Getting Close to Long-Period Objects

Lessons Learned from Past Missions

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Outline

- Reasons to get close to long period objects
- How dust informs us about the Solar System
- Comet 1P/Halley
  - Multiple missions to explore comet 1P/Halley
  - Stardust mission to comet 81P/Wild 2, for comparison
- Challenges for flyby missions
- *In situ* dust instrumentation
- Comet dust environments
- *In situ* dust science
- Considerations for future missions

Why try to get close?

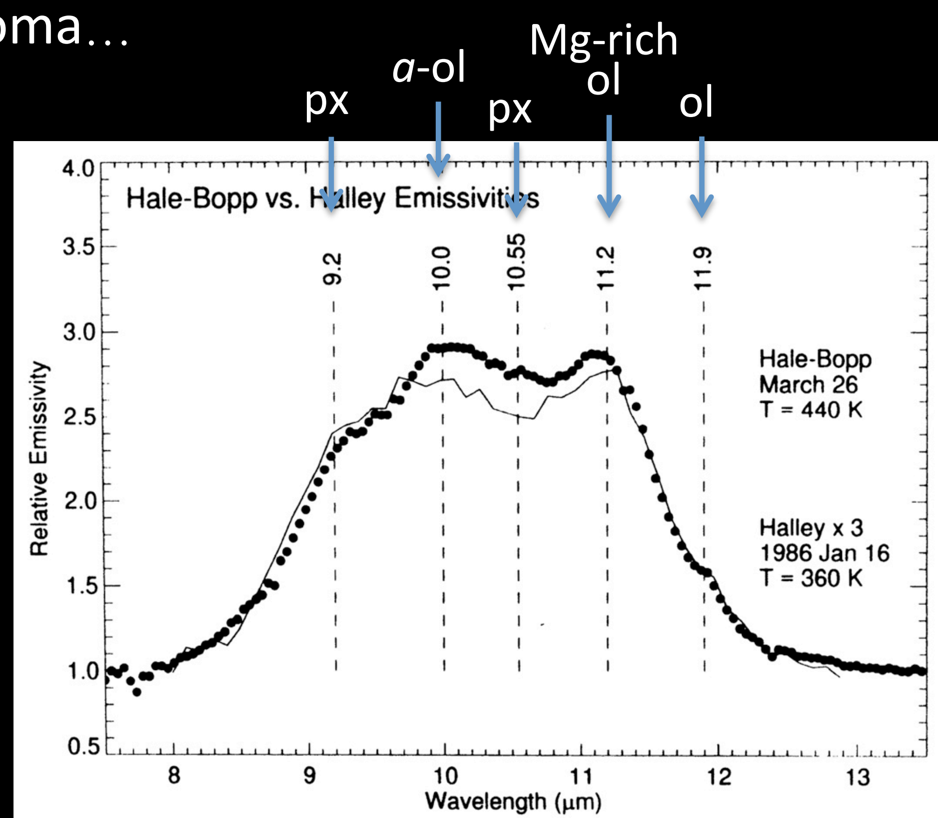
Why not stick to remote observations?

Albedo, activity, molecules in coma…

Mid-IR spectroscopy provides info on mineralogy of dust

- Requires modeling with reference spectra
- Covers a limited particle size range in optically thin comas
- Provides bulk information; no particle-level info

8-13 µm: silicate features



Hanner et al. Earth Moon Planets 1999

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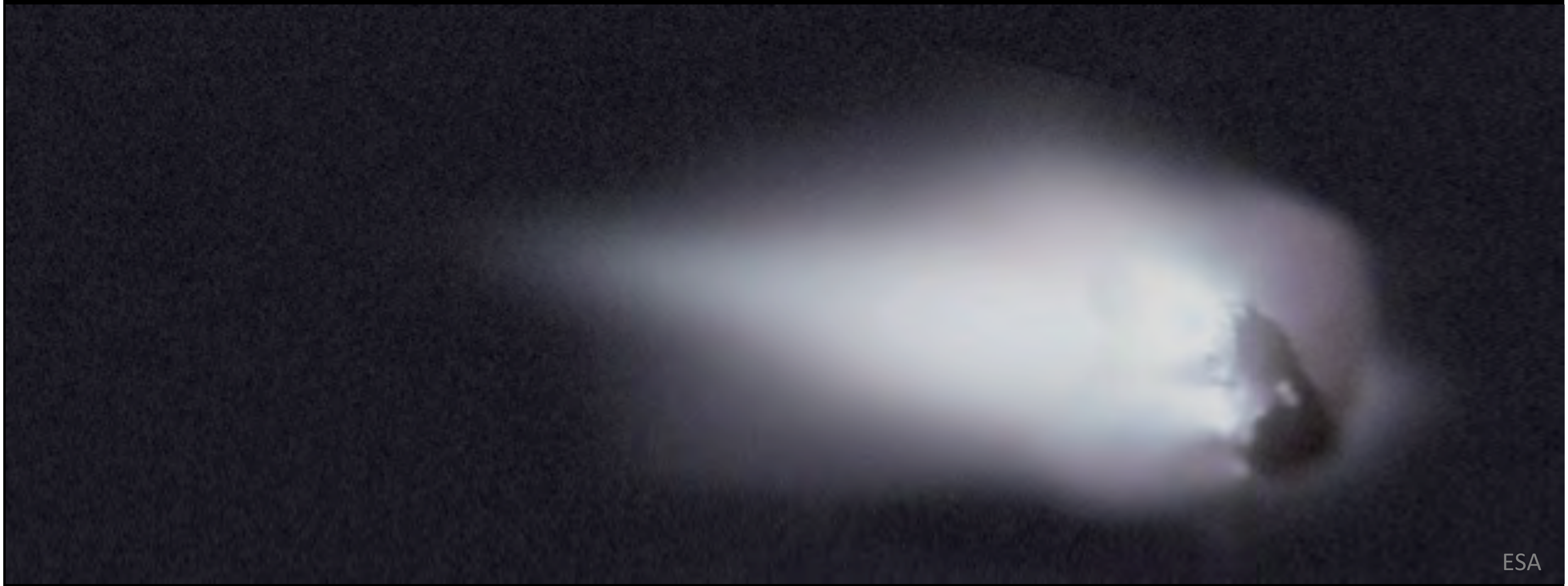

