The Ages of Stars
Proceedings IAU Symposium No. 258, 2008
E.E. Mamajek, D.R. Soderblom & R.F.G. Wyse, eds.

doi:10.1017/S1743921309032025

The rotational evolution of low-mass stars

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Abstract. We summarise recent progress in the understanding of the rotational evolution of low-mass stars (here defined as solar mass down to the hydrogen burning limit) both in terms of observations and modelling. Wide-field imaging surveys on moderate-size telescopes can now efficiently derive rotation periods for hundreds to thousands of open cluster members, providing unprecedented sample sizes which are ripe for exploration. We summarise the available measurements, and provide simple phenomenological and model-based interpretations of the presently-available data, while highlighting regions of parameter space where more observations are required, particularly at the lowest masses and ages $\gtrsim 500$ Myr.

Keywords. stars: late-type, stars: low-mass, stars: pre–main-sequence, stars: rotation

1. Rotation period data

A compilation of most of the available rotation period (and some $v \sin i$) measurements in open clusters for stars with masses $M \lesssim 1.2\ \mathrm{M}_\odot$ is shown in Figure 1 (a list of references is included in Table 1). We plot rotation period as a function of stellar mass, rather than using the more conventional quantities of colour or spectral type on the horizontal axis, since the diagram spans ages from the early pre–main-sequence (PMS), at ~ 1 Myr in the ONC, to the main sequence (MS), and neither colour nor spectral type are invariant for a given star over this age range. The masses are, of course, model-dependent, but the majority of binning in mass and morphological examination used in this work require only that the mass scale is *approximately* correct, which should be reasonably well-satisfied by the PMS stellar evolution tracks. We use those of the Lyon group, from Baraffe *et al.* (1998) and I. Baraffe (private communication), throughout.

An expanded version of Figure 1, omitting many of the more sparsely sampled clusters and all the $v \sin i$ observations, is shown in Figure 2. By examining the evolution of the morphologies of these diagrams, we can already draw some (model-independent) conclusions regarding the evolution of the rotation periods in these clusters. For simplicity, we discuss two broad mass ranges: stars close to solar mass (e.g. $0.9 \lesssim M/\mathrm{M}_\odot \lesssim 1.1$), and fully-convective stars ($M \lesssim 0.4\ \mathrm{M}_\odot$), which represent the "tail" of the distribution which emerges especially in the NGC 2547 and NGC 2516/M35 panels of Figure 2.

Considering the solar mass stars first, it is clear that the behaviour on the PMS (which lasts to ~ 30 Myr for a solar mass star, until it reaches the zero-age main sequence, hereafter ZAMS) and on the MS up to the age of the Hyades, varies as a function of rotation rate. The slowest rotators in the ONC have periods of ~ 10 days. The most basic prediction we can make for the evolution of the rotation rate is to assume angular momentum is conserved, in which case as the star contracts towards the ZAMS, it should spin up. However, for these slowly-rotating stars, the period remains approximately constant all the way to NGC 2362, and has spun up to ~ 8 days by the age of NGC 2547 (~ 40 Myr),

Table 1. List of references for the panels in Figure 1.

