Meteorites from the outer solar system?

Matthieu Gounelle[1,2]

[1]Laboratoire d'Étude de la Matière Extraterrestre (LEME), Muséum National d'Histoire Naturelle, Paris, France

[2]Impacts & Astromaterials Research Center (IARC), Department of Mineralogy, Natural History Museum, London, UK

Meteorites from the outer solar system?

1. Introduction
2. The cometary orbit of the Orgueil meteorite
3. Direct comparison of carbonaceous chondrites and comets
4. Implications & open questions
5. Conclusions

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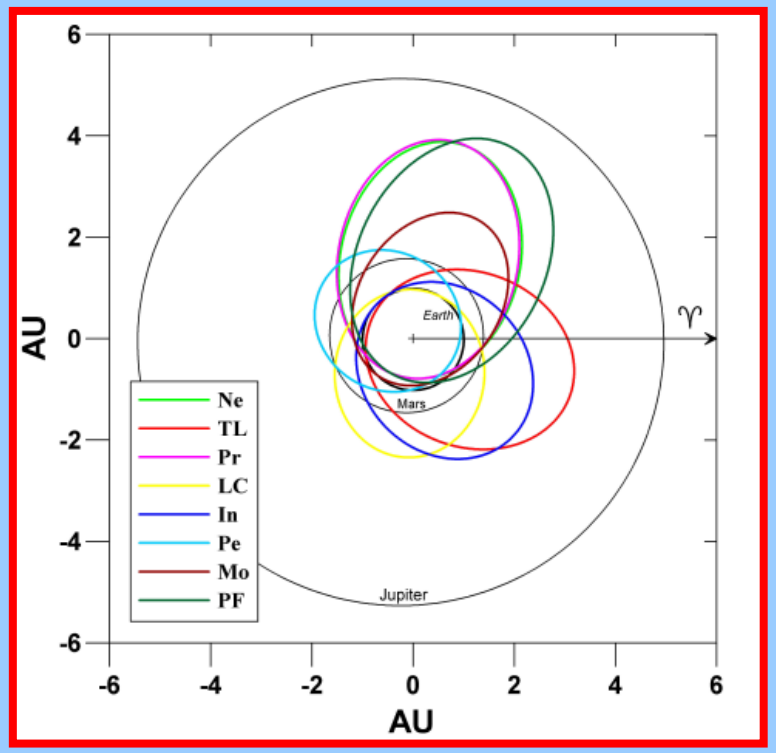
Introduction

- ☆ Meteorites are solid samples (rocks) from outer space
- ☆ The origin of meteorites has been disputed since their identification as extraterrestrial objects
  - ☆ First calculation from Biot (1803)
- ☆ Only the orbit of 8 meteorites is known
  - ☆ All come from the asteroid belt
- ☆ It is now widely accepted that
  - ☆ <u>Most meteorites come from asteroids</u>
  - ☆ 26 meteorites come from Mars
  - ☆ 32 meteorites come from the Moon



- ☆ **Are there any outer solar system (cometary) meteorites?**
  - ☆ Nature of comets (pristine or processed?)
  - ☆ Relationship between comets and asteroids?

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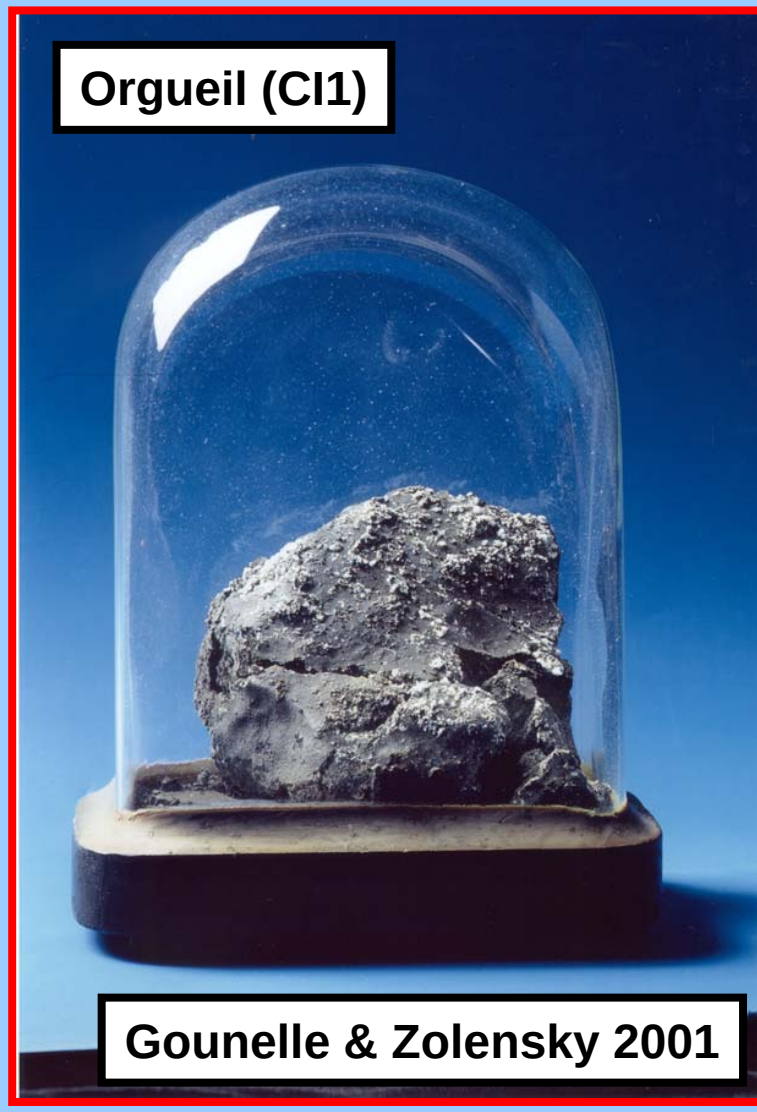
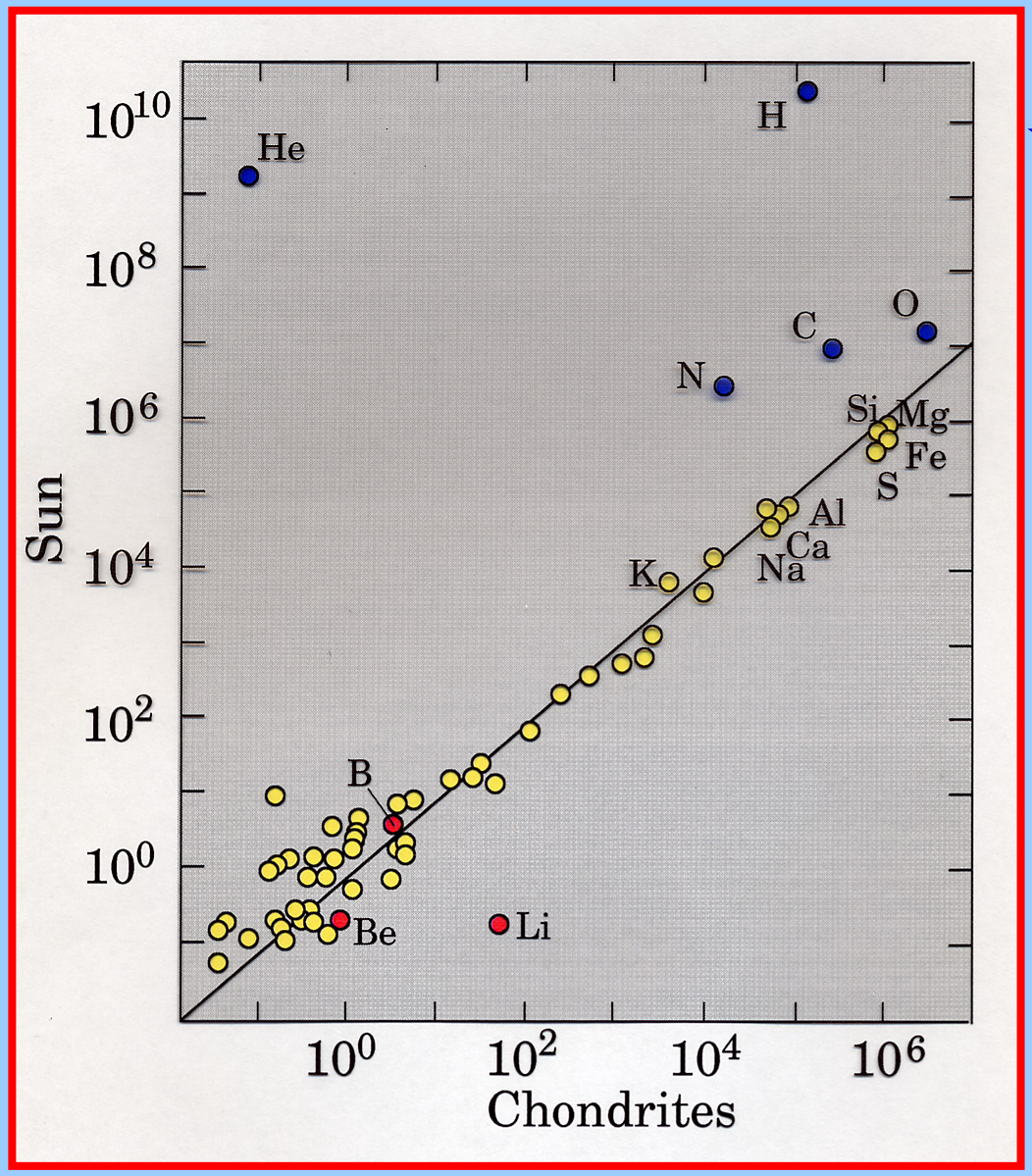
Gounelle, Spurný & Bland (2006) *Meteoritics & Planetary Sciences*, 41, 135-150

