

The Rotation of Young Low-Mass Stars and Brown Dwarfs

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We review the current state of our knowledge concerning the rotation and angular momentum evolution of young stellar objects and brown dwarfs from a primarily observational view point. There has been a tremendous growth in the number of young, low-mass objects with measured rotation periods over the last five years, due to the application of wide field imagers on 1-2 m class telescopes. Periods are typically accurate to 1% and available for about 1700 stars and 30 brown dwarfs in young clusters. Discussion of angular momentum evolution also requires knowledge of stellar radii, which are poorly known for pre-main sequence stars. It is clear that rotation rates at a given age depend strongly on mass; higher mass stars ($0.4-1.2 M_{\odot}$) have longer periods than lower mass stars and brown dwarfs. On the other hand, specific angular momentum is approximately independent of mass for low mass pre-main sequence stars and young brown dwarfs. A spread of about a factor of 30 is seen at any given mass and age. The evolution of rotation of solar-like stars during the first 100 Myr is discussed. A broad, bimodal distribution exists at the earliest observable phases (~ 1 Myr) for stars more massive than $0.4 M_{\odot}$. The rapid rotators (50-60% of the sample) evolve to the ZAMS with little or no angular momentum loss. The slow rotators continue to lose substantial amounts of angular momentum for up to 5 Myr, creating the even broader bimodal distribution characteristic of 30-120 Myr old clusters. Accretion disk signatures are more prevalent among slowly rotating PMS stars, indicating a connection between accretion and rotation. Disks appear to influence rotation for, at most, ~ 5 Myr, and considerably less than that for the majority of stars. This time interval is comparable to the *maximum* life time of accretion disks derived from near-infrared studies, and may be a useful upper limit to the time available for forming giant planets. If the dense clusters studied so far are an accurate guide, then the typical solar-like star may have only ~ 1 Myr for this task. There is less data available for very low mass stars and brown dwarfs but the indication is that the same mechanisms are influencing their rotation as for the solar-like stars. However, it appears that both disk interactions and stellar winds are less efficient at braking these objects. We also review our knowledge of the various types of variability of these objects over as broad as possible a mass range with particular attention to magnetically induced cool spots and magnetically channeled variable mass accretion.

1. Introduction

The study of stellar rotation during the pre-main sequence (PMS) and zero age main sequence (ZAMS) phase provides important clues to the solution of the angular momentum problem of star formation. It is also intimately connected to the evolution of the circumstellar disk out of which planets are believed to form. The angular momentum problem, simply stated, is that the specific angular momentum ($j = J/M$ where J is angular momentum and M is mass) of dense molecular cloud cores, the birth places of low-mass stars, is 5-6 orders of magnitude higher than that

of solar-type stars on the ZAMS (e.g., *Bodenheimer, 1995*). We note that by the time they reach the age of the Sun (~ 5 Gyr), solar-type stars have lost an additional 1-2 orders of magnitude of j due to the cumulative effect of torques from their magnetized coronal winds.

Undoubtedly, the full angular momentum problem is solved by a combination of factors occurring throughout the star formation process, not just a single event at a specific time (*Bodenheimer, 1995*). Important processes at early stages include magnetic torques between the collapsing molecular cloud core and the surrounding interstellar

medium as well as the deposition of large amounts of angular momentum in the orbital motions of a circumstellar disk, planetary system and/or binary star. At later stages the redistribution of angular momentum within the disk and J -loss by magnetically driven outflows and jets become important. Recent HST/STIS studies of optical jets from T Tauri stars (TTSs) (e.g., *Bacciotti et al.*, 2002; *Woitas et al.*, 2005) show that these jets are rotating. In the framework of magnetically driven outflows, the derived rotation velocities of these jets imply large angular momentum loss rates. The magneto-hydrodynamic (MHD) models suggested for the acceleration of bipolar outflows from young stars also involve a strong magnetic coupling between the stellar magnetic field and the inner parts of the circumstellar accretion disk. Hence, it seems likely that the rotation of PMS stars will be influenced by these processes.

On the observational side, the first studies of rotation to include a substantial number of TTSs employed high resolution spectra to measure line broadening (e.g. *Vogel and Kuhl*, 1981; *Hartmann et al.*, 1986; *Bouvier et al.*, 1986). The resulting measurements of rotational velocity (V_{rot}) are inherently uncertain due to the unknown inclination of the stellar rotation axis to the line of sight. It is also difficult to measure V_{rot} for slow rotators since there is very little line broadening in that case. Nonetheless, it was clear from these studies that, in general, TTSs rotated much slower (about a factor of 10, on average) than their critical velocities, although details of the distribution such as its true breadth and bimodal nature were not apparent.

Starting in the mid-1980's the technique of directly measuring the rotation period from photometric monitoring of a spinning, spotted surface was applied to a growing number of TTSs (*Rydgren and Vrba*, 1983; *Herbst et al.*, 1986, 1987; *Bouvier and Bertout*, 1989). Through a proper analysis of these brightness modulations, the rotation period (P), which is independent of inclination angle, can be measured to an accuracy of about 1%, even for the slowest rotators. We note that P , or its equivalent, angular velocity ($\omega = 2\pi/P$), is currently the most accurately known stellar parameter for most PMS stars and it is known for a large number of them.

The amount of available rotation period data has skyrocketed during the last 6 years. This advance occurred as a result of the application of wide field optical imaging devices to the problem. For the first time, it became possible to simultaneously monitor hundreds of PMS stars in young open clusters such as the Orion Nebular Cluster (ONC), NGC 2264 and IC 348 (see e.g., *Mandel and Herbst*, 1991; *Attridge and Herbst*, 1992; *Choi and Herbst*, 1996; *Stassun et al.*, 1999; *Herbst et al.*, 2000a, 2000b, 2001, 2002; *Rebull*, 2001; *Carpenter et al.*, 2001; *Lamm et al.*, 2004, 2005; *Makidon et al.*, 2004; *Littlefair et al.*, 2005; *Kiziloglu et al.*, 2005; *Nordhagen et al.*, in preparation). These imaging devices also provided the first extensive measurements of rotation periods for very low-mass stars (VLMSs) and brown dwarfs (BDs) in PMS and ZAMS clusters (*Scholz*, 2004; *Scholz and Eislöffel*, 2004a,b, 2005). Altogether ~ 1700 pe-

riods of low-mass PMS stars and young VLMSs and BDs are currently available in the literature. In addition, for several ZAMS clusters there are extensive rotation period data available on both solar-type stars (see references in *Herbst and Mundt*, 2005) and VLMSs and BDs (see *Scholz*, 2004; *Scholz and Eislöffel*, 2004b and references therein).

In this article we provide an overview of the rotation period data currently available on PMS objects over the broadest possible mass range that can be investigated with the photometric monitoring technique, i.e. from about $1.5 M_{\odot}$ down into the substellar mass regime. Furthermore, we discuss how our present knowledge of the rotation properties of these objects in ZAMS clusters constrains our current understanding of their angular momentum evolution during the first few Myr. Our chapter is structured as follows: in Section 2 we will describe the observational method employed in measuring rotation periods. The next two sections deal with the rotation properties and the empirical results on angular momentum evolution for solar-type stars, VLMSs and BDs. In Section 5 we review our knowledge of the variability of these objects, the importance of disk-rotation interactions and magnetically-channeled mass accretion over as broad as possible a mass regime. Finally, in Section 6 we discuss the confrontation between observation and theory, in particular the model popularly known as “disk-locking”.

2. Observational Methods

The method of determining stellar rotation periods by monitoring the motion of a surface spot of very different temperature from the surrounding photosphere can be traced back to Christopher Scheiner and Galileo Galilei, who employed it to determine the rotation rate of the Sun at low latitude (see, for example, *Tassoul*, 2000). Modern application of this method exploits the photometric variability induced by the spot or spot group as it is carried around by the star's rotation. Sufficiently dense photometric monitoring over at least a couple of cycles will reveal periodicity in many PMS stars' brightness variations that can be linked with certainty to rotation (*Rydgren and Vrba*, 1983; *Bouvier et al.*, 1986; *Stassun et al.*, 1999; *Rhode et al.*, 2001). This method only works for stars of spectral class G, K or M ($\sim 1.5 M_{\odot}$ and less) and for BDs. It is most effective for the mid-K to early-M stars ($\sim 0.5 M_{\odot}$) where the spot amplitudes are largest (see Section 5).

