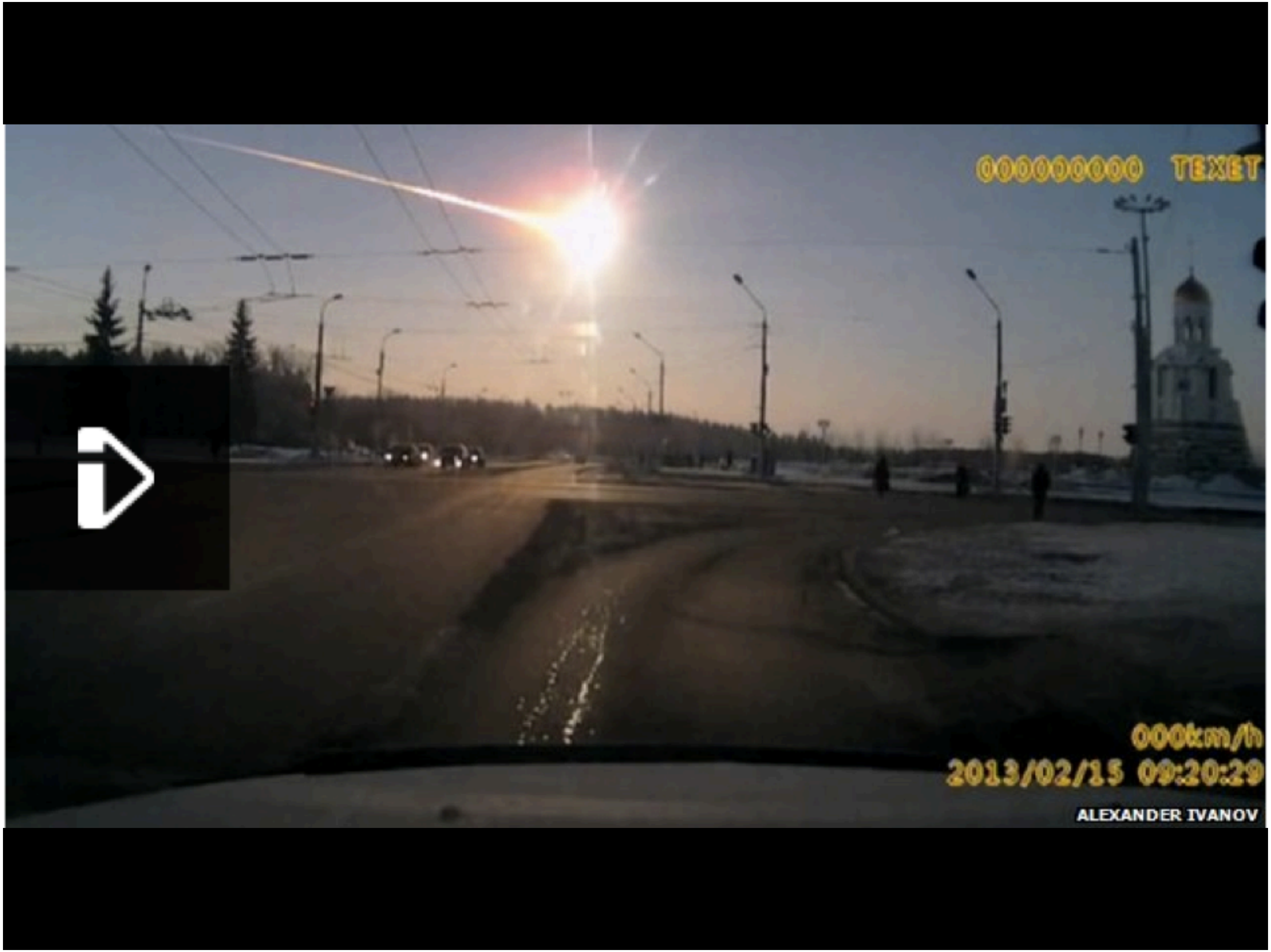
Meteorites and the early solar system

Three lectures by Ian Sanders (Dept of Geology) Feb 2013

Where on Earth do meteorites come from?


000000000 TEXET
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ALEXANDER IVANOV

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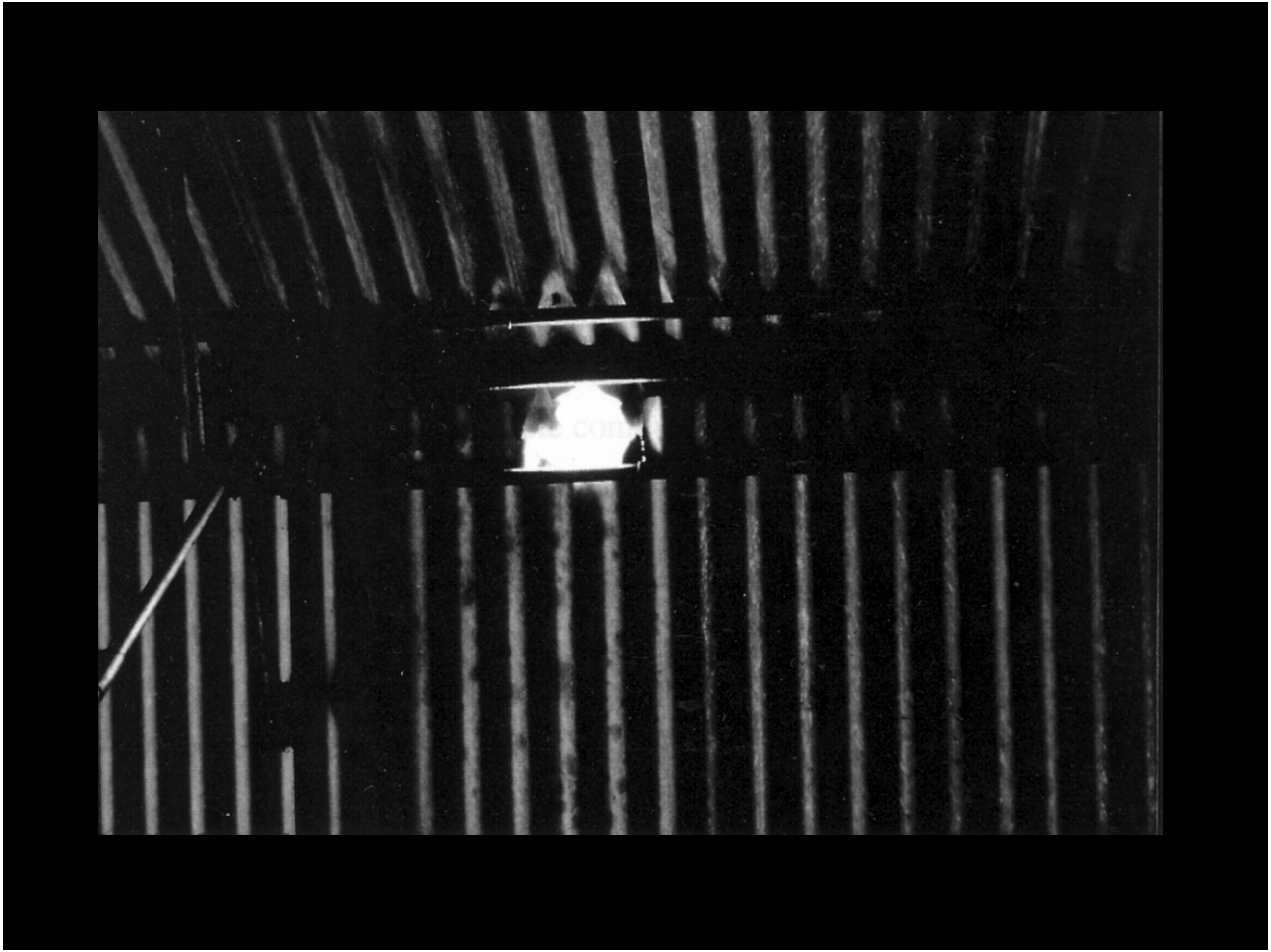
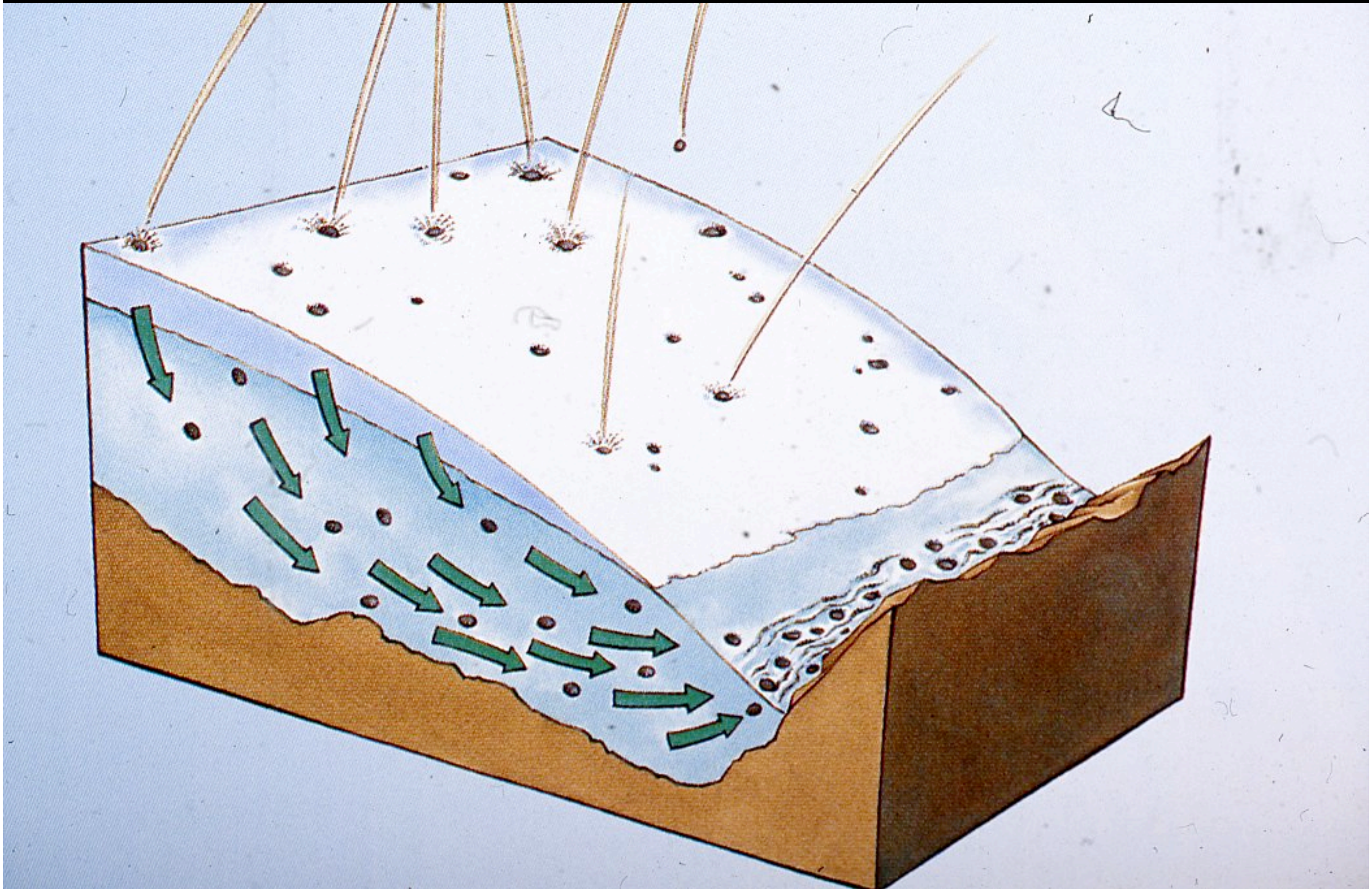
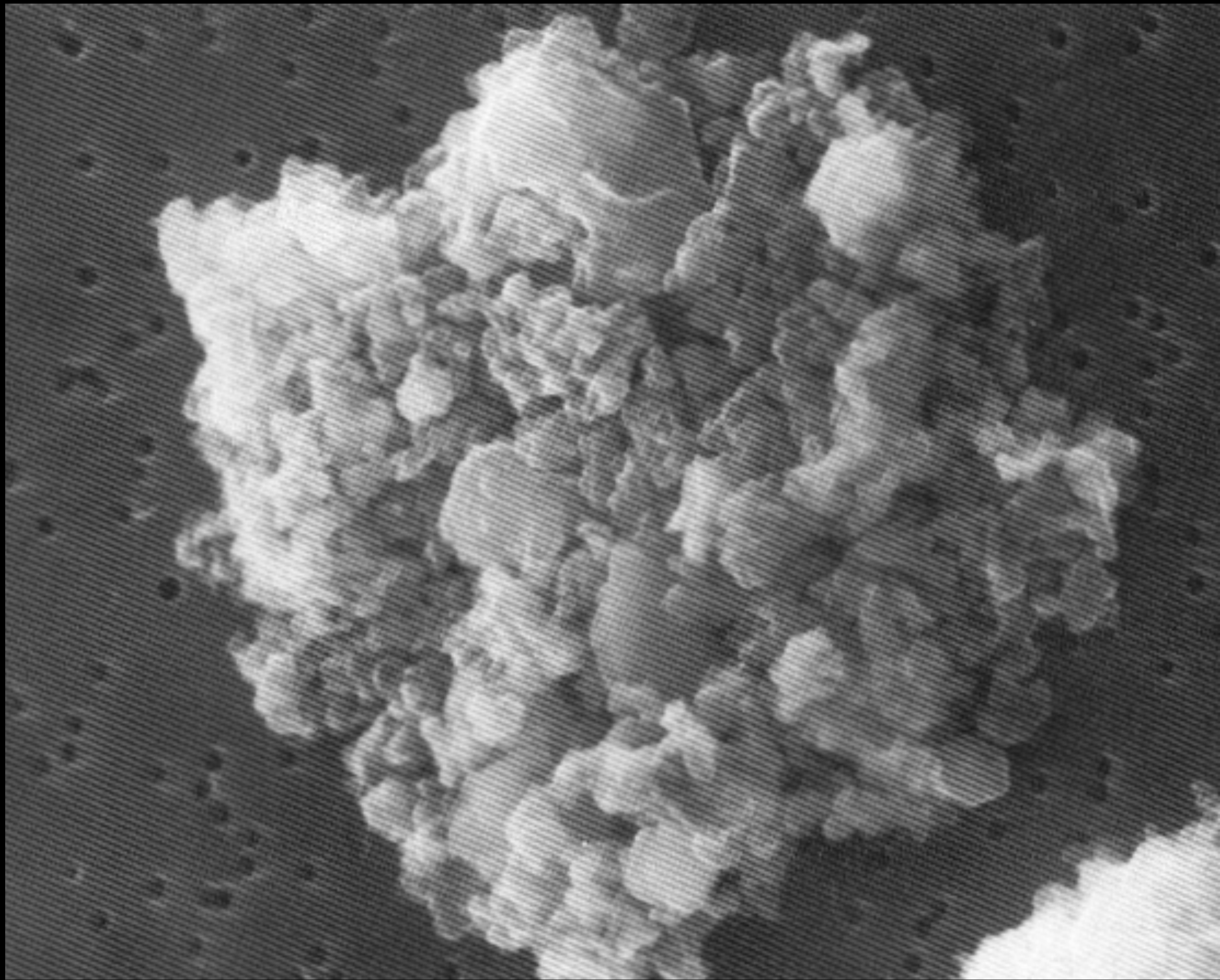
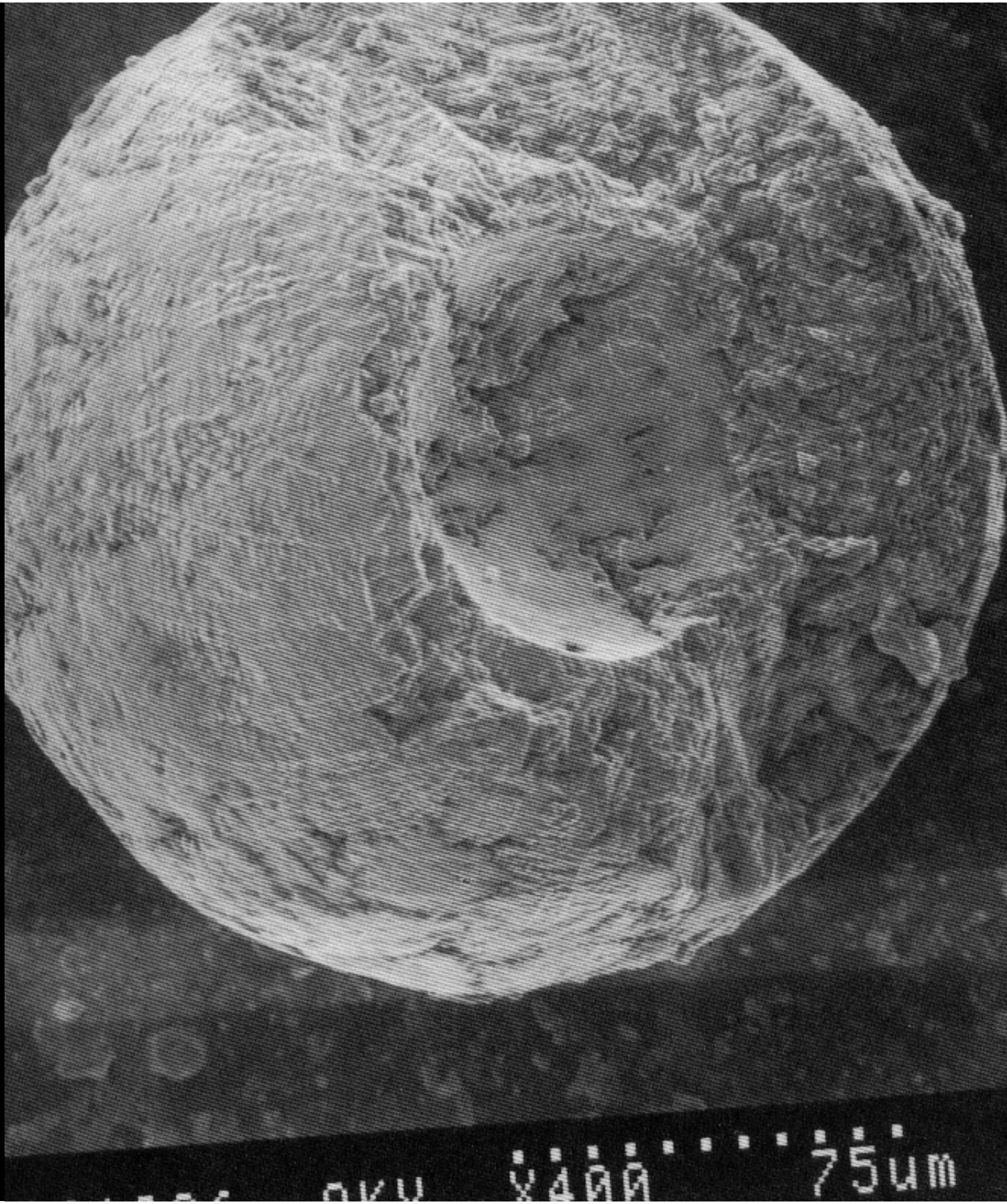
Bovedy 1969

