Towards the molecular complexity in protoplanetary disks

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JEDI meeting
Proto-planetary disks
June 27, 2018
- Production/Destruction of molecules associated with the different stages of star formation

- Evolution and Delivery of interstellar material

  - *Were they altered?*
  - *Or formed in the protoplanetary nebula?*
  - *Or are they a direct ISM heritage?*
  - *Which processes at the icy surface of grains / in gas phase prevail?*
## Molecular inventory of protoplanetary disks

<table>
<thead>
<tr>
<th>Category</th>
<th>Molecules</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atoms</strong></td>
<td>C(^+), O</td>
<td>Meeus et al. (2012)</td>
</tr>
<tr>
<td><strong>Ions</strong></td>
<td>HCO(^+), H(^{13})CO(^+), DCO(^+), N(_2)H(^+), CH(^+)</td>
<td>Dutrey et al. (1997, 2007), van Dishoeck et al. (2003), Thi et al. (2011), Qi et al. (2008, 2013a), Öberg et al. (2015a)</td>
</tr>
<tr>
<td><strong>Carbon reservoirs?</strong></td>
<td>CO, CO(_2)</td>
<td>Koerner &amp; Sargent (1995), Pontoppidan et al. (2010)</td>
</tr>
<tr>
<td><strong>Simple species</strong></td>
<td>(^{13})CO, (^{18})O, OH, HD</td>
<td>Dutrey et al. (1996), Pontoppidan et al. (2010), Bergin et al. (2013), Favre et al. (2013), McClure et al. (2016)</td>
</tr>
<tr>
<td><strong>S-bearing molecules</strong></td>
<td>CS, SO</td>
<td>Dutrey et al. (1997), Guilloteau et al. (2013)</td>
</tr>
<tr>
<td><strong>N-bearing molecules</strong></td>
<td>CN, HCN, HNC, DCN</td>
<td>Dutrey et al. (1997), Qi et al. (2008)</td>
</tr>
<tr>
<td><strong>Carbon chains</strong></td>
<td>CCH, C(_2)H(_2), c-C(_3)H(_2), HC(_3)N</td>
<td>Dutrey et al. (1997), Pontoppidan et al. (2010), Henning et al. (2010), Chapillon et al. (2012), Qi et al. (2013b), Öberg et al. (2015b), Bergner et al. (2018)</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td>H(_2)O</td>
<td>Bergin et al. (2010), Hogerheijde et al. (2011), Podio et al. (2013)</td>
</tr>
<tr>
<td><strong>O-bearing molecules</strong></td>
<td>H(_2)CO</td>
<td>Qi et al. (2013a), Loomis et al. (2015)</td>
</tr>
<tr>
<td></td>
<td>t-HCOOH</td>
<td>Öberg et al. (2017), Carney et al. (2017)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Favre et al. (2018)</td>
</tr>
<tr>
<td><strong>Complex organic molecules</strong></td>
<td>CH(_3)OH, CH(_3)CN</td>
<td>Walsh et al. (2016), Öberg et al. (2015b), Bergner et al. (2018), Loomis et al. (2018)</td>
</tr>
</tbody>
</table>
1. **Protoplanetary disks**
   - Interferometry for astrochemical studies: *sensitivity* & *resolution*

2. **O-bearing and S-bearing molecules in disks**
   - A rich organic chemistry
   - A non solar C/O ratio in T Tauri disks

3. **Planet formation & molecules**
   - Observations of the molecular content that will be partly inherited by the planet(s)
Disks are complex systems

Strong T and n gradients, UV & X-ray

Sketch of physical and chemical structure of protoplanetary disks

Henning & Semenov (2013)
Complex organic molecules in protoplanetary disks

Surface layers: molecules destroyed by UV photodissociation

Inner (r <50 AU -100 AU, T >50-100K): molecules present in warm molecular layers. Production via gas phase chemistry or formation on ices and then release into the gas phase

Outer disk / Mid plane (r >100-200 AU, T <50K): molecules are locked into the icy surface of dust grains ($\chi_{\text{H}_2} \sim 10^{-6} - 10^{-4}$), Only a few percent are in gas-phase ($\chi_{\text{H}_2} \sim 10^{-11} - 10^{-7}$)

The chemical composition of disks is hidden in ices!