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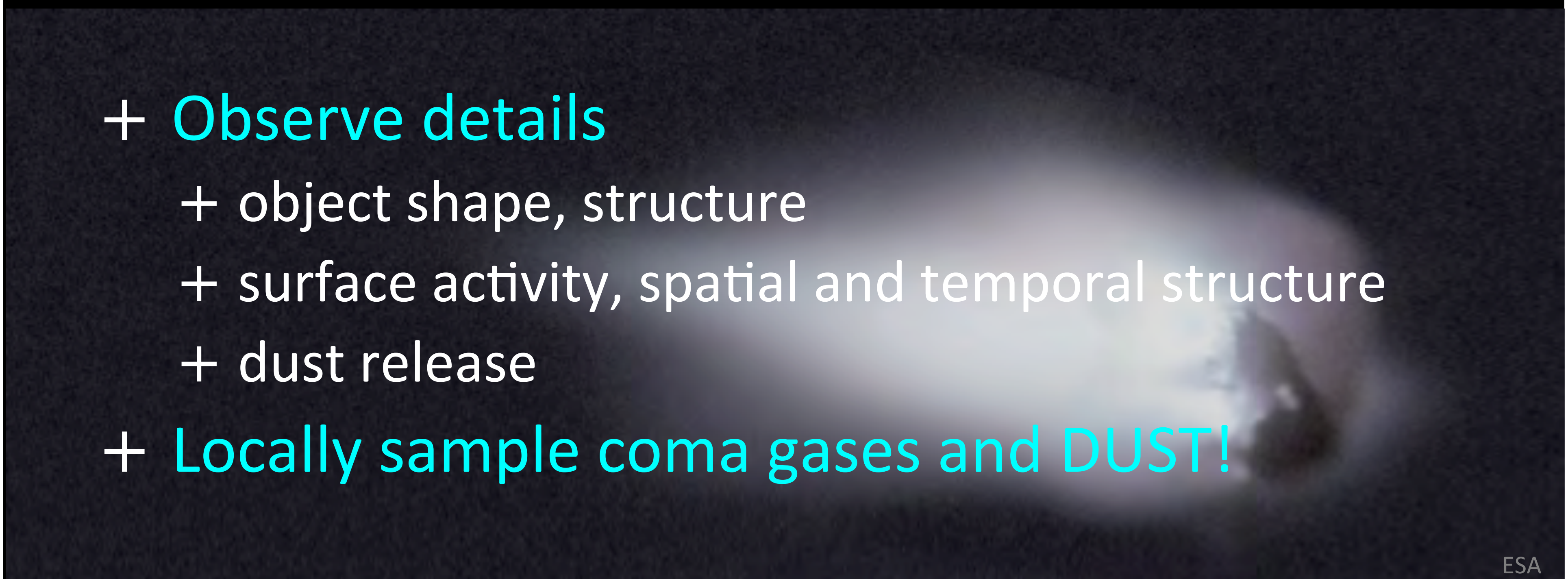


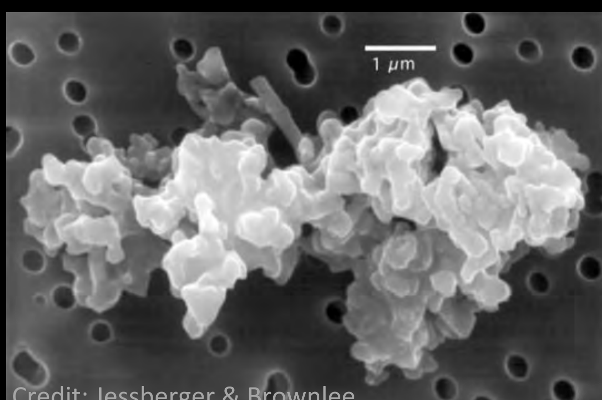
+ Observe details
  + object shape, structure
  + surface activity, spatial and temporal structure
  + dust release
+ Locally sample coma gases and DUST!

ESA

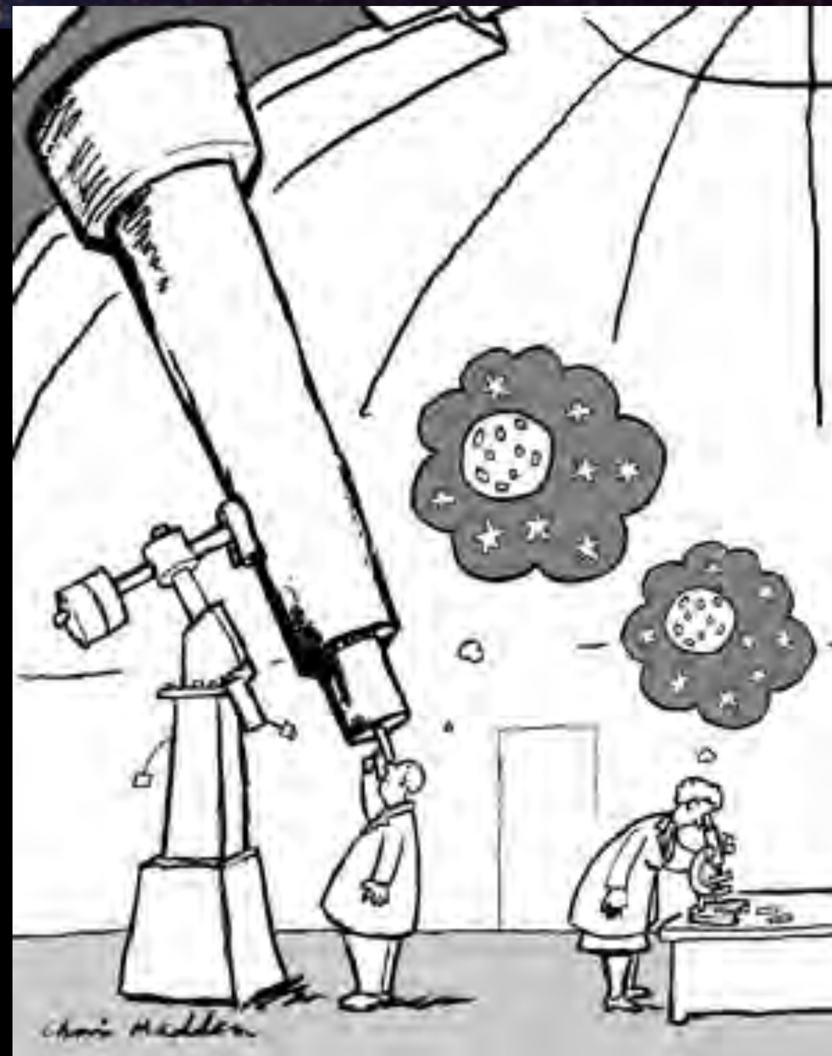
"To see a World in a Grain of Sand..."

Why study ***DUST*** ?
What can it tell us?

Interplanetary dust particles (IDPs) sample parent bodies not represented in our terrestrial collections.

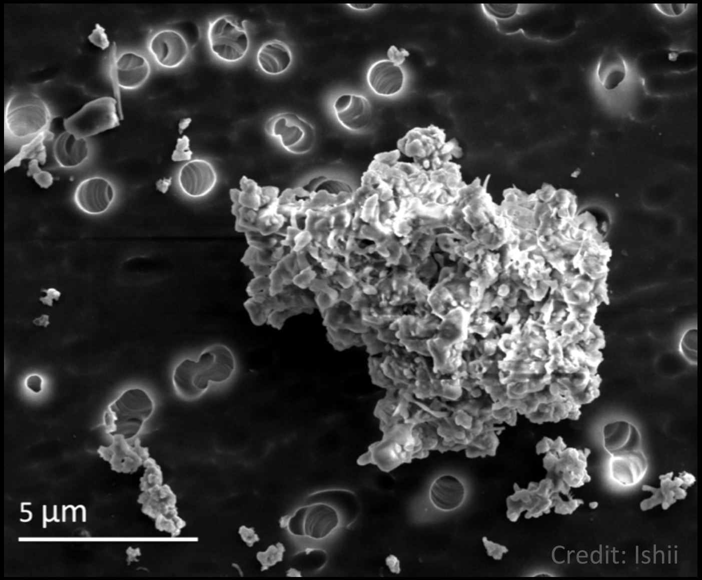


Credit: Jessberger & Brownlee



"To see a World in a Grain of Sand..."

