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ANGULAR MOMENTUM LOSS FROM THE YOUNG SUN: IMPROVED WIND AND DYNAMO MODELS

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ABSTRACT One essential ingredient in modelling the rotational evolution of a late-type star is a proper estimate of the angular momentum loss rate, as a function of rotation rate, surface magnetic field strength, etc. In this contribution, we use different dynamo relations to compute angular momentum loss rates from a grid of improved Weber-Davis type MHD wind models.

INTRODUCTION

Late-type stars have convective envelopes that are coupled to the underlying radiative core by hydrodynamical and/or MHD mechanisms. If the typical timescale of core-envelope coupling (τ_c) is equal to or longer than the spin-down timescale associated with the magnetized wind (τ_J), the wind can act to slow down the convective envelope only, at least near the ZAMS. Within a coupling time τ_c, the radiative interior responds to the rotational deceleration of the overlying convective envelope, transfering angular momentum to the envelope, thereby retarding the deceleration. As the rotation rate decreases, the spin-down time τ_J increases. Then, after the initial envelope spin down, the star is braked as a whole as a result of the coupling, with a more gradual decrease in rotation rate because of the large moment of inertia of the star. We use the simple parametric model of MacGregor & Brenner (1991), where the star is treated as a two-shell configuration (radiative core and convective envelope) to calculate the main sequence rotational evolution of a solar-type star based on the qualitative picture described above.

Essential to this parametric model are the timescales τ_c and τ_J. In this paper, we simply assume a constant coupling timescale of 20 Myr, the canonical age separation of the α Persei and Pleiades clusters. For the spin-down timescale τ_J, we calculate the angular momentum loss rates as predicted by the Weber-Davis (1967) wind model, for a grid of surface rotation rates - surface field strengths ranging from half solar to 60 times the solar values (see Figure IA). The solar wind model used has properties of the low-speed solar wind as described by Withbroe (1988). In the framework of the Weber-Davis model, the constant specific angular momentum L can be evaluated as $L = \Omega r_A^2$, as if there was

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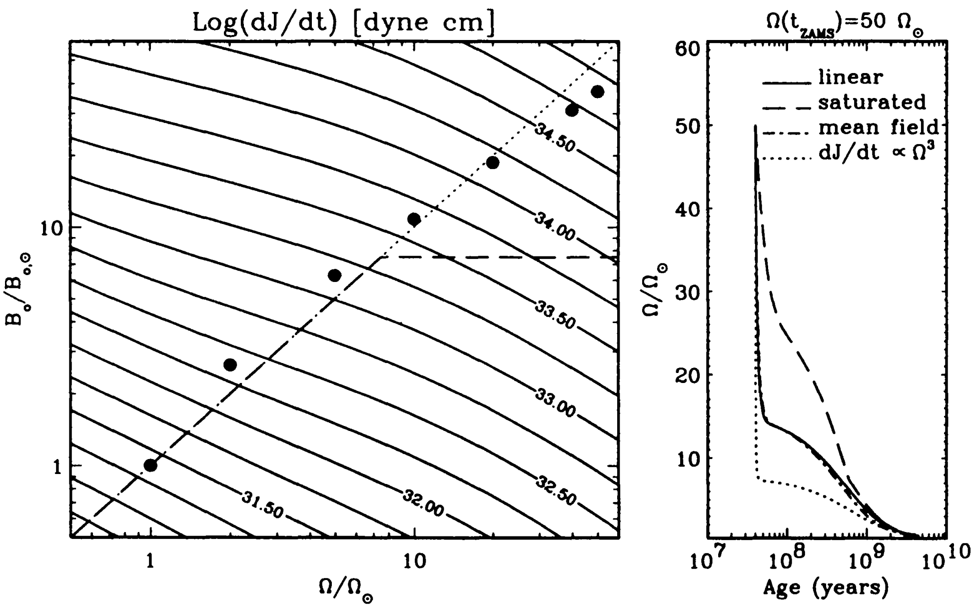

FIGURE I **IA left:** Contour plot of the angular momentum loss rate as predicted by Weber-Davis MHD wind calculations, as a function of rotation rate (with $\Omega_\odot = 3 \times 10^{-6}$ rad s^{-1}) and surface field strength (with $B_{o,\odot} = 2$ G). Dynamo relations are : linear dynamo (dotted line), saturated dynamo (dashed line), mean field dynamo (•). **IB right:** Surface rotational evolution of an initial uniformly rotating star ($\Omega = 50\Omega_\odot$), for the three dynamo relations considered. For comparison, the dotted line is what a relation $\frac{dJ}{dt} \propto \Omega^3$ would predict.

effective corotation out to the Alfvén radius r_A (where the radial flow speed equals the radial Alfvén speed).

