DECIPHERING THE INTERNAL STRUCTURE OF PRIMITIVE ASTEROIDS AND COMETS: EVIDENCE FROM METEOROIDS AND NEO FOLLOW-UPS

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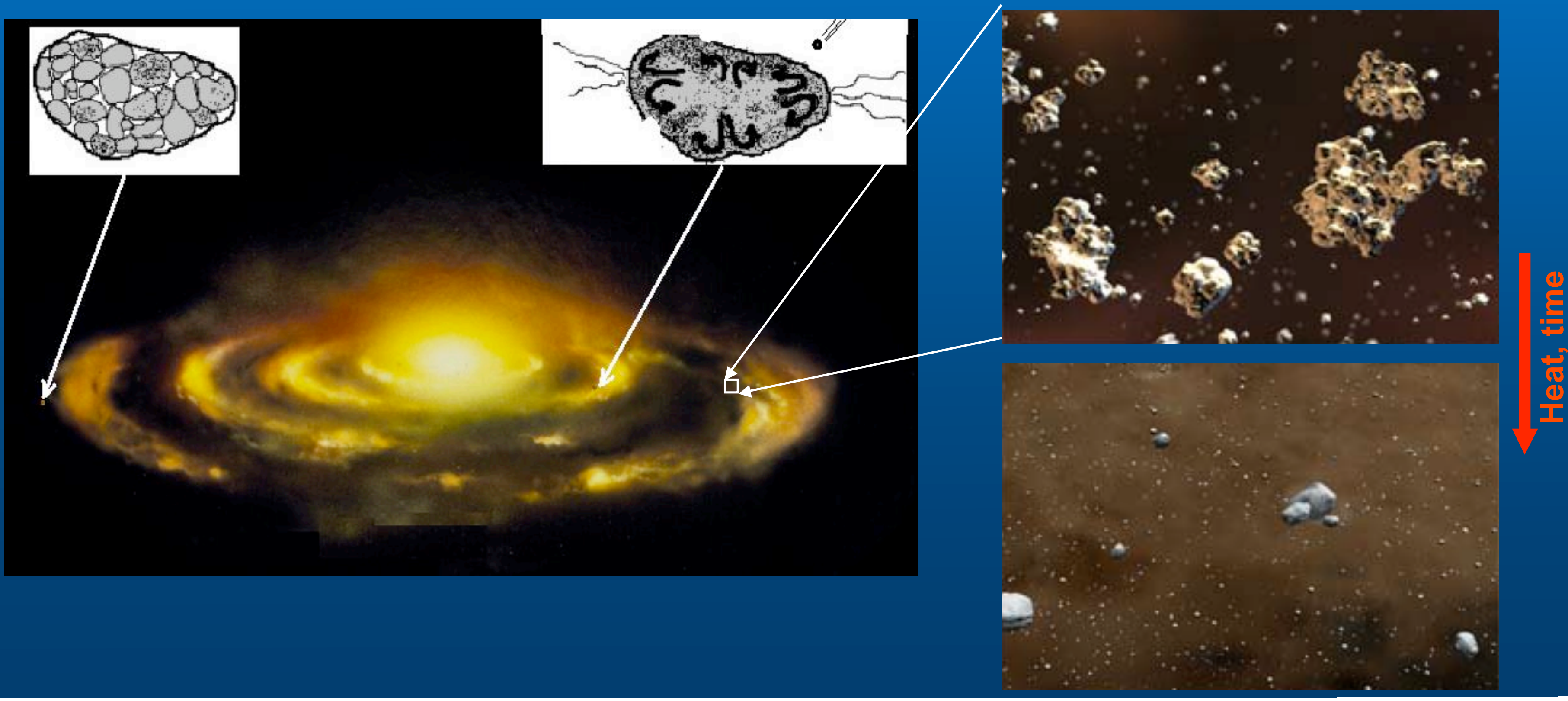
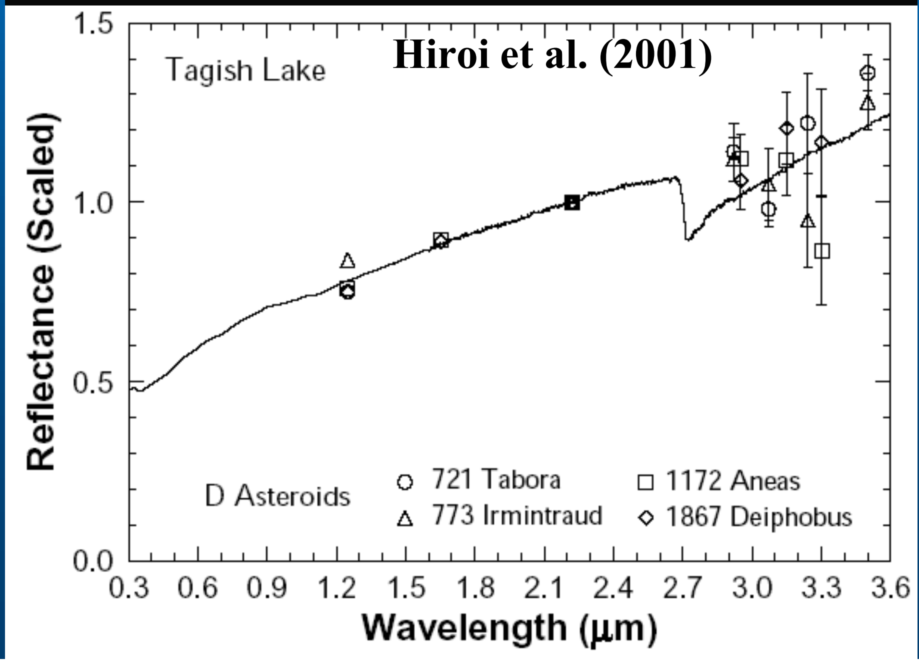


