THE SCIENCE OF LONG-PERIOD COMETS AND INTERSTELLAR OBJECTS
SMD Vision & Voyages (2013-2022) & the Astrobiology Roadmap

How do Habitable Worlds Form?

With thousands of exoplanetary systems known, ours, so far is unique in its architecture with a habitable planet in the habitable zone. Water is the most abundant condensable molecule so solar composition gas should condense water-rich planets, yet the inner solar system is dry.

- Planetesimals gain chemical fingerprints from the disk
- Planetesimals were then scattered by the giant planets
- Did planetesimals drive inward from beyond the snow line to form terrestrial planets?
- Meteorites (cosmochemistry) gives us clues to what happened
- Volatiles in small primitive bodies are the best connection to protoplanetary disks and how habitable worlds are built.
**Formation Details**

**Disk Chemistry Models**
- Ionization at surface
- Thermal structure, snow lines
- Turbulence & accretion
- Chemical reactions
- Ion-molecule reactions / isotope effects
- Interaction with the dust

**Solar System Dynamics**
- Planetesimal growth over 20 orders of magnitude in size in a few Myr
- Streaming instabilities can concentrate pebbles
- In-situ formation vs giant planet migration
- Very different planetesimal scattering

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**References**

DeMeo & Carry (2014), Nature 505, 629.
Comet science pre- & post-Rosetta

LPCs – A long historical interest
• Long period comets account for all of the “great comets” observed historically
• LPCs are more active at larger distances
• Evolution or formation difference?
Recent Great Comets

- C/2013 US10 Mag 6, M. Jager
- C/2006 P1 McNaught; Mag -7
- Halley 1986, Mag 2.6
- West, 1976, Mag -3
- C/1995 O1 Hale-Bopp; Mag -1, A. Dima
- C/2012 S1 ISON; Mag -3, W. Skorupa
- 17P/Holmes, Mag 1.0; 2007 I. Eder
- Hyakutake, 1996; Mag -2
- C/2011 W3 Lovejoy Mag -6
- C/2009 P1 Garradd, Mag 6, J. Nassr
- Ikeya-Seki, 1957, Mag -10
Pre-Mission Knowledge: Earth-based

Volatile and activity

- Activity controlled by $\text{H}_2\text{O} \& \text{CO}$, other species trapped in amorphous ice
- Evidence of different chemical reservoirs $\rightarrow$ not correlated with dynamics (optical and IR data)
- Suggestion that some comets have more volatile ices: CO, CO$_2$
- Isotopes H, C, N, O for a few to a couple dozen comets only

