Multi-Physics of Feedback in Massive Star Formation

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From Stars to Massive Stars
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Feedback in Massive Star Formation

- Radiation Pressure on Dust
- Protostellar Outflows
- Ionization / HII Regions
- Radiation Pressure on Dust
Feedback mechanisms in *chronological order*:

- **Protostellar Outflows**
- **Radiation Pressure**
- **Ionization / HII Regions**
- **Stellar Winds / Mass Loss**
- **Supernova**

*Pre-main sequence*

*Main sequence*

**Time**

Simulation Approach:

- Focus on *small* spatial scales \(R_{\text{sink}} = 3 \text{ AU}; \Delta x_{\text{min}} = 0.3 \text{ AU}\)
- Focus on *long-term* evolution \(t_{\text{end}} = 6 \ t_{\text{free-fall}}\)
- *Multi*-Physics Feedback
Simulation Approach

*Kuiper et al. (2011), ApJ 732*
Software Development / Multi-Physics

- (Magneto-)**Hydrodynamics** PLUTO 4 (Mignone et al. 2007, 2012)
- **Self-Gravity** (Kuiper et al. 2010b)
- **Stellar Evolution** Module (Kuiper & Yorke 2013)
- Dust Sublimation and Evaporation Module
- **Protostellar Outflow** Module (Kuiper, Yorke, & Turner 2015)
- **Radiation** Transport
  - Irradiation + Diffusion Hybrid Scheme (Kuiper et al. 2010a)
  - now also in FLASH 4 (Klassen et al. 2014) & ORION (Anna’s talk)
- Hydrogen **Ionization**
  - Direct Stellar EUV Flux
  - Diffuse EUV Recombination Flux (in contrast to „on-the-spot“)

- Kuiper & Mignone (in prep.)
• Protostellar Outflow series (Kuiper, Turner, & Yorke, in prep.)
  • Collimation (3 different)
  • Accretion/Outflow efficiency ~ 1, 10, 20, 30, 40, 50%
    ▸ 11 Simulations
• Multi-Physics series:
  • 100 Msol in 0.1 pc and 1% Outflow Strength
  • 100 Msol in 0.1 pc and 10% Outflow Strength
  • 1000 Msol in 1 pc and 10% Outflow Strength
    → ,,Finite Mass Reservoir“
  • 36 Simulations
• Dimension: 2D (axial and midplane symmetry) or 3D
  ▸ In total: > 50 simulations
<table>
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<tr>
<th>Multi-Physics Feedback</th>
<th>Stellar Radiation Pressure</th>
<th>Thermal Radiation Pressure</th>
<th>Stellar Ionization</th>
<th>Recombination Ionization</th>
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12 Combinations
Results of Multi-Physics Simulations

- Protostellar Outflow collimates due to in-falling Envelope
- Optically thick Disk causes Shadow
  - Stellar Radiation Pressure and Direct Stellar Ionization Feedback limited to bipolar Regions

Approximately $10^4$ AU or 0.05 pc

Approximately 600 AU
Stellar vs. Thermal Radiation Pressure

- Thermal Radiation Pressure Feedback dominates on envelope-to-disk accretion
- Stellar Radiation Pressure Feedback eventually shuts off disk-to-star accretion
• Both forces act on bipolar regions
• Both effects require / dominated by EUV spectrum
  ▸ Radiation Pressure + Ionization → rather „Merging“ than „Adding up“
Chronology of Feedback Efficiency

Open Question:
Does the Feedback shut off Accretion?
or
Does the Feedback „only“ reduce the available Mass Reservoir for Accretion?
Finite vs. Infinite Mass Reservoirs

Extending the Mass Reservoir from $100 \ M_{\text{sol}}$ in 0.1 pc to $1000 \ M_{\text{sol}}$ in 1 pc sphere, preserving the initial slopes of density and angular momentum.
• Protostellar Outflows rather unimportant (as a limiting Feedback effect).
• Stellar Radiation Pressure (and Ionization) dominate Feedback!
• Stellar Radiation Pressure is able to shut off Stellar Accretion!
Finite vs. Infinite Mass Reservoirs

Speculations:
- "Full" Feedback Simulation will yield $M_{\text{star}} \sim 100+ M_{\odot}$
- Formation of the most massive stars in the present-day universe ($M_{\text{star}} \sim 150 M_{\odot}$) requires
  - large mass reservoirs ($\sim 0.4$ pc) are favored
  - higher-density environments ($M_{\text{res}} \gg 100 M_{\odot}$ in 0.1 pc sphere)
  - higher accretion rates ($10^{-3} M_{\odot}/\text{yr} > \dot{M}_{\text{star}} > 10^{-2} M_{\odot}/\text{yr}$).

See also talk by Kei Tanaka!
Talk by Rowan Smith!
Spiral Arm Formation

- Disks grow in time due to Angular Momentum accreted from large scales
- Formation of Spiral Arms (Disks are Toomre unstable) even at small radii
- Spiral Arms might fragment (Cooling vs. Dynamics)
  ▸ A direct pathway to close-in Massive Binaries !?
Massive Star Formation using FLASH

- Canadian - German Collaboration on Massive Star Formation Research
- FLASH 4 (Fryxell et al. 2000, Dubey et al. 2009)
  - 3D Cartesian AMR Grid, 11 levels of refinement, $\Delta x_{\text{min}} = 10$ AU
- Hybrid Radiation Transport Scheme
  (Klassen, Kuiper, Pudritz, Peters, Banerjee, Buntemeyer 2014)
Radiation Pressure dominated Cavities


- Expanding Cavities remain stable!

See also Poster by Tim Harries!
Massive Accretion Disks

Results:
- Similar to Evolution of Disk at small radii
- Spiral Arm Formation (Toomre unstable)
- No Disk Fragmentation up to 40 kyr ~ 0.8 $t_{ff}$

Next tasks:
- Cluster scale simulations
- Multi-Physics
  - Ionization
  - Turbulence
  - Magnetic Fields
Emmy Noether Group on Massive Star Formation

- Magneto-Hydrodynamics of Jets & Outflows from Massive Protostars
  - See Poster No. 63!

- Line-driven Ablation of Massive Accretion Disks
  - See Poster No. 61!