Comet Surface Sample Return with a New Frontiers Mission

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Why Comets?

- Among the most fundamental questions in planetary science are:
  - What were the starting materials of the Solar System?
  - How did these materials come together to form the Solar System bodies that we see today?
  - How were organics and water – necessities for life – delivered to the early Earth?

- The best way to address these questions is with <u>returned samples</u> from the most primitive Solar System bodies possible.

- The most primitive Solar System bodies from which sample return is practical are Jupiter-family comets.

Why New Frontiers?

- Flagship missions are rare, sometimes once-per-decade occurrences. In the coming decade, continuation of Mars Sample Return is already poised to consume Flagship-class resources.
- New Frontiers missions are large enough to do groundbreaking science, but small enough to happen more often than once per decade.
- New Frontiers missions are competitively selected and PI-led, yielding powerful selective forces that maximize science return per dollar.

Jupiter Family Comet Sample Science

Interstellar Medium to Protoplanetary Disk Transition	Protoplanetary Disk	Geological and Dynamical Evolution

Specific Testable Hypotheses

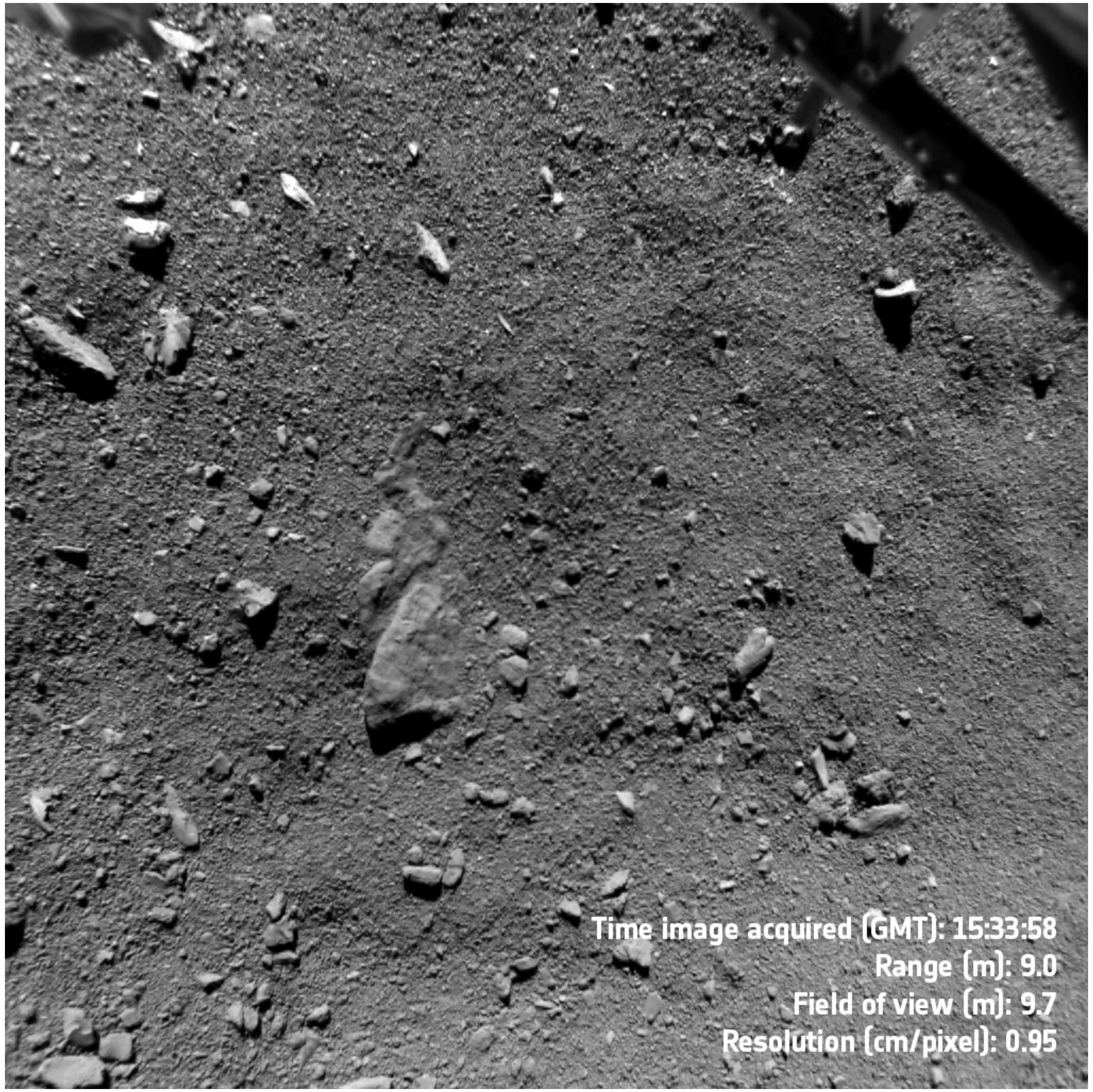
- JFCs contains greater abundance and diversity of circumstellar grains and molecules than asteroids sampled by meteorites.
- JFCs contain mixtures of volatile elements, ices and organic molecules that were trapped during formation of grain mantles in the ISM or outer protoplanetary disk.
- JFCs contain refractory organic compounds that formed in cold molecular clouds and the outermost protosolar disk.
- JFC H_2O and CO retain evidence of O isotopic fractionation from interstellar photochemical self-shielding.

