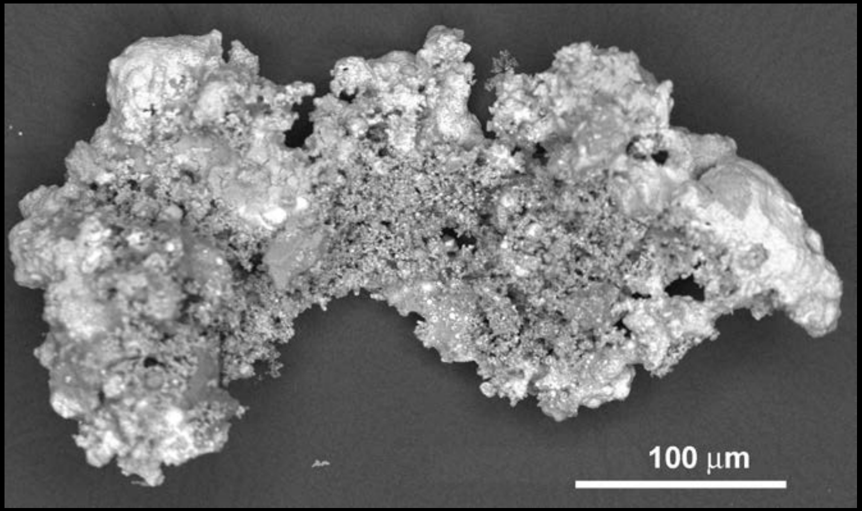
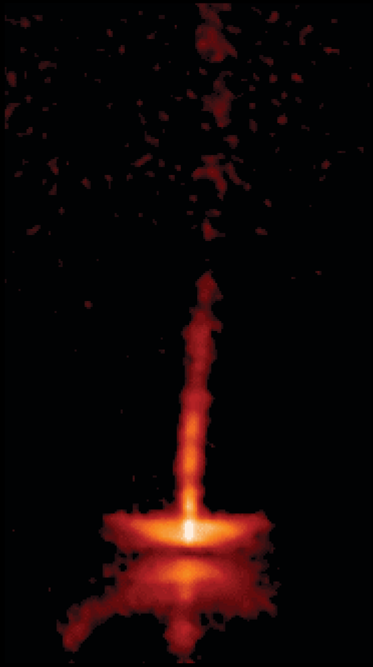
La formation et l'évolution du système solaire,

ce que nous disent les poussières…



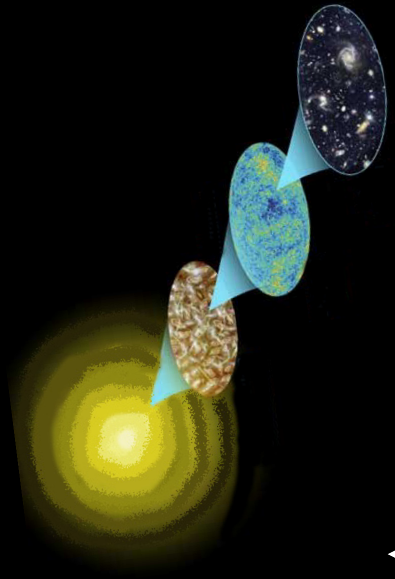


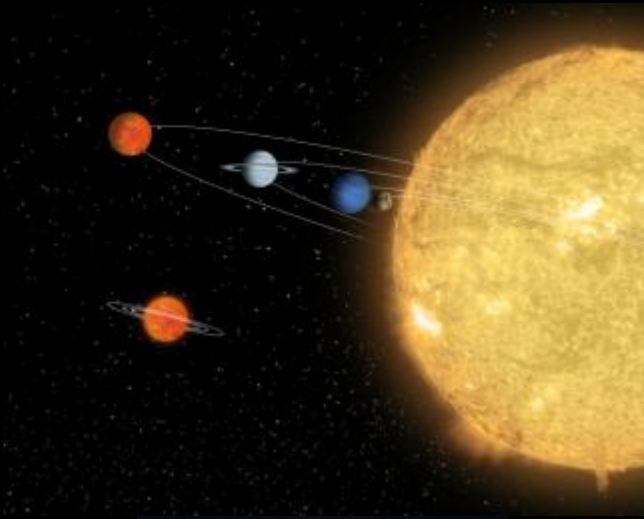
Jean Duprat

CSNSM-CNRS-Université Paris XI

8èmes Journées Informatique de l'IN2P3-IRFU
Lalonde les Maures 24 octobre 2012

Du Big-Bang à nous ...

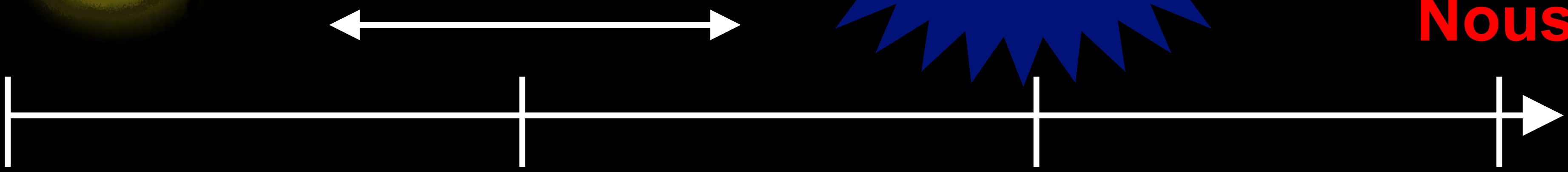




Formation
de notre
Galaxie

**Formation
de notre
Système Solaire**

Nous



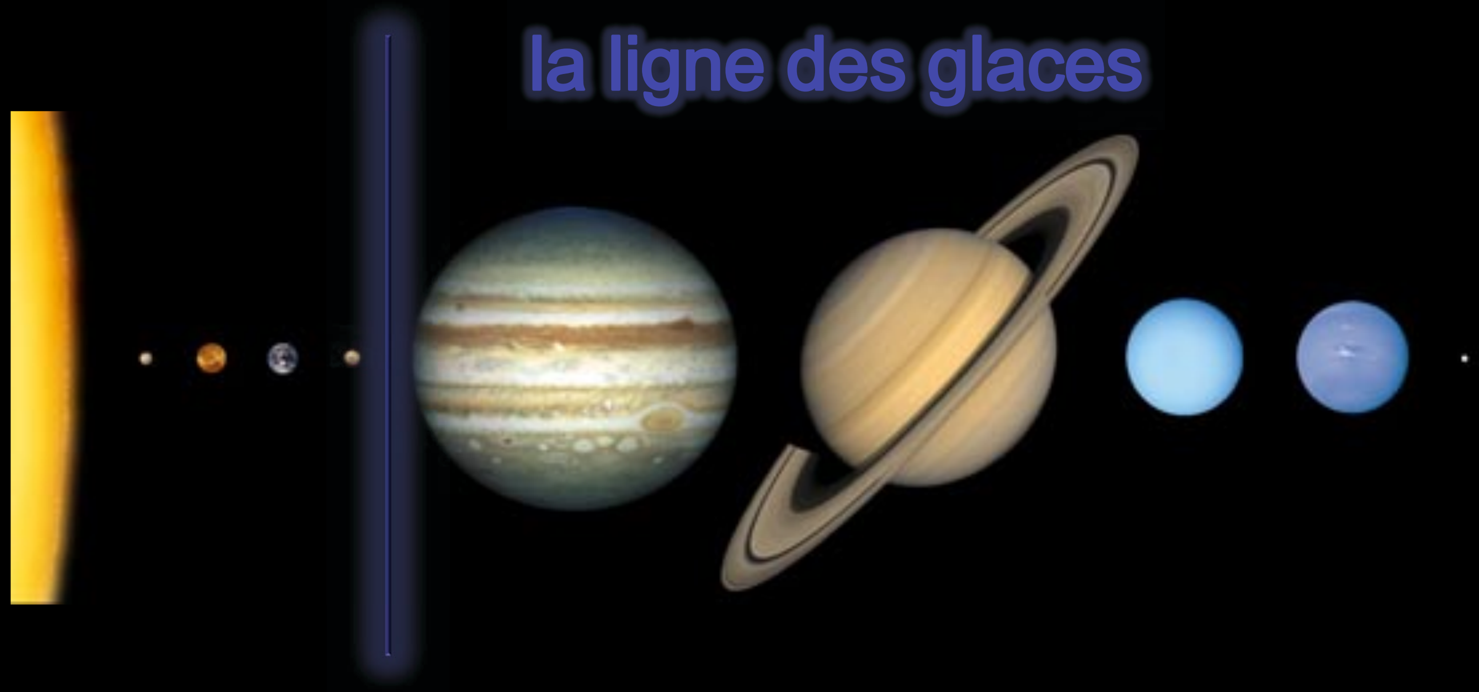
Big-Bang

5
Milliards
d' années

10
Milliards
d' années

15
Milliards
d' années

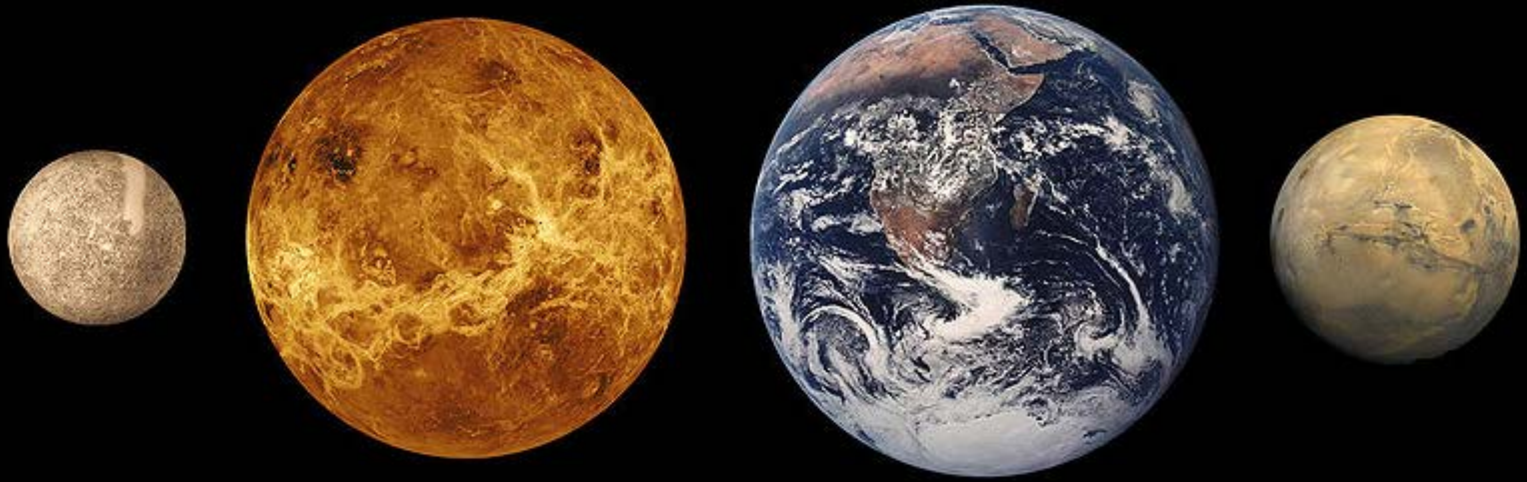
L’ architecture actuelle du système solaire



- M Soleil ($M_{\odot}$) : 1.99 10^{30} kg
- M Terre ($M_{\oplus}$) : 5.97 10^{24} kg
- M Jupiter ($M_{♃}$) : 1.90 10^{27} kg (317 $M_{\oplus}$, 0.1% $M_{\odot}$)

Pourquoi une telle dichotomie entre le système solaire interne et externe ?

En deçà de *la ligne des glaces*, un monde des roches…



- Les planètes « terrestres », le monde tellurique
- Faibles masses (total 2 $M_{\oplus}$)
- Hautes densités (4 - 5.5 g/cm^3)
- Des atmosphères secondaires

Au delà de *la ligne des glaces* : un monde de gaz et de glaces…

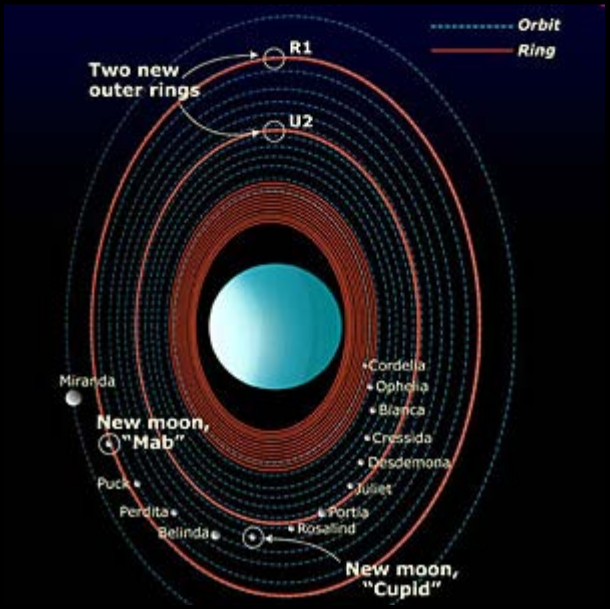
Jupiter, ♃

Saturne

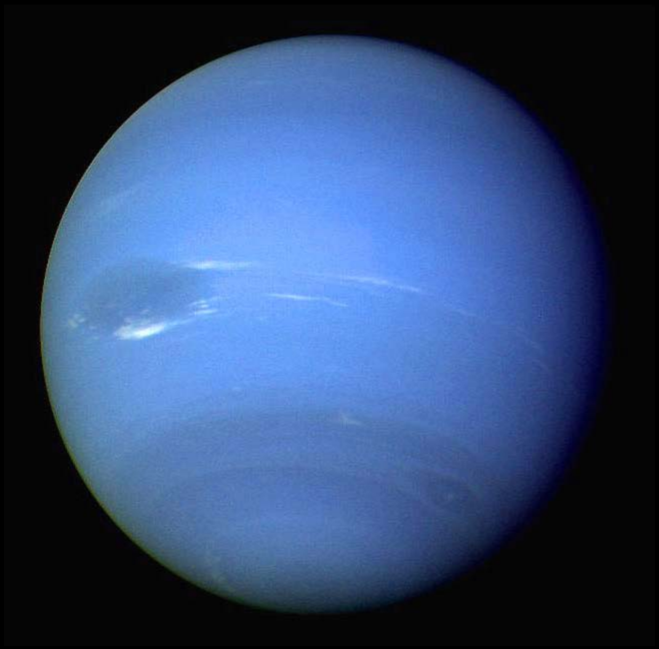
les géantes gazeuses

- Masses élevées (318 and 95 $M_\oplus$)
- Densités faibles (1.3 and 0.7)
- Atmosphère primaire (H, He)

les géantes de glaces


Orbit
Ring
R1
Two new outer rings
U2
Miranda
New moon, "Mab"
Cordelia
Ophelia
Bianca
Cressida
Desdemona
Juliet
Portia
Rosalind
Puck
Perdita
Belinda
New moon, "Cupid"