The value of j , the specific angular momentum at the surface, of a spherically symmetric, uniformly rotating star depends on only two variables – rotation period (P) and radius (R). In general, we may expect a star's surface rotation rate to be a function of latitude, as is well known to be the case for the Sun. Remarkably, this effect has never been convincingly demonstrated for any T Tauri star (see, however, *Herbst et al.*, 2005). On the contrary, one finds that measured rotation periods are stable to within the errors of their

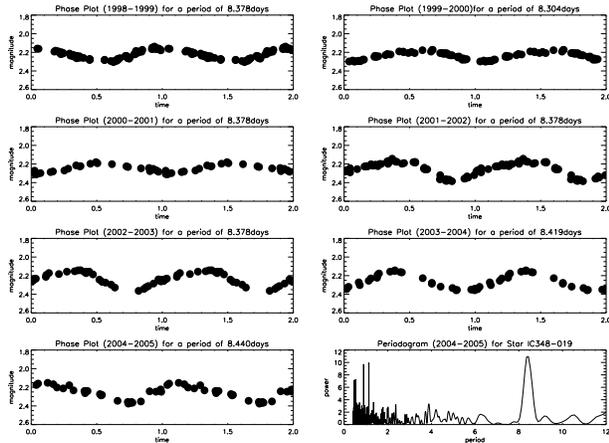


Fig. 1.— Light curve of HMW 19, a WTTS in IC 348, based on seven years of photometric monitoring in the Cousins I band at Wesleyan University (*Nordhagen et al.*, in preparation). The bottom right panel shows the periodogram function for one season. Note how the light curve shape and amplitude changes slightly from year to year while the period remains essentially constant to within the error of measurement.

determination, typically 1% (*Cohen et al.*, 2004; *Kiziloglu et al.*, 2005; *Nordhagen et al.*, in preparation). This presumably means that spots on PMS stars are generally confined to a small range of latitudes or that their surfaces are rotating in much more rigid fashion than the Sun, or both. It is normally assumed by astronomers working in this area that the measured periodicity in brightness is the rotation rate applicable to all latitudes on the surface of the star.

An example of the data is shown in Fig. 1 from the work of *Nordhagen et al.* (in preparation). Typically, one searches for periodicity using the Lomb-Scargle periodogram technique which is effective for unevenly spaced data sets. Evaluation of the *false alarm probability* (FAP) associated with a peak of any given power can be tricky and is best done with a Monte Carlo simulation of the data. Most authors in this field have adopted relatively conservative criteria generally equivalent to a FAP of about 0.01. Data obtained from a single observatory (longitude) have an unavoidable 1 d^{-1} natural frequency embedded in them, imposed by the rotation of the Earth. Truly periodic objects therefore normally have more than one significant peak in their periodograms due to the beat phenomenon. Separating true periods from beat periods can be difficult and often requires qualitative judgments about which period does the best job of phasing the data. Most disagreements about periods in the literature arise from this complication. Continued monitoring, or a $v \sin i$ measurement will permit resolution of the question. Occasionally a star will show periodicity at one-half its true rotation period due to the existence of spots in opposite hemispheres of longitude. Examples are V410 Tau (*Vrba et al.*, 1988) and CB 34V (*Tackett et al.*, 2003).

It is expected on general physical grounds (e.g., *Tassoul*,

2000) that rotation rate will vary with depth into a star and helioseismology has shown this to be the case for the Sun, especially within its convective zone (e.g., *Thompson et al.*, 2003). Since we are very far from having any way of determining, either observationally or theoretically, what the dependence of rotation with depth in a PMS star might be like, there is realistically at present no way of measuring how j might vary in a radial sense. From a purely empirical point of view one can, therefore, discuss only the *surface value* of j . Models, of course, can be and have been constructed with assumed rotation laws (e.g., uniform with depth) and with interior mass distributions satisfying the usual constraints of stellar structure. A common assumption is that fully convective stars are rigid rotators, although rigid rotation is not what is observed in the solar convection zone. These assumptions, of course, do allow one to estimate a value of j applicable to the whole star at the expense of increased uncertainty due to the inability to test critical assumptions.

Finally, we note that the surface value of j for a spherical star (see *Herbst and Mundt*, 2005 for a discussion of non-spherical stars) depends on stellar radius, a notoriously difficult quantity to measure for PMS stars. Debates in the literature on rotational evolution during the PMS stage often center on how to evaluate the somewhat bewildering data on luminosity and effective temperatures of such stars, from which their stellar radii are inferred. Rotation periods are relatively easy to determine, are highly accurate, and are generally not the source of disagreement about interpretation in this field. Radii, on the other hand, are hard to determine for any individual star, show a large scatter among stars of apparently the same mass, within a single cluster, and are at the root of some recent debates in the literature over how to interpret data on stellar rotation (*Rebull et al.*, 2002, 2004; *Lamm et al.*, 2004, 2005; *Makidon et al.*, 2004; *Herbst and Mundt*, 2005). The problem is exacerbated by the fact that the relative ages of PMS stars of the same mass are set by their relative radii. If radii are in error then ages are in error and evolutionary trends become difficult to discern. We return to this difficulty in what follows but first give an overview of recent empirical results on rotation.

3. Rotation of Young Stellar Objects

With ~ 1700 rotation periods measured, there is now a fairly good empirical understanding of spin rates of PMS stars and their dependence on spectral type (or mass). A couple of surprising results have emerged from this, the first of which is the breadth of the rotation period distribution, which extends at least over a factor 30 for all well-observed mass ranges. The second surprising fact is that the measured rotation period distributions are highly mass-dependent. For stars with $0.4 < M < 1.5 M_{\odot}$, the period distribution ranges from $\sim 0.6 \text{ d}$ to $\sim 20 \text{ d}$ and is clearly bimodal with peaks near 2 and 8 days in the ONC and near 1 and 4 days in NGC 2264 (see Fig. 2). For stars with masses

below $0.4 M_{\odot}$ (or $0.25 M_{\odot}$ depending on which PMS models one adopts) the median of the distribution is about a factor 2 shorter in both clusters (*Herbst et al., 2001; Lamm et al., 2004, 2005*).

A recent comparison of the j -distributions of solar-type PMS stars in the ONC and NGC 2264 with solar-type ZAMS stars (0.4 - $1.2 M_{\odot}$) shows that the j -distributions of the PMS and ZAMS sample match very well for high j -values, *but not for low j values* (*Herbst and Mundt, 2005*). For the ZAMS stars the j -distribution extends by about a factor 3 towards lower values. This means that the rapid rotators among the optically observable solar-like PMS stars do not lose much, if any, angular momentum on their way to the ZAMS, while the slow rotators do continue to experience some braking. This again indicates that most of the angular momentum problem is solved by the time these stars become observable in the optical. There is some indication that much younger and much deeper embedded PMS stars (i.e. protostars) have about a factor 2 higher V_{rot} values than their optically visible counterparts (see *Covey et al., 2005* and references therein) suggesting significant angular momentum loss during this phase. Such an increased angular momentum loss seems to be in accordance with the substantial bipolar outflow activity during this phase.

As mentioned in the introduction, the measured periods vary by about a factor of 30 from 0.6 to about 20 days for solar-like stars. This wide range is present at all spectral types and masses and seen in all samples (clusters and associations) where enough data exist. A difficulty in interpreting these data is that PMS stars contract rather rapidly and if they conserve angular momentum will spin up rapidly. For example, a star with an 8 day rotation period at 1 Myr will have a 5 day rotation period at 2 Myr if it conserves angular momentum at its surface. It is, therefore, critical to compare samples at the same age, if one wants to discern a mass dependence.

The dependence of rotation on mass among PMS stars of a common age was first demonstrated for the ONC by *Herbst et al. (2001)*. They found that lower mass stars, in general, rotate faster than their higher mass counterparts. In terms of (surface) j , however, there is little or no dependence on mass. It appears that lower mass stars spin faster primarily because they have smaller radii. When separated at a spectral class of about M2, corresponding to a mass of between 0.25 and 0.4 solar masses (depending on the model adopted), one finds that the higher mass stars have a distinctly bimodal period distribution with peaks near 2 and 8 days, while the lower mass stars, in addition to having a shorter period median, may have a somewhat smoother distribution, perhaps characterized by a single mode, although this is uncertain.

