New Views on Gas in the Planet Formation Region of Disks

Contributions from Spitzer and Ground-based Facilities

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Why Study Gaseous Disks?
How did we get here?

What kinds of disks make what kinds of planets?

Test Planet Formation Theories

Diagnose Ongoing Planet Formation

Explore Astronomical Origin of Prebiotic Molecules and Life on Earth
Extra-terrestrial Origin of Prebiotic Molecules

Were the “chemical building blocks” of life synthesized in clouds and disks and delivered to Earth by asteroids and comets?

Amino acids present in meteorites

Organic molecules, from simple (CO) to complex (HOCH₂CH₂OH), detected in comets.
• Molecular abundances probe chemistry and transport
• Inner disk abundances (within the snow line) probe evaporation products from outer disk + inner disk chemistry.
Gaseous Probes of Inner Disks
(Pre-Spitzer)

Possibilities:
• ISO: MIR $H_2$ detectable
• Ground: NIR $H_2$
Gaseous Probes of Inner Disks

- $0.1 \text{ AU}$: $\sim 1000 \text{ K}$
- $1 \text{ AU}$: $\sim 200 \text{ K}$
- $10 \text{ AU}$: $\sim 50 \text{ K}$

- $H_2 \text{ UV, NIR, MIR}$
- $H_2O \text{ ro-vib}$
- $OH \Delta v=1$
- $CO \Delta v=1$
- $CO \Delta v=2$

- HCN, CO$_2$, C$_2$H$_2$, OH, H$_2$O

$> 20 \text{ AU}$:
- CO, HCO$^+$, CS, N$_2$H$^+$, H$_2$CO, CN, HCN, NHC, H$_2$D$^+$, DCO$^+$, DCN, etc

New diagnostics from Spitzer:
- Water, organic molecules,
- Atomics, e.g., NeII

New diagnostics from Spitzer:
Organic Molecules in Absorption: GV Tau

See also Lahuis et al. 2006 IRS 46

- $\text{C}_2\text{H}_2$, HCN, CO$_2$ detected in absorption (T=550 for HCN)
- 3$\mu$m HCN ~at cloud velocity; absorption in a disk atmosphere?
- Source is very bright in MIR; enables study of other molecules
Disk Spectral Lines

**Emission Lines**
- Temperature Inversion in Optically Thick Disk
- Optically Thin Disk, Hole or Gap

**Absorption Lines**
- Optically Thick, High $M_{\text{acc}}$
  e.g., FU Ori object
- Absorption by Outer Disk
MIR Molecular Absorption at High Spectral Resolution

- Gemini/TEXES (R=100,000)
- FWZI ~ 20 km/s
- Can detect molecules w/o strong bands that Spitzer does not detect.
- Study relative abundances in disk atmospheres.

Related results in Knez et al. (2009) for a disk around a high mass star
Disk Spectral Lines

Emission Lines
- Temperature Inversion in Optically Thick Disk
- Optically Thin Disk, Hole or Gap

Absorption Lines
- Optically Thick, High $M_{\text{acc}}$ e.g., FU Ori object
- Absorption by Outer Disk
Spitzer IRS Spectrum of a Typical T Tauri Star

Low resolution, modest s/n
Spitzer IRS Spectrum of a Typical T Tauri Star

Observed AA Tauri Spectrum

Carr & Najita (2008)

S/N ~ 250
Atomic lines [Ne II], H\textsc{i}
Molecules C$_2$H$_2$, HCN, CO$_2$, H$_2$O, OH

See also Salyk et al. (2008) on Spitzer detection of water in disks.
Continuum-subtracted T Tauri Star Spectrum

Lines of water throughout (*)
### Molecular Emission Properties

<table>
<thead>
<tr>
<th>Molecule</th>
<th>T (K)</th>
<th>N (\times 10^{16}) cm(^{-2})</th>
<th>R (AU)</th>
</tr>
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<tbody>
<tr>
<td>H(_2)O</td>
<td>575</td>
<td>65</td>
<td>2.1</td>
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<tr>
<td>OH</td>
<td>525</td>
<td>8.1</td>
<td>2.2</td>
</tr>
<tr>
<td>HCN</td>
<td>650</td>
<td>6.5</td>
<td>0.6</td>
</tr>
<tr>
<td>C(_2)H(_2)</td>
<td>650</td>
<td>0.81</td>
<td>0.6</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>350</td>
<td>0.2–13</td>
<td>1.2</td>
</tr>
<tr>
<td>CO</td>
<td>900</td>
<td>49</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Temperatures and emitting areas consistent with an origin in the terrestrial planet region of the disk.
Line profiles, temperatures, and emitting areas indicate origin in planet formation region of disk.
AA Tau Molecular Abundances

Higher abundances than hot cores
→ Molecular synthesis in disks
→ Similar chemistry to hot cores?
Hot Core and Disk Chemistry

“Hot core”, e.g. Orion
Molecular Emission is Common, Diverse

- Relative strengths of molecular features vary.
- Abundances are diverse.

