Gas and Dust in Protoplanetary Disk: their connection to materials in our Solar System

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Contents

- Introduction
- Complex Organic Molecules in Disks
- Effect of C/O Ration in Gas in Disks
  Wei, HN, Lee, Ip, Walsh & Millar in prep.
Introduction
Gas & Dust Observations in PPDs

Revealing physical & chemical structure of planet-forming regions
From Molecular Clouds to Planetary Systems

Molecular Cloud Cores, $\sim 10^6$ yr

Class 0, $\sim 10^4$ yr

Class I, $\sim 10^5$ yr

Class II (CTTS), $\sim 10^6$ yr

Class III (WTTS), $\sim 10^7$ yr $\rightarrow$ MS Stars

- [Diagram a) Dark cloud cores]
- [Diagram b) Gravitational collapse]
- [Diagram c) Protestar, embedded in 8000 AU envelope; disk; outflow]
- [Diagram d) T Tauri star, disk, outflow]
- [Diagram e) Pre-main-sequence star, remnant disk]
- [Diagram f) Main-sequence star, planetary system (?)]
From Protoplanetary Disks to Planetary Systems

- Grain growth, settling, radial drift
- Gas dispersal

→ Planetary systems
ALMA Long Baseline Obs. of TW Hya

Spectral index enhances at the gap

→ Depletion of large grains
→ indicating planet formation

Dust optical depth

Spectral index of dust opacity $\kappa_\nu \propto \nu^\beta$

ALMA cycle 3 DDT B4 & B6

(Tsukagoshi et al. 2016)
Dust in Gap Opened by a Planet

Planet opens a gap in gas

→ Distribution of small grains are similar to gas
Large grains are depleted in the gap due to dust filtration

→ only small grains are left in the gap

(Zhu et al. 2012)
ALMA Long Baseline Obs. of TW Hya

ALMA cycle 3 DDT B4 & B6
Spectral index enhances at the gap
→ Depletion of large grains
→ indicating planet formation
⇒ Poster by Seongjoong Kim

(Tsukagoshi et al. 2016)
Chemical Structure of PPDs
(e.g., Dutrey+ 1997, Markwick+2002, Aikawa+ 2002, Bergin+ 2007)

- Depletion of mol. @ midplane of outer disk
- Relatively large molecules @ middle layer
- Radicals @ disk surface
- Desorption of ice @ inner disk

- UV, X-rays
- PDR
- dense clouds
- hot cores
- desorption of icy molecules
- freeze-out of species grain surface reactions

H₂O, CO₂, CH₄, CH₃OH, H₂CO, NH₃, etc.
Complex Organic Molecules in Disks
### Observed Interstellar Molecules

<table>
<thead>
<tr>
<th>CH+</th>
<th>HCN</th>
<th>H2CO</th>
<th>HC3N</th>
<th>CH3OH</th>
<th>HC5N</th>
<th>HCOOCH3</th>
<th>HC7N</th>
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<tr>
<td>CS</td>
<td>HNC</td>
<td>H2CS</td>
<td>HCOOH</td>
<td>CH3CN</td>
<td>CH3CCH</td>
<td>CH3C3N</td>
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<td>CO</td>
<td>HCO</td>
<td>H2CN</td>
<td>CH2NH</td>
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<tr>
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<td>OCS</td>
<td>HNCO</td>
<td>CH2CO</td>
<td>CH3SH</td>
<td>CH3CHO</td>
<td>CH2CHCHO</td>
<td>C2H5CN</td>
</tr>
<tr>
<td>C2</td>
<td>CH2</td>
<td>HNCS</td>
<td>NH2CN</td>
<td>NH2CHO</td>
<td>CH2CHCN</td>
<td>CH2OHCHO</td>
<td>CH3C4H</td>
</tr>
</tbody>
</table>

#### Amino acids in comet

- **@ STARDUST** *(Elsila et al. 2009)*
- **ROSETTA** *(Altwegg et al. 2016)*

#### Amino acids in meteorites

⁻ relation with interstellar molecules ?

- H2C6
- CH3C5N
- H4O
- CH3OCH3
- CHO
- C2H5OH
- H2CO
- CH3CONH2
- CH3COCH3
- OHCH2CH2OH
- C2H5OCHO

<table>
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<th>1970</th>
<th>1980</th>
<th>1995</th>
<th>2018</th>
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</thead>
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<tr>
<td>~10 species</td>
<td>~50 species</td>
<td>~100 species</td>
<td>~210 species</td>
</tr>
</tbody>
</table>
Obs. of Gas in Protoplanetary Disks

**UV**  \( \text{H}_2 \) Lyman-Werner band transitions

**Optical**  \[\text{OI} \] 6300Å

**NIR**  \( \text{H}_2 \) \( v=1-0 \) S(1), S(0), CO \( \Delta v=2, \Delta v=1 \), \( \text{H}_2\text{O}, \text{OH}, \text{HCN}, \text{C}_2\text{H}_2, \text{CH}_4 \)