Cluster	Age (Myr)	Source(s)
ONC	1	Herbst *et al.* (2001,2002) Stassun *et al.* (1999)
NGC 2264	2	Lamm *et al.* (2005) Makidon *et al.* (2004)
IC 348	3	Cohen *et al.* (2004) Littlefair *et al.* (2005) Cieza & Baliber (2006)
σ Ori	5	Scholz & Eislöffel (2004a)
ϵ Ori	5	Scholz & Eislöffel (2005)
NGC 2362	5	Irwin *et al.* (2008b)
IC 2391 IC 2602	30	Patten & Simon (1996) Barnes *et al.* (1999)
NGC 2547	40	Irwin *et al.* (2008a)
α Per	50	Stauffer *et al.* (1985, 1989) Prosser (1991) O'Dell & Collier Cameron (1993) O'Dell *et al.* (1994, 1996) Allain *et al.* (1996) Martín & Zapatero Osorio (1997) Prosser & Randich (1998) Prosser *et al.* (1998) Barnes *et al.* (1998)
Pleiades	100	van Leeuwen *et al.* (1987) Stauffer *et al.* (1987) Magnitskii (1987) Prosser *et al.* (1993a,b,1995) Krishnamurthi *et al.* (1998) Terndrup *et al.* (1999) Scholz & Eislöffel (2004b)
Pleiades $v \sin i$	100	Stauffer *et al.* (1984) Stauffer & Hartmann (1987) Soderblom *et al.* (1993) Jones *et al.* (1996) Queloz *et al.* (1998) Terndrup *et al.* (2000)
M50	130	Irwin *et al.* (2009)
NGC 2516 $v \sin i$ $v \sin i$	150	Irwin *et al.* (2007) Terndrup *et al.* (2002) Jeffries *et al.* (1998)
M35	150	Meibom *et al.* (2008)
M34	200	Irwin *et al.* (2006)
M37	485	Hartman *et al.* (2008)
Hyades	625	Radick *et al.* (1987) Prosser *et al.* (1995)
Praesepe	650	Scholz & Eislöffel (2007)

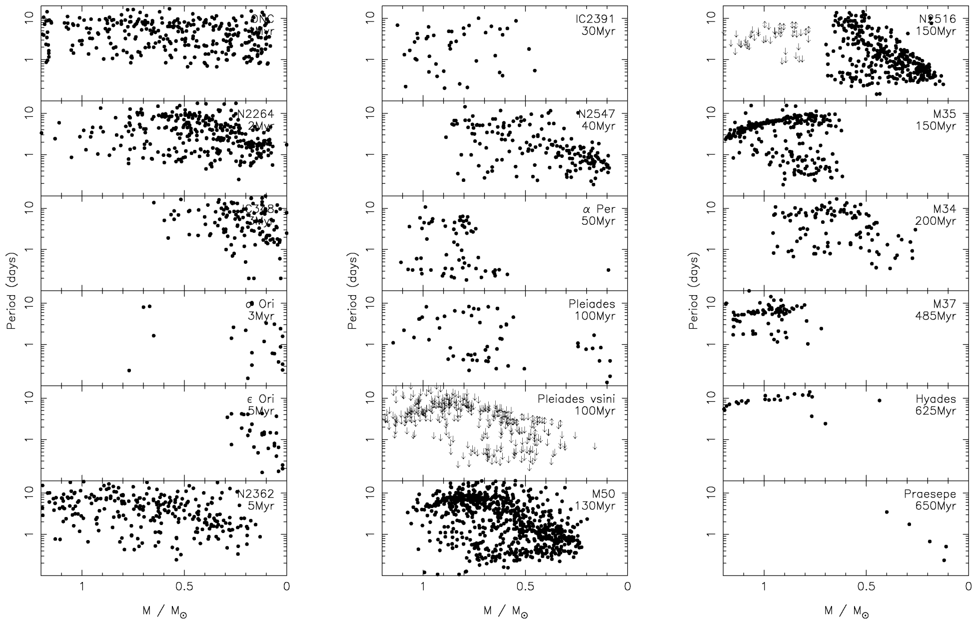

Figure 1. Compilation of 3100 rotation periods (and some $v \sin i$ measurements) for stars with masses $M \lesssim 1.2$ M$_\odot$ in young ($\lesssim 1$ Gyr) open clusters, from the literature. Plotted in each panel is rotation period as a function of stellar mass for a single cluster. The appropriate references for each panel are given in Table 1. All the masses used in this contribution were computed using the I-band luminosities of the sources and the models of Baraffe *et al.* (1998), assuming values of the age, distance modulus and reddening for the clusters taken from the literature.

at which point the contraction ceases. Over the same age range, the most rapid rotators gradually evolve from a period of ~ 1 day at the ONC, to ~ 0.6 days at NGC 2362 (~ 5 Myr), and ~ 0.2 days at NGC 2547. This follows closely the prediction from stellar contraction. We therefore conclude that there is some mechanism removing angular momentum from only the slow rotators, to an age of ~ 5 Myr, and a short time after this the angular momentum losses cease, leaving the star free to spin up for a short time until it reaches the ZAMS. The net result of this is to yield a wide range of rotation rates in the early-MS clusters such as the Pleiades and M35.

