-70% of the stars must be regulated. In a similar study using different methodology, Herbst & Mundt (2005) find that $\sim$40-50% of the stars are regulated. Within the accuracies of both methods, we regard this as a consistent result.

Not only do these results suggest that a significant fraction of PMS stars must be regulated, but also that some stars must evolve while conserving angular momentum. By comparing P and $v \sin i$ for PMS stars with those of young ZAMS clusters (such as the Pleiades and α Per), we find that the ZAMS rapid rotators must evolve from stars that conserve stellar angular momentum from ages < 1 Myr.

We can constrain the specific fraction of stars that must be released early via Monte Carlo simulations to explore the evolution of the *distribution* of periods. As discussed in Rebull et al. (2004), we tested two cases: one in which a fraction of stars was released at t=0, and one in which the disk fraction decreased linearly over 5 Myr. We compared the distribution of periods for stars with and without disks, noting that within our simulation, we have perfect knowledge of stars with and without disks. Within the "instantaneous disk release" model, we find that a distribution of periods resembling the bimodal distribution from the ONC is reproduced when 30% of the stars are released at t=0, and 70% remain regulated for 3 Myr. The populations of disked and non-disked stars can be distinguished based on their period distributions at $t >$1 Myr. However, early instantaneous release ($t <<$1 Myr) can be detected only if the released fraction is at least $\sim$30% for samples $>\sim$200 stars per bin of radius (or age). This is a sample size a factor 2.5-5$\times$ more than we have now! (Messina et al., this volume, are observing more stars and confirming periods that we have in Orion; Irwin et al. and the MONITOR project, also this volume, are obtaining periods for more clusters of more ages.) If there is a gradual release in which the regulated fraction falls to 50% in $t >$1.5 Myr, then Monte Carlo simulations show that there is no clear correlation between disk properties and rotation rate, even with samples $\sim$200 stars per bin of radius (or age). Observations of the P distribution for many 100s of stars in $t >$5 Myr clusters would be very useful for constraining the regulation timescale.

5. Is it really disks that are doing the regulating?

The evidence to this point for disk locking has been ambiguous for three main reasons. First, as seen above, based on the Monte Carlo simulations, even with as many stars as we have now, the sample sizes are still just not large enough to distinguish the period distributions for (disk-) regulated and unregulated stars. The complete range of periods is very broad, spanning a factor of 10. Stars can move around within the distribution and not create a substantial change in the overall shape of the distribution. Subtle (and even not so subtle) differences can be masked even with sample sizes of several hundred stars. Secondly, near-IR excesses cannot identify disks with 100% certainty; the system geometry (inner disk holes and inclination effects) can affect the measured NIR excess (see, e.g., Hillenbrand 1998). Finally, the stars themselves also change with time, so if the

