On the formation of massive stars

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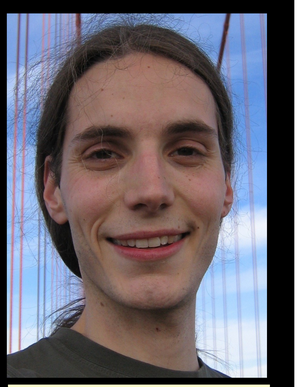

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Abstract

We investigate the radiation pressure problem in the formation of massive stars using a newly developed frequency dependent radiation transport module for three-dimensional hydrodynamics simulations. The nature of the radiative impact depending on the morphology of the stellar environment, e.g. rotating vs. non-rotating cores, is examined in one-, two-, and three-dimensional monolithic collapse calculations of massive pre-stellar cores.

Contrary to previous research, a highly superior frequency dependent stellar feedback is considered, the vicinity of the forming star is resolved down to 1.27 AU, and the evolution computed includes the whole stellar accretion phase up to several 10^5 yr. For the first time a broad survey of the parameter space is possible.

The simulations demonstrate the need of including the dust condensation front to compute the radiative feedback correctly. Earlier calculations, which ignore these physics, lead to an artificial early truncation of the accretion phase. The most fundamental result is that the formation of a massive accretion disk in slowly rotating cores bypasses the radiative flux through the optically thin atmosphere, enabling steady accretion also onto high-mass stars, which would be impossible in spherical symmetric accretion. In the 3D simulations, a revealed close-by gravitational instability in the disk drives a sufficiently high accretion rate to overcome the residual stellar radiation feedback.

For an initial core mass of 60, 120, 240, and 480 M_{sd} these mechanisms allow the star to grow up to 27, 57, 93 and more than 130 M_{sd} respectively.

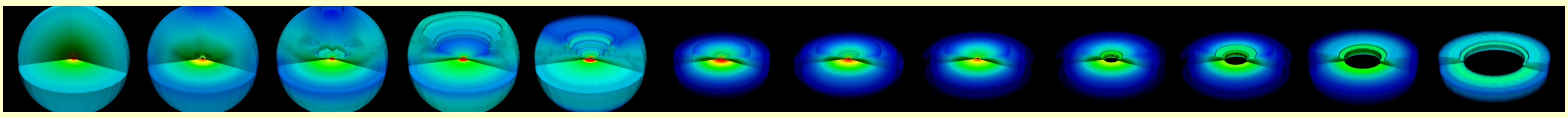

Fig. 1: Simulation snapshots of a collapse of a pre-stellar core of 120 M_{sd}, corresponding to a free fall time of t_{ff} = 47.8 kyr. The star in the center of the core grows up to 57 M_{sd}. 63 M_{sd} are ejected by radiative forces.
The images denote the launching of the bi-polar outflow, the formation of a long-living massive accretion disk, as well as the final removal of the remnant non-opaque accretion disk by the dominating radiation pressure.

Setup

The code

To evolve the equations of hydrodynamics, we use the

- 3D Magneto-Hydrodynamics code Pluto v.3 (Mignone et al.)
- including full tensor viscosity (thanks to Petros Tzeferacos)

We added to this code a ...

- Frequency dependent radiation transport
- Poisson-solver / Self-gravity
- Stellar evolution model (tracks by Hosokawa & Omukai 2009)
- Dust model (Laor & Draine 1993)

Initial Conditions

Initial conditions of pre-stellar cores:

- Outer radius of 0.1 pc.
- Density profile ~ r^{-2}.
- Initial temperature of 20 K.
- Rigid rotation (2D/3D) of $1.6 \cdot 10^{-5}$ yr^{-1}.

Numerical configuration:

- 2^{nd} order accurate in space and time.
- Uses spherical coordinates.
- Semi-permeable boundaries (mass can leave but not enter the core).