By the age of the Hyades however, the rotation rates converge onto a single well-defined sequence. It is clear that this process is well underway by the age of M37 ($\sim$ 485 Myr). There must therefore be another rotation-rate-dependent angular momentum loss mechanism operating on the early-MS, such that more rapid rotators lose more angular momentum, to drive all the stars toward the same rotation rate at a given mass.

In contrast, the behaviour of the lowest mass stars is clearly rather different. On the PMS, these stars all appear to spin up rapidly, and reach very rapid rotation rates at the ZAMS (for a 0.4 M$_\odot$ star, the ZAMS is reached at ~ 150 Myr), and furthermore, the maximum rotation period seen is a very strong function of mass (this is most clear in the NGC 2516 diagram in Figure 2). This indicates that there is little rotation rate dependence in this mass domain due to the similarities between the morphologies of the diagrams especially from NGC 2264 to NGC 2516, and furthermore, that these stars lose little angular momentum on the PMS, in contrast to the slowly rotating solar mass stars. Moreover, between NGC 2516 and Praesepe, the limited quantity of data available suggest that there is essentially no evolution of the rotation period, so little angular momentum appears to be lost on the early-MS, again in contrast to the solar-type stars.

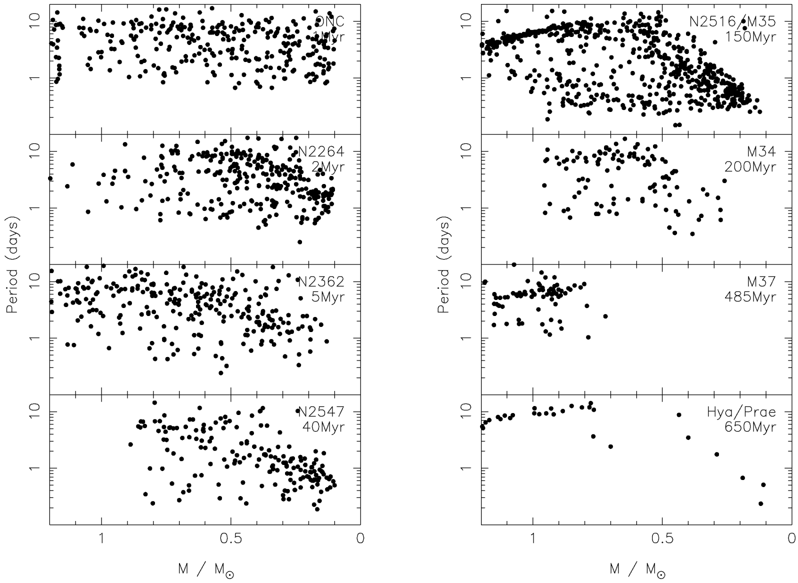

Figure 2. Enlarged version of Figure 1, showing a few selected clusters which have large samples of rotation periods available. NGC 2516 and M35 have been combined into a single panel, since they have essentially identical ages, as have the Hyades and Praesepe.

We proceed in §2 to examine the physical interpretation of these observational results.

2. Models of rotational evolution

Recall from §1 that we needed to invoke two mechanisms of angular momentum removal: one operating for $\sim 5 - 10$ Myr on the PMS, and one operating on the main sequence, with the property that it must produce a convergence in the rotation rates between ~ 100 and 600 Myr.

2.1. *Pre–main-sequence angular momentum losses*

For the first of these, the PMS angular momentum loss, the $\sim 5 - 10$ Myr timescale suggests an obvious candidate: the circumstellar discs that surround these stars in the earliest stages of their evolution dissipate on these timescales (e.g. Haisch *et al.* 2001). The precise mechanism by which angular momentum is removed due to the presence of a disc is still a matter of debate, with the currently-favoured hypothesis being an accretion-driven stellar wind (e.g. Matt & Pudritz 2005), or "disc locking" (e.g. Königl 1991; Collier Cameron *et al.* 1995). For our purposes, we shall simply treat the effect of the disc as holding the angular velocity of the star constant (by removing angular momentum) for the lifetime of the disc.