See also Salyk et al. (2008)
Can Abundances Probe Icy Bodies?

Problem: planetesimals (~1 km) and protoplanets (~$M_{\text{Mars}}$) are too small to open gaps. How to detect them?

Large (> 1km), non-migrating bodies dehydrate inner disk (low $H_2O$); increases C/O; enhances organic molecules?

Cuzzi & Zahnle 2004
Ciesla & Cuzzi 2007
What Can We Learn from Surface Abundances?

May be affected by:
Irradiation (UV, X-rays)
Radial & vertical mixing
Accretion
Grain growth & settling
Planetesimal migration
etc.

Measurable demographics:
$L_X$, $L_{UV}$
Mdot
SED shape
Silicate feature morphology
Crystallinity

Need a big survey: Carr, Blake, van Dishoeck, Pontoppidan, Salyk, Lahuis, & Najita (GO5)
Different Abundances vs. Stellar Mass?
(Pascucci et al. 2008)

T Tauri stars
(HCN > C$_2$H$_2$)

Brown dwarfs
(C$_2$H$_2$ > HCN)
Transition Object SEDs imply evolution

Optically thin inner region
(< $R_{\text{hole}}$ = 1-50 AU)

Optically thick outer disk
(> $R_{\text{hole}}$)

Are they forming giant planets?
Probing Gaseous Disks of Transition Objects

Transition objects with massive outer disks (many $M_J$) typically show stellar accretion, signatures of an inner gaseous disk (CO, UV $H_2$).

(Najita et al. 2003; Bergin et al. 2004; Rettig et al. 2004; Herczeg et al. 2006; Salyk et al. 2007, 2009)
A typical CTTS and a Transition Object

TOs lack strong molecular emission at 10-20µm
- Gap created by an orbiting giant planet?
- Different inner disk chemistry or excitation?

Need theory…or empirical approach?
# Theories of Gaseous Disk Atmospheres

<table>
<thead>
<tr>
<th>Species</th>
<th>Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Meijerink et al. 2007, 2009</td>
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<tr>
<td></td>
<td>Kamp &amp; Dullemond 2004+</td>
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<tr>
<td></td>
<td>Jonkheid et al. 2004+</td>
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<td>Gorti &amp; Hollenbach 2008, 2009</td>
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<tr>
<td>Focus on H₂</td>
<td>Nomura &amp; Millar 2005,</td>
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<tr>
<td>Focus on Atomic</td>
<td>Ercolano et al. 2008+</td>
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<tr>
<td>Water and Organics</td>
<td>Markwick et al. 2002</td>
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<td>Agundez et al. 2008</td>
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<td>Woods &amp; Willacy 2008</td>
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Note: different assumptions about heating processes, chemistry, gaseous hydrostatic equilibrium.
Rich (but Weak) Emission from a Transition Object
Najita et al. (2009)

**Qualitatively New:**
- HI recombination lines
- NeII, NeIII
- H₂ rotational
- Hot OH

Do these probe
- A tenuous disk atmosphere?
- A disk photoevaporative flow?

(Ercolano, Hollenbach/Gorti)

Possible insights into disk dissipation and lifetimes

Are these present in normal T Tauri stars as well?
• Higher sensitivity than Spitzer/IRS, over 5-30µm
• Higher resolution (R=3000) resolves more blends (not velocity structure).
• Detect and characterize more species, measure average N and T.
• GSMT (R=100,000): resolve velocity structure, measure N(r) and T(r).
New Window on Disk Chemical Evolution

Planet Formation Region of Disks:

**Emission**: probe typical sources

**Absorption**: probe large column densities, rare species

Results indicate that disks are chemically active

Anticipate exciting results from Spitzer, JWST, GSMT
New Window on Planet Formation Environments

Abundances are Diverse

• Clues to processes governing physical and chemical evolution of disks (irradiation, transport, accretion, grain growth, planetesimals)

Spectra of Possible Planet-forming Systems Differ from Normal T Tauri stars

• Consistent with giant planet formation, but possibly different chemistry or excitation?