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STARS AND THEIR DISC - A SHORT BUT COMPLEX STORY

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Abstract. Durring their formation, most young stars are surrounded by a protoplanetary disc. The angular momentum evolution of these system is quite complex but still poorly understood despite a lot of effort and some recent breakthrough. Observations indicate that stars with a disc tend to rotate more slowly even though they accrete angular momentum, and that during the first 10Myr, young low-mass stars do not seem to spin-up while they are expected to contract.

To tackle this long-standing problem, we present state-of-the-art stellar evolution models with accretion that include a self-consistent treatment of angular momentum thanks to the results of dynamical multi-D MHD simulations. We explore the observed range of several parameter, such as the accretion rate history, the composition and the thermodynamics of the accreted material as well as the large scale magnetic field strength of the star. We show that the observed spin rate distribution of very young stars can be explained by the complex interplay of the different processes.

Keywords: stars: evolution, stars: formation, stars: low-mass, stars: pre-main sequence, accretion

1 Introduction

Understanding the formation stage of low-mass stellar system is of crucial importance for both planetary and stellar science. The evolution of the total angular momentum of stellar systems in formation has been particularly studied over the last thirty years as it is responsible for the formation of the protoplanetary disc. It is thought to be the birthplace of planets and feeds the star with new material infalling onto the stellar surface.

On one hand, single low-mass stars typically contract, and accrete some material from the surrounding disc during the early evolution which increases again their total angular momentum. Both mechanisms can spin up the stars to extreme rates. On the other hand, bservations are showing that the presence of a disc is linked to a slower rotation period, this is known as the disc-locking scenario (Koenigl 1991; Edwards et al. 1993; Rebull et al. 2004; Bouvier et al. 2007, 2014; Venuti et al. 2017; Rebull et al. 2022) To explain this feature, several theoretical explanations have been proposed to extract angular momentum from the star, such as the X-winds model (Shu et al. 1994; Ferreira et al. 2000), the accretion powered stellar winds (Matt & Pudritz 2005, APSW), or the magnetospheric ejections (Zanni & Ferreira 2009). While none of them are exclusive by essence they have rarely been studied together (Matt et al. 2010; Johnstone et al. 2014; Gallet et al. 2019). The early pre-main sequence is a highly dynamical phase and is therefore hard to model on evolutionary timescales. A common approach is thus to extract scaling laws from short time span multidimensional MHD simulations (Matt & Pudritz 2005; Zanni & Ferreira 2009; Romanova et al. 2021; Ireland et al. 2022), and apply them to 1D evolution models on longer timescales. In this work, we will be using the results from the PLUTO star-disc simulations by Ireland et al. (2022) implemented in the evolution code STAREVOL.

In addition, it was shown that the radius and thus the moment of inertia can be drastically affected by accretion of material with different composition and thermodynamic properties Siess et al. (1997); Baraffe et al. (2009); Hosokawa et al. (2011); Kunitomo et al. (2017), we will thus use stellar evolution tracks that consistently includes accretion.

In section 2, we summarise the physics implemented in STAREVOL and the impact of accretion on stellar evolution. In section 3 we explore how the rotational evolution is modified under the influence of both rotation and an external torque. Finally, we discuss the results and the future work to be done.

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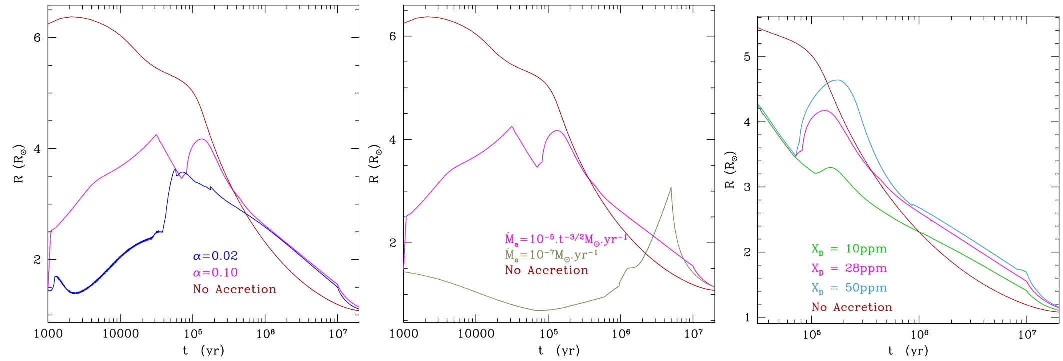

Fig. 1. Radius evolution for accreting models with two different accreted heat contents (left), two accretion histories (middle), and three deuterium content (right). On each panel a 1M$_\odot$ non-accreting model is shown in dark red for comparison.