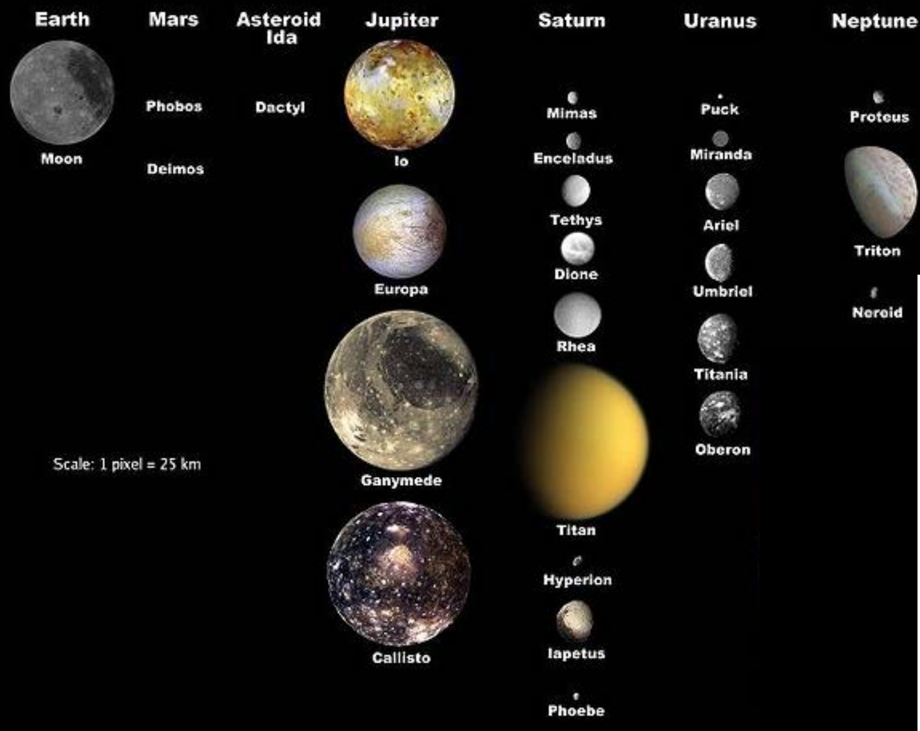
Uranus

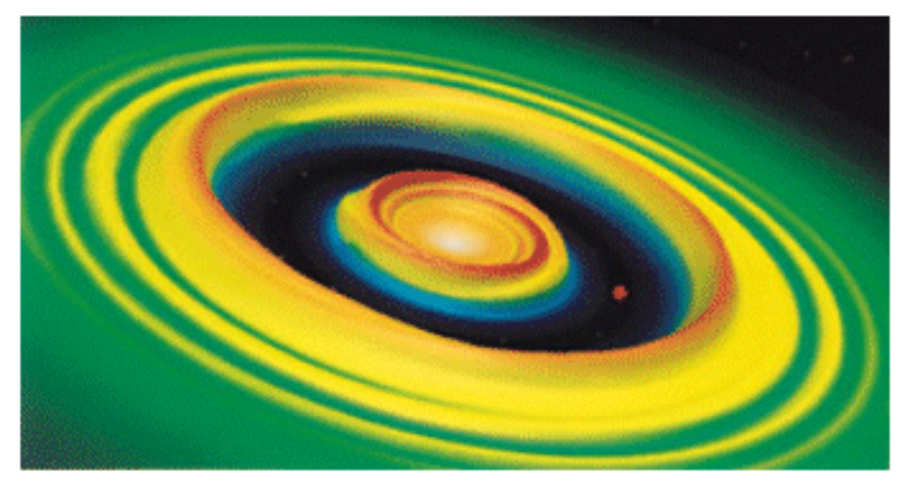


Neptune

- Des objets glacés
- Masses élevées (14.5 et 17.2 $M_\oplus$)
- Densité faible (1.6)

La formation des planètes géantes



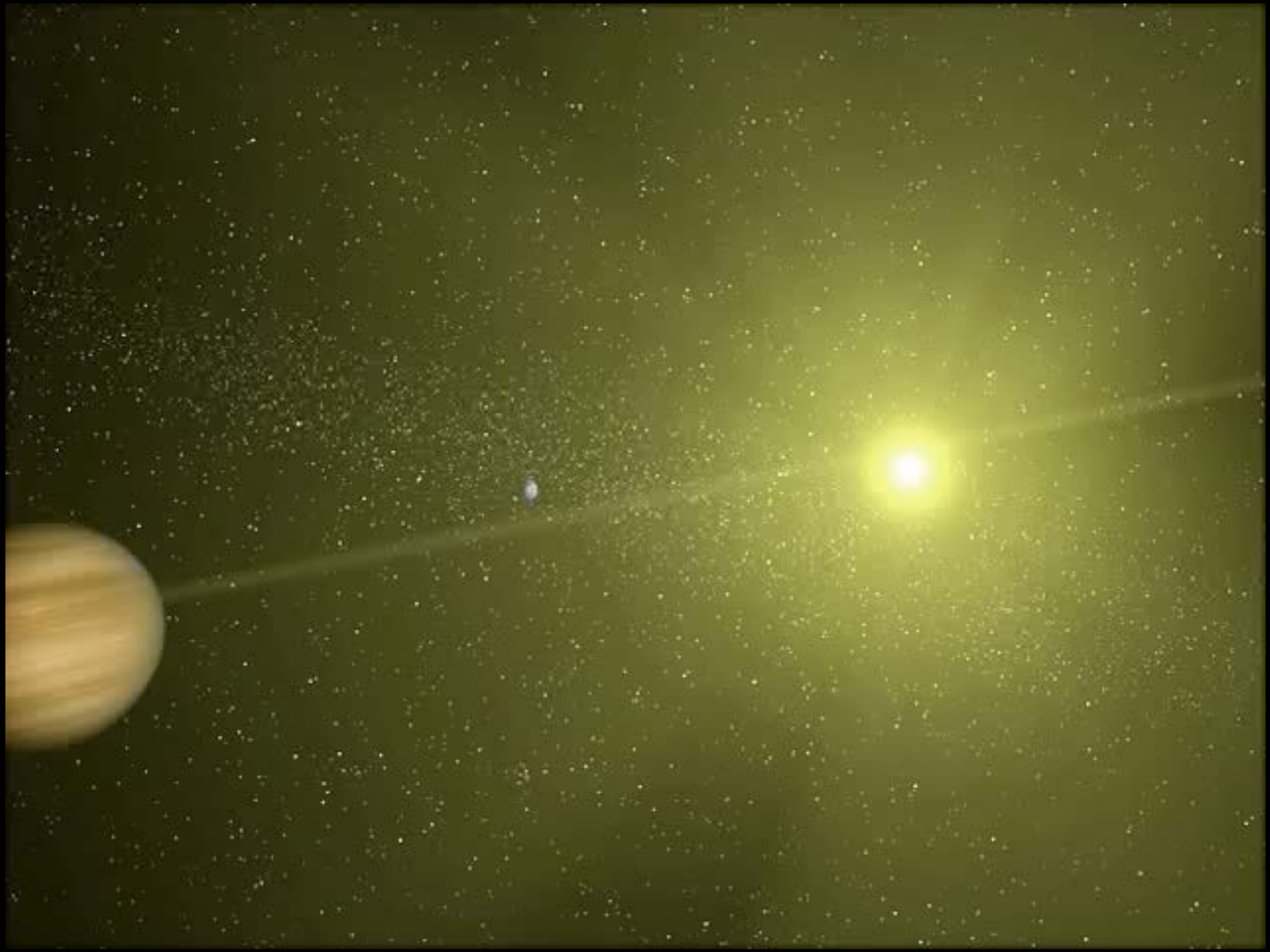


La formation d’un cœur de 10-15 x la masse terrestre a déclenché **l’effondrement local du disque** :

→ de nombreux satellites

→ un système d’anneaux

Il y a 4,5 milliards d'années, le soleil et les planètes se formaient…



NASA Web site,
artiste view

Quels témoins pouvons nous retrouver ?

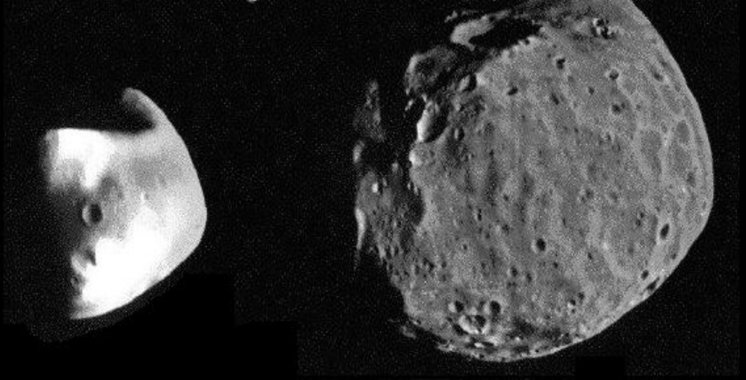
Les asteroides

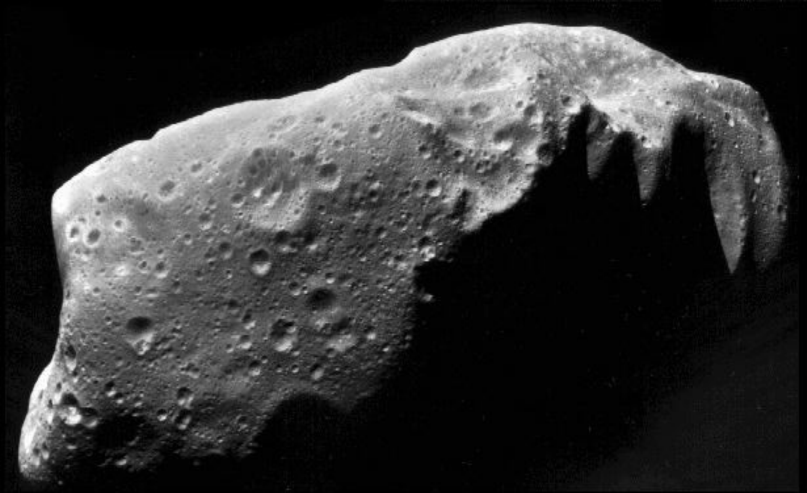
Giuseppe Piazzi
(1746 - 1826)

- Le premier découvert Ceres 1801 (948 km)

- Puis suivis de
  - Pallas 1802 (532 km)
  - Juno 1805
  - Vesta 1807 (529 km)

- Masse totale ~ 4 % de la Lune (0.05% Mt)
- Des dizaines de milliers d’objets
- 1 à 2 millions d’astéroïdes > 1 km





Météorites & Antarctique

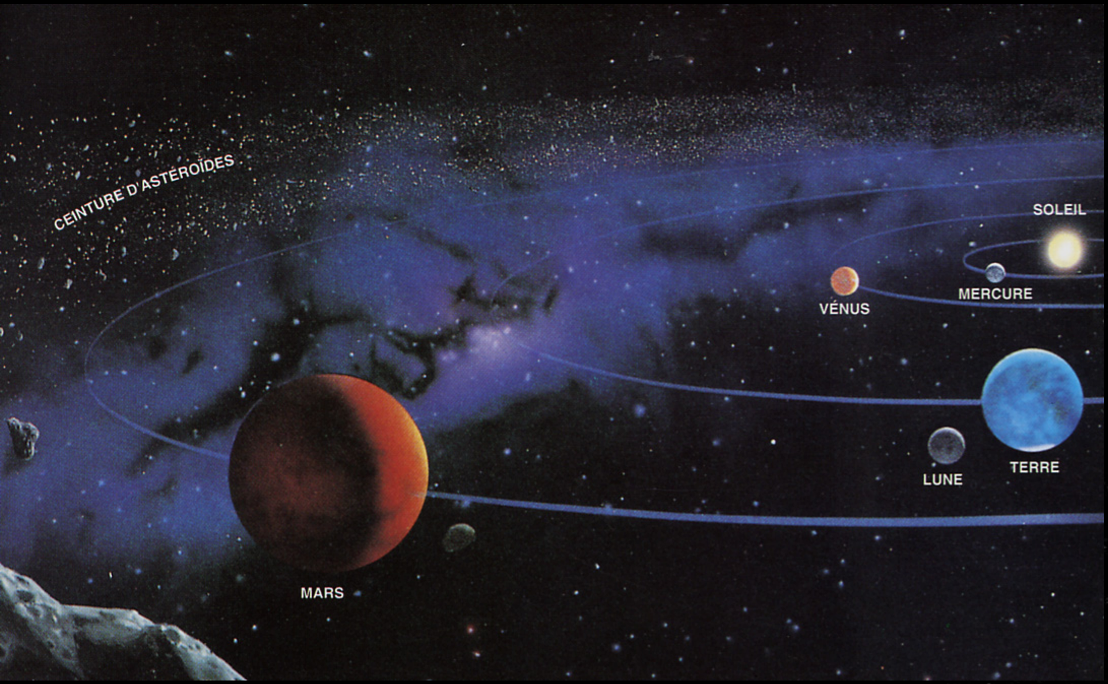
0 0 1 3 2 0 5
0 1 2 3 4

+ 30,000 meteorites
USA, Japon, Italie

ANSMET
THE ANTARCTIC SEARCH FOR METEORITES

Antarctic Meteorite
Research
PI : R. Harvey, Case Univ. US

D’où viennent les météorites ?


CEINTURE D'ASTÉROÏDES
SOLEIL
MERCURE
VÉNUS
TERRE
LUNE
MARS

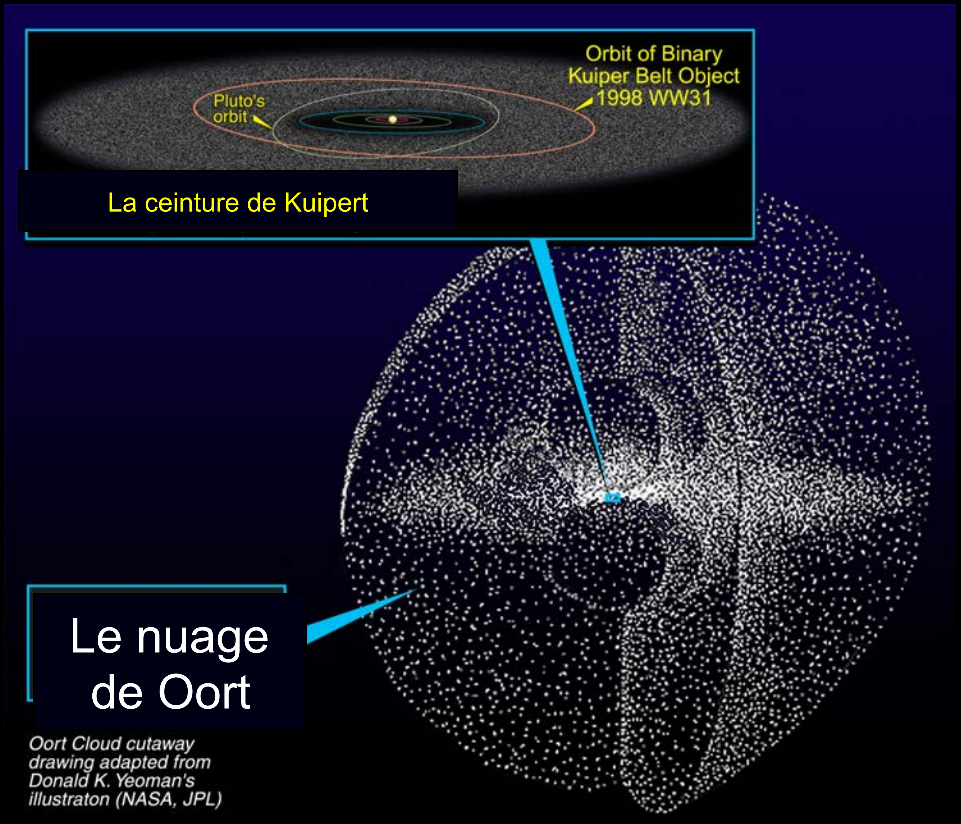
2004 08 14 23:40:48 GST
Real time
Speed: 0.000 m/s
Follow Gaspra
FOV: 25° 36' 6.5" (1.00×)

This addon for the Celestia
3D Space Simulator can be found at
www.celestiamotherlode.net