The special nature of CI1 chondrites

- ☆ Rare rocks (**Orgueil**, Alais, Ivuna, Tonk, Revelstoke)
  - ☆ CI1 chondrites represent 0.5 % of the meteorites falls
- ☆ Extremely porous rocks (up to 35 %)
- ☆ Very dark rocks (low albedos)
- ☆ CI1 chondrites strongly interact with the atmosphere (formation of sulfate veins)

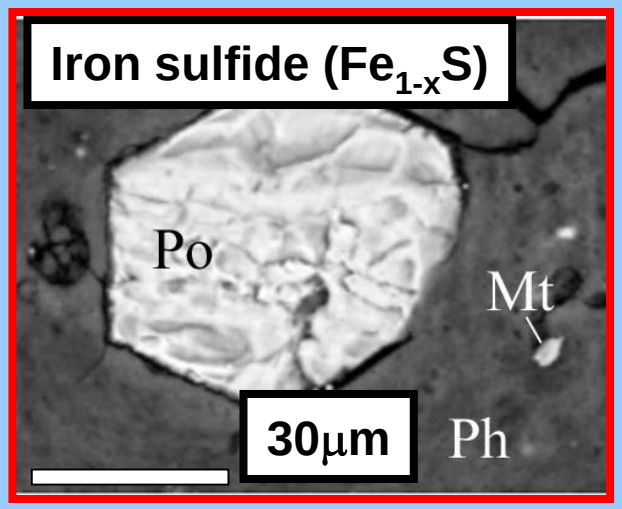


The chemical composition of CI1 chondrites

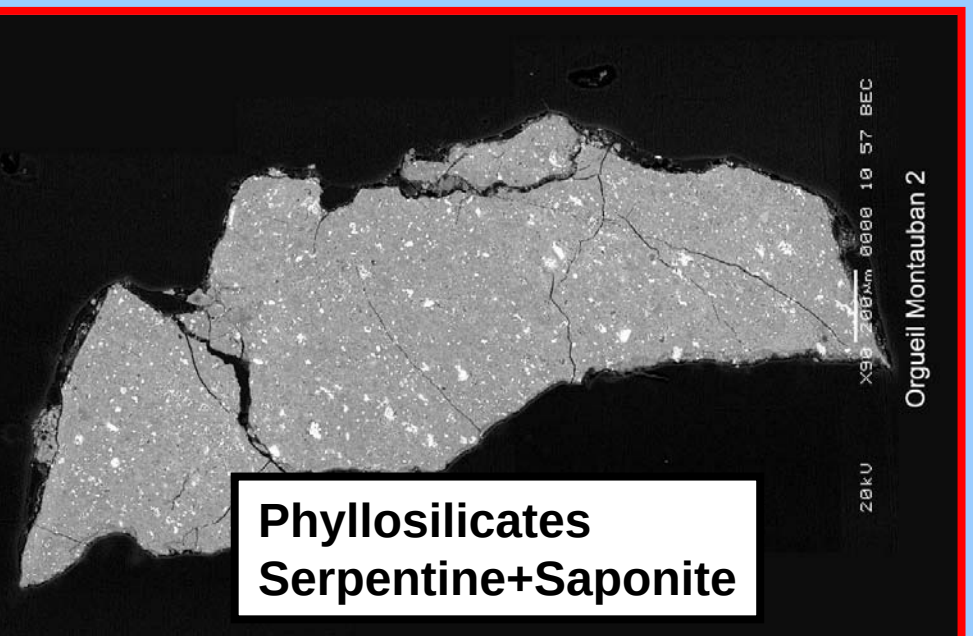


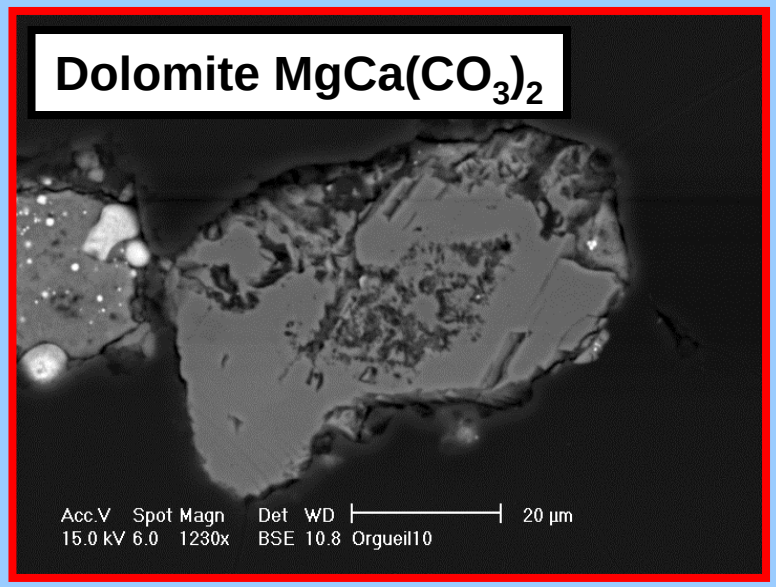
- ☆ Best <u>chemical match</u> with the <u>solar photoshere</u> of all chondrites

Secondary minerals in CI1 chondrites



☆Although chemically pristine, CI1 chondrites are the most <u>hydrothermally altered</u> chondrites (serpentine, saponite, sulfides, Ca-Mg carbonates, magnetite)





The fall of the Orgueil meteorite

- ☆ Orgueil meteorite fell May 18th 1864 in southern France
- ☆ Fireball seen from north of France to north of Spain