- JFCs contain high-temperature materials, such as chondrules, CAIs, and silicates that formed across the Solar System.
- JFCs contain complex refractory organics from the high temperature, inner regions of the protoplanetary disk.
- JFCs are primordial fossils that retain largely unaltered signatures from the protoplanetary disk epoch.

- Some JFCs are collisional remnants of larger planetesimals that underwent internal heating, partial differentiation, sublimation and recondensation, outgassing, and hydrothermal alteration.
- JFCs delivered a substantial fraction of water to Earth.
- JFCs contain prebiotic organic compounds that may have contributed to the origin of life on Earth.
- JFC surface materials record processes of tidal disruption and reaccumulation, resurfacing, and mass wasting.

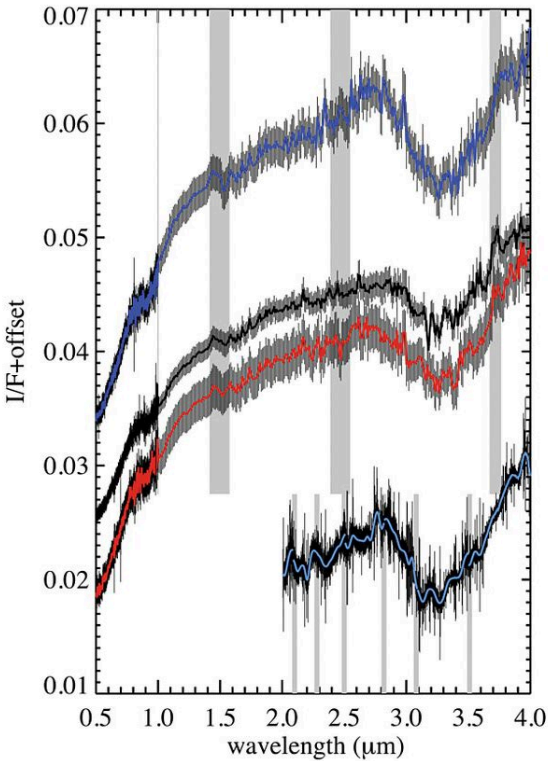
Interstellar Medium to Protoplanetary Disk Transition	
JFCs contains greater abundance and diversity of circumstellar grains and molecules than asteroids sampled by meteorites.	Crystallography, elemental and isotopic compositions of mineral and organic grains; molecule-specific isotopic ratios; noble gases
JFCs contain mixtures of volatile elements, ices and organic molecules that were trapped during formation of grain mantles in the ISM or outer protoplanetary disk.	Isotopic and chemical compositions of volatile elements, organics, and noble gases (GCS). Isotopic compositions of noble gases in non-volatile samples
JFCs contain refractory organic compounds that formed in cold molecular clouds and the outermost protosolar disk.	Isotopic and chemical compositions of refractory organic molecules & carbonaceous grains; Isotopic, chemical and structural properties of macromolecular organic material.
JFC H_2O and CO retain evidence of O isotopic fractionation from interstellar photochemical self-shielding.	Oxygen isotopic compositions of H_2O and CO
Protoplanetary Disk	
JFCs contain high-temperature materials, such as chondrules, CAIs, and silicates that formed across the Solar System.	Mineralogy, chemistry, and isotopic compositions of chondrules, CAIs, metals, sulfides, crystalline and amorphous silicates
JFCs contain complex refractory organics from the high temperature, inner regions of the protoplanetary disk.	Textures, chemistry, and isotopic compositions of refractory organics
JFCs are primordial fossils that retain largely unaltered signatures from the protoplanetary disk epoch.	Textures, mineralogy, crystallography, and isotopic compositions of grains and organics. H and O isotopic ratios of hydrated minerals and H_2O
Geological and Dynamical Evolution	
Some JFCs are collisional remnants of larger planetesimals that underwent internal heating, partial differentiation, sublimation and recondensation, outgassing, and hydrothermal alteration.	Crystallography, petrology, mineral textures, labile element abundances, mineralogy, trace element profiles, H and O isotopic measurements of hydrated minerals and H_2O
JFCs delivered a substantial fraction of water to Earth.	H and O isotopic measurements of H_2O, H isotopic measurements of organics
JFCs contain prebiotic organic compounds that may have contributed to the origin of life on Earth.	Volatile and non-volatile organic molecule abundances, isotopic ratios, and chirality, mineralogical constraints for aqueous alteration
JFC surface materials record processes of tidal disruption and reaccumulation, resurfacing, and mass wasting.	Space weathering rims, mineral microstructures, IR spectra, noble gas abundances and isotopes