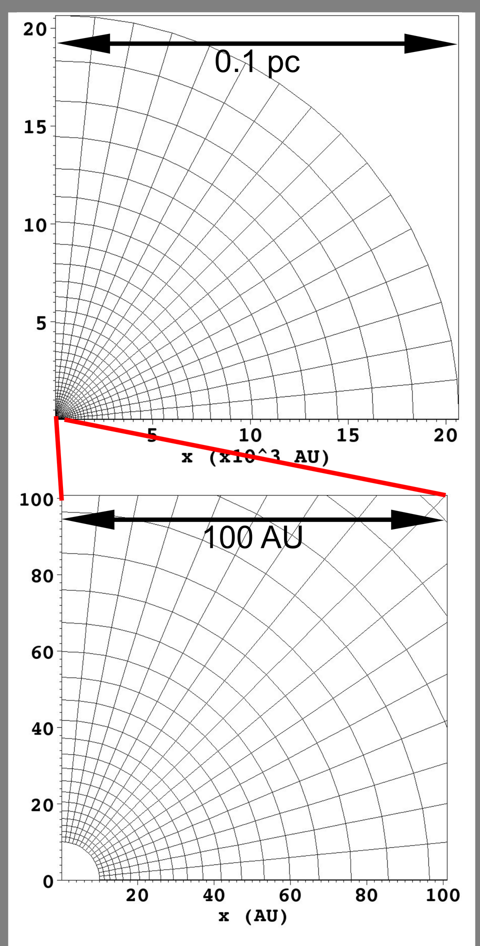

Fig. 2: 64x16 grid.

Key features

- Frequency dependent ray-tracing step (irradiation)
- Fast and robust flux limited diffusion solver (thermal dust emission)
- Resolution down to 1.27 AU
- Complete coverage of the accretion phase (10^5 … 10^6 yr) for the first time
- First broad scan of the parameter space possible
- Convergence runs feasible

Results

The dust sublimation front

- The opaque inner rim of the massive accretion disk generates a highly anisotropic thermal radiation field, diminishing the radiation pressure onto the accretion flow in the radial direction (cp. Fig 3).

→It is essential to resolve the dust sublimation front (Figs. 3+4).

→Reason for too short disk accretion phases in Yorke & Sonnhalter (2002).

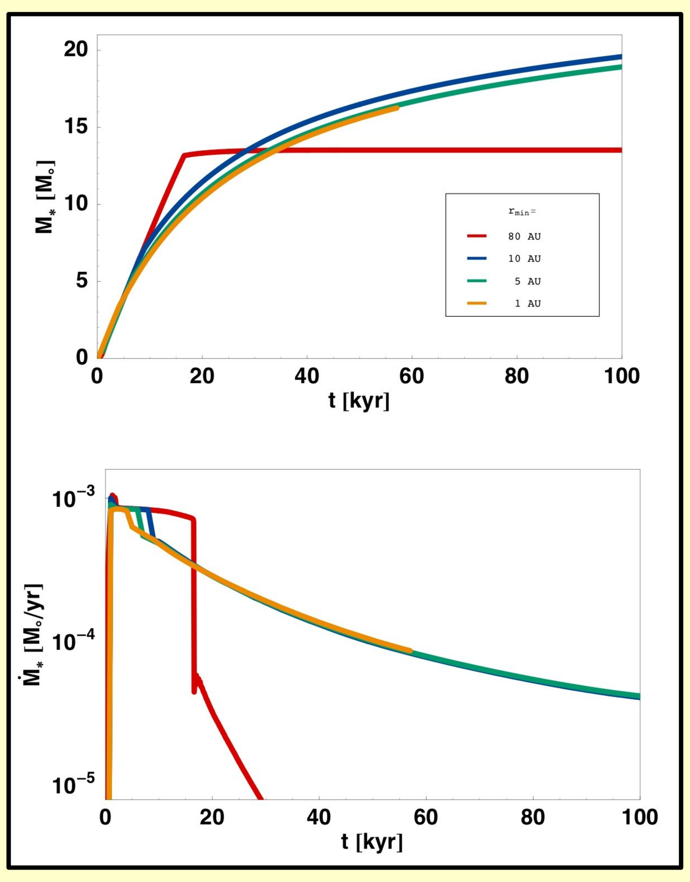

Fig. 3: Stellar mass and accretion rate vs. time for four different sink cell radii.

