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ASTRONOMY AND ASTROPHYSICS

Polar spots and stellar spindown: is dynamo saturation needed?

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Abstract. Dynamo saturation is often invoked when calculating the rotational evolution of cool stars. At rapid rotation rates a saturated dynamo reduces the angular momentum carried away by the stellar wind. This, in turn, may explain the high rotation rates present in the distribution of rotation periods in young clusters.

Here we point out that concentration of magnetic flux near the poles of rapidly rotating cool stars provides an alternative to dynamo saturation. A high-latitude concentration of field on rapid rotators saturates the angular momentum loss induced by the stellar wind, due to the reduced torque arm. We show that the inclusion of this effect in model calculations is able to reproduce the observed high rotation rates without the need for dynamo saturation. Taken together with the results of O'Dell et al. (1995) this argues against dynamo saturation at low rotation rates.

Key words: stars: late-type – stars: rotation – stars: magnetic field, starspots

1. Introduction

Dynamos in cool stars are thought to operate more efficiently and produce more magnetic field on the stellar surface with increasing stellar rotation rate. It has been argued, however, that above a certain rotation frequency, the output of the dynamo becomes independent of the rotation rate, i.e. it saturates.

One of the main arguments for dynamo saturation comes from the observation and modelling of stellar spindown. In order to explain the presence of late-type, very rapid rotators in young main-sequence clusters it is necessary to introduce a saturation of the angular momentum loss rate. Although a number of proposals have been made to explain this saturation (Mestel 1984, 1988, Mestel & Spruit 1987), the most widely accepted interpretation involves saturation of the underlying dynamo (MacGregor & Brenner 1991, Soderblom et al. 1993, Li & Collier Cameron 1993, Collier Cameron & Li 1994, Keppens et al. 1995, cf. MacGregor & Charbonneau 1994).

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In the present paper we reconsider this interpretation and propose an alternative, namely that the magnetic field is concentrated increasingly towards the stellar poles as the star rotates more rapidly. Thus, although the amount of magnetic flux on the stellar surface keeps increasing with increasing rotation rate, the reduced torque arm due to the high latitude of the field counteracts this and affects stellar spindown in a manner similar to a saturated dynamo.

Doppler imaging has provided striking evidence for spots at high latitudes on rapidly rotating pre-main sequence (PMS) and main sequence (MS) stars, in some cases actually straddling the stellar poles (Joncour et al. 1994b, Strassmeier et al. 1994). Schüssler & Solanki (1992) pointed out that spots at high latitudes are a natural consequence of the rapid rotation of these stars, since magnetic flux tubes rising through the convection zone will be deflected by the Coriolis force towards the poles. Finally, Schüssler et al. (1996) have presented numerical simulations of the rise of magnetic flux tubes to the stellar surface from the seat of the dynamo at the bottom of the convection zone. Their calculations confirm that indeed most of the magnetic flux on young rapid rotators emerges at high latitudes (cf. Schüssler 1996 for a review).

The fact that the magnetic activity is concentrated at the poles for high rotation rates has important ramifications when studying stellar spindown. Indeed, the braking torque exerted on the star as a result of its wind is usually estimated from a spherically symmetric stellar wind model (exceptions are the papers by Moss 1986 and by Mestel & Spruit 1987). The angular momentum loss rate is then proportional to R_A^2, where R_A is the global stellar Alfvén radius, beyond which the kinetics of the stellar wind dominate over the magnetic field. Thus, no distinction is made between equatorial and polar regions, aside from a geometrical factor that mimics the reduction in the torque arm towards the poles. In this paper, we will estimate the wind braking torque in a way that properly takes account of the reduction of the torque arm and allows for different Alfvén radii for polar and equatorial regions. The latter choice is inspired by observations by Marsch & Richter (1984). These authors used data gathered by the HELIOS satellite to show that the solar Alfvén radius, R_A, over active regions is 2–3 times as large as over the quiet sun. The mass-loss rate, however, above solar active regions was found to be comparable with that above quiet regions. Since the high latitude active regions on rapidly rotating stars are expected to be much larger than their solar counterparts, we might expect the contrast in R_A to be even larger on rapid rotators. Consequently we expect the Alfvén radius to be particularly large over the poles of such stars.

