The study of comets with ALMA

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Cometary Science with ALMA

or tracing the origins of the Solar System and planet formation

comet and Solar System formation: molecular and isotopic composition, chemical diversity, dust as source of gas

outgassing processes of cometary nuclei: distant activity, outgassing distribution at nucleus surface - gas and dust -, dust to gas ratio

physical properties of comet atmospheres: kinematics, thermodynamics

caracteristics of comet nuclei: size, shape, albedo, thermal properties

Up to now, very few interferometric observations of comets!
Molecular composition

25 molecules identified in comet atmospheres, most of them in mm/submm range


radio

abundances relative to water [%]
Chemical composition of comets as a probe of chemistry in the presolar cloud and/or the Solar Nebula

- Analogies with hot cores
- Analogies with ISM ices
- Some differences too
- Evidence for grain surface chemistry
- Study of comet chemical composition is complementary to chemical studies of star-forming regions and proto-planetary disks.

New molecules: Alma prospect

- **ALMA**: gain in sensitivity of 10 wrt IRAM 30-m
- up to 2.5 more molecules to be detected with ALMA in Hale-Bopp type comet
- little spectral confusion
- detection in yearly comets of molecules only observed in comet Hale-Bopp

**Figure:**

A histogram showing the relative abundances of different molecular species. The x-axis represents the relative abundances, and the y-axis shows the number of molecular species. The data is from Crovisier et al. 2004, A&A 418, L35.
- 2 main comet populations: Oort cloud and Jupiter-family (short-period)
- possibly formed at different places, though this is now debated
Study of chemical diversity

- Halley-type
- Jupiter-family
- Oort cloud

short-period comets poorly studied due to low activity
origin of chemical diversity unexplained: related to time and location of formation in the solar nebula and evolution
ALMA will allow us to access to a large sample of comets

Biver et al. 2002, E.M.P. 90, 323
Isotopic measurements: deuterium

- Only performed in 3 bright Oort-cloud comets
  HDO and HCN only
- Strong enrichments requiring ion-molecules or grain-surface processes
- Key data to constrain early history of the Solar Nebula

ALMA: more systematic measurements, including short-period comets
D/H in other molecules (e.g. HDS, HDCO)

ALMA: competitive with Herschel (HIFI) for HDO measurements (464 GHz line in band 8).
But ALMA will not provide H₂O.
Other isotopic measurements

<table>
<thead>
<tr>
<th>Isotopic Ratio</th>
<th>Species</th>
<th>Value ± Error</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}/^{13}\text{C}$</td>
<td>[C$_2$]</td>
<td>93 ± 10</td>
<td>4 comets</td>
</tr>
<tr>
<td></td>
<td>[CN]</td>
<td>95 ± 12</td>
<td>1P/Halley</td>
</tr>
<tr>
<td></td>
<td>[HCN]</td>
<td>111 ± 12</td>
<td>Hale-Bopp</td>
</tr>
<tr>
<td>$^{14}\text{N}/^{15}\text{N}$</td>
<td>[HCN]</td>
<td>323 ± 46</td>
<td>Hale-Bopp</td>
</tr>
<tr>
<td>$^{16}\text{O}/^{18}\text{O}$</td>
<td>[H$_2$O]</td>
<td>518 ± 45</td>
<td>1P/Halley</td>
</tr>
<tr>
<td></td>
<td>[H$_2$O]</td>
<td>470 ± 40</td>
<td>1P/Halley</td>
</tr>
<tr>
<td></td>
<td>[H$_2$O]</td>
<td>450 ± 50</td>
<td>153P</td>
</tr>
<tr>
<td>$^{32}\text{S}/^{34}\text{S}$</td>
<td>[CS]</td>
<td>27 ± 3</td>
<td>1P/Halley</td>
</tr>
<tr>
<td></td>
<td>[H$_2$S]</td>
<td>16 ± 3</td>
<td>Hale-Bopp</td>
</tr>
</tbody>
</table>

Isotopic anomalies $^{14}\text{N}/^{15}\text{N}$ in CN

- Further measurements in HCN and other N-bearings species required
Exemple of sensibility reached now (16h of telescope time at IRAM 30-m or CSO)