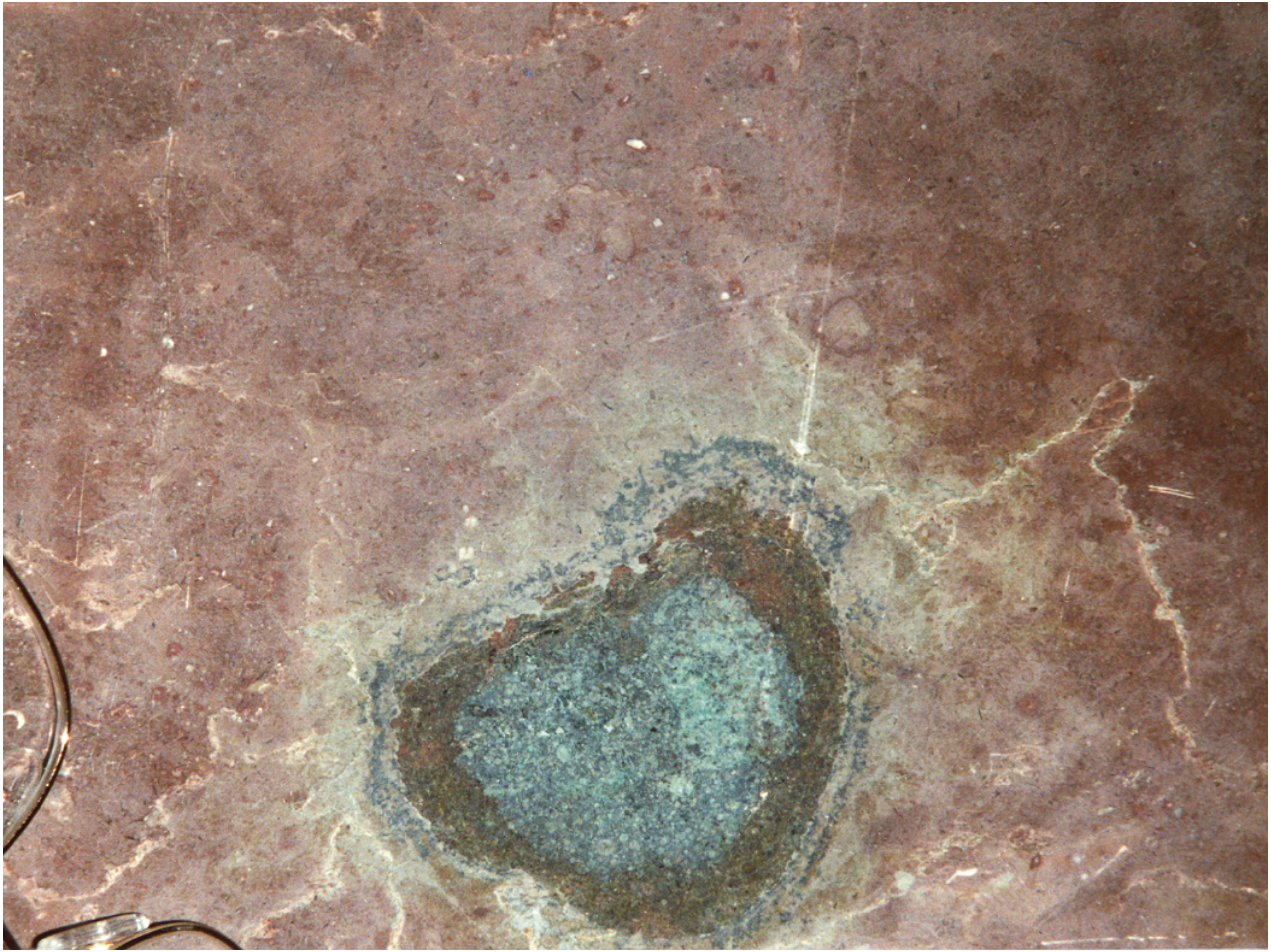



RESCUE

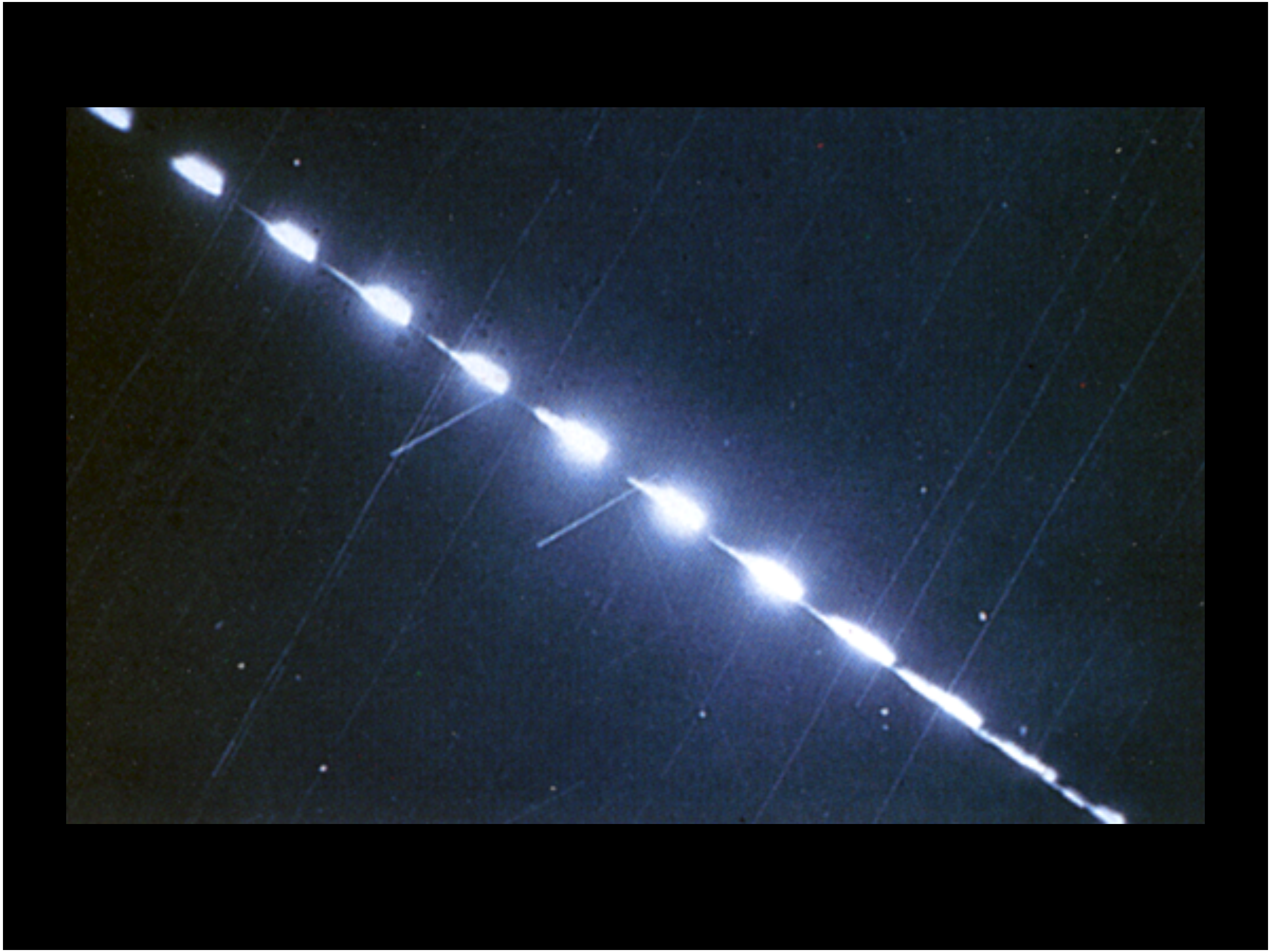


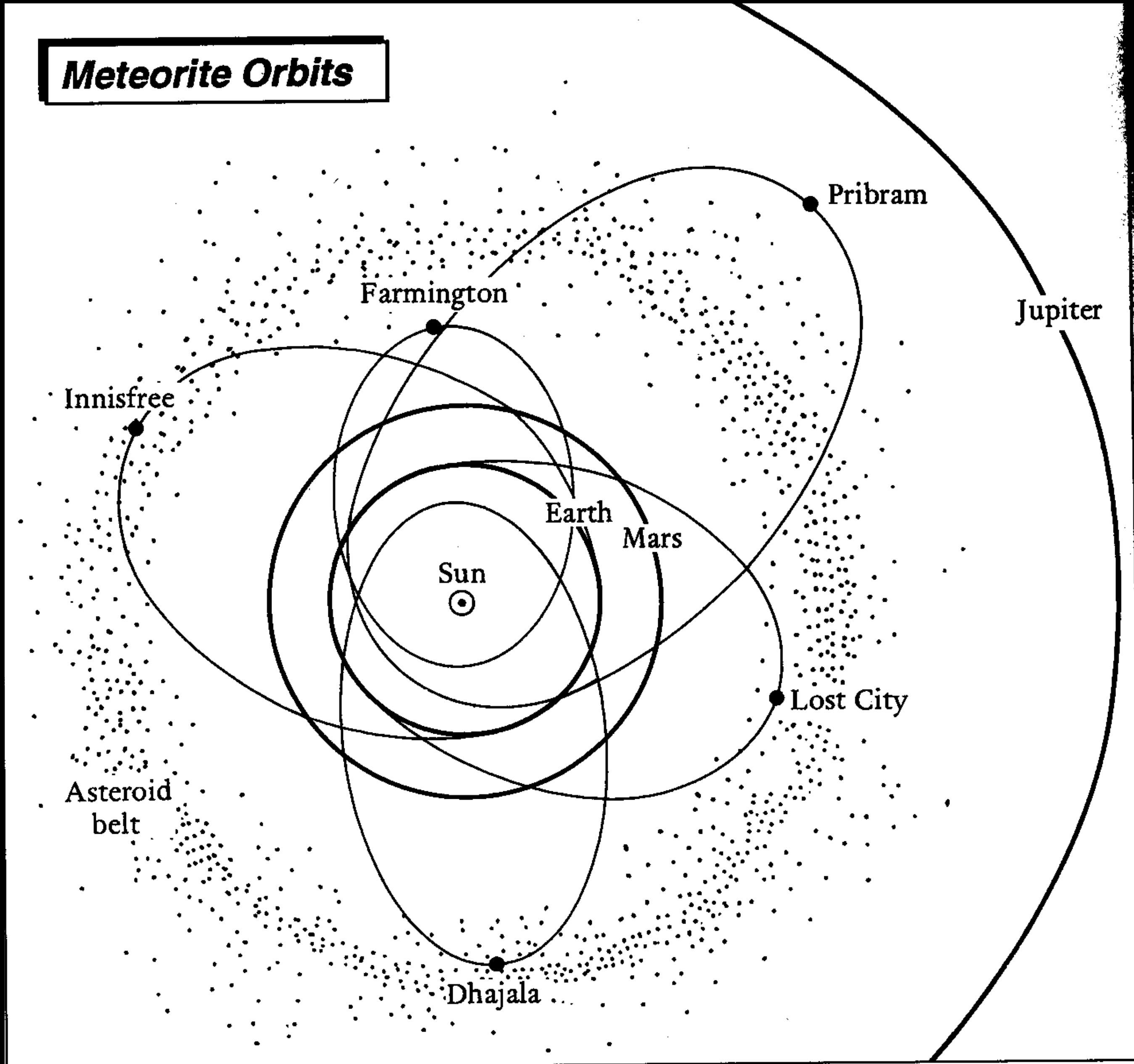


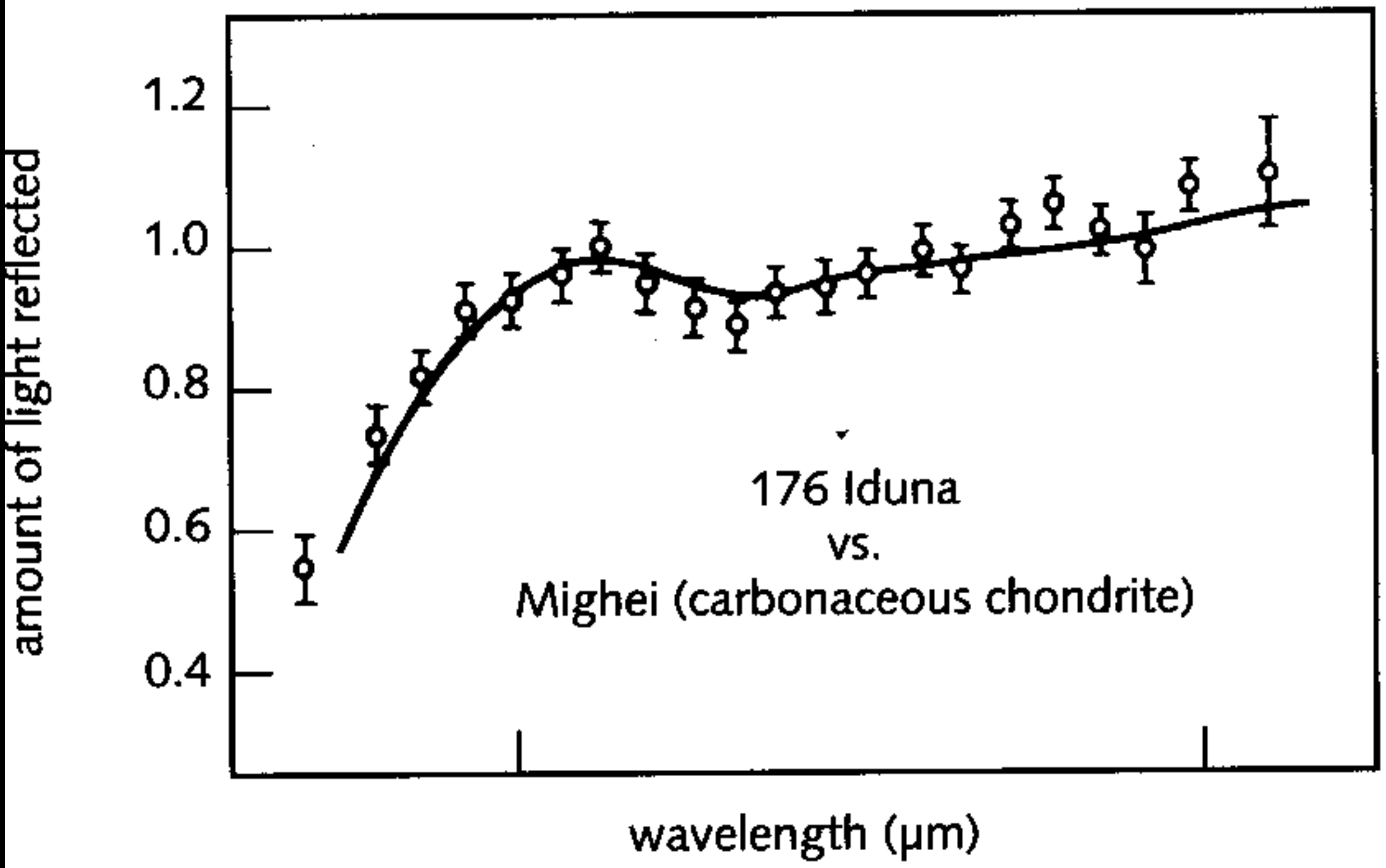

X400
75um



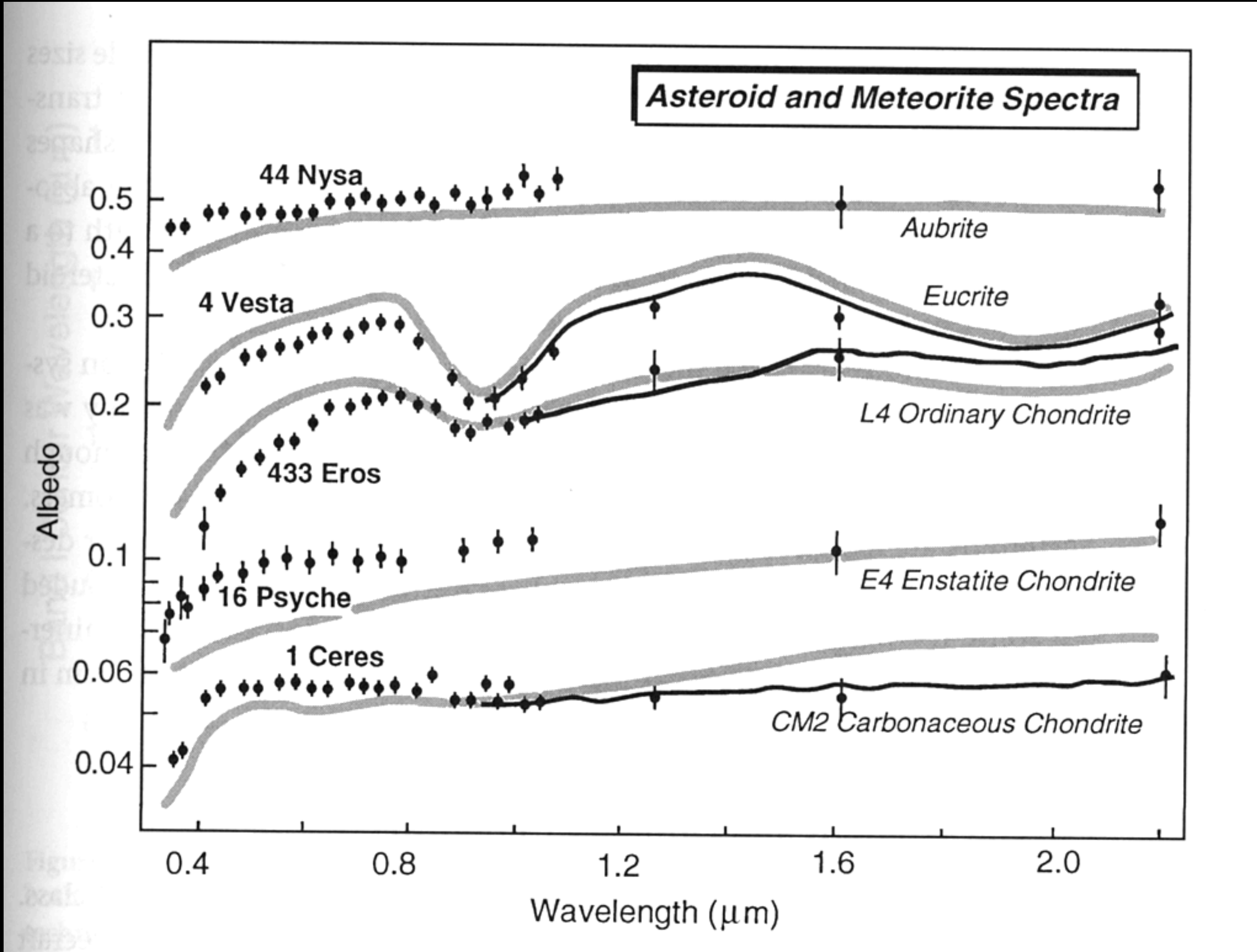
Where in space do meteorites come from?



