Radiation Pressure in Massive Star Formation

R. Kuiper1, 2, H. Klahr2, H. Beuther2, Th. Henning2, H.W. Yorke3

1 Computational Physics, Institute for Astronomy and Astrophysics, University of Tübingen
Auf der Morgenstelle 10, D-72076 Tübingen, Germany
2 Max Planck Institute for Astronomy Heidelberg
Königstuhl 17, D-69117 Heidelberg, Germany
3 Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109, USA

Abstract

Context:
During their evolution, massive stars quickly become so luminous that their radiation pressure onto the environment exceeds their gravitational attraction. Hence, radiation pressure plays a major role in shaping the circumstellar environment.

Methods:
Numerical highlights of our 1D, 2D, and 3D self-gravity radiation hydrodynamics simulations of various collapsing pre-stellar cores of gas and dust include a grid in spherical coordinates with non-uniform resolution down to 1 AU, a highly accurate frequency-dependent ray-tracing approach of the stellar irradiation (Kuiper et al. 2010a), and the consideration of temperature- and density-dependent gas opacities.

Results:
We determine the impact of radiation pressure on accretion disks and bi-polar outflow cavities:
- The well-known radiation pressure problem in the formation of massive stars can be circumvented via classical disk accretion: The formation of long-living massive accretion disks enforces a strong anisotropy of the thermal radiation field, enabling steady accretion through the shielded disk region (Kuiper et al. 2010b).
- This so-called flashlight effect is even amplified by optically thick gas (disks) around forming massive protostars (Kuiper & Yorke 2013a).
- In 3D the self-gravity of the massive accretion disk drives a sufficiently high angular momentum that the radiation pressure remains balanced against the disk accretion flow, thus allowing massive disks to survive and accrete (Kuiper et al. 2012).

Conclusions:
Summing up, the various simulation series draw a consistent picture of the formation of even the most massive stars in the present-day universe by classical disk accretion.

Numerical Highlights

- 1D - 3D Magneto-Hydrodynamics code Pluto (Mignone et al. 2007)
- Hybrid Radiation Transport scheme (Kuiper et al. 2010a)
- Frequency-dependent highly accurate Ray-Tracing step for Stellar Irradiation
- Gray Flux-Limited Diffusion solver for Dust (Re-)Emission
- Dust Model (Laor & Draine 1993)
- Optically Thick Gas Disks (Kuiper & Yorke 2013a)
- Poisson Solver for Self-Gravity
- Resolution down to 1 AU
- Extensive scalar field: The parameter space for more than 50 pre-stellar core collapse simulations published with varying core masses, density profiles, initial angular momentum, spatial resolution, ...
- Long evolution runs up to 10 free-fall times include full stellar accretion phase
  - Stellar and Accretion Luminosity Feedback (radiative heating and radiative force)
- Stellar Evolution sub-grid model for accreting Massive Protostars
- method I: Pre-computed evolutionary tracks (Hosokawa & Omukai 2009)
- method II: Self-consistent Stellar Evolution code (Kuiper & Yorke 2013b)
- Protostellar Outflow Feedback (Kuiper & Yorke, in prep.)

No Radiation Pressure Barrier!

- The formation of a massive star is accompanied by the formation of a massive accretion disk
  - The massive accretion disk is highly optically thick with respect to stellar irradiation
  - This yields a strong anisotropy of the thermal radiation field (upper right panel)
  - This diminishes the radiative force against the disk accretion flow
  - Sustained disk accretion epoch far beyond the radiation pressure limit (lower right panel)
- Classical disk accretion allows the formation of the most massive stars known!

No Radiative Rayleigh-Taylor Instability!

- The gray Flux-Limited Diffusion (FLD) approximation underestimates the long-range radiative force of direct stellar irradiation
  - FLD artificially yields a radiative force, which is in equilibrium with gravity (see „Forces“)
  - Stellar radiative feedback within the FLD approximation leads to Radiative Rayleigh-Taylor instabilities in the bi-polar outflow cavities (left panel)
- Contrary, frequency-dependent Ray-Tracing resembles the stellar radiation feedback
  - The expanding cavity shells remain super-Eddington (right panel)
  - Radiation-pressure-dominated cavities around massive (proto)stars remain stable!

References & Links

Kuiper et al. (2010a), A&A 511
Kuiper et al. (2010b), A&A 722
Kuiper et al. (2012), A&A 533
Kuiper & Yorke (2013a), ApJ 763
Kuiper & Kissien (2013), A&A 555
Mignone et al. (2007), ApJS 170

Further information online: http://www.mpia.de/~kuiper
Animations on YouTube: http://www.youtube.com/user/RolfKuiper