Mid-IR Observations and Mineralogy of Comet Dust Grains with Subaru+COMICS

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Comets and solar system formation

- Ice lines (<~150K)
  - water (amorphous/crystalline)
  - carbon dioxide
  - carbon monoxide

- Organics (<~500K)

- Silicate/carbonate minerals
  - amorphous/crystalline (<~1000K)
  - hydrated
  - pyroxene/olivine, Mg/Fe

- Investigate the thermal history and the original compositional gradient across the entire Solar System

(DeMeo+Carry 2014)
Infrared spectroscopy of cometary ice and dust

- Major molecules
- Silicates
- Water ice
- Water lines
- Silicate minerals: amorphous/crystalline
- Complex organic molecules
- Mid-IR from the ground

Crovisier and Encrenaz (2000)
Crystalline silicate in cometary dust

- Most silicate exist **amorphous** form in interstellar space (degree of crystallinity < 2.2%)
- **Crystalline silicate** was detected in the mid-IR C/Halley spectrum.

![Graph showing Sgr A*, GCS 3, and GCS 4 spectra](image)

- Flux ($10^{-13}$ W m$^{-2}$ μm$^{-1}$)
- Wavelength (λ (μm))

![Graph showing 1P/Halley](image)

- Flux ($10^{-16}$ W cm$^{-2}$ μm$^{-1}$)
- Wavelength (μm)

(Kemper+ 2004)

1P/Halley

Lick observatory
(Bregman et al. 1987)
Mid-IR spectral features are different between amorphous and crystalline forms.
(2) Amorphous silicate had *crystallized near the Sun (>800 K)* by annealing and/or direct condensation of gas.

(3) Crystalline silicate were incorporated into cometary nuclei after its **radial transportation** in the Solar Nebula (SN)

- Crystalline silicate is **more abundant at closer distances from the Sun** in the SN
- **Is there any difference between Oort cloud comets and Jupiter-family comets?**
Mid-IR observations of comets with COMICS

- Subaru Telescope + COMICS
  - N, Q-band imaging:
    - N8.8, N12.4,
    - Q18.8, Q24.5 (and more)
  - low-resolution spectroscopy:
    - 8–13 μm (R~250)
  - slit width and length:
    - 0.33” x 40”

- We observed ~10 short period comets and >10 long period comets so far since 2003 (Thank you COMICS team!).
Mid-IR observations of comets with COMICS
## Mid-IR observations of comets with COMICS

<table>
<thead>
<tr>
<th>Comet</th>
<th>Obs date (UT)</th>
<th>( r_h ) (au)</th>
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<tbody>
<tr>
<td>2P</td>
<td>2003/11/12</td>
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<tr>
<td>4P</td>
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## Jupiter-family comets

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Deep Impact — 9P/Tempel
(Sugita et al. 2005; Ootsubo et al. 2006)

Pre-impact

3-3.5 hrs after impact

28 hrs after impact

Post-impact

I+1 hr

I+2 hrs

I+3 hrs

I+3.5 hrs

Spectroscopy
Outburst comet – 17P

Comet 17P/Holmes

- 1892 Nov. (by E. Holmes during outburst)
- P ~ 7 yrs
- r_h 2.05 au (on 2007 May 4)

On 2007 Oct. 23 the great outburst (~17 → ~2 mag) occurred at ~2.5 au from the Sun
\[
\begin{align*}
\text{Flux density} & \quad (\text{W m}^{-2} \cdot \mu\text{m}^{-1}) \\
\text{Wavelength} & \quad (\mu\text{m})
\end{align*}
\]

<table>
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<tr>
<th>Mineral</th>
<th>Mass fraction</th>
</tr>
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<tr>
<td>Amorphous Olivine</td>
<td>(m_{Ao} = 0.31 \pm 0.03)</td>
</tr>
<tr>
<td>Amorphous Pyroxene</td>
<td>(m_{Ap} = 0.32 \pm 0.03)</td>
</tr>
<tr>
<td>Amorphous Carbon</td>
<td>(m_{Ac} = 0.12 \pm 0.01)</td>
</tr>
<tr>
<td>Crystalline Olivine</td>
<td>(m_{Co} = 0.18 \pm 0.01)</td>
</tr>
<tr>
<td>Crystalline Pyroxene</td>
<td>(m_{Ap} = 0.08 \pm 0.02)</td>
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\(f_{\text{cry}} = 0.28 \pm 0.04\)
Most JFCs we observed show crystalline silicate features (except 2P/Encke).

