Comet Dust Composition and Astrophysical Connections

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A variety of techniques are used to study comet dust: lab analysis, in situ analysis, telescopic (under a variety of geometric circumstances).
Comet Dust

• Origin of dust
• Size, structure, and composition
  • Interplanetary dust particles and *Stardust* samples
  • Thermal emission from comet dust
• Evolution of dust and comets
Origin in the nucleus, and the Solar System

Comet dust origins
Comets are aggregates of
- ICE,
- ROCK (dust), and
- ORGANICS (refractory and volatile).

As a comet approaches the Sun,
- Surface temperature increases,
- Energy propagates inward,
- Ice sublimes,
- Escaping gases drag out the dust.
Dust in comet comae may originate from that upper-layer, or may be more directly from the interior.

The *Deep Impact* mission gave us a look inside a comet. It demonstrated that:

- Volatiles are located very close to the surface (few meters),
- Volatiles are buried beneath a ~1m layer of dust (Kadono et al. 2007),
- Ice and dust are mixed on meter scales, but not at the micrometer scale (Sunshine et al. 2007).

Dust in comet comae may originate from that upper-layer, or may be more directly from the interior.
What does the presence of ice imply?

• Nuclei formed well beyond the “snow line.”

• The presence of highly volatile molecules (CO, CH4, others) indicates interiors have remained cold, $T << 180 \text{ K}$, since formation.

• Consequently:
  - Radiogenic heating never occurred, or
  - That energy was easily lost.

All comet interiors are pristine:
Dust is thermally stable and not aqueously altered.
Comet dust origins

• The formation of dust in the early Solar System is a messy process.

• That newly formed dust is transported out to the comet formation zone.

• Comet interiors have been well preserved for the past 4.5 Gyr.

• Dust comae originate from the (near-)surface of the nucleus.

(ESO/L. Calçada/M. Kornmesser)
Comet dust samples
• Interplanetary dust particles collected in the stratosphere,
• Samples returned from comet Wild 2 by *Stardust*.
• In situ analysis of comet Halley, and soon comet Churyumov-Gerasimenko,
ESA/Rosetta/MPS COSIMA target: 1x1 cm gold plate

~50 and ~70 µm comet dust grains

17/08/2014

24/08/2014
Interplanetary dust particles

- Two relevant types: chondritic porous (CP) and chondritic filled (CF)
  - Chondritic: close to solar elemental abundance,
  - Porous: >90% vacuum,
  - Filled: more solid
- Based on entrance velocities, CP IDPs are more likely cometary in origin.
- Based on the presence of hydrated silicates, CF IDPs are less likely cometary in origin.
Interplanetary dust particles

- CP IDPs are aggregates of smaller units.
- Large grains (0.1-10 μm) are
  - Anhydrous silicates (olivine, pyroxene),
  - Refractory iron sulfides
- Fine-grained (<0.1 μm) matrix consisting of
  - Silicates and carbon,
  - Silicates without carbon (GEMS), or
  - Carbonaceous material.
Crystalline silicates have a range of compositions.

A distributed Mg/Fe is found, but Mg-rich is preferred:
- Forsterite (Mg$_2$SiO$_4$), and
- Enstatite (MgSiO$_3$).

Mg/Fe is a clue from their formation. Mg-rich grains are typically preferred in nebular condensates, cf. solar Mg/Fe $\sim$ 1.
GEMS: Glass with Embedded Metal and Sulfides

- Dominate the amorphous silicate component.

- Are possibly interstellar in origin (still being debated).
  - Tend to have O isotopic compositions indistinguishable from terrestrial materials and chondritic meteorites (Keller and Messenger 2011)
  - Petrology and mineralogy of isotopically anomalous GEMS are indistinguishable from others (Bradley 2013) suggesting a common origin.
Stardust

- One of the few spacecraft missions to return samples of a specific object:
  - Moon
  - Sun
  - Itokawa
  - Wild 2
- Collection was in 2004, sample return in 2006.
Stardust

Returned

• >~ μm-sized grains and aggregates,
• Crystalline silicates consistent with CP IDPs,
• Chondrule fragments, of a range of compositions.

Did not return

• The smallest dust grains,
• Lower temperature species (e.g., phyllosilicates, amorphous silicates),
• GEMS clearly identifiable as cometary.
Select *Stardust* conclusions

Brownlee 2014

The IDP and *Stardust* collections are representative of comets.

The similarity between the two suggests the *Stardust* results can be generalized, at least to first order.

(Zolensky et al. 2008, edited)
Select *Stardust* conclusions

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Comet dust formed close to the Sun

- A wide variety of materials are found in Wild 2
  - CAIs and other “first condensates”
  - Crystalline silicates
  - A range of chondrule fragments
- Given this wide range, annealing of amorphous silicate grains to crystalline silicate grains is not needed to explain their high abundance in comets.
Select *Stardust* conclusions

Brownlee 2014

Pre-solar grains are not in abundance in the Wild 2 collection.

• 600-830 ppm for O-rich grains.
• ~375 ppm is primitive IDP mean.
• Up to 150-200 ppm in meteorite matrix.

• Sampling bias? Most ISM grains are small, amorphous
  • *Stardust* could not directly collect small grains, and
  • Difficult to distinguish amorphous grains from melted aerogel.

Thermal emission
Comet spectral energy distributions are a combination of
• reflected sunlight, and
• thermal emission.

The shape of the thermal emission is sensitive to the dust:
• Size,
• Structure (shape, porosity), and
• Composition.
Grain sizes distribution

Grain temperatures are computed from optical constants and Mie theory.