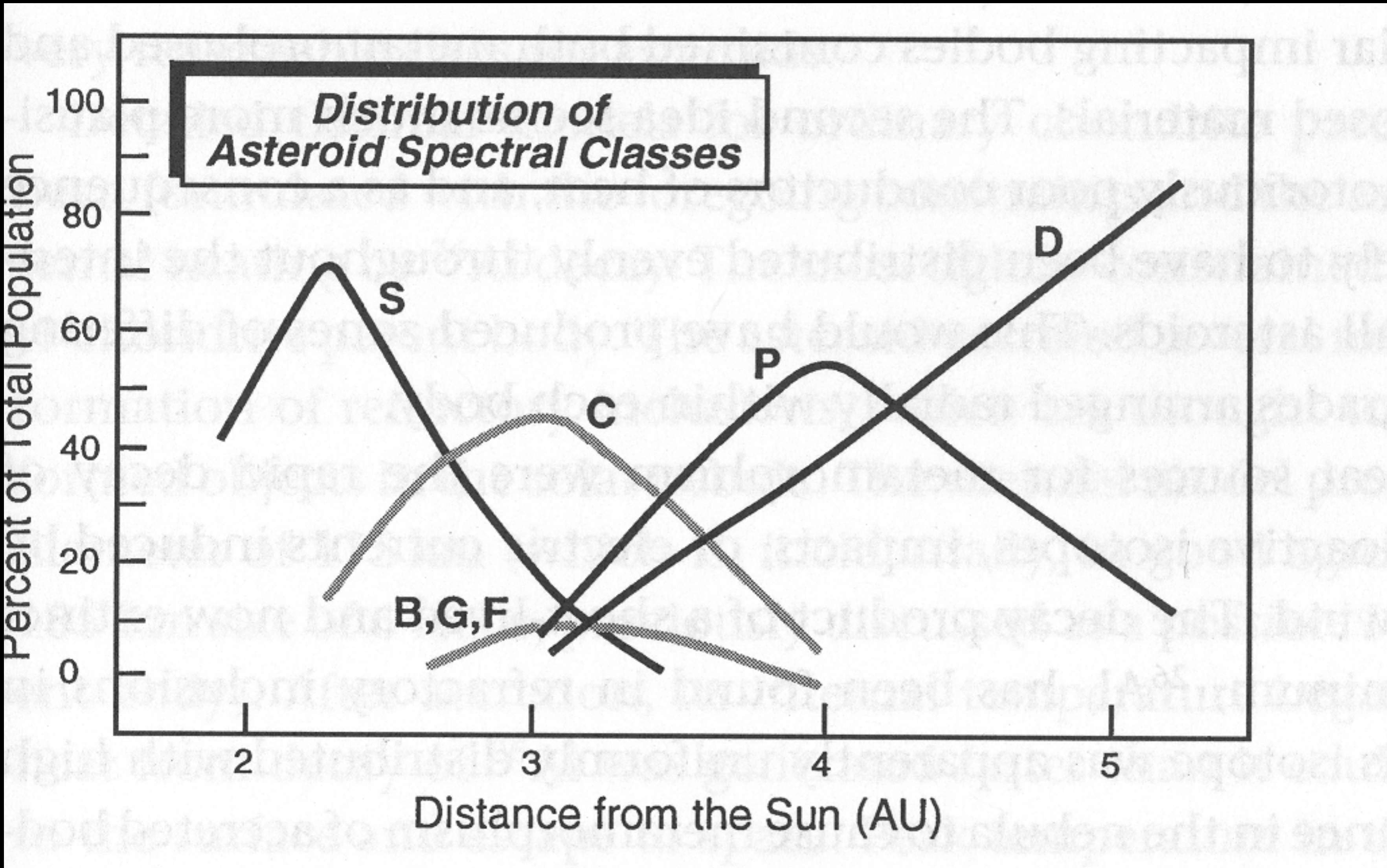

Meteorite Orbits
Pribram
Jupiter
Farmington
Innisfree
Earth
Mars
Sun
Lost City
Asteroid belt
Dhajala



1.2
1.0
0.8
0.6
0.4
amount of light reflected
176 Iduna
vs.
Mighei (carbonaceous chondrite)
wavelength (μm)



Asteroid and Meteorite Spectra
44 Nysa
Aubrite
4 Vesta
Eucrite
L4 Ordinary Chondrite
433 Eros
E4 Enstatite Chondrite
16 Psyche
1 Ceres
CM2 Carbonaceous Chondrite
Albedo
0.5
0.4
0.3
0.2
0.1
0.06
0.04
0.4
0.8
1.2
1.6
2.0
Wavelength (µm)

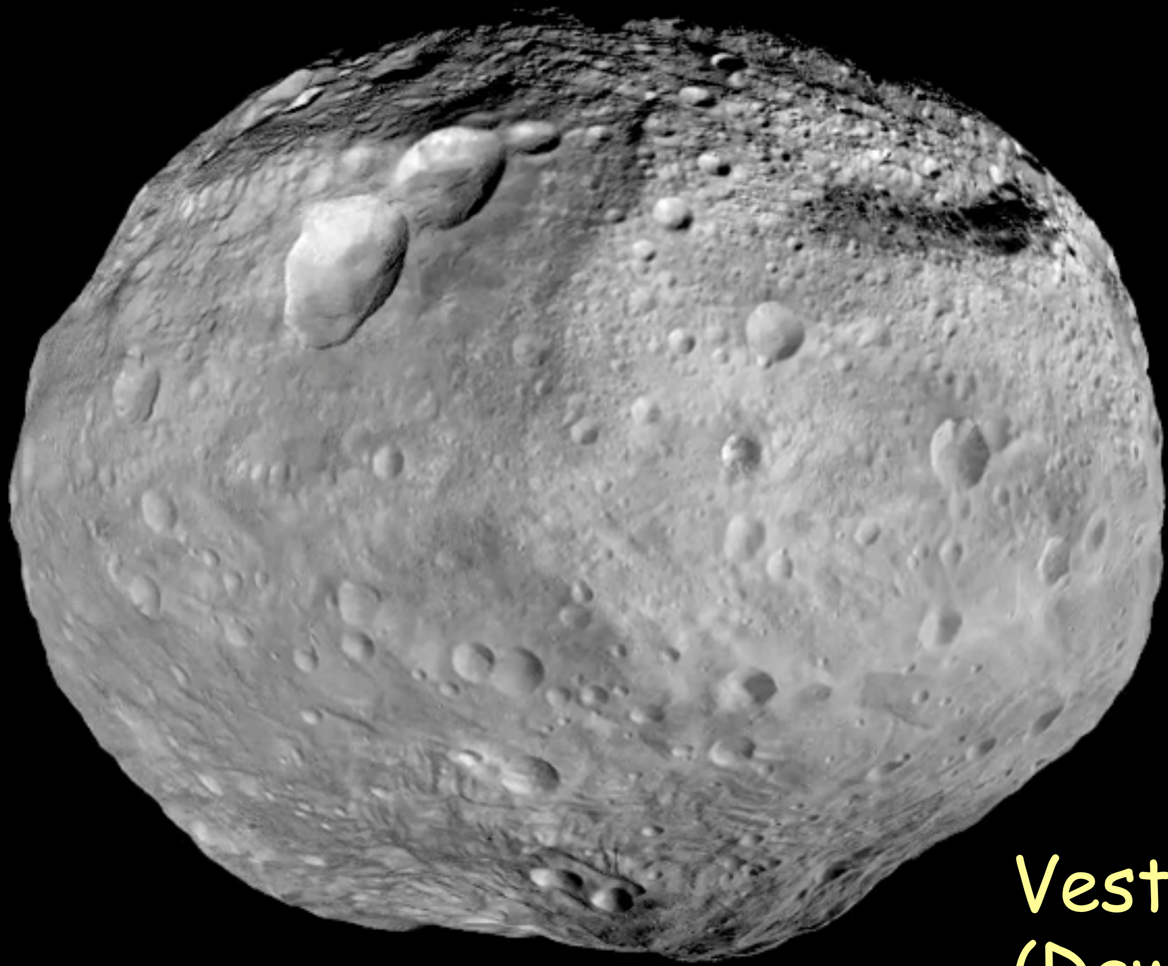


Distribution of Asteroid Spectral Classes
100
80
60
40
20
0
Percent of Total Population
S
C
P
D
B,G,F
2
3
4
5
Distance from the Sun (AU)

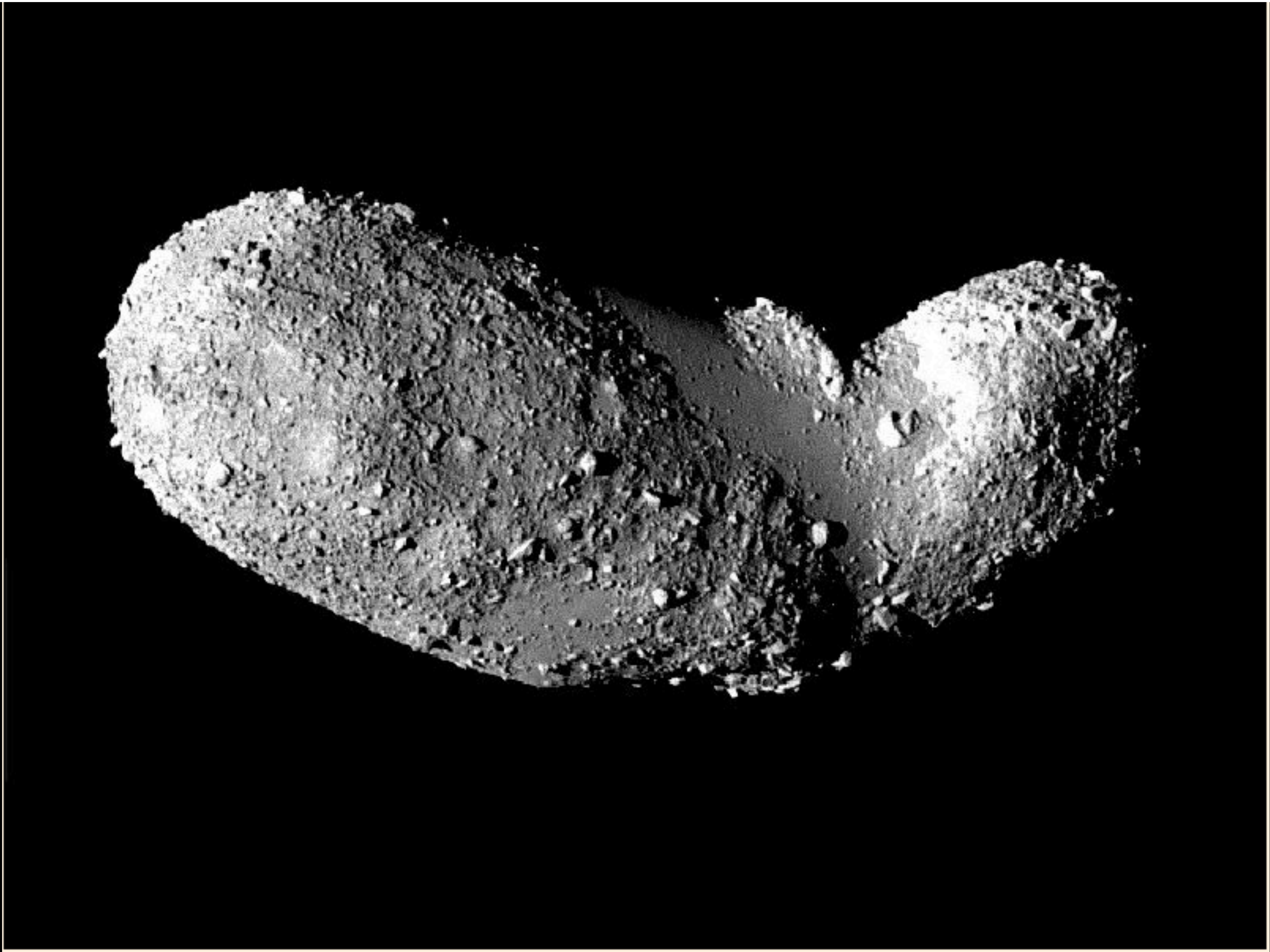

Ida and Dactyl

Eros
(S type)

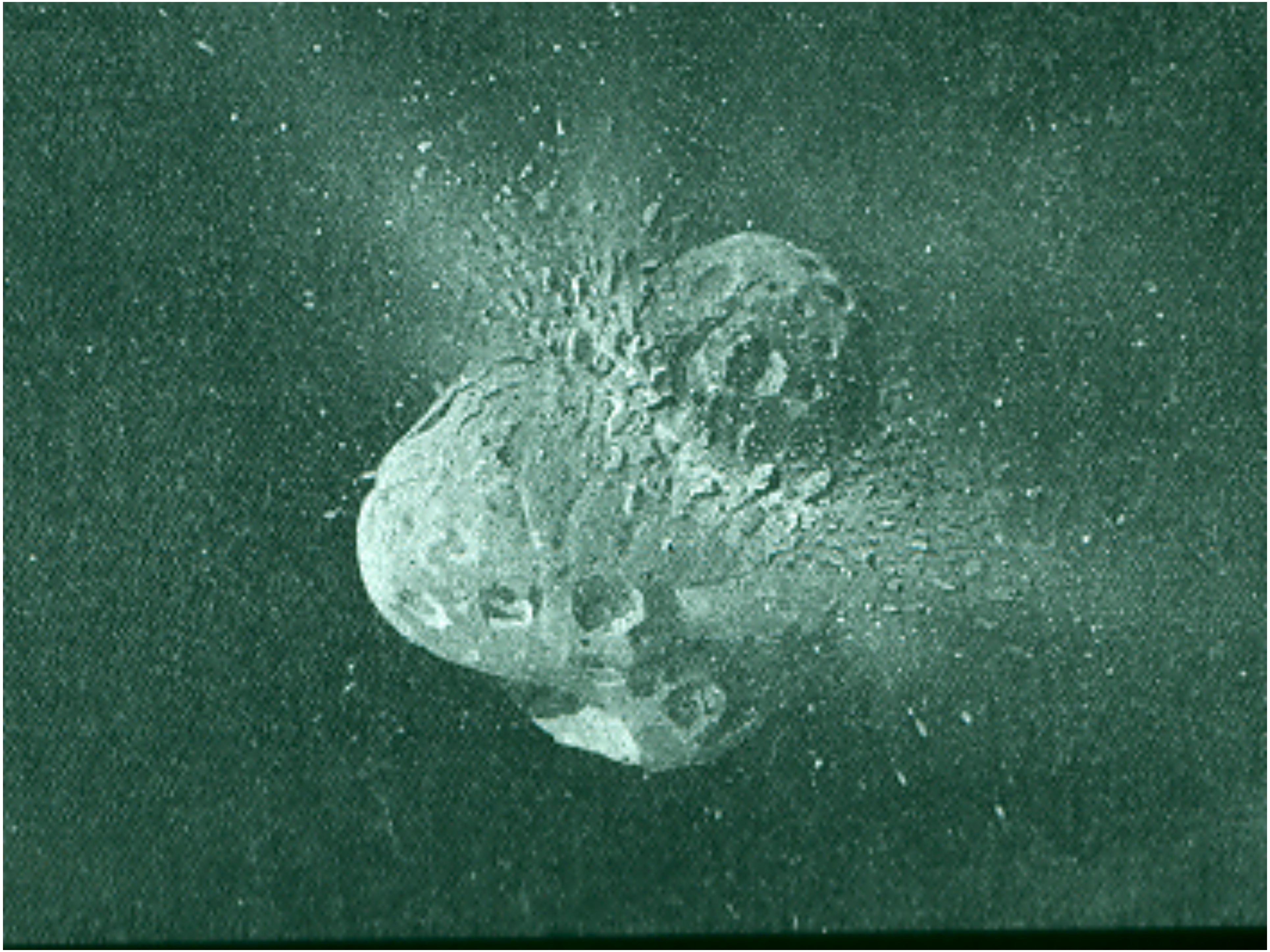

Mathilde
(C type)

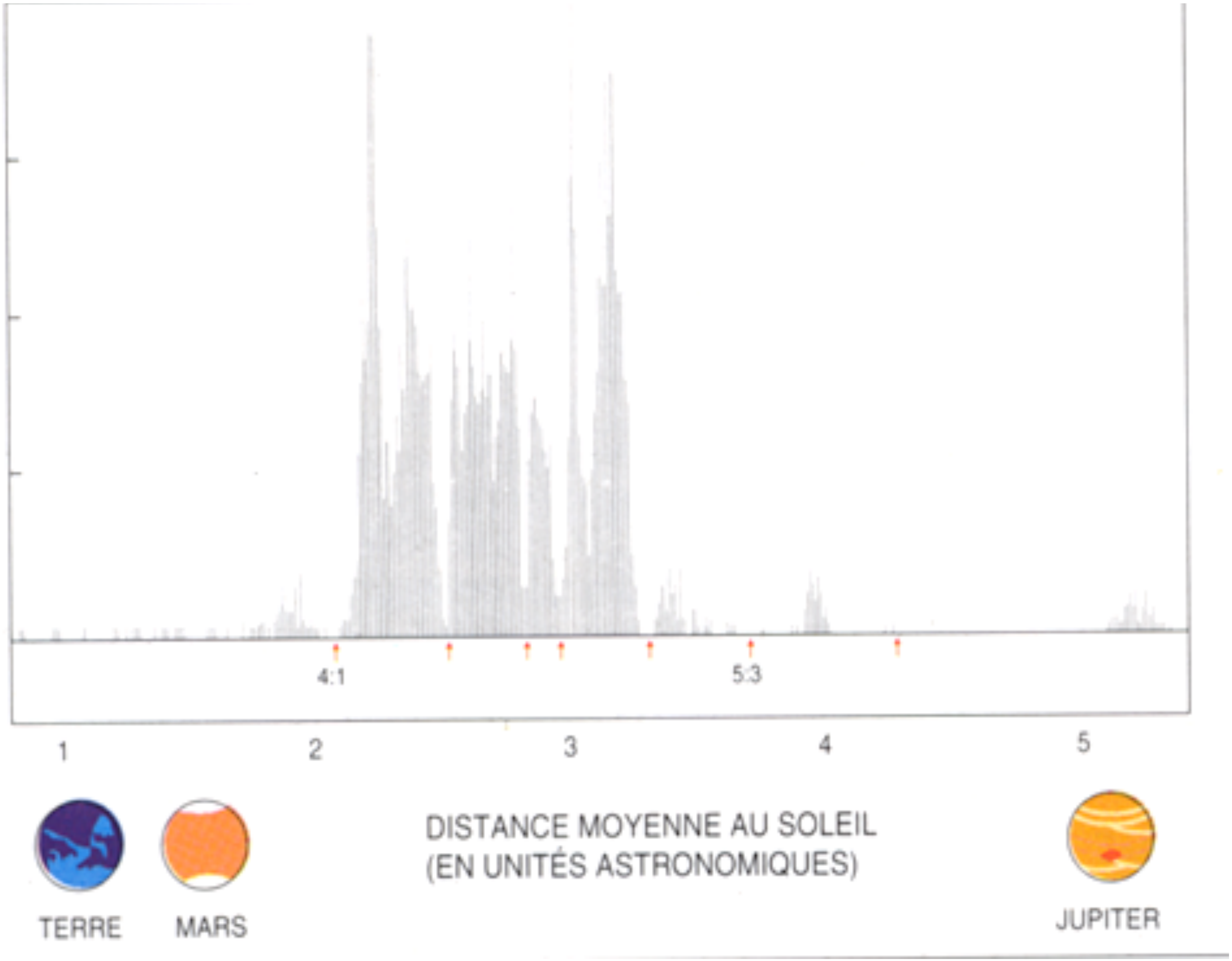


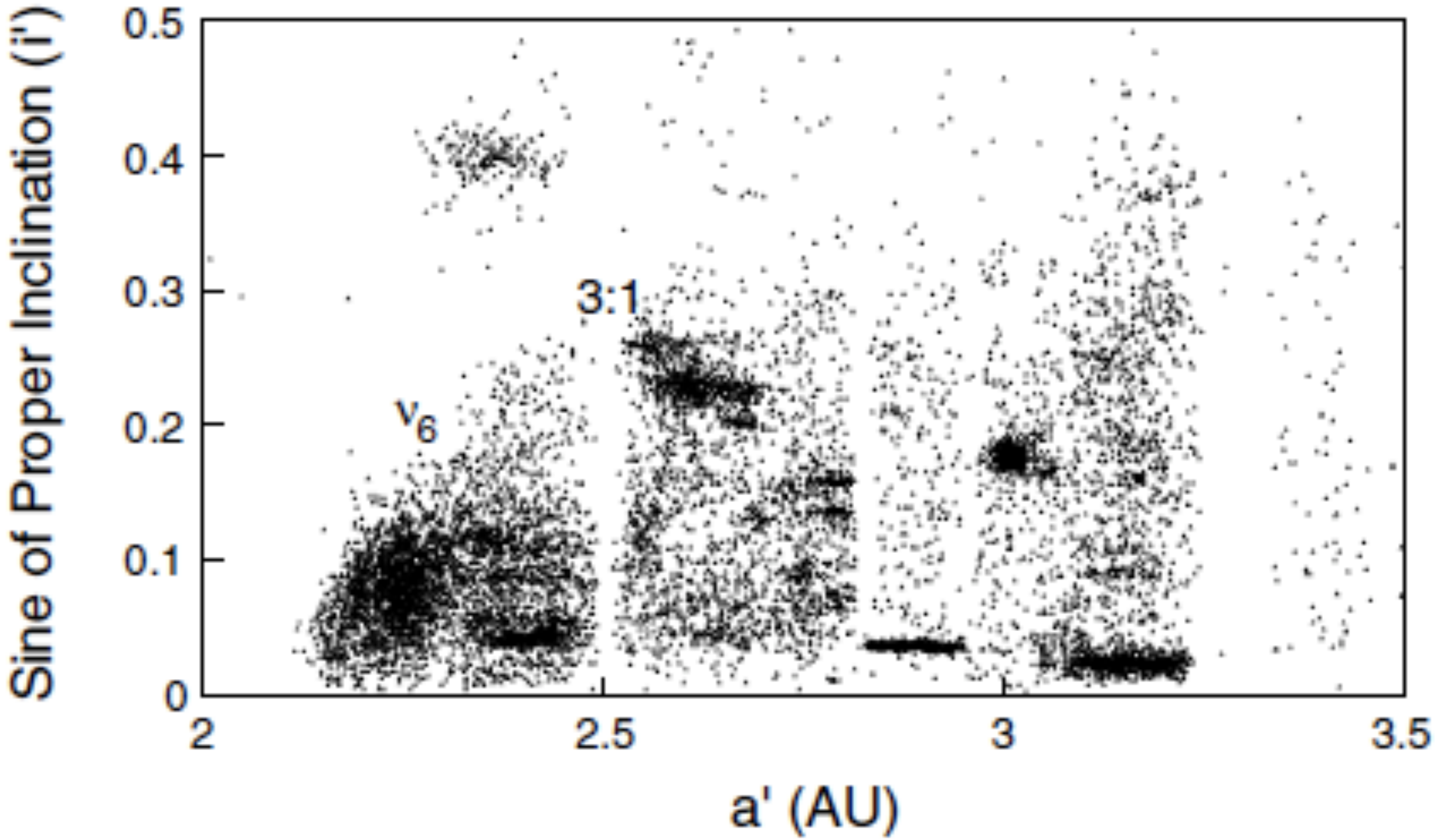
Vesta
(Dawn Mission
2011-2012)