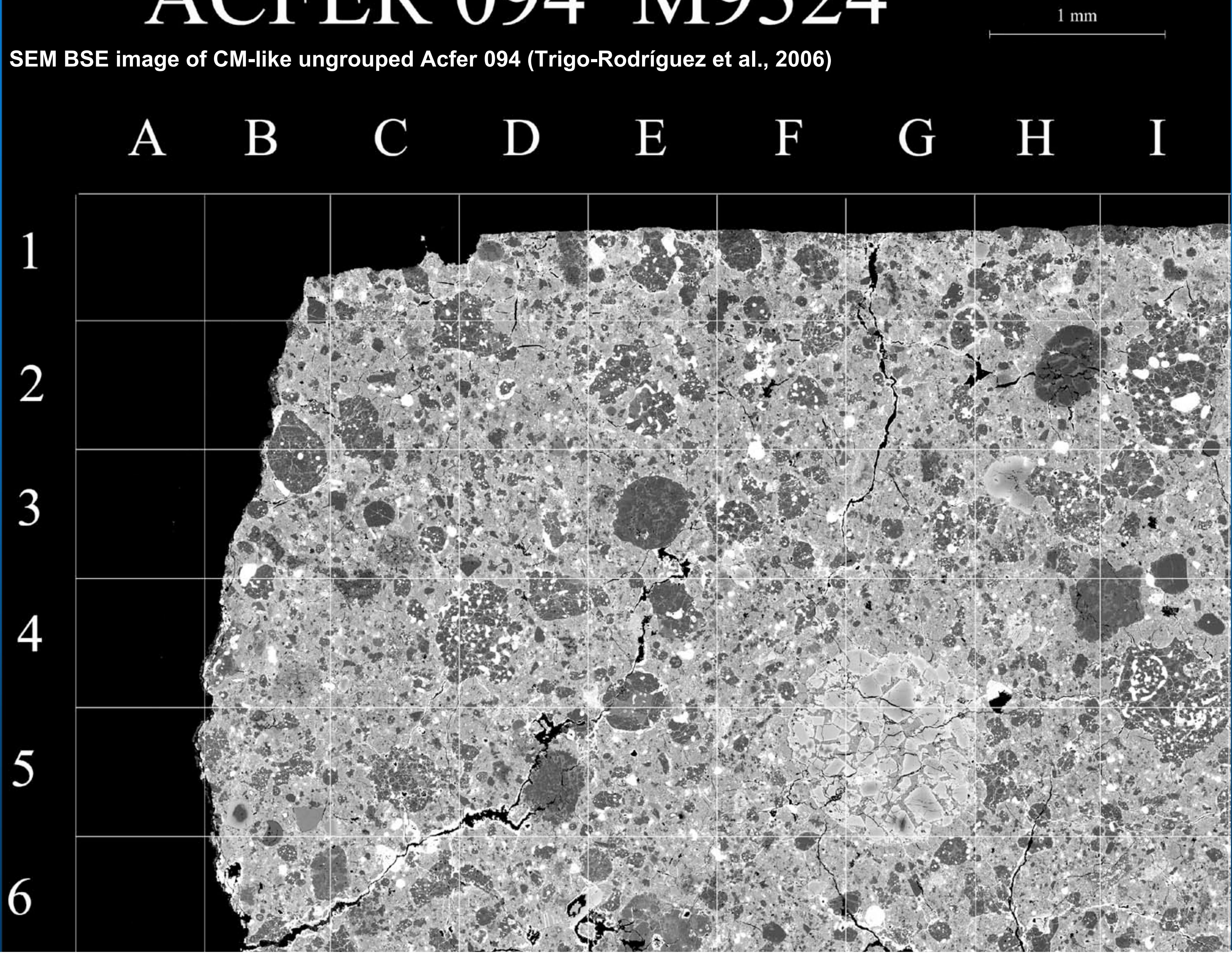
METEORITE EVIDENCE ARRIVED FROM CHONDRITIC ASTEROIDS

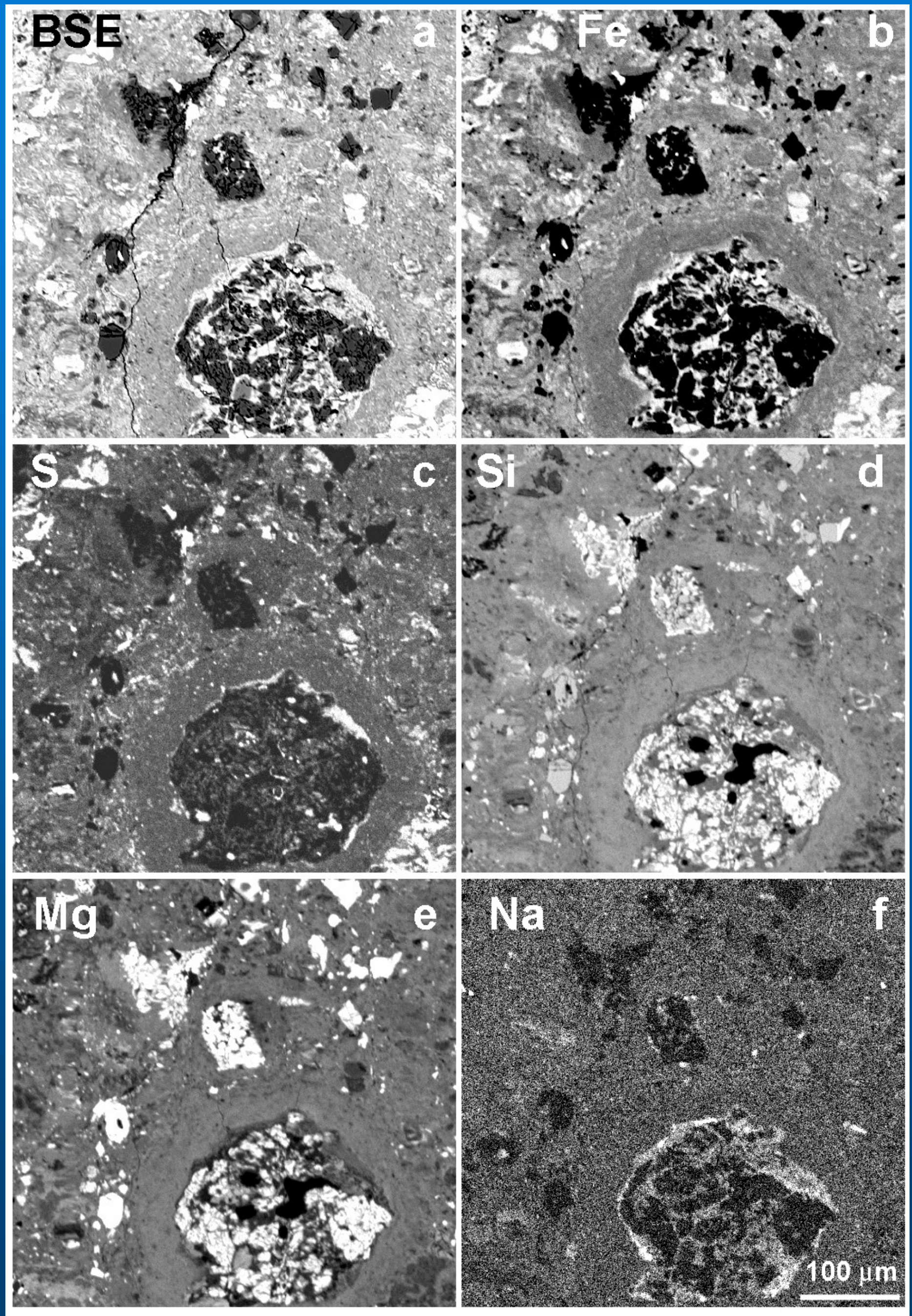


- Chondritic meteorites are coming from undifferentiated bodies:
  - They contain chondrules, refractory inclusions, but also fine dust and organics in the matrix
- Up to date 14 chondrite groups have been identified (see e.g. Weisber et al., 2006)
- Chemical differences among the chondrite groups suggest that each group represents rocks from a different reservoir (see eg. Hutchison, 2004)
- This idea has been reinforced because few chondrite breccias exist containing clasts from different chondrite groups (Bischoff et al, 2006)
- Primitive asteroids are covered by rubble.
  - Chondrite breccias are formed by regolith compaction under the action of impacts, and subsequent aqueous alteration