- ☆ **10 pages** of visual observations published by Daubrée in the main scientific journal of the time
  - ☆ Compte Rendus de l'Académie des Sciences de Paris

The Orgueil fireball observations

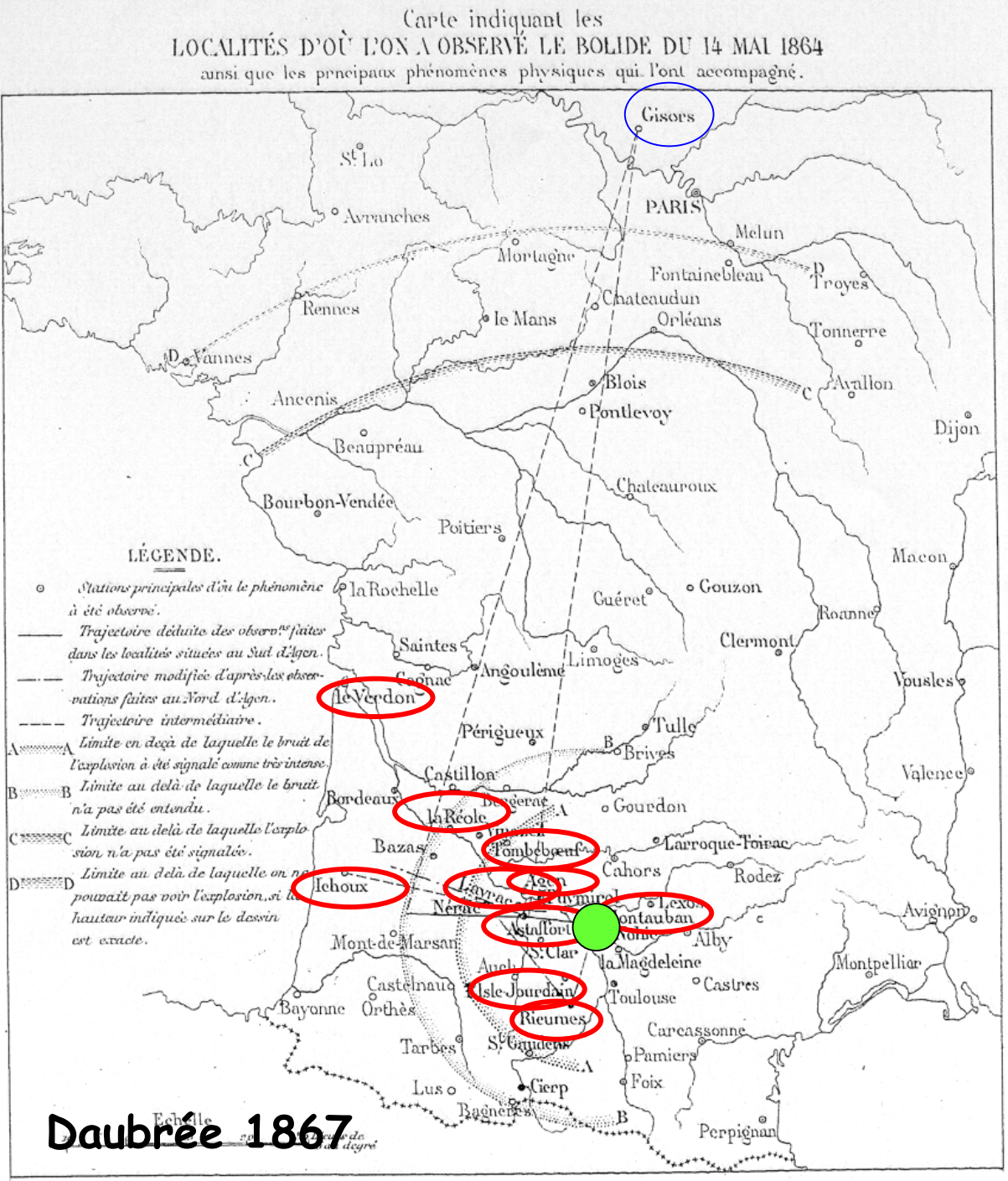
Letter of M. d'Esparbès à M. Le Verrier

At 8.13 pm, a prodigious luminous artifact inundated the city. Everyone thought to be in the middle of the flames. It lasted a few seconds, and was generated by something as large as the full Moon, that crossed the sky as a shooting star would, abandoning a bluish fiery trail. This trail disappeared slowly, and the sky became serene again; however ten minutes after, one could still observe an immobile cloud.

Roughly two minutes after this electric light was produced, a detonation similar to that of a canon, and lasting from 80 to 100 seconds was heard.

It was a delightful May evening. The weather was superb.