- Dust helps us understand
  - the makeup of the least altered materials from our solar system's birth
    - components, including interstellar dust
    - chemistry, organic-inorganic fractions
    - dust/gas ratios
  - variability in small bodies
  - how small bodies evolve
    - physical, chemical, structural alteration mechanisms

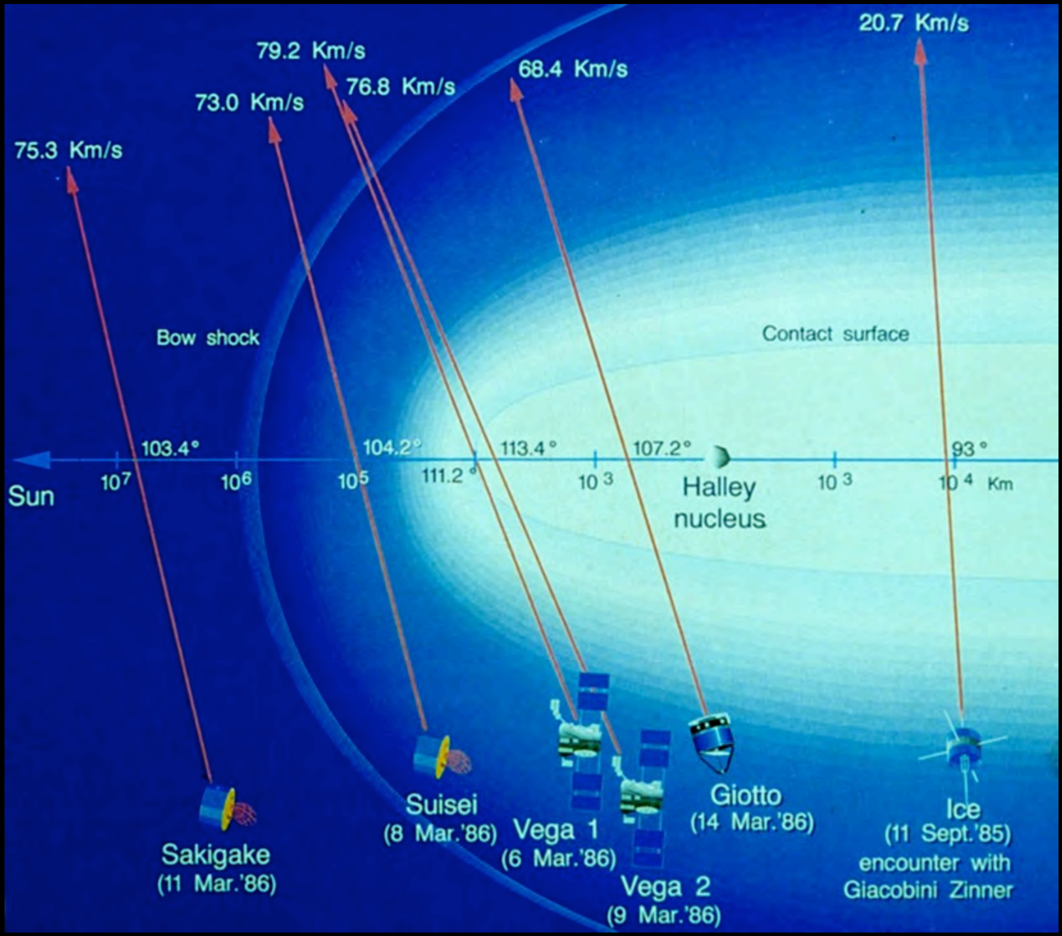


Dust informs us about how solar system materials have mixed, differentiated and evolved.

- Dust may be *only* means of sampling solid components of a long-period object.

Comet 1P/Halley

- 1P/Halley is the longest period object visited by space missions to date.
- In 1986, spacecraft from multiple space agencies encountered comet 1P/Halley.

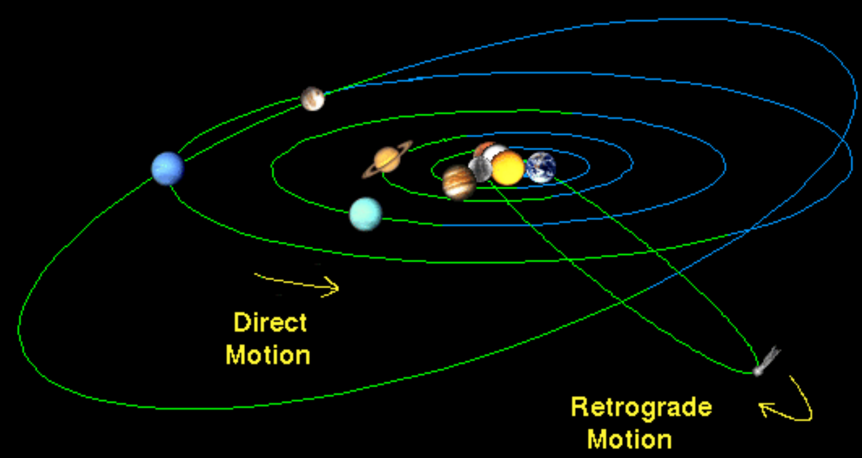


Geiss & Altweg, Space Sci…ESASP 1998

Comet 1P/Halley

- 1P/Halley: Short-period (<200 yr) Halley-family comet
- Orbital period ~74-79 years, 0.6 – 35 AU
- Likely a former Oort cloud object perturbed into an inner solar system orbit
- Inclination 162°(retrograde orbit inclined 18°)
- Highly eccentric orbit: 0.967
  (1 is parabolic)

U. Rochester

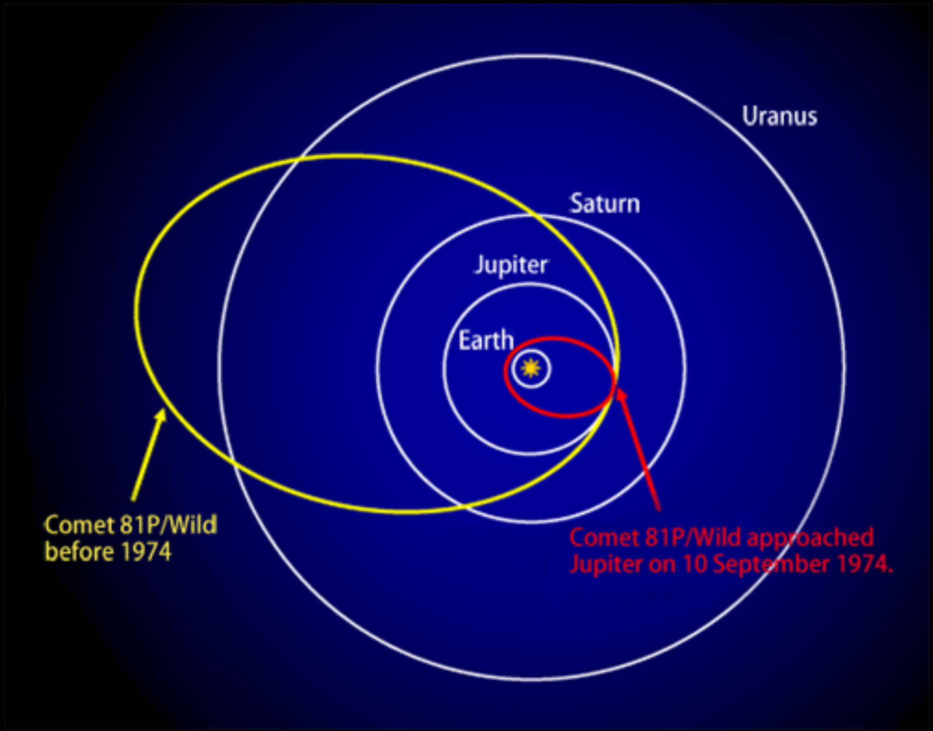


- 8 flyby missions during 1986 apparition
- Offer lessons for targeting future long-period objects