In reality, there will be a range of disc lifetimes, and thus the stars will be "released" from this angular velocity regulation at a range of times, giving rise to a spread of rotation rates on the PMS and ZAMS, as required by the observations. Moreover, examining one of the early-PMS clusters shows us a "snapshot" of this process in action. The best-observed example is the ONC, shown in Figure 3.

If we presuppose that stars begin with a tight distribution of initial rotation periods, centred around $8 - 10$ days, in a histogram of rotation period we should expect to see a population of stars at this period, and then a tail of faster-rotating stars, corresponding to the ones now uncoupled from their discs, with faster rotating stars having

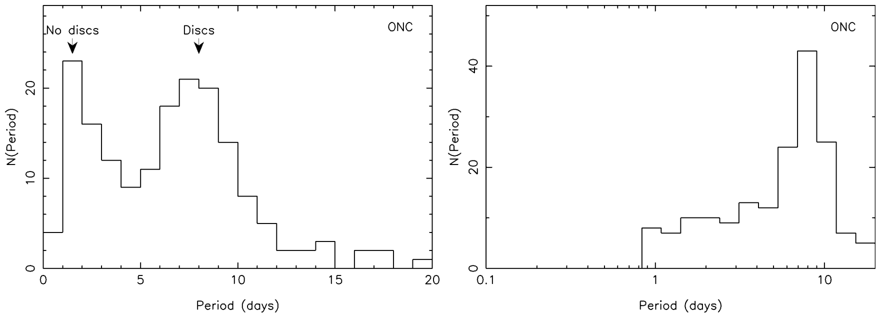

Figure 3. Distribution of rotation periods for ONC stars with masses $M \gtrsim 0.25\ \mathrm{M}_\odot$ (using the D'Antona & Mazzitelli 1998 models; this corresponds to $M \gtrsim 0.4\ \mathrm{M}_\odot$ for the Baraffe *et al.* 1998 models used in this contribution), replotted from Herbst *et al.* (2001). The two panels show the same distribution binned in linear period (left) and log period (right).

uncoupled earlier. This is indeed what is seen in Figure 3, where it is instructive to plot the distribution in log period rather than the more conventional linear period.

Moreover, this hypothesis makes an observationally-testable prediction: the population of slowly-rotating stars should show measurable indications of the presence of a disc (e.g. mid-IR excess) or of active accretion (i.e. be classical T-Tauri stars, CTTS), whereas the rapidly-rotating stars should not have discs, or have recently-dissipated discs, and not be active accretors (i.e. weak-lined T-Tauri stars, WTTS).

In reality, extracting this observational signal from the cluster data has proved to be difficult (see Rebull *et al.* 2004 for a detailed discussion of this issue). Rebull *et al.* (2006) presented the first statistically significant detection of this effect, using mid-IR excess measurements from the IRAC instrument aboard the *Spitzer* space telescope, the current method-of-choice, finding that slowly-rotating stars are indeed more likely to posses discs than rapidly-rotating stars. However, in doing so this study revealed a wrinkle in the argument: they also found a puzzling population of slowly-rotating stars without discs. Several subsequent studies (e.g. Cieza & Baliber 2007) have confirmed these results, which now appear to be placed on a firm footing.

2.2. *Main sequence angular momentum losses*

The mechanism for angular momentum loss on the main sequence, at least for solar mass stars, is thought to be a solar-type magnetised stellar wind. The time-dependence of rotation rates in this age range has been firmly established observationally for solar-type stars since Kraft (1967), and from the age of the Hyades to the Sun, obeys well the famous Skumanich (1972) $t^{1/2}$ law (i.e. $\omega \propto t^{-1/2}$). This can be reproduced on a more theoretically motivated framework from parameterised angular momentum loss laws (usually based on Kawaler 1988; the $t^{1/2}$ law can be reproduced by setting $n = 3/2$ and $a = 1$ in his model).