Published by Daubrée, Compte-rendus de l'Académie des Sciences de Paris, vol 58 (1864)



Observations used for trajectory and orbit determination

More northern observation

Meteorites fall

Orbit calculations made by P. Spurný

The Orgueil fireball observations

No.	Place of observation (Observer)	Geographic coordinates	Original values	Corrected values (used in computations)	Comments
1.	Rieumes (Lajous)	λ=1.118° E φ=43.414° N	1. point A=156°, Z=68° 2. point A=205°, Z=73.5° (flare)	1. point A=156°, Z=68° 2. point A=205°, Z=73.5° (flare)	On the northern sky, from W to E Duration between both points 3s!! After 3 minutes loud sound
2.	Nerac (Lespiault)	λ=0.336° E φ=44.138° N	1. A=87.7°, Z=52.6° (5° S from Pollux) 2. several degrees N from zenith 3. A=283°, Z=39.5° (¼ distance between ε and α Boo from ε) 4. A=300°, Z=65° (flare 15° N from Jupiter)	1. not used – too close to radiant 2. A=180°, Z=1° - rather almost zenith, slightly to N 3. A=287°, Z=39.5° 4. A=288°, Z=65°	Sound exactly 3 minutes after flare
3.	Montauban (Pauliet)	λ=1.353° E φ=44.019° N	1. SW 2. Constellation Leo ≈ A=0°, Z=30° 3. A=324°, Z=56° (left from Saturn and α Vir) 4. A=307°, Z=82° (slightly below Jup.)	1. not used 2. A=0°, Z=38° 3. and 4. not used because these are beyond the impact area	Sound after 1-2 minutes
4.	Agen (Bourrieres)	λ=0.625° E φ=44.198° N	1. over the town, somewhat to the S	1. A=0°, Z=18°	
5.	Layrac (Daubree paper)	λ=0.661° E φ=44.133° N	1. close to the zenith, literally "flew over heads".	1. A=0°, Z=10°	
6.	Astaffort (Lafitte)	λ=0.650° E φ=44.061° N	from NW to SE, very high – in zenith, terminated about 30° above SE horizon	1. A=110°, Z=20° 2. A=0°, Z=0° 3. A=290°, Z=45°	observed at 8 hours and several minutes in the evening sound after 4 minutes
7.	L'Isle Jourdain (Jacquot)	λ=1.080° E φ=43.613° N	almost horizontal flight above northern horizon from west to east	1. A=130°, Z=62° 2. A=205°, Z=61°	sound after 3-4 minutes exploded and fragmented into many pieces; persistent train 15min
8.	Ichoux (newspaper)	λ=0.968° W φ=44.328° N	almost perpendicularly to the horizon, direction from west to east	1. A=277°, Z=45° 2. A=284°, Z=83°	around 8 hours in the evening, duration several seconds, 3 detonations
9.	Verdon (Laussedat)	λ=0.628° E φ=44.814° N	1. A=29.5°, Z=43.6° - across the Moon	1. A=29.5°, Z=54°	

The Orgueil fireball observations

10.	La Reole (Laussedat)	λ=0.036° W φ=44.588° N	1. A=29.6°, Z=44.4° (Moon position) above or across the Moon	1. A=30°, Z=30° shifted about 14° above the Moon – in agreement with observation	
11.	Bezu-Saint-Eloi (Brongniart)	λ=1.695° E φ=49.296° N	On southern horizon, somewhat to the west, near horizon (~10-15°), slope to the horizon about 20-25°	1. A=15°, Z=86° 2. A=9°, Z=88° must be much closer to horizon	between 7:50 and 8:00 in the evening
12.	Tombeboeuf (Cruzel)	λ=0.455° E φ=44.508° N	WNW→above Leo→left from Saturn and α Vir 1. point A=49°, Z=20° (above Leo) 2. point A=330°, Z=55° (flare, between Saturn and α Vir) 3. point A=307°, Z=82° (end near to Jupiter)	1. point A=49°, Z=38° 2. point A=338°, Z=55° 3. point A=312°, Z=82°	sound 2.5 minutes after
13.	Orgueil (meteorite position)	λ=1.400° E φ=43.875° N	1. A=0°, Z=0° (in zenith)	1. A=110°, Z=1° (in zenith)	impact place

- ☆ From all these observations reported by Daubrée in the Compte-rendus, we (Pavel Spurný)
  - ☆ Calculated the atmospheric trajectory of the Orgueil meteor
  - ☆ Calculated the orbit of the Orgueil meteorid

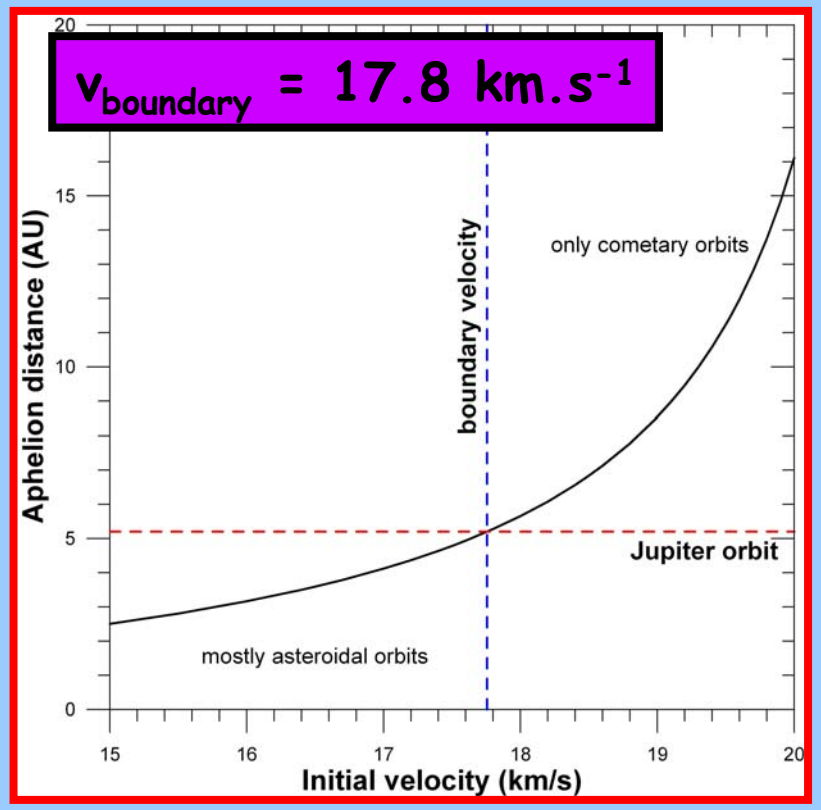
The orbit of the Orgueil meteorid

- ☆ There are 6 orbital parameters to determine
- ☆ The inclination, argument of perihelion, longitude of ascending node, perihelion distance, time of perihelion passage are <u>precisely determined</u>

- ☆ The aphelion distance (Q) depends on the fireball entry velocity

- ☆ The entry velocity can be related to the fireball duration, t

- ☆ If t<10 s, the orbit is cometary



The fireball duration

☆ M.Lajous (CRAS vol 58 page 1067)

"The time during which the fireball moved between the two observed points has been evaluated to be 3 seconds"

☆ M. de SaintAmans (CRAS vol 58 page 1069)

"The duration of the fireball apparition has been a few seconds at most"

☆ M. Laurentie (CRAS vol 58 page 1069)

"Its velocity was less than a shooting star: the duration of its apparition was no more than 5 to 6 seconds"