ACFER 094 M9324

SEM BSE image of CM-like ungrouped Acfer 094 (Trigo-Rodríguez et al., 2006)



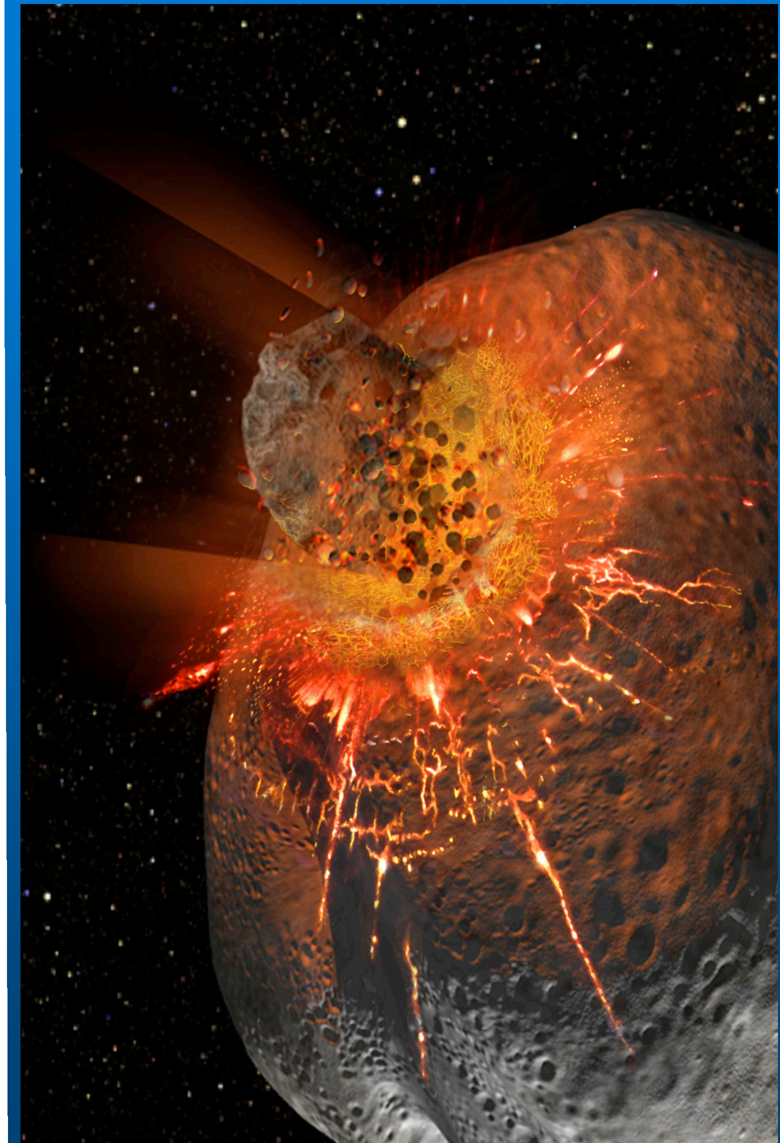


CM Murchison (Trigo-Rodriguez et al., GCA, 2006)

ION MICROPROBE

- Besides the Back-Scattered Electron (BSE) image this probe provides X-ray maps showing the abundance of chemical elements by locking at their respective wavelengths
  - It allows an easy identification of the mineral phases
  - Accurate measurements of chemical composition by just putting the beam on the selected region
- Valuable information on the thermal and aqueous alteration processes:
  - Most chondrites experienced significant compaction, and aqueous alteration
  - Unaltered samples are very weird

PARENT BODY PROCESSING



Don Dixon

- Bulk porosity *P* of asteroids (Britt et al., 2002)
  - From *P*<15% Differentiated Bodies: e.g. 1 Ceres, 2 Pallas, 4 Vesta, etc…
  - 15%<*P*<50%: Like e.g. 243 Ida, 433 Eros, …
  - *P*>50%. Like e.g. 22 Kalliope, 16 Psyshe, …
- Main consequences of impacts:
  - COMPACTION: Porosity attenuates the stress wave generated in an impact. Materials are heated, shacked and redistributed
  - Volatiles participate in the break up of the object, water may be released internally to soak the body
  - Re-aggregation: rubble piles (Michel et al.)
- Primitive (undifferentiated) bodies should have higher degree of porosity.
  - But most asteroids are moderately compacted
  - Importance of NEO follow-ups to decipher physical properties

LABORATORY EXPERIMENTS

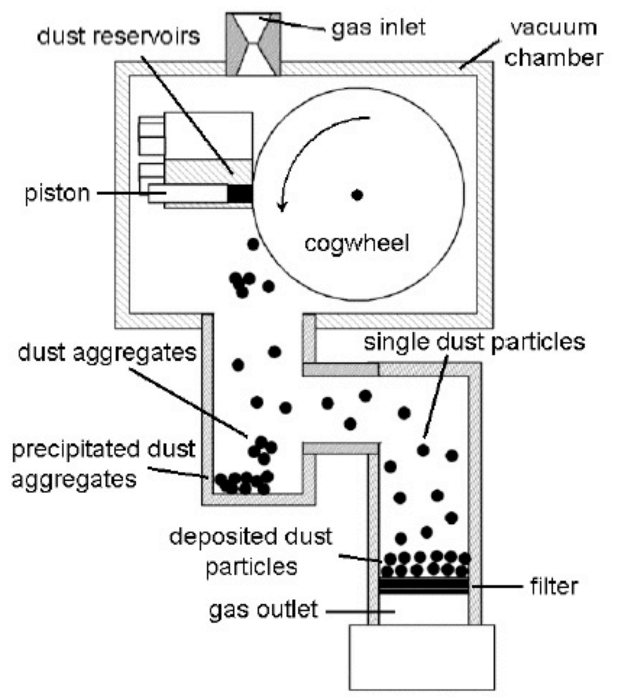
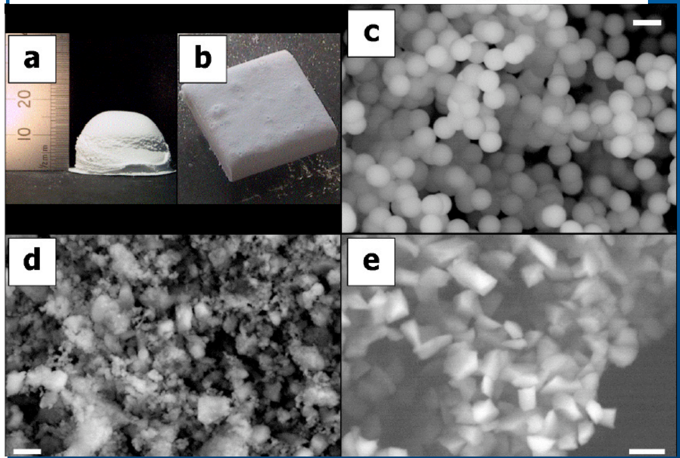


