Comets Near and Not-That-Far: Review of cometary research in the Solar System

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- Nomenclature
- Dynamics & origins
- Physical Characteristics
- Mass-loss rates
- Exocomet

I will concentrate on observed characteristics and not talk much about theoretical modelling, laboratory studies...sorry!
What is a comet?

That is a comet!
What is a comet?

In the Solar System, a comet is normally a small ice-rich body whose volatiles are observed to be sublimating due to Solar irradiation.

How small? 
How ice-rich? 
Which volatiles?

Pyroxine
Refractory Organics
Water Ice

0.1 au 
1.0 au 
10.0 au 

Sublimation Distance
Comet Dynamical Classifications

Long Period Comets
(Oort Cloud Comets)

Sunskirting Comets

Sungrazing Comets

Main-Belt Comets

Short Period Comets
(Jupiter Family Comets)
Current Solar System Reservoirs: Trans-Neptunian Region

- Predicted from observed orbital distribution of SPCs (Fernandez 1980).
- ‘Cold Classical’ Kuiper belt forms a relatively stable kernel of objects at 42-46 au.
- Significant number of resonant objects trapped by Neptune migration.
- SPCs come from Scattered Disk (Bernstein et al., Astron. J. 128, 1364, 2004).
Current Solar System Reservoirs: Oort Cloud

- Comets scattered out of protoplanetary disk by planetary perturbations and migration.

- Objects with large aphelia $>10^4$ au have orbits circularised by galactic tides and stellar encounters.

- Oort cloud dominated by comets formed in Saturn-Neptune region, but contains small fraction of objects from Jupiter-Saturn region.

Dones et al., Comets II, 153 (2004)
Current Solar System Reservoirs: Oort Cloud

- End-to-End simulations show plausible structure of current TNO & Oort Cloud regions (Vokrouhlický et al., AJ 157, 181, 2019).
- Scattered disk extends to ~1000 au.
- Inner Oort Cloud at $10^3 - 10^4$ au inert and invisible.
- Active Oort Cloud extends from $10^4 - 10^5$ au (~0.5 pc).
- All comets a> 40,000 au are dynamically ‘new’ (Krolikowska and Dybczynski, MNRAS 462, 4634, 2017).
Current Solar System Reservoirs: Main-Belt Comets

- Objects with asteroidal orbits showing repeated dust emission at selected true anomalies each orbit.
- Paradigm is activation by small impacts revealing sub-surface ice.
- Ice must be within 15m of the surface for porous carbonaceous asteroids (Haghighipour et al., ApJ 855, 60, 2018).
- 8 confirmed MBCs, ~140 MBCs should exist down to D~500m (Hsieh et al. 2015).

Hsieh et al., Icarus 248, 289 (2015)
Comet Nuclei

1P/Halley (Giotto, Vega 1&2)
81P/Wild 2 (Stardust)
19P/Borrelly (Deep Space 1)
9P/Tempel 1 (Deep Impact, Stardust)
103P/Hartley 2 (EPOXI)
67P/Churyumov-Gerasimenko (Rosetta)
# Comet Nuclei

<table>
<thead>
<tr>
<th>Parameter</th>
<th>All comets</th>
<th>67P</th>
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<tbody>
<tr>
<td><strong>Radius</strong></td>
<td>27km (29P/SW 1; Stansberry et al. 2004)</td>
<td>~1.7 km (Sierks et al. 2015)</td>
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<td></td>
<td>0.20km (47P/Kushida-Muramatsu; Lamy et al. 2004)</td>
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<tr>
<td><strong>Density</strong></td>
<td>&lt;~0.6 gm/cm³ (Rotation rates; Kokotanekova et al. 2019)</td>
<td>0.533 gm/cm³ (Pätzold et al. 2016)</td>
</tr>
<tr>
<td><strong>Geometric Albedo</strong></td>
<td>~0.04 (Lamy et al. 2004)</td>
<td>0.062 (Ciarniello et al. 2015)</td>
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<tr>
<td><strong>Thermal Inertia</strong></td>
<td>0 – 60 J K⁻¹ m⁻² s⁻¹/² (Groussin et al. 2018)</td>
<td>10 – 170 J K⁻¹ m⁻² s⁻¹/² (Leyrat et al. 2015)</td>
</tr>
<tr>
<td><strong>Tensile Strength</strong></td>
<td>5 Pa (SL9; Asphaug and Benz 1996)</td>
<td>3 – 15 Pa (Groussin et al. 2015)</td>
</tr>
<tr>
<td></td>
<td>1–100 Pa (Rotation rates; Toth &amp; Lisse 2006)</td>
<td>&gt;0.02 – 1.02 Pa (Attree et al. 2018)</td>
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Cometary outgassing and evolution

Comets primarily lose mass from H2O sublimation at <4 AU.