☆ Quote from a Perigueux newspaper (CRAS vol 58 page 1070)

"The duration of the phenomenon has been of a few seconds"

☆ M. Triger (CRAS vol 58 page 1071)

"Duration of the phenomenon was a few seconds"

☆ M. Hende (CRAS vol 58 page 1071)

"Duration of its fall was evaluated to be 5 to 6 seconds"

The orbit of the Orgueil meteorid

- ☆ The most common observation is of a few seconds
- ☆ The longest estimate is 6 seconds

- ☆ **Question: would observers distinguish a few seconds from 10 s?**

- ☆ **Answer: probably**
  - ☆ The good agreement between six different **independent** observers strengthen the validity of observations (coherent observers)
  - ☆ Observers are casual but concerned enough by science development to report to the Académie their observations (trustworthy observers)
  - ☆ The language used is very assertive ("No more than 5 to 6 seconds", reflexive observers)
  - ☆ **Intense signals tend to be surestimated** (Fraisse, Annual Review of Psychology 1984)

- ☆ All observations point towards $t < 10$ s and $v > 17.8$ km.s^{-1}

- ☆ All observations favour a cometary origin for Orgueil *[most probable solution but not certainty]*
- ☆ Related meteorites could also come from comets
  - ☆ CI1 chondrites
  - ☆ Tagish Lake (ungrouped C chondrite)

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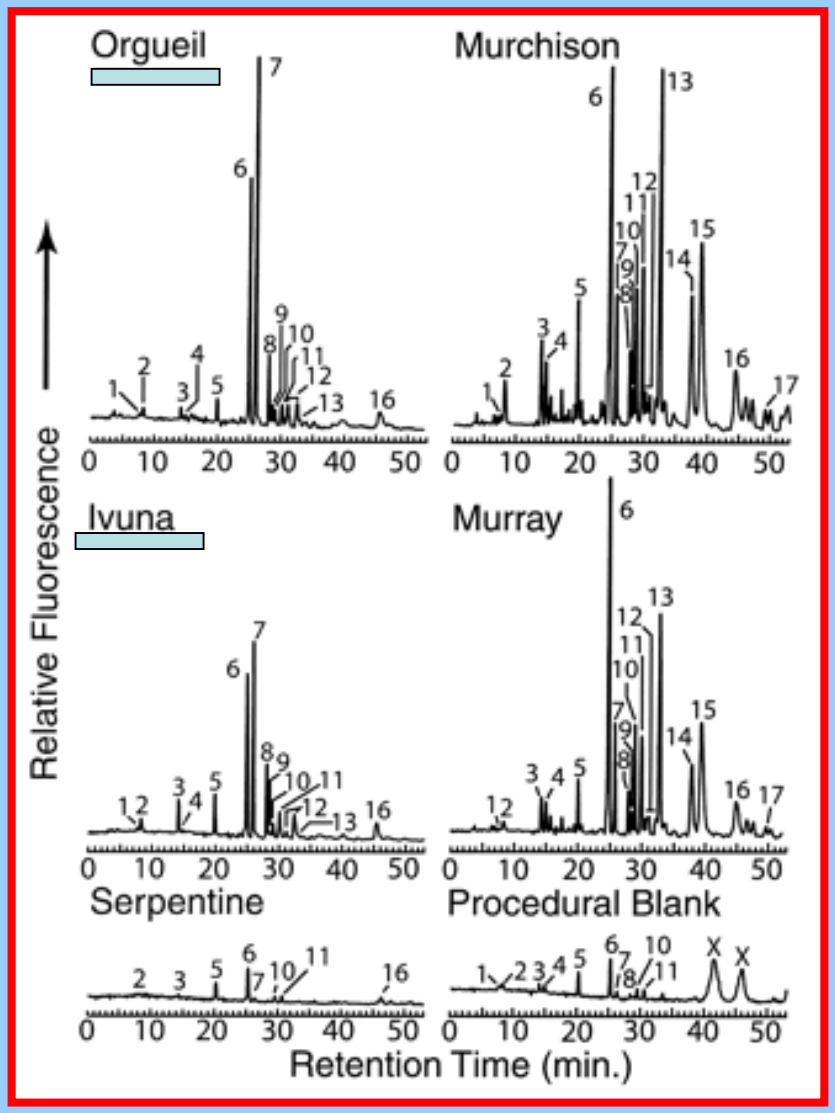
Comparison between comets and CI1 chondrites 1. Chemistry

- ☆ Comets are assumed to be chemically unfractionated samples from the accretion disk. So is Orgueil
- ☆ Orgueil (and Ivuna) is rich in amino acids such as β-alanine and glycine which can be made by HCN-polymerization (Ehrenfreund et al. 2000). Comets are rich in HCN
- ☆ Comets contain PAHs, pure C grains and complex organic matter as carbonaceous chondrites do



Ehrenfreund et al. 2000

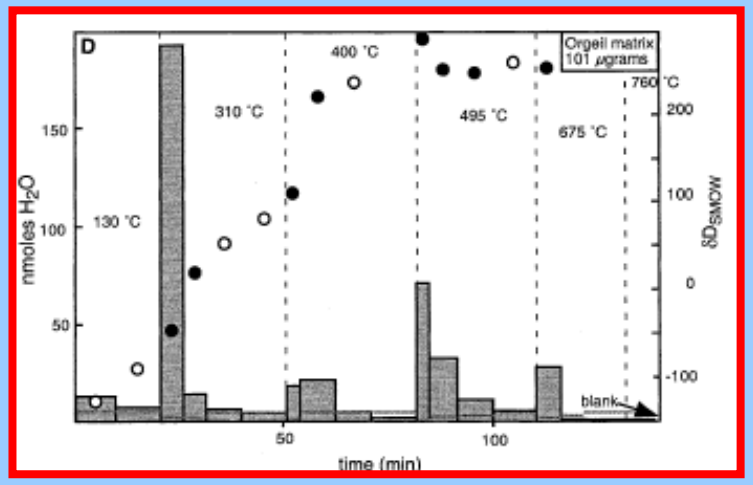
Comparison between comets and CI1 chondrites 2. The D/H ratio

- ☆ The D/H ratio of comets is usually considered to be higher than the D/H ratio of chondritic material
- ☆ This would contradict the cometary origin of CI1 chondrites