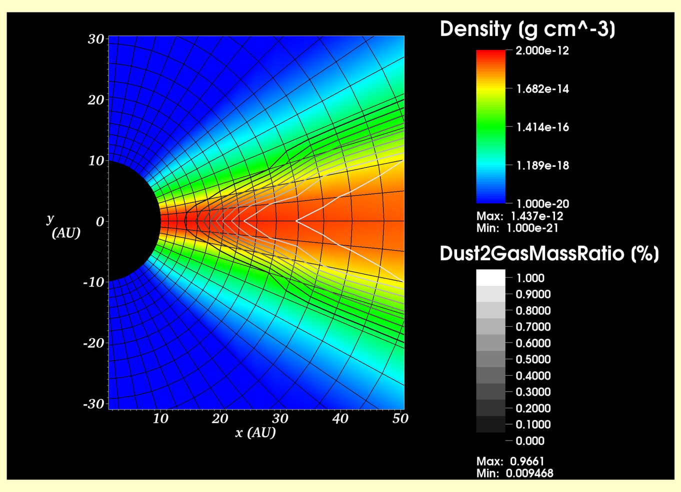

Fig. 4: Zoom into 50 AU x 60 AU region.

Overcoming the radiation pressure barrier

- Steady disk accretion easily overcomes the remnant radiation pressure in the disk.
- The shadowing of the disk regions behind the dust sublimation front allows a continuous disk accretion for several free-fall times.
- The 1D-radiation pressure barrier ($M_* \sim 40$ M_{sd}) is broken in the disk accretion models (Fig. 5).

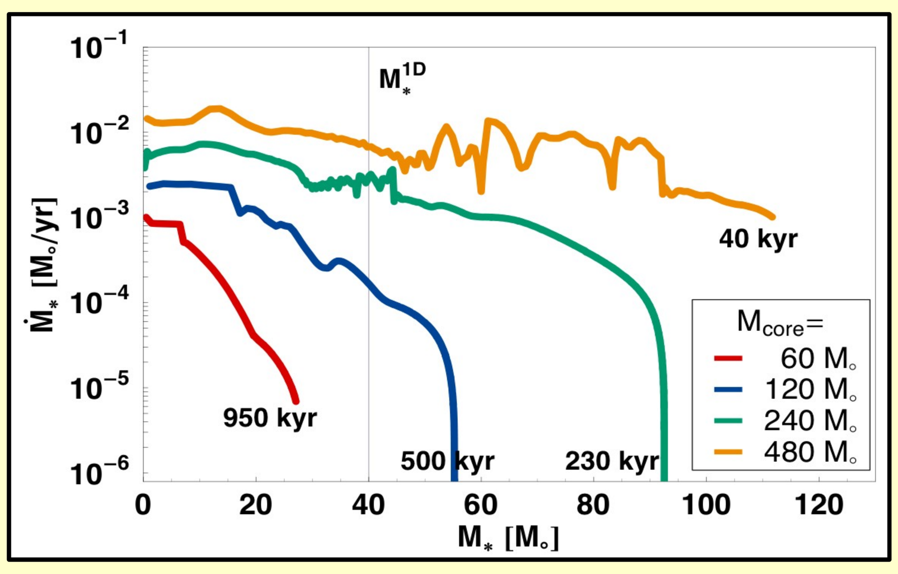

Fig. 5: Accretion rate vs. stellar mass of the disk accretion model for four different initial core masses.

Angular momentum transport

- Evolving gravitational instabilities in the massive accretion disk with 1 < Toomre Q < 2 (Fig. 6).
- Self-gravity of the accretion disk drives a sufficiently high angular momentum transport to allow the formation of massive stars (Fig. 7).