Lamm (2003) and collaborators (*Lamm et al., 2004, 2005*) found similar results for another young cluster in which the stars can reasonably be regarded as mostly coeval. His results are shown in Fig. 2, where the bimodal nature of the higher mass stars in both the ONC and NGC 2264 is clearly seen, as is the more rapid rotation and, per-

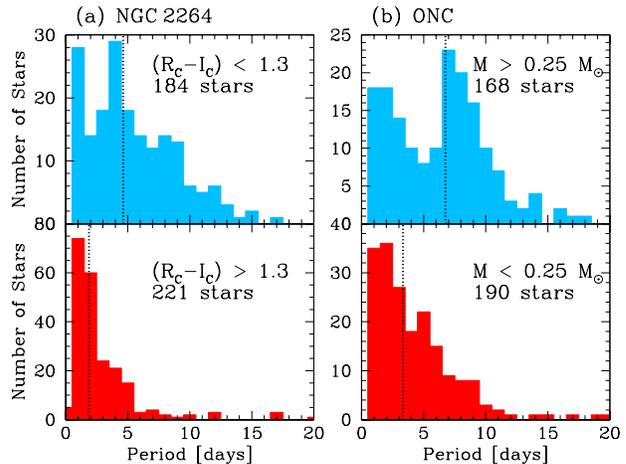


Fig. 2.— The rotation period distribution in NGC 2264 and the ONC divided by mass range. Vertical lines indicate the median value of each sample. It is clear that the higher mass stars in both clusters have longer rotation periods and exhibit bimodal distributions. It is also clear that, within both mass ranges, stars in the ONC tend to have longer rotation periods. The division for the ONC is actually by effective temperature and translates to $0.4 M_{\odot}$ for some PMS models.

haps, single mode distribution of the lower mass stars. The figure also demonstrates that, for PMS stars of the same mass range, those in NGC 2264 rotate about twice as fast as those in the ONC. Statistical analyses of the distributions confirms this claim; NGC 2264 stars cannot have been drawn from the same parent population as ONC stars.

The interpretation of the difference in rotation rates between the clusters favored by *Lamm* and collaborators is that NGC 2264 is a factor of 2 older than the ONC and that a significant fraction of the stars have spun up as they contracted, roughly conserving angular momentum. At the same time, not all of the stars could have spun up since there remains a fairly well-populated tail of slow rotators at all masses among the NGC 2264 stars. There is no evidence that these slower rotators are, as a group, larger (i.e. younger) than the rapid rotators in the cluster, so an age spread within the cluster does not seem to account for the breadth of the rotation distribution. We discuss in more detail below, the interpretation of the broad, bimodal rotation distribution. First, however, we turn to a discussion of the evolution of the rotation of higher mass stars with time over a broader time frame (~ 100 Myr).

4. Angular Momentum Evolution: Empirical Results

Since the rotation rates of PMS stars are mass dependent it is only appropriate to discuss the evolution of j with time within restricted mass regimes. One such important regime, in part because it includes the Sun, is 0.4 - $1.2 M_{\odot}$.

Two other regimes are the very low mass PMS stars, corresponding to spectral class M2.5 and later, and the brown dwarfs. At present, the only mass range which is reasonably well constrained by observations is the solar-like range because ZAMS rotation periods are known for a significant number of such stars from studies of young clusters such as the Pleiades, IC 2602 and the α Per cluster (see references in *Herbst and Mundt, 2005*). Here we will discuss the time evolution of j for the 0.4-1.2 M_{\odot} stars in some detail and then briefly say how this may depend on mass.

4.1. Solar-like stars (0.4-1.2 M_{\odot})

It has been known for more than a decade that ZAMS stars of around 1 M_{\odot} display an enormous range of rotation rates, larger even than is seen among PMS stars. Photometric monitoring of spotted stars in three clusters with ages around 30-120 Myr has provided periods for about 150 ZAMS (or close to ZAMS) stars (see references in *Herbst and Mundt, 2005*). Radii are well known for these stars, so it is possible to determine the j -distribution with some certitude. This provides a “goal” for the evolution of the PMS distributions.

Early studies of the evolution from PMS to MS assumed that stars started from a somewhat narrow j -distribution (e.g., *Bouvier, 1994*) and that the breadth observed on the ZAMS developed during the PMS phase. A common assumption was that all PMS stars had 8 day periods to start with, based on the larger peak in the distribution of the ONC stars and the corresponding peak for CTTS (*Bouvier et al., 1993*). With increased data samples it is now clear that most of the breadth of the ZAMS population is already built in at the earliest observable PMS phases, represented by the ONC. The current problem divides into understanding how the broad PMS distribution at 1 Myr came into existence and how rotation evolves between the PMS and ZAMS.

The first question is difficult to constrain with data because Class 0 and 1 proto-stars are rare and it is hard to ascertain essential data on them, in particular their masses, radii and rotation rates. No rotation periods have yet been discovered for proto-stars. Line broadening measurements, however, have been made for 38 Class I/flat spectrum objects by *Covey et al. (2005)*. Although the sample is necessarily small and heterogeneous, the authors do find an average $v \sin i$ for the sample of 38 km/s, which they argue is significantly larger than for CTTS. Since proto-stars should be, if anything, larger than CTTS, this implies that, as a group, they have larger values of surface angular momenta than CTTS. These data, therefore, reinforce the view that the protostellar or very early PMS stage is a time during which large amounts of angular momentum are lost. This is when the jets and winds which are needed to carry off angular momentum are most prominent and active. This is also the relatively brief period of time (~ 1 Myr) when a majority of stars must lose substantial amounts of angular

momentum to reduce their j values to the levels observed in the ONC.

The second aspect of understanding the origin of the ZAMS j -distribution is more amenable to an observational approach, but is not without its own set of complications. The goal is to understand how a 1 Myr old j -distribution, as represented by the ONC, evolves to a 100 Myr old distribution, as represented by the ZAMS clusters and the problem is that there are very few signposts along the way. That is, one requires a substantial number of stars of homogeneous origin (or at least common age) and data on young clusters are scarce. At present, there are really only two PMS clusters with enough periods known to reasonably define the rotation distributions – the ONC and NGC 2264. IC 348 may soon be included among these (see *Nordhagen et al., in preparation*).

Figure 3 shows the observed situation for these clusters and for the set of ZAMS (or nearly ZAMS) stars drawn from the Pleiades, IC 2602 and the α Per clusters (*Herbst and Mundt, 2005*). There are many *caveats* and considerations in comparing these samples and the interested reader is referred to the original work for the details. Here we touch only on the main points, the first of which is that there are clear, statistically significant differences between the three j -distributions represented by the ONC, NGC 2264 and the ZAMS clusters. If one assumes that each sample had similar initial rotation parameters, then these differences can be interpreted as an evolutionary sequence.

The age of the ONC is about 1 Myr and the average radius of its 0.4-1.2 M_{\odot} stars is 2.1 R_{\odot} . NGC 2264 stars of the same mass (spectral class) range are significantly smaller, with a mean radius of 1.7 R_{\odot} , implying an age of about 2 Myr. ZAMS cluster stars are, of course, even smaller and individual radii can be employed in calculating j for them since their effective temperatures and luminosities are much more secure than for the PMS stars. Note that radius evolution is very non-linear over the course of the first 30 Myr; most of the contraction occurs within the initial few Myr.

It is evident, to a first approximation, from Fig. 3 that the evolution of j occurs in a bimodal fashion. The high- j stars (i.e. the rapid rotators) evolve with essentially no loss of angular momentum from ONC age to the ZAMS clusters. In this interpretation, no physical mechanism beyond conservation of angular momentum is required to explain the evolution of about half the sample. Empirically, there is no need for angular momentum loss (by disk locking, stellar winds or any other process) for the 50-60% of the sample that is already among the rapid rotators at ONC age. Conversely, there is no need to invoke any special mechanism to explain the fast rotation of these stars. They were already spinning rapidly at 1 Myr and they have spun even faster as they contracted to the ZAMS.

On the other hand, the initially slowly rotating stars in the ONC follow a different evolution. It is clearly seen that they continue to lose angular momentum as they evolve to NGC 2264 age and beyond. The ZAMS j -distribution is

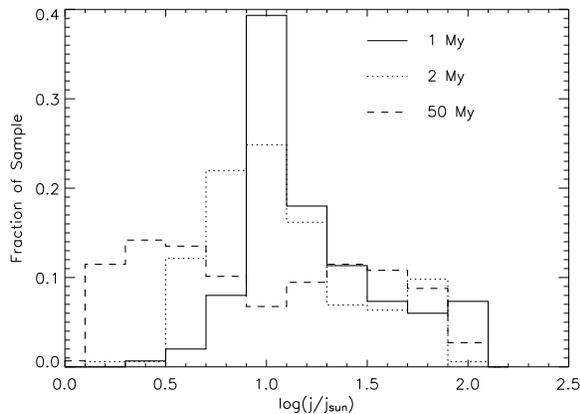


Fig. 3.— The observed j -distribution of the ONC, NGC 2264, and combined three other clusters corrected for wind losses. It is clear that there is little change on the high- j side, implying that rapidly rotating stars nearly conserve angular momentum as they evolve from the PMS to the MS. However, there is a broadening of the distribution on the low- j side which is already noticeable in the comparison of the 1 My old ONC with the 2 My old NGC 2264 cluster and becomes quite dramatic when comparing the PMS and ZAMS clusters. This indicates that slowly rotating PMS stars must lose substantial additional amounts (factor of 3 or more) of their surface angular momentum during contraction to the ZAMS.

about a factor of 3-5 broader than the ONC j -distribution entirely because of the low- j stars. To summarize, we can understand to a first approximation the evolution from PMS to ZAMS in terms of only two processes: angular momentum conservation, which applies for the initially rapidly rotating half of the sample, and a braking mechanism that applies for the initially slowly rotating half. The distribution broadens on one side only – the slowly rotating side. This is an important clue to the braking mechanism, which we discuss in Section 6.

