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Massive star formation by accretion: how to circumvent the angular momentum barrier?

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Abstract. We present pre-main sequence models for massive star formation computed with the GENEVA stellar evolution code self-consistently including accretion and rotation. The models show that a braking mechanism is needed in order to circumvent the angular momentum barrier. This mechanism has to be efficient enough to remove more than 2/3 of the angular momentum from the inner accretion disc.

1. Introduction

Star formation requires mechanisms that extract angular momentum from collapsing cores. If angular momentum was locally conserved during the collapse, initial turbulent motions would lead to high rotation velocities as contraction proceeds, exceeding the break-up velocity and preventing the collapse towards stellar densities (e.g. Maeder 2009).

In the present work, we study which constraints pre-main sequence (pre-MS) evolution gives to this angular momentum problem, in the context of massive star formation. See Haemmerlé et al. (2017) for more details.

2. Numerical and physical inputs

We compute pre-MS models using the GENEVA stellar evolution code (1D hydrostatic code, see Eggenberger et al. 2008). The code includes a self-consistent treatment of accretion and rotation, with mass- and angular momentum-accretion rates ($\dot{M}$ and $\dot{J}$) as free parameters. Accretion is treated with the assumption of *cold disc accretion*: the thermal properties of the accreted material match that of the stellar surface. Three mechanisms of internal angular momentum transport are included: convection, meridional circulation and shear diffusion. We consider $\dot{M}$ in the range $10^{-5} - 10^{-3}$ $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, and we use three prescriptions for $\dot{J}$:

1. **Smooth-J accretion:** The angular velocity of the accreted material equals that of the stellar surface.
2. **Constant-J accretion:** The specific angular momentum of the accreted material ($\mathrm{d}J/\mathrm{d}M=\dot{J}/\dot{M}$) is constant.
3. **Keplerian-J accretion:** The specific angular momentum of the accreted material is a constant fraction of the Keplerian value at the stellar surface.

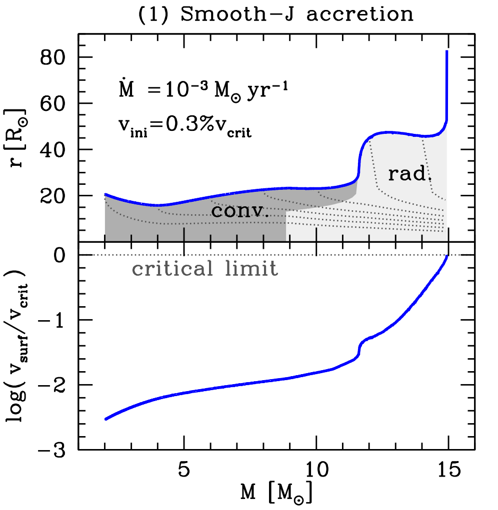

Fig. 1. Stellar structure (upper panel) and surface rotation velocity (ratio to the critical velocity, lower panel) in the smooth-J case, as a function of the stellar mass, which is a time coordinate in case of accretion. On the upper panel, the coloured line is the photospheric radius, the dark grey areas are convection regions and the light grey ones are radiative. The dotted lines follow the Lagrangian layers. The mass-accretion rate and initial surface rotation velocity are indicated.

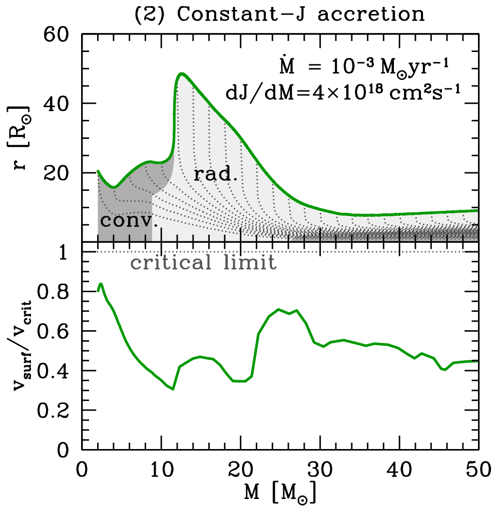

Fig. 2. Same as Fig. 1 in the constant-J case.

We define the *critical limit* as the point where the centrifugal force cancels gravity. This gives the upper limit of the surface rotation velocity (the critical velocity v_{crit}) for a star in hydrostatic equilibrium. Above this limit, accretion stops and the star loses mass.

3. Results

For smooth-J accretion (Fig. 1), the star reaches the critical limit at masses of 10 – 15 $M_\odot$, independently of the initial rotation velocity and the accretion rate. Only a change in the J-accretion history allows to circumvent this angular momentum barrier and to reach any mass without facing the critical limit (Fig. 2). For Keplerian-J accretion, if dJ/dM exceeds 1/3 of the Keplerian value, the star reaches the critical limit at 3 – 4 $M_\odot$, due to the internal angular momentum transport by convection.

4. Conclusions

Smooth-J accretion leads to an angular momentum barrier that prevents from forming massive stars by accretion. A braking mechanism that removes more than 2/3 of the angular momentum from the inner accretion disc is needed in order to circumvent this angular momentum barrier. Careful choice of the J-accretion history allows production of stars of any mass and rotation velocity compatible with structure equations.

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