THE SURFACE AND INTERNAL ROTATION OF LOW-MASS STARS IN YOUNG CLUSTERS*

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ABSTRACT. Many new and exciting results on the rotation of low-mass young stars have been obtained during the past year. New clusters, with an age intermediate between the Pleiades and the Hyades, have been studied, which provides a more accurate estimate of the spin down timescale of solar-type stars on the main sequence. The rotation rates of the lowest-mass stars in the Pleiades and the Hyades have been measured with large telescopes, which bring clues onto how angular momentum losses depend upon stellar mass. The slowest rotators in the Alpha Persei and Pleiades clusters had their velocity resolved, leading to the derivation of the complete distribution of equatorial velocity in these 2 clusters. These major results and their implications for the evolution of surface and internal rotation, lithium depletion and stellar activity are reviewed and discussed.

1. Introduction

The unexpected discovery of very fast rotators among solar-type members of the Pleiades cluster by Van Leeuwen and Alphenaar in 1982 was the starting point of a complete renewal of concepts regarding the early angular momentum evolution of low-mass stars. The following 15 years have seen a lot of efforts devoted to measure the distribution of rotation rates in young stars and a number of models were developped to account for the observations.

A year ago, 3 clusters dominated the observational stage: Alpha Persei (50 Myr), Pleiades (100 Myr) and Hyades (600 Myr). By the time of this meeting, at least 4 new clusters have been added to the database: IC2602/IC2391 (35 Myr), M7/M34 (200 Myr) (Patten & Simon 1996, Stauffer et al. 1997a, Prosser et al. 1995, Jones et al. 1997). Being slightly younger than Alpha Persei, the IC clusters sample the distribution of rotation right at the ZAMS for solar-mass stars. The intermediate-age Messier clusters fill the gap between Pleiades and Hyades, thus yielding a more accurate estimate of the spin down timescale of fast rotators on the main sequence. The narrower temporal sampling of the evolution of rotation rates in young stars obtained from these observations brings new insight into the processes that drive angular momentum evolution close to the ZAMS (Section 2).

Another major area of progress has been the measurements of the rotation rates of the *slowest* rotators in the Alpha Persei and Pleiades clusters (Allain et al. 1997,

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Queloz et al. 1997). A year ago, about half of the late-type stars in these clusters only had $v\sin i$ upper limits of about 7-10 km s^{-1} . While it may seem unimportant to know whether a star rotates at 8 or 4 km s^{-1} on the ZAMS, such a small difference has in fact a tremendous impact on models and on our understanding of the angular momentum evolution of slow rotators. These upper limits have therefore been a long-standing source of embarrassment. During the past year, all these upper limits have been resolved for stars more massive than 0.6 M$_\odot$. For the first time, the *complete* $v\sin i$ distributions of low-mass stars in the 2 clusters are available. These distributions and their implications are discussed in Sections 2-4.

Up to a year ago, most observational studies and theoretical modelling were limited to stars more massive than about 0.6 M$_\odot$. Most lower-mass cluster stars were simply too faint to have their $v\sin i$ measured with 4m-class telescopes. And evolutionary codes for very low-mass stars were not quite mature yet. The advent of larger telescopes has solved the former problem, and a new generation of stellar evolution codes is in the process of solving the latter (Baraffe & Chabrier 1996). Today, the rotation rates of very low-mass stars (M$\leq$0.3 M$_\odot$) have been measured in the Alpha Persei, Pleiades and Hyades clusters (Jones et al. 1996, Martín & Zapatero-Osorio 1997, Stauffer et al. 1997b), as well as in the field (Basri & Marcy 1995, Delfosse et al. 1997). The evolution of rotation in very low-mass stars is easier to model than that of higher-mass ones if uniform rotation may be assumed in their fully convective interiors. This relieves the models from uncertain assumptions regarding the transport of angular momentum in the partially radiative interiors of higher mass stars. Therefore, very low-mass stars provide a much more direct test bench for the modelling of angular momentum loss (Section 5).