Although the Skumanich (1972) law provides a good description of the evolution of solar-type stars from the age of the Hyades to the Sun, and for the majority of stars in the Pleiades to the age of the Hyades, simply evolving the Pleiades distribution forward in time to the age of the Hyades using this law produces stars which are rotating much more rapidly than observed in the Hyades. Therefore, most modelers modify the Kawaler (1988) formalism to incorporate saturation of the angular momentum losses above a critical angular velocity $\omega_{\rm sat}$ (Stauffer & Hartmann 1987; Barnes & Sofia 1996). The saturation is further assumed to be mass-dependent, to account for the mass-dependent spin-down timescales observed on the early-MS.

The resulting angular momentum loss law assumed in our models is:

$$\left(\frac{dJ}{dt}\right)_{\rm wind} = \begin{cases} -K\ \omega^3\ \left(\frac{R}{R_\odot}\right)^{1/2} \left(\frac{M}{M_\odot}\right)^{-1/2}, \omega < \omega_{\rm sat} \\ -K\ \omega\ \omega_{\rm sat}^2\ \left(\frac{R}{R_\odot}\right)^{1/2} \left(\frac{M}{M_\odot}\right)^{-1/2}, \omega \geqslant \omega_{\rm sat} \end{cases} \tag{2.1}$$

We note that although saturation is reasonably well-motivated observationally (e.g. by the saturation observed in the relationship between X-ray activity and rotation rate), this is a rather unsatisfactory feature of the present models, since there is a certain amount of arbitrariness in the way this parameter is introduced (for example, the choice of power of ω in Eq. 2.1 for the saturated angular velocity dependence of dJ/dt is arbitrary). An important area for future work is to develop a theoretical framework for this phenomenon, and for solar-type winds in general.

2.3. *Comparison of models to data*

The models of rotational evolution we use are described in detail in Bouvier *et al.* (1997), Allain (1998), Irwin *et al.* (2007) and Irwin (2007). We summarise only the most salient features in this contribution.

The methodology of Bouvier *et al.* (1997) which we adopt here essentially implements a rotational evolution model by using a standard non-rotating PMS stellar evolution track to compute the variation of the stellar parameters as a function of time, principally the moments of inertia of the radiative and convective regions of the star, which are then used as an input to determine the angular velocity as a function of time.

This model in the simple form described has four parameters (which could all be functions of mass): the initial angular velocity ω_0, normalisation of the solar-type angular momentum loss law K (see Eq. 2.1), saturation velocity $\omega_{\rm sat}$, and the lifetime of the circumstellar disc $\tau_{\rm disc}$. For solar-type stars, we can fix K by requiring that the model reproduces the observed rotation rate of the Sun.

Figure 4 shows the result of fitting this model to the rotation period data using a simple nonlinear least squares routine. For the moment, we have required the radiative core and convective envelope to have the same angular velocity, i.e. a "solid body" model.

The results show that the model does a reasonable job for the late-time evolution from the Hyades to the Sun, but this is largely by construction since we used the Skumanich (1972) law as an input! At earlier times, in general, we find that the rapid rotators are better-reproduced by the model, with the only major issue being at $\sim$ 150 Myr where the model underpredicts the upper bound to the observed rotation rates. For the slow rotators, the model rotates too rapidly given the ONC and NGC 2362 as an initial condition around the ZAMS and early-MS. The disc lifetimes behave as expected, being shorter for the rapid rotators.

The difficulty fitting the slow rotators motivates the introduction of an additional parameter into the model. In particular, we now relax the assumption of solid body rotation, and allow the core and envelope to have different angular velocities, coupling angular momentum between them on a timescale τ_c (this is done in a fashion which tries to equalise their angular velocities). $\tau_c = 0$ represents the solid body case already considered. The net effect of this "core-envelope decoupling" from the point of view of the observed rotation rate (which is that of the envelope) is to "hide" angular momentum in the core when it forms, which is then coupled back into the envelope gradually, providing a "late-time replenishment" of the surface angular velocity.

