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MAGNETIC FIELD AND ANGULAR MOMENTUM EVOLUTION MODELS

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Abstract. The magnetic field in young stellar object is clearly the most important component when one dealing with the angular momentum evolution of solar-like stars. It controls this latter one from the pre-main sequence, during the "disk locking" phase where the stars magnetically interact with their surrounding disk, to the main-sequence through powerful stellar winds that remove angular momentum from the stellar surface. We present new models for the rotational evolution of solar-like stars between 1 Myr and 10 Gyr with the aim to reproduce the distributions of rotational periods observed for star forming regions and young open clusters within this age range. Our simulations are produced by a recent model dedicated to the study of the angular momentum evolution of solar-type stars. This model include a new wind braking law based on recent numerical simulations of magnetized stellar winds and a specific dynamo and mass-loss prescription are used to link the angular momentum loss-rate to angular velocity evolution. The model additionally allows for a core/envelope decoupling with an angular momentum transfer between these two regions. Since this former model didn't include any physical star/disk interaction description, two star/disk interaction processes are eventually added to it in order to reproduce the apparent small angular velocities to which the stellar surface is subject during the disk accretion phase. We have developed rotational evolution models for slow, median and fast rotators including two star/disk interaction scenarios that are the magnetospheric ejection and the accretion powered stellar winds processes. The models appear to fail at reproducing the rotational behaviour of solar-type stars except when a more intense magnetic field is used during the disk accretion phase.

Keywords: Stars: solar-type, Stars: magnetic field, Stars: evolution, Stars: rotation, Stars: winds, outflows subject, verb, noun, apostrophe

1 Introduction

Classical T Tauri stars (CTTs) are very active pre-main sequence stars surrounded by an accretion disk (Edwards et al. 1994; Hartmann et al. 1998). The impact of their magnetic field on their dynamics and on the structure of their environment is very strong and lead to numerous physical phenomenon such as the truncation the disk and accretion of the material from it along funnel flows down to the stellar surface, launch of stellar winds along the opened magnetic field lines (Matt & Pudritz 2008a; Matt et al. 2012; Cranmer & Saar 2011), and ejection of material because of magnetic star/disk interaction (Shu et al. 1994; Ferreira et al. 2000; Romanova et al. 2009; Zanni & Ferreira 2009, 2013). The magnetic interaction between the star and its surrounding accretion disk remains one of the major unsolved issue concerning the angular momentum evolution of CTTs. It is now observationally clear (see Edwards et al. 1993; Bouvier et al. 1993; Rebull et al. 2004) that during the first 10 Myr of their life the stars are prone to held constant their rotation for several Myr (Irwin & Bouvier 2009; Gallet & Bouvier 2013). Since CTTs accrete mass and angular momentum from their disk and they still contract during the pre-main sequence (PMS), they should spin-up in a few million years. Hence, this suggests that during this period a large fraction of the angular momentum is removed from the stars. Many theoretical advances have been made during the last years about the impact of the accretion/ejection phenomenon on the angular momentum evolution of young suns such as the magnetospheric ejection process (hereafter MEP, Zanni & Ferreira 2013) that describes the magnetic interaction between a stellar magnetosphere and an accretion disk, and the accretion power stellar wind (hereafter APSW, Matt & Pudritz 2005, 2008a,b) that predicts powerful stellar jets powered directly by the accreted material.

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The aim here is to examine the impact of these different star/disk interaction scenarios on the angular velocity evolution and the conditions for which the surface angular velocity of the stars is held constant during the early PMS phase when the stars are still surrounded by an accretion disk. Since some previous works by Collier Cameron et al. (1995) and Matt et al. (2010) already studied such interaction we will focus on reproducing the rotational evolution of solar-like stars by comparing the models to the observations. This is the first time that these specific scenarios are incorporated into a "global" angular momentum evolution model which gives us the chance to analyse the impact of these interactions on the MS rotational behaviour.

2 Angular velocity evolution

We use the model described in Gallet & Bouvier (2013) that is dedicated to the study of the angular momentum evolution of solar-type star. Since this model didn't include any physical description of the star/disk interaction process we want to examine the impact of star/disk interaction scenarios on the early PMS angular momentum evolution. A more detailed description of the former model can be found in Gallet & Bouvier (2013). In this "new" model we combined the magnetospheric ejection (Zanni & Ferreira 2013) and accretion powered stellar wind (Matt & Pudritz 2005) processes during the disk accretion phase. We found that a more intense magnetic field, compare to the mean magnetic field used in Gallet & Bouvier (2013), is required to reproduce the early-PMS clusters.

The free parameters of the model are the initial rotation period P_{init} at 1 Myr, the core-envelope coupling time-scale τ_{c-e}, the disk lifetime τ_{disk}, and the calibration constant of the wind braking law K_1. This study adopts the same parametrization as described in Gallet & Bouvier (2013). Additionally, two free parameters are added here: the mass loss rate efficiency constant Q_{acc}, and the strength of the magnetic field B_{mod}. We computed the angular velocity evolution of the fast, median, and slow rotator models, and examine the impact of the two star/disk interaction mechanisms on this evolution. Figure 1 shows the angular velocity evolution of the fast, median, and slow rotator models, respectively in blue, green, and red.