2. Distribution of rotation in young clusters

Starting in the mid-80s, the CfA and StSci groups (Stauffer et al., Prosser et al., Soderblom et al.) have provided most of the published measurements of projected velocities for late-type members of the α Per and Pleiades clusters (see Stauffer's 1991 review). For many years, the resulting $v\sin i$ distributions have been used to develop models of angular momentum evolution (Pinsonneault et al. 1989, Soderblom et al. 1993, Bouvier 1994, Cameron et al. 1995, Keppens et al. 1995, Krishnamurthi et al. 1997). Up to until last year, however, the comparison between models and observations was limited by the velocity resolution of 7-10 km s^{-1} of most observational studies, which left about half of the cluster stars with unknown $v\sin i$. This situation was improved upon by the Geneva and Grenoble groups (Queloz et al., Allain et al., Mermilliod et al.) who used the new generation CORAVEL spectrograph, ELODIE at Observatoire de Haute-Provence, with a velocity resolution of 2 km s^{-1} , to measure the $v\sin i$ of all slow rotators in the two clusters. By combining the results of all groups, *complete* $v\sin i$ distributions are now available for low-mass stars in the α Per and Pleiades clusters.

The new $v\sin i$ distributions are shown as a function of mass in Figure 1. The progress made over the past year in the definition of $v\sin i$ distributions is strikingly illustrated by the comparison of Figure 1 with Figure 1 of Soderblom et al. (1996). The eye can now easily distinguish a clear rotational main sequence in the Pleiades, with a rapidly decreasing $v\sin i$ towards lower mass stars, down to about 5-6 km s^{-1} at 0.8 M$_\odot$, which

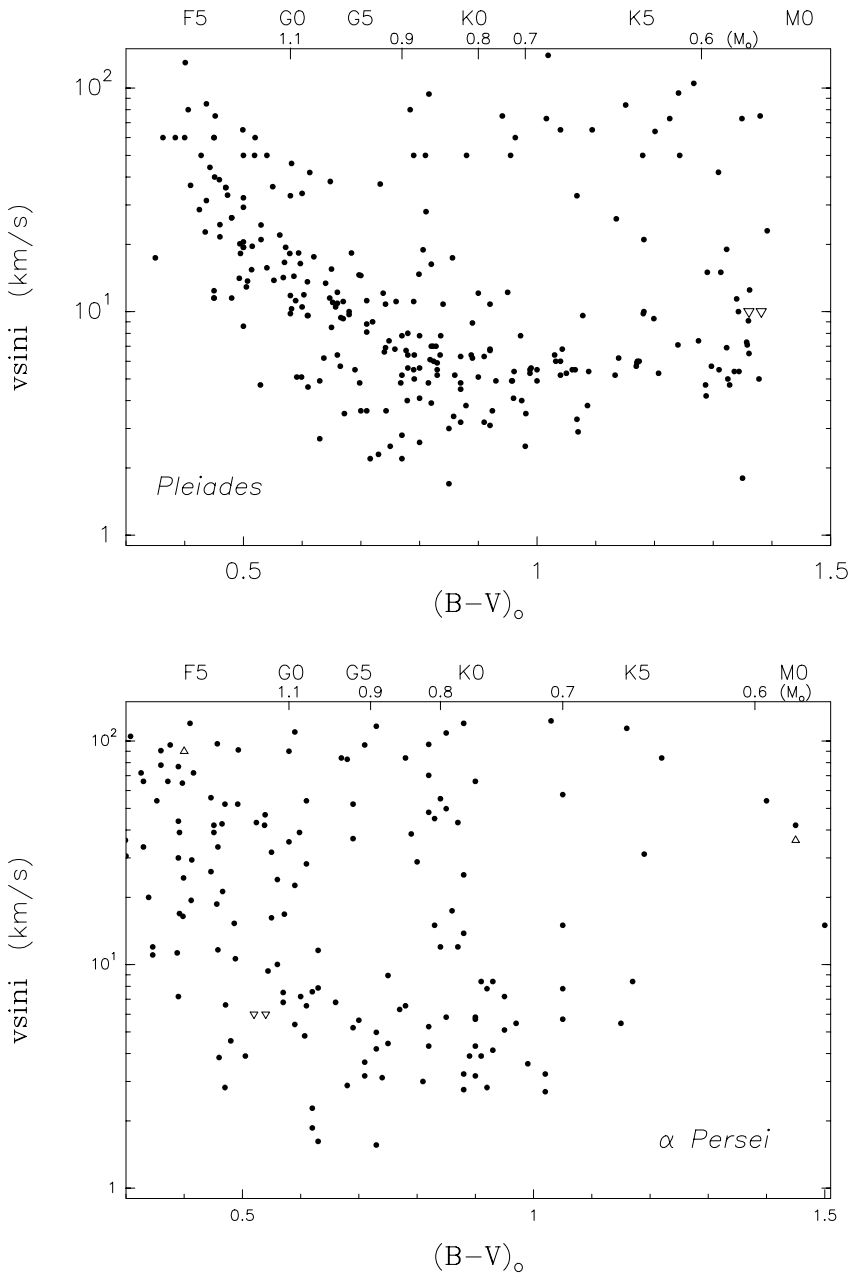

Fig. 1. Observed $v\sin i$ distributions for Pleiades (upper panel) and α Per (lower panel) late-type stars (adapted from Queloz et al. 1997, Allain et al. 1997).