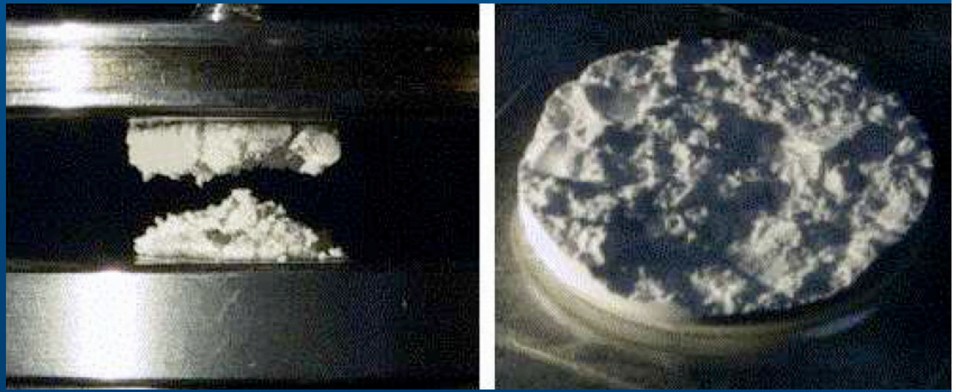
Fig. 1.— Principles of the experimental setup for the formation of macroscopic dust aggregates.



Blum et al., ApJ (2006)

- **Main goal:**
  - To learn about the expected physical properties of primeval accretionary bodies
- **Study of macroscopic aggregates (a,b) built from different types of grains:**
  - c) Spherical monodisperse SiO_2 grains
  - d) Irregular diamonds
  - e) Irregular polydisperse SiO_2
- **Resulting porosities of the order of 80 to 67% for the maximum compression of planetesimals (relative velocities of 50 m/s)**
- **Tensile strengths in the range of 0.2 to 1.1 kPa**

Tensile Strength Determination experiment



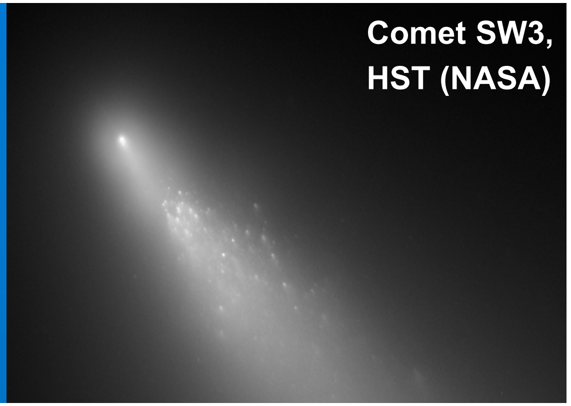
POROSITY AND DENSITY OF METEORITES

Measured and modelled porosities and bulk densities for primitive meteorites (CCs and ordinary) compared to other processed meteorites (achondrites, enstatite and stony-iron). Only those meteorite groups with a representative number of measured meteorites ($N_{met} \geq 3$) are included. Data from Britt and Consolmagno (2003).

Meteorite Class	Group	N_{met}	Average Porosity π (%)	Bulk density (g/cm^3)
Carbonaceous chondrite	CM	18	23.0 ± 7.5	2.12 ± 0.26
Carbonaceous chondrite	CO	8	19.8 ± 4.1	2.95 ± 0.11
Carbonaceous chondrite	CV	10	13.8 ± 9.1	2.95 ± 0.26
Carbonaceous chondrite	CI	4	11.3	2.11
Carbonaceous chondrite	CR	3	6.4 ± 3.8	3.10
Ordinary chondrite	H	157	6.4 ± 4.2	3.40 ± 0.18
Ordinary chondrite	L	160	4.5 ± 4.6	3.35 ± 0.16
Ordinary chondrite	LL	39	7.9 ± 4.2	3.21 ± 0.22
Enstatite chondrite	EH	5	-1.2 ± 2.5	3.72 ± 0.02
Enstatite chondrite	EL	7	2.7	3.55 ± 0.10
Achondrite	Diogenites	3	2.5	3.26 ± 0.17
Achondrite	Eucrites	9	8.6 ± 4.6	2.86 ± 0.07
Achondrite	Howardites	5	4.7 ± 0.5	3.02 ± 0.19
Achondrite	Aubrites	6	0	3.12 ± 0.15
Achondrite	Ureilites	3	8.9	3.05 ± 0.22
Stony-Iron	Pallasites	5	0.0 ± 5.2	4.76 ± 0.10
	Mesosiderites	3	3.0 ± 8.1	4.25 ± 0.02

- **All meteorites arriving at Earth are compacted samples:**
  - **Materials are also biased during atmospheric transition towards the tougher objects (!)**

MORE PRISTINE OBJECTS: COMETS!



Blum et al. (2006) ApJ.

COMETARY DENSITIES.