2. Model and test calculations

All calculations have been carried out using a modified version of the code described by Keppens et al. (1995), which in turn is an extended and modified version of the code of MacGregor & Brenner (1991). The code calculates the temporal evolution of $J_{\rm env}$ and $J_{\rm core}$, the angular momenta of the convective envelope and the radiative core. Core and envelope are each thought to rotate homogeneously, but separately from each other. The coupling between them is governed by the coupling time-scale, τ_c, which is an input free parameter. For the physics underlying the coupling parameterized in this simple manner see, e.g., Charbonneau & MacGregor (1992). The angular momenta are related to the surface (or envelope) and core rotation rates, Ω_* and $\Omega_{\rm core}$, via

$$\begin{aligned} J_{\rm env} &= I_{\rm env}\Omega_* \ , \\ J_{\rm core} &= I_{\rm core}\Omega_{\rm core} \ , \end{aligned} \tag{1}$$

where $I_{\rm env}$ and $I_{\rm core}$ are the respective moments of inertia. The input requirements of the code are: a sequence of stellar models, a table of stellar wind solutions (tabulated as a function of Ω_* and magnetic field strength averaged over the stellar surface, B_*), an initial equatorial velocity $v_{\rm eq}$, the coupling time τ_c, a disc-coupling time in the T-Tauri stage, τ_d, and a dynamo relation, i.e. a relation between Ω_* and B_*.
The equations governing the evolution of $J_{\rm env}$ and $J_{\rm core}$ read (MacGregor & Brenner 1991)

$$\frac{dJ_{\rm env}}{dt} = \frac{\Delta J}{\tau_c} - f\frac{dM_{\rm core}}{dt} - \frac{J_{\rm env}}{\tau_{\rm w}} \ , \tag{2}$$

$$\frac{dJ_{\rm core}}{dt} = -\frac{\Delta J}{\tau_c} + f\frac{dM_{\rm core}}{dt} \ . \tag{3}$$

Here

$$\Delta J = \frac{I_{\rm core}I_{\rm env}}{I_{\rm core}+I_{\rm env}}(\Omega_{\rm core} - \Omega_*) \ , \tag{4}$$

$$f = \tfrac{2}{3}\Omega_* R_{\rm core}^2 \tag{5}$$

($R_{\rm core}$ is the radius of the radiative core), and $\tau_{\rm w}$ is the wind-braking time. This timescale $\tau_{\rm w}$ determines the rate at which angular momentum is carried away from the star by its stellar wind. To determine the stellar wind solution in the equatorial plane, we use the model of Weber & Davis (1967). To extrapolate this wind solution out of the equatorial plane and derive a wind braking time $\tau_{\rm w}$, one could assume a spherically symmetric stellar wind. This then leads to

$$\tau_{\rm w} = \frac{3}{2}\frac{I_{\rm env}}{\dot{M}_* R_A^2} \ , \tag{6}$$

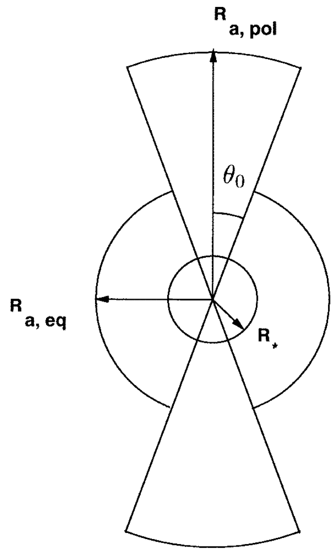

Fig. 1. Sketch of the considered geometry. R_* is the stellar radius and R_A the Alfvén radius. We distinguish between the polar regions, with $R_A = R_{A,\rm pol}$, and an equatorial ring with $R_A = R_{A,\rm eq}$. The angle θ_0 marks the co-latitude of the boundary between the two parts of the stellar surface

where R_A is the Alfvén radius, $\dot{M}_*$ is the mass-loss rate due to the stellar wind and the factor $\frac{3}{2}$ takes into account that only $R_A \sin\theta$ is relevant for angular momentum loss.

