Complex organic chemistry in solar-type protostars: new detections in the framework of the ALMA-PILS survey

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Image credit: ESO/B. Tafreshi
The building blocks of Life

- Water

- Prebiotic molecules

  Molecules thought to be involved in the process leading to the origin of Life (Herbst & van Dishoeck 2009)

  High interest: amino acids, sugars, nucleobases

Glycine
Comets and asteroids rich in water and complex organic species such as amino acids and sugars.

Delivery to Earth through bombardments of comets and asteroids.

Origin of the molecular complexity of asteroids and comets?

Study of other star-forming regions in order to characterize the chemical content available when planets, comets and asteroids form.

The building blocks of Life

Credit: New England Meteoritical Services
Star formation and chemistry

Stage of star formation

Chemistry

Molecular cloud

Grain

H$_2$O-rich
Star formation and chemistry

Stage of star formation

Collapse

Chemistry

Grain

CO-rich

H₂O-rich
Star formation and chemistry

Stage of star formation

Chemistry

Grain

CO-rich

H$_2$O-rich

H$_2$CO  CH$_3$OH
Star formation and chemistry

Stage of star formation

Collapse

Chemistry

Grain

CO-rich

H₂O-rich

Radicals

H₂CO  CH₃OH
Star formation and chemistry

Stage of star formation

Chemistry

Grain

CO-rich

H₂O-rich

Radicals

H₂CO  CH₃OH
Star formation and chemistry

Stage of star formation

Increase of the temperature

Chemistry

Grain

Diffusion of the radicals and formation of the complex organic molecules

CO-rich

H$_2$O-rich

COMs

H$_2$CO, CH$_3$OH

COMs
Star formation and chemistry

- Protostellar envelope
- Dark cloud
- Protoplanetary disk
- Formation of planets, comets and asteroids
- Hot core/corino > 100 K
- Outflow

- Thermal desorption of the icy grain mantles
- Detection of a large variety of COMs + water in the gas phase
A lot of COMs detected first towards high mass star-forming regions

First COMs detected in solar-type protostars in 2003 (Cazaux et al.)

How complex is the chemistry in hot cores and hot corinos?

- Solar-type protostars can be as rich as the high mass versions

Acetaldehyde
Dimethyl ether
Methyl formate
Ethyl cyanide
New detections with ALMA and NOEMA

- Very high spatial resolution
  
  *Sources spatially resolved*

- High sensibility
  
  *Detection of less abundant species*

- Broad spectral coverage with high spectral resolution
  
  *More lines to confirm detections*

Revolutionizing our understanding of the complex chemistry in star-forming regions
First detection of glycolaldehyde towards a solar-type protostar

**CH₂OHCHO**
Glycolaldehyde

- Prebiotic molecule
- Simplest sugar
- First product in the formation of ribose (essential constituent of RNA)

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Jørgensen et al. 2012
The ALMA-PILS survey

Solar-type protostar
IRAS 16293-2422
(d = 141 pc)

Rho Ophiuchi cloud

PILS: Protostellar Interferometric Line Survey
(Jørgensen et al. 2016)

Spectral survey with ALMA: 329-363 GHz

- Spectral resolution 0.2 km/s
- 0.5” (60 AU) angular resolution
- RMS ~ 5 mJy (1 km/s)
The ALMA-PILS survey

- FWHM ~ 1 km/s towards source B
- FWHM > 3 km/s towards source A
- Less line confusion in source B
- Source B ideal to search for new molecules and isotopologues
PILS: new detections in solar-type protostars

Acetone ($\text{CH}_3\text{COCH}_3$)  
(detected in comet 67P, Goesmann et al. 2015)

Propanal ($\text{CH}_3\text{CH}_2\text{CHO}$)  
(detected in comet 67P, Goesmann et al. 2015)

Ethylene oxide ($\text{C}_2\text{H}_4\text{O}$)  

Lykke et al. 2017
Acetone ($\text{CH}_3\text{COCH}_3$)  
(detected in comet 67P, Goesmann et al. 2015)

Propanal ($\text{CH}_3\text{CH}_2\text{CHO}$)  
(detected in comet 67P, Goesmann et al. 2015)

Ethylene oxide ($\text{C}_2\text{H}_4\text{O}$)

Acetaldehyde ($\text{CH}_3\text{CHO}$)
A revision of the formation (and destruction) pathways of these species is needed.
Methyl isocyanate
\(\text{CH}_3\text{NCO}\)

HNCO

NH\(_2\)CHO

Peptide bond (synthesis of proteins)

**PILS : new detections in solar-type protostars**

**Figure 3.**

\[ \text{ex} = \text{PILS} : \text{new detections in solar-type protostars} \]
**PILS: new detection in the interstellar medium**

Methyl chloride (Freon-40)

$\text{CH}_3\text{Cl}$

- Produced on Earth through biological and industrial processes
- Previously considered as a biomarker in the search for Life on exoplanets

Detection towards both IRAS 16293-2422 and comet 67P (Fayolle et al. 2017)