appears to flatten out towards very low-mass stars. This sequence parallels that seen in the much older Hyades cluster and lies slightly above, indicative of angular momentum loss occuring between the Pleiades and Hyades age even for slow rotators. The α Per cluster does not show such a well-defined rotational sequence. Part of it may be due to the smaller sample size. However, especially for F and early G stars, there seems to be an enhanced $v\sin i$ dispersion in the α Per distributions compared to Pleiades ones.

Assuming a random distribution of rotational axes, it is now possible to apply statistical methods in order to derive the distribution of *equatorial* velocities from the complete distribution of *projected* velocities (Gaigé 1986), i.e., to get rid of the unknown $\sin i$ projection factor. This has been done for the two clusters in various mass bins and the results are reported elsewhere in this volume (Allain et al., Queloz et al.). The derivation of complete equatorial velocity distributions allows a much more precise comparison with the models. In Figure 2, the evolution of rotation in slow, intermediate and fast rotators is shown as a function of time. The importance of $v\sin i$ measurements in intermediate-age clusters, such as M34 (Jones et al. 1997), is clearly seen from these plots: by filling the huge age gap between Pleiades and Hyades, they provide a much more accurate estimate of the spin down time scale of fast rotators on the early main sequence. The comparison between the upper and lower panels of Figure 2 shows how the evolution of rotation depends upon mass. It was already known that the spin down timescale of fast rotators increases for lower mass stars: the decrease of the maximum velocity on the early main sequence is much steeper for the 0.9-1.1 $M_\odot$ sample than for the 0.6-0.9 $M_\odot$ one. In contrast, slow rotators appear to experience more braking between the Pleiades and Hyades clusters in the 0.6-0.9 $M_\odot$ range than in the 0.9-1.1 $M_\odot$ range.

Perhaps the most important feature revealed by these plots is the different evolution of surface rotation between fast and slow rotators. While the equatorial velocity of fast rotators steadily decreases on the main sequence, slow rotators show evidence for braking on the ZAMS, between α Per and Pleiades , but their surface velocity exhibits little change, at least for solar-mass stars, between the Pleiades and Hyades cluster. This plateau, which lasts for about 600 Myr, is indicative of angular momentum being transported from the radiative core to the convective envelope on a timescale of several 100 Myr. The lack of such a plateau for rapid rotators suggests a much faster redistribution of angular momentum in the stellar interior. These qualitative statements can be put on more quantitative grounds by comparing the observations with the predictions of various classes of models.

Figure 3 shows how models with (Allain 1997) and without (Bouvier et al. 1997) core-envelope decoupling compare with observations. The results are shown only for solar-mass stars, but the same conclusions apply to 0.6-0.9 $M_\odot$ stars. The steadily decrease of equatorial velocity of fast rotators on the main sequence is well reproduced by solid-body models. Decoupled models would predict a much flatter spin down curve due to the resurfacing in the convective envelope of angular momentum tapped in the radiative core during PMS and ZAMS evolution. In contrast, the evolution of slow rotators is better accounted for by decoupled models. Both the ZAMS braking and the rotational plateau on the early main sequence result from core-envelope decoupling. In solid-body rotation, ZAMS braking does not occur because the whole star instead of