4.2. Very low-mass stars ($< 0.4 M_{\odot}$)

The two largest homogeneous samples of rotation periods, in the ONC and NGC 2264, include about 200 periods per cluster for very low mass stars, an object class here defined as stars with spectral class later than M2, corresponding to $M < 0.4 M_{\odot}$ or so, depending on the stellar models chosen. Together with smaller VLM period samples for slightly older objects, most notably in the σ Ori cluster (Scholz and Eislöffel, 2004a), the ϵ Ori cluster (Scholz and Eislöffel, 2005), and the much older Pleiades (Scholz and Eislöffel, 2004b), they allow us to make meaningful statistical comparisons between periods for VLM stars and their higher mass siblings.

The initial period distribution of VLM stars is well-defined by the large samples in the ONC and NGC 2264.

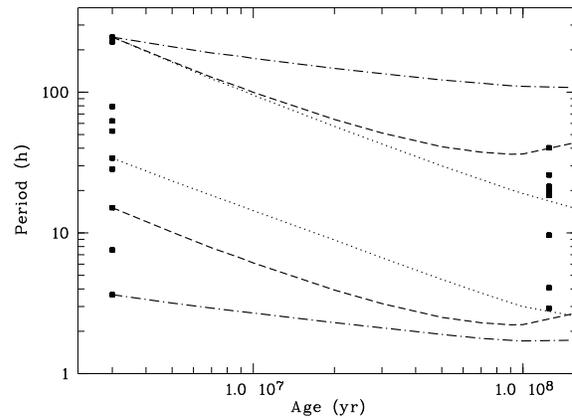


Fig. 4.— Rotation period of VLM stars in the σ Ori cluster and the Pleiades as a function of age (taken from Scholz and Eislöffel, 2004b). The lines show model calculations, which use the periods in σ Ori as starting values. Evolutionary tracks are shown for three assumptions: angular momentum conservation (dotted lines), Skumanich-type wind losses (dashed-dotted lines) and exponential wind braking (dashed lines).

Periods usually range from a few hours up to 10 d in both clusters, a dynamic range similar to solar-like stars. As evident in the bottom panel of Fig. 2, however, slow rotators are clearly much rarer in the VLM regime. For example, in NGC 2264 only 4% of the VLM stars have $P > 10$ d. This change is reflected in the median period, which is 3.33 d for VLM stars in the ONC and 1.88 d in NGC 2264, about a factor of 2 lower than for more massive stars (see Fig. 2). The period distribution in the slightly older clusters σ Ori and ϵ Ori is, as shown by Scholz (2004) and Scholz and Eislöffel (2005), roughly comparable to the NGC 2264 sample, both in median period and limiting values. These similar distributions are not surprising in consideration of the similar ages estimated for the clusters.

First attempts to model the angular momentum evolution in the VLM regime have been made by Terndrup *et al.* (1999) and Sills *et al.* (2000), both based on rotational velocity data of clusters with ages between 30 and 700 Myr. Both papers arrive at the conclusion that the rotational braking by stellar winds changes in the VLM regime: the so-called ‘saturation limit’ (ω_{crit}) probably drops quickly at very low masses, with the result that basically all VLM stars rotate with $\omega > \omega_{\text{crit}}$, and are considered to be in the ‘saturated’ regime of the rotation-activity relation. As a consequence, the rotational braking by stellar winds follows an exponential law ($\omega \propto \exp(-t)$) rather than the established Skumanich law ($\omega \propto \sqrt{t}$) for stars of solar-like mass.

With the available VLM period data, it is now possible to have a more detailed look at their angular momentum evolution. Based on the VLM periods in σ Ori (age ~ 3 Myr) and the Pleiades (age ~ 120 Myr) Scholz and Eislöffel (2004b) investigated the rotational evolution on timescales of ~ 100 Myr by using the σ Ori periods as start-

ing points and evolving these periods forward in time, taking into account basic angular momentum regulation mechanisms. That way, evolutionary tracks in the period-age diagram were produced which can then be compared with period distributions in older clusters.

Fig. 4 shows the results from *Scholz and Eislöffel* (2004b). Plotted are the VLM periods for σ Ori and the Pleiades plus evolutionary tracks. The dotted lines show the evolution assuming angular momentum conservation, i.e. the tracks are completely determined by the contraction process. It is clear that this is not a reasonable description of the available period data, because the models predict an upper period limit < 20 h in the Pleiades, whereas the observed periods range up to ~ 40 h. Furthermore, it is evident from Fig. 4 that the most rapid rotators in σ Ori would rotate at periods well below 1 hr at the age of the Pleiades (i.e. faster than the break-up velocity). We would like to point out that this upper period limit in the Pleiades is nicely confirmed by $v \sin i$ data from *Terndrup et al.* (2000). Thus, some kind of rotational braking must play a role for VLM objects on these timescales. The second model (dash-dotted lines) includes a Skumanich-type wind-braking law as observed for solar-type stars. In this case, the model predicts an upper period limit > 100 h in the Pleiades, significantly higher than the observed value. Thus, the Skumanich braking is too strong and cannot be applied in the VLM regime. In a third model (dashed lines), the model uses an exponential wind braking approach. Except for the two fastest rotators in σ Ori, model and period agree fairly well. Thus, in agreement with *Terndrup et al.* (2000), it was found that the period evolution for VLM objects on timescales of ~ 100 Myrs is mainly determined by contraction and exponential angular momentum loss by stellar winds.

How can we explain the failure of the best-fitting model for the fastest rotators in σ Ori? First of all, the existence of these fast rotators in σ Ori has been confirmed independently by *Zapatero-Osorio et al.* (2003), who found a brown dwarf with a period of only 3.1 h in this cluster (see Section. 4.3). It has to be mentioned that these objects rotate fast in terms of their breakup period, which is around 3-5 h for VLM stars at the age of σ Ori. Their fast rotation might change the physics of these objects, e.g., it can be expected that they are strongly oblate. It is, perhaps, not surprising that the simple models by *Scholz and Eislöffel*, (2004b) cannot provide a correct description of the ultra-fast rotators. Clearly more sophisticated modeling has to be done for these objects.

The fact that the rotation of VLM objects follows a weak exponential braking law rather than the Skumanich law has been interpreted in terms of the magnetic field structure of these objects (*Barnes*, 2003; *Scholz and Eislöffel* 2004b). VLM objects are fully-convective throughout their lifetime, and will never develop a radiative core. As a consequence, they are probably not able to host a solar-type, large-scale dynamo, which is believed to operate in the transition layer between convective and radiative zone. Alternative mechanisms to explain the magnetic activity in the VLM regime

are the so-called turbulent dynamo (*Durney et al.*, 1993) and the α^2 (*Chabrier and Kueker*, 2006). Both types of dynamos predict reduced Alfvén radii in comparison with the solar-type $\alpha\omega$ dynamo and thus only weak braking by stellar winds. Therefore, the results from the rotational evolution analysis are consistent with the possibility of a change of dynamo mechanism in the VLM regime.

It should be noted that the cited models are not able to constrain the influence of more rapid angular loss mechanisms (e.g., from a disk interaction) on the rotational evolution, because they operate on timescales of 100 Myr. Disk-interaction timescales, for example, are probably only a few Myr (see Section 6). To assess the validity of efficient loss mechanisms such as the disk-interaction hypothesis in the VLM regime, it is clear that younger object samples have to be considered. This has been done by *Lamm et al.* (2005), in their comparison of the period samples in the ONC and NGC 2264. They found that the period evolution for VLM stars from ~ 1 Myr (ONC) to ~ 2 Myr (NGC 2264) can be described with a scenario of ‘imperfect’ disk-locking, in the sense that the rotation of the stars is not actually ‘locked’ with constant period. Instead, it spins up, but not as fast as it would with the assumption of angular momentum conservation. Thus, the disk brakes the rotation somewhat, but the interaction between star and disk is less efficient than for solar-mass stars. See Section 6 for more discussion of this.