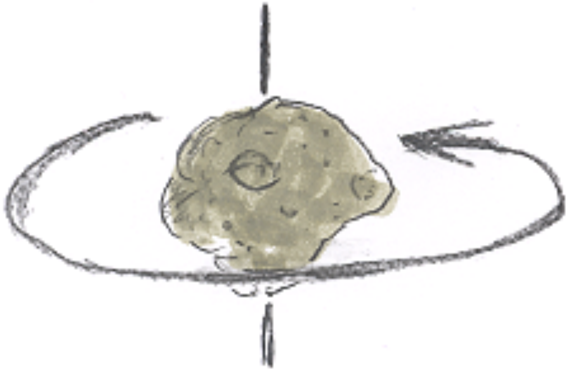
Asteroid Itokawa



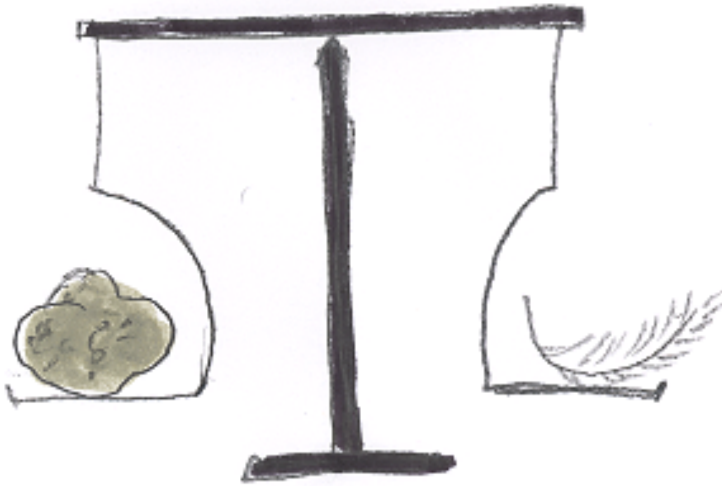

4:1
5:3
1
2
3
4
5
DISTANCE MOYENNE AU SOLEIL
(EN UNITÉS ASTRONOMIQUES)
TERRE
MARS
JUPITER



Sine of Proper Inclination (i')
a' (AU)
0.5
0.4
0.3
0.2
0.1
0
2
2.5
3
3.5
3:1
ν_6

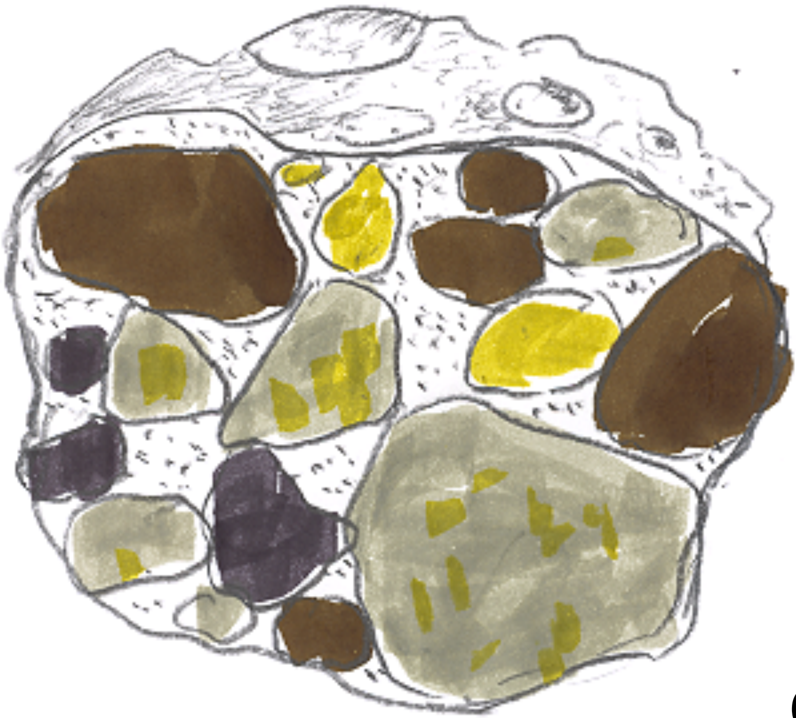


Slow spin

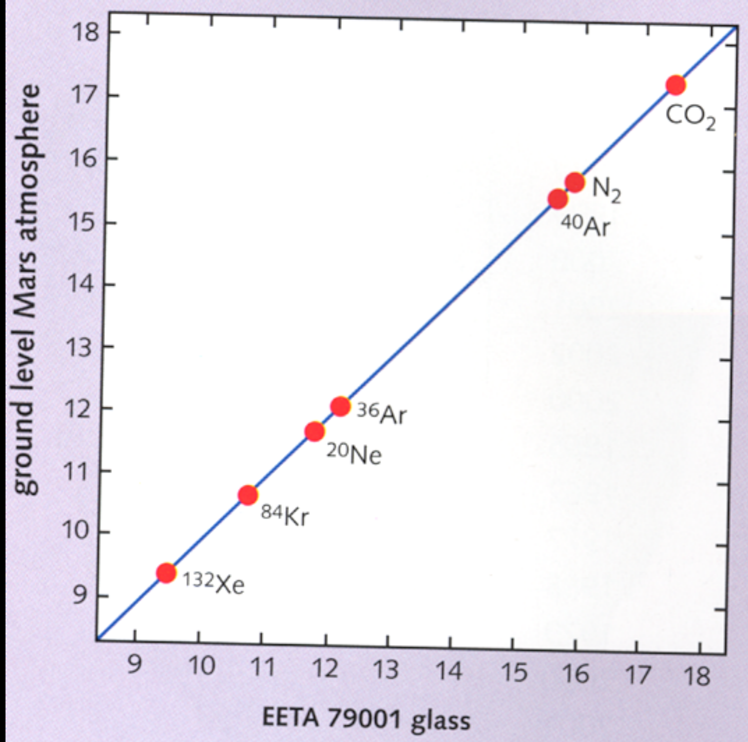


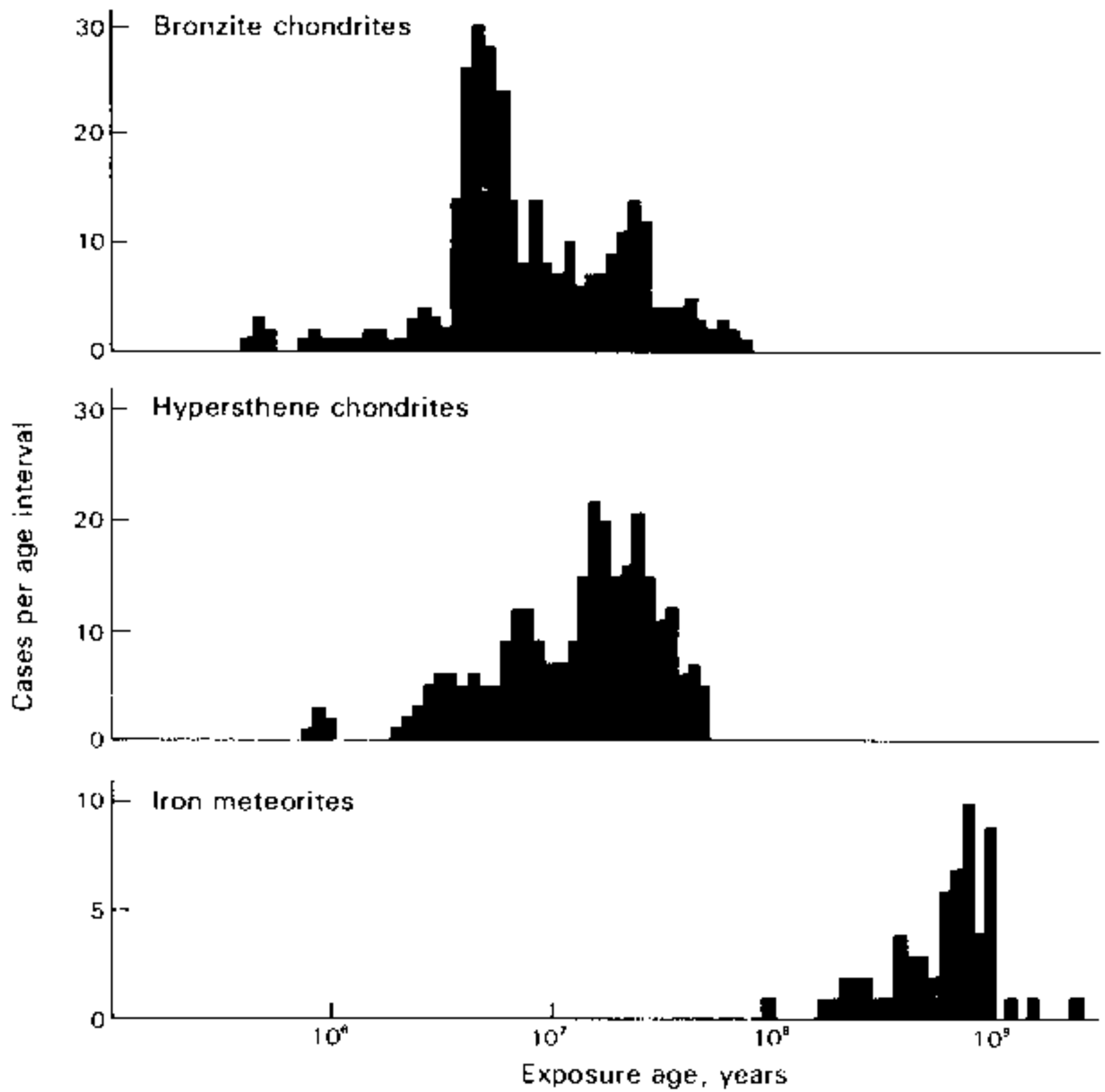
Low density

Odd shapes



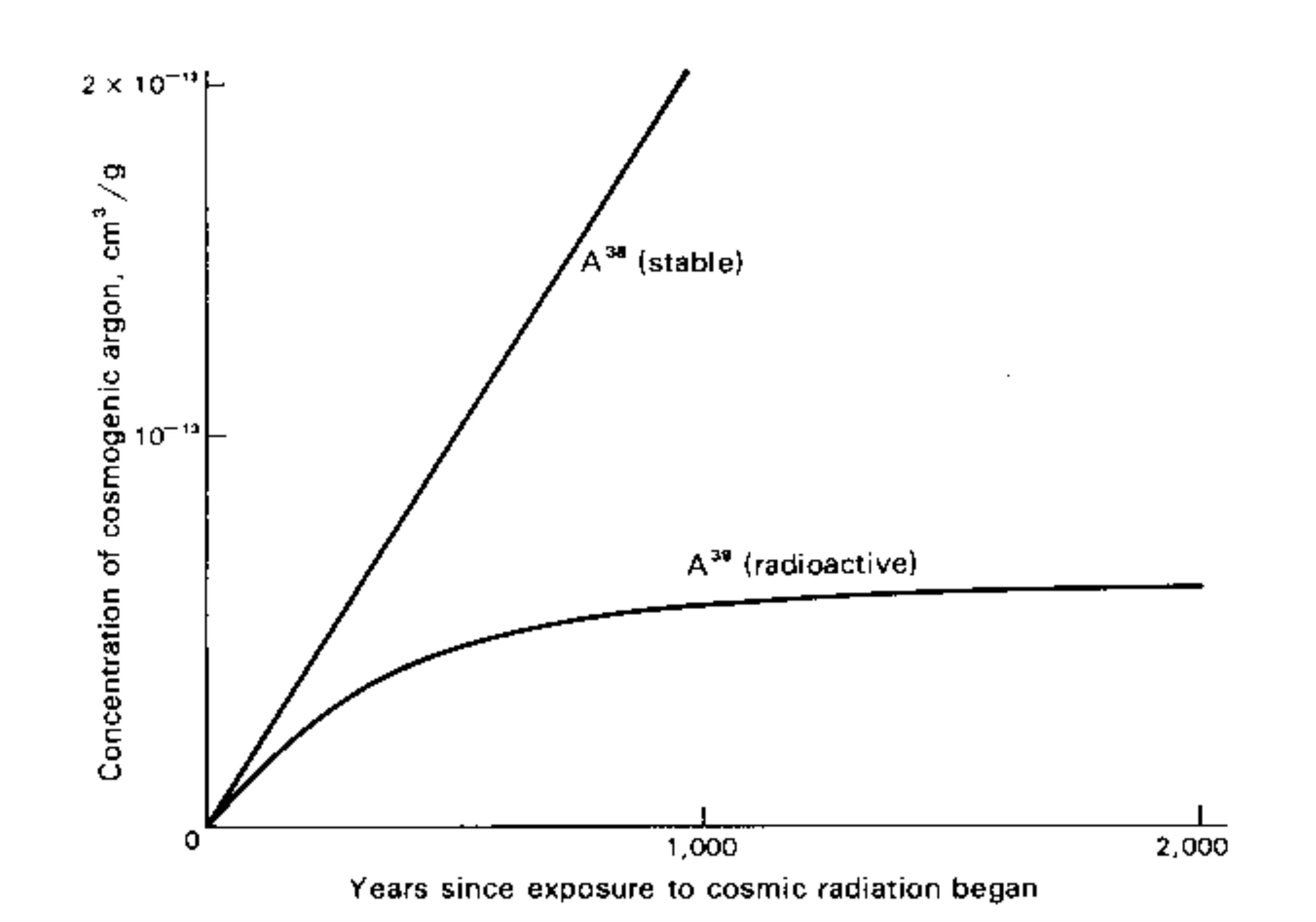
Conclusion:
asteroids are rubble-piles


ground level Mars atmosphere
EETA 79001 glass
9
10
11
12
13
14
15
16
17
18
CO_2
N_2
^{40}Ar
^{36}Ar
^{20}Ne
^{84}Kr
^{132}Xe


Bronzite chondrites
Hypersthene chondrites
Iron meteorites
Cases per age interval
Exposure age, years
0
10
20
30
5
10^6
10^7
10^8
10^9

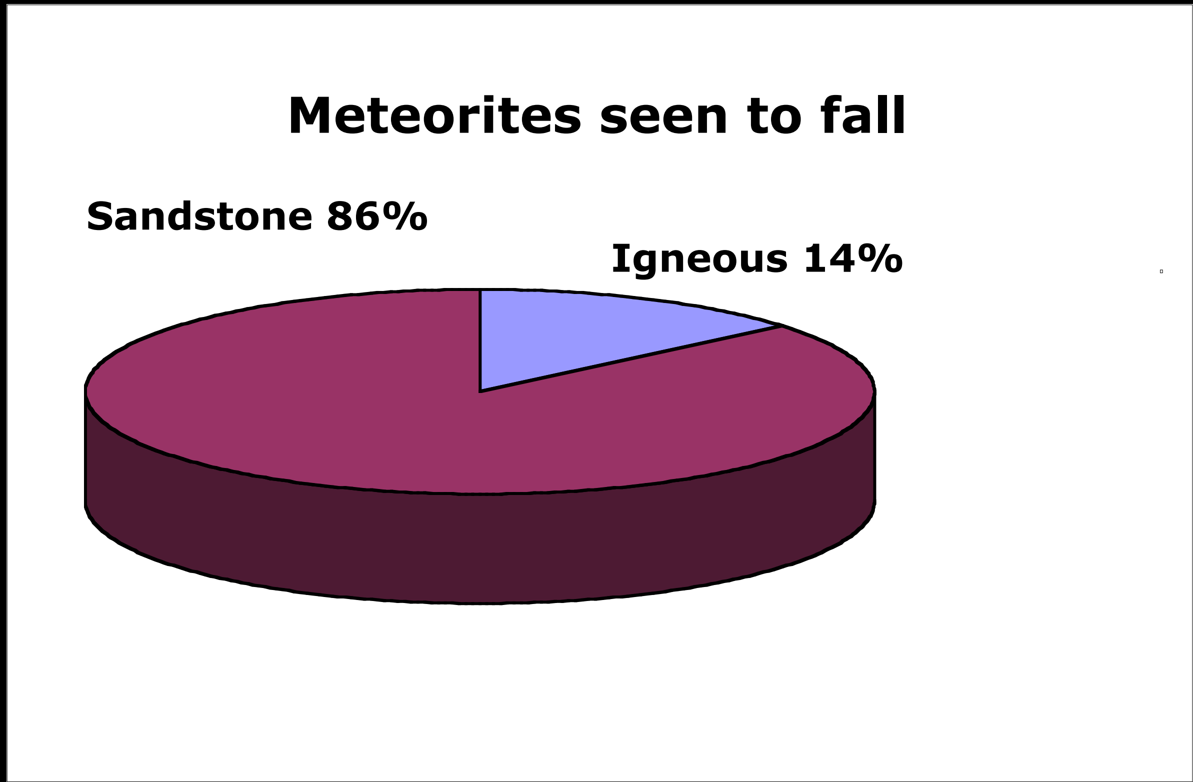
$$Fe^{56} + H^{1} \rightarrow Cl^{36} + \underbrace{H^{3} + 2He^{4} + He^{3} + 3H^{1} + 4\ \text{neutrons}}$$

Fe^{56}	H^{1}	Cl^{36}	$H^{3} + 2He^{4} + He^{3} + 3H^{1} + 4$ neutrons
nucleus before being struck	high-energy proton	remainder of Fe^{56} nucleus	debris spalled off from Fe^{56} nucleus (plus impacting proton)



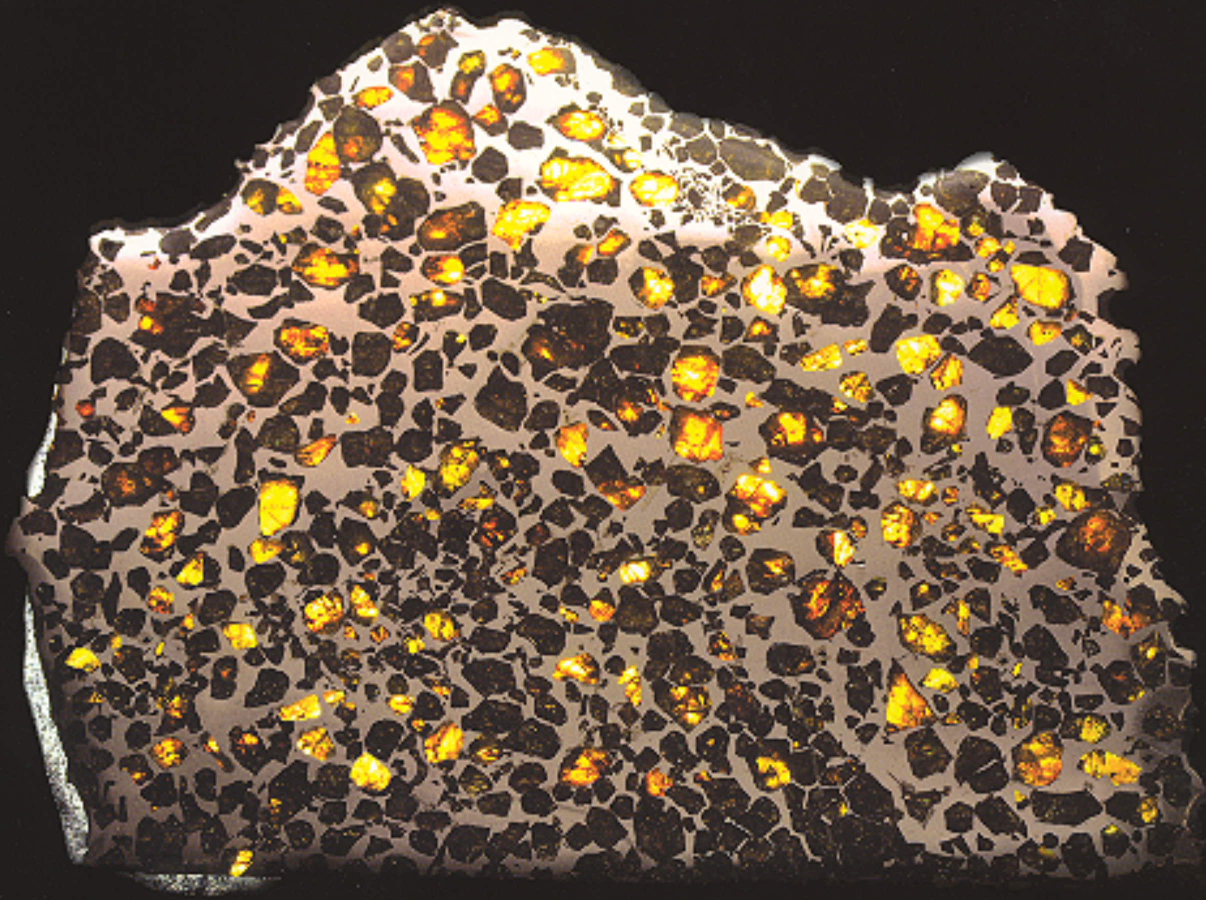
2×10^{-13}
10^{-13}
Concentration of cosmogenic argon, cm^3 / g
A^{38} (stable)
A^{39} (radioactive)
0
1,000
2,000
Years since exposure to cosmic radiation began

What are meteorites made of ?