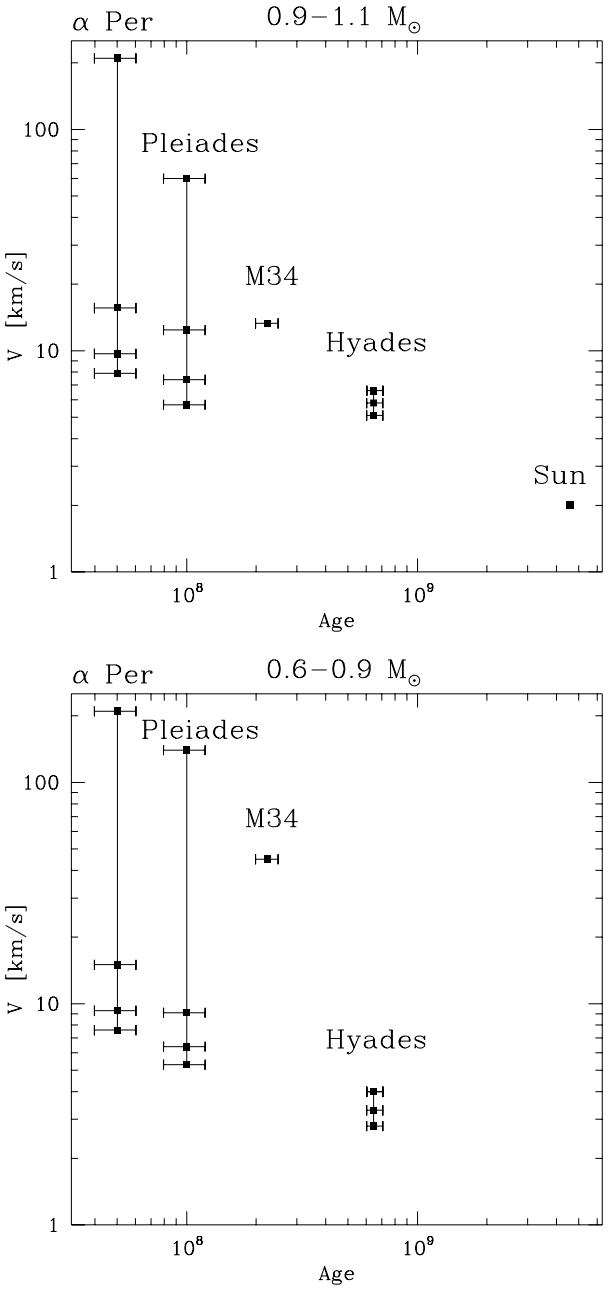

Fig. 2. The evolution of equatorial velocity of 0.9-1.1 $M_\odot$ (upper panel) and 0.6-0.9 $M_\odot$ (lower panel) stars. For the α Per and Pleiades clusters, 4 velocities are illustrated. The two lower velocities correspond to the 10 and 20% level of the cumulative distribution of equatorial velocities F(v), respectively, and are taken to be representative of the minimum velocity in the cluster, the median velocity corresponds to F(v)=50%, and the maximum velocity corresponds to F(v)$\simeq$100%. For M34 (Jones et al. 1997), only the maximum velocity is plotted, since the limited size of the sample and the presence of $v\sin i$ upper limits does not allow us yet to derive the distribution of equatorial velocities. The maximum $v\sin i$ in this cluster ought to be a good estimate of the maximum equatorial velocity. For the Hyades, the minimum, median and maximum equatorial velocities were computed from the rotational period measurements of Radick et al. (1987).

