Accretion disks I:
during star formation
(before planet formation?)

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University of Amsterdam
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• September 24 Evolution of Galaxies and things "normal"
  – Reionization (Other facilities -- evidence of large early structures)
  – Large Scale Structure
  – Mass Assembly of Galaxies
  – Evolution of Galaxies
  – Star Formation and IMF (normal conditions)
  – Protostellar accretion disks
• September 25 IGM -- astrochemistry -- life
  – Evolution of Early IGM
  – Most of the Baryons
  – Origin & Evol of IGM (recent)
  – Astrochemistry of star forming regions
  – Accretion disks 2: Planets
  – Exoplanets
• September 26 AGN and things "Extreme"
  – First Stars
  – Reionization (JWST)
  – Growth &Evol. of AGN
  – Stellar Evolution & Death
  – Star Formation & IMF under Extreme Conditions
Figure from Greene 2001)
Disks in a nutshell

• Infalling matter has non-zero angular momentum, lands on rotation plane away from star
• Star mass dominates, matter on largely Keplerian orbits
• Some kind of viscosity couples different annuli of the disk, matter spreads, most falls onto star, some mass moves outward and carries angular momentum
• As infall stops, disk mass decreases, eventually disappears into star, planets, or space!
• Gas and dust are initially well mixed
• Dust dominates the opacity at almost any wavelength
• Disk is thick because of hydrostatic equilibrium (pressure against gravity).
  - Density decreases exponentially with height
  - When small grains exist, stellar radiation is absorbed at about 4 pressure scale heights.
What would we like to know?

- Formation and Evolution
- Spectral Energy Distributions
  - and what they do and don't tell us
- Grains
  - Sizes
  - Composition
  - Distribution as function of r,z,t
- Gas
  - Mass
  - Composition
  - Distribution as function of r,z,t
- Dynamics
  - Rotation and inflow
Dust, Gas, Radiation

Hot gas
- CO, H₂O

Dead?

UV
- PAH
- small grains, PAH
- small(?), large grains

CR, X
- Ice mantles, H₃⁺

PDR: atoms, ions, small molecules
- CI, NeII...

Molecules: CO, HCO⁺...
Scattered light:
The disk surface
Fig. 1.—Observations of the 114-426 disk at Hα (0.656 μm; HST/WFPC2),

Shadow imaging

Throop et al 2001
Shuping et al 2003
Mid-IR imaging:
Still the upper
IR spectroscopy: Dust features
Absorption Studies
Submm: whole disk
SED: Information about geometry
Measuring infall onto disks
Line profile of collapsing cloud

But absorption only on observer’s side (i.e. on redshifted side)

Blue, i.e. toward the observer

Red, i.e. away from observer

Example:
Observations of B335 cloud.
Zhou et al. (1993)
Infall observed

H$_2$CO

Di Francesco et al 2001
# Impact: Infall on disks

<table>
<thead>
<tr>
<th>Facility</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>JWST</td>
<td>High resolution imaging in MIR</td>
</tr>
<tr>
<td>ALMA</td>
<td>Isolate infall region, observe absorption</td>
</tr>
<tr>
<td>HERSCHEL</td>
<td></td>
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<tr>
<td>SOFIA</td>
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</tbody>
</table>
SEDs and geometry of Disks
Multi-color blackbody disk SED

\[ \nu F_\nu \]

Wien region

Rayleigh-Jeans region

multi-color region
Disk emission around stars
SED differences in FIR

As before, but replacing mass by large grains at the equator instead of removing it.
## Impact: SEDs and disk structure

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<tbody>
<tr>
<td>JWST</td>
<td>NIR, MIR for weak/distant sources, go beyond Spitzer</td>
</tr>
<tr>
<td>ALMA</td>
<td>measure weak submm fluxes</td>
</tr>
<tr>
<td>HERSCHEL</td>
<td>Fill SED holes in FIR range, critical PDR lines like CI, C⁺</td>
</tr>
<tr>
<td>SOFIA</td>
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</table>
Gas chemistry and mixing
Tracing gas in the cold midplane of disks

- Main molecule $H_2$ unobservable
- Need to use trace molecules:
- Most important: CO
Molecules in disks


- Severe depletion but not everything frozen out
Sources of Water and CO in the disk:

- Photo desorption
- Photo dissociation
- Gas phase formation route
- Freeze-out/reformation
A cut through the PDR at 770AU
Photodesorption of CO ice

Simulate interstellar (UV) radiation field by special H$_2$ MW discharge lamp (7-10.5 eV).

Rate ~ $3 \times 10^{-3}$ CO molecules / UV photon

* Much more efficient than assumed so far in astrochemical models.
* Explains why molecules are observed in the gas phase at temperatures where all species should be accreted onto ices.
Alternative:

Semenov et al 2006
Chemistry with mixing

without mixing

with mixing
Imaging chemistry

- Kessler et al. 2003, OVRO
- Different molecules show very different distributions
Impact: Chemistry

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<tr>
<td>JWST</td>
<td>Atomic/molecular gas lines like $H_2$, $CO$, $H_2O$, $CH_4$, $SiII$, $SI$, $FeII$, $NeII$... Absorption studies high incl disks</td>
</tr>
<tr>
<td>ALMA</td>
<td>Many new species, imaging to ~few AU level, huge impact</td>
</tr>
<tr>
<td>HERSCHEL</td>
<td>Potential to see new lines, but beam/sensitivity issues?</td>
</tr>
<tr>
<td>SOFIA</td>
<td>High resolution line spectra. Water?</td>
</tr>
</tbody>
</table>
Grain sizes and spatial distribution
0.1\(\mu\text{m}\) + settled layer 1.0\(\mu\text{m}\)
Scattered light at 11.8\textmu m in HK Tau B

McCabe et al 2003
Scattered light images of GG Tau

Duchene et al 2004
Evidence for grain growth

Small grain

Large grain

v Boekel et al 2003
Most T Tauri disks shows evidence for grain growth

Kessler-Silacci et al. 2006, 2007

Observations (Obs)

Models

10 µm band

20 µm band
Evidence for grain growth– edge-on disks

Shape and depth of mid-IR “valley” very sensitive to grain size. For this source, grains at least ten mm in size are inferred.

