Formation of the Most Massive Stars

- **Radiation Pressure Barrier** at $M_{\text{star}} \sim 40 M_{\odot}$
  (Kahn 1974, Yorke & Krügel 1977)

- **Optically thick Disk**

- **Anisotropy of Infrared Radiation / Disk Flashlight Effect**
  (Nakano 1989, Yorke & Bodenheimer 1999)

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Kuiper et al. (2010)
Formation of the Most Massive Stars

Spherical Infall

\[ \dot{M}_* \left[ \text{M}_\odot \text{ yr}^{-1} \right] \]

\[ M_{\text{core}} = 480 \text{ M}_\odot \]

\[ M_{\text{core}} = 240 \text{ M}_\odot \]

\[ M_{\text{core}} = 120 \text{ M}_\odot \]

\[ M_{\text{core}} = 60 \text{ M}_\odot \]

Kuiper et al. (2010)
Formation of the Most Massive Stars

Disk Accretion

Kuiper et al. (2010)
Formation of the Most Massive Stars

Disk Accretion

- Formation of the Most Massive Stars
  - Disk Accretion
  - Kuiper et al. (2010)

→ Talks by Aida Ahmadi and Adam Ginsburg!

Kuiper et al. (2010)

\[ M_{\text{core}} = 480 \, M_\odot \]

\[ M_{\text{core}} = 240 \, M_\odot \]

\[ M_{\text{core}} = 120 \, M_\odot \]

\[ M_{\text{core}} = 60 \, M_\odot \]

Rolf Kuiper (rolf.kuiper@uni-tuebingen.de)
Is there a Stellar Upper Mass Limit due to Feedback?

What about Photo-Evaporation of the Disk?
Photoionization + Radiation Forces

Initial Condition:
- 1000 M☉ mass reservoir (R = 1 pc)
  = 100 M☉ pre-stellar core fed by large-scales

Feedback Physics:
- Outflows
- Radiation Forces
- Photoionization / HII Regions

Grid:
- Axial and midplane symmetry (2D)
- \( R_{\text{sink}} = 3 \text{ au} \), \( \Delta x = 0.3 \text{ au} \)

Kuiper & Hosokawa (2018)
Feedback and Star Formation Efficiencies

- Outflows
- Photoionization
- Radiation Forces

\[ \dot{M}_* [M_\odot \text{ yr}^{-1}] \]

\[ M_* [M_\odot] \]

\[ \times \text{Outflows} \quad M_{\text{star}} = 95 \, M_\odot, \quad t_{\text{acc}} \sim 0.13 \, \text{Myr} \]

\[ \times \text{Photoionization} \quad R_{\text{res}} \sim 0.24 \, \text{pc}, \quad M_{\text{res}} \sim 240 \, M_\odot \]

\[ \checkmark \text{Radiation Forces} \]

Kuiper & Hosokawa (2018)
Feedback and Star Formation Efficiencies

\[ \dot{M}_* [M_\odot \text{ yr}^{-1}] \]

![Graph showing outflows, photoionization, and radiation forces](image)

- Outflows
- Photoionization
- Radiation Forces

\[ M_{\text{star}} = 95 \, M_\odot, \quad t_{\text{acc}} \sim 0.13 \, \text{Myr} \]

\[ R_{\text{res}} \sim 0.24 \, \text{pc}, \quad M_{\text{res}} \sim 240 \, M_\odot \]

→ Talk by Alessio Traficante!

Kuiper & Hosokawa (2018)
Feedback and Outflow Broadening

Kuiper & Hosokawa (2018)
Feedback and Outflow Broadening

Cluster
1.0 pc

Core
0.1 pc

Disk
0.01 pc
2000 AU

Outflow only
Out + Ionization
Out + Radiation
Out + Ion + Rad

Photoionization $>$ Radiation Forces
HII Region Expansion decreases Infall by 50%

Ram Pressure from Infall collimates Outflow
Radiation Forces $>$ Photoionization

Disk Structure sets Opening Angle
✗ Photoionization
✓ Radiation Forces

Kuiper & Hosokawa (2018)
Feedback and Outflow Broadening

Cluster 1.0 pc

Core 0.1 pc

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Outflow only
Out + Ionization
Out + Radiation
Out + Ion + Rad

Photoionization > Radiation Forces
HII Region Expansion decreases Infall by 50%

→ **Talks by Annie Zavagno and Jeong-Gyu Kim!**

Ram Pressure from Infall collimates Outflow
Radiation Forces > Photoionization

Disk Structure sets Opening Angle

X Photoionization
✓ Radiation Forces

Kuiper & Hosokawa (2018)
Is there a Stellar Upper Mass Limit due to Feedback?