Pre-Mission Knowledge: Earth-based

<table>
<thead>
<tr>
<th>Isotopic ratio</th>
<th>Species</th>
<th>Value</th>
<th>Comet</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/H</td>
<td>H₂O</td>
<td>(3.06 ± 0.34) 10⁻⁴</td>
<td>1P/Halley</td>
<td>Eberhardt et al. (1995)</td>
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<tr>
<td></td>
<td></td>
<td>(3.08±0.38/−0.53) 10⁻⁴</td>
<td>1P/Halley</td>
<td>Balsiger, Altwegg &amp; Geiss (1995)</td>
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<tr>
<td></td>
<td></td>
<td>(2.9 ± 1.0) 10⁻⁴</td>
<td>C/1996 B2 (Hyakutake)</td>
<td>Bockelée-Morvan et al. (1998)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3.3 ± 0.8) 10⁻⁴</td>
<td>C/1995 O1(Hale-Bopp)</td>
<td>Meier et al. (1998b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2.5 ± 0.7) 10⁻⁴</td>
<td>C/2002 T7 (LINEAR)</td>
<td>Hutsemékers et al. (2008)</td>
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<tr>
<td></td>
<td>HCN</td>
<td>(4.6 ± 1.4) 10⁻⁴</td>
<td>C/2001 Q4 (NEAT)</td>
<td>Weaver et al. (2008)</td>
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<tr>
<td></td>
<td></td>
<td>(4.0 ± 1.4) 10⁻⁴</td>
<td>8P/Tuttle</td>
<td>Villanueva et al. (2009)</td>
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<tr>
<td></td>
<td></td>
<td>(2.3 ± 0.4) 10⁻³</td>
<td>C/1995 O1(Hale-Bopp)</td>
<td>Meier et al. (1998a)</td>
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<tr>
<td>¹⁴N/¹⁵N</td>
<td>CN</td>
<td>147.8 ± 5.7</td>
<td>18 comets</td>
<td>Manfroid et al. (2009)</td>
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<tr>
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<td>HCN</td>
<td>205 ± 70</td>
<td>C/1995 O1(Hale-Bopp)</td>
<td>Bockelée-Morvan et al. (2008)</td>
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<tr>
<td></td>
<td>HCN</td>
<td>139 ± 26</td>
<td>17P/Holmes</td>
<td>Bockelée-Morvan et al. (2008)</td>
</tr>
<tr>
<td>¹²C/¹³C</td>
<td>C₂</td>
<td>93 ± 10</td>
<td>4 OC comets</td>
<td>Wyckoff et al. (2000)</td>
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<tr>
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<td>CN</td>
<td>91.0 ± 3.6</td>
<td>18 comets</td>
<td>Manfroid et al. 2009</td>
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<td>111 ± 12</td>
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<td>Jewitt et al. (1997)</td>
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<td>HCN</td>
<td>114 ± 26</td>
<td>17P/Holmes</td>
<td>Bockelée-Morvan et al. (2008)</td>
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<tr>
<td>¹⁶O/¹⁸O</td>
<td>H₂O</td>
<td>518 ± 45</td>
<td>1P/Halley</td>
<td>Balsiger, Altwegg &amp; Geiss (1995)</td>
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<tr>
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<td>470 ± 40</td>
<td>1P/Halley</td>
<td>Eberhardt et al. (1995)</td>
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<tr>
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<td>520 ± 25</td>
<td>4 OC comets</td>
<td>Biver et al. (2007)</td>
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<tr>
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<td>OH</td>
<td>425 ± 55</td>
<td>C/2002 T7 (LINEAR)</td>
<td>Hutsemékers et al. (2008)</td>
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<tr>
<td>³²S/³⁴S</td>
<td>S⁺</td>
<td>23 ± 6</td>
<td>1P/Halley</td>
<td>Altwegg (1996)</td>
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<tr>
<td></td>
<td>CS</td>
<td>27 ± 3</td>
<td>C/1995 O1(Hale-Bopp)</td>
<td>Jewitt et al. (1997)</td>
</tr>
<tr>
<td></td>
<td>H₂S</td>
<td>17 ± 4</td>
<td>C/1995 O1(Hale-Bopp)</td>
<td>Crovisier et al. (2004a)</td>
</tr>
</tbody>
</table>

Mumma & Charnley (2011), ARAA 49, 471. C, O, S are terrestrial, N is depleted 2x, H enriched.
Pre-Mission Knowledge: Earth-based

**Nucleus and Dust**

- Short period comet nucleus sizes consistent with collisional population; small ones (sub-km) missing
  - Upper limits for 5 dynamical new comets from HST
  - Measurements (WISE) for 8 LPCs
- Very low albedos 2-6%, little variation
- Dust: amorphous olivine, pyroxene, crystalline olivine
- Low density (< 1000 kg/m³)
  - Non gravitational motion, Giotto, SL9, Rotation, Chiron exopause: 100-200 kg/m³

Data from: Bauer (2015), Fernandez (2013)

Missions Pre-Rosetta

ICE: Giacobini Zinner
- L: Aug 12, 1978; E: Sep 11, 1985
- Fly through plasma tail

Giotto (+ Russia, Japan): Comet Halley
- L: July 2, 1985; E: Mar 14, 1986
- Science: Proved solid nucleus; organic dust (CHON); volatiles: 80% H$_2$O, 10% CO$_2$

Deep Space 1: 19P/Borrelly
- L: Oct 4, 1998; E: Sep 22, 2001 (Test space technologies)
- Science: 1$^{st}$ hint of smooth plateaus; No direct evidence of H$_2$O ice

Stardust - 1$^{st}$ sample return
- Science: Comets dust $\rightarrow$ migration in early solar system

Deep Impact (EPOXI, NExT)
- L: Jan 12, 2005, E: Jul 4, 2005 (1$^{st}$ Active experiment)
- Science: Comets are good insulators; Little surface ice; New ideas about formation; cryovolcanos
Rosetta Results - Volatiles

- Little surface ice exposure
- Prebiotic materials detected
- Noble gases –
  - \( \text{Ar/Kr and Kr/Xe lower than solar (formed very cold)} \)
  - Measurements not precise enough to distinguish between SS reservoirs
  - Xe required an exotic pre-solar component
- Nitrogen \( (\text{N}_2) / \text{CO} \) – \( 25\pm9 \times \) depletion from protosolar
- D/H – enriched; \textit{this comet} didn’t deliver Earth’s water
- Abundant super volatiles, don’t see solar nebula chemistry – Comet has remained cold \( \rightarrow \) interstellar signature?