Comet Surface Materials

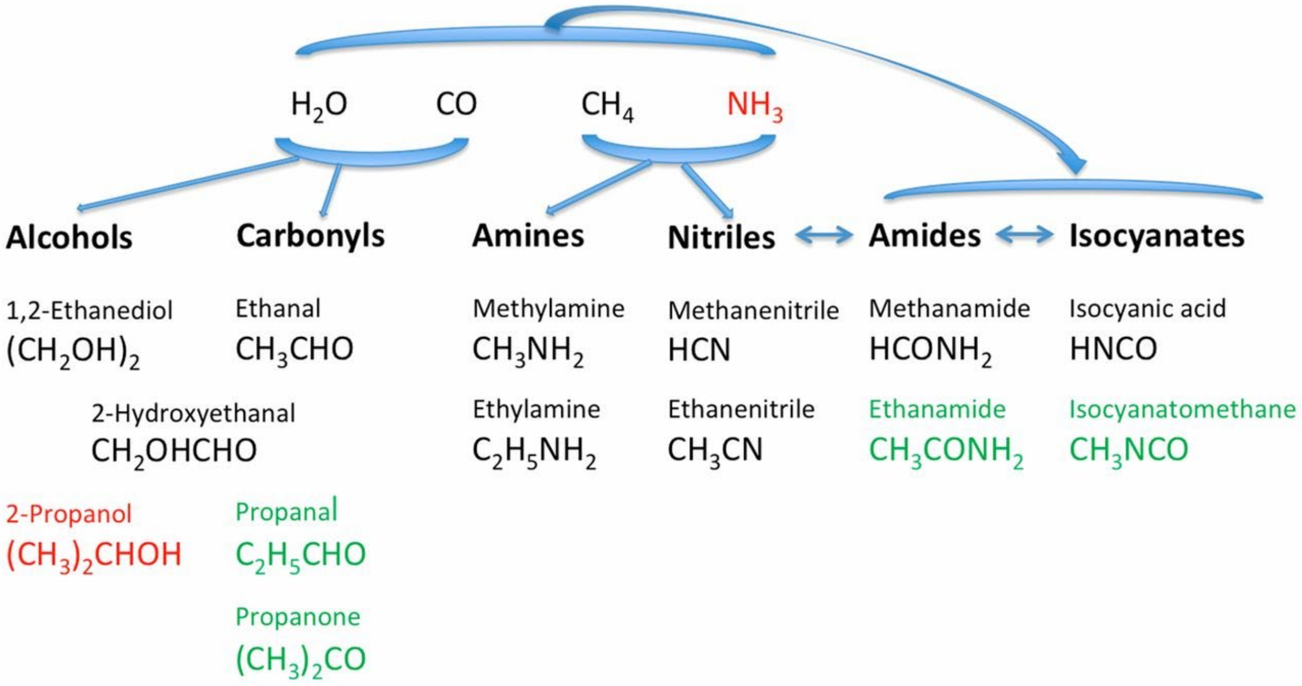


- The surfaces of comet nuclei include materials that are granular, disaggregated, and probably straightforward to sample.
- These materials are fallback debris sourced from many locations on the nucleus, and therefore sample the nucleus's diversity.
- They are rich in organics and ices.

Rich in Organics

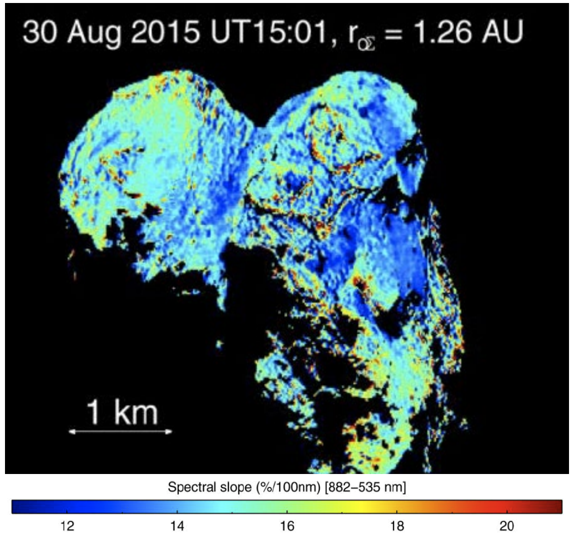


(Capaccioni *et al.*, 2015)