In the present paper we modify Eq. (6) in order to allow two discrete magnetic components on the stellar surface, one covering the poles, the other forming an equatorial belt. The geometry is illustrated in Fig. 1. The simplicity of our model reflects the aim of this paper, namely to demonstrate that a concentration of the field towards the poles of rapidly rotating cool stars affects their rotational evolution in a manner similar to dynamo saturation. In the plotted case the polar field is stronger than the equatorial field. Consequently R_A is larger in the polar direction than towards the equator. We denote the co-latitude of the boundary between the polar and equatorial field components by θ_0. From Doppler images and theoretical considerations we expect the magnetic field distribution on the stellar surface to be a function of Ω_*. On slow rotators the magnetic field distribution is expected to be nearly homogeneous or even slightly concentrated towards the equator. For large Ω_* the field is expected to be increasingly concentrated at high latitudes.

Therefore, we take $\tau_{\rm w}$ to be a composite of the $\tau_{\rm w}$ in the equatorial and polar regions, $\tau_{\rm w,eq}$ and $\tau_{\rm w,pol}$, respectively:

$$\frac{1}{\tau_{\rm w}} = \frac{c_{\rm eq}}{\tau_{\rm w,eq}} + \frac{c_{\rm pol}}{\tau_{\rm w,pol}} \ , \tag{7}$$

with

$$c_{\rm eq} = \cos\theta_0 - \tfrac{1}{3}\cos^3\theta_0 \ , \tag{8}$$

$$c_{\rm pol} = \tfrac{2}{3} - c_{\rm eq} \ , \tag{9}$$

and

$$\tau_{\mathrm{w},k} = \frac{I_{\mathrm{env}}}{\dot{M}_k\ R_{A,k}^2}\ , \tag{10}$$

where k = "eq" or "pol". The coefficients c_{eq} and c_{pol} have a dual purpose. Firstly, they represent the relative surface areas on which the equatorial and polar torques act with timescales $\tau_{\mathrm{w,eq}}$ and $\tau_{\mathrm{w,pol}}$. Secondly, they also take into account the $\sin\theta$ weight of R_A, entering into the torque arm.

For a given stellar model the quantities $\dot{M}_{\mathrm{eq}}$, $\dot{M}_{\mathrm{pol}}$, $R_{A,\mathrm{eq}}$ and $R_{A,\mathrm{pol}}$ are obtained from the wind solutions once Ω_*, B_{eq} and B_{pol} are known (See, e.g., Keppens et al. 1995), where B_{eq} and B_{pol} are the spatially averaged field strengths in the equatorial and polar regions, respectively. The stellar structure parameters were kindly provided by D. Vandenberg.

We now need to express B_{eq} and B_{pol} in terms of known quantities. Let A_{eq} and A_{pol} be the areas on the stellar surface covered by the two magnetic components. They must fulfil the following conditions:

$$B_{\mathrm{pol}}A_{\mathrm{pol}} + B_{\mathrm{eq}}A_{\mathrm{eq}} = 4\pi R_*^2 B_*\ , \tag{11}$$

$$A_{\mathrm{pol}} + A_{\mathrm{eq}} = 4\pi R_*^2\ , \tag{12}$$

where R_* is the stellar radius and B_* is the surface-averaged magnetic field of the star. In stellar spindown studies B_* is generally assumed to be related to Ω_* via a simple dynamo relation. Here we employ a linear relation without saturation,