2 Accretion in stellar evolution

The accretion of material onto a star brings mass, energy and new chemical elements, the effects are thus plural. We use the STAREVOL code which already has a scheme to treat accretion of material during the pre-main sequence (See Siess et al. 1997, 2000). The energy equation is modified accordingly where the In the current case, we make the following assumptions : 1) the accreted mass is mixed with the upper 1% in mass of the star, 2) the thermal and kinetic energy brought by the material is also added within the upper 1% in mass of the star, mimicking a shear layer where the material is deposited. 3) The chemicals are deposited at the surface and transported by convection in the rest of the star, the case of Deuterium will be discussed later. 4) The material comes in with a low entropy, and thus needs to be thermalised, thus only a fraction f_{acc} of the accreted energy is absorbed by the star. In addition, we set the reference model with an initial seed of $0.01M_\odot$ with a radius of about $1.4R_\odot$ on which mass is accreted at a rate $\dot{M}_{\rm acc} = 1.3.10^5.\,(t/t_{\rm init})^{-1.5}$ for 10 million years.

On Figure 1, we explore the role played by a few parameters on the radius evolution, which controls the moment of inertia and thus impacts the rotational evolution.

Heat content - In agreement with the work by Kunitomo et al. (2017) and as shown on the left panel, we find that a thermalised material increases the energy content of the star and puffs up the radius, this is most obvious during the early evolution. Kunitomo et al. (2017) and Baraffe et al. (2009) showed in particular that a cold material ($\alpha = 0$) hinders the development of the star which may keep a small radius all the way to the end of the pre-main sequence.

Deuterium content - When our seed reaches about 10^5yr, the temperature at the base of the convective zone becomes hot enough to burn the fresh deuterium brought by accretion. We can see on the middle panel that the deuterium content in the accreted material makes a difference from that moment to the end of the accretion phase. As already noted by Kunitomo et al. (2017), as long as the deuterium is consumed, the contraction is a little delayed when compared to the non-accreting case.

Accretion history - The right panel of figure 1 shows that the accretion history has a very large impact on the evolution, the pink model has a very large accretion at first which strongly increases the radius for 30 years, after which the star contracts as the accretion rate decays. On the other end, the constant accretion rate at $2.10^{-7}M_\odot.yr^{-1}$ leads to a very small radius (also because the mass is increasing slower) for a long time. At the end of the disc phase though, the accretion rate is comparatively very high and in particular, the amount of fresh Deuterium accreted brings a lot of energy to the star.

3 Rotation and accretion from a disc

3.1 Description

STAREVOL is able to evolve models with the effect of rotations and to treat the angular momentum evolution consistently along the stellar structure evolution (See Palacios et al. 2003; Amard et al. 2019). The novelty comes from the inclusion of Ireland et al. (2022)'s formalism to compute external torques associated to the star-disc interaction. The formalism comes from 2.5D PLUTO simulations of a magnetised star accreting from

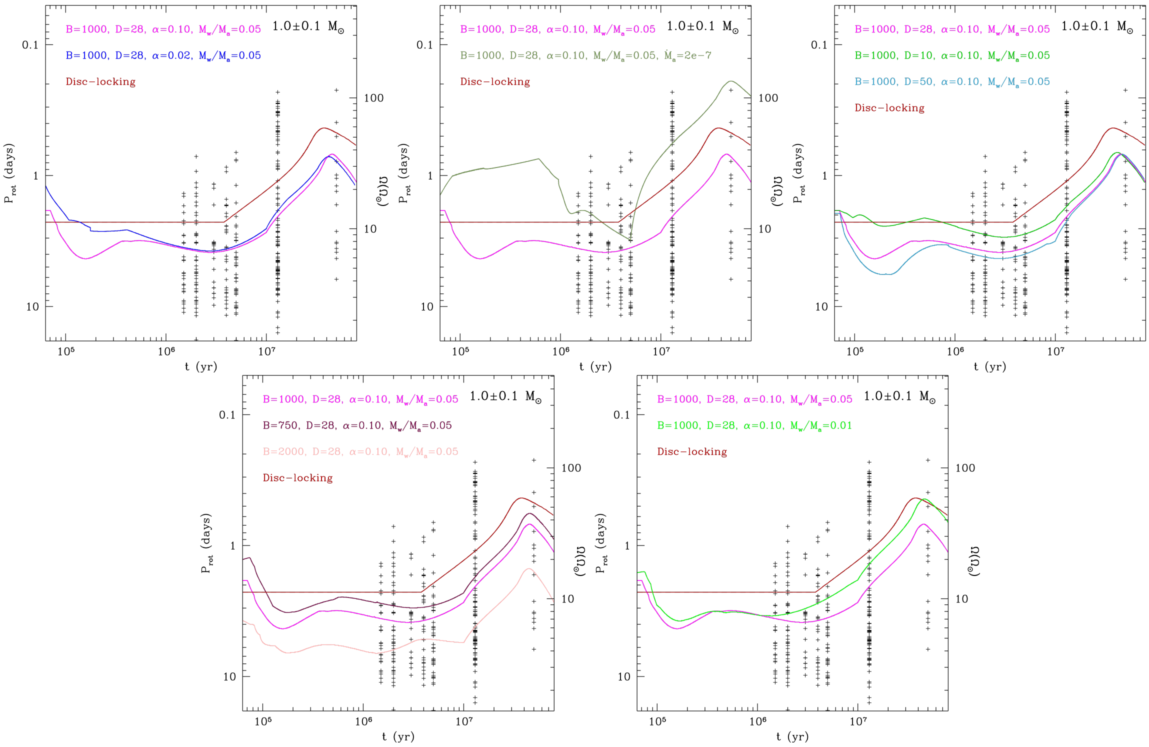

Fig. 2. Rotation period evolution as a function of time for different heat contents of the accreted material (top left), accretion histories (top center), deuterium contents (top right), magnetic field strengths (bottom left), and mass-loss/accretion ratios (bottom right). On all panel, the reference model is plotted in magenta and the disc-locking scenario is in dark red. The colour code follows the legend for the other models. The background displays rotation period observations from young open clusters.