Comet 81P/Wild 2

- Also explored by flyby: NASA Stardust in 2004
- Sample return of hypervelocity captured dust

- Short-period (<200 yr) Jupiter-family comet
- Likely a Kuiper Belt object
- Orbital period of 43 → 6.4 years in 1974
- 1.6 – 5.3 AU (~5 – 25 AU prior to 1974)
- Inclination 3.2°
- Eccentric orbit: 0.538



From SPring-8 Research Highlight No.43

Missions to Comet 1P/Halley

From far away

- Suisei: 3/8/86, to 151,000 km; Japan
  UV imaging of H corona
- Sakigake: 3/11/86, to 7M km; Japan
  plasma, magnetic field measurements
- Pioneer 7: 3/20/86, to 12M km; USA
  H tail interaction with solar wind
- ICE: 3/25/86, to 28M km; USA
  plasma, magnetic field measurements
- Pioneer Venus Orbiter: 2/3/86 to 40M km; USA
  UV spectrometer water loss observations


NASA

Missions to Comet 1P/Halley

Close approaches

- Vega-1: 3/6/86, to 8,889 km; USSR/France
  imaging, dust spectrometer, magnetic field, plasma, thermal
- Vega-2: 3/9/86, to 8,030 km; USSR/France
  imaging, dust spectrometer, magnetic field, plasma, thermal
- Giotto: 3/14/86, to 596 km, with Whipple shield; Europe
  multicolor imaging, gas and dust spectrometers, magnetic field, plasma, etc.

Suisei, Sakigake, Vega-1, Vega-2 and Giotto were coordinated as *The Halley Armada*

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Overview of Challenges

- Getting there
- High relative speed
- Getting close

- Unknown and/or variable activity and dust environment
- Limitations of *in situ* instrument performance and telemetry

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Challenges: Speed & Distance

Relative speed

- Giotto Halley flyby @ 68.4 km/s (152,000 mph)
  retrograde orbit + high inclination
- Stardust Wild 2 flyby @ 6.1 km/s (13,500 mph)

Smithsonian

Getting close

- Giotto: 596 km … but only after Vega-1,2 returned precision targeting data from 8000 km!
- Vegas got dust data at 8000 km from an *active* object
- Stardust: 237 km

Challenges: Activity & Dust

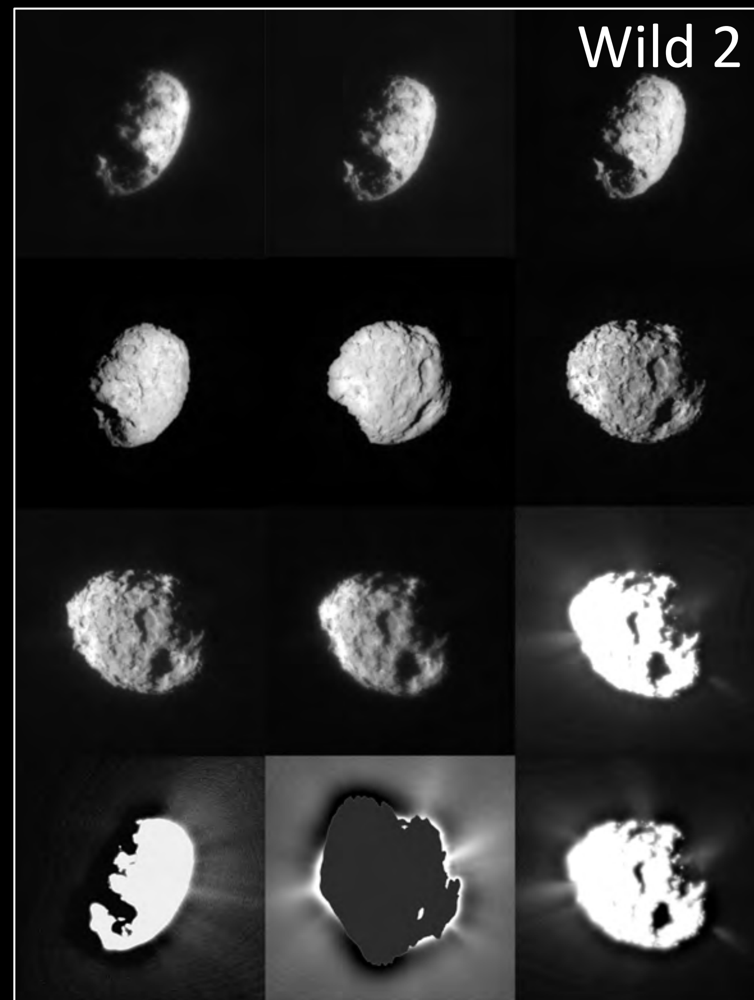
Dust is a health risk to spacecraft.

Vega-2: 8030 km
- 80% solar power loss

Giotto: 596 km
- Spin destabilized ~30 min. and lost communications
- MultiColor Camera broken

Stardust: 237 km
- No major spacecraft issues
- Less active comet

Comet Activity Differences



Brownlee et al. Science 2004

Wild 2 ⟶

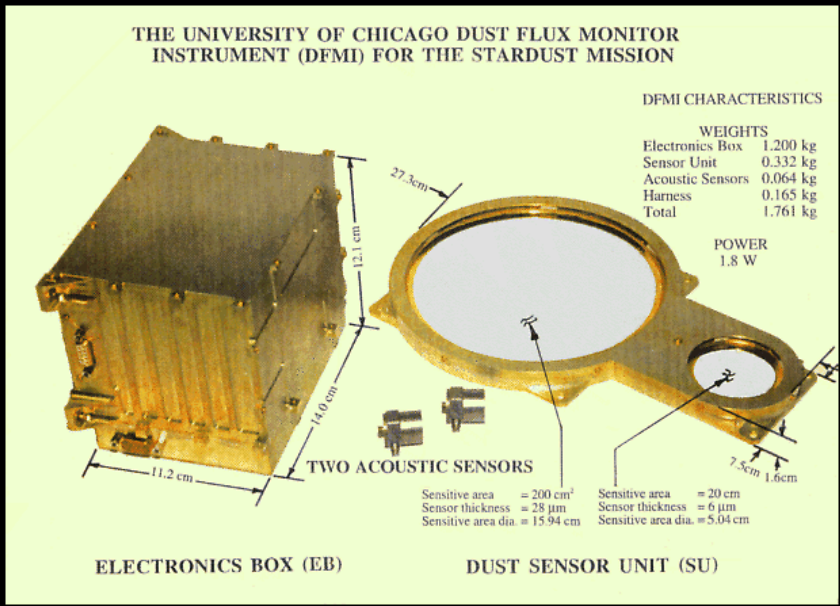
- 10 – 20 x less water loss
- Long exposures required to image jets