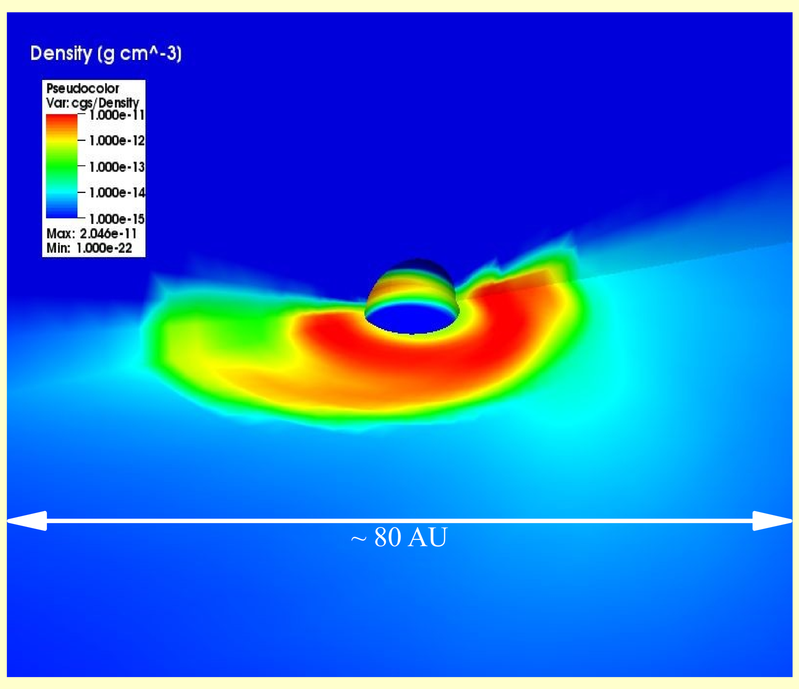

Fig. 6: Simulation snapshot of the inner disk region showing gravitational torques of the accretion disk.

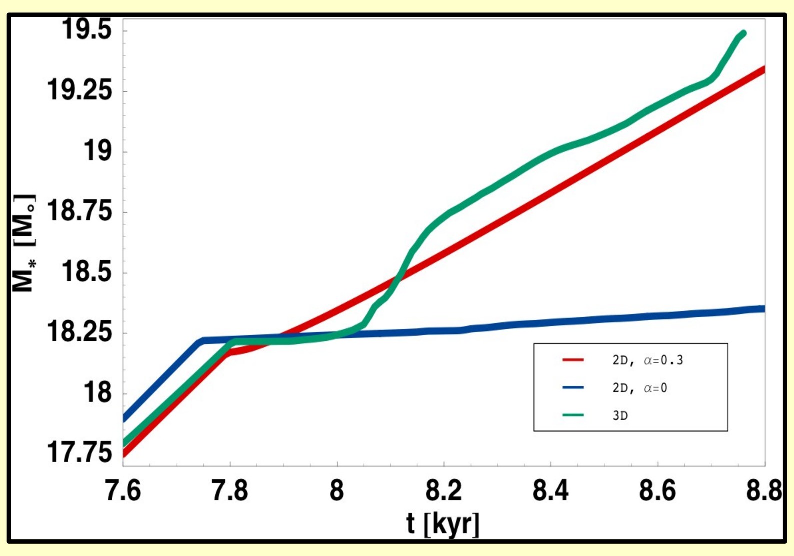

Fig. 7: Stellar mass vs. time of the disk accretion model for axial symmetric alpha-viscosity models and 3D self-gravity driven angular momentum transport.

References

Hosokawa & Omukai (2009), ApJ vol. 691 pp. 823
Kuiper et al. (2010a), A&A vol. 511 pp. 81
Kuiper et al. (2010b), submitted to ApJ
Kuiper et al. (2010c), in prep.
Laor & Draine (1993), ApJ vol. 402 pp. 441
Mignone et al. (2007), ApJS vol. 170 pp. 228
Yorke & Sonnhalter (2002), ApJ vol. 569 pp. 846