How is the gas accreted from the disk to the star?

→ UV-Line Scattering Forces!
UV-Line Scattering Feedback

Kee, Owocki, & Kuiper (2018a,b)
UV-Line Scattering Feedback

Kee, Owocki, & Kuiper (2018a,b)
UV-Line Scattering Feedback

Kee, Owocki, & Kuiper (2018a,b)
• resolved Stellar Photosphere
• 3D Ray-Tracing (> 2 million rays / timestep) using CAK theory
  ▶ Ablation rates (as function of stellar and disk parameters)

Kee & Kuiper (2018)
Rolf Kuiper

Stellar Upper Mass Limit

Metallicity-dependence

Figure 6.

The percentage of a 10

\(\frac{\dot{M}_{\text{ab}}}{\dot{M}_{\text{acc}}}(\%)\)

\(\dot{M}_{\text{acc}} = 10^{-4} M_{\odot}/yr\)

Kee & Kuiper (2018)
What else is new?

- **RMHD-driven Jets & Outflows** (Kölligan & Kuiper 2018, Nies & Kuiper, subm.)
  - Collimated Jets (magneto-centrifugally-driven à la Blandford & Payne 1982)
  - Disk Winds (magnetic-pressure-driven à la Lynden-Bell 2003)
  - Ejection/Accretion efficiency ~ 10%

  → **Talks by Willice Obonyo and Patrick Koch!**

- **Disk Fragmentation**
  - Spectroscopic Binaries / Multiplicity (Meyer et al. 2018)
  - Accretion Bursts (Meyer et al. 2017)

  → **Talks by Igor Zinchenko, Johan van der Walt, and Aida Ahmadi!**

- **1st and 2nd Larson Cores**
  - 1st Larson cores do not exist in high-mass star formation (Bhandare et al. 2018)
  - 2nd Larson cores are convective (Bhandare et al., in prep.)

  → **Poster #14 by Asmita Bhandare!**
Is there a Stellar Upper Mass Limit due to Feedback?

• **MHD-Jets** remove ~10% of Accretion

• **Photoionization** (only) important on Cluster scales

• **Disk Fragmentation** yields Multiplicity and Accretion Bursts

• **Continuum Radiation** Forces set Disk Lifetime!
  + Large-scale Cloud Fragmentation $\rightarrow$ Upper Mass Limit

• **UV-Line Radiation** Forces stop Disk-to-Star Accretion!
  + Disk Accretion Physics $\rightarrow$ Upper Mass Limit

Thanks for your attention!
Protostar keeps bloated until $\sim 30$ kyr / $\sim 30 \ M_{\text{sol}}$
(Hosokawa & Omukai 2009, Kuiper & Yorke 2013)

- HII Region fills Bipolar Outflow Cavity
- Thermal Pressure Feedback in the polar directions acts like Scissor Handles

Kuiper & Hosokawa (2018)
Feedback and Star Formation Efficiencies

Finite Mass Reservoir

"Infinite" Mass Reservoir

- Outflows
- Photoionization
- Radiation Forces

✔ Outflows
✔ Radiation Forces

见到 also Talk by Anna Rosen

Kuiper & Hosokawa (2018)

$M_{\text{star}} = 95 \, M_\odot$, $t_{\text{acc}} \sim 0.13$ Myr
$R_{\text{res}} \sim 0.24$ pc, $M_{\text{res}} \sim 240 \, M_\odot$
Phase Diagram(s) of Feedback

R. Kuiper and T. Hosokawa: Radiation forces and photoionization feedback in massive star formation

Fig. 5. Phase diagrams (gas temperature–gas density plane) for the different epochs of the evolution of the stellar surrounding. The time after the onset of the initial global gravitational collapse and the current mass of the (proto)star is given at the bottom right corner of each panel, the associated label is given in the sub-caption. Data is taken from the fiducial case "1.0pc-PO-RAD-ION".

