COMPOSITIONS OF EXOCOMETS: A PROTOPLANETARY DISK PERSPECTIVE

Ilse Cleeves
Assistant Professor, University of Virginia
Lorentz Center Exocomets Workshop
May 13, 2019
A "TYPICAL" EXOCOMET?

What do we expect the typical composition of an exocomet to look like?

Will they be "Solar System"-like or something entirely different?
Large fraction of cometary dust is organic. Volatiles dominated by water, then CO, CO$_2$, maybe O$_2$??
Solar system comets contain much of the available volatiles at formation.
Chemistry of (exo-)comets set by at least two stages:

1) Formation: Initial compositions established in the protoplanetary disk phase (timeline uncertain, but probably mostly assembled < 10 Myr). What reservoirs?

2) Post disk: Byrs of irradiation by cosmic rays (e.g., Oort Cloud), an active young star like an M-dwarf (particles, UV), or even post-main sequence evolution? (e.g., Siyi Yu's talk)

The latter is important to consider when we compare data from different exocomet populations
ASIDE: EXOCOMET POPULATIONS

More possible definitions (populations?):

1) Comets in bound orbits around other stars

2) Free-floating comets that encounter the Solar System
1) Bound exocomets: Really young stuff – debris belts *(Luca)* and old-ish stuff - white dwarf pollution, 100s Myrs *(Siyi)*

2) Free-floating comets – LSST *(Stefanie?)*. On average going to be fairly old...
1) Bound exocomets: Really young stuff – debris belts (Luca) and old-ish stuff - white dwarf pollution, 100s Myrs (Siyi)

2) Free-floating comets – LSST (Stefanie?). On average going to be fairly old
CHEMISTRY IMPARTED FROM DISKS

Chemistry of (exo-)comets set by at least two stages:

1) Formation: Initial compositions established in the protoplanetary disk phase (timeline uncertain, but probably mostly assembled < 10 Myr). What reservoirs?

2) Post disk: Byrs of irradiation by cosmic rays (e.g., Oort Cloud), an active young star like an M-dwarf (particles, UV), or even post-main sequence evolution? (e.g., Siyi Yu's talk)

The latter is important to consider when we compare data from different exocomet populations.
The protoplanetary disk's compositions initially set by the parent molecular cloud, some amount of reprocessing as the central star(s) form.

- Cloud: ~10s of Myr
- Protostar: ~100s of kyr
- Protoplanetary Disk: ~1-20 Myr
- Debris disk, planetary system: > Myr - Gyr
PRE-COMET (DISK) COMPOSITION
Dust opacity sets the thermal structure and shields the disk from stellar radiation, such as UV and X-rays.
DISK GAS COMPOSITION

"Snow Line"
Implications: Compositions of the rocky/icy planetesimals set by their formation locations

This is also an important factor for core-accretion driven planet formation (Pollack+96)
SNOW LINES AND PLANET(ESIMALS)

Note, being below a certain snow line temperature doesn't guarantee that the ice exists.

Similar to "Habitable Zone" does not guarantee inhabited. It's where that ice could exist in principle.
To first order, for a "normal" interstellar composition:

"Paint on" interstellar ice abundances:

- $\frac{H_2O}{H} \sim 10^{-4}$
- $\frac{CO_2}{H} \sim 3 \times 10^{-5}$
- $\frac{CO}{H} \sim 1.3 \times 10^{-4}$

(e.g. Boogert + 2015 and Ripple + 2013 for CO)

Snow line locations depend on condensation temperatures.
Baseline expectation: freeze-out changes the chemical environment from which comets, asteroids, planets accrete.

Formation distance changes relative amount of carbon to oxygen in your comet.

Assuming interstellar composition (Öberg, Murray-Clay and Bergin 2011)
SNOW LINES AND PLANETS

Also makes a prediction for the atmospheric composition of gas-giant planets, testable with JWST?

Assuming interstellar composition (Öberg, Murray-Clay and Bergin 2011)
Nice picture, but some caveats...

Disks are expected to be actively chemically evolving over ~0.1 to Myr+ time scales

- Winds (removal of light species)
- Gas transport and mixing (dredge up ices from the midplane, or send UV processed material downward)
- Galactic chemical evolution...?
- Ice transport on the surfaces of growing/fragmenting dust grains
- What are "interstellar abundances?"
Nice picture, but some caveats...
Disks are actively chemically evolving over ~0.1 to Myr+ time scales

- Winds (removal of light species)
- Gas transport and mixing (dredge up ices from the midplane, or send UV processed material downward)
- Galactic chemical evolution...?
- Ice transport on the surfaces of growing/fragmenting dust grains

So what are the typical disk compositions, and by proxy, their cometary compositions?

We need measurements!
**OBSERVATIONAL WINDOWS**

- **Scattered light, optical NIR**
  - Hot molecular emission of CO, H$_2$O, HCN, CO$_2$, CH$_4$, C$_2$H$_2$ and more (NIR)

- **Sub-mm/mm rotational lines**
  - CO, HCN, CS, H$_2$CO, etc.