<table>
<thead>
<tr>
<th></th>
<th>C/2004 Q2 (Machholz)</th>
<th>73P/SW3</th>
<th>Measured in Hale-Bopp</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCN/HCN</td>
<td>&lt;1/90</td>
<td>&lt; 1/40</td>
<td>1/500</td>
</tr>
<tr>
<td>H^{13}CN/H^{12}CN</td>
<td>&lt; 1/60</td>
<td>&lt;1/35</td>
<td>1/111</td>
</tr>
<tr>
<td>HC^{15}N/HC^{14}N</td>
<td>&lt; 1/113</td>
<td>&lt;1/35</td>
<td>1/320</td>
</tr>
<tr>
<td>H_{2}^{34}S/H_{2}^{32}S</td>
<td>&lt; 1/17</td>
<td>&lt; 1/13</td>
<td>1/16</td>
</tr>
</tbody>
</table>

C/2004 Q2 (Machholz) : a yearly bright Oort cloud comet observed in 2005
73P/ SW3 : a short-period comet at 0.1 AU from Earth observed in 2006
Monitoring of comet gaseous activity

Study of nuclear ices structure, differentiation, and seasonal effects

ALMA: monitoring will be possible more routinely and in distant comets

Biver et al. 2002, E.M.P. 90, 5
Alma will provide simultaneous maps of gaseous species (3-D) and dust at high angular resolution (50-100 km) and good temporal resolution (thanks to good instantaneous uv-coverage)

- Study of gas sources at nucleus surface
- Dust/gas interrelations
- Origin of species in the coma (extended sources)
Mosaic image of HCN(1-0) with BIMA array (10 arcsec resolution)

Hale-Bopp, April 6 1997

Wright et al. (1998)
Plateau de Bure observations of comet Hale-Bopp

CO rotating jet seen at 230 GHz

Henry et al. 1999, Bockelée-Morvan et al. 2006
Spectral maps over 8 h integration
Hydrodynamic simulations in comet Hale-Bopp

Only topography effects

With a CO jet at the nucleus surface

20000 x 20000 km
(20 x 20 arcsec)

See poster of Boissier et al.
Extended sources in the coma

Some species are not subliming from nucleus surface
- photolysis products
- decomposition of organic grains or icy grains
- product of coma chemistry

Examples of results obtained in comet Hale-Bopp at PdB (2-4 arcsec resolution):
- $\text{H}_2\text{S}$ and $\text{CO}$: nucleus production
- $\text{SO}$: photolysis product of $\text{SO}$, constraints on $\text{SO}$ lifetime
  (poster of Boissier et al.)
- $\text{H}_2\text{CO}$: extended distribution, likely POM ((-$\text{H}_2\text{CO}$-$)n) thermal degradation
Dust coma

ALMA: maps of dust thermal emission
- simultaneous to gaseous maps: relations between gas and dust jets
- measurements of dust production rate
- uncertainties on dust opacity $K_\nu$
- constraints on size distribution from multi-$\lambda$ studies
- complementary to IR and visible measurements (sensitive to small particles)

Continuum in comet Hale-Bopp at PdBI

Altenhoff et al. 1999
Comet nuclei

1P/Halley
Giotto
1986

15x7x7 km

14 mas at 1AU

19P/Borrelly
Deep Space 1
2001

8x3 km

5 mas at 1AU

81P/Wild 2
Stardust
2004

5x4x3 km

9P/Tempel 1
Deep Impact
2005

5x8 km

Hard to resolve with ALMA!
Comet nuclei with ALMA

Measurement of thermal emission: size and albedo
only known for ~ 10 comets

Size distribution is important for studies of accretion
and collisional processes in early Solar System
possibly shape measurements (from lightcurves)

\[ F = 0.07 \, r_h^{-0.25} \, R^2/D^2 \, [\text{mJy}] \]