 Courtesy Linda Podio

Aikawa et al. (2002)
Dullemond et al. (2007)
Bergin et al. (2007)

Water snow line

$T_{\text{evaporation}} = 150$ K
$R_{\text{snow}} \sim 2\text{-}3$ AU

Water snow line

10 AU
100 AU

X-rays

UV

atomic/ionized

molecular chemistry
Interferometry is needed to access the molecular content in disk

Bergin et al. (2007)

High angular resolution!

1 AU = Distance between the Sun and the Earth

3 AU = 0.02” at 140 pc

10 AU = 0.07” at 140 pc

50 AU = 0.4” at 140 pc

100 AU = 0.7” at 140 pc
**Interferometry is needed to access the molecular content in disk**

The emissive area is expected to be small (and might be closed to the central object)

It is really hard to detect a not intense transition

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**High sensitivity!**

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Öberg et al. (2015a)
Loomis et al. (2018)

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Favre et al. (2013)
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Towards O-bearing molecules in protoplanetary disks

Podio et al., in prep.
Qi et al. (2013)
Carney et al. (2016)
Öberg et al. (2017)

H$_2$CO emits from beyond the CO snowline

Efficient formation of organics on icy grain for $R > R_{CO}$ to explain the H$_2$CO ring
Towards complex molecules in protoplanetary disks

Complex Organic Molecules

**CH₃OH: a key molecule in the formation routes to larger O-bearing molecules**

**Table 1**
Methanol Transitions

<table>
<thead>
<tr>
<th>Transition</th>
<th>Frequency (GHz)</th>
<th>Upper Level Energy (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2₁₁−2₀₂ (A)</td>
<td>304.208</td>
<td>21.6</td>
</tr>
<tr>
<td>3₁₂−3₀₃ (A)</td>
<td>305.473</td>
<td>28.6</td>
</tr>
<tr>
<td>4₁₃−4₀₄ (A)</td>
<td>307.166</td>
<td>38.0</td>
</tr>
<tr>
<td>8₁₇−8₀₈ (A)</td>
<td>318.319</td>
<td>98.8</td>
</tr>
</tbody>
</table>

Walsh et al. (2016)
Towards O-bearing molecules in protoplanetary disks

First detection of HCOOH at the 4σ level without stacking!

- Rich organic chemistry: (that can lead to larger organic molecules, likely takes place at the verge of planet formation in protoplanetary disks)

- HCOOH emission extends beyond 200 AU (mm dust continuum): contribution of small grains likely contribute to the HCOOH production

N(HCOOH) \sim (2-4) \times 10^{12} \text{ cm}^{-2}

HCOOH/\text{CH}_3\text{OH} \leq 1
A depletion of elemental C in T Tauri disks

Favre et al. (2013)
Schwarz et al. (2016)
Kama et al. (2016)
Miotello et al. (2017)

CO abundance relative to H$_2$: $(0.1-3) \times 10^{-5}$ in the disk’s warm molecular layers ($T>20K$), lower than the canonical value of $\chi$(CO) = $10^{-4}$

Carbon chemistry?
(Aikawa et al. 1997, Reboussin et al. 2015)

CO chemical destruction via reactions with He$^+$
Followed by rapid formation of carbon chains ($C_xH_x$) or CO$_2$
Freeze-out T higher than CO $\rightarrow$ trap the carbon in ices

Carbon reservoir in gas?
A non solar C/O ratio observed via the emission of c-C$_3$H$_2$ and S-bearing molecules

Where

Bergin et al. (2016)
Favre, Fedele, kamp (in prep.)

C/O $\geq 1$

Carbon chemistry?

Oxygen chemistry?


Oxygen locking from the disk molecular layer by the freeze-out of water onto sedimenting large dust grains
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**Planet(s) formation seen in both gas and dust**

*Talk by D. Fedele*

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**Favre et al. (in prep.)**

*see also Isella et al. (2016), Teague et al. (2018), Muro-Arena et al. (2018)*

One should be able to observe the molecular content in these objects that is directly inherited by the forming planets (and small bodies)
Summary

Complex molecules (N- and O-bearing) are present towards proto-planetary disks

Observations suggest that chemistry leading to molecular complexity likely takes place in proto-planetary disks where planets might form

- ISM inheritance?
- Reprocessed?

ALMA
(resolution and sensitivity)

key interferometer for astrochemical studies

But still it will be difficult to detect larger species
« For your attention
I thank you »