Meteorites seen to fall
Sandstone 86%
Igneous 14%

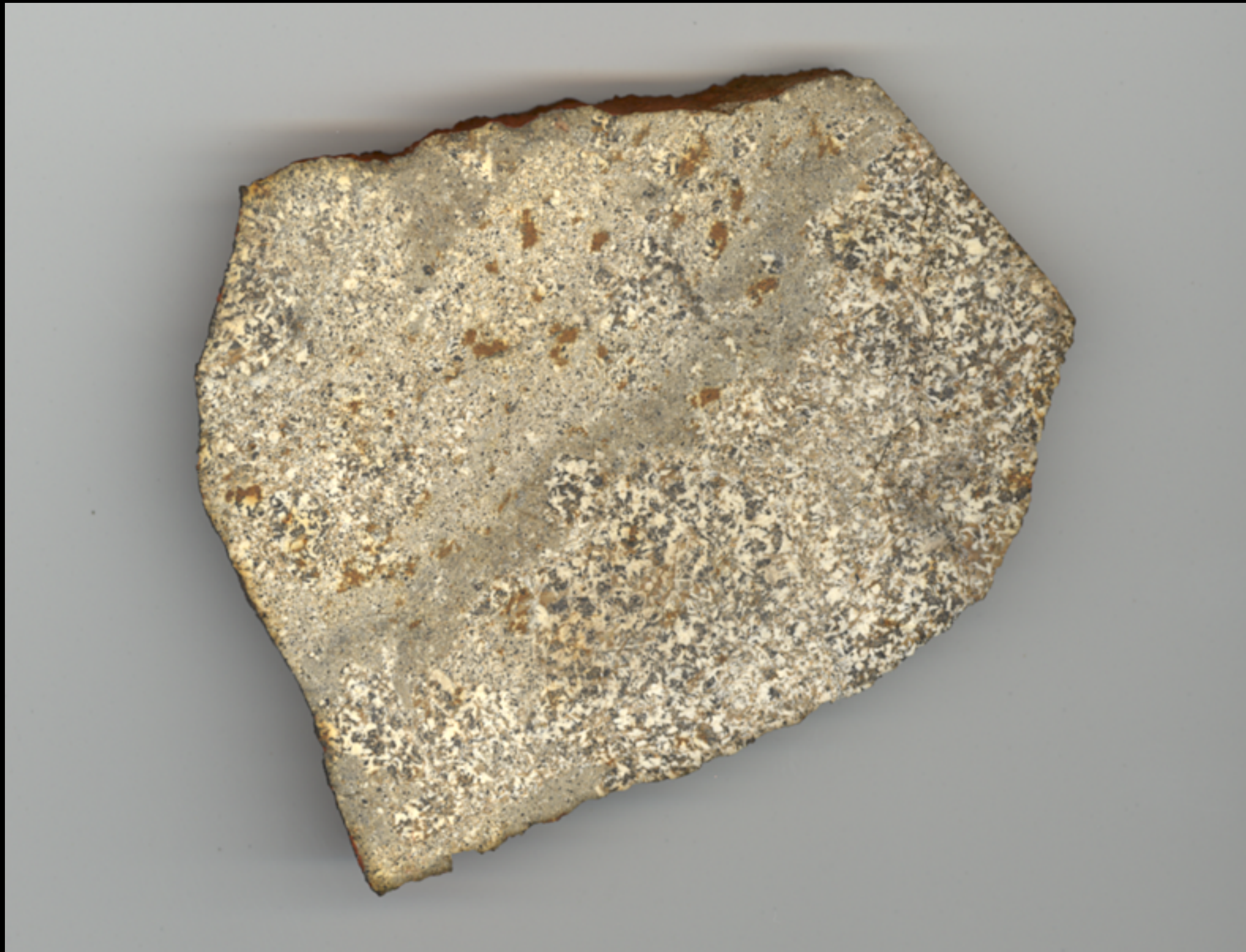
METEORITES

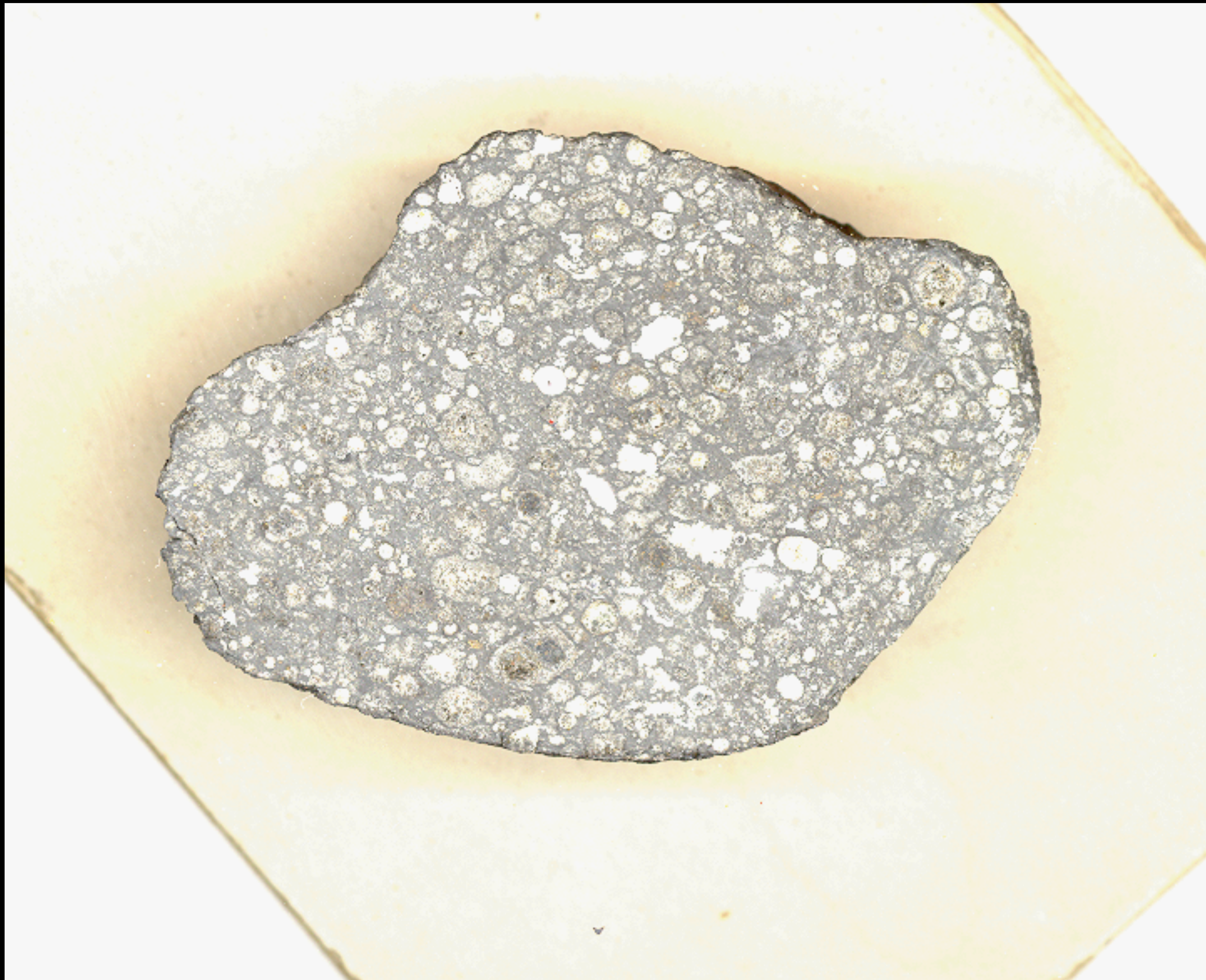
SECOND EDITION

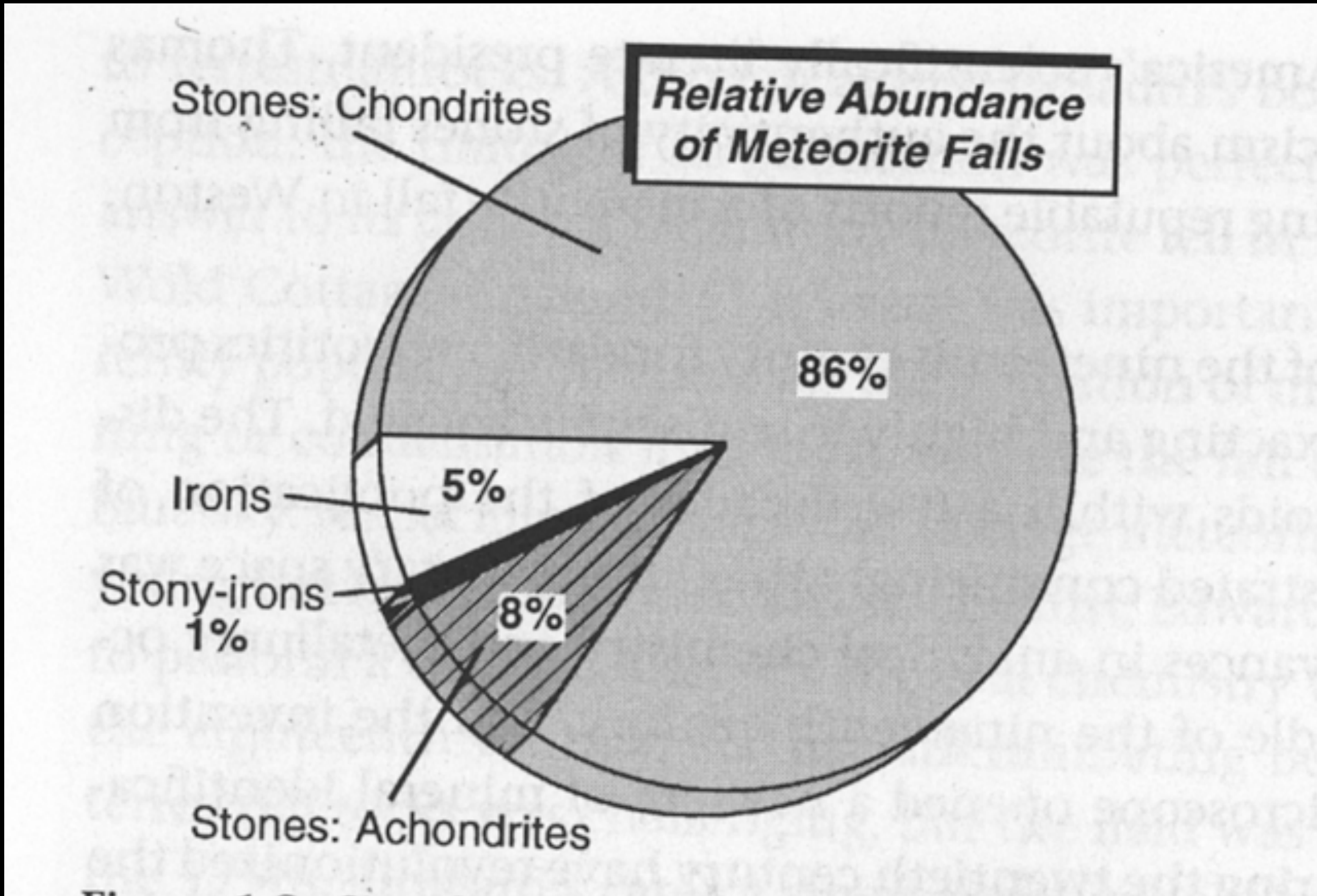


SARA RUSSELL AND MONICA GRADY

THE NATURAL HISTORY MUSEUM





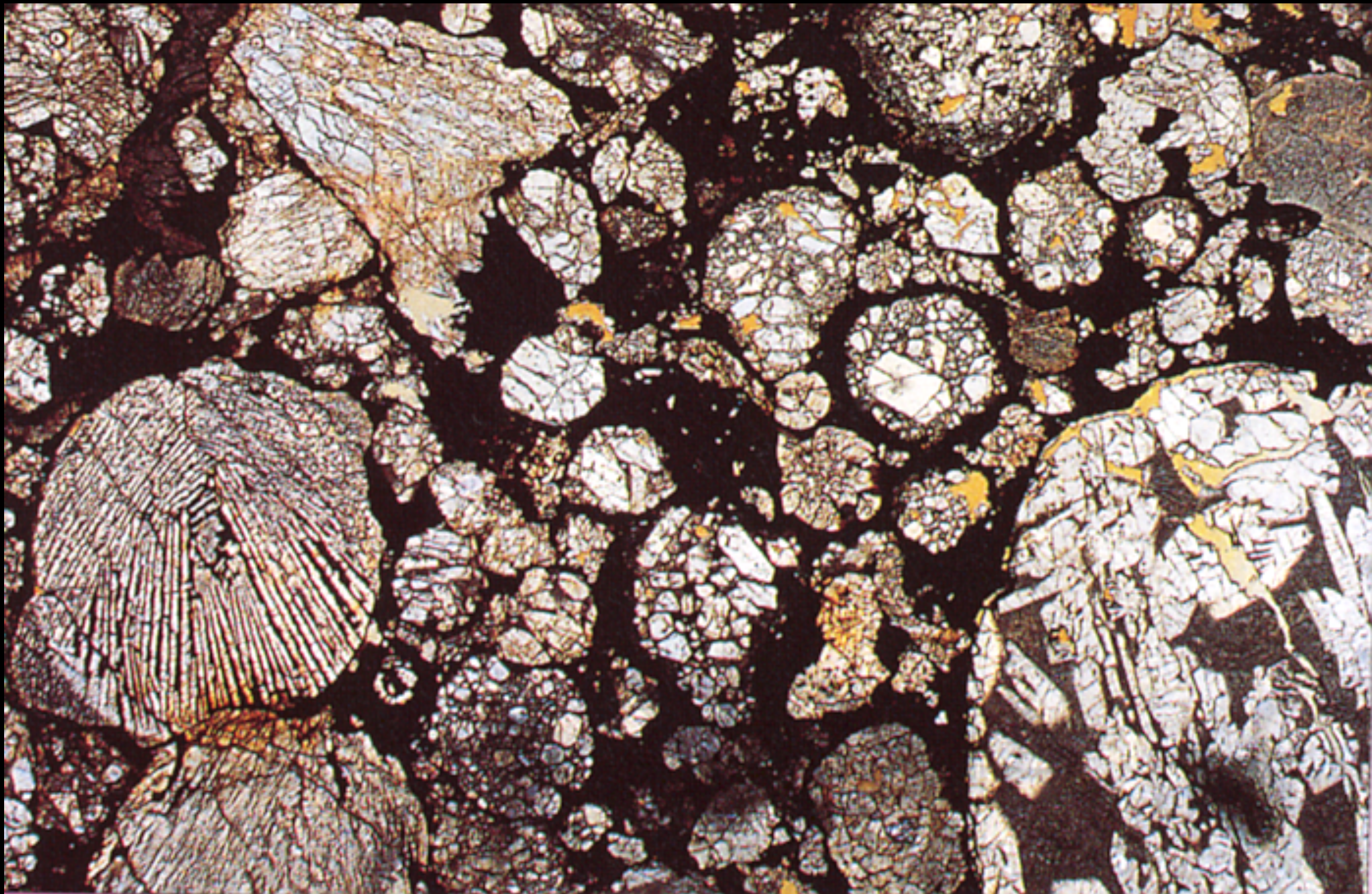

Relative Abundance of Meteorite Falls
Stones: Chondrites
86%
Irons
5%
Stony-irons
1%
8%
Stones: Achondrites

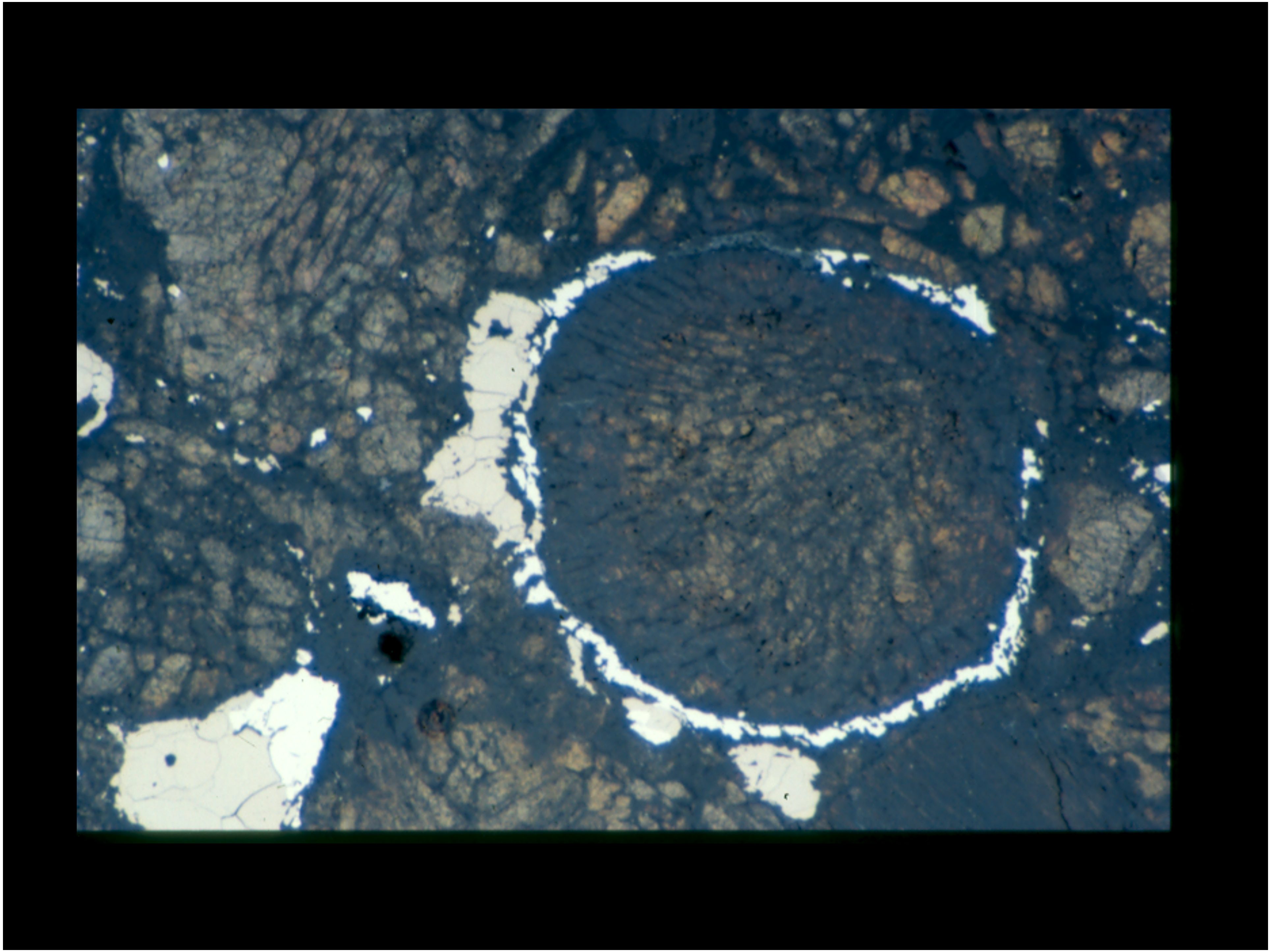
What are chondrites like ?