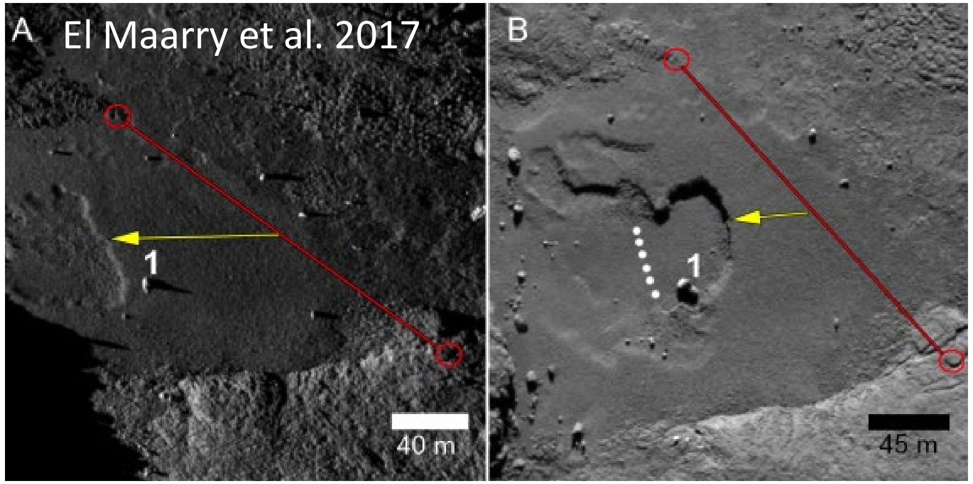


A wide range of organics was identified by the Philae COSAC instrument in the smooth, disaggregated terrain (above, Goesmann *et al.* 2015). Rosetta ROSINA also detected volatile organics in the coma (LeRoy et al., 2015).

Rich in Ice



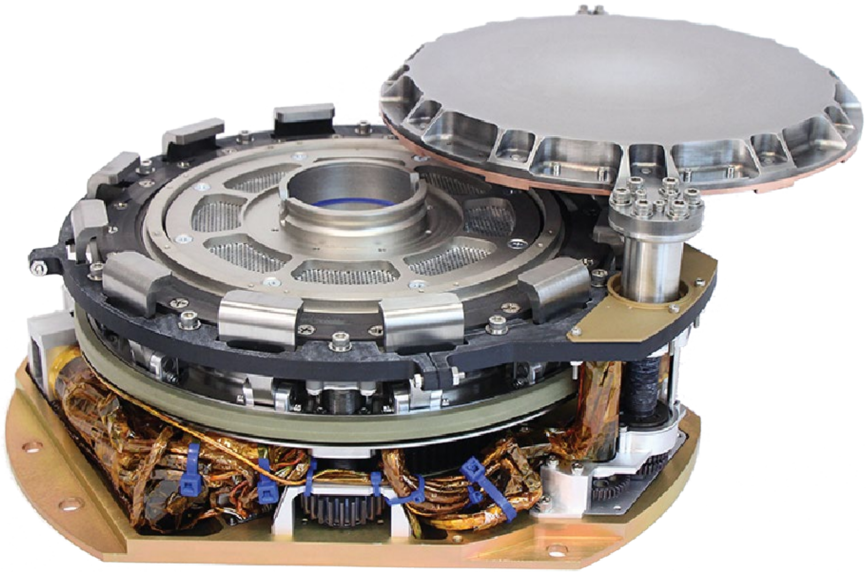
Major change of smooth terrain color after equinox indicates ice just below the surface (Fornasier *et al.* 2016, Ciarniello *et al*. 2016)