Figure 5 shows the result of applying this revised model to the solar-type stars. We can see that the fit is substantially improved. Importantly, we find that the value of τ_c for the

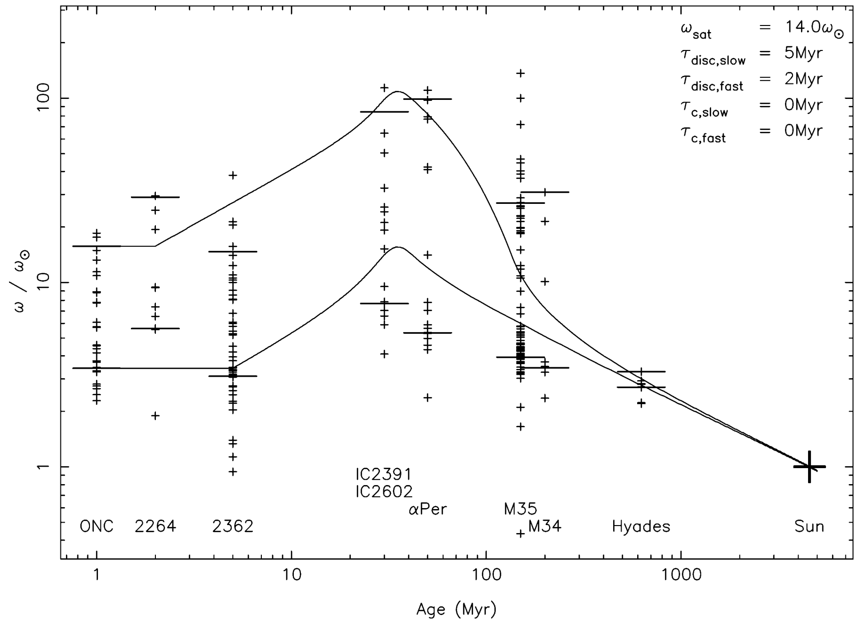

Figure 4. Rotational angular velocity ω plotted as a function of time for stars with masses $0.9 < M/\mathrm{M}_\odot \leqslant 1.1$. Crosses show the open cluster rotation period data such that each cluster collapses into a vertical stripe on the diagram, and short horizontal lines show the 25th and 90th percentiles of ω, used to characterise the slow and fast rotators respectively. The lines show rotational evolution models for 1.0 $\mathrm{M}_\odot$ stars, fit to the percentiles for each cluster using a simple unweighted least squares method. For this plot, we have assumed the stars rotate as solid bodies (i.e. constant ω as a function of radius inside the star). Plotted are the ONC, NGC 2264, NGC 2362, IC 2391, IC 2602, α Per, M35, M34, the Hyades, and the Sun.

slow rotators is relatively large, $\sim$ 110 Myr indicating inefficient core-envelope coupling, whereas for the fast rotators it is short, $\sim$ 6 Myr: these stars have efficient core-envelope coupling and rotate more like solid bodies. A corollary of this is that slow rotators develop a higher degree of rotational shear across the convective/radiative boundary.

This result may have important observationally-testable consequences. Bouvier (2008) discusses one of these: the impact on the surface abundance of lithium. In particular, the higher rotational shear in the slow rotators is likely to induce additional mixing in these stars, which may bring Li down into the star where it can be burnt. The net effect would be a higher level of lithium depletion in slow rotators than fast rotators, and these should therefore display a lower lithium abundance on the main sequence. Indeed, Soderblom *et al.* (1993) report that this appears to be the case in the Pleiades.

Having examined the models for solar-type stars, we now proceed to the fully-convective, very low-mass stars ($M \lesssim 0.4\ \mathrm{M}_\odot$). Figure 6 shows the results of applying the same models to this mass domain. Since these stars are fully-convective, there is no possibility for core-envelope decoupling, so they should rotate as solid bodies.