Density ($kg\,m^{-3}$)	Comment	Comet
500 – 1200	Lower value preferred	1P/Halley
600 (+900/ – 600)		1P/Halley
700 (+4200/ – 670)		1P/Halley
$\lesssim$ 500		17 JFCs
490 (+340/ – 200)		19P/Borrelly
180 – 300		19P/Borrelly
100 – 370	Preferred range	67P/Churyumov–Gerasimenko
$\lesssim$ 600		67P/Churyumov–Gerasimenko
220 – 330		67P/Churyumov–Gerasimenko
$\lesssim$ 600 – 800		81P/Wild 2
450 ± 250		9P/Tempel 1
400 ± 300		9P/Tempel 1
600 ± 100	Nucleus not rotating	D/1993 F1 Shoemaker–Levy 9
$\lesssim$ 1000	9h period assumed	D/1993 F1 Shoemaker–Levy 9
500 – 600		D/1993 F1 Shoemaker–Levy 9
250		D/1993 F1 Shoemaker–Levy 9
$\gtrsim$ 440	If strengthless	6P/d'Arrest
$\gtrsim$ 250	If strengthless	10P/Tempel 2
$\gtrsim$ 530	If strengthless	31P/Schwassmann–Wachmann 2
$\gtrsim$ 350	If strengthless	46P/Wirtanen
$\gtrsim$ 370	If strengthless	95P/Chiron
$\gtrsim$ 340	If strengthless	107P/Wilson–Harrington
$\gtrsim$ 1300	If strengthless	133P/Elst–Pizarro
$\gtrsim$ 100	If $Y \gtrsim 200$ Pa	133P/Elst–Pizarro
$\gtrsim$ 200	If strengthless	C/1991 L3 Levy
500 – 900	Near-surface layer	C/1983 H1 IRAS–Araki–Alcock
500 – 1000	Near-surface layer	2P/Encke
700 – 1300	Near-surface layer	26P/Grigg–Skjellerup
700 – 1300	Near-surface layer	C/1983 J1 Sugano–Saigusa–Fujikawa
200 – 400	Near-surface layer	C/1996 B2 Hyakutake
300 – 800		C/1996 B2 Hyakutake

COMETARY AND METEOROID TENSILE STRENGTHS. THE REFERENCE NUMBERS REFER TO [A] KLINGER ET AL. (1989), [B] MÖHLMANN (1996), [C] DAVIDSSON (2001), [D] LISSE ET AL. (1999), [E] TRIGO-RODRÍGUEZ AND LLORCA (2006).

Tensile strength (Pa)	Comet/Meteoroid Source	Reference
Comet		
10,000, > 100 . . . 1,000	Sun-grazing comets	[A]
500 ± 450	46P/Wirtanen	[B]
> 3 . . . 6	6P/d'Arrest	[C]
> 47	Levy 1991 XI	[C]
> 2	28P/Neujmin I	[C]
> 5	29P/Schwassmann-Wachmann 1	[C]
> 13 . . . 53	29P/Schwassmann-Wachmann 2	[C]
> 6 . . . 9	10P/Tempel 2	[C]
> 4 . . . 7	107P/Wilson-Harrington	[C]
> 1	46P/Wirtanen	[C]
> 7,700 . . . 46,000	95P/Chiron	[C]
> 20 . . . 400	C/1996 B2 Huyakutake	[D]
Meteoroid Source		
34,000 ± 7000	2P/Encke (Taurids)	[E]
6,000 ± 300	7P/Pons-Winnecke	[E]
400 ± 100	21P/Giacobini-Zinner	[E]
22,000 ± 2,000	45P/Honda-Mrkos-Pajdusakova (Alpha Capricornids)	[E]
6,000 ± 3,000	55P/Tempel-Tuttle (Leonids)	[E]
12,000 ± 3,000	109P/Swift-Tuttle (Perseids)	[E]

- **Low bulk densities and tensile strengths are indicators of the degree of primitiveness of minor bodies (Trigo-Rodríguez and Blum, 2009)**
- **Comets, and their dormant remnants can be among the less-processed solar system objects**

CLUES FROM THERMAL INERTIA

- Additional clues on the structure of the surface can be obtained from remote thermal inertia (Γ) measurements:
  - An imaging mid-IR spectrometer like the proposed by Bowles et al. (2009)
- Γ is defined as a measure of the resistance of a material to temperature changes. It is given by: $\Gamma = \sqrt{\rho \cdot \kappa \cdot c}$

  Being the bulk density (ρ), the thermal conductivity (κ), and the heat capacity (c).
- Note that $\Gamma \rightarrow 0$ shows that the surface is in instantaneous equilibrium with solar radiation. In other words, the ability of such a body to conduct and store heat is very low due to the presence of fine-grained materials. A good example was comet 9P/ Tempel 1 (Groussin et al., 2006)
- Formation of a rubble mantle, and its ulterior compaction under impacts change the contact between the grains. As κ has been found to be strongly dependent on microstructure of porous materials, it implies changes in Γ

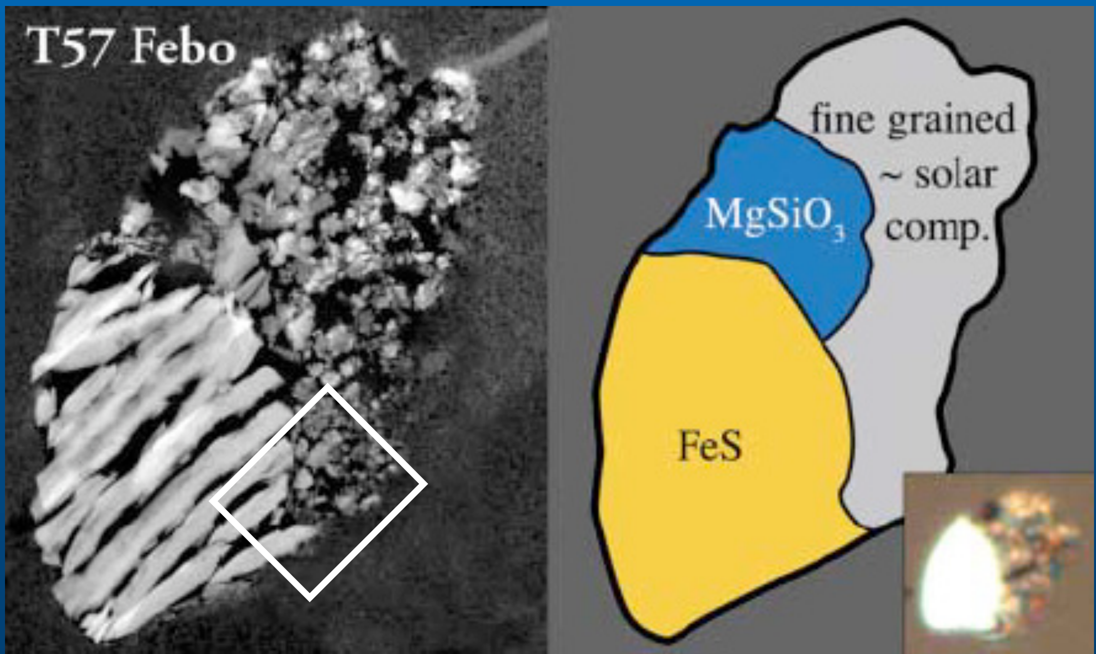
9P/Tempel 1, Deep Impact (NASA)

Body	Description	Γ ($J\cdot m^{-2}\cdot s^{-1/2}\cdot K^{-1}$)	Reference
Largest MB asteroids	Fine dust	5-25	Müller & Lagerros, 1998
asteroids	Regolith	30	Delbó et al. (2007)
Moon	Lunar regolith	50	Mellon et al. (2008)
Mercury		70	Spencer et al. 1989
Planetary surfaces	Coarse sands	400-1500	Mellon et al. (2008)
Saturn rings	Bare solid rocks	2500	Mellon et al. (2008)