BUT

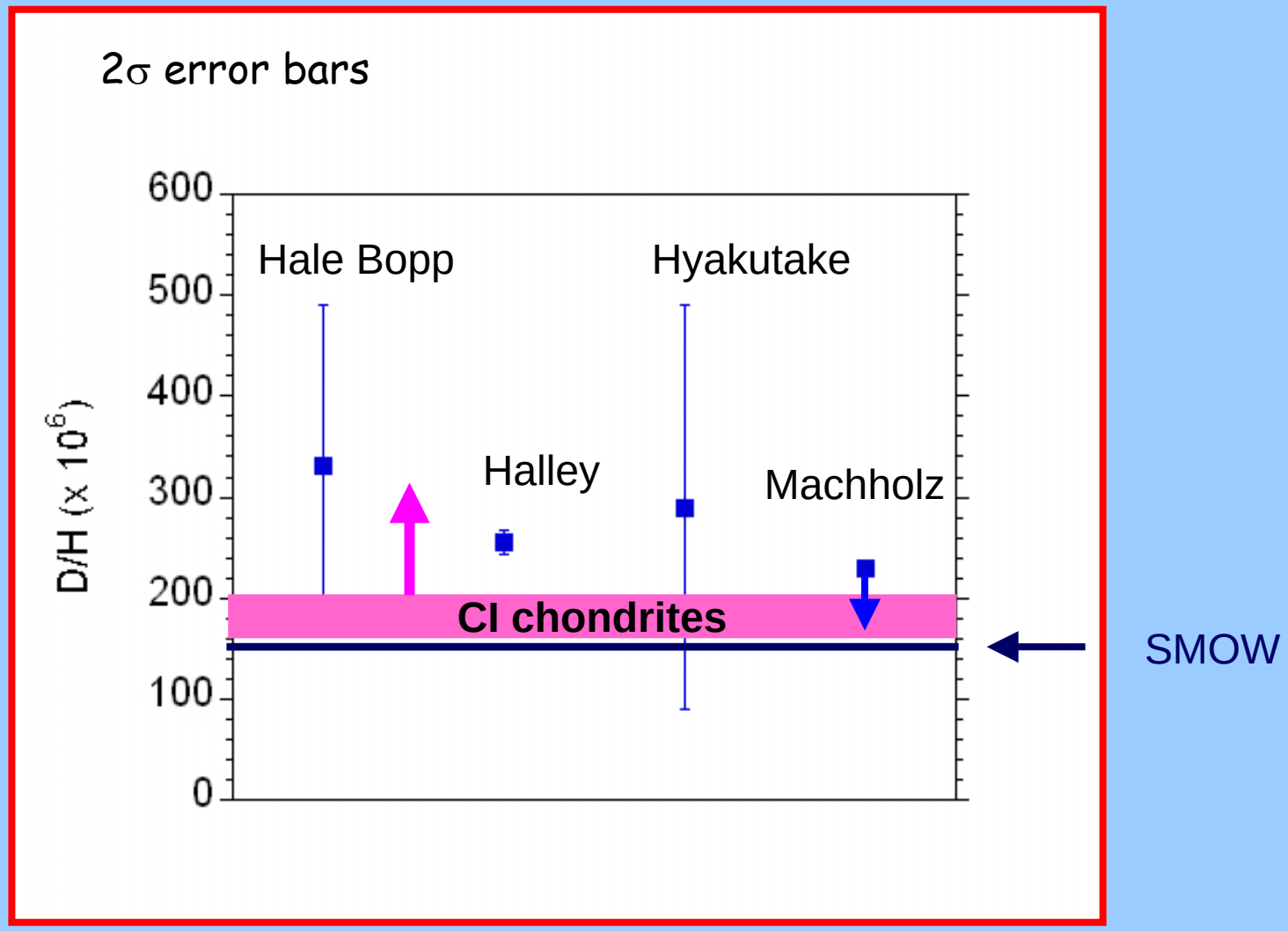
- ☆ The D/H ratio of CI1 chondrites probably largely surestimated because of terrestrial contamination
- ☆ When 2σ error bars are plotted, only comet Halley is significantly different from CI1 chondrites

Eiler & Kirchen 2004



Also do not forget that comparison is made between the gas phase (comets) and solid phase (chondrites) isotopic composition. Possible fractionation?

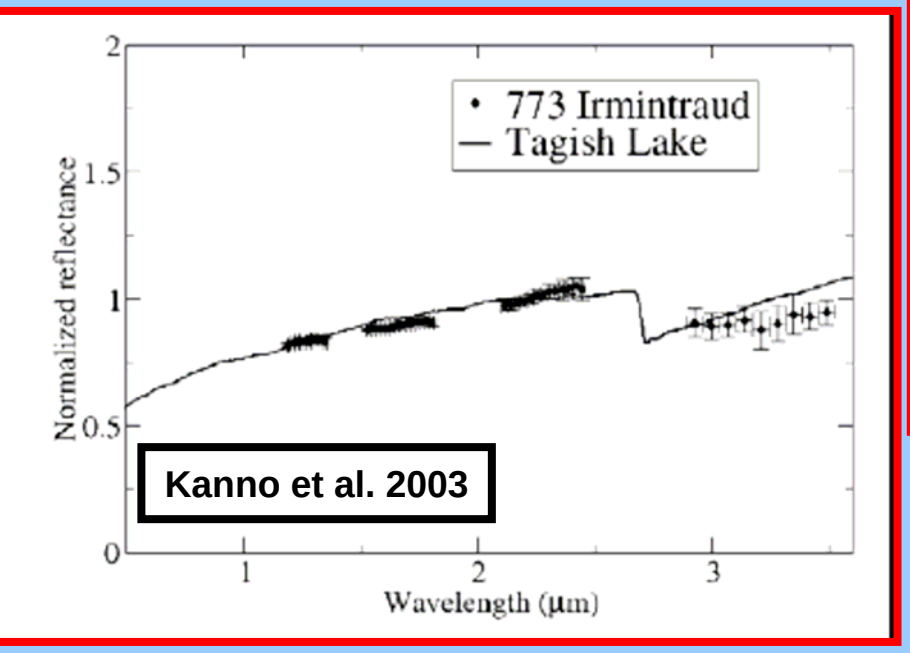
Comparison between comets and CI1 chondrites 2. The D/H ratio

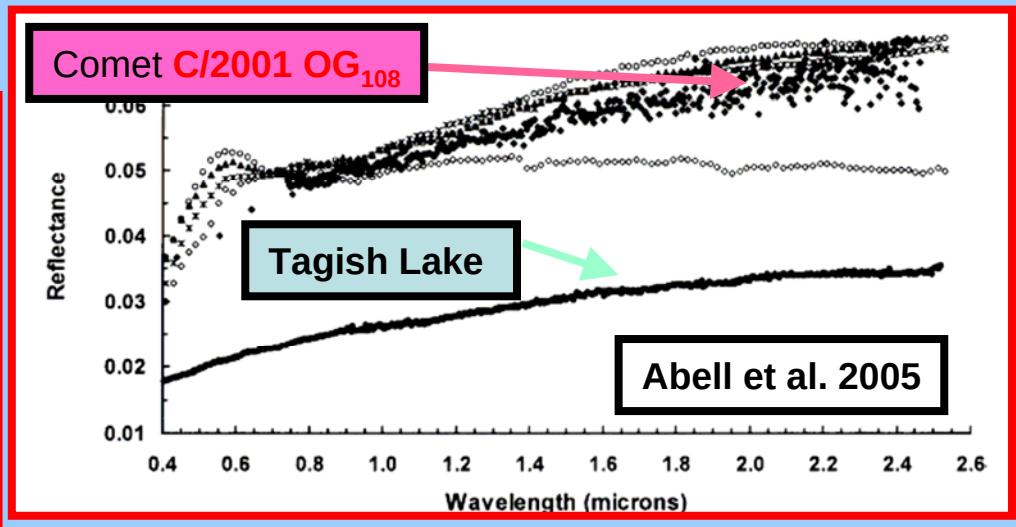


Comets data from Meier et al. (98), Eberhardt et al. (95), Bockelée-Morvan et al. (98), Crovisier et al. (05)
CI1 data from Kerridge (1985) and Eiler & Kitchen (2004)