\textbf{Clear primordial signature preserved. High precision isotope measurements will be the key to understanding what this means with respect to formation}
**Initial Observations** — Matched disk chemistry models

**Herschel measurement of 103P** — Revise disk chemistry models

**Rosetta** — “we have to re-think where oceans came from”

Comets formed over a wide range of distances; disk dynamics has scrambled the signature — one isotope isn’t enough to understand origins.
Rosetta (& other Mission) Results - Nucleus

- **Dust**
  - 1P – CHON, 81P – nebular mixing, 9P – nebular processing, hydration
  - 67P – organics, compounds needed to make sugars

- **Albedo**
  - Very low (0.02-0.06) – organic rich
  - Small variations (icy regions brighter, bluer)

- **Nucleus Density (kg/m³) – Low**
  - 67P: 532±7, 9P: 450; 19P: 180-300; 81P: 600-800

- **Porosity & Strength**
  - Strength
    - SL9: 3-270 Pa
    - Rosetta: Overhangs: 3-30 Pa; Hard substrate: kPa-MPa
  - Porosity
    - 9P: 88%
    - 67P: 75-85%

  *Dark, organic rich surfaces
  Low densities suggest highly porous → primitive
  Sizes consistent with collisional fragments*
Where Do We Stand after Rosetta?

**Rosetta is the most ambitious and productive comet mission to date**
- “The findings at 67P are similar to what we see on 81P and 9P, but at higher resolution”
- “Comets have heritage from their formation, but it is a really mixed reservoir”

**Findings**
- Interior structure relatively uniform
- Rich array of pre-biotic chemical species
- Comets may represent primordial planetesimals (density, porosity, low T ices)
- Comets form from a wide range of distances
- New insight into how comets work

**Questions**
- What is primordial and what is the effect of insolation? (How do comets work?)
- How and where do comets form?
- What role do comets play in bringing volatiles to the inner solar system – i.e. Earth?
LPC vs SPC

Discovery stats on LPCs

- Big surveys – routinely 3 yrs pre-perihelion, sometimes >6 yrs
- LSST brings this ~ 10 yrs

Differences between LPC and SPCs

- Only the LPCs are CO rich, both classes have CO$_2$
- Sublimation from CO or CO$_2$ from sub surface $\rightarrow$ large debris
- We are likely sampling a different part our Solar System’s primordial disk
PANSTARRS1 Survey discovers ~inactive LPC

- Faint tail, consistent with H₂O sublimation
- Spectrum consistent with S-type asteroids
- May have formed near snowline, ejected to Oort cloud early in SS history

We may be seeing fresh “preserved” Earth building material
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New Types of LPOs – The Manxes
10/19 – Discovered by PS1 $\rightarrow$ P10Ee5V

10/18 – Pre-discovery images found in PS1 data
  ◦ Follow up ESA ground station – data rejected, large e
  ◦ Classified as an Earth-orbit crossing asteroid

10/20 – Catalina Sky Survey data $\rightarrow$ short-period comet

10/22 – CFHT observations: orbit is hyperbolic: $e = 1.188$

10/24 – MPEC 2017-U181 posted a name: C/2017 U1

10/26 – MPEC 2017-U183 – named A/2017 U1
1837 – Passed inside 1000 au
Jan 18, 2017 – inside 5.2 au
Aug 10, 2017 – inside 1.0 au
Sep 9, 2017 – perihelion q = 0.255 au
Oct 11, 2017 – outside 1.0 au
Oct 14, 2017 – close Earth approach Δ = 0.162 au

Morning object Feb 1, 2017 mag 30
July 29, mag 25.0, r=1.28 au
Aug 12, mag 24.4, r=0.93 au → solar conj.
Oct 2, mag 23.7, r=0.79 au
Feb 3, 2018, mag 28.6, r=3.5 au → solar conj

May 3, 2018 outside 5.2 au
Jun 2022 – 30 au
Feb 2024 – 39 au
Dec 2025 – 50 au
Jul 2038 – 121 au
2196 – 1000 au
The Timeline