RESULTS

To calculate the instantaneous angular momentum loss rates $\tau_J(t)$ resulting from the magnetically coupled stellar wind requires knowledge of the dynamo relation that links the surface field strength $B_o(t)$ with the rotation rate $\Omega(t)$. We consider three dynamo relationships. A **linear dynamo** relation, as given by $\frac{\Omega}{\Omega_\odot} = \frac{B_o}{B_{o,\odot}}$. A **saturated dynamo**, where we artificially saturate the linear dynamo relation at $7.5\Omega_\odot$. A third dynamo relation we explore is the result of a **mean-field dynamo** calculation (A. Brandenburg).

Each of the three dynamo relations can be used to predict the angular momentum loss rates for a solar-type star at different stages of the star's main sequence spin-down using the Weber-Davis wind model. In Figure IA, we present the calculated angular momentum loss rates $\dot{J}_\odot = \frac{2}{3}\Omega r_A^2 \dot{M}$ as a function of rotation rate and surface field strength. This loss rate is the product of the specific angular momentum L and the mass loss rate ($\dot{M}$). **The angular momentum loss rate increases with Ω at constant B, and with B at constant Ω.** The increase with rotation at constant surface magnetic field strength has contributions from both the change in specific angular momentum (Ωr_A^2) and the increase in mass loss rate ($\dot{M}$). The mass loss rate increases because of the additional magneto-centrifugal acceleration at the coronal base. The specific angular momentum L first increases with rotation, but at higher rotation the Alfvén point moves inwards (since the centrifugal acceleration increases the flow speed), and L eventually decreases. The increase with B at constant Ω is mainly related to the increase of specific angular momentum (L), since the Alfvén point moves outward with increasing B. Increasing the surface magnetic field at constant Ω leaves the mass loss rate virtually unchanged, but enforces effective corotation out to larger distances. We emphasize the failure of representing the angular momentum loss rate as a simple parametric relation (e.g. of the form $\frac{dJ}{dt} \propto \Omega^3$, yielding the so-called Skumanich relation for a fixed moment of inertia I) of rotation rate : the interplay of rotation and magnetism causes changes in specific angular momentum and mass loss rate far too complex to be represented by a single power law for $\dot{J}(\Omega)$.

The rotational evolution predicted by the two-shell model is illustrated in Figure IB. This Figure shows the rotational evolution of an initial uniformly rotating ($\Omega_{core} = \Omega_{conv} = 50\Omega_\odot$) $1M_\odot$ star using the three different dynamo relations. We plotted surface rotation rates as functions of age. The **linear dynamo** relation predicts rapid spin-down within 10 to 20 million years after t_{ZAMS} (taken as 4×10^7 yr) such that the initial $v \sin i = 100$ km s^{-1} falls off to ~ 30 km s^{-1} at the age of the α Persei cluster (5×10^7 yr), and to ~ 12 km s^{-1} at the age of the Hyades cluster (6×10^8 yr). The **saturated dynamo** predicts a slower spin-down rate in the first few $10^7 - 10^8$ yr, and preserves a larger rotational velocity out to the age of the Pleiades (7×10^7 yr). By the Hyades age, the rotational evolution is much like the linear dynamo calculation, and the subsequent evolution is (virtually) identical since the same linear dynamo relation holds for $\Omega/\Omega_\odot < 7.5$. The **mean field dynamo** is almost identical to the linear dynamo calculation, but predicts a spin-down to somewhat lower rotational velocities at the solar age.

CONCLUSIONS

We point out that (1) the dynamo relation used influences mostly the initial spin-down rates, and thus the persistence of fast surface rotation at the beginning of the main sequence evolution. (2) In all cases considered, the variations of $\dot{J}(\Omega)$ are too complex to be fitted with simple parametric relations. (3) At the solar age, 'memory' of the initial condition is essentially lost. The (main sequence) rotational evolution calculated tends towards solar-like rotations at the solar age, almost independently of the initial rotational speed and the adopted dynamo relation.

REFERENCES

MacGregor, K.B. & Brenner, M. 1991, ApJ, **376**, 204

Weber, E.J. & Davis, L.Jr. 1967, ApJ, **148**, 217

Withbroe, G.L. 1988, ApJ, **325**, 442