$$\frac{B_*(t)}{B_\odot} = \left(\frac{R_*(t_\odot)}{R_*(t)}\right)^2 \frac{\Omega_*(t)}{\Omega_\odot}\ , \tag{13}$$

where the subscript "$\odot$" signifies solar values and the factor $(R_*(t_\odot)/R_*(t))^2$ ensures that the magnetic flux is affected by the angular velocity alone and not directly by changes in stellar radius. We also impose

$$B_{\mathrm{pol}}A_{\mathrm{pol}} = x\ B_{\mathrm{eq}}A_{\mathrm{eq}}\ , \tag{14}$$

with x being a free parameter of order unity that remains unchanged over the star's lifetime. Thus the ratio of the polar to the equatorial magnetic flux is constant in this model, but the stellar surface area covered by each of these components is a function of Ω.

Finally, in order to close the system of equations we need to know how, e.g., A_{pol} varies with Ω_*. Although this information can in principle be obtained from simulations such as those of Schüssler et al. (1996), such calculations are computationally expensive and have so far only been carried out for a few illustrative cases. We therefore provide a simple prescription for A_{pol} (Ω) and A_{eq} (Ω), parameterized in terms of $\theta_0(\Omega)$, which uses the simulations of Schüssler et al. (1996) as a guide. We have found the results to be relatively robust as far as the exact functional dependence of θ_0 (Ω) is concerned. Consequently, we discuss here only a simple linear relation:

$$\theta_0 = \frac{\pi}{2}\ \left(1 - \frac{\Omega_*}{\Omega_{\mathrm{crit}}}\right)\ . \tag{15}$$

In Eq. (14) θ_0 is in radians and Ω_{crit} is a free parameter that is expected to lie in the range 10–20$\Omega_\odot$ based on flux emergence simulations. Furthermore, again guided by our knowledge of the surface distribution of stellar magnetic fields, we impose $25^\circ \le \theta_0 \le 70^\circ$. This choice avoids peaks of unrealistically strong fields at the poles of rapidly rotating and the equator of slowly rotating stars.

Consider now what happens as a rotating star contracts towards the zero-age main sequence (ZAMS). Following the dynamo relation (Eq. 12), the stellar field B_* increases as the star spins up while it contracts. When one assumes that the star is always homogeneously magnetized, the increase in B_* shortens the wind-braking timescale τ_{w} (Eq. 6) since the Alfvén point R_A moves out. At the same time, the mass-loss rate increases with rotation as well, due to the additional magneto-centrifugal acceleration of the stellar wind. [1] Hence, the wind-driven angular momentum loss counteracts the stellar spin-up on the pre-main sequence. When the contraction comes to a halt at the ZAMS, the short τ_{w} subsequently leads to a rapid spindown.

The scenario alters drastically when one accounts for two magnetic components, as in our model. Consider first just the polar region: Due to the contraction of the polar surface relative to the total stellar surface area B_{pol} increases more rapidly than B_* and consequently $\tau_{\mathrm{w,pol}}$ also decreases more rapidly than the τ_{w} of the homogeneously magnetized star. At the same time, however, A_{pol} and the $\sin\theta$ factor to R_A both diminish, so that c_{pol} decreases more rapidly than B_{pol}/B_* increases. The net result is that the ratio $c_{\mathrm{pol}}/\tau_{\mathrm{w,pol}}$ does not increase as rapidly as $1/\tau_{\mathrm{w}}$ of a homogeneously magnetized star. $c_{\mathrm{eq}}/\tau_{\mathrm{w,eq}}$ exhibits a similar behaviour. Consequently, the timescale τ_{w} resulting from the model becomes comparatively longer than the τ_{w} of a uniformly magnetized star and a linear dynamo relation.