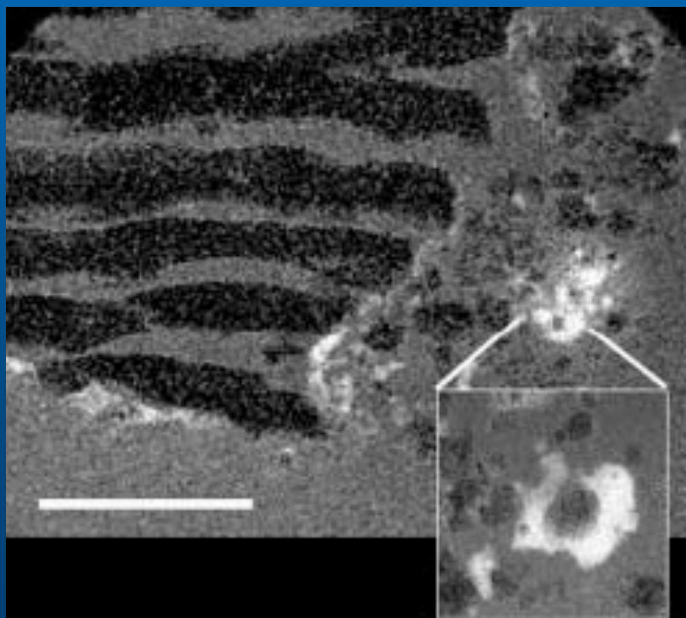
THE NATURE OF 81P/WILD 2

- The largest recovered grains are ~5-15μm in diameter.
  - The toughest fragments that survived the capture process (biasing)
  - But some particles (like e.g. Febo) reveal that large grains are embedded in fragile aggregates similar to the matrix of carbonaceous chondrites, except for being highly porous

- This fine-grained component rich in organics contains important isotopic anomalies:
  - Detected enrichments in $^{15}N/^{14}N$
  - Such anomalies would be diluted under compaction, and aqueous alteration processes

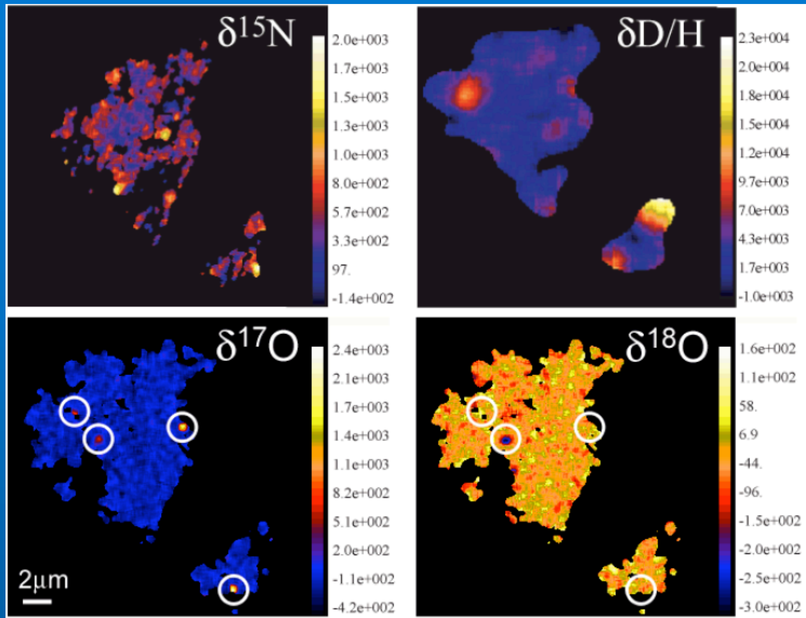


8 μm-size particle (FEBO) (Brownlee et al., 2006)


TEM image showing ^{15}N hotspot (PET/NASA)

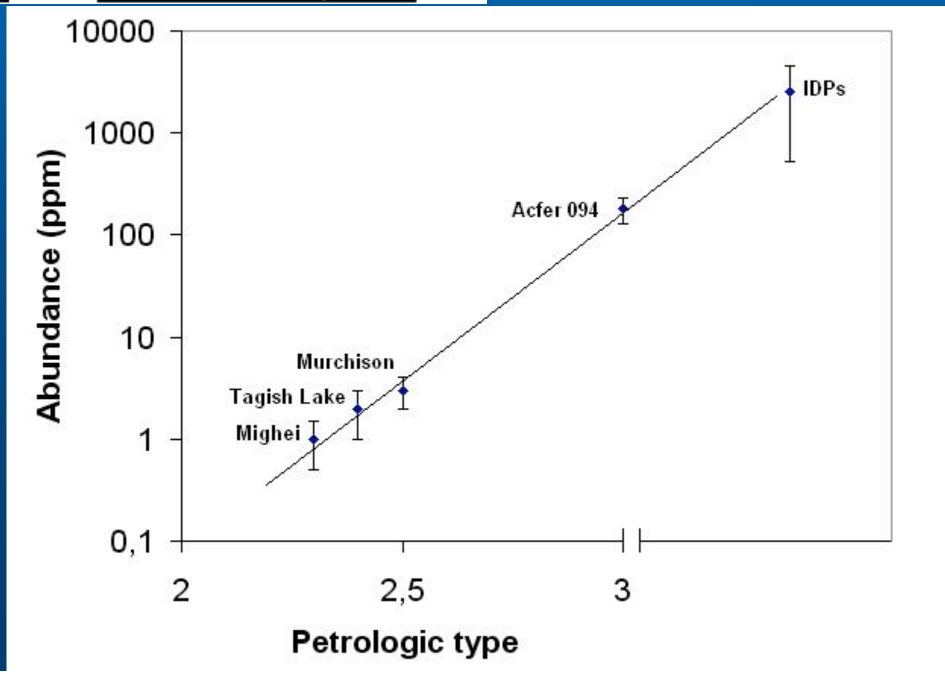
IDPs FROM 26P/GRIGG-SKJELLERUP

- IDPs also preserve isotopic anomalies, particularly in N, H and O presumably associated with molecular cloud chemistry
- Isotopic anomalies are heterogeneously distributed, mostly surrounding presolar grains
- Some comets have preserved the solar system "starting" materials
  - They not experienced significant collisional compaction and aqueous alteration