Entre Mars et Jupiter, les astéroïdes…
nos voisins immédiats

Aux confins du système solaire…

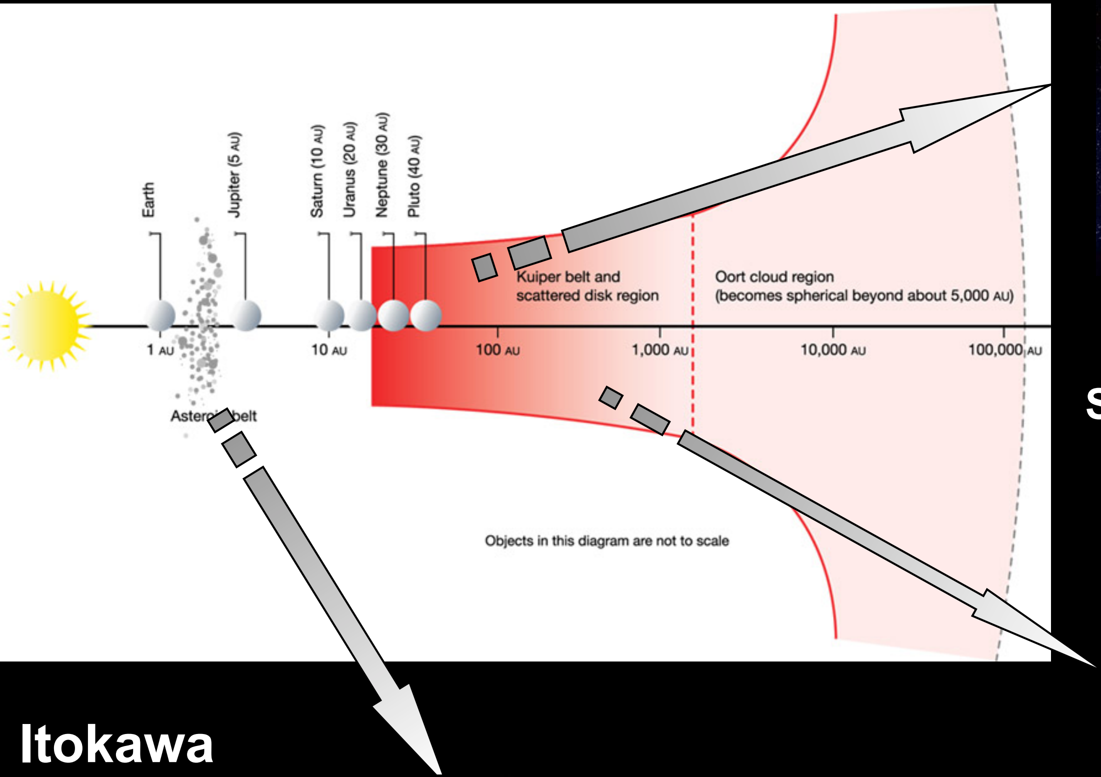
les comètes

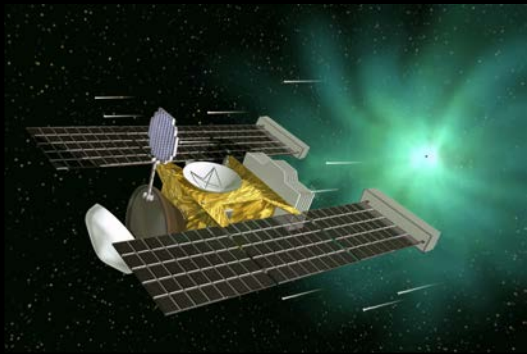

Orbit of Binary
Kuiper Belt Object
1998 WW31
Pluto's
orbit
La ceinture de Kuipert
Le nuage
de Oort

Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustraton (NASA, JPL)

Terre soleil : **1 UA** = 10^9 km
Pluton : 50 UA
La ceinture de Kuiper : 70 UA
Le Nuage Oort : > 50 000 UA

Qu'est ce que le matériau cométaire ?


Earth
Jupiter (5 AU)
Saturn (10 AU)
Uranus (20 AU)
Neptune (30 AU)
Pluto (40 AU)
1 AU
10 AU
100 AU
1,000 AU
10,000 AU
100,000 AU
Astero belt
Kuiper belt and
scattered disk region
Oort cloud region
(becomes spherical beyond about 5,000 AU)
Objects in this diagram are not to scale

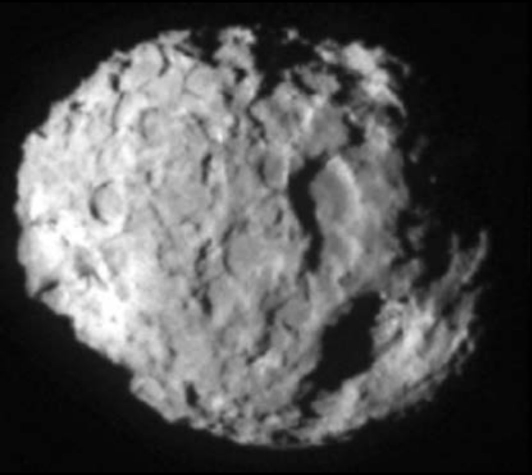


STARDUST mission
(janvier 2006)

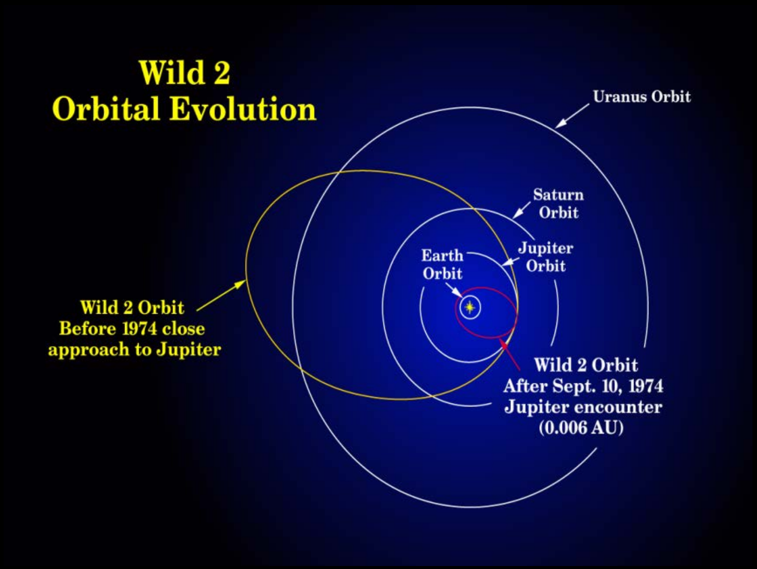
La mission **ROSETTA**
(novembre 2014)

Itokawa
Mission Hayabusa
(Juin 2010)

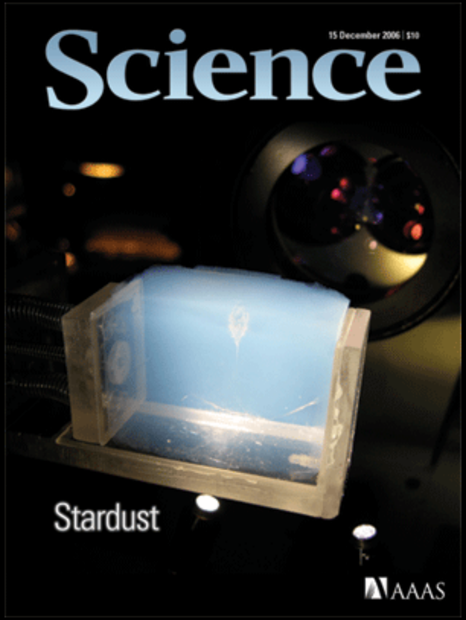
Janvier 2006, le retour de la mission STARDUST (NASA)

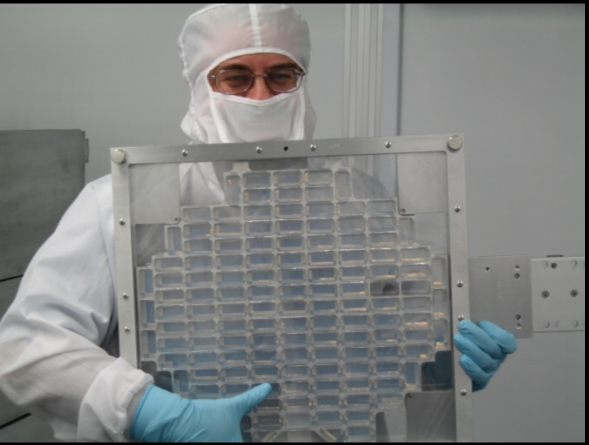


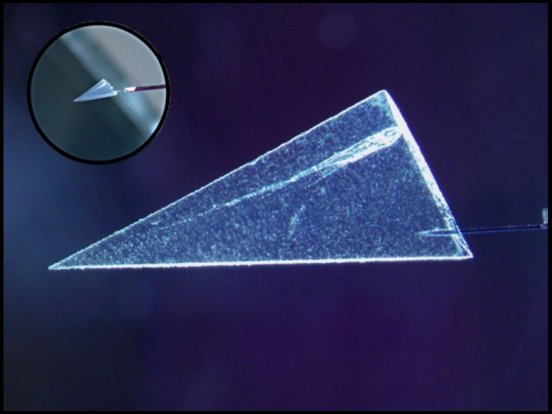
Janvier 2004
Comète 81P/Wild 2


Wild 2
Orbital Evolution
Uranus Orbit
Saturn Orbit
Jupiter Orbit
Earth Orbit
Wild 2 Orbit Before 1974 close approach to Jupiter
Wild 2 Orbit After Sept. 10, 1974 Jupiter encounter (0.006 AU)

January 2006

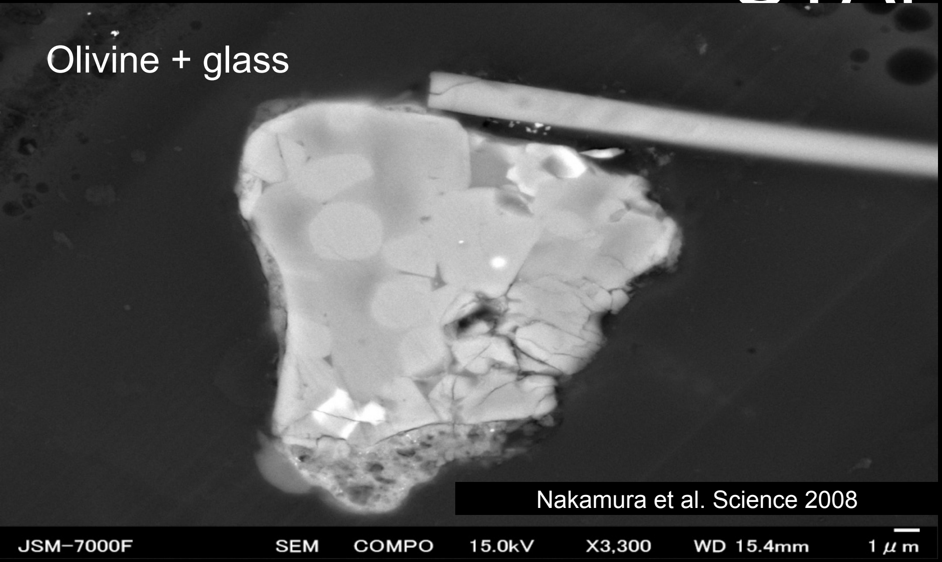

Science
15 December 2006 | $10
Stardust
AAAS



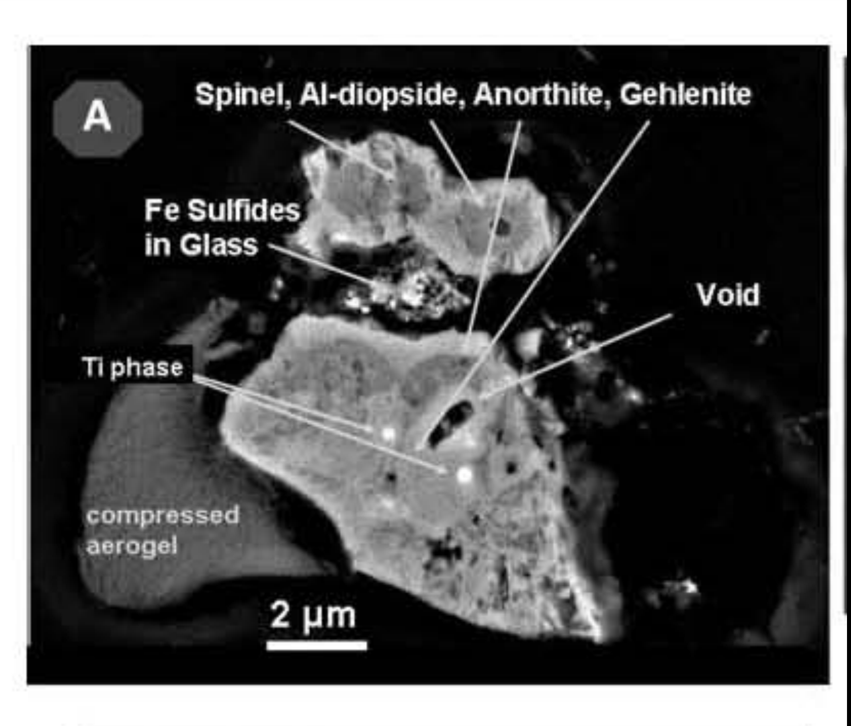


Décembre 2006, les premiers résultats

Les principaux résultats de la mission STARDUST


Olivine + glass
JSM−7000F
SEM
COMPO
15.0kV
X3,300
WD 15.4mm
1 μm

Nakamura et al. Science 2008


A
Spinel, Al-diopside, Anorthite, Gehlenite
Fe Sulfides in Glass
Void
Ti phase
compressed aerogel
2 μm

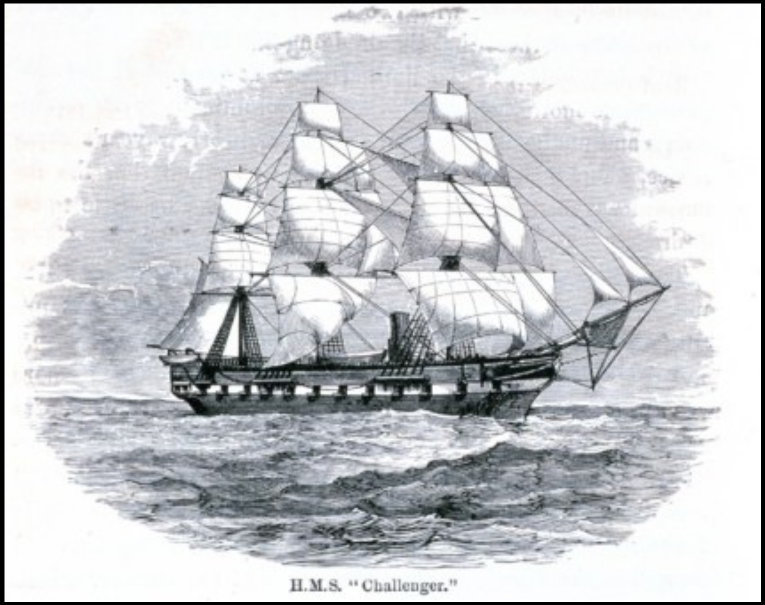
"Remarkably enough, we have found fire and ice"

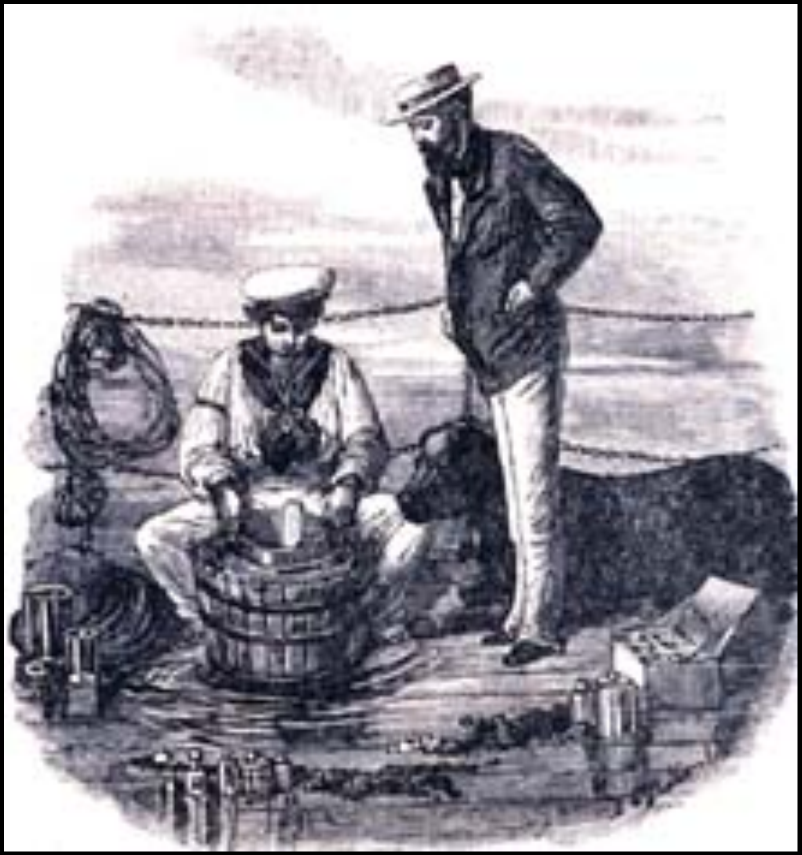
- Taille 1-10 μm
- Une composition moyenne identique à celles des chondrites (CI).
- Présence de phase réfractaires (CAI, chondres).