Next we illustrate the similarity between the rotational evolution in the presence of a saturated dynamo and the rotational evolution resulting from our prescription. In Fig. 2 the temporal evolution of Ω_* and Ω_{core} of a $1M_\odot$ star computed for the following three cases is presented: the linear dynamo relation ($B_*/B_\odot \sim \Omega_*/\Omega_\odot$) with a homogeneous suface distribution of the field (dashed curves), a saturated dynamo with $B_* \sim \Omega_* \le 20\Omega_\odot = \Omega_{\mathrm{sat}}$ and B_* independent of Ω_* for $\Omega_* > \Omega_{\mathrm{sat}}$ (dotted curves), and our model with the surface field distribution described by Eqs. (10)–(14). We have chosen $x = 0.7$, $\Omega_{\mathrm{crit}} = 15\Omega_\odot$ and the initial equatorial velocity, v_{eq}, of the star as 80 km s^{-1}. Such a large value of v_{eq} was chosen since it leads to a particularly marked difference between the rotational evolution with the linear dynamo relation and with the saturated one.

Clearly, the saturated dynamo and our model give relatively similar rotation curves, justifying our claim that the (observed!)

[1] Note, however, that the centrifugal contribution to the wind speed *reduces* the net angular momentum loss, compared with what one gets for pure thermal driving at a fixed coronal temperature. The gas reaches the Alfvén radius earler than it would without this extra accelerating term, and so reduces somewhat the effect of the increased B^* (cf. Mestel & Spruit 1987).

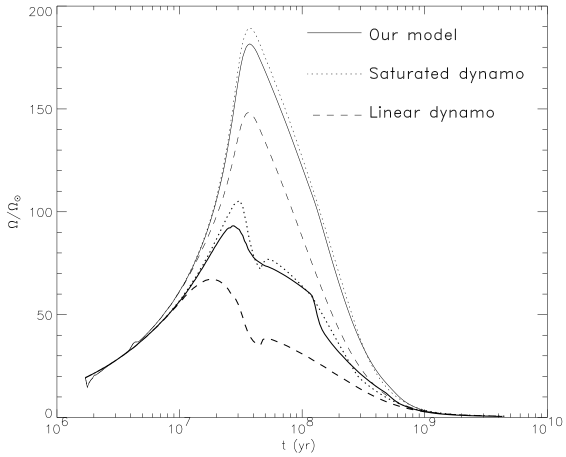

Fig. 2. Angular velocity relative to solar angular velocity $\Omega_*/\Omega_\odot$ vs. time. Plotted are the $\Omega_*/\Omega_\odot$ values of the convection zone (i.e. the surface rotation rate, thick curves) and the radiative core (thin curves). *Solid curves*: our model, based on a linear dynamo relation, i.e. field strength $B_* \sim \Omega_*$ and a two-component surface distribution of the field having the geometry indicated in Fig. 1 (with x = 0.7 and $\Omega_{\rm crit}$ = $15\Omega_\odot$). *Dashed curves*: linear dynamo relation and a homogeneous surface field distribution. *Dotted curves*: saturated dynamo with B independent of Ω_* for $\Omega_* > 20\Omega_\odot$ and a homogeneous surface field distribution. The star started with an initial equatorial velocity of $v_{\rm eq}$ = 80km s^{-1}

concentration of the field at high latitudes on rapid rotators mimics the effects of dynamo saturation.

In order to test their influence on the results we varied the two parameters x and $\Omega_{\rm crit}$ within the ranges $0.3 \leq x \leq 0.9$ and $7 \leq \Omega_{\rm crit} \leq 20\Omega_\odot$. The results obtained for different $v_{\rm eq}$ show that increasing x has a similar effect as decreasing $\Omega_{\rm sat}$, while an increase in $\Omega_{\rm crit}$ acts like an increase in $\Omega_{\rm sat}$. Within the tested ranges of the parameters the influence of $\Omega_{\rm crit}$ is smaller than of x.

3. Rotational distribution of young clusters

As a final comparison between the results of previous calculations (including dynamo saturation) and our model we calculate the rotational evolution of a sample of 75 stars. We compare the Ω_* distributions resulting from our model with those obtained by Keppens et al. (1995) for a saturated dynamo at the ages of three young clusters.