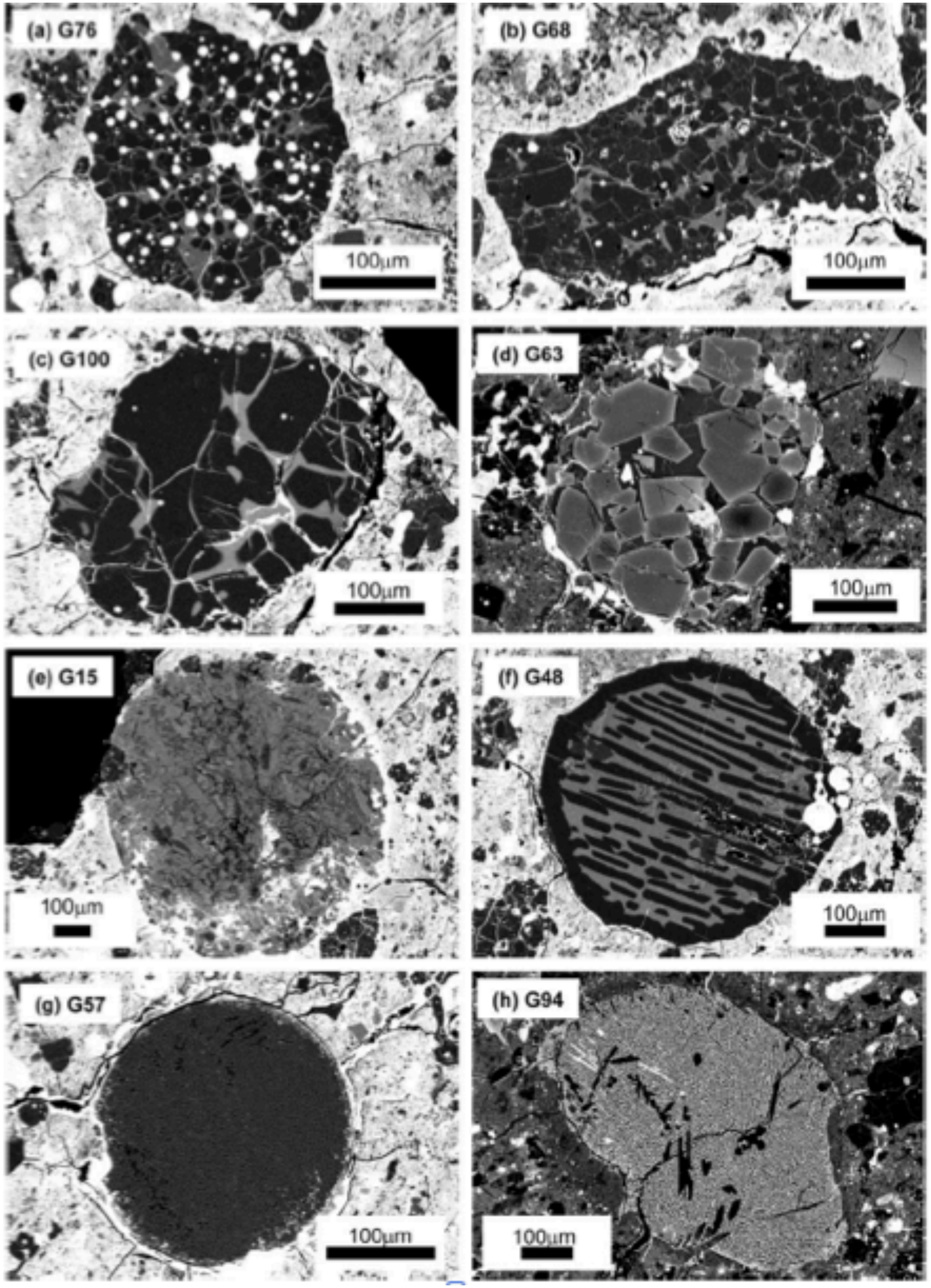
Chondritic (sandstone) meteorites

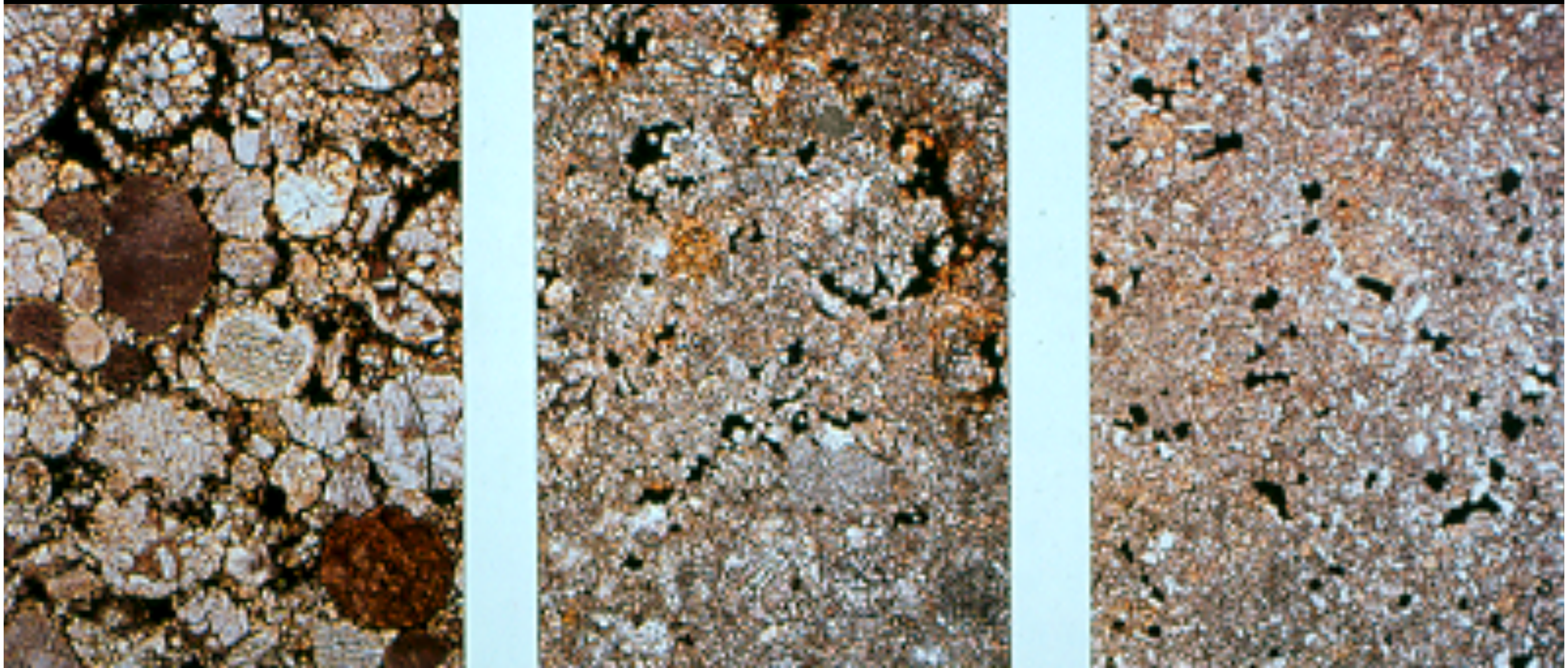
Chondrules and other bits
Heating effects
Shock effects
CAIs: ^{26}Al and Pb-Pb age
Pre-solar grains
Organics
Bulk chemistry
Chondrite groups

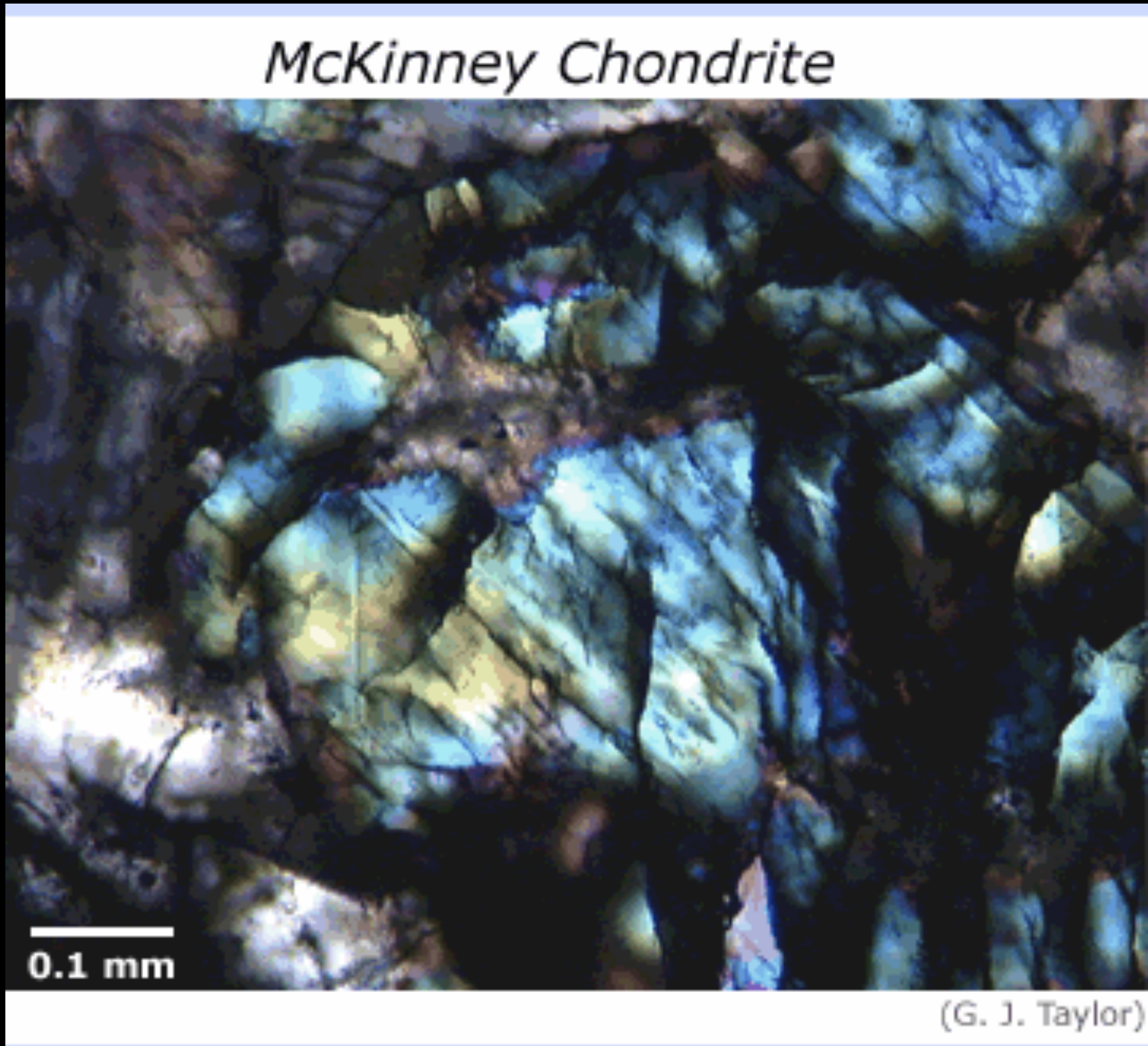

chondrules






(a) G76
100µm
(b) G68
100µm
(c) G100
100µm
(d) G63
100µm
(e) G15
100µm
(f) G48
100µm
(g) G57
100µm
(h) G94
100µm



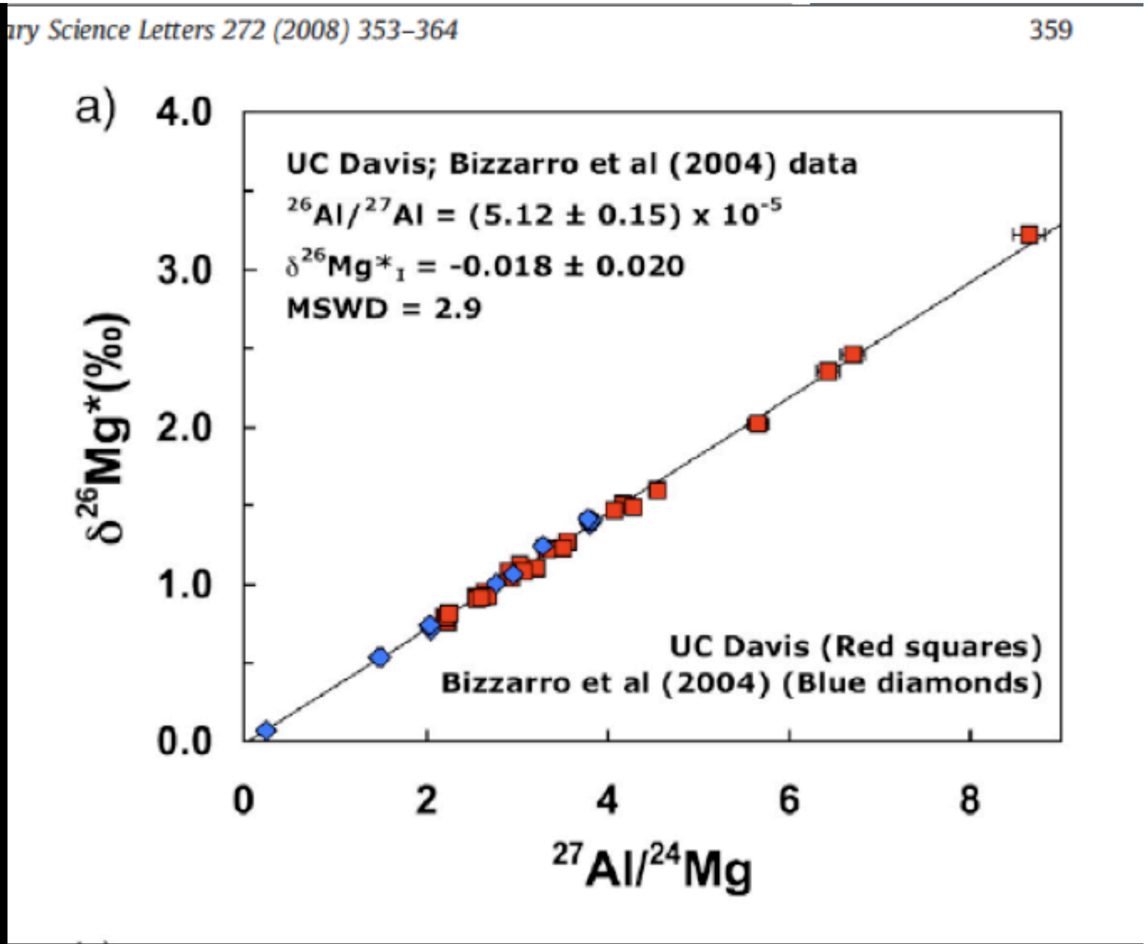


McKinney – an intensely shocked chondrite

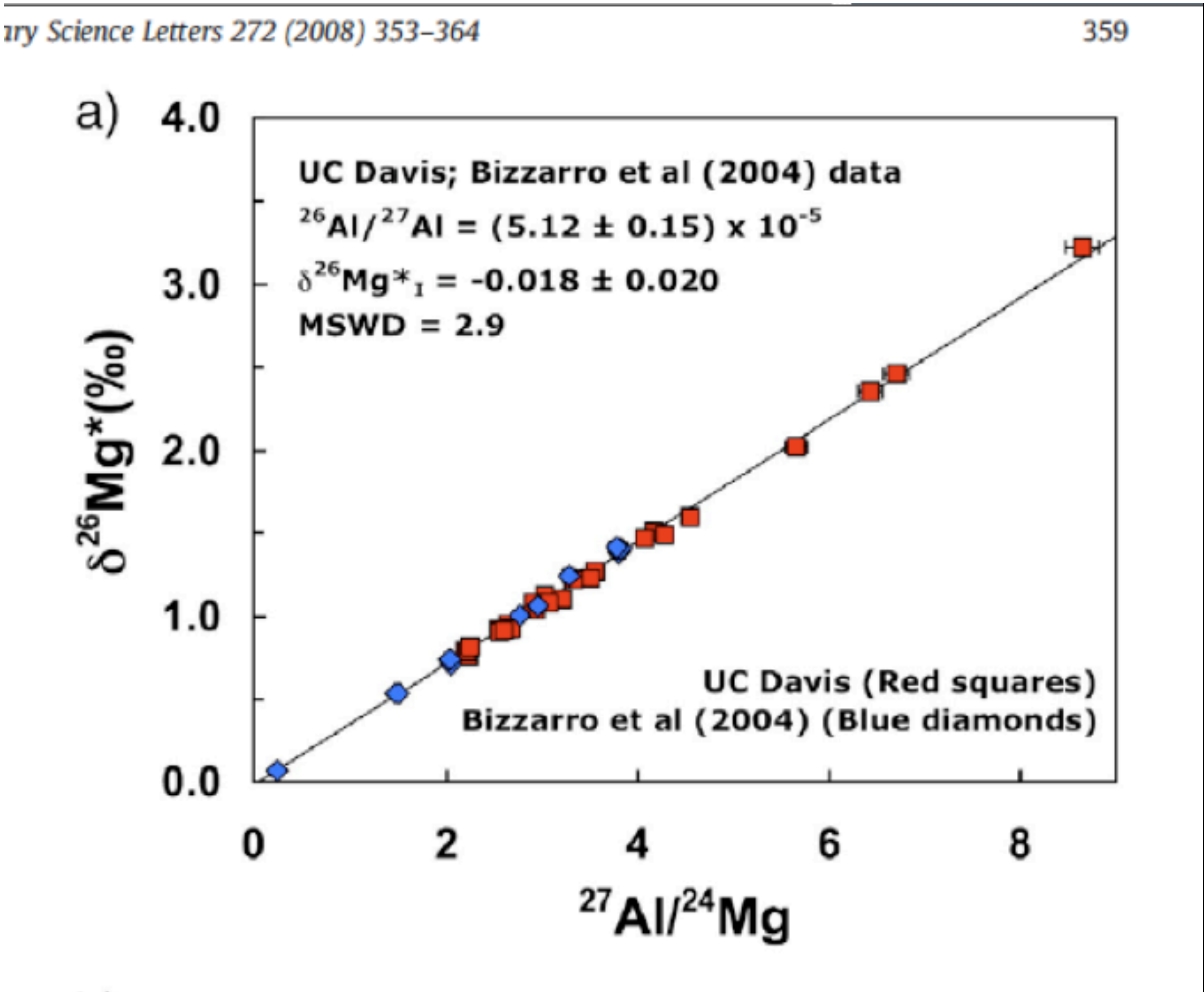

Calcium-aluminium-rich inclusion (CAI)

Calcium-aluminium-rich inclusion (CAI)

CAIs were radioactive - they contained short-lived ^{26}Al, half-life 0.73 Myr, which quickly decayed away



Evidence for ^{26}Al:
$^{26}Mg/^{24}Mg$ is everywhere the same in meteorites, and on Earth, but in CAIs (Al-rich, Mg-poor) it is anomalously high. The excess ^{26}Mg correlates with Al/Mg so is presumably the daughter of ^{26}Al.