The model is clearly a poor match to the observations. In particular, the solar-type wind appears to loose too much angular momentum at late-times, resulting in a sharp drop in the predicted rotation rates starting at $\sim$ 200 Myr, which does not appear to be seen, although the available data are still very limited at present, with $v \sin i$ measurements giving only upper limits for the slowest rotating stars. This cannot be "fixed" by invoking saturation, since this has already been done for the model shown in Figure 6, which has $\omega_{\rm sat} = 1.8\ \omega_\odot$ (i.e. every star is saturated in the relevant age range).

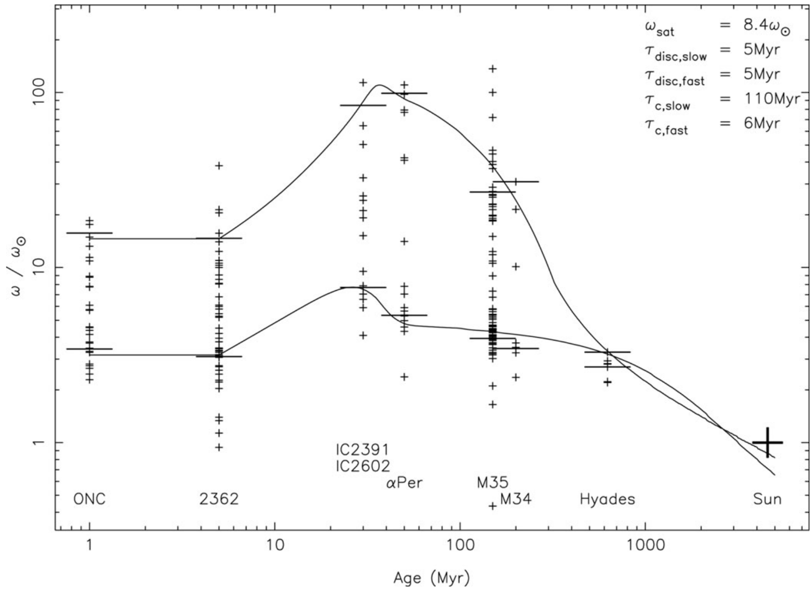

Figure 5. As Figure 4, but now allowing the radiative core and convective envelope of the stars to have different angular velocities, coupling angular momentum between the two on a timescale τ_c. We have also omitted NGC 2264, since the models presently have difficulty explaining the observations in this cluster.