Process produces body with low-albedo carbon-rich “dusty” surface.

End states may be:
1. Complete vapourisation/fragmentation.
2. Desiccation leading to inert body.

Rate of evolution depends on orbital parameters.
Cometary outgassing and evolution

Erosion on 67P

Comet 73P
Comet Size Distribution

\[ \frac{dN(R)}{dR} \propto R^{-q} \]

\[ N( > R) \propto R^\beta \propto R^{1-q} \]

- A population in collisional equilibrium has $q=3.5$
- Studies have found $q=2.9$ to $3.5$
- Lack of small comets at $R<1\text{km}$.
- Recent suggestion of a very shallow LPC size distribution.

Fernandez et al., Icarus 226, 1138 (2013)

Bauer et al., AJ 154, 53 (2017)
Current TNO size distributions come from Earth-based observations down to D~30km and the cratering record on Charon from New Horizons. (Greenstreet et al., ApJL 872, L5, 2019)

- Size distribution at R=1–50km consistent with SPC measurements.
- Shallow size distribution at R<1km would be primordial and not due to erosion/disruption of SPCs.
Mass-Loss Rates - Gas

See talks by Bodewits (today) and Opitom (tomorrow)

- Mass-loss rates for $>10^2$ of comets obtained from UV/optical/NIR/sub-mm spectroscopy and imaging.

- Within ~3 au, water-driven sublimation studied via UV, NIR emission. May be inferred from minor species optical emission, or correlation with brightness (if nothing else).

- At >3au, more volatile species (CO, CO$_2$) can now be observed in NIR (WISE, Spitzer)

- Mass-loss rates (production rates) range from $10^{31}$ to $10^{26}$ molecules/sec (~$10^5$ to 1 kg/sec).

Biver et al., EMP 90, 5 (2002)
• Detection more sensitive than spectroscopy, but harder to quantify. e.g. ~0.02 kg/s for D/1819 W1 (Jewitt 2006).

• Simple dust/gas mass ratios implied from observations range from >5 (Hale-Bopp) to 0.02 (2P/Encke), with normal ratios ~0.1-1 (Spinrad et al. 1989; Jewitt et al. 1998).

• Remote interpretation depends on assumptions of size distribution and albedo.

• Prevalent fragmentation of dust particles at all sizes.

Bulk Compositions

Sub-mm Gas Compositions
Mumma & Charney, ARAA 49, 471 (2011)

Spacecraft Dust Compositions
Lavasseur-Regourd et al, SSR 214, 64 (2018)
Exocomet Analogues - Bright/Great Comets


- Most have high mass-loss rates, allowing measurements/discoveries with current generation of astronomical equipment (i.e. gas release from dust grains).

- All are LPC/Oort-Cloud comets. Current/new sky surveys (Pan-STARRS/Catalina/LSST) allow discovery up to 5 years before perihelion.

The sodium tail of comet Hale-Bopp
Exocomet Analogues - Sungrazing/skirting Comets

(See poster by Knight).

- Great comets show metal emission lines of Na I, Ca II and Fe I (e.g. Dufay et al., ApJ 142, 1698, 1965).

- All sungrazing comets show signs of fragmentation/splitting/disintegration such as ISON (e.g. Keane et al, ApJ 831, 207, 2016).

- Kreutz sungrazing family due to fragmentation of large (Great?) comet nucleus.

- Sunskirting comets may survive.

- 322P/SOHO has photometric properties consistent with an end-state Near-Earth Asteroid.

Knight et al., ApJL 823, L6 (2016)
Summary

- The current observable comet population is a product of 4.6 billion years of dynamical evolution.
- Observed comet nuclei have radii of $0.2 < R < 17\text{ km}$, low densities and strength.
- Lack of nuclei with radii $< 1\text{ km}$, may be primordial.
- Largest mass loss rates measured $\sim 10^5 \text{ kg/sec}$, lower limit is observationally set.
- Sungrazing comets will have everything sublimate, but much will still be light elements (unless it's an asteroid).