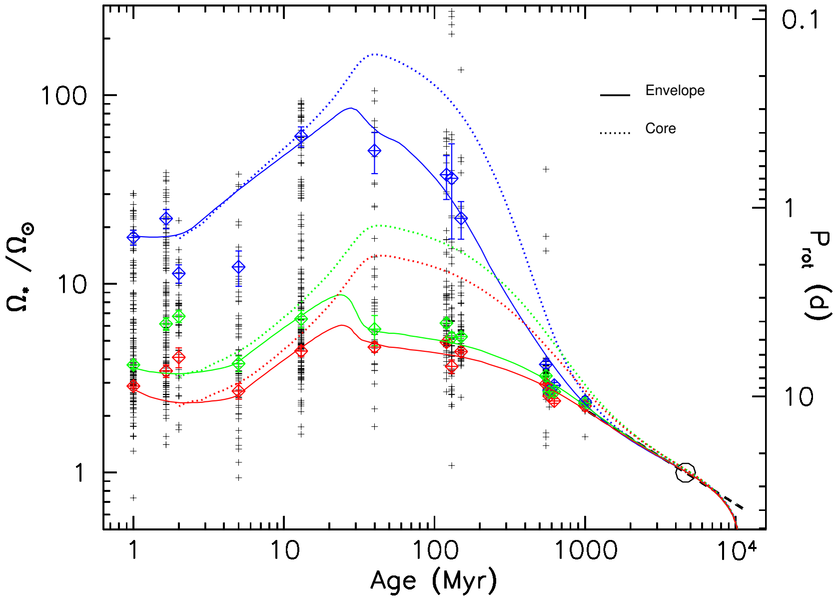

Fig. 1. Angular velocity of the radiative core (dashed lines) and of the convective envelope (solid lines) is shown as a function of time for fast (blue), median (green), and slow (red) rotator models in the case $Q_{acc} = 1\%$. The angular velocity is scaled to the angular velocity of the present Sun. The blue, red and green tilted square and associated error bars represent the 90th percentile, the 25th percentile, and the median, respectively, of the rotational distributions of solar-type stars in star forming regions and young open clusters obtained with a rejection sampling method (see Gallet & Bouvier 2013)). The open circle is the angular velocity of the present Sun and the dashed black line illustrates the Skumanich's relationship, $\Omega_* \propto t^{-1/2}$.

For the fast rotator model a disk's lifetime of 2.5 Myr is used that lead to a rapid increase of the surface angular velocity of the stars during the PMS. The quite low initial rotation period $P_{init} = 1.4$ d is dictated by the fast rotation rate exhibited in the Orion Nebulae Cluster at 1 Myr and the NGC 6530 cluster at 1.65 Myr. To fit the observational constraints from the PMS to the ZAMS a relatively short core/envelope coupling timescale of 10-15 Myr is needed. To reproduce the early-PMS observations we numerically set $B_{mod} = 1000$ G. For the median and slow rotator models the initial rotation periods are 7 and 9 d, respectively, as fixed by the rotation period distributions of the youngest PMS clusters. For both models we chose a disk lifetime of 5 Myr to reproduce the late PMS clusters. To account for the moderate velocities on the ZAMS, we had to assume a much longer core-envelope coupling timescale than for fast rotators, namely 28 and 30 Myr for median and slow rotator models, respectively. The slow decline of surface rotation is due to angular momentum of the core resurfacing at the stellar surface on a timescale of $\simeq$100 Myr in slow and moderate rotators and it accounts for the observed evolution of the lower envelope of the rotational distributions of early MS clusters. To reproduce the observations in these cases, B_{mod} is set at 1600 and 1300 G for the slow and median rotator models, respectively.

3 Conclusions

We combined two star/disk interaction scenarios in the “global” angular momentum evolution model described in Gallet & Bouvier (2013) with the aim to study the angular velocity evolution of solar-like stars during the early-PMS phase. We found that the models fail to reproduce the observations except when a more intense magnetic field is used during the disk accretion phase. In presence of weak magnetic field the torque applied by the accretion disk on its star is not sufficient enough to efficiently extract angular momentum from the stellar surface to compensate the stellar contraction that otherwise dominate this evolution. These results are certainly not new since the star/disk interaction process is not a modern issue and that it has already been studied in the literature through different mechanisms (e.g. Collier Cameron et al. (1995); Matt et al. (2010)). The major difference of this study is that the resulting angular velocity evolution produces by the star/disk interaction is directly compare to the observations. However, this is a preliminary result and a more physical model is still to be developed especially in studying the impact of a non-axisymmetric and multipolar magnetic field on the angular velocity evolution.

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