In situ Dust Science Instruments

- 68-78 km/s (Halley)
  - Dust flux monitor
  - Dust impact ionization mass spectrometers (PIA/PUMA)
    - Mixed results
    - Succeeded in providing 1st semi-quantitative comet dust composition
- 6 km/s (Wild 2)
  - Dust flux monitor
  - Dust impact ionization mass spectrometer (CIDA)
    - ~Same as PIA/PUMA
    - Very limited usefulness
  - Dust captured in silica aerogel for sample return
    - Mineralogy and petrology of >1 micron grains

Dust Flux Monitors

- Individual impactor mass and timing
- Giotto Dust Impact Detection System
  - 1 m^2 area, masses ~10^{-10} – 2 x 10^{-2} g
- Stardust Dust Flux Monitor Instrument
  - 220 cm^2 area, masses ~10^{-11} – 10^{-2} kg
  - 120 x better spatial resolution due to lower encounter speed
  - Developed noise problems, operated nominally during 30 min of closest approach



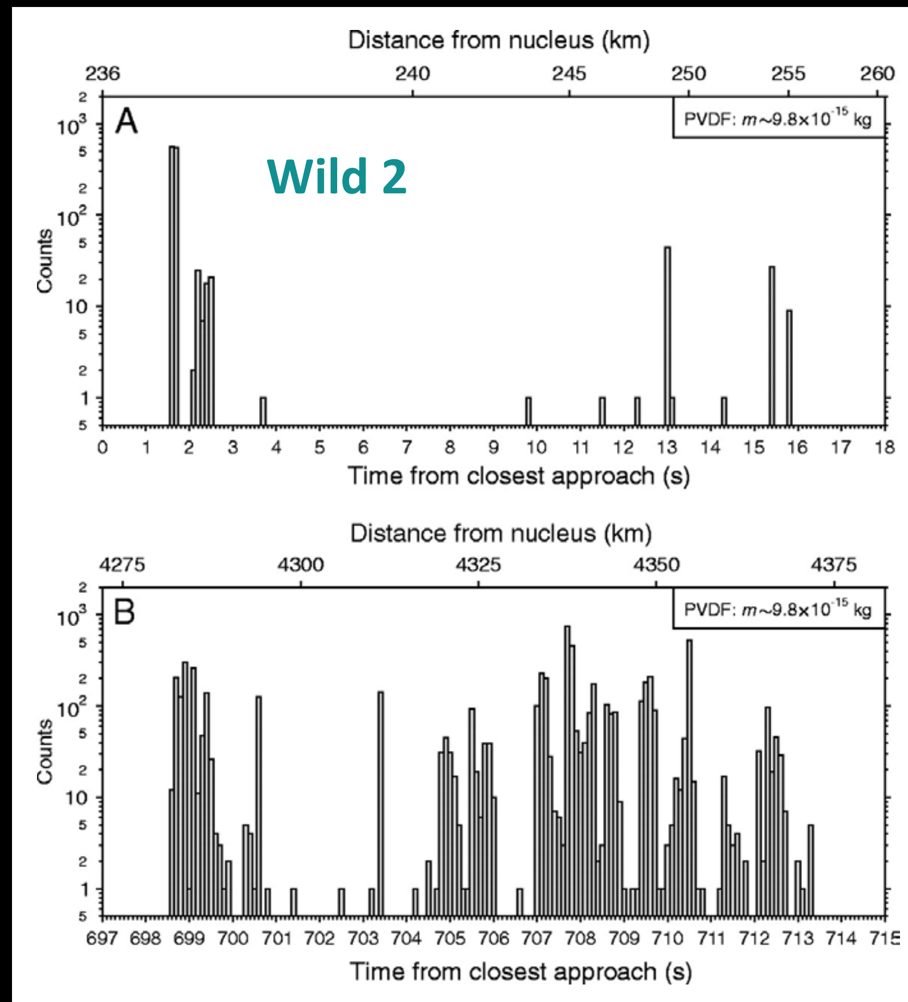
Comet Dust Environment

Comet Activity Variability

- Both Halley and Wild 2 showed highly variable dust flux with time.
- Localized jets over estimated ≤ 10% of Halley's surface; 1-5% of Wild 2's surface
- Dust fragmentation upon release

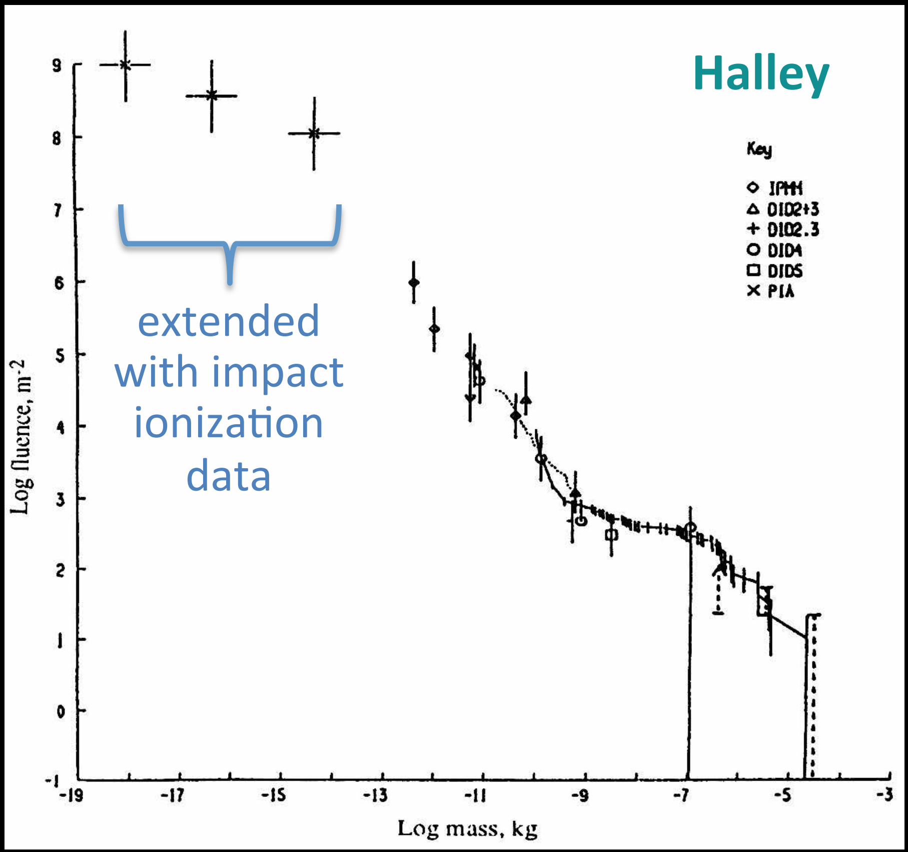
  Vega-1 and -2:
  Beyond 100,000 km, larger particles depleted *(less sensitive to radiation pressure)* and smaller particles enhanced