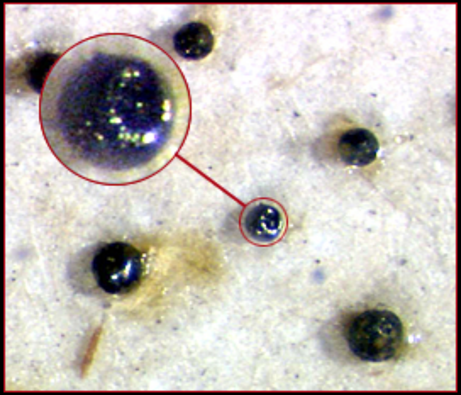
«…Their presence in a comet proves that the formation of the solar system included mixing on the grandest scales…» Brownlee et al. Science 2006

De la poussière extraterrestre, les premières collectes terrestres…

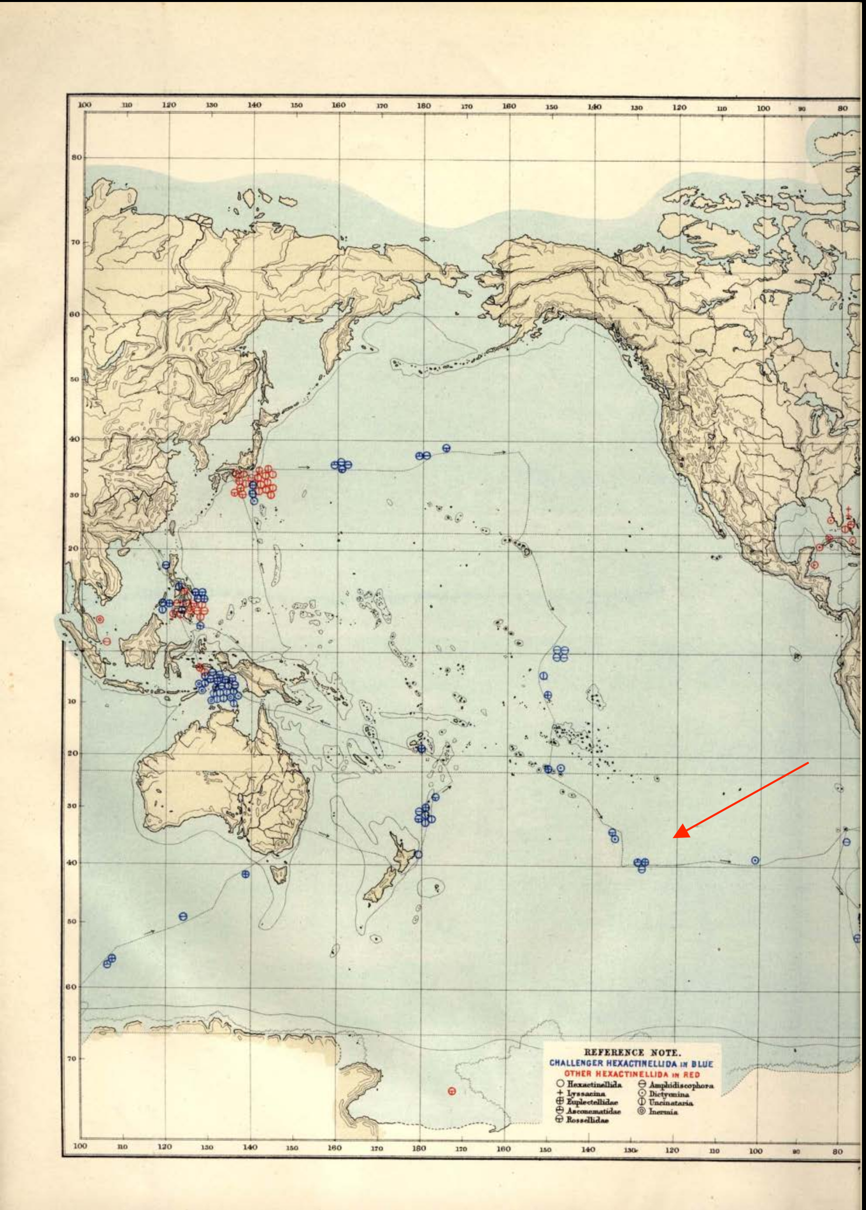
1873-1876 : l’expédition HMS *Challenger*

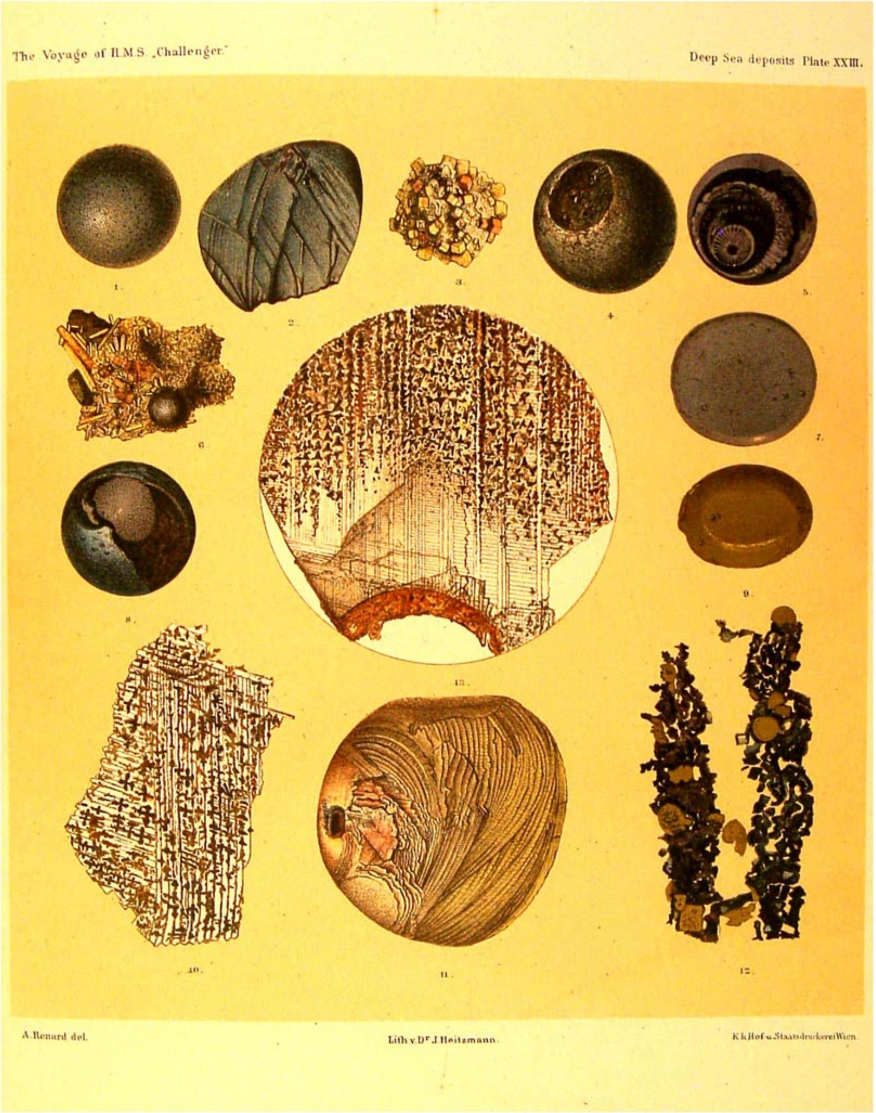

H.M.S. "Challenger."


Murray 1876


-> Sphérules cosmiques
(micrométéorites fondues lors de l’entrée atmosphérique)

Des sphérules cosmiques au centre des océans


REFERENCE NOTE.
CHALLENGER HEXACTINELLIDA IN BLUE
OTHER HEXACTINELLIDA IN RED
○ Hexactinellida
+ Lyssacina
⊕ Euplectellidae
⊕ Asconematidae
⊕ Rossellidae
⊖ Amphidiscophora
⊙ Dictyonina
⦶ Uncinataria
◎ Inermia



The Voyage of H.M.S. „Challenger."

Deep Sea deposits Plate XXIII.

1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.

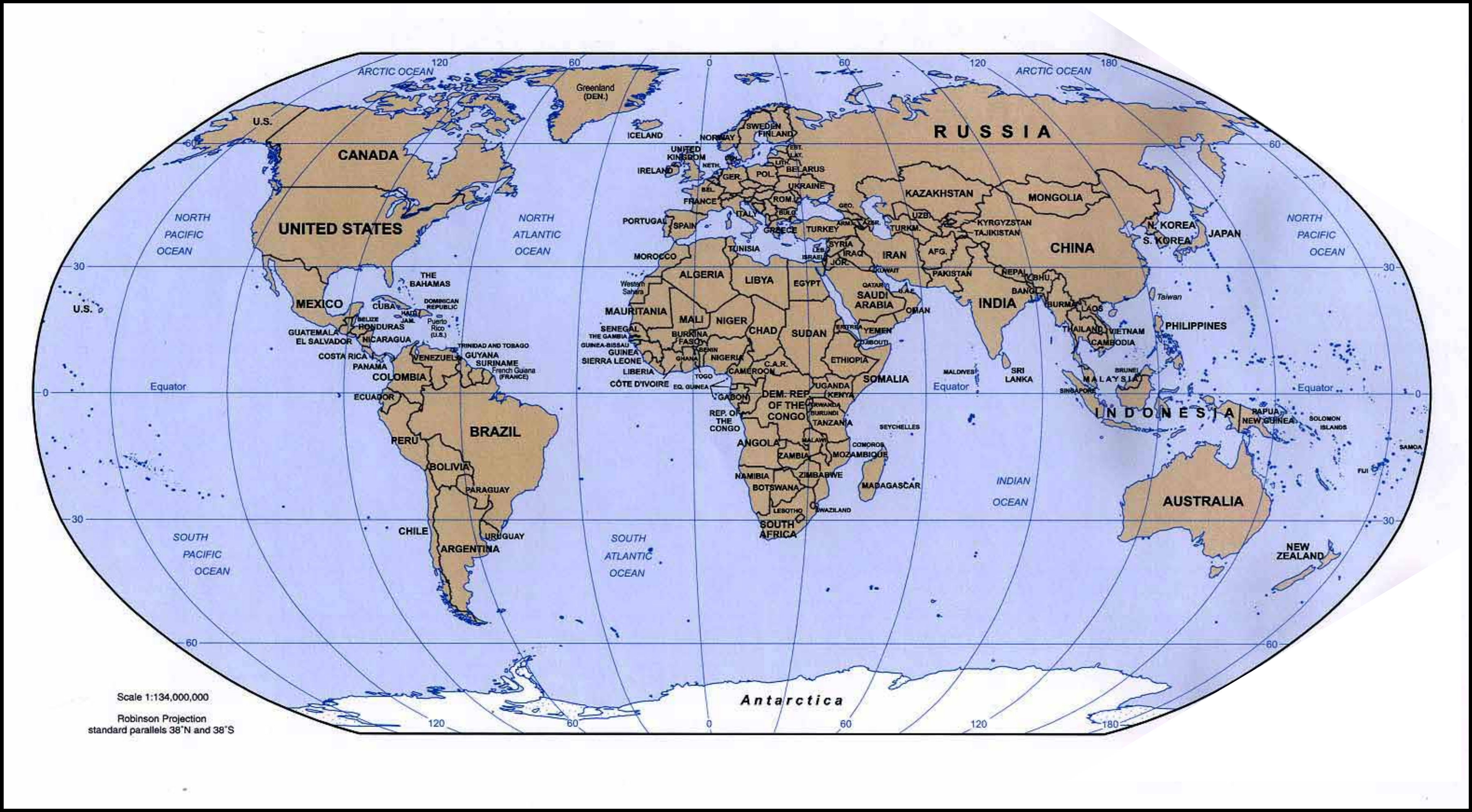
A. Renard del.

Lith. v. Dr J. Heitzmann.

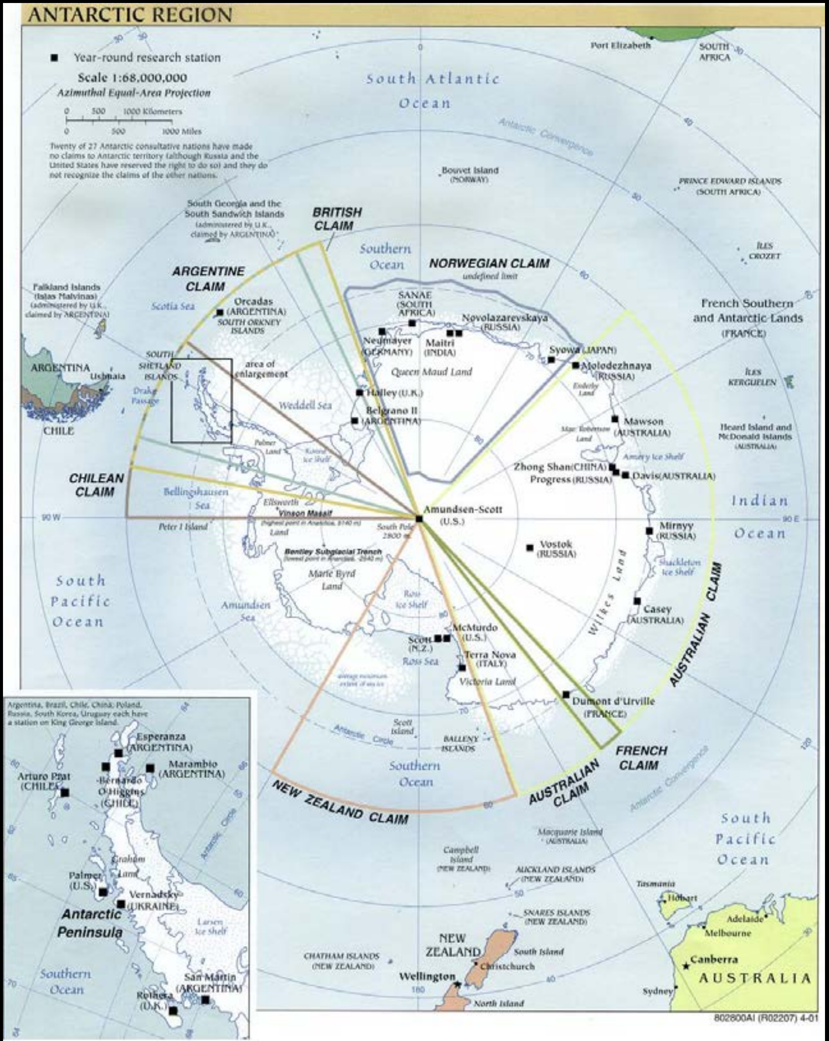
K. k. Hof- u. Staatsdruckerei Wien.

Murray & Renard 1891

Et sur terre… est-il possible de trouver des poussières interplanétaires ?