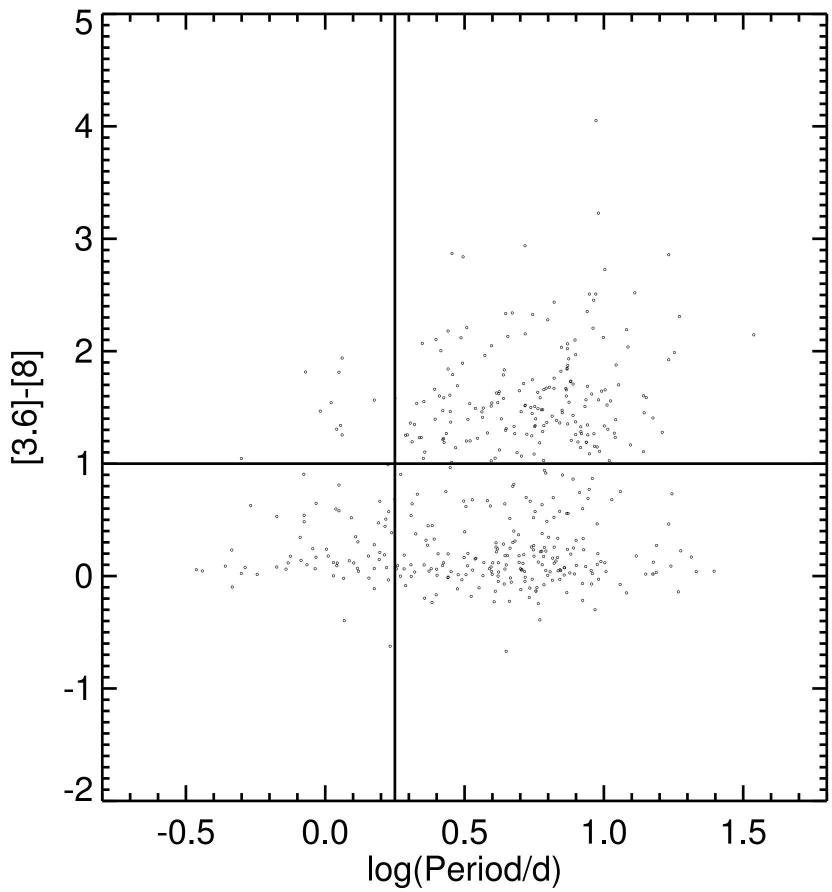

Figure 4. Plot of IRAC color ([3.6]−[8]) vs. period for stars in Orion. The disked population is clearly separate from the non-disked population (boundary at [3.6]−[8]=1). Slowly rotating stars are much more likely to have disks than fast-rotating stars (boundary at log P=0.25).

photometric measurements were not obtained contemporaneously (for example, using K from 2MASS and I from the monitoring conducted during a different year), the colors used to assess disk presence may be unreliable.

Now we are in in a position to change this! There are ∼900 stars currently known with periods in Orion alone, with periods accumulating in other clusters as well. Whereas before, the the near-IR could be an unreliable disk indicator, now, we have Spitzer/IRAC disk indicators, which provides a longer-wavelength, much less ambiguous measurement of disk presence. The IRAC fluxes sample the disks at much greater distances from the central object; whereas JHK measurements sample ∼10-20 R_* from the central object, IRAC colors detect disks at ∼40-80 R_* (for stellar parameters typical of the sample). Moreover, the IRAC measurements are obtained essentially contemporaneously; IRAC obtains data in 4 colors (3.6, 4.5, 5.8, and 8 microns) very nearly at the same time, so the stars do not have much of a chance to vary between measurements.

Figure 4 (taken from Rebull et al. 2006) shows the IRAC color (3.6 − 8 microns) vs. P for stars in Orion. The disked population is clearly distinct from the non-disked population; the stars with [3.6]−[8]>1 are the disked stars, and there is a gap in the distribution near [3.6]−[8]$\sim$1. This separation of the disked and non-disked populations does not exist when using NIR disk indicators. There are slow rotators with and without disks, but essentially all of the fast rotators do not have disks. While still not as striking as the original Edwards et al. (1993) result in Taurus, this is still the best evidence yet that, although infrared excesses don't necessarily require longer periods, a star with a longer P is much more likely to have an excess than a star with a shorter P. This is somewhat surprising because IRAC colors are sampling disks so far away from the star that it is hard to understand how the disk locking model could work with disks at $\sim$100 R_* rather than $\sim$10 R_*. Perhaps this result is cleaner than that found using NIR indicators because IRAC is telling us about the recently regulated as well as the currently regulated stars, so it provides a larger sample of potentially slowly rotating stars.

Even using IRAC colors as disk indicators, there are likely to be mass effects as well; see Rebull et al. (2006) for much more discussion. While the nebula is so bright at these wavelengths as to preclude getting reliable photometry for the lowest mass (faintest) stars with known periods (especially in the heart of the ONC), even with the existing data, we can see a hint of a mass-related effect. There is more scatter in the lower-mass stars ($M < 0.25 M_\odot$), and a less-well-defined disk population. The clump in the higher-mass population at longer periods may mean the average disk ceases to influence the stars at longer P in the more massive stars.