**MIR**  \( \text{H}_2 \) \( v=0-0 \) S(1), S(2), S(4)

**FIR**  \[\text{OI} \] 63μm, 145μm, \( \text{CO}, \text{H}_2\text{O}, \text{CH}^+, \text{HD}, \text{NH}_3 \), etc.

**(sub)mm**  CO, \(^{13}\text{CO}, \text{C}^{18}\text{O}, \text{C}^{17}\text{O}, \text{^{13}C}^{18}\text{O}, \text{HCO}^+, \text{H}^{13}\text{CO}^+, \text{DCO}^+, \text{[Cl]}, \text{C}_2\text{H}, \text{c-}C_3\text{H}_2, \text{H}_2\text{CO}, \text{CH}_3\text{OH}, \text{HCN}, \text{H}^{13}\text{CN}, \text{DCN}, \text{HC}^{15}\text{N}, \text{HNC}, \text{CN}, \text{N}_2\text{H}^+, \text{N}_2\text{D}^+, \text{HC}_3\text{N}, \text{CH}_3\text{CN}, \text{CS}, \text{C}^{34}\text{S}, \text{SO} 

etc.

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**Herschel Space Observatory**

**Spitzer Space Telescope**

**Herschel Space Observatory**

**ALMA**

**Spitzer Space Telescope**

**Herschel Space Observatory**

**ALMA**
Complex Organic Molecules in Disks

$\text{HC}_3\text{N} \ J = 16-15, 12-11, 10-9 \ @ \ 146, 109, 91\text{GHz}$

MWC480, LkCa15, GO Tau, IRAM 30m, PdBI

(Chapillon et al. 2012)

$c\text{-C}_3\text{H}_2 \ J = 6-5 \ @ \ 218\text{GHz}$

HD163296, ALMA SV

(Chapillon et al. 2012)

$\text{CH}_3\text{CN}$

$14_0-13_0, \ 14_1-13_1, \ @ \ 257\text{GHz},$

MWC480, ALMA cycle 2

(Oberg et al. 2015)

→more complex mol. will be found by ALMA
Complex organic mol. are formed efficiently by grain surface reactions near the disk midplane.
First detection of $\text{CH}_3\text{OH}$ from protoplanetary disk!

$\text{CH}_3\text{OH}$ @ 304, 305, 307GHz

TW Hya, ALMA cycle 2
Stacking three lines of $\text{CH}_3\text{OH}$

$\text{CH}_3\text{OH}/\text{H}_2\text{O} \sim 0.7-5\%$

$\leftrightarrow$ comets

$R \sim 30-100\text{AU}$

Non-thermal desorption


First detection of $\text{CH}_3\text{OH}$ from protoplanetary disk!
CH$_3$CN & HC$_3$N detection in Disks

TW Hya

CH$_3$CN/HCN

HC$_3$N/HCN

CH$_3$CN/HCN

HC$_3$N/HCN

Further detection & further investigation is needed
Abundances of relatively small molecules are consistent, but we need more complete model especially for larger molecules.
Model Spectra of More COMs in Disks

Searching more COMs in disks by ALMA!

(Walsh et al. 2017)
Effect of C/O Ratio in Gas in Disks
Carbon Depletion in Inner Solar System

How does carbon grain destruction affect molecular abundance distribution in disks?

Carbon grains must be destroyed and carbon bearing species in gas escape from the Solar Nebular.
Effect of carbon grain destruction

w/o C-grain destruction
C/O < 1 in gas
→ CO + O
→ rich in O-bearing species (molecular clouds)

with C-grain destruction
C/O > 1 in gas
→ CO + C
→ rich in C-bearing species (cf. carbon stars)

HCN gas abundance is significantly affected at 2AU<R<20AU (Wei, HN, et al. in prep.)
Effect of carbon grain destruction

Physical model + chemical reactions + line radiative transfer

C/O < 1 in gas
H\textsuperscript{13}CN 4-3 integrated intensity map

C/O > 1 in gas
H\textsuperscript{13}CN 4-3 integrated intensity map

H\textsuperscript{13}CN intensity map is affected at R<20AU → testable by ALMA observations?

Herbig Ae disk

(Wei, HN et al. in prep.)
Effect of carbon grain destruction

w/o C-grain destruction

C/O < 1 in gas
→ CO + O
→ rich in O-bearing species (molecular clouds)

C/O > 1 in gas
→ CO + C
→ rich in C-bearing species (cf. carbon stars)

Effect on composition of C-bearing species in ice

T Tauri disk → Solar system objects (Wei, HN et al. in prep.)
Summary
Observation & modelling of organic molecules in protoplanetary disks by ALMA

- Detection of HC$_3$N, CH$_3$CN, CH$_3$OH from disks
- Observed CH$_3$OH could be formed via grain surface reactions and non-thermally desorbed into gas
- CH$_3$OH/ H$_2$O ratio consistent with that in comets
- Further investigation is needed for connection to Solar System objects

Effect of C/O ratio in gas on disk chemistry

- Carbon grain destruction leads to enhancement of carbon-bearing species, such as HCN and carbon-chain molecules → testable by ALMA observations, effect on Solar System objects?
C/O ratio in gas changes across the snowlines

C-rich in Ice
O-rich in Gas

O-rich in Ice
C-rich in Gas

H₂O snow line

UV, X-rays

Disk Radius [AU]

Abundances

C/O > 1
C/O < 1

C/O ratio

Disk Radius [AU]