We start with the initial $v_{\rm eq}$ distribution of T Tauri stars constructed by Keppens et al. (1995) from observations by Walker (1990), Mandel & Herbst (1991), Attridge & Herbst (1992) and Bouvier et al. (1993). Also following Keppens et al. (1995) we assume that the T Tauri stars producing the low $v_{\rm eq}$ peak of the bimodal $v_{\rm eq}$ distribution are surrounded by and coupled to accretion disks (i.e. stars with an initial period larger than 5 days have a circumstellar disk for 4 Myr after they develop a radiative core). In fact we have adopted the values of all the parameters influencing the calculations from that paper. Hence the only difference to their simulations is the dynamo relation and the way the field is distributed on the stellar surface.

The $v_{\rm eq}$ distributions at the ages of the three young clusters α Persei, Pleiades and Hyades produced by the saturated dynamo model ($\Omega_{\rm sat}$ = $20\Omega_\odot$) and by our model (x = 0.7, $\Omega_{\rm crit}$ = $15\Omega_\odot$) are plotted in Figs. 3 and 4, respectively. The results of both sets of calculations are remarkably similar, once again supporting our initial premise that the concentration of field at high latitudes in rapid rotators is a viable alternative to dynamo saturation in the context of cool-star angular momentum evolution.

4. Discussion and conclusions: is dynamo saturation at low rotation rates needed?

Observations show that a certain fraction of cool stars in young clusters like α Persei and the Pleiades rotate at a rate so high that it calls for a reduction of angular momentum loss for a certain period in the star's youth. This reduction has been associated with a saturation of the dynamo-produced field above a rotation frequency of 10–20 $\Omega_\odot$.[2]

In the present paper we show that the saturation of angular momentum loss can also be the result of a different surface distribution of the magnetic field on rapid and on slow rotators. Doppler images (e.g., Joncour et al. 1994a, b, Kürster et al. 1994, Strassmeier et al. 1994, Unruh et al. 1995, Hatzes 1995), as well as the theory of magnetic flux transport through the convection zone (Schüssler & Solanki 1992; Caligari et al. 1996; Schüssler et al. 1996) suggest that on young, rapidly rotating stars the magnetic field is primarily concentrated towards the stellar poles. Consequently, the increase in the Alfvén radius due to the dynamo relation (12) is concentrated preferentially at high latitudes where the torque arm is correspondingly smaller. This leads in a completely natural manner to a reduction in the angular momentum loss, as compared with that from a star with the same magnetic flux but without a high-latitude concentration.

We have shown that even a very simple model that is based on a linear dynamo relation, but incorporating the observed qualitative difference between the way flux is distributed on slow versus rapid rotators, reproduces the observations accurately. Our work therefore weakens the need for dynamo saturation at relatively low rotation rates from the point of view of stellar rotational evolution. Note, however, that the effect of polar concentration of surface flux may be less pronounced in the Mestel & Spruit (1987) model, in which the near-equatorial field lines close to form a "dead zone" within which the wind does not flow. Thus only the field anchored at relatively high latitudes takes part in the angular momentum loss anyway.

In addition to stellar spindown there are three other lines of evidence favouring dynamo saturation. One argument is based on the observed saturation of emission from the outer layers of cool stars above a certain rotation rate (Vilhu 1984; Vilhu & Rucinski 1983; Stauffer et al. 1994, Mathioudakis et al. 1995). Another results from the saturation of stellar magnetic flux measured using unpolarized line profiles (Saar 1991). Finally, there

[2] For a deviant point of view see, e.g., Bouvier (1994)