6. Environmental effects

Orion is a much denser environment than many other star-forming regions, and most of the stars in our Galaxy may not have formed in an Orion-like environment. There are tantalizing hints that the environment may matter for the distribution and evolution of stellar angular momentum.

The relationship between rotation and IRAC excess does not seem to be present in Taurus based on preliminary work (Rebull et al. in preparation), although Taurus is of a similar age to Orion, so expectations were that the relationship would be present. Kundurthy et al. (2006), using ground-based mid-IR, do in fact find a correlation between infrared excess and rotation, providing that only single stars are considered. Further work is pending.

Another cluster with many newly-measured periods is IC 348. Cieza & Baliber find no correlation between infrared excess and period, although they do find that the disk fraction decreases significantly for P <1.5 days, as we found for Orion above. It is an open question as to why the distributions are different. Baliber & Cieza (this volume) report on improved Monte Carlo simulations of the distributions of rotation rates.

Since the disk regulation mechanisms require an intense interaction between the disk and the star, there is an expectation that we should be looking not just for disk presence, but evidence of active interaction between the star and the disk, e.g., accretion. Jayawardhana et al. (2006) report on rotation rates and accretion for several clusters: Eta Cha (6 Myr), TWA (8 Myr), BPMG (12 Myr), and Tuc-Hor (30 Myr). They find that all accretors are slow rotators, but they have very few stars.

7. Concluding thoughts and future work

It seems clear that a substantial fraction of the stars <3-5 Myr old evolve at constant angular velocity; two different independent studies confirm it (Rebull et al. 2004: at least 60-70% regulated; Herbst et al. 2005: 40-50% regulated). Based on results in Orion, it appears that the culprit is disks that radiate in IRAC wavelengths (dusty disks). In Orion in particular, IRAC excesses don't necessarily imply long periods, but rapidly rotating stars are very unlikely to have significant excesses. In Taurus and IC 348, the correlations with IRAC excesses are not as dramatic, but neither are the numbers of stars, at least so far. Disks are still the best solution. It is disappointing that there is no clear correlation, but perhaps we shouldn't expect it – several factors will mask any correlation, especially for small samples. The initial distribution of periods, even for the youngest stars, appears to be fairly broad, so there is likely to be some overlap in periods between slowly rotating stars regulated by disks and intrinsically very slow rotators. Regulated stars that have been very recently released from their disks will not have had time to spin up, and so we can expect to find slowly rotating stars without disks. And, the radius change is most rapid during the first $\sim$1 Myr of evolution such that at later stages of evolution, the distinction between evolution at constant P becomes harder to distinguish from evolution at constant angular momentum.

In order to tease apart the influences of all of the relevant factors, including environment, we need enough stars so that we can make important cuts on the data and STILL have 100s of stars for each step in age, enough to beat down the scatter inherent in the broad distribution. Binarity, mass, age (apparent or actual, within cluster), disk dispersion timescales, and environment are likely to leave an imprint on the distribution of rotation rates. We need to look for correlations with accretion rate, not just disk presence, because locking requires the interaction of star with its disk, not just a passive disk; IRAC tells us about the dust, not the gas or accretion.

We are still struggling to obtain the "initial" distribution for the youngest objects and make it map ultimately into the Pleiades and α Per. A significant gap in the existing data are the 5-10 Myr old clusters, and efforts should be made to fill this important gap. The timescale for disk clearing may be comparable to other important timescales here. The stars that have IRAC excesses may be showing evidence of recent disk locking with closer-in disks, only recently having cleared out to IRAC radii, perhaps simply still behaving as disk-locked. The disk could be influencing the star's rotation without actual locking taking place. We need better theoretical models, and Matt et al. (this volume) discusses efforts to obtain these.

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