- **Warm atomic/molecular lines (FIR)** [OI], H$_2$O, CO, OH, HD

- **IR - X-rays!**

- **NIR cont.**

- **FIR cont.**

- **cm/mm cont.**

- **10 K**

- **100s-1000 K**

- **Near infrared**
  - 100s-1000 K
  - ~10$^{12}$ cm$^{-3}$

- **Mid-infrared**
  - ~10$^6$ cm$^{-3}$

- **Far-infrared**
  - ~10$^{12}$ cm$^{-3}$
IMAGING DISK DUST (PRE-COMET BELTS?) WITH ALMA

Credit: ESO, Marinkovic

DSHARP ALMA Large Program
PI: Sean Andrews
MIDPLANE VOLATILES HARDER TO OBSERVE

Scattered light, optical NIR
sub-mm/mm CO, HCN, CS, H$_2$CO, etc.

hot molecular emission of CO, H$_2$O, HCN, CO$_2$, CH$_4$, C$_2$H$_2$ and more (NIR)

Zone of freeze-out and poor excitation :

10 K  100s-1000 K

warm atomic/molecular lines (FIR) [OI], H$_2$O, CO, OH, HD

~10$^{12}$ cm$^{-3}$ ~10$^6$ cm$^{-3}$
DISK GAS OBSERVATIONS WITH ALMA

And even some we expected to be bright were much fainter than expected.
We are limited in our list of observable species. We cannot see total N, C, O, etc. Chemical models (non-equilibrium) are necessary to "back out" bulk gas compositions from the unobservable species, e.g. N$_2$. 
Moreover, with gas-phase observations, we observe just the "tip of the iceberg."
For now we can infer midplane abundances using models that reproduce the surface gas, but much uncertainty.

But future observations with JWST will (hopefully) help us study the icy bulk!
Aikawa+2012 used the AKARI satellite to study ice toward edge-on YSOs (some more disky than others).

<table>
<thead>
<tr>
<th>Absorption peak [µm]</th>
<th>H$_2$O</th>
<th>HDO</th>
<th>$^{12}$CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band strength $10^{-17}$ cm molecule$^{-1}$</td>
<td>3.05</td>
<td>4.07</td>
<td>4.27</td>
</tr>
<tr>
<td>Column density $10^{17}$ [cm$^{-2}$]</td>
<td>20</td>
<td>4.3</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Even here most of the ice is associated with foreground cloud... Exception being the 2MASS source, which has only 2 mag foreground.
EXAMPLE: DISK H$_2$O WITH HERSCHEL

- TW Hya, $\sim$40-80x low in H$_2$O vapor (Hogerheijde+2010, Bergin+2013).
- DM Tau, $\leq$50x (Bergin et al. 2010 + rev. mass).
- See also Herschel H$_2$O survey (Du et al. 2017).
Emission significantly (1 - 2 orders of magnitude) weaker than Fogel+2011 models predicted.

The mystery of missing water ice?

• Is water gone, or is the overall mass of gas gone?
• Or are the physical structures and models used to interpret the data faulty? (Kamp+2013)
• Could be that the ices are "coated" with something more refractory, and unable to desorb volatiles?
• Could it also be that the disk surface dust is just "dry"?
CO-EVOLVING DUST & CHEMISTRY

Vertical Settling

Icy

Bare

Observable surface

Radial Drift

e.g., Krijt+2016, Stammler+2017
"LARGE" SOLIDS ARE COMPACT COMPARED TO GAS

The large ice-coated grains are decoupling dynamically from the gas (e.g., Weidenschilling 1977). What are the implications for disk composition?
WHAT DETERMINES DISK/COMETARY COMPOSITION?

Many open questions…

❖ What disk composition is normal? Still small number statistics…
❖ How much was preserved from the molecular cloud? Isotope ratios in disks may help, but we still have to overcome surface vs. midplane
❖ Cloud-to-cloud variations? Differing amounts of C, N, O, etc?
❖ Role of stellar environment, binarity?
❖ Timescale of comet/planet formation? (Planet formation seems to be happening earlier than previously assumed, e.g., HL Tau)
❖ And more!

Still TBD, a unifying theory to explain these abundance patterns in disks, and they need to be tested in a much larger sample. Most efforts are currently on a handful of bright disks.
Questions for you...

❖ What are the observed spreads in cometary abundances in the solar system?

❖ From the disk perspective, if planet formation happens early, we should have pretty consistent abundances for comets formed interior (Oort cloud?) and exterior (Kuiper Belt/JFCs) to the CO snow line.

❖ How consistent are they?
EXOCOMETS AMONG US?

- Forbes & Loeb 2018

- ~45 solar system comets with orbital properties that could be consistent with exocomets
  - If they are, their compositions should be unlike ours
SUMMARY

❖ Comet composition should(?) be set initially by processes in the protoplanetary parent disk, followed by any post formation chemical evolution (radiolysis?)

❖ Unclear currently if all disks around similar types of stars result in the same initial comet compositions, or how much variation there is. ALMA will help.

❖ Suggestive initial results from disk gas observations consistent with grain growth transporting volatile ice-coatings from the observable surface. JWST will help test this (midplane ice over-density?), but still unclear where the ices actually go radially (onto the star, stuck in rings???)

❖ ALMA seems to tell us planets (or rings) form early, in 100s kyrs! Still deeply embedded in envelope. Not much time for midplane disk chemistry to occur.

❖ Implication would be chemistry set by the cloud and not matter so much on the host star (besides in setting snow line distances). Would really simplify the picture?