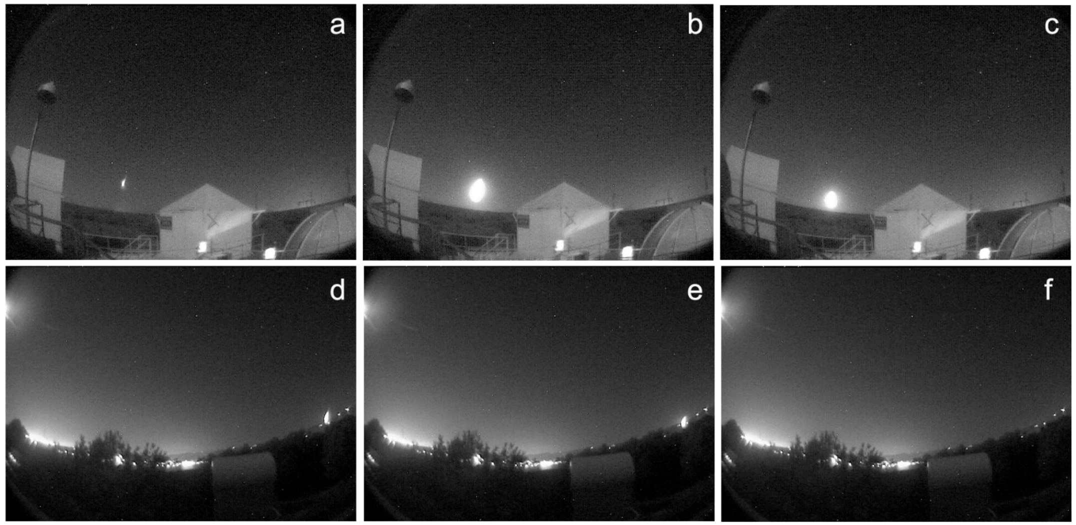
Isotopic ratio images of IDP L2054 E1
Likely from comet 26P
(Nguyen et al., 2007)

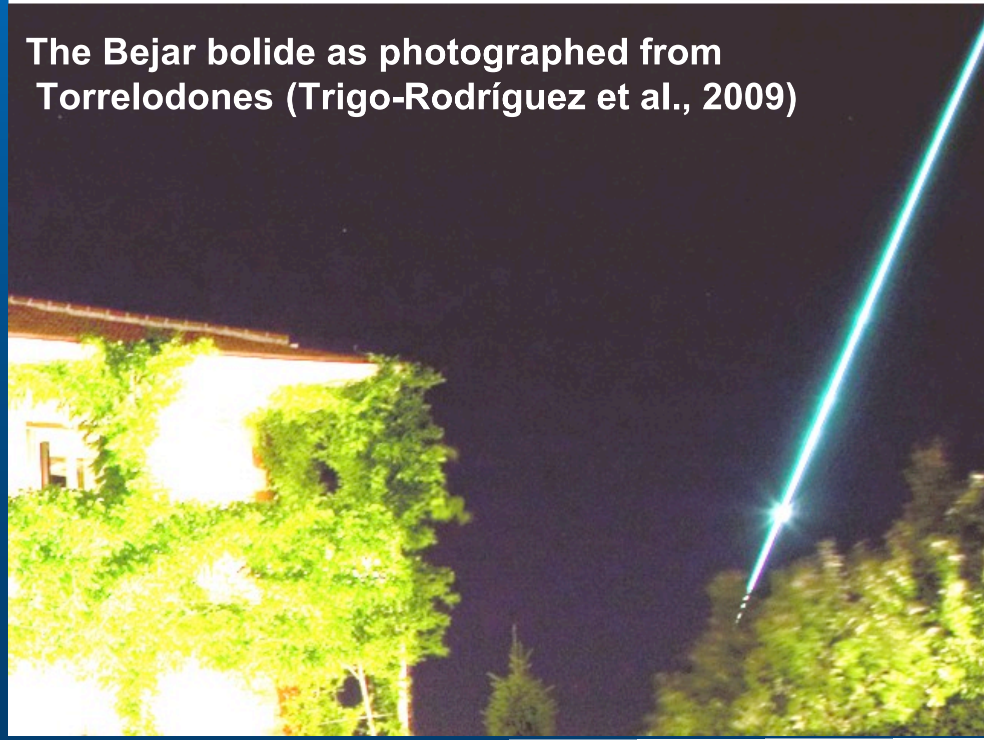
Presolar grains abundance as a function of petrologic type
Trigo-Rodríguez & Blum, in preparation



HIGH-STRENGTH ROCKS FROM COMETS?

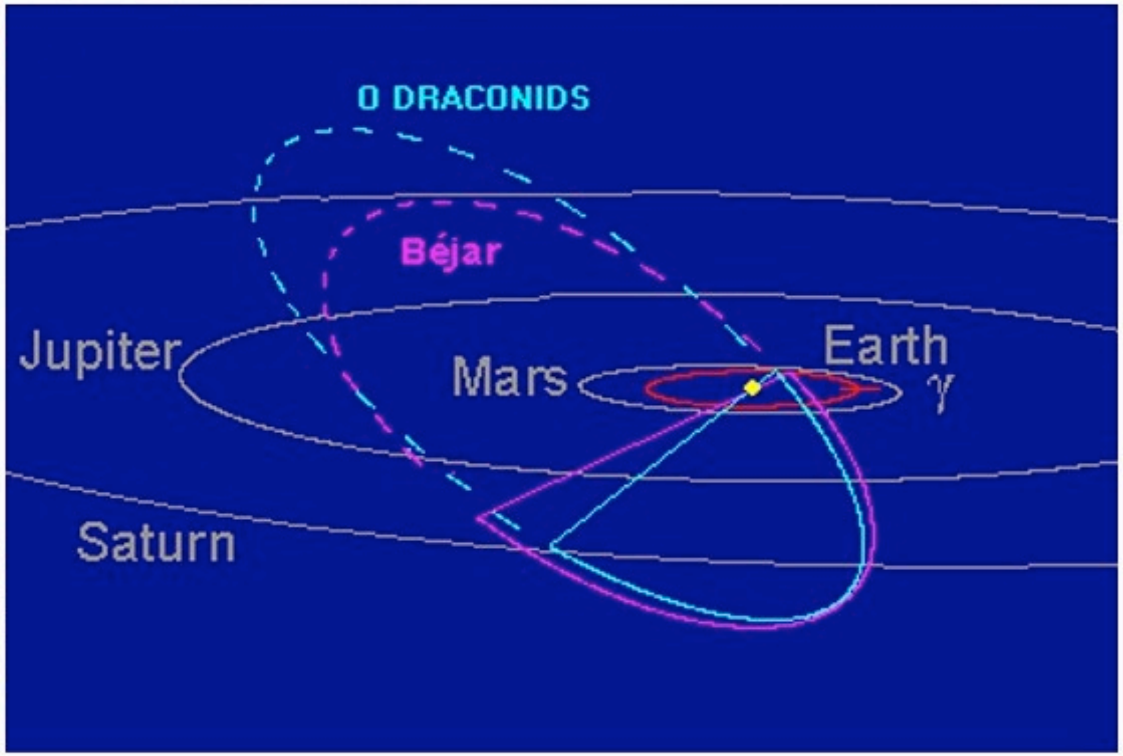
- The Béjar bolide recorded on July 11, 2008 is the brightest recorded by the SPMN in about one decade (M_{abs}=-18)
- The incoming mass was over 1 Tm, deepening until a height of 22 km, indicative of meteorite survival
- High-strength boulders released during the fragmentation of a cometary nucleus as opposed to the fluffy grains ejected during normal outgassing:
  - Growing evidence that cometary nuclei are also rubble piles
- Some comets might have meter-sized rocks in their interiors:
  - Remote observations of disrupted comets: e.g. C/1999S4 LINEAR