Clark et al. JGR Planets 2004; Boehnhardt et al. A&A 1990

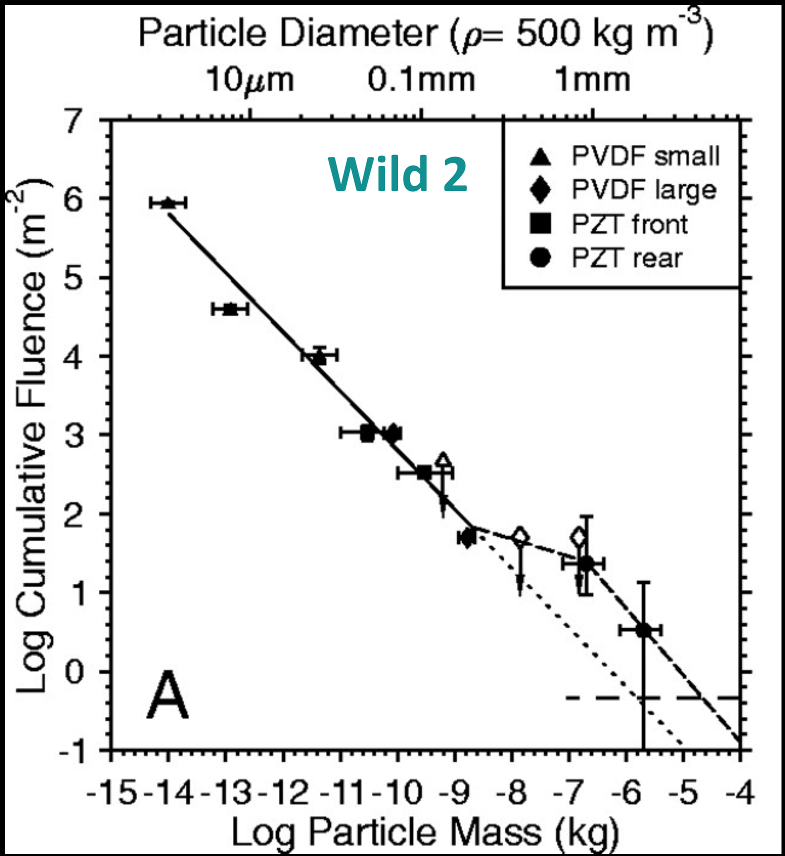


Tuzzolino et al. Science 2004

Most Mass in Large Particles



McDonnell et al. in Comets in the Post-Halley Era 1991

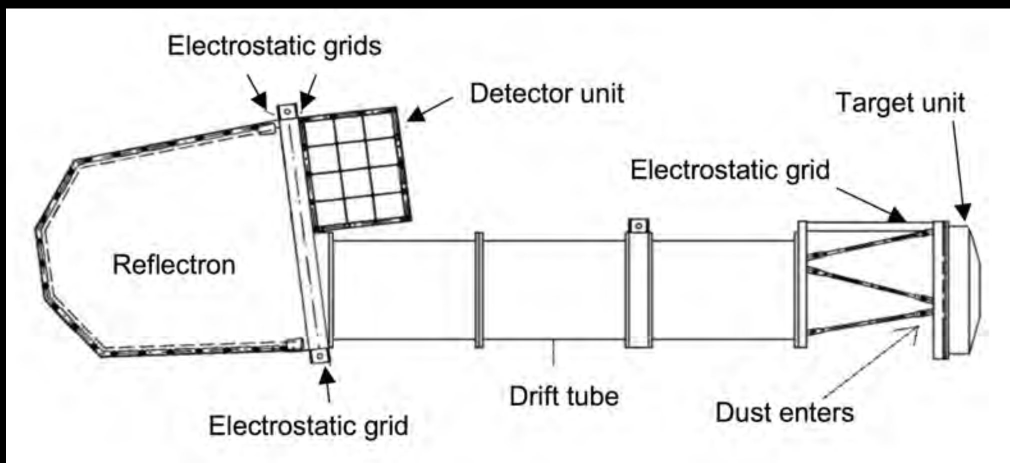


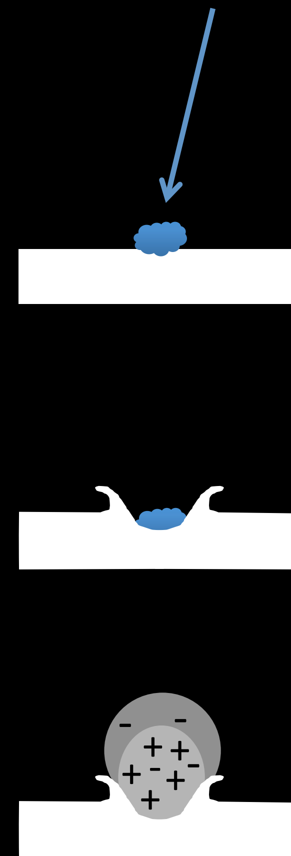
Tuzzolino et al. Science 2004

Giotto thermal emission measurements indicate high abundance of submicron silicate grains. Reconcile with excess large mass particles by large high-porosity aggregates of µm- to subµm-sized grains ***or*** by large particles leftover from earlier outbursts.

Impact Ionization Mass Spectrometers

PIA (Giotto) / PUMA (VEGAs) / CIDA (Stardust)
all same basic design





- Time of flight reflects mass
- Masses between ~10^{-16} and ~10^{-10} g detectable
- Mass resolution ($m/\Delta m$) 50-200 for most spectra (depends on impactor size and ion reflector voltage)

Sagdeev et al. ESA SP-250 1986

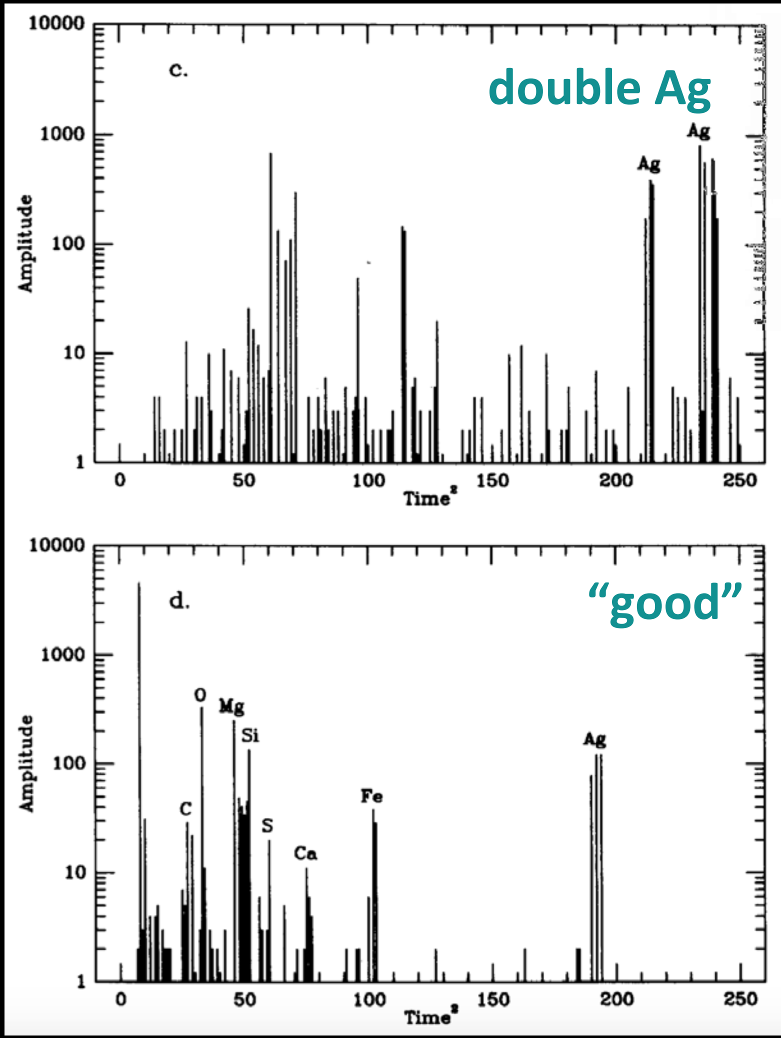
→ distinguish mass lines up to Fe but not mass overlaps