Abiotic formation in the interstellar medium
Cyanamide

Previous detections

• Milky Way: massive star-forming regions Sgr B2 and Orion KL
• Extragalactic medium: NGC 253 and M82

Prebiotic chemistry

• In liquid water, conversion into urea
• Isomerisation into carbodiimide (HNCNH) in photochemically and thermally induced reactions in interstellar ice analogs (Duvernay et al. 2005)

Molecules with the carbodiimide moiety (–NCN–) find use in various biological processes (e.g., assembly of amino acids into peptides)
**First detection of cyanamide in solar-type protostars**

**IRAS16293-2422 (ALMA-PILS)**

_Coutens et al. 2018_

**NGC1333 IRAS2A**

**NGC1333 IRAS 2A**

_PdBI_

_RA (J2000) 317716.1 MHz 55.7s 25.6s 3h28m15s5.5s_
First detection of cyanamide in solar-type protostars

IRAS16293-2422 (ALMA-PILS)  

Coutens et al. 2018

NH$_{2}^{13}$CN

NHDCN (first detection in the ISM)
First detection of cyanamide in solar-type protostars

IRAS16293-2422 (ALMA-PILS)  

Coutens et al. 2018

Other first detections of deuterated COMs in the ALMA-PILS survey:
- Formamide (Coutens et al. 2016)
- Glycolaldehyde (Jørgensen et al. 2016)
First detection of cyanamide in solar-type protostars

IRAS16293-2422 (ALMA-PILS)  

Coutens et al. 2018

NH$_2^{13}$CN

NHDCN (first detection in the ISM)

D/H (NH$_2$CN) ~ 1.7 %

D/H (NH$_2$CHO) ~ 2 %

D/H (other COMs) ~ 1-8%
Formation pathways of cyanamide

- Gas phase: no formation pathways
- Grain surface: so far not explored

Observations:
- Similar D/H ratio for NH$_2$CN and NH$_2$CHO
- Similar spatial distribution

\[ \text{Formation from a same precursor } \text{NH}_2 \]

\[ \text{NH}_2 + \text{CN} \rightarrow \text{NH}_2\text{CN} \]
**Formation pathways of cyanamide**

- MAGICKAL gas-grain chemistry code
- Collapse (to \( n_H \)) followed by warm-up to 400 K

![Graph showing formation pathways of cyanamide](image)

Observations

\[ n_H = 6 \times 10^{10} \text{ cm}^{-3} \]

(density IRAS16293B)

Highlights the necessity for future models of hot cores/corinos to treat the rising density and temperature in such cores concurrently, rather than as a two-stage process
**PILS: new detections in solar-type protostars**

- Methanimine $\text{CH}_2\text{NH}$
- Nitrous oxide $\text{N}_2\text{O}$
- CH$_3$NH$_2$ and NH$_2$OH not detected
  *Ligterink et al. submitted*

**Table 1. PILS: new detections in solar-type protostars**

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Chemical formula</th>
<th>$N_{\text{tot}}^\dagger$ (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitric oxide</td>
<td>NO</td>
<td>$(1.5 - 2.5) \times 10^{16}$</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>N$_2$O</td>
<td>$\geq 4.0 \times 10^{16}$</td>
</tr>
<tr>
<td>Hydroxylamine</td>
<td>NH$_2$OH</td>
<td>$\leq 3.7 \times 10^{14}$</td>
</tr>
<tr>
<td>Methanimine</td>
<td>CH$_2$NH</td>
<td>$(6.0 - 10.0) \times 10^{14}$</td>
</tr>
<tr>
<td>Methylamine</td>
<td>CH$_3$NH$_2$</td>
<td>$\leq 5.3 \times 10^{14}$</td>
</tr>
</tbody>
</table>

**CH$_3$NC**
Methyl isocyanide

**CH$_2$CHCN**
Vinyl cyanide
*Calcutt et al. 2018a*

**IRAS 16293B**
- $T_{\text{ex}} = 150 \pm 20$ K
- $N_{\text{tot}} = 2.0 \pm 0.2 \times 10^{14}$ cm$^{-2}$
- $N(\text{H}_2\text{CO})/N(\text{CH}_3\text{CN}) = 200$

**IRAS 16293A**
- $T_{\text{ex}} = 150^a$ K
- $N_{\text{tot}} = <1.45 \times 10^{13}b$ cm$^{-2}$
- $N(\text{H}_2\text{CO})/N(\text{CH}_3\text{CN}) = >5317$

*Calcutt et al. 2018b*
Conclusions

• Very rich chemistry in solar-type protostars

• A lot of things can be learned about their molecular content with ALMA

• ALMA-PILS survey:
  - Detections of acetone, propanal, ethylene oxide, methyl isocyanate, methyl chloride, cyanamide, vinyl cyanide, methanimine, nitrous oxide, methyl isocyanide
  - First detections of deuterated forms of COMs (formamide, glycolaldehyde, cyanamide)

• More to come…
Thanks