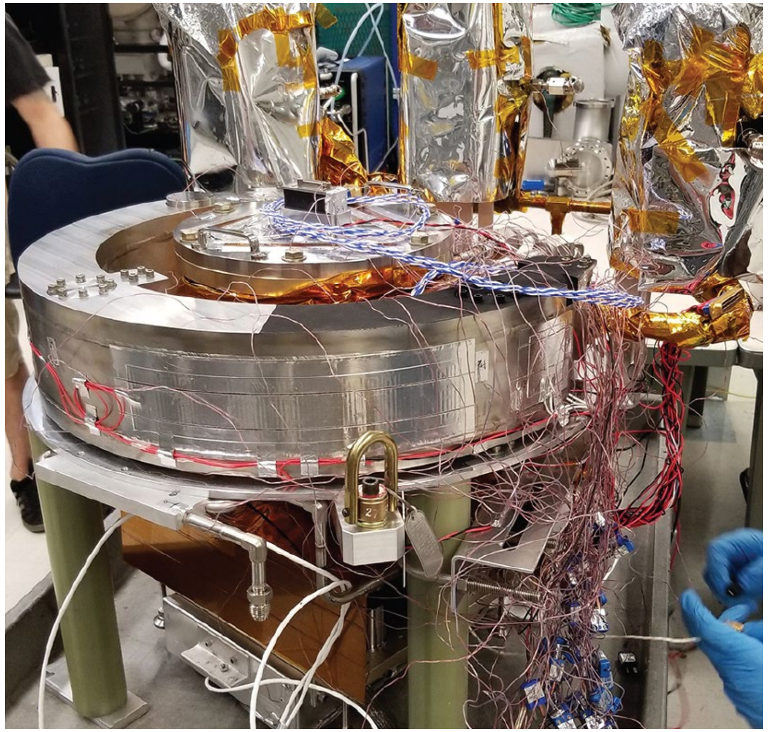


Rapid scarp retreat in smooth terrain implies a large reservoir of water ice (3-5% by mass) just below the diurnal skin depth (~3 cm) (El Maary et al. 2017, Groussin et al. 2015, Hu et al. 2017, Birch et al. 2019)

"Ice is abundant just beneath the surface on the whole nucleus,"
"The smooth areas commonly thought to be covered with material that fell back on the surface must be water-ice rich." (Fornasier *et al.* 2016)

Sample Collection and Preservation





Mature techniques exist for collecting comet surface samples, and for preserving organics and volatiles that they contain.

Comet Surface Sample Return in Past Decadals

- First Planetary Decadal Survey (*New Frontiers in the Solar System*):
  - Highest priority primitive bodies mission was *Kuiper Belt-Pluto Explorer*. This became *New Horizons*.
  - Second highest priority primitive bodies mission was *Comet Surface Sample Return*. Multiple missions proposed for New Frontiers 1-3. None selected, largely due to cost and risk issues.
- Second Planetary Decadal Survey (*Visions and Voyages*):
  - Highest priority primitive bodies mission was *Comet Surface Sample Return*.
  - Three missions proposed for New Frontiers 4. All were Category 2 or above. One was funded for a Phase A study. Ultimately *Dragonfly* was selected.

How has CSSR Become Achievable Under New Frontiers Cost Constraints?

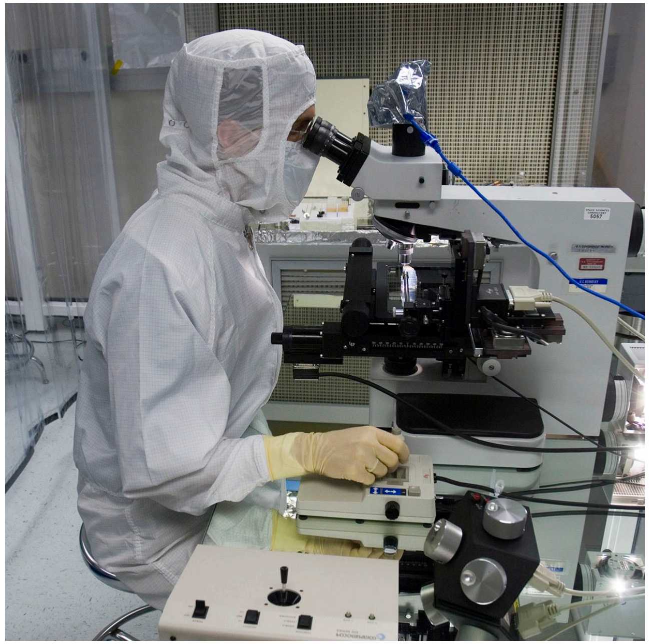
- Data from Rosetta have enabled design of effective sample acquisition and containment systems.

- Experience from OSIRIS-REx, Hayabusa, and Hayabusa2 has enabled safe proximity and sampling operations near small, irregular bodies.

- Competitive pressures have driven proposal teams to sharpen their science focus and find cost-effective solutions.

Comet nucleus samples hold keys to understanding Solar System origins and how ingredients for life came to Earth.

Comet surface materials that are easily sampled are rich in accessible organics and ices.



A Comet Surface Sample Return mission's payload is effectively the combined scientific power of all the world's laboratories for decades to come.

Comet Surface Sample Return is achievable within the cost constraints of the New Frontiers Program.