\( R = \) nucleus radius \( r_h, D : \) helio- and geocentric distances

Long baselines required to separate nucleus from dust emission

<table>
<thead>
<tr>
<th></th>
<th>R (km)</th>
<th>D (AU)</th>
<th>S/N –1h 0.8 mm</th>
<th>Nucleus/Dust Contrast 5 km baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hale-Bopp</td>
<td>30</td>
<td>1.4</td>
<td>2500</td>
<td>10</td>
</tr>
<tr>
<td>Hartley 2</td>
<td>1</td>
<td>0.13</td>
<td>320</td>
<td>100</td>
</tr>
<tr>
<td>Typical</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>29P/SW1</td>
<td>30</td>
<td>6</td>
<td>55</td>
<td>2</td>
</tr>
</tbody>
</table>
**Which Alma configuration for comet studies?**

**Atmosphere**: Not so big! But no definite size:
- for dust and nuclear species: brightness distribution in 1/r size limited by image sensitivity
- for daughter species: brightness distribution more extended

**Compact configuration or auto-correlation measurements**
more appropriate for relatively weak lines or dust continuum

**Nucleus**: extended ALMA configuration

**Comparison of S/N ratios with ALMA**
On-off versus various configurations

![Graph showing comparison of S/N ratios with baseline (km)]
<table>
<thead>
<tr>
<th>Comet</th>
<th>date</th>
<th>$Q_{H_2O}$</th>
<th>$\Delta$</th>
<th>Molecules detectable</th>
<th>Isotopes</th>
<th>Monitoring</th>
<th>Coma imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>22P/Kopff</td>
<td>07/2009</td>
<td>$10^{28}$</td>
<td>0.8</td>
<td>~6</td>
<td>-</td>
<td>-</td>
<td>Low res.</td>
</tr>
<tr>
<td>81P/Wild 2</td>
<td>03/2010</td>
<td>$10^{28}$</td>
<td>0.7</td>
<td>~6</td>
<td>$H^{13}CN$</td>
<td>-</td>
<td>Low rés.</td>
</tr>
<tr>
<td>103P/Hartley2</td>
<td>10/2010</td>
<td>$2.10^{28}$</td>
<td>0.13</td>
<td>15 + New molec.</td>
<td>$^{13}C,^{34}S,\ D,^{15}N$</td>
<td>-</td>
<td>High res., dust, 6 molec.</td>
</tr>
<tr>
<td>45P/H.-M.-P.</td>
<td>08/2011</td>
<td>$2.10^{27}$</td>
<td>0.07</td>
<td>~10</td>
<td>$^{13}C,^{34}S$</td>
<td>-</td>
<td>Med. res.</td>
</tr>
<tr>
<td>2P/Encke</td>
<td>10/2013</td>
<td>$6.10^{27}$</td>
<td>0.5</td>
<td>~8</td>
<td>-</td>
<td>-</td>
<td>Low res.</td>
</tr>
<tr>
<td>New comet</td>
<td>One per year</td>
<td>$1.10^{29}$</td>
<td>0.6</td>
<td>~15</td>
<td>$^{13}C,^{34}S,\ D,^{15}N$in 7 molec.</td>
<td>&lt;1- 5 UA</td>
<td>-</td>
</tr>
<tr>
<td>« Great Comet&quot;</td>
<td>Every 5 years</td>
<td>$5.10^{29}$</td>
<td>0.6</td>
<td>15 + New molec</td>
<td>$^{13}C,^{34}S,\ D,^{15}N, &gt;10$ molec</td>
<td>1- 10 UA</td>
<td>high res., Dust, 10 molec</td>
</tr>
<tr>
<td>Slide from Biver (2006)</td>
<td></td>
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</tbody>
</table>
Specificity of comet observations

- Fixed time observations
- Targets Of Opportunity
- Time variable objects
- For a « Great comet » early discovered, important to have ALMA in appropriate configuration
- Need for autocorrelation measurements (with the ALMA array !)
- Accurate position tracking required (e.g., not yet fully functional with APEX) - ephemeris program or user-provided ephemeris -
- Necessity of velocity tracking (or tools for afterwards corrections in the pipeline)
Conclusion

By offering great sensitivity and uv-coverage, ALMA will be a great tool for cometary science.

On many topics, will be complementary to space missions and even provide unique measurements.

Thanks for your attention