ARCTIC OCEAN
Greenland (DEN.)
U.S.
CANADA
ICELAND
NORWAY
SWEDEN
FINLAND
RUSSIA
UNITED KINGDOM
IRELAND
EST.
LAT.
LITH.
BELARUS
NETH.
GER.
POL.
BEL.
UKRAINE
FRANCE
ROM.
BULG.
ITALY
GREECE
TURKEY
GEO.
ARM.
AZER.
KAZAKHSTAN
MONGOLIA
UZB.
TURKM.
KYRGYZSTAN
TAJIKISTAN
N. KOREA
S. KOREA
JAPAN
CHINA
UNITED STATES
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
PORTUGAL
SPAIN
MOROCCO
TUNISIA
SYRIA
LEB.
ISRAEL
JOR.
IRAQ
IRAN
AFG.
PAKISTAN
NEPAL
BHU.
BANG.
INDIA
ALGERIA
LIBYA
EGYPT
KUWAIT
QATAR
SAUDI ARABIA
U.A.E.
OMAN
Western Sahara
MAURITANIA
MALI
NIGER
CHAD
SUDAN
ERITREA
YEMEN
DJIBOUTI
SENEGAL
THE GAMBIA
GUINEA-BISSAU
GUINEA
SIERRA LEONE
LIBERIA
BURKINA FASO
GHANA
BENIN
TOGO
NIGERIA
CÔTE D'IVOIRE
CAMEROON
C.A.R.
ETHIOPIA
SOMALIA
EQ. GUINEA
GABON
REP. OF THE CONGO
DEM. REP. OF THE CONGO
UGANDA
KENYA
RWANDA
BURUNDI
TANZANIA
SEYCHELLES
ANGOLA
MALAWI
ZAMBIA
COMOROS
MOZAMBIQUE
NAMIBIA
ZIMBABWE
BOTSWANA
MADAGASCAR
LESOTHO
SWAZILAND
SOUTH AFRICA
BURMA
LAOS
Taiwan
THAILAND
VIETNAM
CAMBODIA
PHILIPPINES
MALDIVES
SRI LANKA
BRUNEI
MALAYSIA
SINGAPORE
INDONESIA
PAPUA NEW GUINEA
SOLOMON ISLANDS
SAMOA
FIJI
AUSTRALIA
NEW ZEALAND
INDIAN OCEAN
THE BAHAMAS
MEXICO
CUBA
HAITI
DOMINICAN REPUBLIC
JAM.
Puerto Rico (U.S.)
BELIZE
HONDURAS
GUATEMALA
EL SALVADOR
NICARAGUA
COSTA RICA
PANAMA
TRINIDAD AND TOBAGO
VENEZUELA
GUYANA
SURINAME
French Guiana (FRANCE)
COLOMBIA
ECUADOR
PERU
BRAZIL
BOLIVIA
PARAGUAY
CHILE
URUGUAY
ARGENTINA
SOUTH PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
Equator
Antarctica
120
60
0
60
120
180
30
0
30
60
Scale 1:134,000,000
Robinson Projection
standard parallels 38°N and 38°S

Les bases scientifiques en Antarctique


ANTARCTIC REGION

Twenty of 27 Antarctic consultative nations have made no claims to Antarctic territory (although Russia and the United States have reserved the right to do so) and they do not recognize the claims of the other nations.

Argentina, Brazil, Chile, China, Poland, Russia, South Korea, Uruguay each have a station on King George Island.

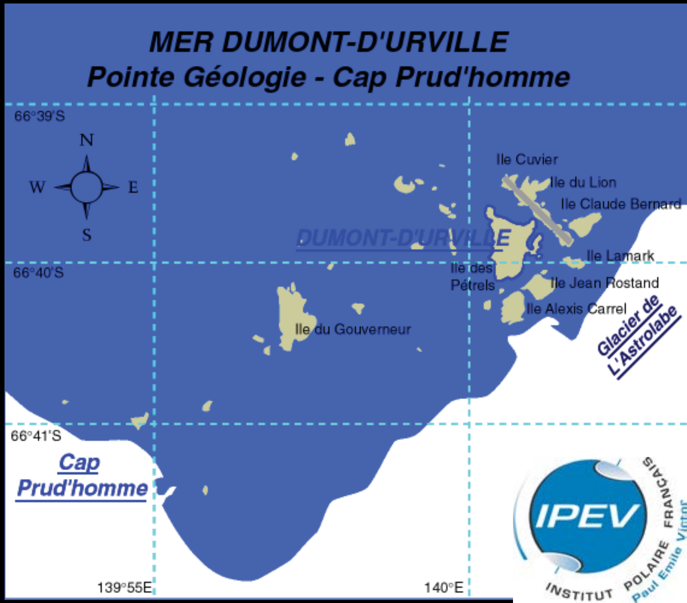
■ Year-round research station
Scale 1:68,000,000
Azimuthal Equal-Area Projection
0 500 1000 Kilometers
0 500 1000 Miles
South Atlantic Ocean
Southern Ocean
Indian Ocean
South Pacific Ocean
BRITISH CLAIM
ARGENTINE CLAIM
NORWEGIAN CLAIM
CHILEAN CLAIM
AUSTRALIAN CLAIM
FRENCH CLAIM
NEW ZEALAND CLAIM
South Georgia and the South Sandwich Islands (administered by U.K., claimed by ARGENTINA)
Falkland Islands (Islas Malvinas) (administered by U.K., claimed by ARGENTINA)
Bouvet Island (NORWAY)
PRINCE EDWARD ISLANDS (SOUTH AFRICA)
ÎLES CROZET
French Southern and Antarctic Lands (FRANCE)
ÎLES KERGUELEN
Heard Island and McDonald Islands (AUSTRALIA)
Port Elizabeth
SOUTH AFRICA
ARGENTINA
CHILE
Ushuaia
Orcadas (ARGENTINA)
SOUTH ORKNEY ISLANDS
SOUTH SHETLAND ISLANDS
area of enlargement
SANAE (SOUTH AFRICA)
Neumayer (GERMANY)
Maitri (INDIA)
Novolazarevskaya (RUSSIA)
Syowa (JAPAN)
Molodezhnaya (RUSSIA)
Halley (U.K.)
Belgrano II (ARGENTINA)
Mawson (AUSTRALIA)
Zhong Shan (CHINA)
Progress (RUSSIA)
Davis (AUSTRALIA)
Amundsen-Scott (U.S.)
Mirnyy (RUSSIA)
Vostok (RUSSIA)
Casey (AUSTRALIA)
McMurdo (U.S.)
Scott (N.Z.)
Terra Nova (ITALY)
Dumont d'Urville (FRANCE)
Queen Maud Land
Weddell Sea
Scotia Sea
Drake Passage
Bellingshausen Sea
Amundsen Sea
Ross Sea
Ross Ice Shelf
Vinson Massif
Marie Byrd Land
Wilkes Land
Victoria Land
Peter I Island
Scott Island
BALLENY ISLANDS
Macquarie Island (AUSTRALIA)
Campbell Island (NEW ZEALAND)
AUCKLAND ISLANDS (NEW ZEALAND)
SNARES ISLANDS (NEW ZEALAND)
CHATHAM ISLANDS (NEW ZEALAND)
NEW ZEALAND
Wellington
Christchurch
Tasmania
Hobart
Adelaide
Melbourne
Canberra
Sydney
AUSTRALIA
Esperanza (ARGENTINA)
Marambio (ARGENTINA)
Arturo Prat (CHILE)
Bernardo O'Higgins (CHILE)
Palmer (U.S.)
Vernadsky (UKRAINE)
Antarctic Peninsula
San Martin (ARGENTINA)
Rothera (U.K.)
802800AI (R02207) 4-01

INSTITUT POLAIRE
TAAF

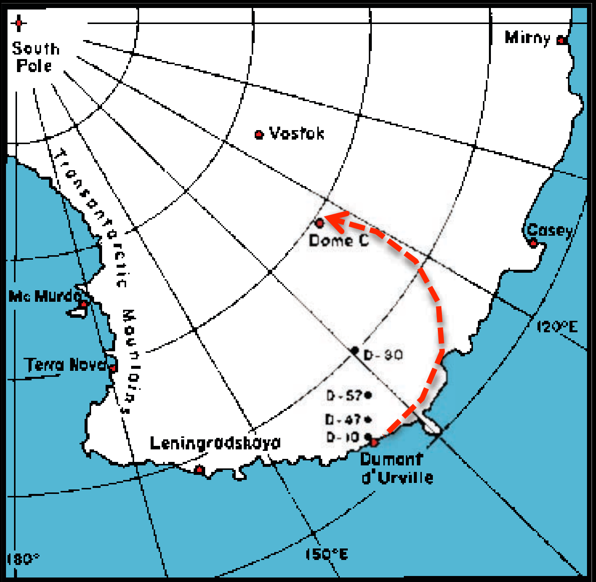
CSNSM-IN2P3-CNRS IPEV

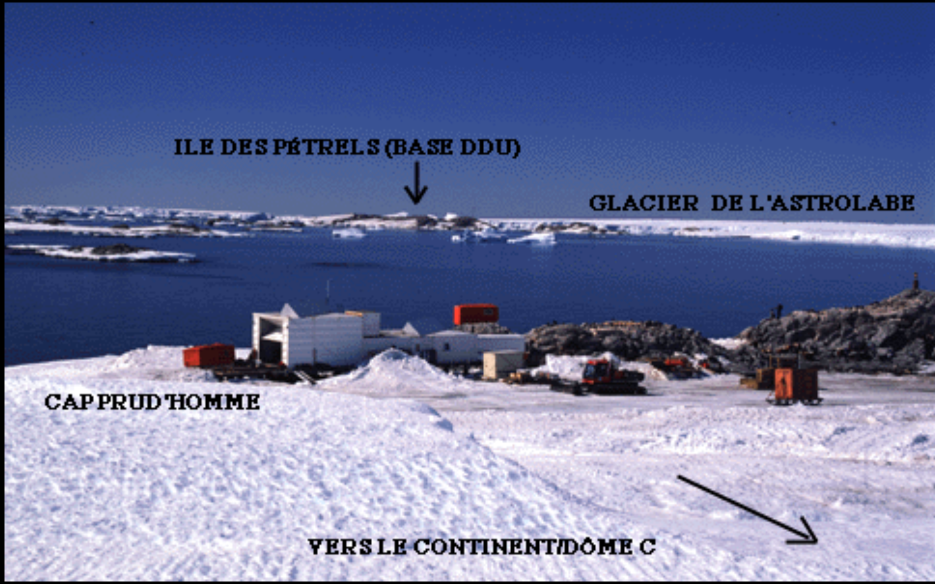
Le matériel et les chercheurs sont transportés de Tasmanie vers la Terre Adélie

La station côtière de Dumont D’Urville

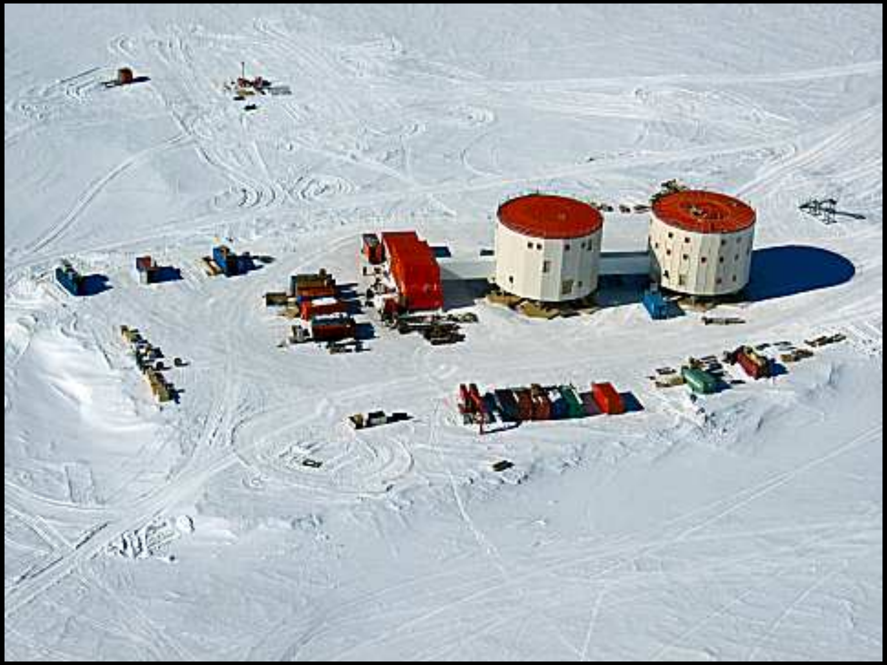

MER DUMONT-D'URVILLE
Pointe Géologie - Cap Prud'homme
66°39'S
N
W
E
S
66°40'S
66°41'S
Ile Cuvier
Ile du Lion
Ile Claude Bernard
DUMONT-D'URVILLE
Ile Lamark
Ile des Pétrels
Ile Jean Rostand
Ile Alexis Carrel
Ile du Gouverneur
Glacier de L'Astrolabe
Cap Prud'homme
139°55E
140°E
IPEV
INSTITUT POLAIRE FRANÇAIS
Paul Emile Victor

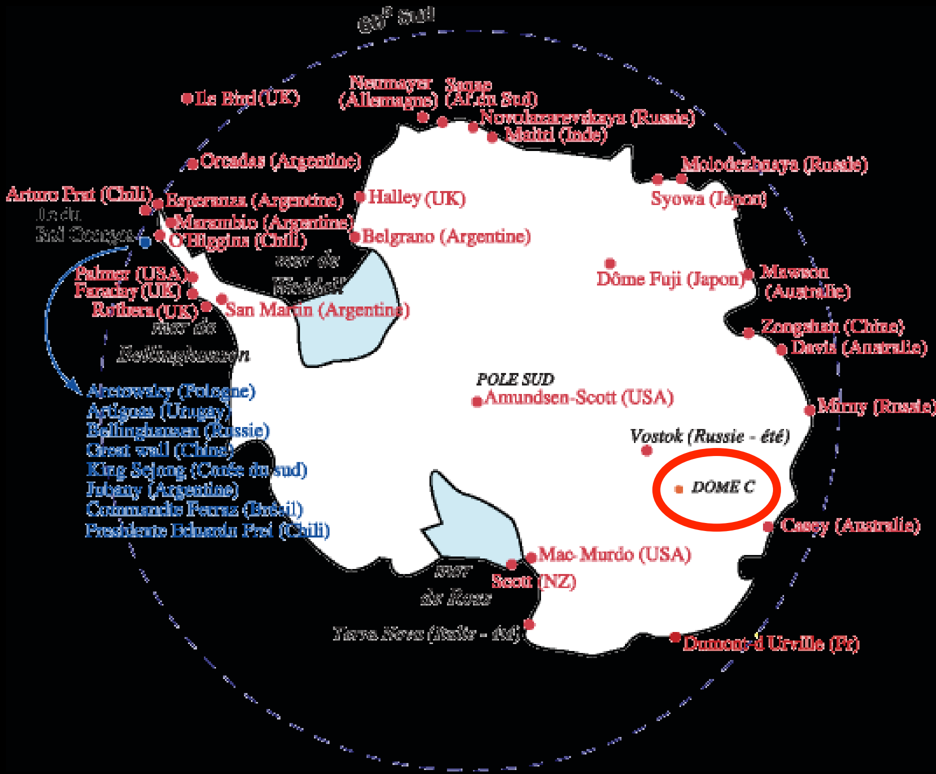
De Cap Prud’ Homme à Dôme C


South Pole
Mirny
Vostok
Transantarctic Mountains
Dome C
Casey
Mc Murdo
120°E
Terra Nova
D-80
D-57
D-47
D-10
Leningradskaya
Dumont d'Urville
180°
150°E


ILE DES PÉTRELS (BASE DDU)
GLACIER DE L'ASTROLABE
CAP PRUD'HOMME
VERS LE CONTINENT/DÔME C

Dôme C (75°S, 123°E)
la station CONCORDIA




60° Sud
Le Bird (UK)
Neumayer (Allemagne)
Sanae (Af. du Sud)
Nowolazarevskaya (Russie)
Maitri (Inde)
Orcadas (Argentine)
Molodezhnaya (Russie)
Syowa (Japon)
Arturo Prat (Chili)
Ile du Roi George
Esperanza (Argentine)
Marambio (Argentine)
O'Higgins (Chili)
Halley (UK)
Belgrano (Argentine)
mer de Weddell
Palmer (USA)
Faraday (UK)
Rothera (UK)
San Martin (Argentine)
mer de Bellinghausen
Dôme Fuji (Japon)
Mawson (Australie)
Zongshan (Chine)
Davis (Australie)
Arctowsky (Pologne)
Artigas (Uruguay)
Bellinghausen (Russie)
Great wall (Chine)
King Sejong (Corée du sud)
Jubany (Argentine)
Commandte Ferraz (Brésil)
Presidente Eduardo Frei (Chili)
POLE SUD
Amundsen-Scott (USA)
Mirny (Russie)
Vostok (Russie - été)
DOME C
Casey (Australie)
Mac-Murdo (USA)
Scott (NZ)
mer de Ross
Terra Nova (Italie - été)
Dumont-d'Urville (Fr)