Comparison between comets and CI1 chondrites 3. Spectroscopy

- **Meteorites and cometary nuclei spectra are difficult to compare**
  - Few bare nuclei spectra
  - Space weathering of comets
  - The CI1 chondrites have interacted with the atmosphere (extra features?)
  - Tagish Lake's spectrum compares well to comet C/2001 OG_{108} and very well to D asteroids





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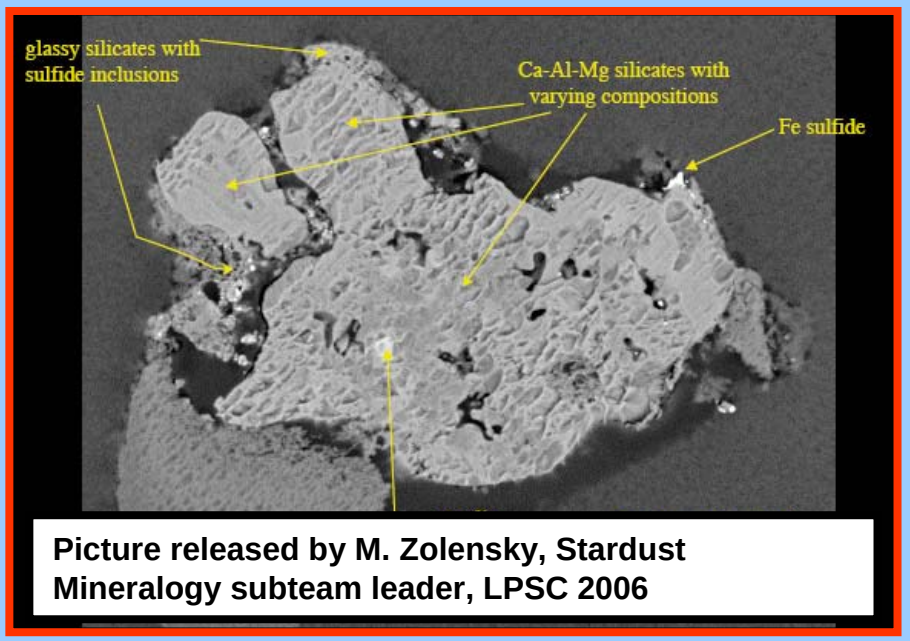
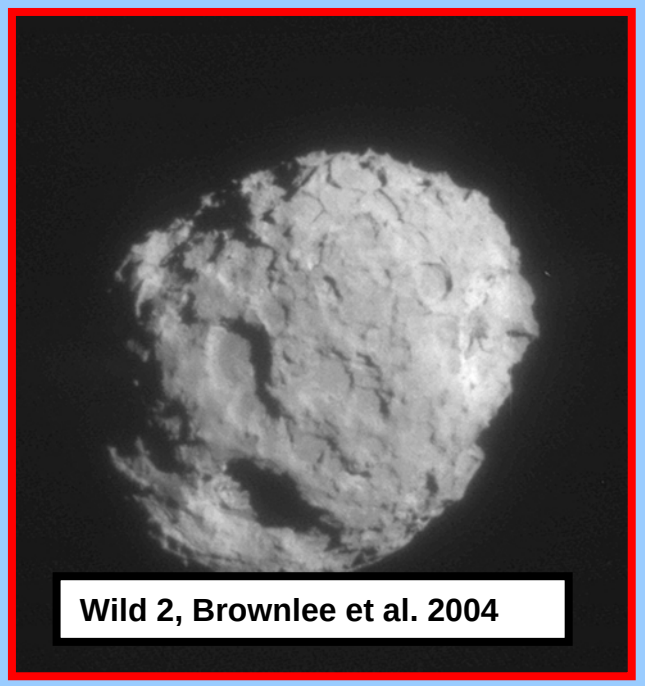
Comets are no longer primitive samples

- For a long time, comets were envisoned as an aggregate of primitive interstellar matter
- CI1 chondrites have been hydrothermally altered: so comets
  - Interaction between water and anhydrous minerals such as olivine, pyroxene produce secondary minerals (phyllosilicates, carbonates, sulfides…)
- Hydrothermal activity in comets is not surprising…
  - Comets are rich in water…
  - Possible heat sources are **impacts** or extinct **radioactive** decay (^{26}Al…)
  - The discovery of craters at the surface of comet Wild 2 and of CAI fragments among Stardust samples strengthen both possibilities