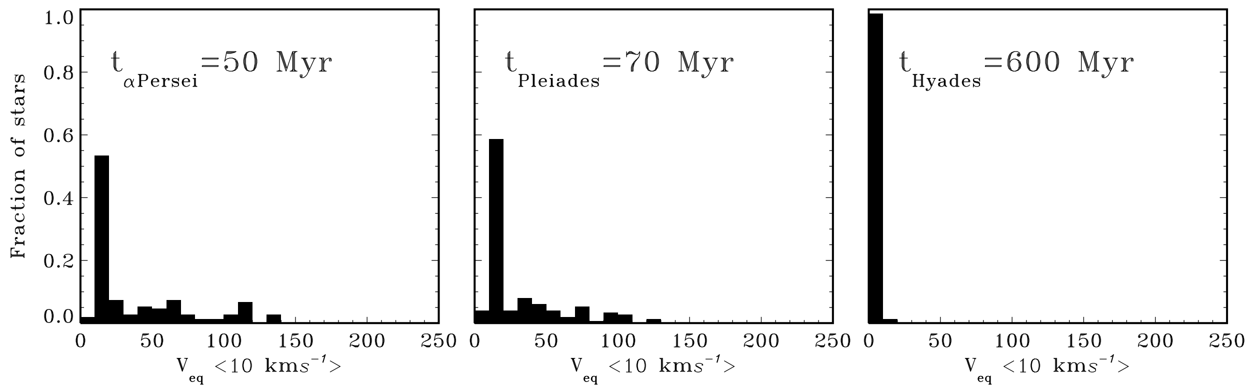

Fig. 3. Calculated velocity distribution at the ages of three young clusters, α Persei (left), Pleiades (centre) and Hyades (right). A saturated dynamo with $\Omega_{\rm sat}$ = $20\Omega_\odot$ underlies these calculations. This figure corresponds to the last three frames of Fig. 9 of Keppens et al. (1995)

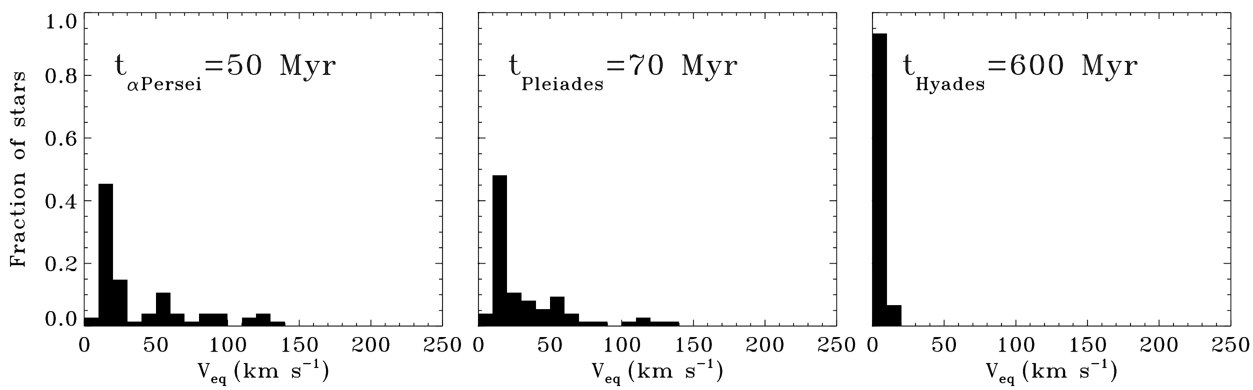

Fig. 4. Same as Fig. 3, but for our model with the parameters described in the text

are theoretical arguments that above a certain field strength the stellar dynamo saturates, or at least the α effect does (Durney & Robinson 1982, Kitchatinov & Rüdiger 1993).

Recently arguments have also been raised against dynamo saturation. First we mention the argument voiced by O'Dell et al. (1995). These authors have shown that unlike the upper atmospheric emission, which saturates at roughly $\Omega_*/\Omega_\odot \approx 10$ (Stauffer et al. 1994), the rotational modulation of photospheric light (presumably mainly due to starspots) does not appear to saturate even for much larger $\Omega_*/\Omega_\odot$ values. Based on these observations O'Dell et al. (1995) place a lower limit of approximately 50 $\Omega_\odot$ on the rotational frequency at which the dyamo saturates.