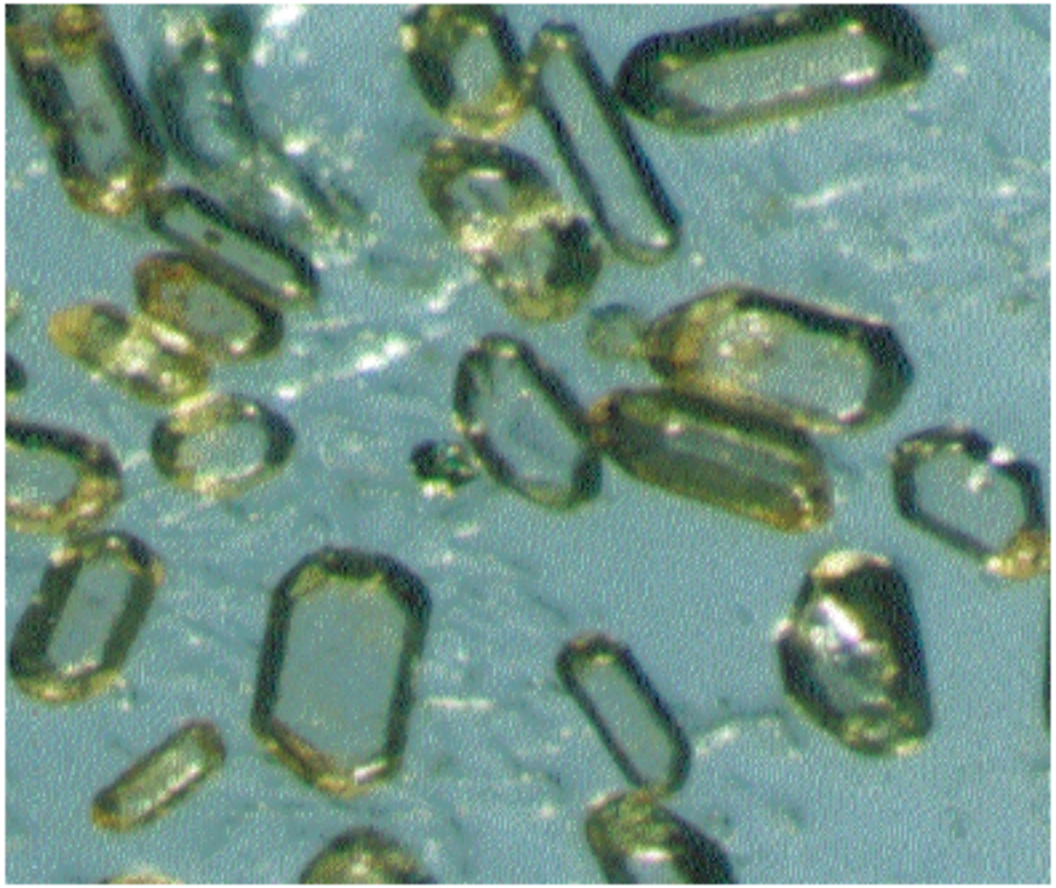


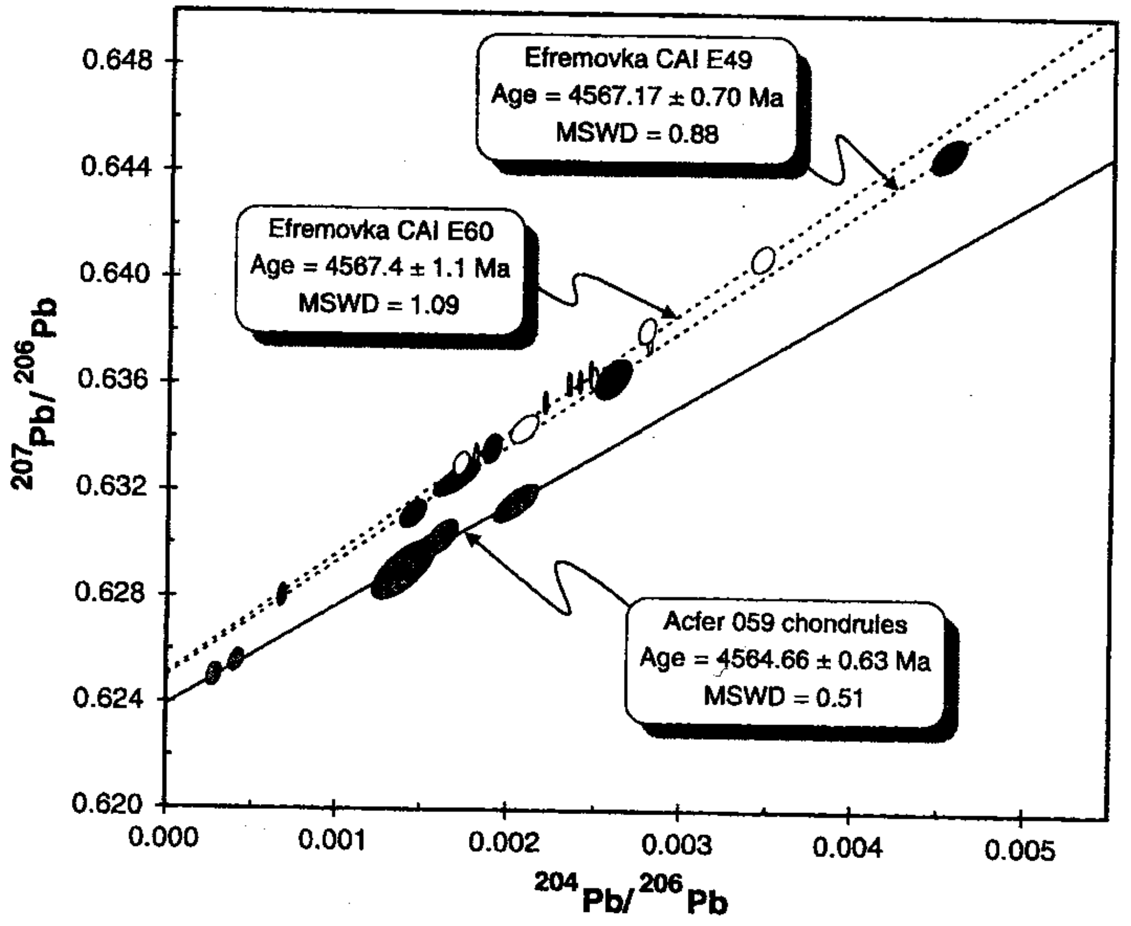
CAIs contained 5 atoms of radioactive ^{26}Al for every 100,000 atoms of ^{27}Al.

i.e. when CAIs were made, $^{26}Al/^{27}Al$ was 5×10^{-5}

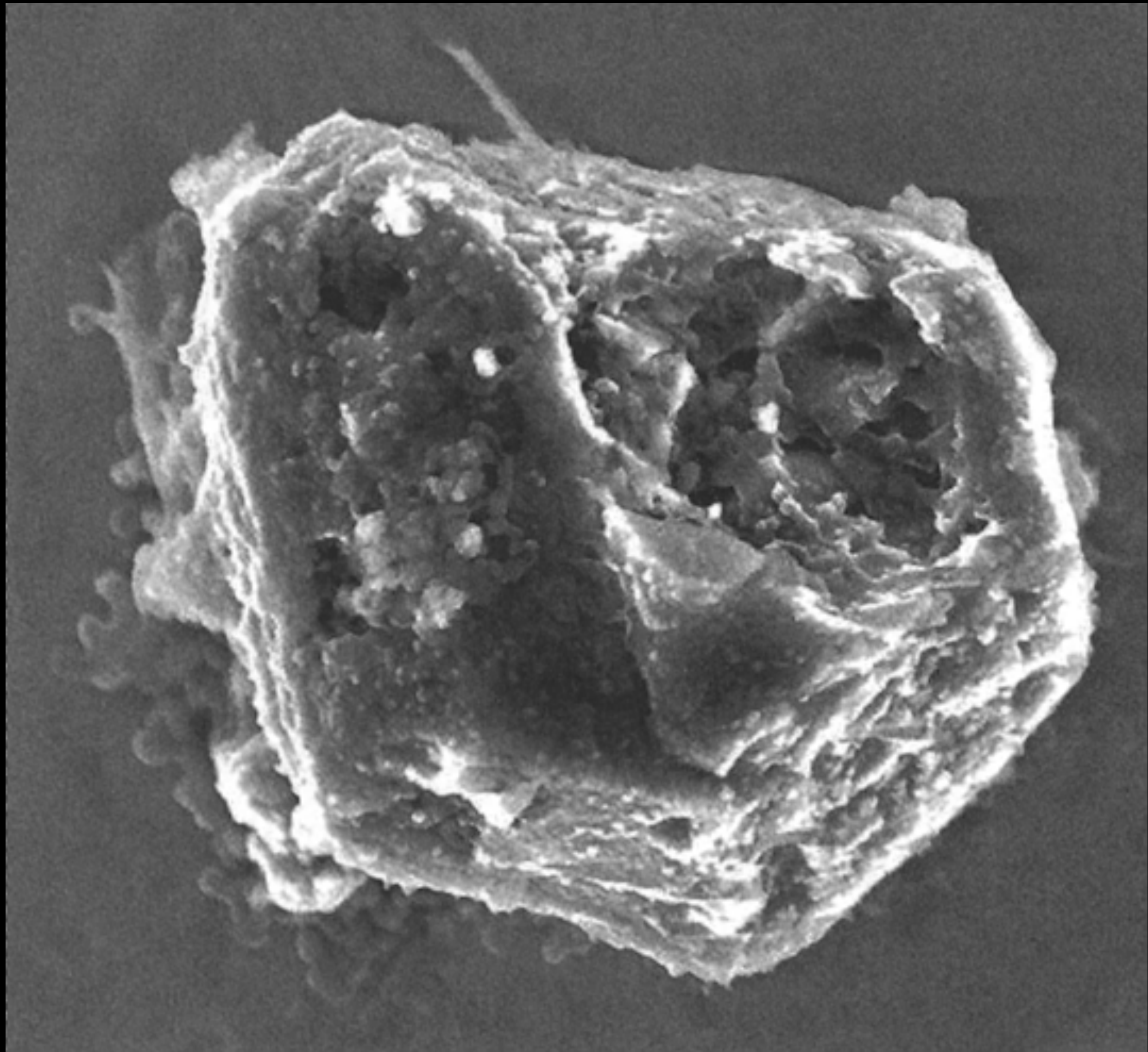
Secondary ion mass spectrometer (SIMS)

Figure 25 Tiny crystals of zircon seen through a microscope. They are up to about a tenth of a millimetre long. They were picked out of crushed granite from the Ox Mountains in County Sligo. The crushed granite is sieved, and then dropped into a very dense liquid called methyl iodide. Quartz, feldspar and mica float in this liquid, but zircon, being extremely dense, sinks and can be separated.





CAIs are the oldest surviving bits of the solar system, first dated precisely by the $^{207}Pb/^{206}Pb$ method by Yuri Amelin in 2002. Their age of 4567 Myr is taken as the age of the solar system.



Tiny grains with unusual isotopic ratios are found in the matrix of chondrites that never got hot. In this 5 micron SiC grain $^{12}C/^{13}C$ is only 39

(Normally it is 89)

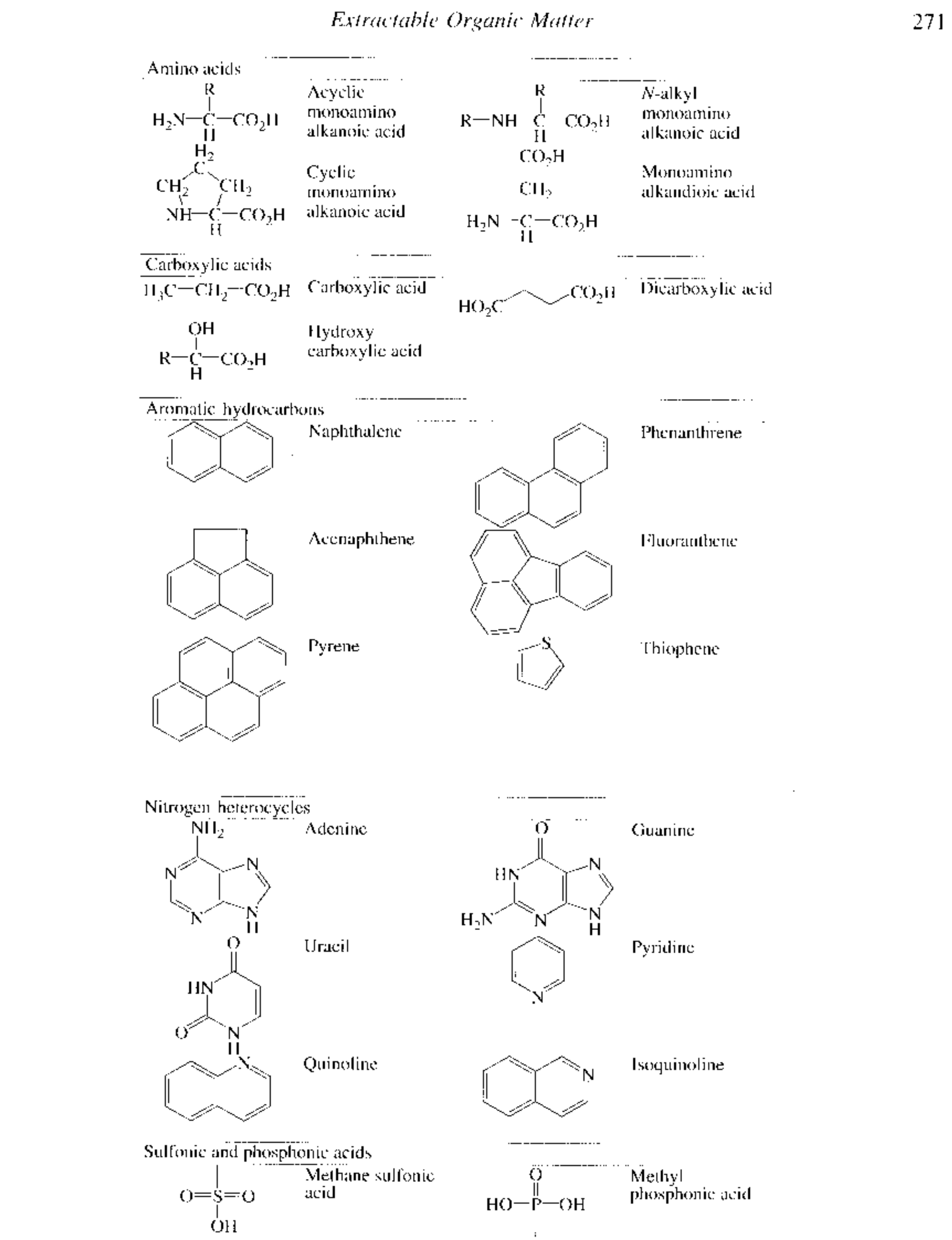
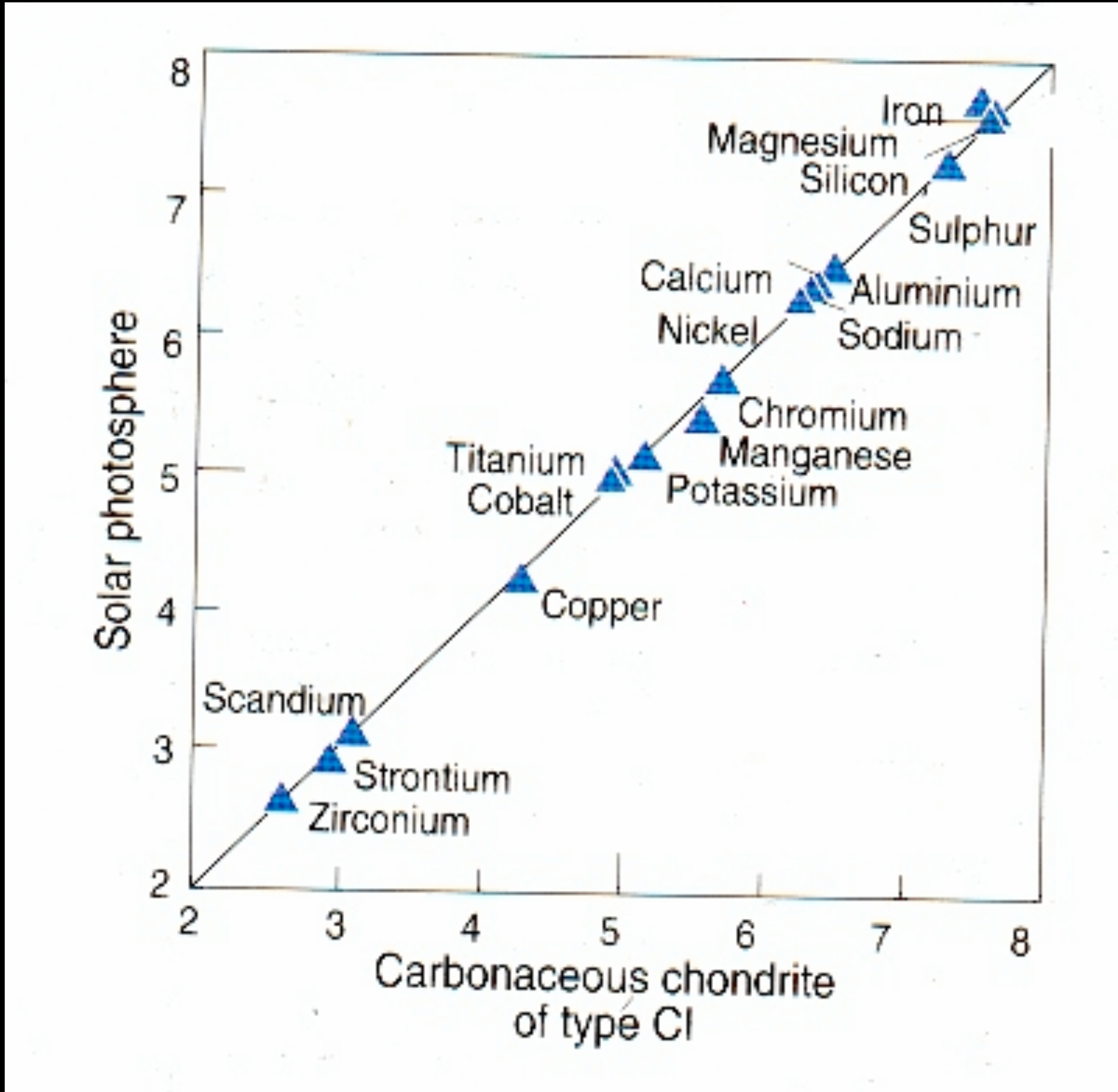
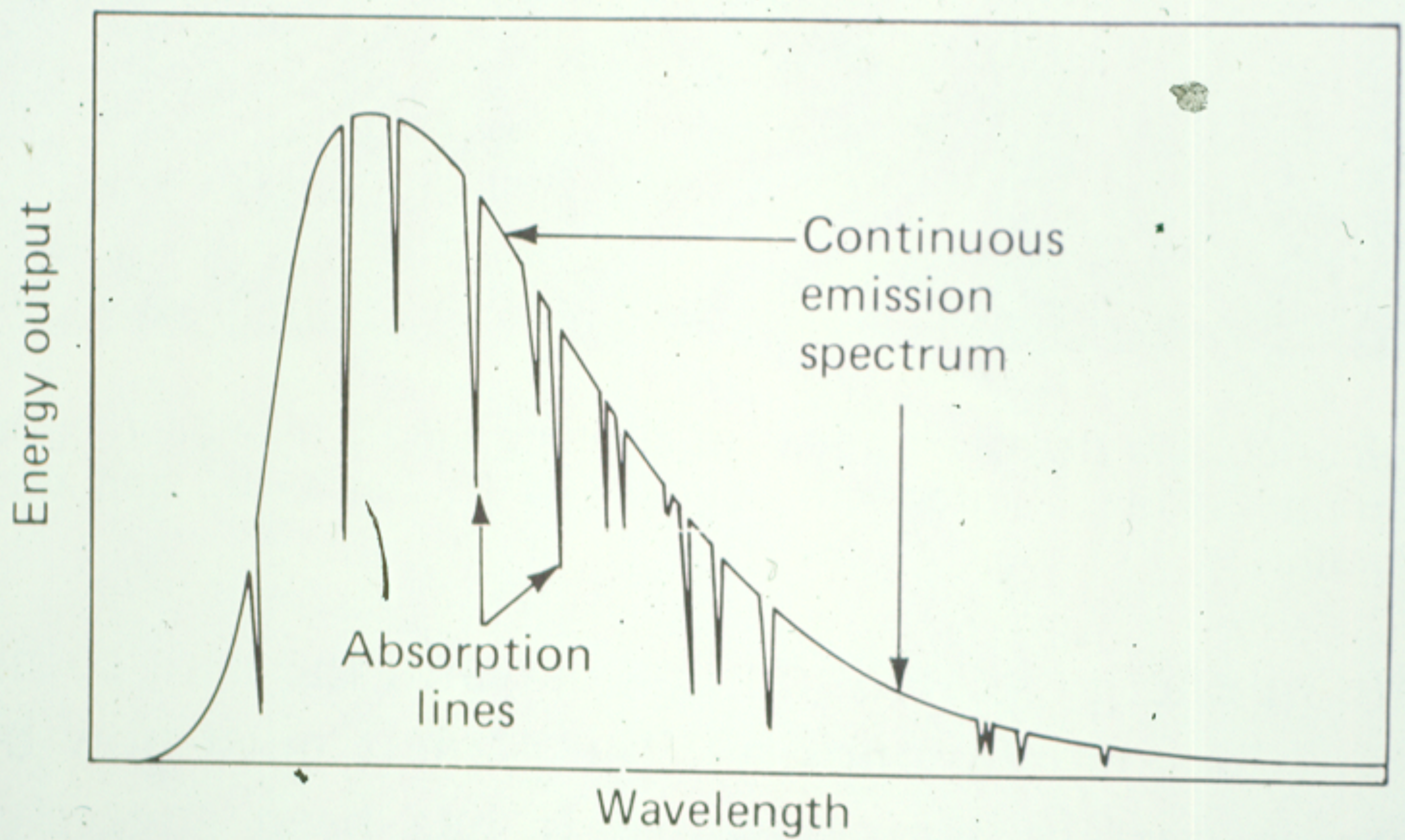