We conclude that the mechanisms of angular momentum regulation in the VLM regime are similar to solar-mass stars, but the efficiency of these mechanisms is a function of mass. They appear to be less efficient in the VLM regime, resulting in more rapidly rotating objects on the ZAMS. We also note that, since the radii of the VLM stars are smaller, at all ages, than their solar-like siblings, for a given amount of specific angular momentum they spin faster. As *Herbst et al.* (2001) have shown, j does not vary much with mass in the ONC, so the faster rotation of the VLM stars at 1 Myr may be entirely a result of their having contracted to smaller sizes than the higher mass stars.

4.3. Brown Dwarfs

In this section we discuss the available rotational data for brown dwarfs (BDs), i.e. substellar objects intermediate in mass between stars and planets. BDs are defined as objects with masses below the hydrogen burning mass limit ($\sim 0.08 M_{\odot}$, *Chabrier and Baraffe*, 1997). Since it is only rarely possible to determine the object mass directly, the effective temperature and luminosity in combination with stellar evolutionary tracks is usually used to identify BDs. Therefore, in the following we refer to ‘brown dwarfs’ as objects whose spectral types and luminosities classify them as substellar, although some of them might have masses slightly higher than the substellar limit, because of uncertainties in spectral typing and atmosphere modeling.

Following the discovery of the first BDs (*Nakajima et al.*, 1995, *Rebolo et al.*, 1995), hundreds of them have been identified in star forming regions (e.g., *Comerón et*

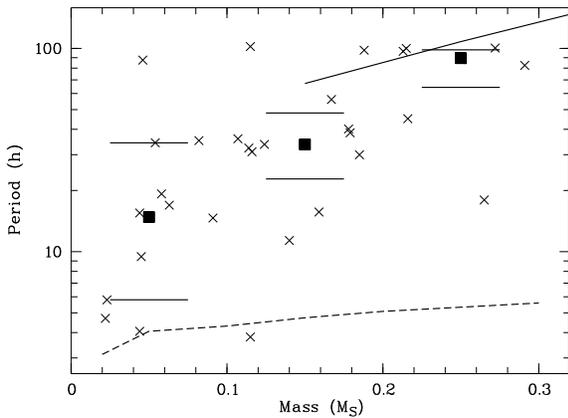


Fig. 5.— Period vs. mass for the ϵ Ori cluster (figure from Scholz and Eislöffel 2005). Filled squares mark the period median, horizontal lines the quartiles. The solid line is the period median for the ONC, the dashed line the breakup limit for ϵ Ori.

al., 2000, López Martí et al., 2004), open clusters (e.g., Zapatero-Osorio et al., 1997, Barrado y Navascués et al., 2001), and in the field (Kirkpatrick et al., 1999, Phan-Bao et al., 2001). A large number of follow-up studies led to rapid progress in our understanding of the physical properties of these objects. For example, about 30 rotation periods have been measured for BDs at different ages, complemented by rotational velocity ($v \sin i$) data. Here, we review the available periods and their implications for our understanding of rotation and the angular momentum evolution of brown dwarfs.

The first rotation period for a likely BD was published for an object in the open cluster α Per, which has an age of ~ 50 Myr (Martín and Zapatero-Osorio, 1997). In the following years, periods have been measured for three BDs in the ~ 1 Myr old Cha I star forming region (Joergens et al., 2003), three objects in the ~ 3 Myr old σ Ori cluster (Bailer-Jones and Mundt, 2001, Zapatero-Osorio et al., 2003), one object in the ~ 120 Myr old Pleiades cluster (Terndrup et al., 1999), and three so-called ‘ultracool dwarfs’ in the field (Bailer-Jones and Mundt, 2001, Clarke et al., 2002), with late-M or early-L spectral types. We would like to caution that it is not, in all cases, unambiguously clear that the photometrically derived period corresponds to the rotation period. This is particularly important for the ultracool field dwarfs which, in many cases, have relatively sparse sampling and, perhaps, less stable surface features, factors that hamper a reliable period detection. In this review, we include discussion only of periods that authors themselves consider to be likely rotation periods.

It is interesting to note that until 2003 all known periods for objects with ages > 1 Myr were shorter than one day, providing the first evidence that evolved BDs are, in general, very rapid rotators. This is supported by spectroscopic rotational velocity data, indicating that the majority of evolved BDs have $v \sin i > 10 \text{ km s}^{-1}$ (Mohanty and

Basri, 2003; Bailer-Jones, 2004). By contrast, the rotation periods for the three youngest objects in the sample, i.e. those in Cha I, are in the range of 2 to 4 days.

In the last two years, deep wide-field monitoring campaigns have more than doubled the number of known periods for BDs. In the young open clusters σ Ori and ϵ Ori, Scholz and Eislöffel (2004a, 2005) measured photometric periods for 18 probably substellar objects, 9 for each cluster. Both clusters belong to the young population of the Ori OB1b association, which has an age of about 3 Myr, although the σ Ori objects are on average probably slightly younger than those in ϵ Ori (Sherry, 2003). In σ Ori, the periods cover a range from 5.8 to 74 h with a median of 14.7 h, whereas in ϵ Ori the total range is 4.1 to 88 h with a median of 15.5 h. Thus, the BD periods in both clusters are comparable. Additionally, periods for two likely substellar members of the Pleiades (Scholz and Eislöffel, 2004b) and IC4665 (age ~ 40 Myr, Scholz, 2004) have been published. In total, the rotation sample for BDs (or objects very close to the substellar limit, see above) comprises 31 periods. In the following, we will discuss the period-mass relationship and rotational evolution in the substellar regime based on this dataset.

To separate age and mass effects, the period-mass relationship has to be studied for each age separately. In Fig. 5 (taken from Scholz and Eislöffel, 2005) period vs. mass is plotted for the ϵ Ori objects (crosses), where one of the largest BD period samples is available. The figure additionally shows the median period for certain mass bins (filled squares), together with the period-mass relationship in the ONC (solid line). We have already demonstrated in Section 4.2 that the average period decreases with decreasing object mass in the very low mass star regime. As can be seen in Fig. 5, this trend continues well-down into the substellar regime. The median in the BD regime is clearly lower than for VLM stars. The same result is obtained for the period sample in the σ Ori cluster. It is particularly interesting that the BD period range in young open clusters extends down to the breakup period, which is the physical limit of the rotational velocity. In Fig. 5 the breakup limit is over-plotted as dashed line (calculated using the evolutionary tracks of Baraffe et al., 1998). For masses below $0.1 M_{\odot}$ a sub-sample of objects rotates very close to breakup. Since extremely fast rotation affects the evolution of the objects, as we know from massive stars, this has to be taken into account in future evolutionary models for rapidly rotating BDs.

All available BD periods are plotted in Fig. 6 as a function of age. For the matter of simplicity, we assigned an arbitrary age of 1 Gyr to all evolved field objects. Whereas very young BDs have periods ranging from a few hours up to four days, all periods for older objects are shorter than 15 h. Please note that the upper period limit in the youngest clusters may be set, in part, by the upper period detection limit. In the σ Ori cluster, however, the detection limit is ~ 10 d (Scholz and Eislöffel, 2004a), leading us to the tentative conclusion that 100 h might be a realistic value for the

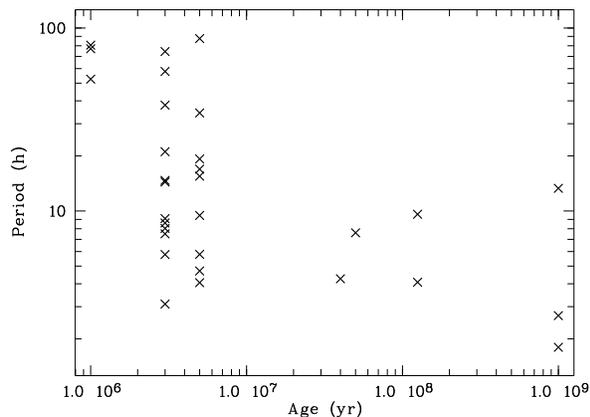


Fig. 6.— Rotation period of brown dwarfs (and objects very close to the substellar limit) as a function of age. For simplicity, periods for evolved field dwarfs were all plotted at an age of 1 Gyr.

upper period limit at very young ages. Two clear trends can be seen from Fig. 6, related to the upper and the lower period limit, which we will discuss separately in the following paragraphs.