Such a difference in behaviour between the two types of data (enhanced upper atmospheric emission vs. V-band brightness modulation) is compatible with the different physics underlying upper atmospheric and photospheric emission. In particular, setting upper atmospheric emission equal to magnetic flux assumes a linearity that is not evident on the sun. There is clear evidence that sunspots, the largest and most strongly magnetic features in the solar photosphere, are not associated with the strongest transition region emission. According to Gurman (1993) and Harmon et al. (1993) the umbral transition region is practically indistinguishable from the quiet sun transition region. Thus both the saturation of upper atmosphere emission and the non-saturation of starspot brightness modulation can be accomodated into a picture in which, for increasingly rapid rotation, increasingly larger fractions of the stellar magnetic field are concentrated into starspots.

Such a conclusion is supported by the finding of Radick et al. (1989) and Lockwood et al. (1992) that although brightness variations of stars with activity levels similar to the sun are dominated by faculae (like the sun these stars are brighter at the times of their activity maxima), more active (and thus more rapidly rotating) stars show the opposite trend. This suggests that for the latter a larger fraction of the magnetic field is concentrated into starspots. Further support comes from indications that the fraction of an active region's area covered by spots increases with the size of the active region (Chapman et al. 1996, Foukal et al. 1996, cf. Solanki 1996). As pointed out by O'Dell et al. (1995) the saturation in magnetic flux observed by Saar (1991) at $\Omega_* \approx 10$–$16\Omega_\odot$ is compatible with the picture drawn above since only plage magnetic flux is detected (e.g. Saar & Solanki 1996).

These findings raise additional questions: 1. How strongly do stellar spots contribute to the open field lines and the stellar wind, which are finally responsible for the angular momentum loss? On the sun this fraction is not precisely known, but is generally not considered to be large. However, the Alfvén radius over solar active regions is significantly *larger* than over quiet solar regions, while the mass-loss rates are comparable (Marsch & Richter 1984). This suggests that a substantial fraction of the field lines emanating from active regions (including those from sunspots) are open. One simple geometry supporting both open and closed field lines in a bipolar region is that of the helmet streamer.

2. What is the influence of the increasing fraction of magnetic flux in starspots with increasing rotation rate? Firstly, we expect that with increasing rotation rate an increasing fraction of the magnetic flux at *all* latitudes is concentrated into starspots. Hence to first order such an increase should not influence our conclusion significantly. We have, however, assumed that the fraction of open field lines in starspots is the same as in stellar plages. If the fraction is smaller in starspots (which may be true) then the increased fraction of flux in spots provides an additional source of saturation of angular momentum loss in rapid rotators. This source too is independent of the dynamo, and reinforces our conclusion that dynamo saturation at low rotation rates is not required to explain the observed stellar spindown.

Finally, consider only the theoretical evidence for the saturation of the α-effect. It is unknown to what extent the mean-field models of Kitchatinov & Rüdiger (1993) give quantitatively correct predictions of the Ω_* at which this saturation occurs. For example, there is considerable evidence in favour of a flux-tube dynamo (Schüssler 1993). Of course, we expect stellar dynamos to eventually saturate at sufficiently high rotation rates, since at some point the back-reaction of the magnetic field on convection and differential rotation becomes appreciable. The rotation rate at which this back-reaction becomes sufficiently large is not known, however.

In summary, from the work of O'Dell et al. (1995) and others, as well as from the present paper it follows that there is currently no unequivocal need for a saturation of stellar dynamos at relatively low rotation rates, such as $10 - 20\Omega_\odot$. The evidence does not, however, exclude saturation above, say, $\Omega \gtrsim 50\Omega_\odot$ and theoretically such a saturation is expected above some (as yet unknown) Ω value.

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