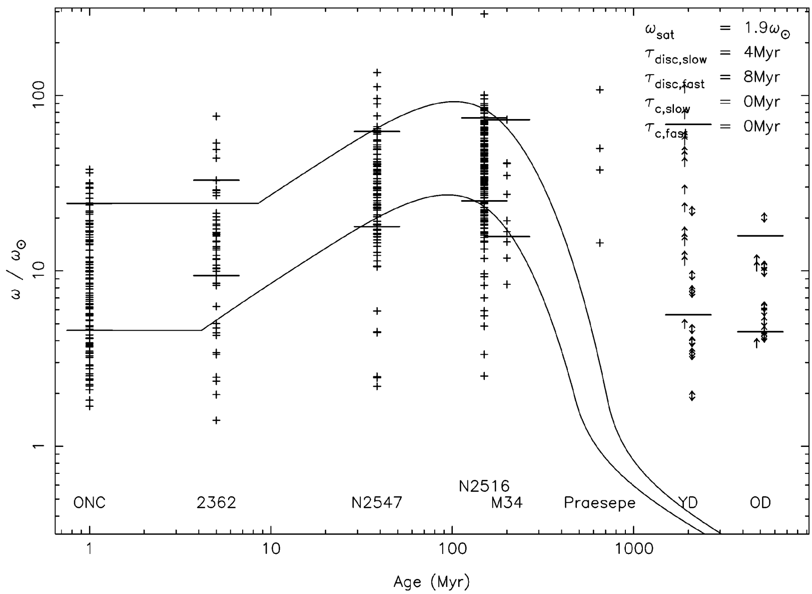

Figure 6. As Figure 5, except for stars with masses $0.1 < M/\mathrm{M}_\odot \leqslant 0.4$, and models for 0.25 $\mathrm{M}_\odot$. Data for NGC 2547, NGC 2516 and Praesepe are shown in addition to those clusters already included in Figure 5. We have also included lower limits from $v \sin i$ measurements for field M-dwarfs from Delfosse *et al.* (1998), placing the young disc population at 2 Gyr and the old disc at 5 Gyr (e.g. Feltzing & Bensby 2008; although note that in reality, these populations have a wide dispersion in age). Many of their points are only upper limits in $v \sin i$, and are shown as double-headed arrows in the figure, plotted offset slightly from the other data in age for clarity. Note the sparse coverage of cluster data, and particularly rotation periods, at the oldest ages. This is largely due to the intrinsic faintness of old, mid−late M-dwarfs. Several proposed surveys aim to fill in this region of parameter space within the next couple of years.

It would not be surprising that a solar-type wind does not reproduce the evolution of fully-convective stars, since this is thought to be launched at a tachocline of shear at the radiative/convective interface, and these stars posses none. However, as highlighted by J. Stauffer in the questions, we should be cautious in overinterpreting the rather sparse data presently available at these masses and ages, especially given the large number of $v \sin i$ upper limits and the natural bias of the rotation period method toward more active, and hence presumably more rapidly-rotating, stars, resulting from the extremely small photometric amplitudes of the rotational modulations at these old ages.

This domain of very low-masses and late ($\gtrsim$ 500 Myr) ages represents an important area for future observational studies to explore, and could provide us with a valuable insight into the winds of fully-convective stars.

Acknowledgments

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France, the WEBDA database, operated at the Institute for Astronomy of the University of Vienna, and the Open Cluster Database, as provided by C.F. Prosser and J.R. Stauffer, which may currently be accessed at `http://www.noao.edu/noao/staff/cprosser/`, or by anonymous ftp to `140.252.1.11`, `cd /pub/prosser/clusters/`. We thank Isabelle Baraffe for providing the stellar evolution tracks used to compute the models in §2.3.

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Discussion

T. Naylor: 1) You mentioned that you had missed the young cluster NGC 2264 from your plots. Why was this missing, and what about IC348? 2) Could it be there is a second parameter for the young clusters which means that age ordering and gyrochronological orderings are different?

J. Irwin: 1) NGC 2264 (and indeed IC 348) using the "literature" ages don't seem to fit in well with the models I showed. This is somewhat puzzling and I am not really sure of the reason yet. 2) Yes, absolutely, this is quite strongly possible especially given the difference in "environment" in these young clusters.

J. Stauffer: The old (Praesepe/Hyades) M stars are an example of where it is useful to combine the information from spectroscopy ($v \sin i$) with the period data. Most of the Hyades and Praesepe M dwarfs are slow rotators: the small number of Praesepe stars with periods are very likely a biased set (but the $v \sin i$ values show most are slow rotators, and you also do see the fast rotators).

J. Irwin: Absolutely, this is something that needs to be included in the models I showed. Indeed, the periods may well be an activity-biased sample at these old ages so we must be cautious in their interpretation.

G. Meynet: What might be the physical cause of decoupling/non-decoupling behavior between the core/envelope. Can it be magnetic fields?

J. Irwin: I am no expert but it seems that magnetic fields are often invoked to explain the core-envelope coupling in the literature.

D. Soderblom: You have presented a large quantity of high-quality observations of rotation periods in clusters, and have applied some physics to the problem as well. Converting color to a mass is the right thing to do, even given the differences in PMS mass tracks. My question is this: Your clusters range from the sparse to the very rich. Is there any evidence that rich clusters partition their angular momentum any differently from sparse clusters?

J. Irwin: At the moment, I have not really seen evidence for differences. In Irwin (2008, arXiv:0810.5110), I show there is no statistically significant difference between the almost identically-aged clusters NGC 2516, M50, and M35, but more work is clearly needed. This may explain the differences between some of the earliest PMS clusters.

Jonathan Irwin