First, the upper period limit is apparently more or less constant for ages < 5 Myr and is decreased by a factor of about 6-10 in the more evolved clusters with ages > 40 Myr. The second aspect of Fig. 6 that we wish to discuss is the lower period limit, which appears to be in the range of a few hours at all evolutionary stages. The only exception is the (very sparse) period sample for Cha I at 1 Myr, but this might be related to small number statistics or a time series sampling unable to detect short periods. Within the statistical uncertainties, the lower period limit is constant with age. Thus, for a fraction of ultrafast rotating BDs the period changes by less than a factor of two on timescales of ~ 1 Gyr. This is surprising, because on the same timescales BDs contract and we should therefore expect a rotational acceleration at least by a factor of about ten. One possible explanation is that we have not yet found the fastest rotators among the evolved BDs. Assuming angular momentum conservation, we should expect objects with periods down to ~ 0.5 h at ages > 200 Myr, i.e. when the contraction process is finished. Whether these objects exist or not, has to be probed by future observations.

If the lower period limit for evolved BDs, however, is really in the range of a few hours, as indicated by the available period data, the fastest rotators among the BDs have to experience strong angular momentum loss on timescales of 1 Gyr. It is unclear what mechanism could be responsible for this rotational braking. To summarize this section, while the rotation data on BDs are still very scanty compared to the low mass stars, they appear to be a natural extension of the phenomena observed for stars. There is nothing yet to suggest that their rotation properties and evolution are discontinuous in any way from stars.

5. Overview of Variability, Spots, Accretion and Magnetic Star-Disk Interactions in YSOs and BDs

Most of our knowledge of the rotational properties of the objects discussed here is based on variability studies. Therefore we regard it as important to give an overview on this subject, with particular attention to magnetically induced cool stellar spots and magnetically channeled variable mass accretion, the principle variability mechanisms in weak (WTTS) and classical (CTTS) T Tauri stars, respectively.

A detailed study of the various sources of TTS variability has been carried out by *Herbst et al.* (1994), based on a large electronic UBVR catalog with about 10,000 entries for several hundred stars. A further variability study, with particular attention to periodic variations, has been carried out by *Bouvier et al.* (1995). On the basis of these two and related studies one can distinguish at least 5 types of common PMS variability, at least the first two of which are also seen in BDs. These are:

1. Periodic variability caused by rotational modulation of the stellar flux by an asymmetric distribution of cool spots or spot groups on the stellar surface. This type of variability is more frequently seen in WTTSs but can also be observed in the CTTSs. An example is shown in Fig. 1. The typical amplitudes for these variations range from about 0.03-0.3 mag in the V band, with the most extreme values reaching 0.8 mag in V and 0.5 mag in I. Spot sizes and temperatures have been derived from the observed amplitudes and the derived spot coverage factors range from a few percent up to 30% (for $\Delta V=0.5$ mag, see *Bouvier et al.*, 1995).

2. Irregular variations, probably caused by highly variable, magnetically channeled accretion from the circumstellar disk onto the star. The accretion rate onto the star is not only variable in time but the accretion zones are certainly not uniformly distributed over the stellar surface. The complex interaction between the stellar magnetosphere and the inner disk is evidently highly dynamic and time dependent. The typical amplitudes of the resulting (largely) irregular variations are a factor of 2-5 larger in V than those of the periodic variations observed in many WTTs. Variations by 1.5 mag in V within a few days are not unusual and some stars can vary that much within hours. This type of variability is designated as Type II by *Herbst et al.* (1994).

3. Periodic variations due to hot spots. This type of variation (also known as Type IIp) is only seen in CTTS and the hot spots are presumably at the base of the magnetic channels. The periodicity typically persists for only a couple of rotation cycles. Since the magnetic field configuration is highly unstable, the size and location of these spots is correspondingly changing within a few rotation periods. This is quite in contrast to the cool spots which may last for hundreds to thousands of rotations. The amplitudes of the rotational modulation by hot spots is typically a factor 2-3 larger in V than those seen in WTTS due to cool spots, but

more extreme cases have been observed in some CTTSs.

4. Flare-like variations, mainly seen in the U and B-band in the WTTs. This type of variability is probably also present in CTTS, but difficult to distinguish from the strong irregular variability.

5. UX Ori-type variability (also referred to as UXors) is mostly seen in early type TTS (earlier than K0) and in Herbig Ae/Be stars. It is designated as Type III variability by *Herbst et al.* (1994). The variation amplitudes can be very large (up to 2.8 mag in V), but the time scales are about a factor of 2-10 longer compared to the irregular variations of CTTS. Also, the stars often get bluer when fainter and the $H\alpha$ flux does not correlate with the continuum flux as it does in the CTTS. *Herbst and Shevchenko* (1999) discuss this type of variability in detail. Its cause is still uncertain although many authors believe it derives from variations in circumstellar extinction.

The photometric behavior of numerous periodically variable WTTs on timescales of several years has been studied in the ONC by *Choi and Herbst* (1996) and *Steinhauer et al.* (1996) and in IC 348 by *Cohen et al.* (2004) and *Nordhagen et al.* (in preparation). In the latter case the study now extends over 7 years. These investigators found clear variations in the amplitude and light-curve shape of these periodic variables on time scales of less than one year, probably due to changes in the spot sizes and spot distributions (see Fig. 1). In no case, however, did they find definitive evidence for a change in period by more than the measurement limit of about 1%, indicating that differential rotation in WTTs is much less than in the Sun or that spots are confined to certain latitude zones. This conclusion is also supported by the very similar rotation period values found in the ONC by *Herbst et al.* (2002) in comparison to previous studies by *Stassun et al.* (1999) and *Herbst et al.*, (2000a). In NGC 1333 there may be an “exception that proves the rule”. A T Tauri star in that region has been found with a period of 5.6 d over three seasons and then 4.6 days over the next two seasons, a change exceeding 20% (*Herbst et al.*, 2005). This proves that such stars can be found, but they are clearly exceedingly rare.

It is apparent in the data that the amplitudes due to rotational modulations by cool spots strongly decrease with age. While WTTs commonly have spot amplitudes of 0.1-0.3 mag in V, this drops to about 0.02 mag for stars in the Hyades (600 Myr) and at least another factor of 10 in the case of our Sun (*Strassmeier*, 1992). The same is true for VLM stars. While the amplitudes for the VLM stars in NGC 2264 (see Fig. 7) are similar to those observed in the Pleiades (*Scholz and Eislöffel*, 2004b – which could be due to biasing of detections towards large amplitudes) they drop by about a factor 3 for late field M stars (*Rockenfeller et al.*, in preparation). It is obvious that the decreasing amplitudes with increasing age makes it more difficult to study photometrically the rotational properties of ZAMS and older clusters.

The dependence of amplitudes of the periodic light variations in PMS stars on mass (or effective temperature) has

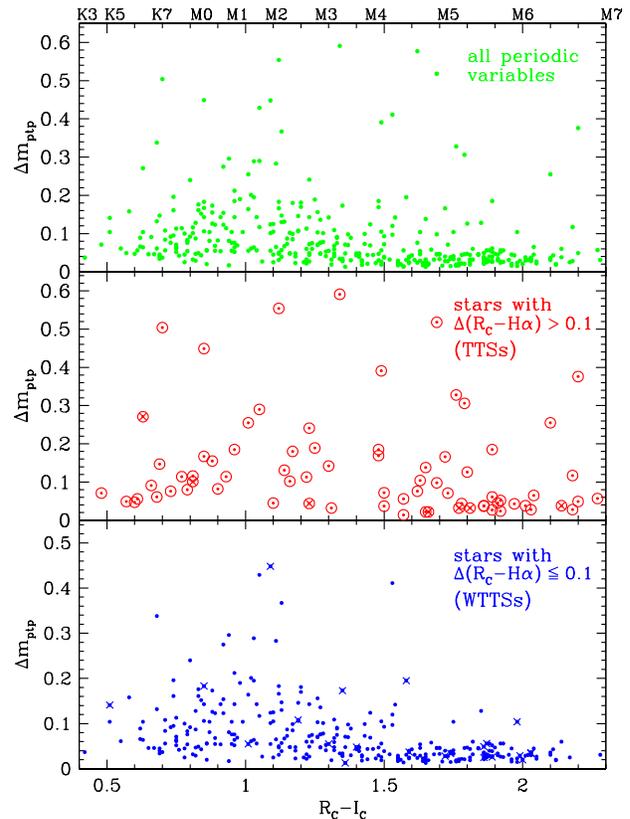


Fig. 7.— The peak-to-peak variation of the 405 periodic variables in NGC 2264 found by *Lamm et al.* (2004) as a function of their R-I color. In the top panel all 405 periodic variables are shown. The diagram in the middle panel contains only 89 stars with strong $H\alpha$ emission. In the bottom panel only the 316 stars with weak $H\alpha$ emission (WTTs) are shown. Note the strong decrease in amplitude, by about a factor 3 for the WTTs in the bottom panel with $R-I \geq 1.5$ (from *Mundt et al.*, in preparation).