Impact Ionization Issues

- Cannot be readily calibrated for all minerals at relevant impact velocities. → Collect data and try to figure out ion yields after.
- At high impact velocities (Halley), material is more thoroughly broken down, and individual atomic ions are produced → generally representative of bulk particle composition.
- At lower impact velocities (Wild 2), complex molecular ions are also produced → very complicated to interpret.
  (Stardust: only 29 organic spectra)
- Cannot determine mineralogy; Structural information is very indirect.
- Isotopic information is limited due to signal-to-noise limitations.
- Total mass analyzed is small (few ngs for Halley *vs* < mg for Stardust).

Impact Ionization Mass Spec Issues

- PIA (Giotto) malfunctioned, but some useful data.
- PUMA-2 (Vega-2) had low dynamic range and low sensitivity due to limited data transfer rate.
- PUMA-1 (Vega-1) is the most usable dataset (>6200 spectra); at 78 km/s, it generated mostly singly charged atomic ions.
- 4 modes of data collection (3 compressed): Mode 0 spectra (4%) most like lab spectra. Other modes had issues associated with compression and a jitter in the $(\text{time})^2$ signal requiring careful selection.
- Still, on order of 500 usable Halley spectra
- CIDA (Stardust) gave 29 organic spectra
  (ionization efficiency)



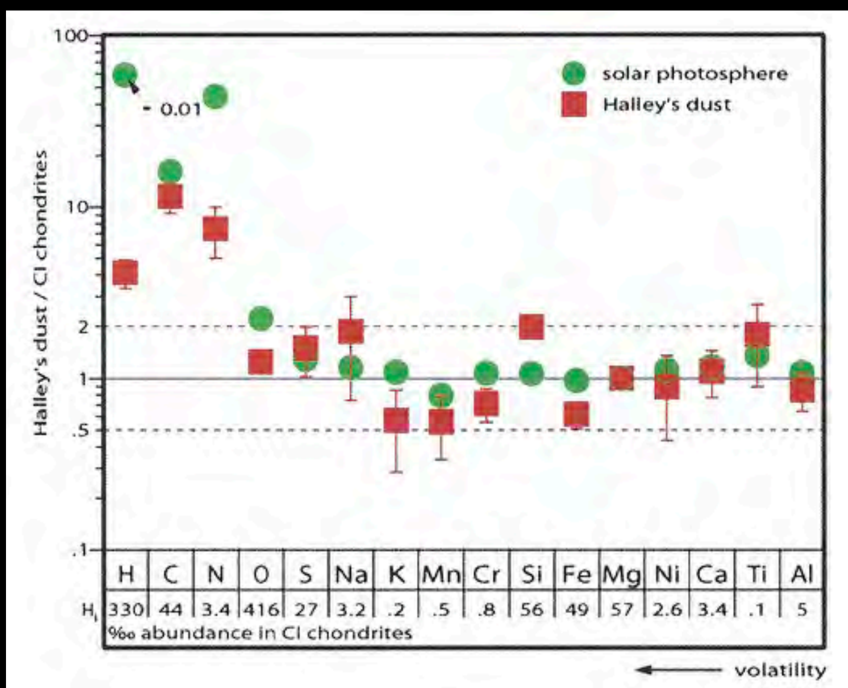
Lawler et al. Icarus 1989

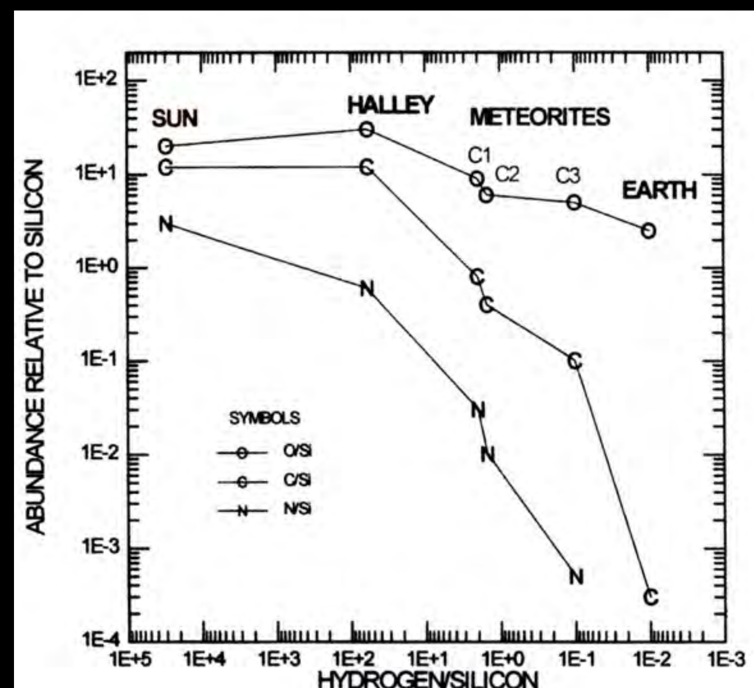
In situ Dust Science

Icy Dirtballs of Primitive Matter

- Comets are icy dirtballs instead of dirty snowballs
  - Dust/gas ratio ~2.2 : 1, far greater than was anticipated
- Halley-type comets accreted undifferentiated primitive matter
  - gas + dust = solar (within 2×), wide range of Fe/Mg, narrow range of Si/Mg

Grün & Jessberger in Phys & Chem of Comets 1990; Hughes in Origins 1988; Jessberger et al. Nature 1988, 1989; Lawler et al. Icarus 1989





Figures: Mann & Jessberger in Astromineralogy 2010; and Geiss & Altwegg ESA-SP 1998.

Fine-grained dust mixed with organics

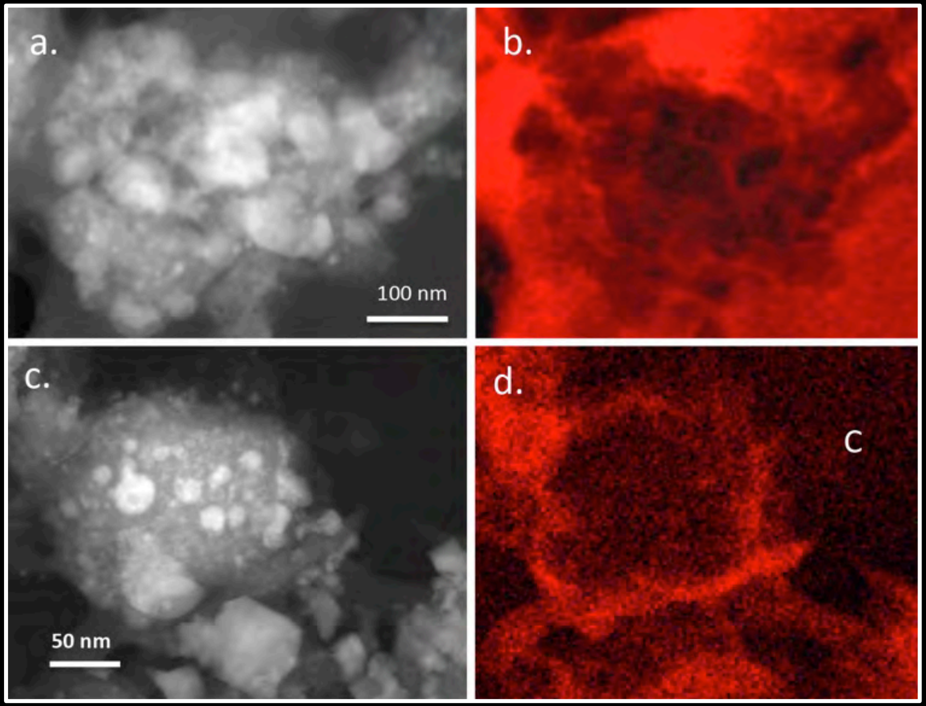
Dust is fine-grained, and organics and rock are intimately mixed – even for the sub-micron grains.