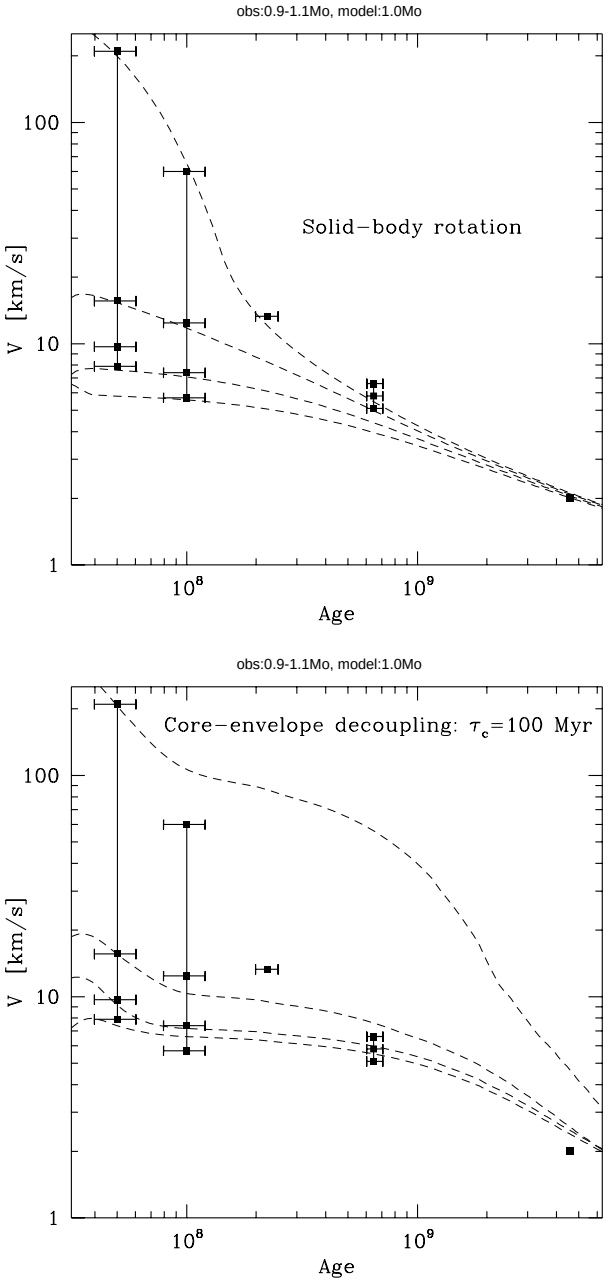

Fig. 3. Comparison between observations and models with (lower panel) and without (upper panel) core-envelope decoupling. The models in the upper panel have been computed for 1 $M_\odot$ stars assuming solid-body rotation. Those in the lower panel were computed for 1 $M_\odot$ stars following McGregor (1991) prescription for core-envelope decoupling with a recoupling timescale of 100 Myr.

only the convective envelope has to be braked, which occurs on a much longer timescale. And the plateau cannnot be reproduced as the whole star is steadily braked over the main sequence evolution if uniform rotation is assumed.

Thus, the modelling of surface rotation and its evolution near the ZAMS brings clues to the internal rotation profile of young stars. It suggests that fast rotators have little internal differential rotation, while, on the opposite, slow rotators develop large internal velocity gradients during their PMS and ZAMS evolution. Why are the internal rotation profiles of fast and slow rotators different on the ZAMS is yet unclear. The amount of differential rotation in the stellar interior depends upon the relative timescale for angular momentum loss at the stellar surface, τ_J , and the timescale for redistribution of angular momentum in the stellar interior, $\tau_{\Delta J}$. Strong angular momentum losses and inefficient angular momentum redistribution, i.e. τ_J /$\tau_{\Delta J}$ $<<1$, lead to large internal velocity gradient and vice-versa. Krishnamurthi et al. (1997) argued that $\tau_{\Delta J}$ is much longer is slow rotators than in fast ones, which could account for their respective rotational profiles on the ZAMS. Alternatively, τ_J is much shorter in slow rotators than in fast ones during the PMS (cf Bouvier et al. 1997, Fig.6), which would also provide a qualitative explanation for their differing internal rotation on the ZAMS. Most likely, both τ_J and $\tau_{\Delta J}$ depends upon the instantaneous rotational state of the star, and much theoretical work remains to be done to estimate their relative importance in dictating the internal rotation profile of young stars.

Regardless of the physical mechanism which is at the origin of differential rotation in ZAMS slow rotators and solid-body rotation in rapid rotators, this result has some important implications for the lithium depletion problem and for the dynamo process that leads to the strong magnetic activity observed in young cluster stars. These topics are discussed in the next 2 sections.

3. Lithium depletion and angular momentum loss

The pattern of lithium abundances in young clusters shows a number of yet unexplained features (Randich et al. 1997, Jones et al. 1997, see the review by Martín, this volume). G stars suffer little Li-depletion up to an age of a few 100 Myr. In young K stars, a large dispersion of lithium abundances is observed which scales with rotation: rapid rotators are Li-undepleted, while the slow rotators have suffered significant PMS Li-depletion. By the age of the Hyades, the dispersion in Li abundances has disappeared, but later on the main sequence, a large Li dispersion is observed among G stars (Pasquini et al. 1997). The Li-rotation relationship observed for 0.7-0.9 $M_\odot$ stars in young clusters suggests that the amount of Li depletion may be, at least partly, controlled by the PMS rotational history of the star. For instance, it has been suggested that angular momentum loss at the stellar surface triggers enhanced angular momentum transport in the stellar interior, and that the resulting extra-mixing shortens the timescale for Li burning (Pinsonneault et al. 1990, Zahn 1992).