1100 kms des côtes de Terre Adélie, 3200 m d'altitude

Un désert froid et sec

T° :[-80° ; -30°]

10 cm de neige /an (3-4 g d'eau/cm2/an)

Le Programme « *Micrométéorites @ Dôme C* »

Dôme C, Janvier 2000

Neige de surface

(0-80 cm) @ 3 km du camp

Dôme C, Janvier 2002

Tranchée 3-4 mètres

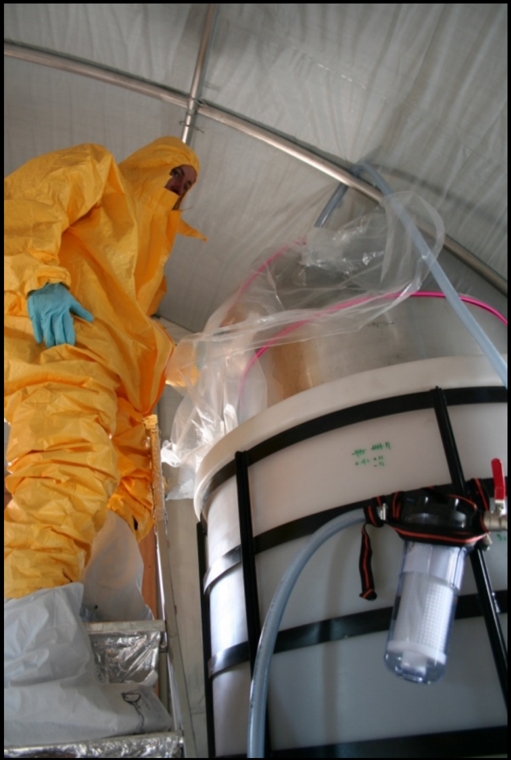
V = 11 m^3

Dôme C, Janvier 2006

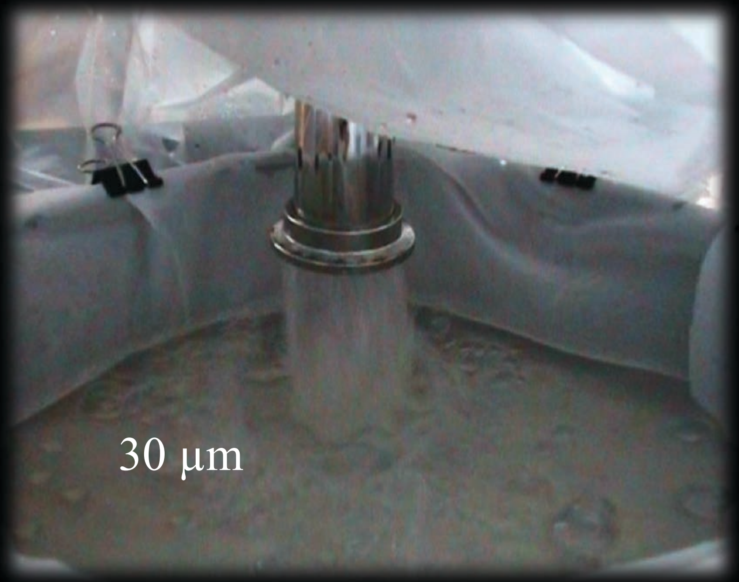
Tranchée 4-5 mètres

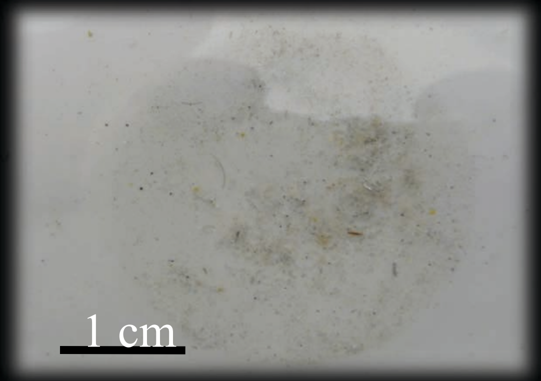
V = 25 m^3

La fonte et la filtration



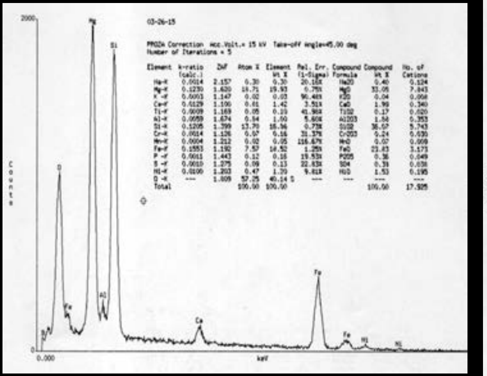
Le fondoir

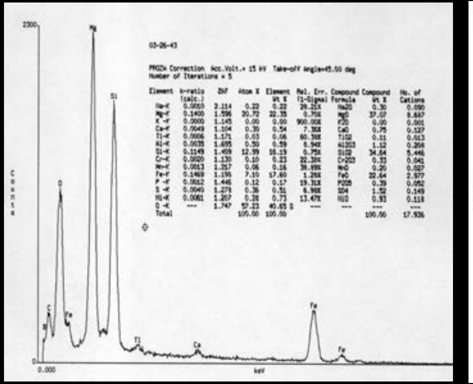


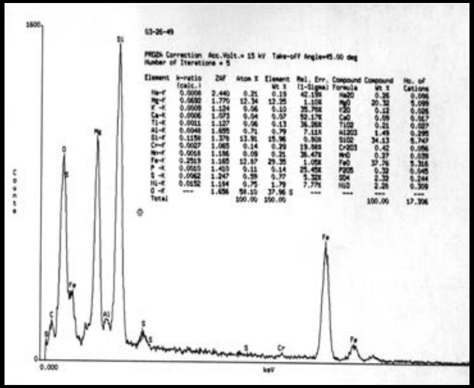


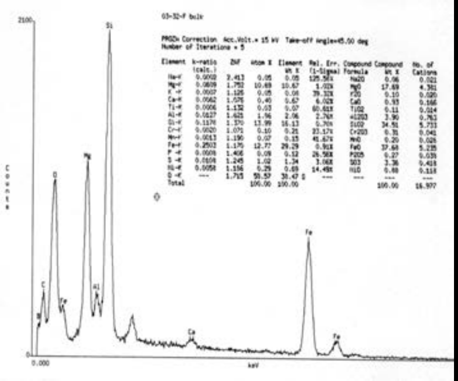
Les filtres de 30 µm sont analysés après chaque collecte pour contrôler les contaminations terrestres

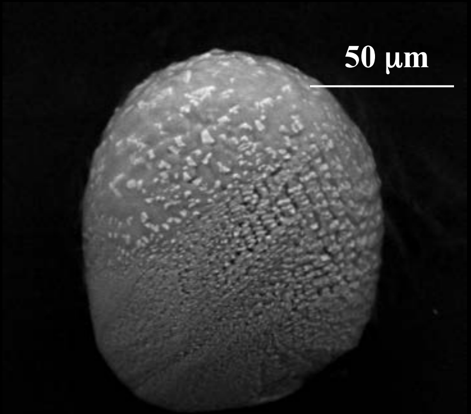
Les différents types de poussières extraterrestres



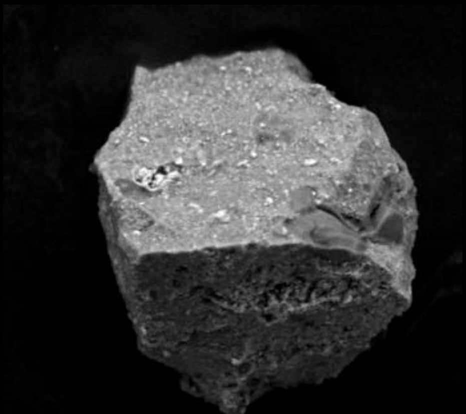




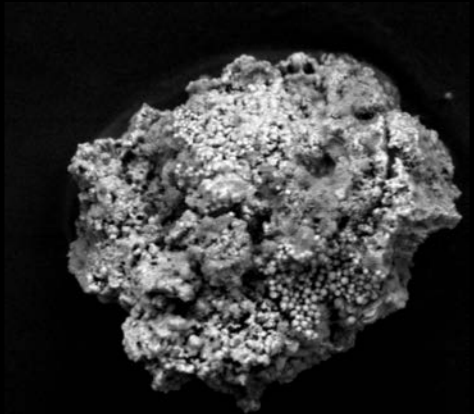




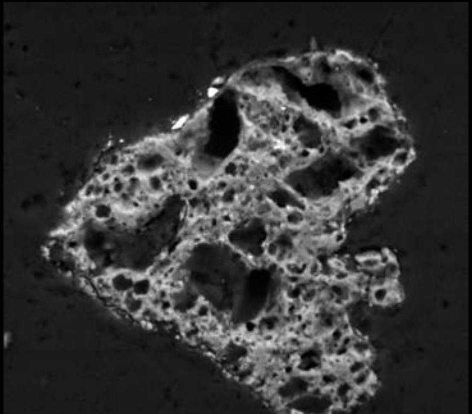
CONCORDIA # 03-26-15



CONCORDIA # 03-26-43



CONCORDIA # 03-26-49



CONCORDIA # 03-32-F

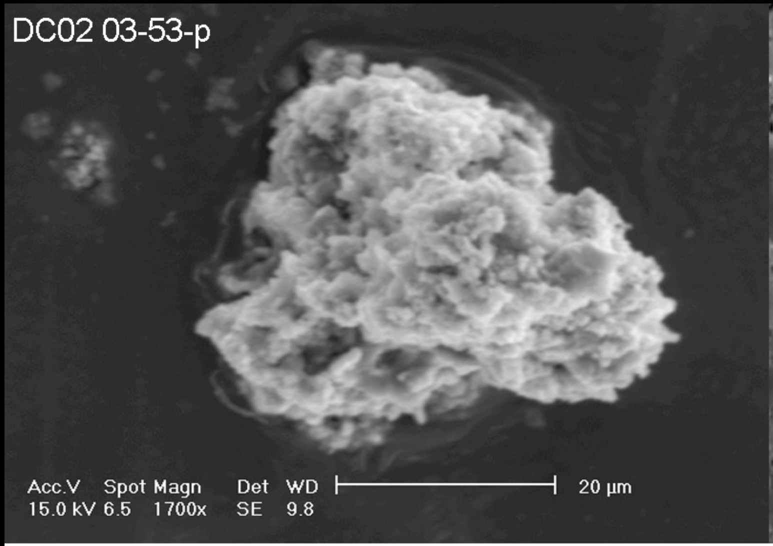
Identiques à celles découvertes par M. Maurette, pionnier de cette recherche au Groenland puis sur les côtes Antarctiques .

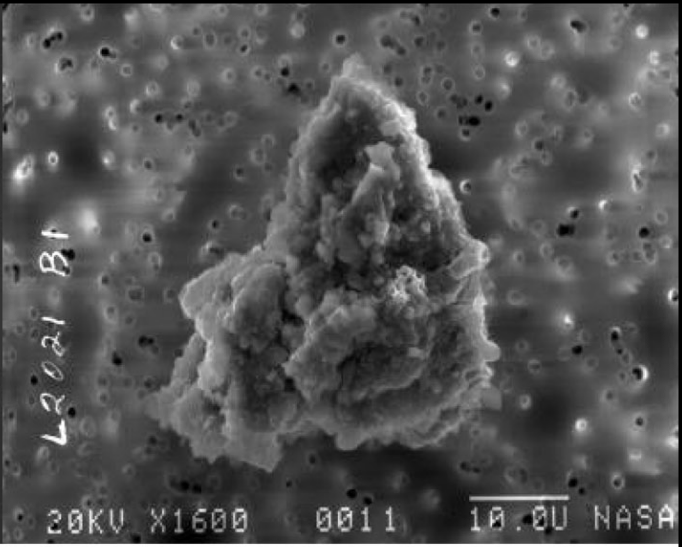
CSNSM-IN2P3-CNRS

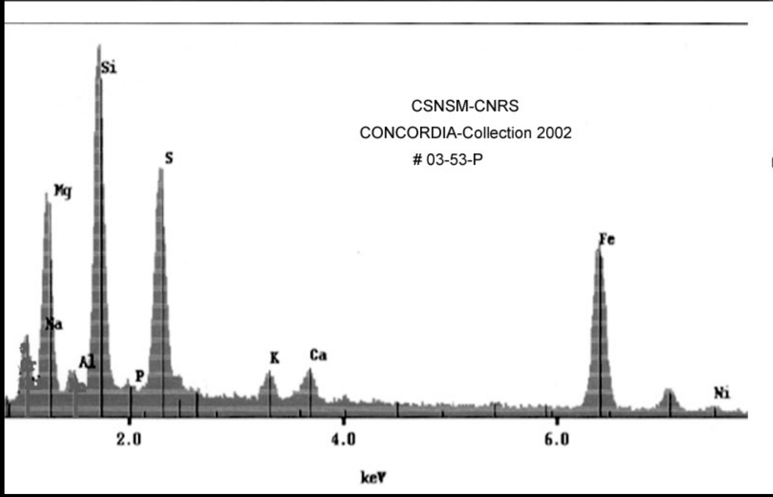
À la recherche de grains friables…

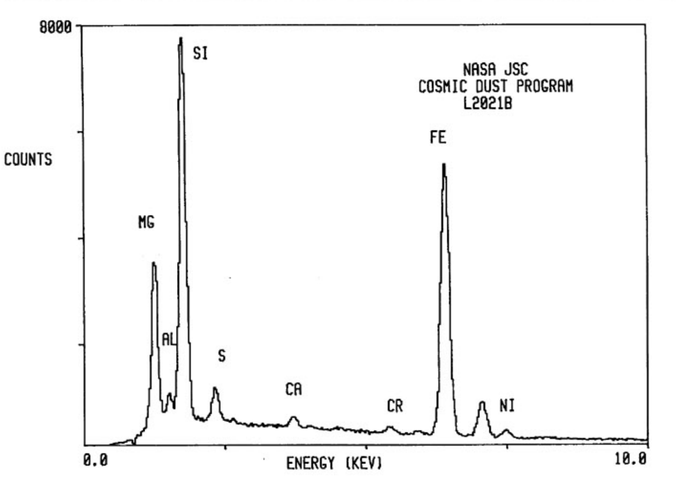
CONCORDIA Collection

Grain cométaire (NASA)