been investigated by *Mundt et al.* (in preparation) for the case of NGC 2264 over a broad range of spectral types from $\sim K3$ to $\sim M6.5$. This investigation is based on the data of *Lamm et al.* (2004, 2005). The main results are illustrated in Fig. 7, which shows the peak-to-peak variation as a function of the $(R_C - I_C)$ color for three different subsamples of the periodic variables. The peak-to-peak amplitudes were derived by fitting a sine wave to the phased light curves. In the top panel of Fig. 7, all 405 periodic variables are shown. In the middle panel only the peak-to-peak variations of the 89 stars with large $H\alpha$ -indices ($\Delta(R_C - H\alpha) > 0.1$ mag, i. e. strong $H\alpha$ emitters) are shown. It is evident that these stars show a large scatter in their peak-to-peak variations, i.e. we probably deal with a mixture of stars in which either cool or hot spots are responsible for the periodic variability. Most important for our discussion is the bottom panel of Fig. 7, which shows the peak-to-peak variations for the remaining 316 stars which are mostly WTTs due to their weak $H\alpha$ emission (i. e.

$\Delta(R_C - H\alpha) \leq 0.1$ mag). From this panel it is clearly evident that the peak-to-peak variations of the cooler WTTs with $(R_C - I_C) \gtrsim 1.5$ mag show on average a factor ~ 3 smaller peak-to-peak variations than stars with $(R_C - I_C) \lesssim 1.3$ mag. This impressive decrease in the peak-to-peak variations for stars with $(R_C - I_C) \gtrsim 1.5$ mag is practically independent of the period of the investigated stars. Only for the slowest rotators might there be a tendency for somewhat higher peak-to-peak variations. We note that the objects with $(R_C - I_C) \gtrsim 2.0$ mag are all VLM stars ($\leq 0.1-0.15M_\odot$) with some of them probably falling below the substellar limit. A similar decrease in the peak-to-peak variations of the periodic variables with decreasing mass was found by *Scholz and Eisloffel* (2004) in the Pleiades.

This tremendous decrease in the peak-to-peak variations of the coolest periodically variable WTTs either implies that the spot coverage of the stellar surface, the asymmetry of the spot distribution, and/or the contrast between the spot and the photospheric environment has decreased. It has been argued by *Mundt et al.* (in preparation) that the spot coverage (spot size) has probably decreased as a result of the much poorer coupling between the magnetic fields and the atmospheric plasma caused by the low ionization fraction in the atmosphere of these very cool objects. The change in peak-to-peak variations of WTTs due to cool spots was also investigated by *Bouvier et al.* (1995) but only for spectral types between about G0 and K7 and only for a sample of 23 stars. In this spectral range the peak-to-peak variations apparently *increase* with decreasing temperature. Such a behavior is not inconsistent with the data displayed in Fig. 7, since there the median value for the peak-to-peak variations, in fact, increases until $(R_C - I_C) \sim 1$ mag ($\sim M1$).

It is quite obvious from Fig. 7 and the work summarized above that periodic light modulations due to cool spots are observable over a very large mass range; i.e. from about $1.5M_\odot$ well down into the substellar mass regime. We know that the same is true for variable mass accretion and accretion related activity phenomena. Such CTTS-like phenomena are observable in young VLM stars and young BDs down to masses near the deuterium burning limit (see e.g., *Mohanty et al.*, 2005a for a review). Examples of such accretion-related activity are numerous and include strong line-emission (e.g., *Mohanty et al.*, 2005b), variable line-emission (e.g., *Barrado y Navascués et al.*, 2003), irregular variations in the continuum flux (e.g., *Zapatero-Osorio et al.*, 2003, *Scholz and Eisloffel*, 2004a, 2005), and bipolar emission line jets (*Whelan et al.*, 2005). It remains for us to discuss the confrontation between theory and observation which involves the connection between rotation, magnetic fields and accretion disks in all of the mass ranges discussed here from stellar to substellar.

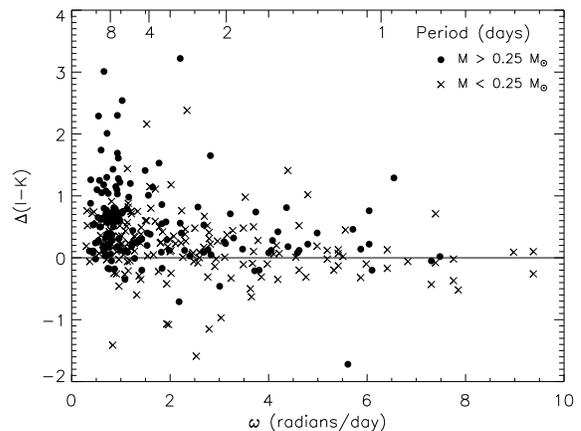


Fig. 8.— Infrared excess emission depends on rotation for PMS stars in the ONC (from *Herbst et al.*, 2002). The indicated mass range is based on a spectral class range and would translate into masses greater than 0.4 solar masses by some models. Since infrared excess is an indication of an accretion disk, this figure clearly demonstrates the rotation-disk connection.

6. Interpretations: Comparison of Empirical Results with Theory

The leading theory to account for the slower than critical rotation rates observed for T Tauri stars is commonly known as “disk locking” and was first proposed by *Camenzind* (1990) and *Königl* (1991). It has been worked out in more detail by *Shu et al.* (1994) and others, most recently by *Long et al.* (2005). Its principal success in the rotation arena is in predicting an equilibrium rotation period in the 2 to 8 day range, characteristic of the observations, when other parameters, such as surface magnetic field strength and accretion rate, are set to nominally representative values. Observational credence is given to this picture by the fact that a statistically significant anti-correlation does exist between angular velocity and various disk indicators such as near-infrared excess and $H\alpha$ equivalent width (*Edwards et al.*, 1993; *Herbst et al.*, 2002; *Lamm et al.*, 2004, 2005; *Dahm and Simon*, 2005; *Rebull et al.*, 2005). Fig. 8 shows the anti-correlation for one cluster, the ONC.

Note that these anti-correlations, including the one in Fig. 8, generally indicate that rapid rotators are very unlikely to have disks, while slow rotators may or may not have them. This is actually what one would expect from a disk locking (or, more generally, disk regulation) scenario. In particular, a star does not respond instantaneously to the loss of angular velocity regulation. It takes time for a star to contract and spin up. Some stars that are no longer regulated, i.e. have lost their accretion disks recently, would be expected not to have had time yet to spin up. They would appear as slow rotators that lacked accretion disks. It would be harder, in this scenario, to explain rapid rotators with disks and, indeed, such stars are rare in the sample. It would

be interesting to inquire more deeply if there are, in fact, any such cases that cannot be ascribed to errors of observation.

In spite of its successes, the disk locking theory has been controversial over the years. Many authors have pointed to various shortcomings of either the theory or its confrontation with observation (e.g., *Stassun et al.*, 1999, 2001; *Rebull*, 2001; *Bouvier et al.*, 2004; *Uzdensky*, 2004; *Littlefair et al.*, 2005; *Matt and Pudritz*, 2004, 2005a,b). The interested reader is referred to the meeting report by *Stassun and Terndrup* (2003) and references therein, as well as to the recent review by *Mathieu* (2004) for further discussion. Here we note that the difficulties appear to us to be rooted in the natural complexity of the phenomena and our limited ability to either model them or to obtain a sufficient amount of accurate data to empirically constrain them. As with all MHD processes, theoretical progress can only be made with simplifying assumptions such as axisymmetric magnetic fields and steady accretion, which we know in the case of T Tauri stars are not realistic. For example, if the geometry of the problem were truly axisymmetric for a typical star then we would not observe cyclic photometric variations with the rotation period. If accretion were truly steady, we would not see the large amplitude irregular photometric variations characteristic of CTTS.