Nominal coma emission

More small, hot grains

More large, cool grains
Fluffy aggregate, radiates more like a collection of individual grains.

Compact aggregate, radiates more like a solid particle.

Grain structure addressed with effective medium theory: mixing vacuum into grains at the optical constant level.

(Mukai et al. 1992)
Composition

• Our thermal models are based on the compositions of IDPs and Hale-Bopp.

• Right: Building up the 10-μm silicate emission feature of comet Hale-Bopp (Wooden et al. 1999).
  Spectrum normalized with a Planck function.
  Top: Just amorphous olivine.
  Middle: Add Mg-rich crystalline olivine.
  Bottom: Add amorphous pyroxene
Crystalline fraction

<table>
<thead>
<tr>
<th>Comet</th>
<th>f_{cryst} (%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/2007 N3 (Lulin)</td>
<td>14 ± 4</td>
<td>Woodward et al. 2011</td>
</tr>
<tr>
<td>9P/Tempel 1</td>
<td>13 – 35</td>
<td>Harker et al. 2005</td>
</tr>
<tr>
<td>73P/S-W 3C</td>
<td>26 ± 4</td>
<td>Harker et al. 2011</td>
</tr>
<tr>
<td>C/2001 HT50 (LINEAR-NEAT)</td>
<td>28</td>
<td>Kelley et al. 2006</td>
</tr>
<tr>
<td>73P/S-W 3B</td>
<td>34 ± 10</td>
<td>Harker et al. 2011</td>
</tr>
<tr>
<td>17P/Holmes</td>
<td>60</td>
<td>Reach et al. 2007</td>
</tr>
<tr>
<td>C/2002 V1 (NEAT)</td>
<td>66</td>
<td>Ootsubo et al. 2007</td>
</tr>
<tr>
<td>C/1995 O1 (Hale-Bopp)</td>
<td>60 – 80</td>
<td>Harker et al. 2002</td>
</tr>
</tbody>
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- How much inner-Solar System material mixed with ISM dust in the outer-disk?
- Several comets have been measured, and a couple surveys by our team will be published in the next few years.
- A wide range, 14% to 70%.
- Much more varied than T-Tauri disks: 10-20% (Oliveira et al. 2011).

Is our Solar System unique/rare? Are there small scale variations in T-Tauri disks not evident in Spitzer spectra?
Comet evolution
Cold storage

• Comet interiors are preserved, but not necessarily their surfaces.
• Galactic cosmic rays and a long residence in the Oort cloud will alter the upper few meters.
• Amorphize silicate crystals?
• Carbonize organics?
Oort Cloud Comet Hale-Bopp

- Extreme dust properties, which seem to be rare in the comet population:
  - Strong amorphous and crystalline silicate features.
  - Strong thermal continuum at short wavelengths.
  - Nearly an optically thick coma at perihelion ($\tau \ll 1$).

A preponderance of small, silicate rich dust grains
(Harker et al. 2002).
Old vs. New

• Reciprocal semi-major axis, computed before being perturbed by the planets, indicates the likelihood of a comet being on its first perihelion passage (Oort 1950).
  • \( \frac{1}{a} < 50 \times 10^{-6} \text{ AU}^{-1} \) considered to be dynamically new
  • Jupiter’s average kick is about \( 1000 \times 10^{-6} \text{ AU}^{-1} \).

• Comet Hale-Bopp had been to the inner solar system several times:
  • \( \frac{1}{a} = 3800 \times 10^{-6} \text{ AU}^{-1} \)

Hale-Bopp was pristine in the Solar System sense, but not a preserved relic from the Oort Cloud.
Comet C/2012 S1 (ISON)

- A dynamically new sungrazing comet discovered at 6 AU.
- It appeared to be on its first inner-Solar System passage since being placed in the Oort cloud.
- As a sungrazer it could easily lose 10’s of meters of material: the irradiated mantle would be lost in one perihelion passage.
- Thus an opportunity to compare the irradiated mantle to the deeper interior.
Comet C/2012 S1 (ISON)

11-, 20-, and 32-µm filter photometry of comet ISON with SOFIA/FORCAST.
Wooden et al. in preparation

- We fit the SED along with two constraints from Subaru/COMICS (Ootsubo et al., in prep.):
  - continuum temperature, and
  - silicate feature strength.
- A family of models is obtained, the most plausible suggest:
  - Narrow size distribution (mono-disperse) with a preponderance of 1-μm grains, and
  - Low silicate mass fraction (<20%).
- Post-outburst mid-IR spectra show a more typical comet (Russell et al., in prep.).

Did we observe the irradiated mantle?
C/2012 K1 (PanSTARRS)

- Also a dynamically new comet.
- Observed with SOFIA/FORCAST in June 2014.
- Spectral extractions calibrated based on our ground-based and Kuiper Airborne Observatory experience.
- Data look great! Analysis is ongoing. More details at the DPS Meeting in Tucson (Woodward et al.).
• Comet dust grains are relics from our Solar System’s formation.
  • They simultaneously represent the inputs and the outputs of planetesimal formation.

• Our knowledge of their compositions are guided by laboratory and in situ analyses.
  • Telescopic observations are still needed to give us bulk coma properties and an understanding of comet-to-comet variations.

• Comet dust grains originate from a wide variety of processes:
  • Interstellar medium grain growth and processing,
  • Chondrule formation,
  • Grain condensation.

• Mid-infrared spectra reveal a diversity not seen in T-Tauri disks.
  • Statistically significant comet surveys will address if the mean comet agrees with the mean T-Tauri disk.