- ~50% of grains are a mixture of organic and inorganic components
- Remainder are 50/50 organic-dominated or inorganic-dominated (90%)
- High abundance of small particles <10^{-15} g rich in organics.

Geiss & Altwegg ESA-SP 1998; Fomenkova et al. Science1992; Lawler et al. Icarus 1989

Given complications of detections, does intimate mixing of organics and rock make sense?

Yes! We see it in anhydrous chondritic porous IDPs →



Ishii et al. PNAS 2018

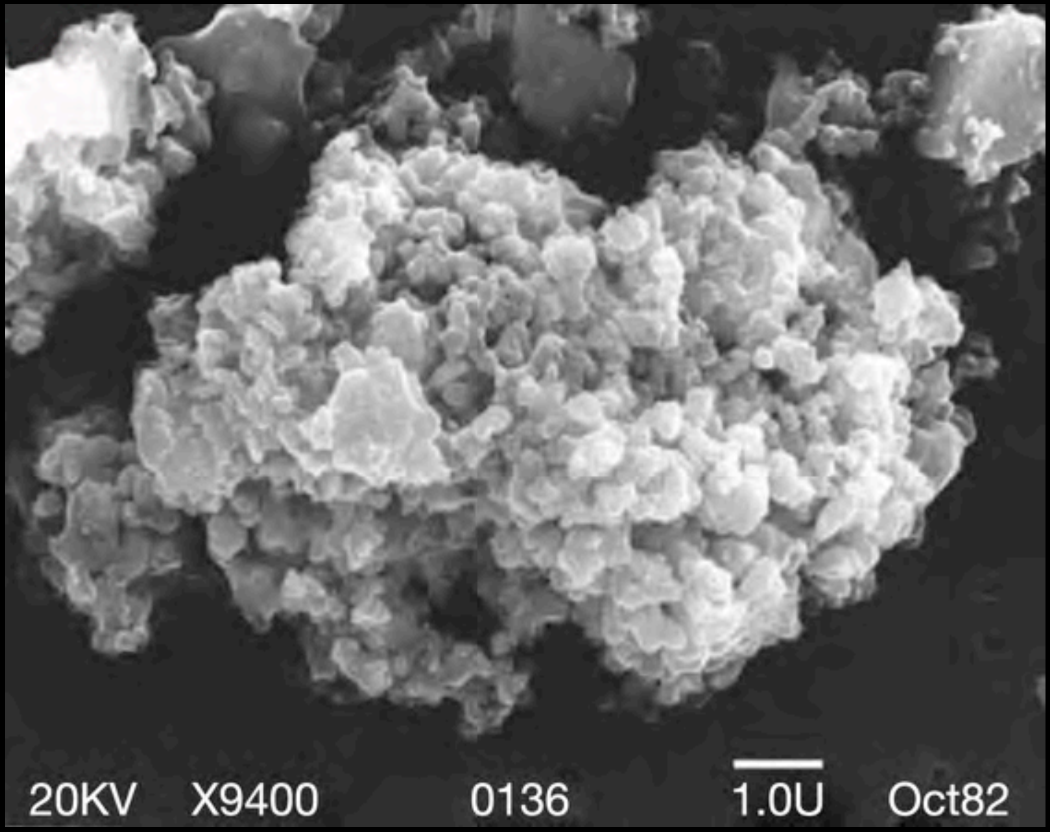
Likely Aggregated…Organic coated?

Dust grains may be organic-coated (*a la* Greenberg model) & aggregated like IDPs.

Greenberg in Comets 1982

- More organic-bearing dust near nucleus, more rocky dust further away
  → Partial volatilization of organics with time in coma.
  \+ Organics vary in composition and spatial distribution.
  Fomenkova et al. Geochim Cosmochim Acta 1994

- More efficient ionization of coating, less of rocky interior? Would help explain higher carbon than anticipated based on IDPs and on primitive meteorites. (C not from ices as they would already have sublimed.)
  Sekanina et al. in Interplanetary Dust 2001



Bradley in Treatise of Geochemistry 2014

Halley Dust is like Anhydrous CP IDPs

Halley's dust ~ anhydrous chondritic porous interplanetary dust (CP IDPs).

- Silicates are Mg-rich, amorphous + crystalline = interstellar silicates + early SS condensates? (Other comets can show less crystalline silicates.)
- Minor sulfides, metal and oxides; no Ca-Al-rich grains, SiC grains

  (but upper limits are high)
- Some isotopically light C-bearing grains identified

Brownlee et al. 1987; Jessberger et al. 1988, 1989; Lawler et al. 1989; Jessberger & Kissel 1991; Jessberger 1993; Bradley GCA 1988; Bradley et al. EPSL 1989; Germani et al EPSL 1990

Table 3. Estimated mineralogical composition of Halley's dust.

Mineral group	Estimated modal proportion	Mineral chemistry	Possible minerals
Mg silicates	>20%	Fe-poor, Ca-poor	Mg-rich pyroxene and/or olivine
Fe sulfides	~10%	some Ni-rich	pyrrhotite, pentlandite
Fe metal	1–2%	Ni-poor	kamacite
Fe oxide	<1%		magnetite

Schultze et al. in From Stardust to Planetesimals 1997.

A *Few* Additional Dust Insights from JFCs

- Comets are not "individuals"!
- 81P/Wild 2: Stardust flyby and sample return
  - Presence of high temperature components from the inner solar protoplanetary disk indicates large-scale transport of dust.
- 67P/Churyumov-Gerasimenko: Rosetta orbiter and lander
  - Remarkably high dust/gas ratio ~4-6
  - Dry organic-rich dust mantle at surface with high compressive strength, maybe from thermal processing
  - Fluffy aggregate + compact dust particle morphologies suggest no impacts > 1 m/s since accretion

Considerations for Future Missions

- Dust is a hazard to spacecraft.
- Dust provides a wealth of structural and chemical information relevant to understanding the early solar system.
- Relative velocity is a crucial factor for high fidelity, interpretable dust data.
- Comet activities vary, and dust environments are spatially and temporally variable.
- *In situ* dust spectrometers have major limitations that depend on relative velocity, dust properties and telemetry capabilities.
- Despite limitations, massive amounts of science can be extracted.

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