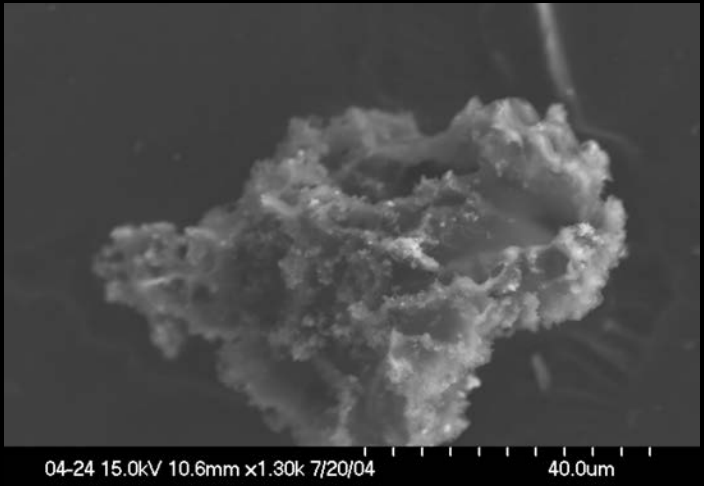

DC02 03-53-p
Acc.V Spot Magn Det WD
15.0 kV 6.5 1700x SE 9.8
20 µm

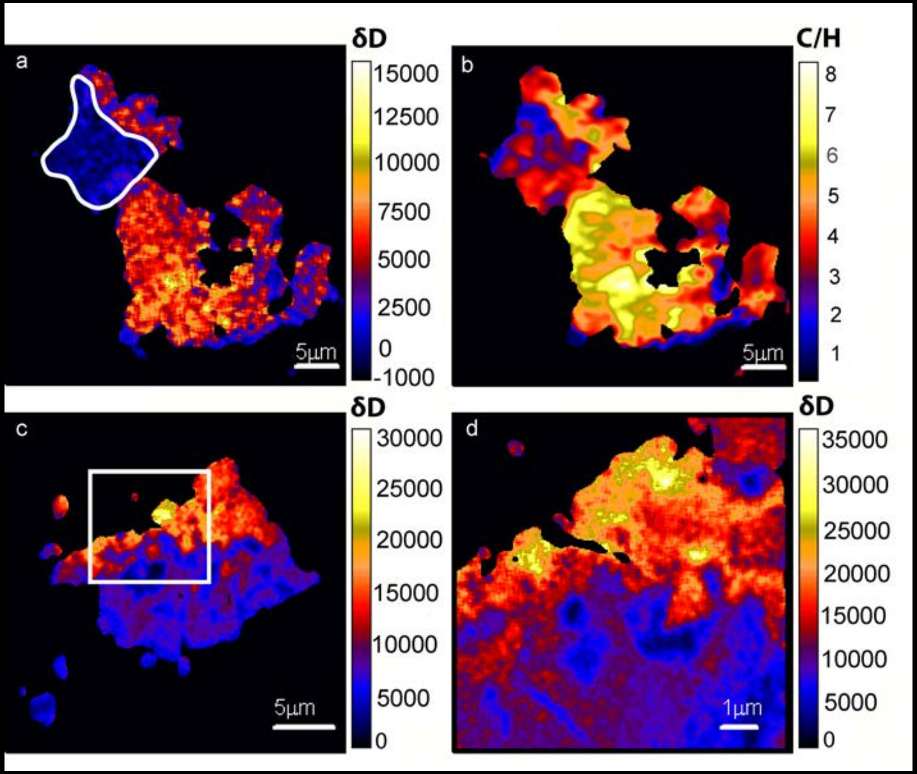

L2021 B1
20KV X1600 0011 10.0U NASA

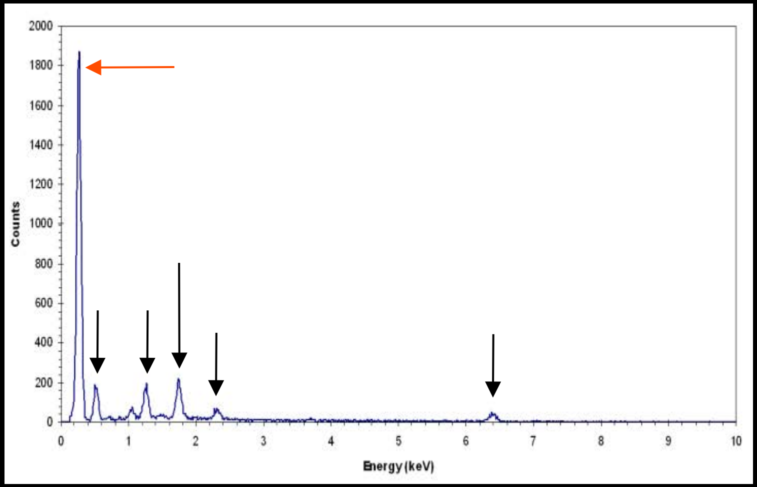




Les Micrométéorites Ultracarbonées


04-24 15.0kV 10.6mm x1.30k 7/20/04
40.0um

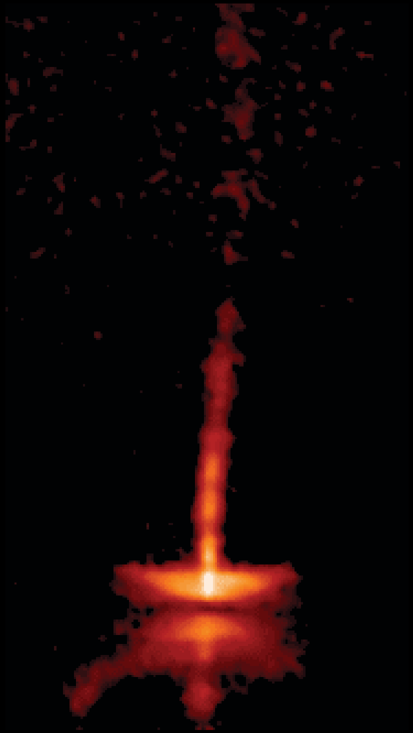




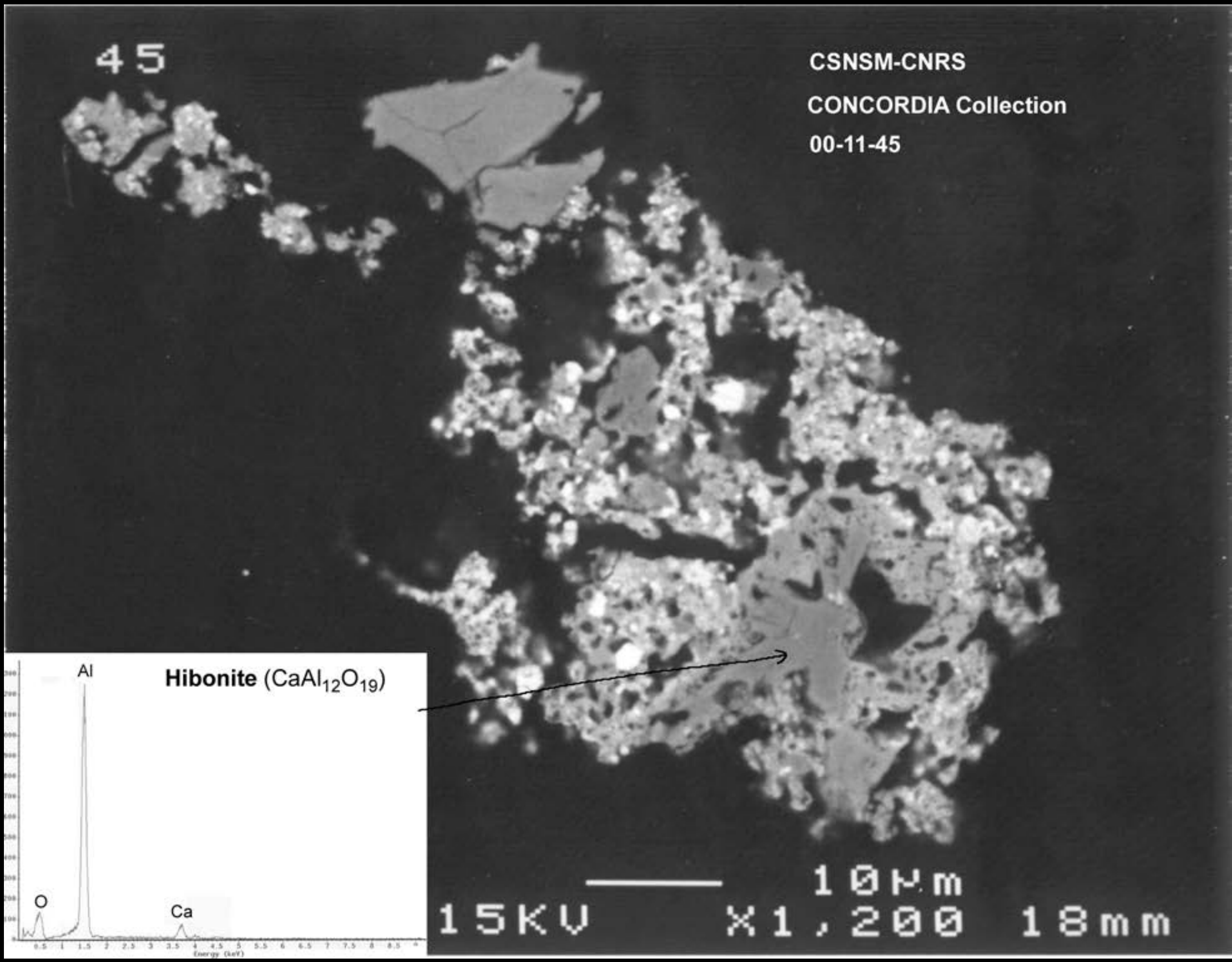
- Des **teneurs en Carbone très élevées**
  [C] = 50-85 vol%
- Des **enrichissement extrêmes en Deutérium**
  D/H = 10-30 x celui des océans

Similaires aux grains CHON identifiés dans la comète 1P/Halley

Les premières phases minérales du Système Solaire



HH 30
Télescope Hubble
V= 500 000 km/h
Disk = 64 10^9 km = 500 UA

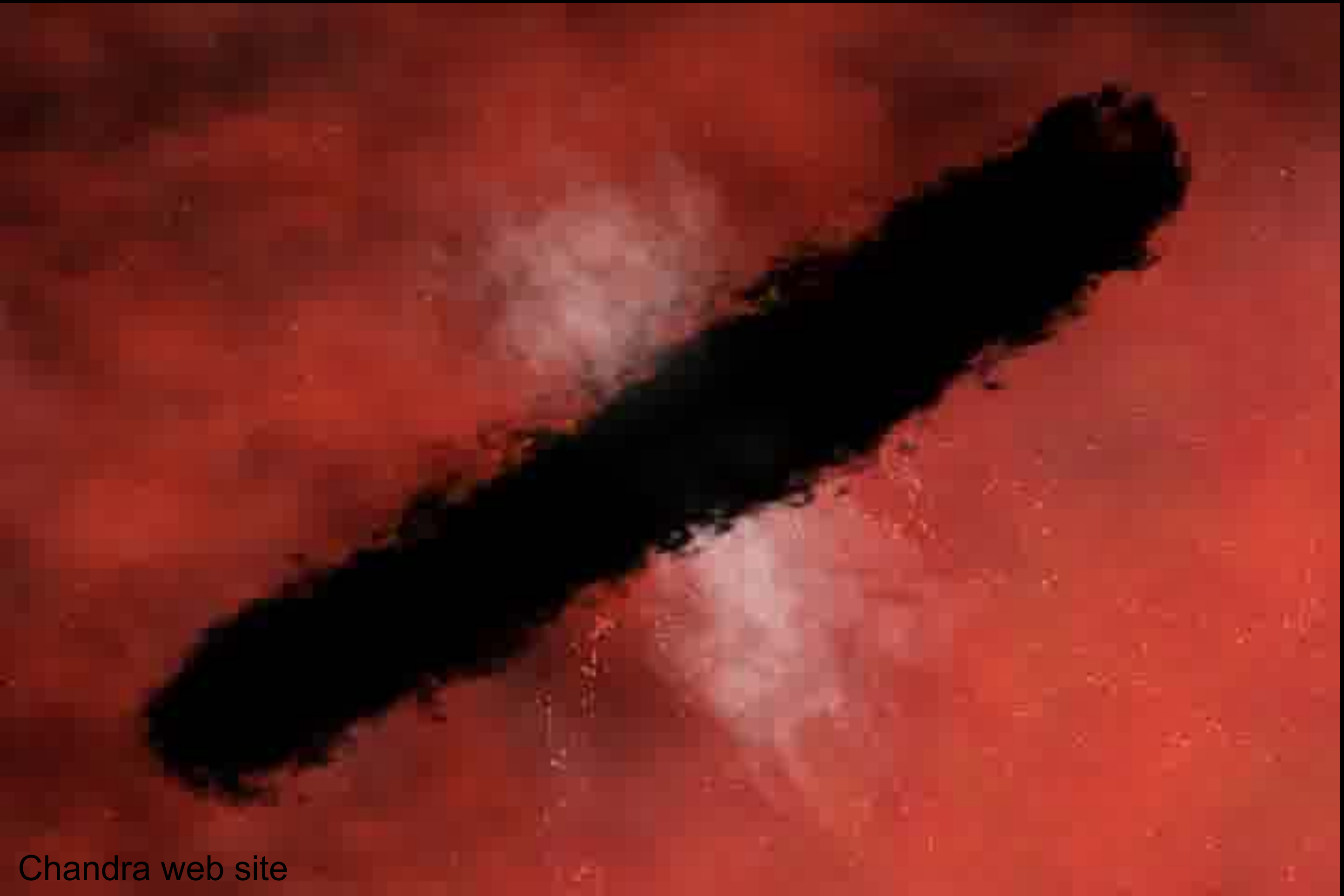

45
CSNSM-CNRS
CONCORDIA Collection
00-11-45
Al
Hibonite ($CaAl_{12}O_{19}$)
O
Ca
Energy (keV)
10µm
15KV
X1,200
18mm

Les micrométéorites CONCORDIA

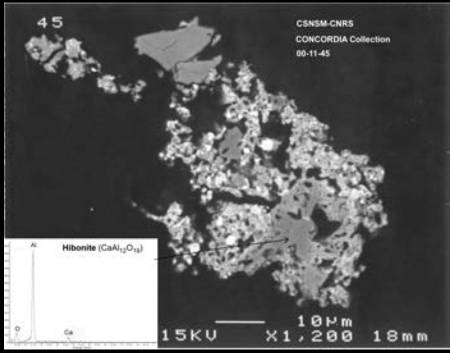
nous apportent des informations sur

les premiers millions d'années

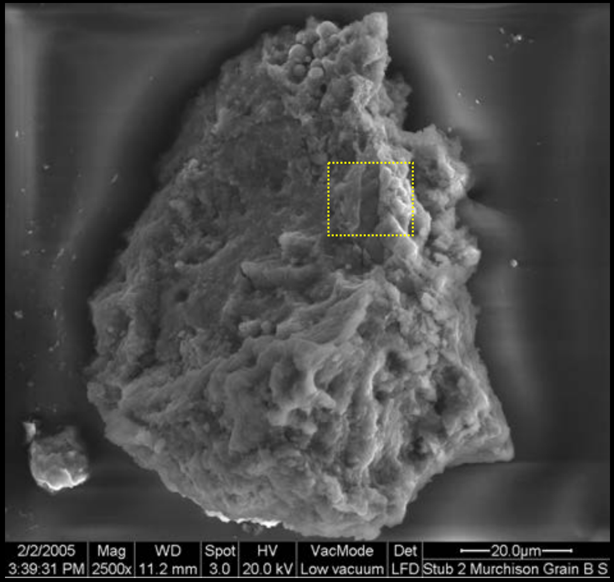
après la naissance du Soleil…

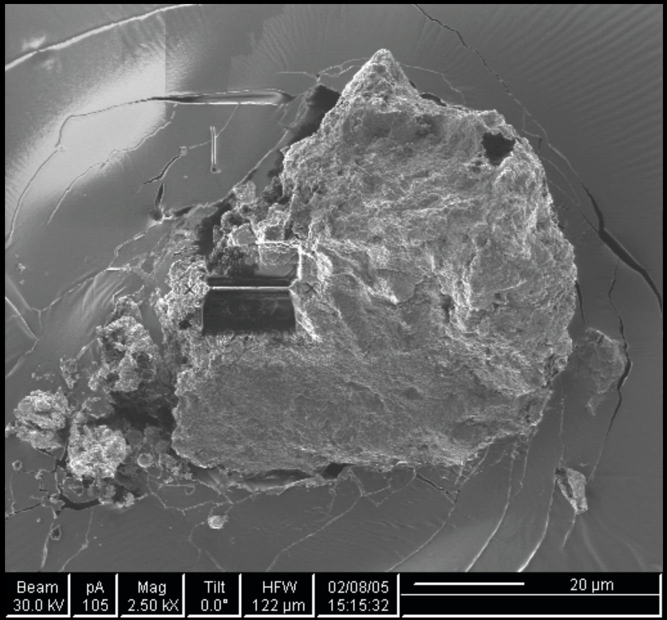


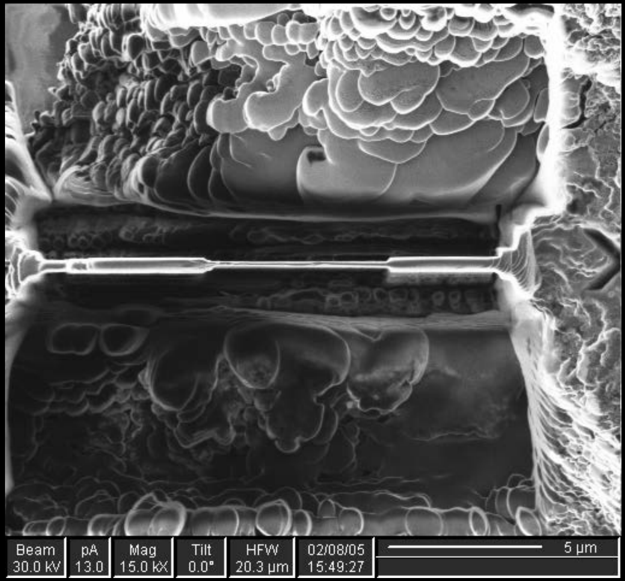
Chandra web site

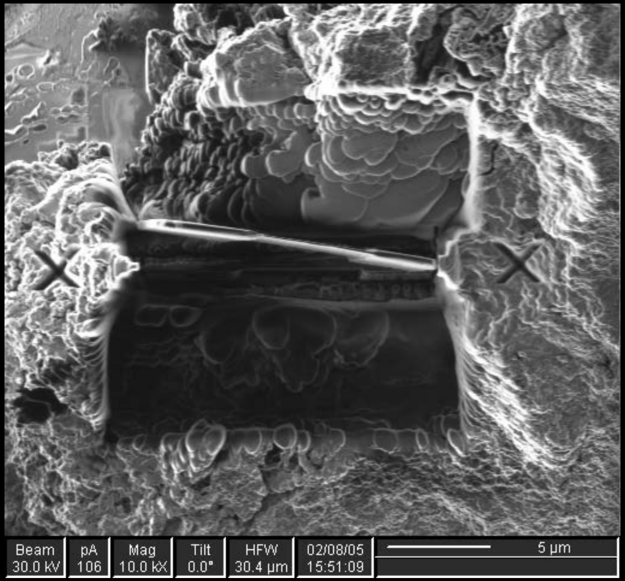

45
CSNSM-CNRS
CONCORDIA Collection
00-11-45
Al
Hibonite ($CaAl_{12}O_{19}$)
O
Ca
10µm
15KV
X1,200
18mm

La station FIB au CSNSM (Focus Ion Beam)