According to recent models, the evolution of rotation in low-mass stars during the PMS is primarily controlled by the interaction between the star and its circumstellar disk. Figure 4 shows the total angular momentum of slow and fast rotators as a function of time. Stars with long-lived circumstellar disks are strongly braked during the PMS

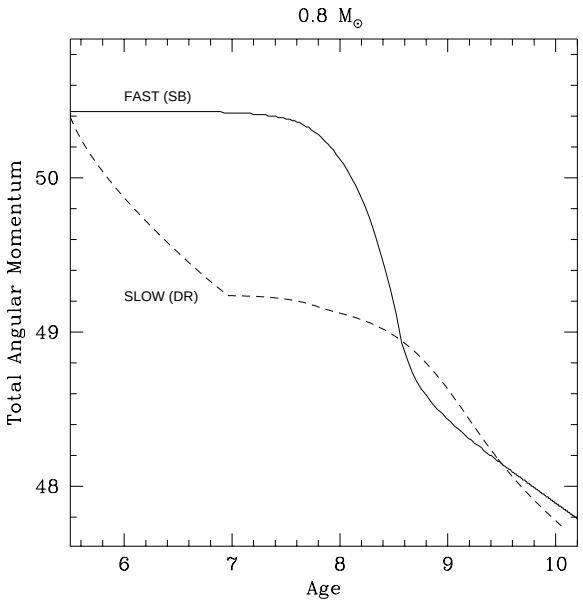

Fig. 4. The angular momentum evolution of slow and fast rotators. The models for slow and fast rotators are the same as those shown in Figure 3, i.e. SB rotation for fast rotators, and DR for slow ones.

and reach the ZAMS as slow rotators. On the opposite, those with short-lived disks hardly lose angular momentum and reach the ZAMS as rapid rotators. The *timing* of angular momentum loss is thus very different in the 2 cases: slow rotators lose most of their angular momentum during the PMS, while fast rotators do so only on the early MS.

Assuming that extra-mixing (i.e. beyond the conventional convective mixing) is induced by angular momentum loss, one would then expect slow rotators to be more Li-depleted than rapid ones on the ZAMS. This is, qualitatively, what the observations show for 0.7-0.9 $M_\odot$ stars. The effect of extra-mixing will be less pronounced in higher-mass stars, because of their shallower convective zone. It will also be marginal in very low mass stars, whose PMS Li depletion primarily results from deep convective mixing. Extra-mixing induced by enhanced angular momentum loss during the PMS will have a significant effect on Li depletion only in the mass range where the bottom of the convective zone is close enough to the Li-burning layer.

Once on the ZAMS, the slow rotators lose angular momentum at a very slow pace and Li depletion will now take place on a much longer timescale. At the same time, however, fast rotators lose most of their angular momentum (Fig.4). If J loss-induced mixing is at work, fast rotators are expected to deplete Li on the early MS, between the age of the Pleiades and that of the Hyades. Thus, the initially large dispersion of Li abundances observed at the ZAMS decreases on a timescale of a few 100 Myr.

Later on the MS, no fast rotators remain in the mass range 0.5-1.1 $M_\odot$ and Li depletion proceeds primarily due to convective mixing. The evolutionary timescale is now much longer (several Gyr), so that convective mixing has more time to operate beyond the age of the Hyades. Indeed, low-mass stars of the field are all strongly Li-depleted.

The addition of J loss-induced mixing to convective mixing leads to a somewhat surprising prediction for the late-MS. Once all the stars, regardless of their past rotational history, have reached similar surface and internal rotation, i.e., by the age of the Sun, the overall extra-Li depletion due to J loss-induced mixing amounts to:

$$\Delta[Li] \propto \int_{t_{Li}}^{t_\odot} \dot{J}_{loss}(t)dt$$

where t_{Li} is the epoch during the PMS when Li burning starts due to the development of the radiative core (e.g. $t_{Li} \simeq 2$ Myr for 0.8 $M_\odot$). Figure 4 shows that slow rotators lose significant amount of angular momentum *before* t_{Li}, when Li cannot be burnt yet. Therefore, integrated over the whole rotational history, the overall lithium depletion $\Delta[Li]$ due to rotational-mixing will be less in slow rotators than in fast rotators (contrary to what it is on the ZAMS). Hence, some dispersion in the lithium abundances is expected to remain in the late-MS (Pasquini et al. 1994, 1997). At an age of a few Gyr, stars may have forgotten their past rotational history (i.e., all surface rotation rates are uniformly low), but part of it may still be reflected in their lithium content. Applying this speculation to the (Li over-depleted) Sun would suggest that it once was a fast rotator on the ZAMS.

The purpose of the above speculations is merely to stress that: *if rotation plays a role in the lithium depletion rate, then Li-depletion models have to worry about the whole rotational history of the stars.* In particular, they should include the phase of strong angular momentum losses experienced by slow rotators during the PMS, which has been largely overlooked so far. Indeed, it is not the instantaneous rotation rate of a star at a given time that matters for Li depletion but its whole past rotational history. In this respect, the different timing of the major phases of angular momentum losses in slow and fast rotators, occuring during the PMS for the former and during the early MS for the latter, may prove to be important to understand the evolution of the Li pattern in young clusters.