Silicate feature strength is typically ~10-20% to continuum.

Intrinsic dust properties? or Dust evolution on the surface of comet nucleus?

Correlation with the orbital evolution (perihelion distance, etc.) must be studied.
Oort cloud comets

- Oort cloud comets show various shapes and strength of silicate features.
- Some OCCs don’t show crystalline feature.
- Should we observe OCCs at $r_h < 2$ au to derive the dust property itself (not affected by ices)?

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Is there effects by ice coating of dust grains to the comet spectrum even around 2 au?
Silicate features change at different heliocentric distances even for the same comet
Silicate features change at different heliocentric distances even for the same comet.

- **2013-Oct-19 UT**
  - $T_{\text{cont}} \sim 260$ K
  - Subaru+COMICS (Ootsubo+2014)

- **2013 Nov 11&12**
  - $T_{\text{cont}} \sim 330$ K
  - IRTF/SpeX+BASS (Sitko+2014)
Crystalline fraction in silicate

- Crystalline fraction in silicate grains is typically 30%-70%
- OCCs has a bit higher $f_{\text{cry}}$ than JFCs?
- We should investigate this with much more samples
- About 20 cometary spectra were taken by the COMICS and 10 are analyzed, but..

**Mass fraction of crystalline silicate, $f_{\text{cry}}**

- $f_{\text{cry}} = \text{a mass fraction of crystalline components in small (~sub-μm) silicate grains}$
Complex organics in comets

Rosetta detects glycine ($\text{C}_2\text{H}_5\text{NO}_2$) together with methylamine ($\text{CH}_5\text{N}$), and ethylamine ($\text{C}_2\text{H}_7\text{N}$) in the coma of 67P.

Altwegg et al. (2016)
Hydrocarbons and simple organic molecules are detected in 3-5μm comet spectra.

Complex organic materials?

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Complex organic materials?
Comet 21P/Giacobini-Zinner

21P/Giacobini-Zinner

- Parent comet of the October Draconids meteor shower
- Peculiar dust properties
  - depleted in $C_2$, $C_3$, NH
  - negative linear polarization gradient

Subaru+COMICS
- 2005 July 5 UT
- 8.8, 12.4, 18.8 + NLspec

![Comet Image]

(Michael Jaeger 2018-08-22)

(Ootsubo+ 2020)
Organics in comet: 21P

(Ootsubo+ 2020)
Organic molecule 9 μm feature

- 9.2 μm feature can be attributed to aliphatic hydrocarbons, which heated up to ~500 K--730 K

Vacuum pyrolysis of pure cellulose

Heated up to 730 K

Aliphatic features disappeared

Heated up to 600 K

9.4μm

(Blanco et al. 1988)
Organics in comet: 21P

Small (sub-μm) silicate dust: $f_{cry} \sim 0.45$ (typical)

→ Birthplace of 21P is similar to that of other comets
Complex organics in 21P

- We detect the unidentified infrared (UIR) emission features of comet 21P/G-Z at $\sim8.2$, $\sim8.5$, $\sim9.2$, $\sim11.2$, and $\sim12.7$ $\mu$m.

- Likely due to complex organic molecules (both aromatic and aliphatic hydrocarbons), which could be contaminated by N- or O-atoms.

- Crystalline fraction in silicate grains is typical.

- This suggests that 21P formed at a similar distance from the Sun as other comets, but a bit warmer place in the solar nebula. Circumplanetary disk?
Results of COMICS observations

Silicate features

- **Crystalline** fraction in silicate grains is typically 30%-70%. OCCs has a bit higher $f_{\text{cry}}$ than JFCs?
- Ongoing project, and we need more samples.

Organics

- We detect the UIR features of comet 21P/G-Z at ~8.2, ~8.5, ~9.2, ~11.2, and ~12.7 $\mu$m.
- Likely due to complex organic molecules (both aliphatic and aromatic hydrocarbons), contaminated by N- or O-atoms.
Future Mid-IR observation of comets

- Ground-based observations
  - We need reliable spectra at 7.5--8.0 $\mu$m (for organics, 7.7 $\mu$m PAH feature, ...)
  - Q-band spectrum (to obtain reliable Olv:Pyx)

- We have several new comet targets for mid-IR spectroscopy every year!

- COMICS is still the best mid-IR instrument for the observations of Solar System minor bodies.
Comets we should observe in MIR

67P & 19P

- Both comets were visited by spacecrafts (Rosetta and Deep Space 1)
- We need good mid-IR instruments to observe comets around 2022 Jan, ...