### Observations
- ~65 hrs on 4-10 m telescopes (1 wk)
- ~30 hrs on Spitzer, 9 HST orbits

### Results
- 53 papers arXiv, 37 published

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<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
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<tbody>
<tr>
<td>Oct 14</td>
<td>HST observations</td>
</tr>
<tr>
<td>Nov 13</td>
<td>Effective obs window</td>
</tr>
<tr>
<td>Dec 13</td>
<td></td>
</tr>
<tr>
<td>Jan 2</td>
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<table>
<thead>
<tr>
<th>Sun</th>
<th>Mon</th>
<th>Tue</th>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
<th>Sat</th>
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<tbody>
<tr>
<td>← Sep 9 Perihelion</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18-PS1 Precovery</td>
<td>19-PS1 Discovery</td>
<td>20-Astrometry</td>
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<tr>
<td>22- Hyperbolic orbit confirmed</td>
<td>23-DD prop VLT, GS; VLT Approve</td>
<td>24- GS prop Approved; MPEC orbit announce</td>
<td>25-VLT Obs, HST prop submit, UKIRT DD award; ★</td>
<td>26- VLT, GS obs; HST Approve; PR ★</td>
<td>27- GS, CFHT, UKIRT, Keck obs</td>
<td>28- UKIRT obs ★</td>
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<tr>
<td>29 – Hawaiian name</td>
<td>30- ★</td>
<td>31- Nature paper submit</td>
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<td>8-Resubmit paper</td>
<td>9</td>
<td>10-Paper in production</td>
<td>11</td>
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</table>

Our Nature paper was accepted Nov. 13 published online on Nov. 20
Results from the international campaign

**Brightness is related to size (and how reflective)**
- Average radius $102 \pm 4\,\text{m}$ (assuming albedo 0.04)

**Dust & Activity Limits**
- $< 1\,\text{kg}\,\mu\text{m}$-sized dust within 750 km from nucleus

**Surface composition**
- Red (23±3% / 100 nm) – “comet-like”

**Excited Rotation**
- $8.67 \pm 0.34\,\text{h}$ – precesses around L vector
- Long-lived – damping time $10^9$-$10^{10}\,\text{yr}$

**Astrometric orbit fit**
- Requires an acceleration away from sun $r^{-2}$

**Spitzer non-detection**
- Likely higher albedo, no CO, CO2

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Which Way Home and Gaia DR2

<table>
<thead>
<tr>
<th>Star</th>
<th>Type</th>
<th>Enc Dist</th>
<th>Enc vel</th>
<th>When</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIP 3757</td>
<td>M2.5 dwarf</td>
<td>0.6 pc</td>
<td>24.7 km/s</td>
<td>1.0 Myr</td>
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<tr>
<td>HD 292249</td>
<td>G5 dwarf</td>
<td>1.6 pc</td>
<td>10.7 km/s</td>
<td>3.8 Myr</td>
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<td>Home 3</td>
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<td>1.0 pc</td>
<td>14.3 km/s</td>
<td>6.3 Myr</td>
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<tr>
<td>Home 4</td>
<td></td>
<td>0.9 pc</td>
<td>18.0 km/s</td>
<td>1.2 Myr</td>
</tr>
</tbody>
</table>

**Which way home?**
- Non-grav asymptote to trace back the path
- Giant planet – difficult because of high ejection velocities
- Binary system more likely to match velocities
- None of the 4 systems have known exoplanets or are known binaries

**The ISO Population**
- Generated random (direction, v) ISO population
- Simulated the detection of synthetic ISOs using PS1, Mt. Lemmon, and Catalina sky surveys

## Science From Long Period Objects

<table>
<thead>
<tr>
<th><strong>Long Period Comets</strong></th>
<th><strong>Manxes</strong></th>
<th><strong>ISOs</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bulk physical properties</td>
<td>1. Surface composition</td>
<td>1. Basic physical properties</td>
</tr>
<tr>
<td>4. Dust composition</td>
<td></td>
<td>4. Isotopes</td>
</tr>
<tr>
<td>5. Noble gases</td>
<td></td>
<td>5. Are these the same as our SS planetesimals?</td>
</tr>
</tbody>
</table>

Items 1, 5 require in-situ

Going after some of the ices seen in Rosetta N2, O2 requires in-situ

Item 1 from the ground (want statistics)

Items 2,3 requires in situ

Items 1-3 – From Earth

Items 4-6 – in-situ

Detailed view of the surface – affects of travel through ISM
**Rapid growth of Jupiter’s Core**

- Distinct W and Mo isotopic composition between carbonaceous chondrites and ordinary chondrites → spatially separated
- Jupiter core after 1 Myr opens disk gap
- Groups remained separated for 3-4 Myr

**Gap in disk controls what arrives in inner solar system**

- Stops inward drift of particles from the outer disk
- As Jupiter grows it can scatter planetesimals as it grows and / or migrates in the disk

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