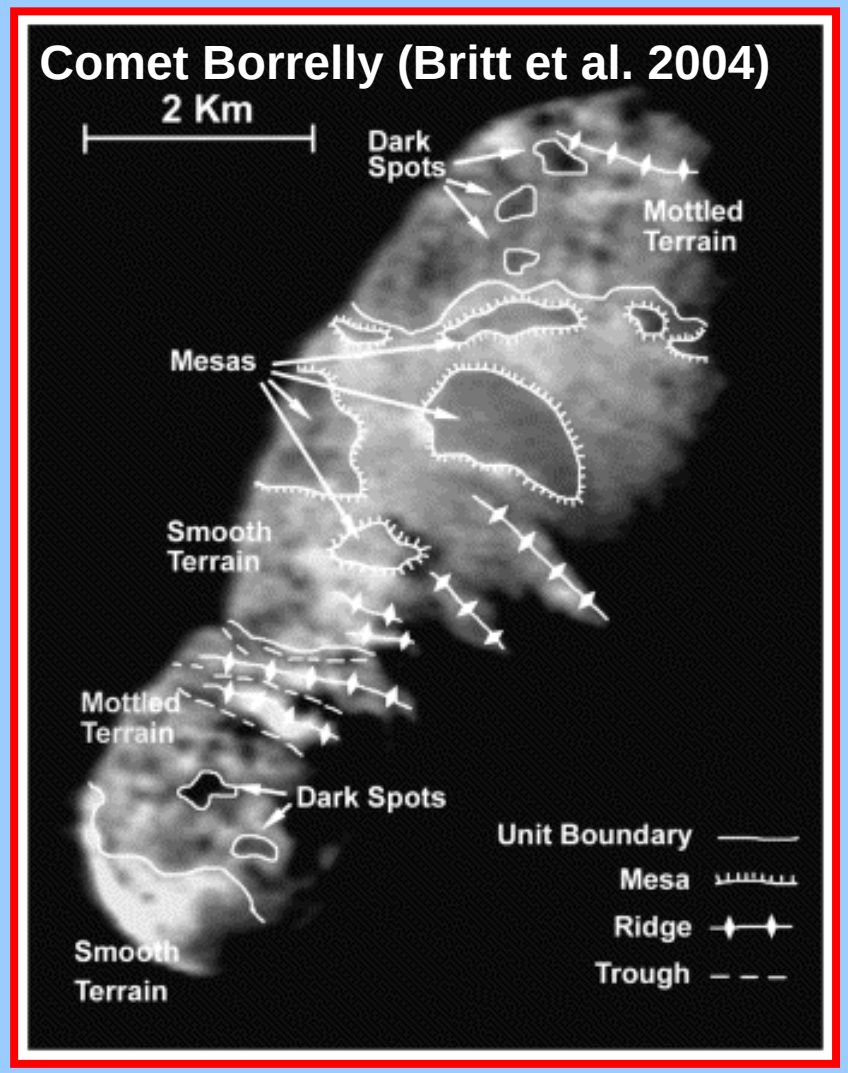


Picture released by M. Zolensky, Stardust Mineralogy subteam leader, LPSC 2006



Wild 2, Brownlee et al. 2004

There is an asteroid-comet continuum

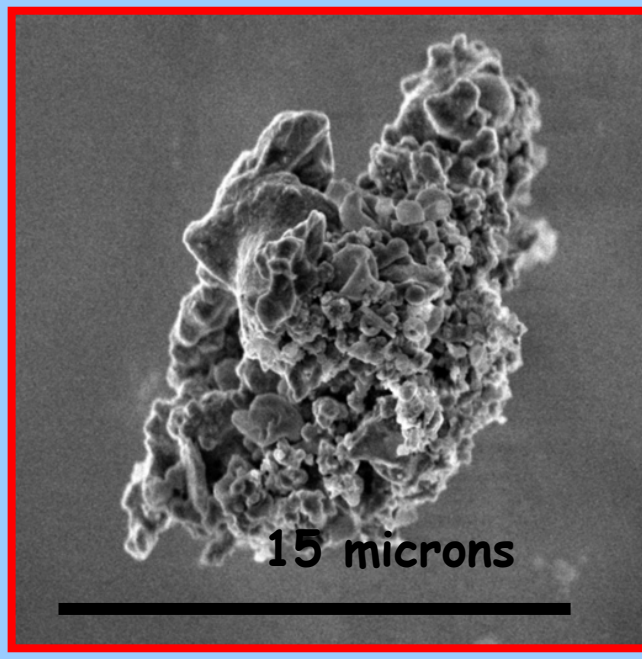


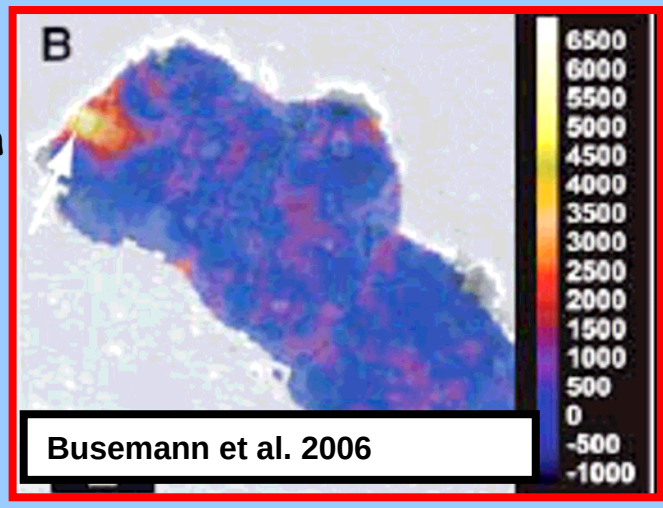
- ☆ Existence of ambiguous/variable objects
  - ☆ 3200 Phaeton and 4015 Wilson-Harrington
  - ☆ Main Belt Comets (Hsieh & Jewitt 2006)
- ☆ Difference between a water-rich asteroid and a dust-rich comet?
  - ☆ Dust/gas of comets > 1, i.e <u>comets are rocky objects</u>
  - ☆ Asteroid Ceres is rich enough in water to have differenciated (Thomas et al. 2005)

Comets have geological features: rocks?

Open question: Where do anhydrous IDPs come from?

- ☆ Anhydrous IDPs are a subset of the Interplanetary Dust Particles collected in the stratosphere by NASA
- ☆ They are mainly made of olivine and pyroxene
- ☆ **They do NOT contain hydrated silicates or carbonates**
- ☆ For a long time, it has been argued they come from comets
  - ☆ Because they have large hotspots of D enrichments
  - ☆ Because they are friable (see picture)
- ☆ D enrichments are now found in carbonaceous chondrites (Busemann et al. 2006)
- ☆ The friable nature of cometary dust is uncertain
- ☆ **There is no definitive argument for the cometary origin of IDPs**
- ☆ Anhydrous IDPs AND hydrated carbonaceous chondrites could both come from comets as there are probably many different types of comets





Busemann et al. 2006

Open question: What do Stardust samples tell us?

- ☆ The NASA mission Stardust brought back to Earth in January 2006 samples from the Jupiter Family Comet Wild 2
- ☆ Some nanograms of samples have been analyzed so far
- ☆ No presence of phyllosilicates and carbonates so far
  - ☆ Unlike CI1 chondrites, unlike Tagish Lake
- ☆ <u>Does it mean that CI1 chondrites cannot come from comets?</u>
- ☆ The answer is <u>NO</u>. Stardust sampled the *surface* of *one* comet
  - ☆ Comets are probably different one from the other
  - ☆ Altered rocks probably made in the interior of the comet (e.g. Young et al. 1998)
  - ☆ **Phyllosilicates and carbonates detected in the ejecta of Tempel 1** (Deep Impact mission, Lisse et al. 2006)

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Conclusions

- ☆ The orbit of the Orgueil CI1 chondrite is compatible with that of a comet rather than with that of an asteroid. Could **Orgueil be the first identified cometary meteorite?**
- ☆ When directly compared, comets and CI1 chondrites (as well as Tagish Lake) exhibit some similarities (and differences)
- ☆ Only comet Halley has a significantly higher D/H ratio than CI1 chondrites
- ☆ CI1 chondrites endured severe hydrothermal alteration. So did comets? **Comets are NOT primitive aggregates of interstellar matter**
- ☆ **There is probably a continuum between dark asteroids and comets** typified by CI1 chondrites, Tagish Lake and CM2 chondrites
- ☆ Some open questions remain
  - ☆ Origin of IDPs
  - ☆ Stardust samples vs CI1 chondrites