4. Implications for magnetic activity: the nature of the dynamo

Magnetic activity in late-type stars is linked to rotation through a dynamo process. The activity-rotation relationships exhibited by low-mass stars in young clusters provide a clear confirmation of this physical link, and show that saturation of magnetic activity diagnostics occurs at relatively low velocity (5–15 km s^{-1} , see Randich, this volume). The usual interpretation, in the framework of the $\alpha - \omega$ dynamo model, is that the level of surface magnetic activity scales with the amount of magnetic flux generated internally by the action of differential rotation and turbulent convection on seed magnetic fields. It is further assumed that internal diferential rotation increases with surface rotation, so that the enhanced magnetic activity of fast rotators naturally results.

The latter assumption is questioned by the modelling of rotation in young clusters, which suggests that, at least on the ZAMS, fast rotators behave like solid-bodies while slow rotators harbour large internal velocity gradients. That is: *the amount of internal differential rotation does not seem to scale with the surface rotation rate on the ZAMS*, but perhaps quite the opposite (this may also be true later on the MS, see Donahue et al. 1996). Another type of dynamo would then be instrumental in fast rotators, which relies primarily on turbulence rather than on differential rotation. Rüdiger & Kitchatinov (1993), for instance, have shown that such an α^2 dynamo has the same basic properties as an $\alpha - \omega$ dynamo, namely: the magnetic flux increases with rotation (due to the effect of rotation on turbulence) and saturates at high rotation rates. Therefore, an α^2 dynamo is as plausible as an $\alpha - \omega$ dynamo for the interpretation of saturated activity-rotation relationships in young clusters.

There is independent evidence that turbulent dynamos, instead of the solar-like shell dynamo, are at work in stars with thick convective zones. For instance, Delfosse et al. (1997) found no break in the activity-rotation relationships in late-type field dwarfs across the mass-boundary where stars become fully convective ($\simeq$0.3-0.4 $M_\odot$).

Different kinds of dynamos might thus be instrumental on the ZAMS: a solar-like shell dynamo in slow rotators (whose convective envelope is uncoupled from the radiative core with strong velocity gradients at the interface) and a turbulent dynamo in fast rotators (which have nearly uniform internal rotation). In the saturation regime, $L_X \propto R_\star^2$ (Fleming 1989), and the 2 dynamos cannot be distinguished (i.e., the saturation level is independent of the nature of the dynamo). It is only when the dynamo desaturates that one can hope to see evidence for different processes. Such an evidence is perhaps provided by the 2 "branches" of the activity-rotation relationship observed for M-type dwarfs in the Hyades (Stauffer et al. 1997b). The ascending branch at low velocity would correspond to the shell dynamo (slow rotators), and the second branch at slightly higher velocity to the desaturation of the turbulent dynamo (fast rotators). The second branch does not appear until the ultrafast rotators are braked, thus allowing the turbulent dynamo to desaturate, and is therefore not seen in M-type dwarfs belonging to clusters younger than the Hyades.

5. The rotation of the lowest-mass stars

Measurement of the rotation rates of the very low-mass stars started to be obtained in the last few years both in young clusters (Jones et al. 1996, Martín & Zapatero-Osorio 1997, Stauffer et al. 1997b) and in the field (Basri & Marcy 1995, Martín et al. 1996, Delfosse et al. 1997). The results consistently revealed that many of the stars in the mass range 0.1-0.3 $M_\odot$ have significant rotation, with $v\sin i$ up to 30-50 km s^{-1} , corresponding to extremelly short rotational periods of a few hours. Even old field stars (1-10 Gyr) exhibit rotation in excess of 10 km s^{-1} (Delfosse et al. 1997).

These results have two immediate implications: 1) the angular momentum loss experienced by very low-mass (VLM) stars must be very small. Stauffer et al. (1997b) showed that the rotation rates observed for VLM stars in young clusters were compatible with models without angular momentum loss; 2) the braking timescale of VLM stars is much longer than that of higher mass stars. Delfosse et al. (1997) estimated the

braking timescale to be of the order of a few Gyr for 0.2 $M_\odot$ stars, and of about 10 Myr for 0.1 $M_\odot$ stars.