Well in determining the Keplerian gravito-centrifugal equilibrium velocity.

In Fig. 8, we present the evolution of the disk sizes with time. Here, the disk size \( R_{\text{disk}} \) is determined as the maximum radius in the disk’s midplane which is still in a \( \pm 15\% \) range around gravito-centrifugal equilibrium. The innermost 0.1 pc of the computational domains are initially set up identically, hence, the growth phase of the accretion disk remains identical for roughly the free-fall time of this inner 0.1 pc region containing \( 100 M_\odot \), explicitly \( t \approx 52 \) kyr. After this initial free-fall time, the disk in the limited mass reservoir has reached its maximum radius by definition, because no material from larger scales can bring in higher angular momentum. As a net effect of the ongoing (although decreasing in time) disk-to-star accretion and no feeding of the disk from large scales, the accretion disk decreases in mass and radius.

In the large scale, virtually unlimited mass reservoir simulation, the accretion disk would in principle be able to further increase in size, fed by the material from larger scales. As depicted in Fig. 8 however, the evolution of the accretion disk at

Kuiper & Hosokawa (2018)

**Table:**

<table>
<thead>
<tr>
<th>Region</th>
<th>Selection Criterion</th>
<th>Color Code</th>
</tr>
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<tbody>
<tr>
<td>Infall</td>
<td>( v_r &lt; 0 ) and (</td>
<td>v_r</td>
</tr>
<tr>
<td>Torus</td>
<td>( v_r &lt; 0 ) and (</td>
<td>v_r</td>
</tr>
<tr>
<td>Disk</td>
<td>( v_\phi \approx v_{\text{Kepler}} )</td>
<td>Gray</td>
</tr>
<tr>
<td>Outflow</td>
<td>( v_r &gt; 1 ) \text{ km s}^{-1}</td>
<td>Orange</td>
</tr>
<tr>
<td>Jet</td>
<td>( v_r &gt; 100 ) \text{ km s}^{-1}</td>
<td>Red</td>
</tr>
<tr>
<td>HII</td>
<td>( x &gt; 0.5 )</td>
<td>Purple</td>
</tr>
</tbody>
</table>
Software Development

- **Magneto-Hydrodynamics** PLUTO 4.1 (Mignone et al. 2007, 2012)
- **Self-Gravity** (Kuiper et al. 2010b)
- **Stellar Evolution** (Kuiper & Yorke 2013)
- **Dust Evolution**: Sublimation and Evaporation
- **Protostellar Outflows** (Kuiper, Yorke, & Turner 2015; Kuiper, Turner, & Yorke 2016)
  - **MHD-driven Jets & Outflows** (Kölligan & Kuiper 2018; Nies & Kuiper subm.)
- **Radiation**:
  - Hybrid Scheme: Stellar Irradiation + Continuum (Re-)Emission (Kuiper et al. 2010a)
  - now also in FLASH 4 (Klassen, Kuiper et al. 2014) & ORION (Rosen et al. 2017)
- **Variable Equation of State**: Thermal Dissociation and Ionization (Vaidya et al. 2015)
- **Photoionization**: Stellar Feedback + Recombination (Kuiper, Yorke, & Mignone, subm.)
- **UV-Line Scattering** (Kee, Owocki, & Kuiper 2018a,b; Kee & Kuiper 2018)
Log-spherical Grid Approach

General Properties:

• Resolution ~ Radius
  ‣ High Dynamic Range

Example:

• $234 \times 64 \times 128 \approx 2 \text{ mill.}$
• $R_{\text{sink}} = 10^0 \ldots R_{\text{max}} = 10^5$
• $\Delta r @ R_{\text{sink}} = 0.05$
  ($\approx 22$ levels of Cartesian AMR)