The Bejar bolide as photographed from Torrelodones (Trigo-Rodríguez et al., 2009)

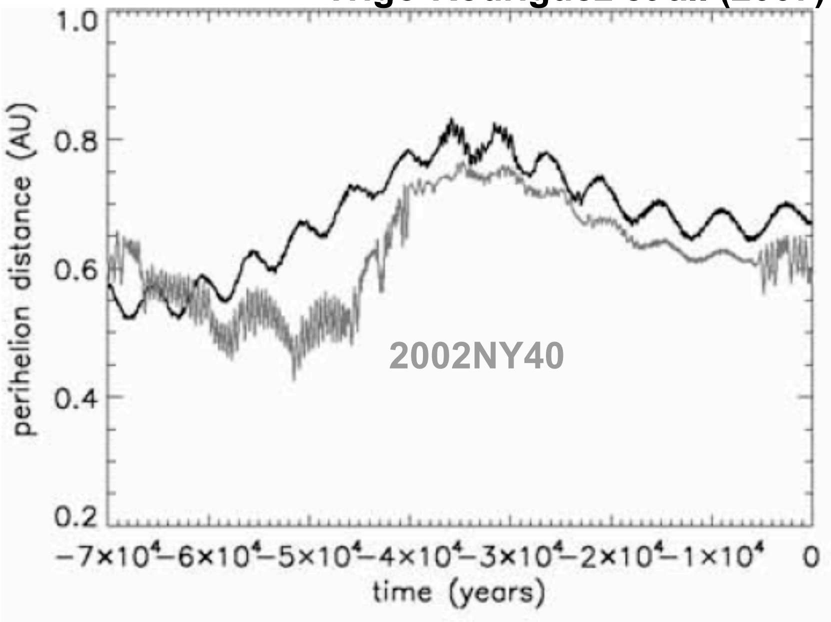
DISRUPTION OF C/1919Q2 METCALF: A JUPITER FAMILY COMET

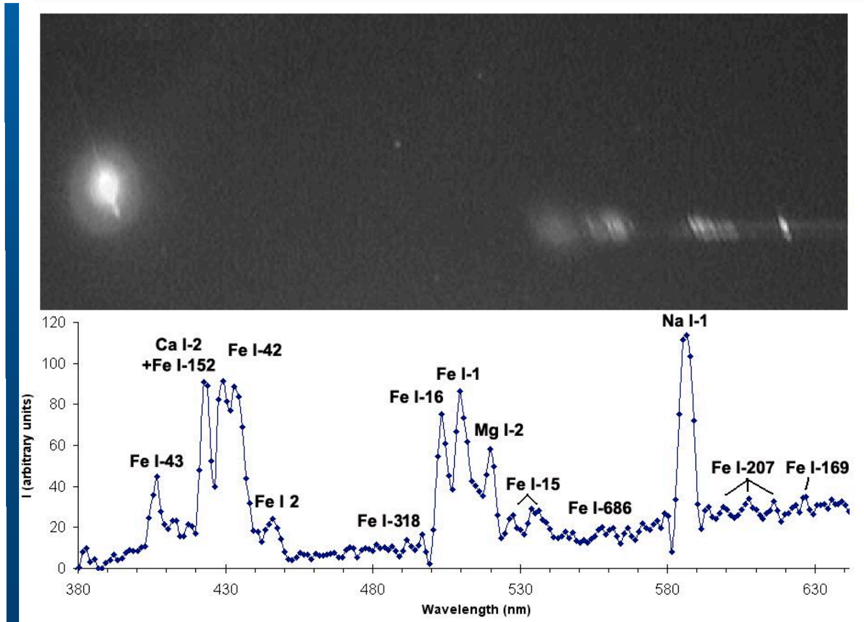


- The orbit computed for the Béjar bolide suggests an origin behind Jupiter, opening a pathway for meteorites from the outer solar system (Trigo-Rodríguez et al., 2009, MNRAS)
- Some comets would also deliver meteorites (Orgueil?, Gounelle et al., 2006)
- A deep penetrating radar like e.g. CONSERT would search for heterogeneity in the internal structure of Marco Polo target (Kofman et al., 2007)

LOOKING FOR GOOD TARGETS...

Trigo-Rodríguez et al. (2007)





- Dehydration, and weathered mineralogy is produced by solar irradiation, and impacts.
  - *Thermal skin depth* useful to estimate how the T amplitude at the surface is damped as a function of depth, and the rotation period
  - Spinel features likely associated with unequilibrated mineralogy: "fresh" CAI-rich chondritic materials (Sunshine et al., 2008)
- Objects with C- or D- reflection spectrum:
  - Either the NEOs already suggested: 1999 JU3
  - Comet 107P/Wilson-Harrington (4015)
  - Others to be characterized shortly:
    - 2008ED69 is a likely carbonaceous 1-3 km-sized Apollo asteroid progenitor of the κ Cygnid meteoroid stream (Jenniskens & Vaubaillon, 2008)
    - Fireball spectrum exhibiting chondritic features (Trigo-Rodríguez et al., MNRAS, 2009)
- Phaeton and 2005 UD associated with Geminids, and experiencing significant heating at perihelion are also interesting from other point of view

CONCLUSIONS

- If we wish to recover "pristine" materials to get direct information on the nature of early solar system:
  - Marco Polo target should be carefully selected: surface mineralogy vs. interior
  - Dynamical evolution: Backwards integration of the orbital elements can give clues on collisional, irradiative, and aqueous processing
- NEO follow-ups can contribute to assess: thermal inertia, reflectance features, and bulk density: useful to decipher how evolved is the target
- To obtain primitive samples:
  - C or D-class asteroids might be considered, but preferentially avoiding those suspicious to have experienced significant processing
  - We should figure out how dormant comets look like remotely
  - Meteoroid studies can allow identifying other interesting candidates
- The internal structure of Marco Polo's target should be also studied:
  - A deep penetrating radar should be considered during the mapping phase of the mission
  - Such instrument would also help to decipher the best place to land.

- Thanks for your attention: let's work together to achieve Marco Polo exploration of a primitive body!