2/2/2005
3:39:31 PM
Mag
2500x
WD
11.2 mm
Spot
3.0
HV
20.0 kV
VacMode
Low vacuum
Det
LFD
20.0µm
Stub 2 Murchison Grain B S

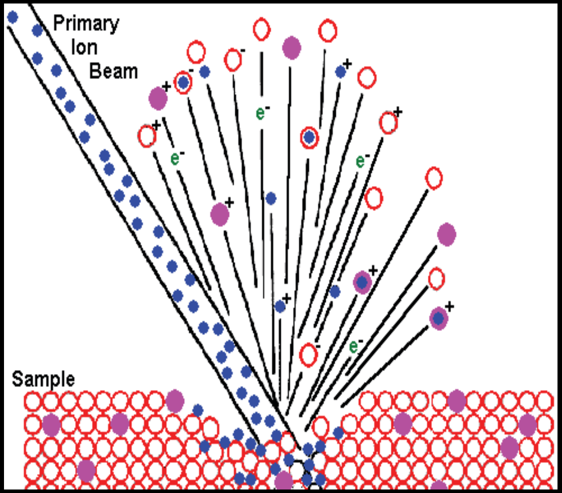

Beam
30.0 kV
pA
105
Mag
2.50 kX
Tilt
0.0°
HFW
122 µm
02/08/05
15:15:32
20 µm

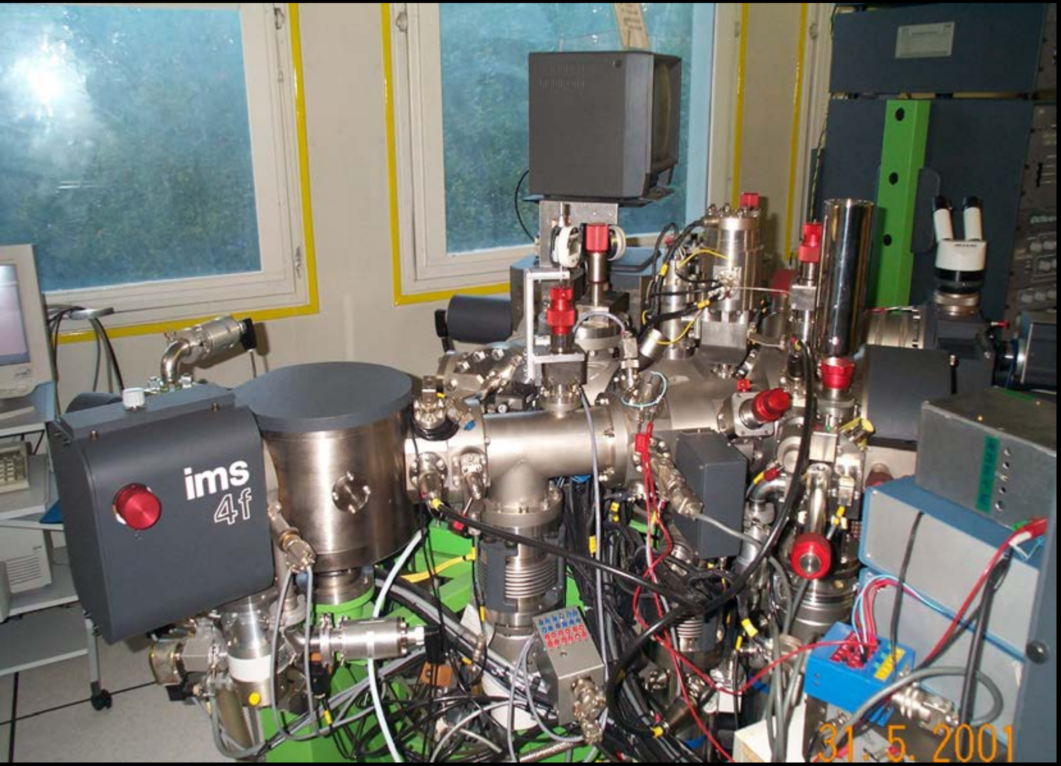

Beam
30.0 kV
pA
13.0
Mag
15.0 kX
Tilt
0.0°
HFW
20.3 µm
02/08/05
15:49:27
5 µm


Beam
30.0 kV
pA
106
Mag
10.0 kX
Tilt
0.0°
HFW
30.4 µm
02/08/05
15:51:09
5 µm

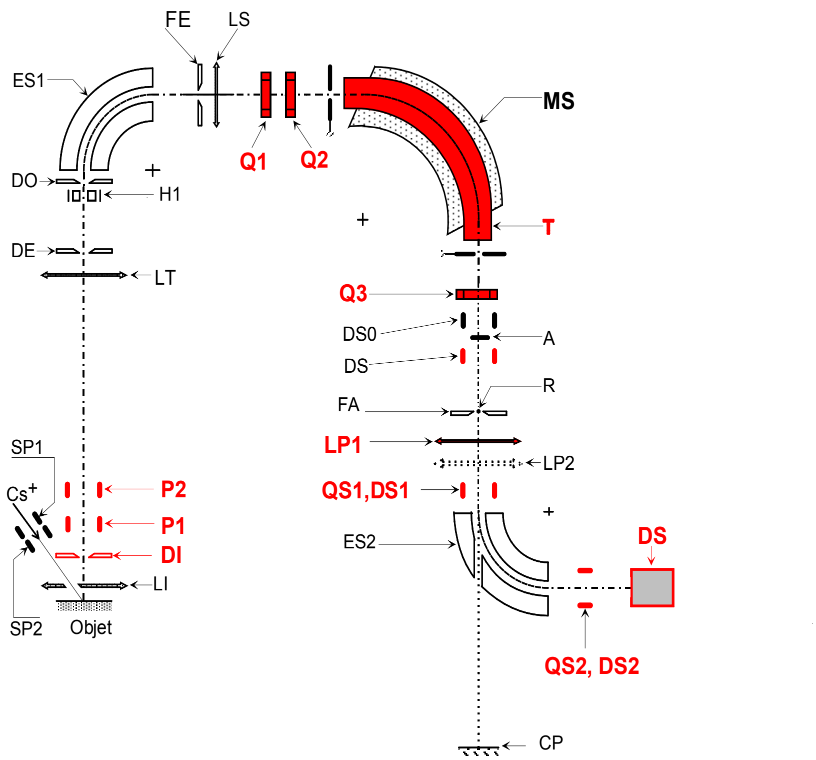
UNIVERSITÉ PARIS SUD
Comprendre le monde, construire l'avenir®

Spectroscopie de Masse
CSNSM ORSAY

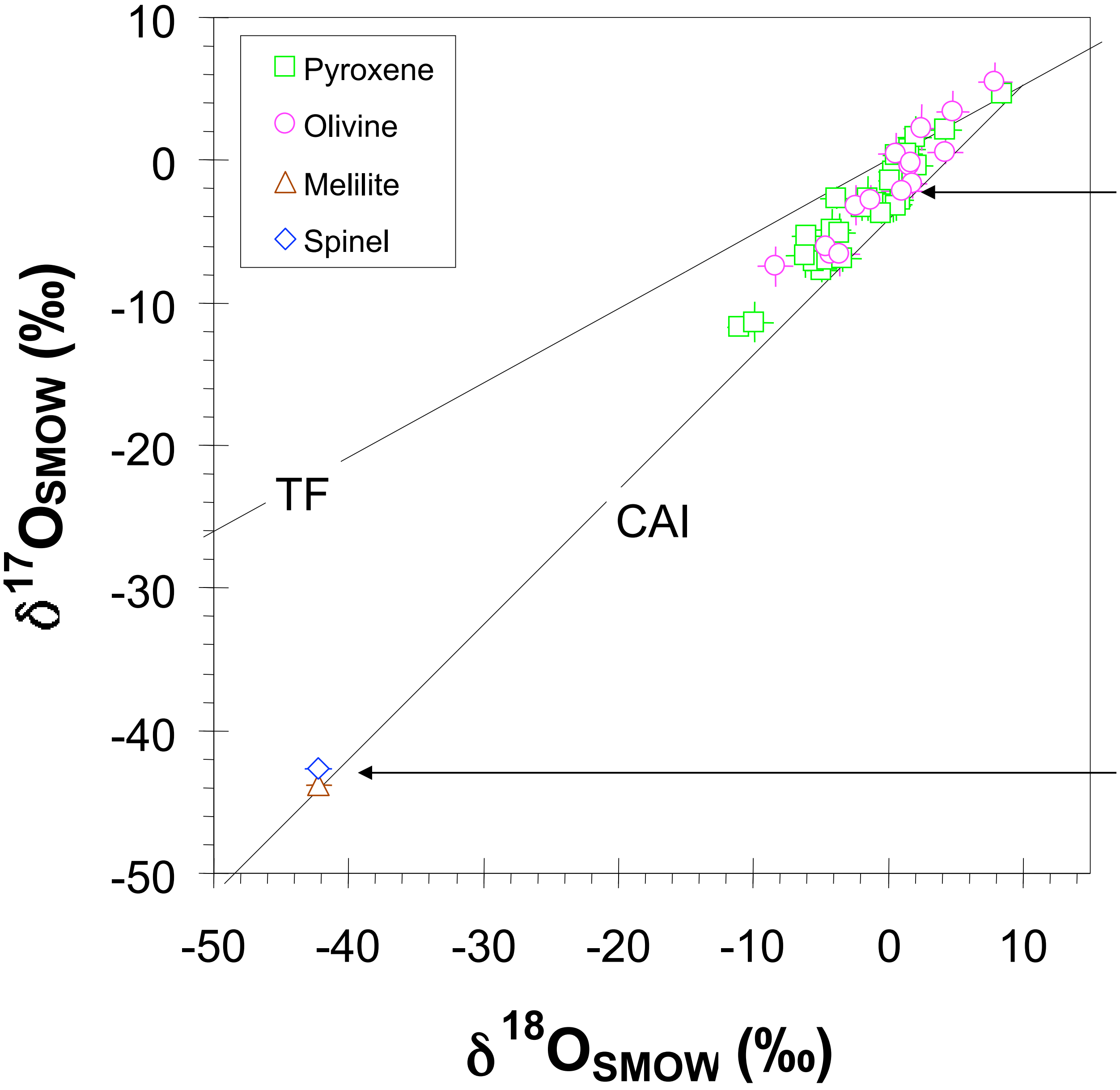

Primary
Ion
Beam
Sample
e-

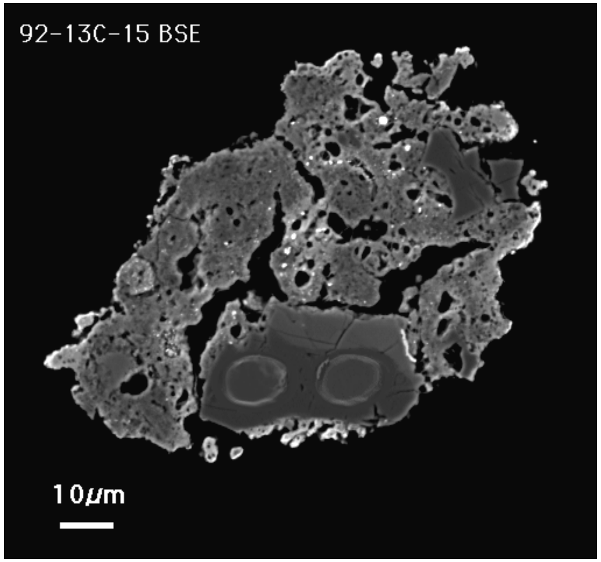

ims
4f
31. 5. 2001

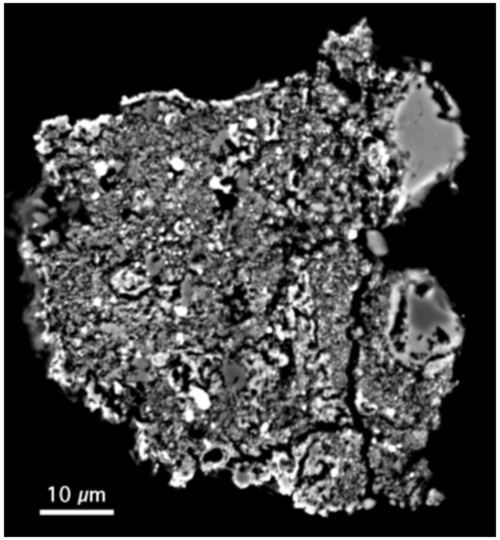
The **IMS-Orsay** ion micro-probe


FE
LS
ES1
Q1
Q2
MS
DO
H1
T
DE
LT
Q3
DS0
A
DS
R
FA
LP1
LP2
SP1
Cs+
P2
QS1,DS1
P1
DI
ES2
DS
LI
SP2
Objet
QS2, DS2
CP

Micrometeorites *in-situ* isotopic analysis

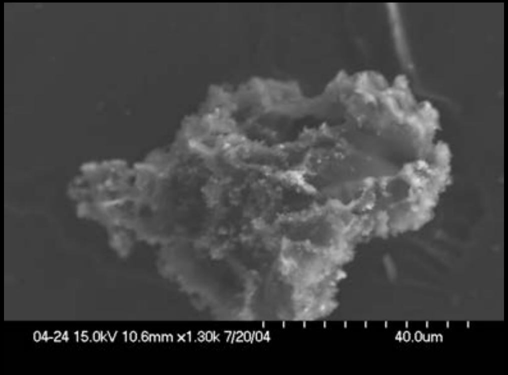
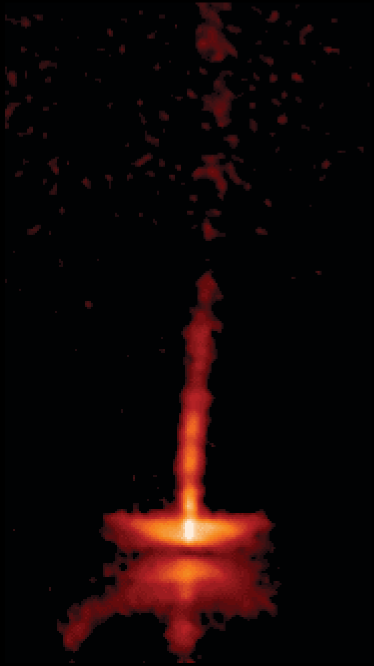



92-13C-15 BSE
10µm



Engrand et al, 1999

Merci pour votre attention!


04-24 15.0kV 10.6mm x1.30k 7/20/04
40.0um