Whether these observations can be fully accounted for with the same set of assumptions used for modelling the rotational evolution of higher mass stars still awaits the development of dedicated models. However, these results support the trends observed for higher mass stars. The braking timescale is known to lengthen from G ($\simeq$ 40 Myr) to K ($\simeq$ 300 Myr) to early-M stars ($\simeq$ 700 Myr). According to the models, this is the result of the saturation of angular momentum losses, which occurs at lower rotation rates for lower mass stars. The very long braking timescales estimated by Delfosse et al. (1997) suggest that VLM stars may spend most of their life in the saturation regime, leading to little angular momentum losses. These preliminary results therefore support the idea that angular momentum loss is a strong function of stellar mass, rapidly weakening towards the lowest-mass stars.

6. Conclusion: back to the pre-main sequence

Many properties of the stars belonging to young clusters may still reflect physical processes which were at work during the pre-main sequence. In particular, the interaction between the PMS star and its circumstellar disk might have much further reaching consequences than envisioned so far. It is now widely accepted that this interaction, presumably through the star's magnetosphere, controls the angular momentum evolution of the star during the pre-main sequence (e.g. Edwards 1997). As different stars lose their disk at different times, a wide dispersion of angular momentum builds up during the PMS and culminates at the ZAMS. A number of other processes might be related to the history of PMS angular momentum loss:

1) The state of internal rotation at the ZAMS:

The surface of slow rotators is strongly braked by the disk during the PMS. Their interior may not have enough time to adjust to the surface torque and they reach the ZAMS as differential rotators, with a fast rotating radiative core. On the contrary, the surface torque is much weaker in (diskless) fast rotators, which may therefore be able to maintain solid-body rotation to the ZAMS. The rotational profile at the ZAMS might thus be primarily dictated by surface angular momentum loss during the PMS, which is ultimately controlled by the star-disk interaction.

2) The nature of the dynamo:

By dictating the internal profile of rotation at the ZAMS, PMS angular momentum losses would also control the type of dynamo that dominates in slow and fast rotators on the ZAMS. A shell a dynamo in slow rotators with strong core-envelope decoupling, and a turbulent dynamo in fast, solid-body rotators. The different nature of the dynamos in slow and fast rotators may be the origin of the saturation of angular momentum losses in fast rotators (Durney et al. 1993).

3) The lithium depletion pattern:

Although the link between lithium depletion and rotation is not elucidated yet, there has been suggestions that angular momentum loss at the stellar surface leads to enhanced lithium depletion. In such a case, the star-disk interaction, by imposing strong angular momentum losses during the PMS, might be largely responsible for the pattern

of lithium depletion observed on the ZAMS.

The pre-main sequence phase of evolution, though short, possibly holds important keys for our understanding of the various properties of low-mass stars in young open clusters. Observational work is certainly needed in order to derive more rotation measurements of PMS stars from the youngest T Tauri stars to those approaching the ZAMS (e.g. Stauffer et al. 1997a, Wichmann et al. 1997) and models dealing with angular momentum evolution and lithium depletion should systematically include the PMS.

7. Perspectives

This review dealt only with $v\sin i$ distributions and not with rotational periods. The reason is that the latter are known for still too few stars in young clusters, and usually biased towards fast rotators. This situation is likely to change in the next few years as several groups are very active in trying to improve the rotational period database in young clusters. Complete (i.e. unbiased) distribution of rotational periods will be superior than $v\sin i$ ones in identifying the subtle aspects of the rotational evolution of low-mass stars close to the ZAMS.

Another area which still need to be developped is the determination of rotation rates ($v\sin i$ and periods) in intermediate-age clusters. The work has already started with the measurements of $v\sin i$ in M7 and M34, and should be pursued both to enlarge the samples in each cluster and to study other clusters spanning the age range between 200 and 600 Myr. It is during this time frame that the effect of core-envelope recoupling on the surface rotation rate is expected to show up the more clearly.

On the more theoretical side, the broad aspects of angular momentum evolution seem to be accounted for by current models: PMS spin up due to the decreasing moment of inertia of the contracting star (fast rotators), PMS disk locking preventing the spin up (slow rotators), mass-dependent wind braking on the ZAMS, saturation of the angular momentum loss at high rotation, core-envelope decoupling. Our understanding of these processes remains, however, somewhat superficial. What is the real nature of the PMS disk locking process, and how long does it last? Why is the ZAMS wind braking mass-dependent? Is the saturation of angular momentum loss at high velocities due to the dynamo process itself, to the filling of the stellar surface, or to some other process? What is the dominant mechanism for angular momentum transport in stellar interiors: hydrodynamical instabilities? MHD torques? gravity waves? Is the internal rotation profile of the Sun representative of all stars of its class and age? Much theoretical work remains to be done to address these issues.

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