“Flying Saucer” in Oph

i~85° => Very weak at mid-IR
## Impact: Grains sizes

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<td>coronographic imaging of scattered light, MIR spectra from weak sources, Absorption from edge-on disks, shadow imaging of proplyds</td>
</tr>
<tr>
<td>ALMA</td>
<td>Measure mm-sized grains as function of distance</td>
</tr>
<tr>
<td>HERSCHEL</td>
<td>by way of SED measurements?</td>
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</table>
Dust mineralogy
Spectroscopy of young disks
Radial mixing

Spatially resolved spectroscopy

Whole Disk

Inner disk

Outer disk
Different scenarios for crystallization and mixing

Meijer et al. 2007
Spectra resulting from different scenarios
Dust diagnostics in the FIR
## Dust features in the Far IR

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical Formula</th>
<th>Wavelengths (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forsterite</td>
<td>$\text{Mg}_2\text{SiO}_4$</td>
<td>69-70</td>
</tr>
<tr>
<td>Fayalite</td>
<td>$\text{Fe}_2\text{SiO}_4$</td>
<td>93-94,110</td>
</tr>
<tr>
<td>Diopside</td>
<td>$\text{CaMgSi}_2\text{O}_6$</td>
<td>65-66</td>
</tr>
<tr>
<td>Calcite</td>
<td>$\text{CaCO}_3$</td>
<td>92</td>
</tr>
<tr>
<td>Graphite</td>
<td>$\text{C}$</td>
<td>50-70</td>
</tr>
<tr>
<td>Water ice</td>
<td>$\text{H}_2\text{O}$</td>
<td>62</td>
</tr>
<tr>
<td>Methanol icem</td>
<td>$\alpha-\text{CH}_3\text{OH}$</td>
<td>68,88.5</td>
</tr>
<tr>
<td>Dry ice</td>
<td>$\text{CO}_2$</td>
<td>85</td>
</tr>
<tr>
<td>Montmorillonite</td>
<td>$(\text{Na, Ca})0.33(\text{Al, Mg})_2(\text{Si}<em>4\text{O}</em>{10})(\text{OH})_2 \cdot n\text{H}_2\text{O}$</td>
<td>80-100</td>
</tr>
<tr>
<td>Serpentine</td>
<td>$(\text{Mg, Fe})_6\text{Si}_2\text{O}_5(\text{OH})_2$</td>
<td>47</td>
</tr>
</tbody>
</table>

References:
- Posh et al 2004
- Jena database
- Koike et al
# Impact: Dust mineralogy

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<td>JWST</td>
<td>Mineralogy of weak sources</td>
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<td></td>
<td>Absorption in edge-on disks</td>
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<tr>
<td>ALMA</td>
<td></td>
</tr>
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<td>HERSCHEL</td>
<td>FIR features with PACS</td>
</tr>
<tr>
<td>SOFIA</td>
<td>FIR features absorption??</td>
</tr>
</tbody>
</table>
Dynamics

Rotation, radial flows and turbulence
Rotation from CO mm lines: a velocity gradient

HD163296: 12CO J=2-1

$M_{\star} = 2.0 \pm 0.5 \ M_{\odot}$

$\text{incl} = 45^\circ$
Deviations from Keplerian:

• Hogerheijde 2001
  - infall in TMC1

• Pietu et al. 2005
  - $V \propto R^{0.41 \pm 0.01}$ in AB Aur
Keplerian rotation in the inner disk

\[ V=1-0 \text{ at } 4.8\mu \text{m} \]

\[ V=2-1 \text{ at } 2.4\mu \text{m} \]

Keplerian rotation in the inner disk

- Consistent with Keplerian rotation in the inner disk
- Formation on the disk surface or in the inner, dust-free disk
- Consistent with Keplerian rotation in the inner disk
The deadzone in accretion disks

Gas-grain chemistry, t = 10^6 yrs

$r$ (AU)

$Z$, AU

$10^{-6}$ $M_\odot$ yr$^{-1}$

$x_M = 10^{-15}$, $10^{-12}$, $10^{-9}$

$3.8 \times 10^{13}$
Turbulence from first overtone CO or water

- SVS 13 YSO (Carr et al 2004): 11.3 km/s local broadening needed, ~ Mach 2
- Hartman et al, 2004, FU Ori objects, broadening needed
## Impact: Dynamics

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<td>JWST</td>
<td>Line profiles as function of distance, measure turbulence. Face-on disks, different molecules for different heights</td>
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<tr>
<td>ALMA</td>
<td>High resolution line profiles from inner disk, e.g. H\textsubscript{2} (28 µm), S I (25 µm), Fe II (26 µm), also H\textsubscript{2}O, CH\textsubscript{4}, CO, HCN and C\textsubscript{2}H\textsubscript{2}.</td>
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