a disc. They derive three torques : 1)a spin-up torque due to the accretion of material from the inner boundary of the disc, 2)a spin-down torque from the magnetised winds, which is enhanced by the presence of the disc, and 3)a torque related to some magnetic reconnection leading to the ejection of large plasma bubble known as magnetospheric ejections (ME, Zanni & Ferreira 2009). The balance between the three torques varies with the ratio between the truncation radius of the inner disc* and the co-rotation radius in the disc. We implemented Ireland et al. (2022)'s work in STAREVOL as an external torque in the angular momentum module. We refer to the original paper for the details of the formalism and the calibration of the torques. The models has now two extra parameters : the polar magnetic field strength (assuming a dominant dipolar field) which governs the truncation radius, and the ratio between the accreted mass and the lost mass. The latter is coming from the Accretion-Powered Stellar Wind scenario (Matt & Pudritz 2005), it assumes that a fraction of the infalling mass ends up being bounced back and can be considered a loss of mass.

3.2 Results

We thus explored five parameters, the three mentioned in the non-rotating case, the magnetic field strength B_p, and the lost to accreted mass ratio $\dot{M}_{\rm w}/\dot{M}_{\rm acc}$. On figure 2, we present the surface rotation period evolution for a variety of parameter. Observational evidence of rotation during this early phase are relatively hard to find, we thus relied on a few very young open clusters from Gallet & Bouvier (2015) to guide the eye and verify that the rotation evolution stays within the expected boundaries. We use as a comparison the usual disc-locking scenario (red on each panel), and a reference model set as the one described in Section 2 with $B_p = 1$kG and $\dot{M}_{\rm w}/\dot{M}_{\rm acc} = 5\%$ and shown in magenta in each panel.

*The inner boundary is limited by the stellar surface

- Heat - As expected from Section 2, the larger radius due to a warmer accretion leads to a slower rotation rate during the early evolution. However, we can see on the top left panel of fig. 2 that after 1 Myr, the two evolutions join and the models evolve almost identically.

- Accretion history - The top central panel shows the evolution for the two type of accretion history (constant and decaying). The constant accretion model has a much smaller radius and thus spins up very fast for about a Myr before starting to spin down under the influence of the stellar winds, the MEs and the radial expansion as the star gains mass and reaches end of the disc phase.

- Deuterium content - The amount of deuterium affects the size of the star as soon as it can be burnt in the inner layers of the star. Consequently, the more Deuterium the star accretes, the larger the radius and thus, as seen on the top right panel of fig. 2, the slower the spin. Note however that even a low level of Deuterium (green) remains within the realm of possibilities with this set of parameter.

- Magnetic field strength - The magnetic field strength is likely the most important parameter for the SDI torques since it constrains the distance at which the stellar magnetic field line will plunge in the disc and extract material, thus truncating the disc. On the bottom left panel of fig. 2, we explore 2 extra values, a lower dipolar field at 750G (purple) and a stronger one at 2kG. The stronger magnetic field efficiently removes angular momentum from the star, enhancing the wind and efficiently putting the star in the so-called *propeller stage* in which the MEs efficiently extract angular momentum. On the other end, a weaker dipole leads to shorter rotation periods. Note that the decrease is only a factor 2 and is not as important as was presented in Gallet et al. (2019) where the effects of accretion were not taken into account.

- $\dot{M}_{\rm w}/\dot{M}_{\rm acc}$ ratio - This last parameter is a large unknown and was shown to be potentially quite small and probably around a percent or less (Zanni & Ferreira 2011). On the bottom right panel of fig. 2, we explored the case where only percent of the accreted mass was lost as a stellar wind (green track). The rotational evolution is almost unchanged for the first Myr but during the later stages, the weaker wind torque allows the star to spin-up at an earlier stage. Note however that the rotational evolution is still well within the rotation period observations.

4 Conclusions

We realised a systematic parameter study for the first low-mass stellar evolution models including both a realistic treatment of accretion and angular momentum evolution. The results are very promising and confirms the findings of Gallet et al. (2019) that these types of models allow to globally explain the overall constant rotation period observed in open clusters. In addition, the multiplicity and the variability of possible parameters (initial deuterium, accretion history, energy content of the accreted material, total magnetic energy and mass-loss rate) can explain the rotation period discrepancy observed in young open clusters. We invite the reader to look for Amard & Matt (in prep) for the details on the torques, and a larger and more complete parameter study.

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