Time-dependent magnetic accretion models may result in a decreased braking of the stellar rotation rates in comparison to the simple disk locking scenario (*Agapitou and Papaloizou*, 2000). It has been argued by *Matt and Pudritz*, (2005a,b) that the magnetic braking of PMS stars may not be due to a magnetic star-disk interaction, but may result from a magnetically driven wind emanating directly from the star. If the high rotation rates of Class I protostars compared to Class II protostars (CTTSs) observed by *Covey et al.* (2005) are confirmed by further studies they may imply angular momentum loss rates higher than predicted by the disk locking scenario. Note that in the disk locking scenario the Class II sources should rotate as fast as the Class I sources. If they in fact rotate a factor of 2 slower, it may demand a braking mechanism more efficient than disk locking to account for the observations. A strong magnetically driven wind, as proposed by *Matt and Pudritz* (2005a,b), is certainly an idea which deserves further study. An observational argument in favor of a wind emanating directly from the stellar surface is the broad and deep P Cygni profiles observed in some CTTSs (see e.g., *Mundt*, 1984). The deep blue-shifted absorptions of these line profiles would be much harder to understand if the wind acceleration region is far from the stellar surface, as would be the case for a disk wind.

From the theoretical side, part of the difficulty in testing the disk locking theory is that it is hard to pin down specific, testable predictions that are based on realistic models, especially when parameters such as the magnetic field strength are involved, that are hard to observe. Some attempts to test the theory in detail have met with mixed success (*Johns-Krull and Gafford*, 2002). Observationally, we are further faced with the problem of a very broad distribution of ro-

tation rates at any given mass and age as well as the difficulties of even establishing mass and age for PMS stars. Magnetic phenomena are notoriously complex and this apparition of their importance is no exception. Considerations such as these have led *Lamm et al.* (2004, 2005) for example to employ the terminology “imperfect” disk-locking to account for the data. The notion that a star’s rotation is fully controlled by its interaction with a disk during all of its PMS phase in a way that can accurately be described by a current disk-locking theory is probably oversimplified. Nonetheless, the concept of disk regulation of, or at least effect on, rotation seems undeniable in the light of the observed correlations, such as seen in Fig. 8.

Indeed, there is no way to understand the evolution of rotation of stars from PMS to ZAMS without invoking significant braking for a significant amount of time (c.f. Figure 3). All attempts to model this have employed such “disk locking” (e.g., *Armitage and Clarke* 1996; *Bouvier et al.*, 1997; *Krishnamurthi et al.*, 1997; *Sills et al.*, 2000; *Barnes et al.*, 2001; *Tinker et al.*, 2002; *Herbst et al.*, 2002; *Barnes*, 2003; *Rebull et al.*, 2004; *Herbst and Mundt*, 2005). Usually, the approach is to include the “disk locking time” as a parameter in the models. In its simplest form this is the time that the period remains constant, after which it is allowed to change in response to the contraction of the star.

Obviously a real star would not be expected to maintain a constant rotation period for times of order 1 Myr, even if the disk locking theory were strictly true, since other parameters of the problem, such as magnetic field strength and accretion rate are likely to vary on this time scale (or shorter – perhaps much shorter). Hence, the parameterized models are only approximations of reality. What is interesting and significant is that it is simply not possible to model the rotational evolution of solar-like ($0.4-1.2 M_{\odot}$) stars from PMS to ZAMS without significant braking for about half of them. And, the observations show that the half that must be braked is the half already slowly rotating (Figure 3), precisely the same stars that are most likely to show evidence of circumstellar disks (Figure 8). We note that the maximum braking times found by various authors are of the same order, normally around 5-10 Myr, comparable to the maximum lifetime of accretion disks derived from near-infrared studies (e.g., *Haisch et al.*, 2001). Of course, it is possible that the influence of a disk on rotation may wane before its detectability in the infrared, so if disk-locking times are somewhat shorter than disk-detectability times this may not be surprising. Nonetheless, rotation studies and infrared excess emission studies appear to concur in indicating that substantial gaseous accretion disks have disappeared by about 5 Myr for almost all stars and by about 1 Myr for half of them. This, in turn, implies that the era for gas giant planet formation has ended. Terrestrial planets may, of course, continue to form around such stars for much longer periods of time.

Finally, we would like to make some comments on the disk locking scenario and on magnetic star-disk coupling in general as it applies to VLMs and BDs. As discussed above,

the disk locking scenario is quite successful, in some ways, in explaining important aspects of the rotational evolution of low-mass stars with masses larger than about $0.4 M_{\odot}$. On the other hand for VLM stars below this mass limit the evidence is less convincing (see e.g., *Lamm et al.*, 2005). Nevertheless, it appears from the available data that those VLM objects showing evidence for active accretion (e.g., strong H_{α} emission) do rotate on average much slower than those stars without any accretion indicators. This means that these low-mass objects do indeed lose angular momentum, but probably at a lower rate than in the case of precise disk locking. Therefore the term “moderate angular momentum loss” was proposed by (*Lamm et al.*, 2005).

The efficiency of disk locking is likely to decrease in the VLM star and BD regimes. Unfortunately, it is very difficult to test these ideas observationally because of the difficulties of determining rotation periods, masses and ages for large samples of VLMs and BDs. In particular, we lack a sufficient amount of data for ZAMS VLMs that could provide a goal for the PMS evolution analogous to what is available for the solar-type stars. As argued in Section 4.2, rotational braking by stellar winds is also probably less efficient for VLM objects, either because they have no solar-like dynamo or because of little coupling between gas and magnetic field due to low gas temperatures in the atmosphere. As already noted above, the period distribution at very young ages extends down to the breakup limit (see Fig. 5). This might have an effect on the fastest rotators, in the sense that strong centrifugal forces remove angular momentum and thus brake the rotation, as argued by *Scholz and Eislöffel* (2005). If and how this can explain the observed period evolution has to be investigated with detailed future modeling.

Even in the substellar regime there is some evidence for disk braking or some other form of angular momentum loss related to disks. Accreting, very young objects are nearly exclusively slow rotators, whereas non-accretors cover a broad range of rotation rates (*Scholz and Eislöffel*, 2004a, *Mohanty et al.*, 2005a). The magnetic braking of the disk in the PMS phase is probably less strong than for solar-like stars, but it still might be able to prevent the objects from conserving angular momentum during the first few Myrs of their evolution. After that, there seems to be very little chance for significantly slowing the rotation of BDs and their rotational evolution is probably dominated by conservation of angular momentum as they continue to contract. Since the radii of substellar objects are expected to decrease by a factor of ~ 3 , due to hydrostatic contraction, on timescales of ~ 200 Myr (*Baraffe et al.*, 1998), the periods should decrease by a factor of ~ 9 on the same time scale, assuming angular momentum conservation. Thus, the decline of the upper period limit between 5 Myr and the older clusters seen on Fig. 6, is probably just reflecting conservation of angular momentum and is roughly consistent with it quantitatively. Finally, while at young ages, substellar objects are clearly able to maintain magnetic activity which should lead to mild rotational braking by stellar winds on

timescales of about 100 Myr, they seem to lose their magnetic signatures as they age and cool. Objects with spectral type L, into which these objects evolve, have been found to be too cool to maintain significant chromospheric and coronal activity (*Mohanty and Basri*, 2003). Hence, there is probably little or no rotational braking by stellar winds on very long timescales, explaining why the upper period limit on Figure 6 stays at a very low levels for a very long time. Again, it will clearly be necessary to expand the data sample in order to test these ideas more rigorously.

To summarize, in the time since Protostars and Planets IV we have seen a tremendous growth, by a factor of 10 or more, in the number of PMS stars for which we know the rotation period. Coupled with similar data for young clusters we now have a good, statistical picture of the evolution of surface angular momentum for solar-like stars from 1 Myr to the ZAMS (Fig. 3). To a first approximation, at 1 Myr the stars already divide into a slower rotating half and a more rapidly rotating half. The division is exaggerated over the next few Myr as the slower rotating stars continue to suffer substantial rotational braking while the faster rotators spin up in rough agreement with angular momentum conservation as they contract towards the ZAMS. The braking is disk related (see Figure 8) and persists for around 5-6 Myr.

At the same time we have begun to probe into the low mass and substellar mass regimes with the same photometric technique, although the amplitudes of the variations (Figure 7) and faintness of the objects make it a more difficult problem to find rotation periods. Nonetheless, the data show similar kinds of behavior for these stars (Figure 5), although braking by both disks and winds appears to become increasingly less efficient as one progresses to smaller mass objects (Figure 6). It is in this mass regime that we expect the next five years to bring particular progress, since there is so much to be done. It is also likely that the improved data on disks coming from the *Spitzer Infrared Telescope* and elsewhere will help sharpen the observational tests relevant to disk locking and other theories. Finally, the difficult problem of what happens during the first 1 Myr (i.e. the proto-stellar and early PMS phases) to produce such a broad rotational distribution already in the ONC will hopefully become clearer as data on the highly embedded objects continue to accumulate.

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