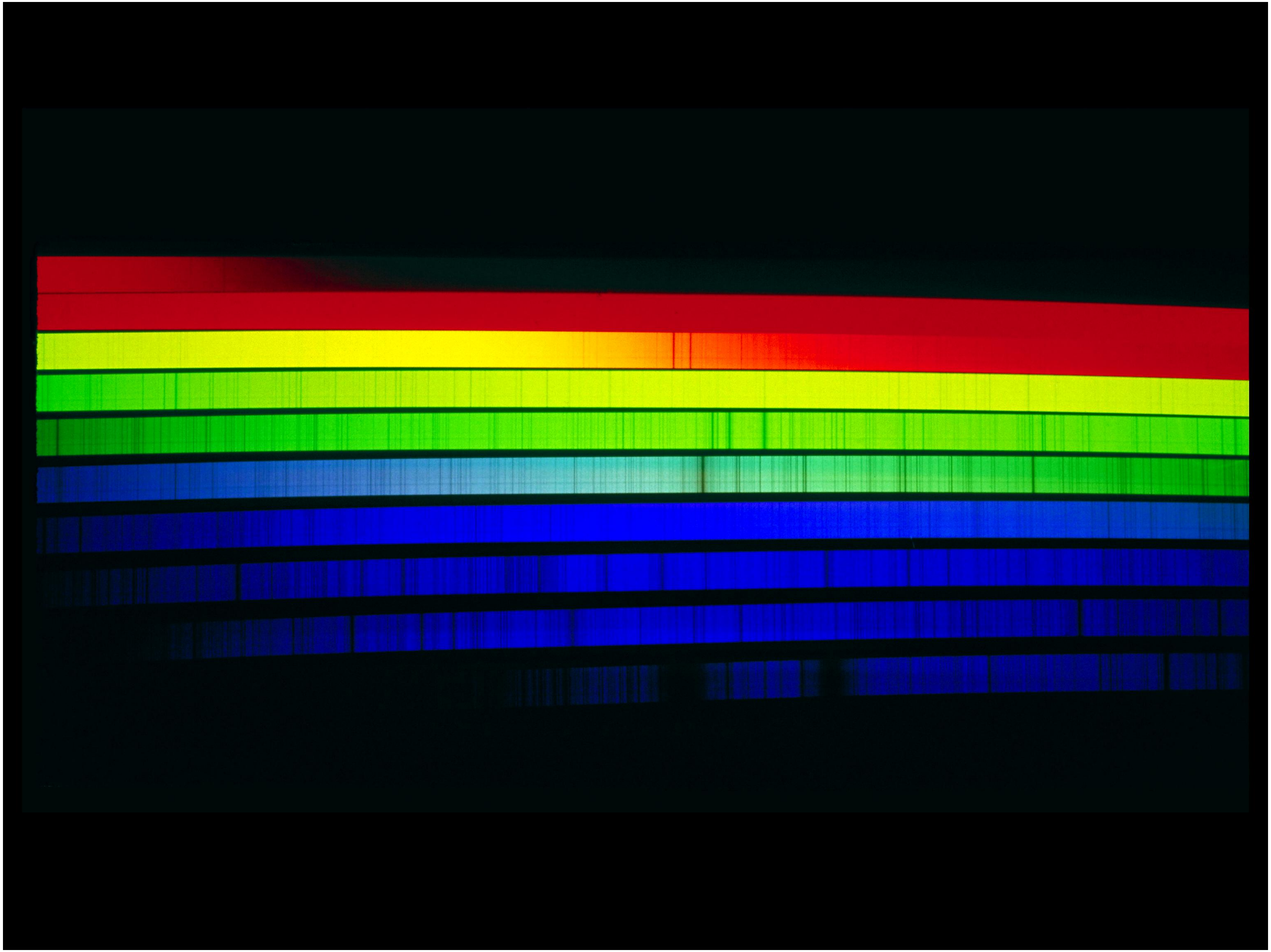
Figure 1 Representative structures of classes of organic compounds identified in carbonaceous chondrites.

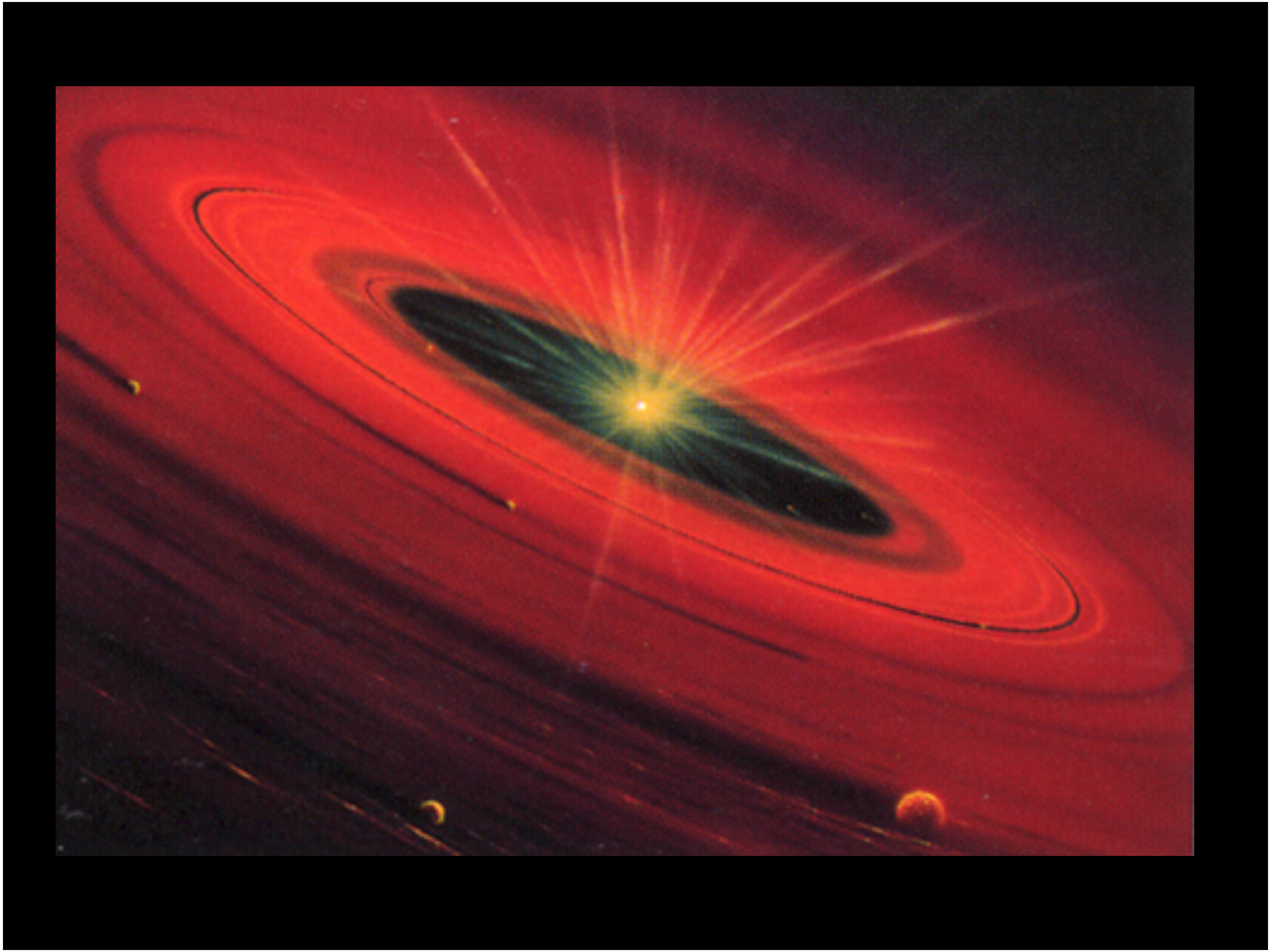
Organic molecules extracted from a carbonaceous chondrite that never got hot

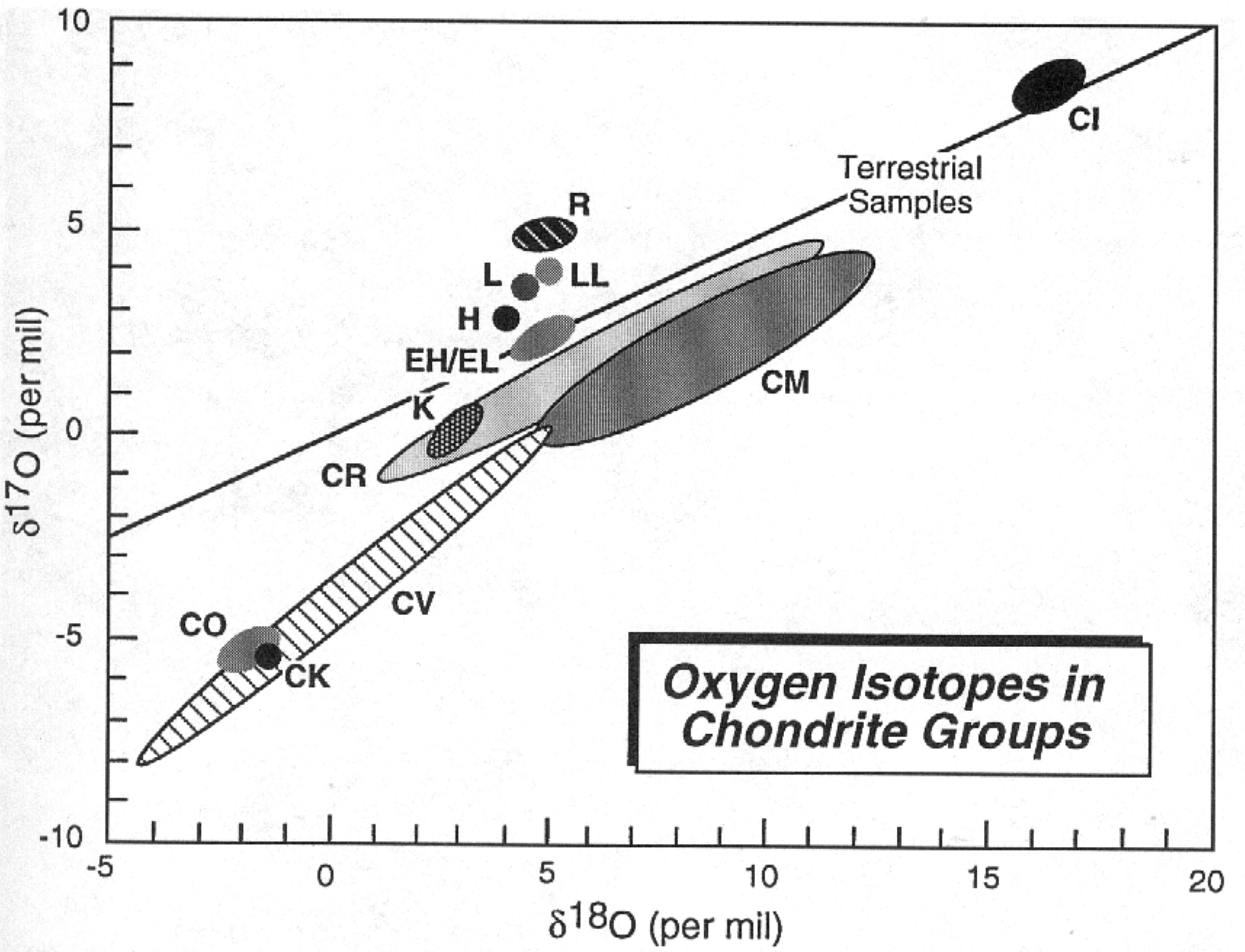


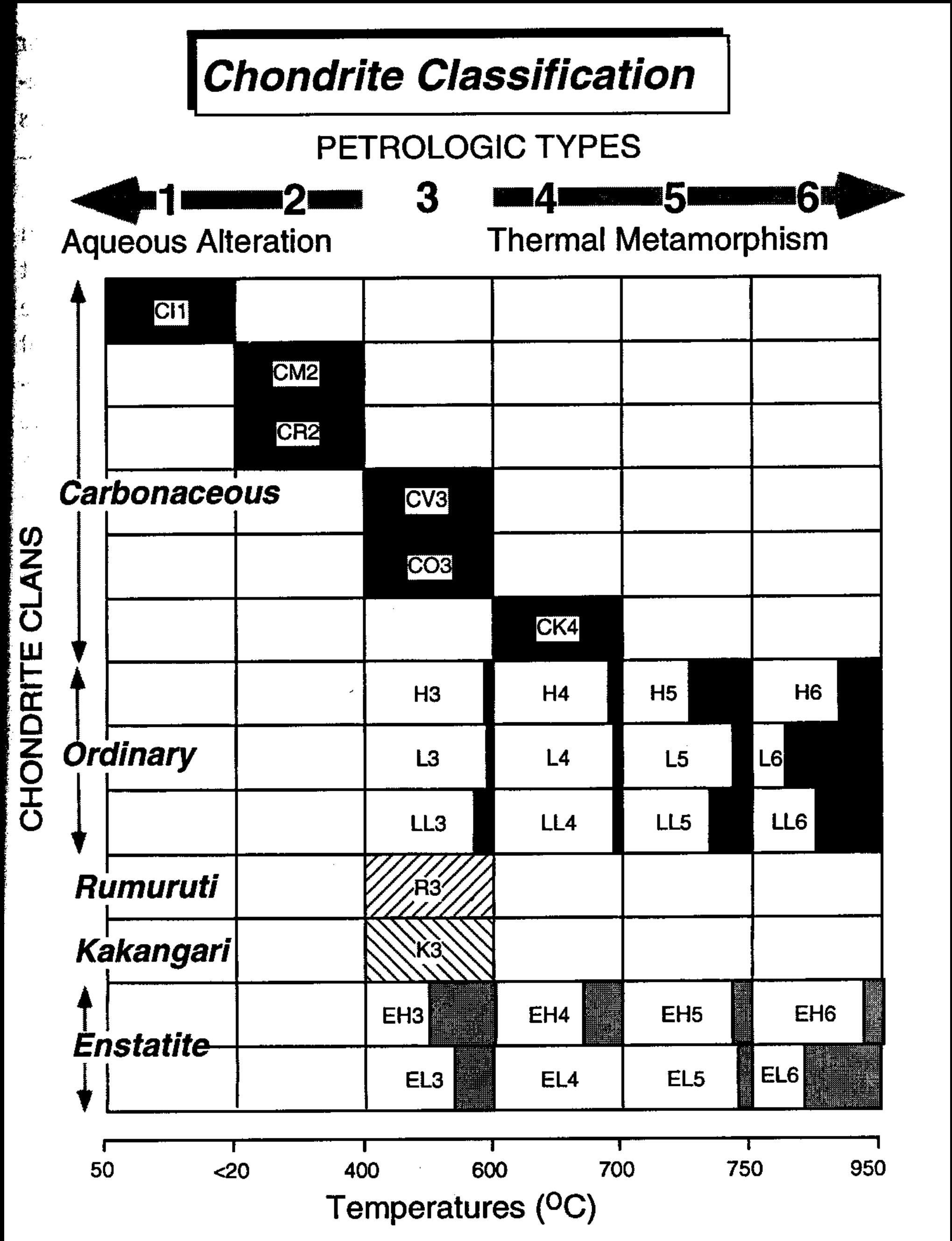
Solar photosphere
Carbonaceous chondrite of type CI
Iron
Magnesium
Silicon
Sulphur
Calcium
Aluminium
Nickel
Sodium
Chromium
Manganese
Titanium
Cobalt
Potassium
Copper
Scandium
Strontium
Zirconium
2
3
4
5
6
7
8


Energy output
Continuous
emission
spectrum
Absorption
lines
Wavelength



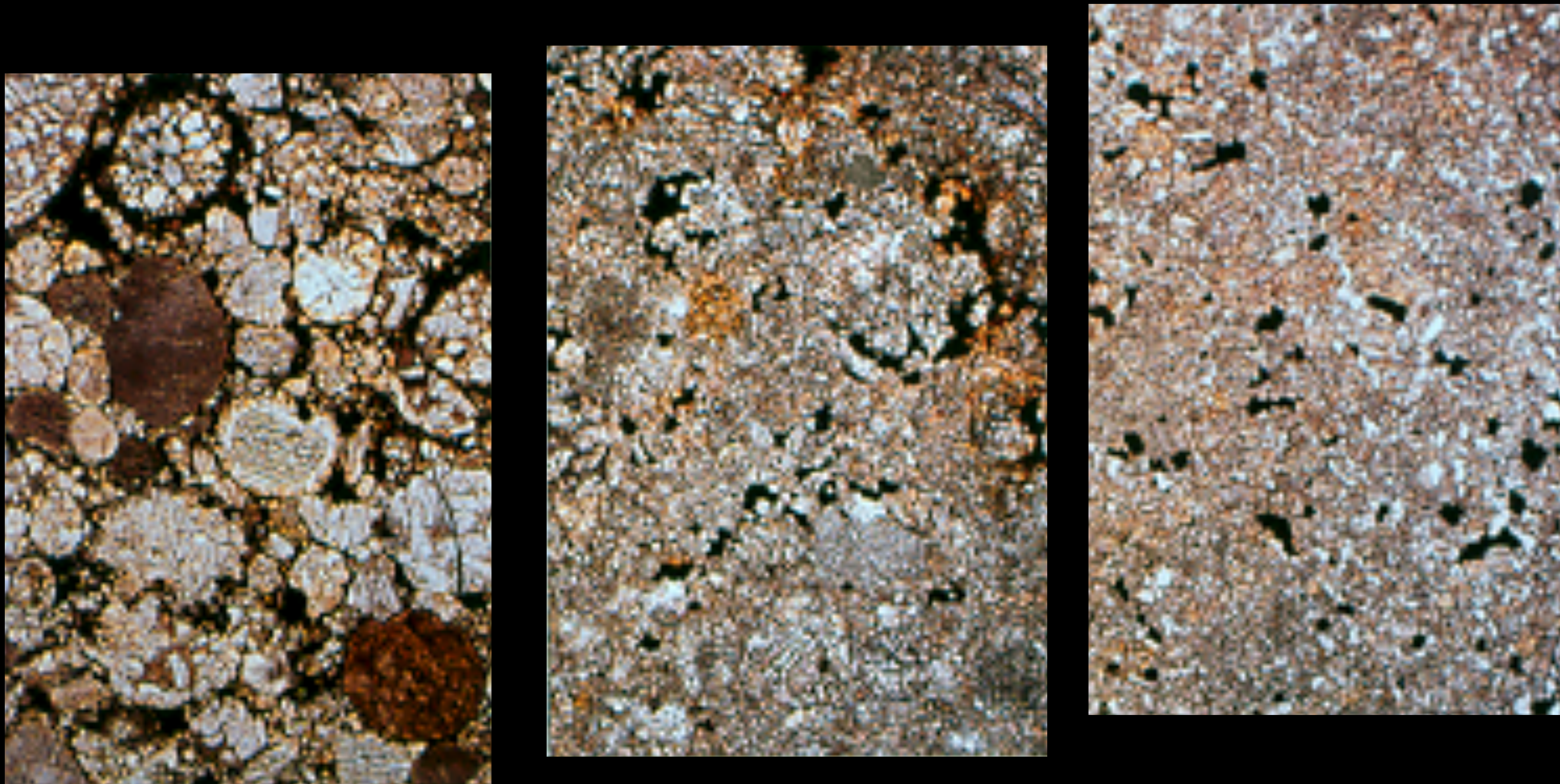



Oxygen Isotopes in Chondrite Groups
δ17O (per mil)
δ18O (per mil)
10
5
0
-5
-10
-5
0
5
10
15
20
CI
Terrestrial Samples
R
L
LL
H
EH/EL
K
CM
CR
CV
CO
CK

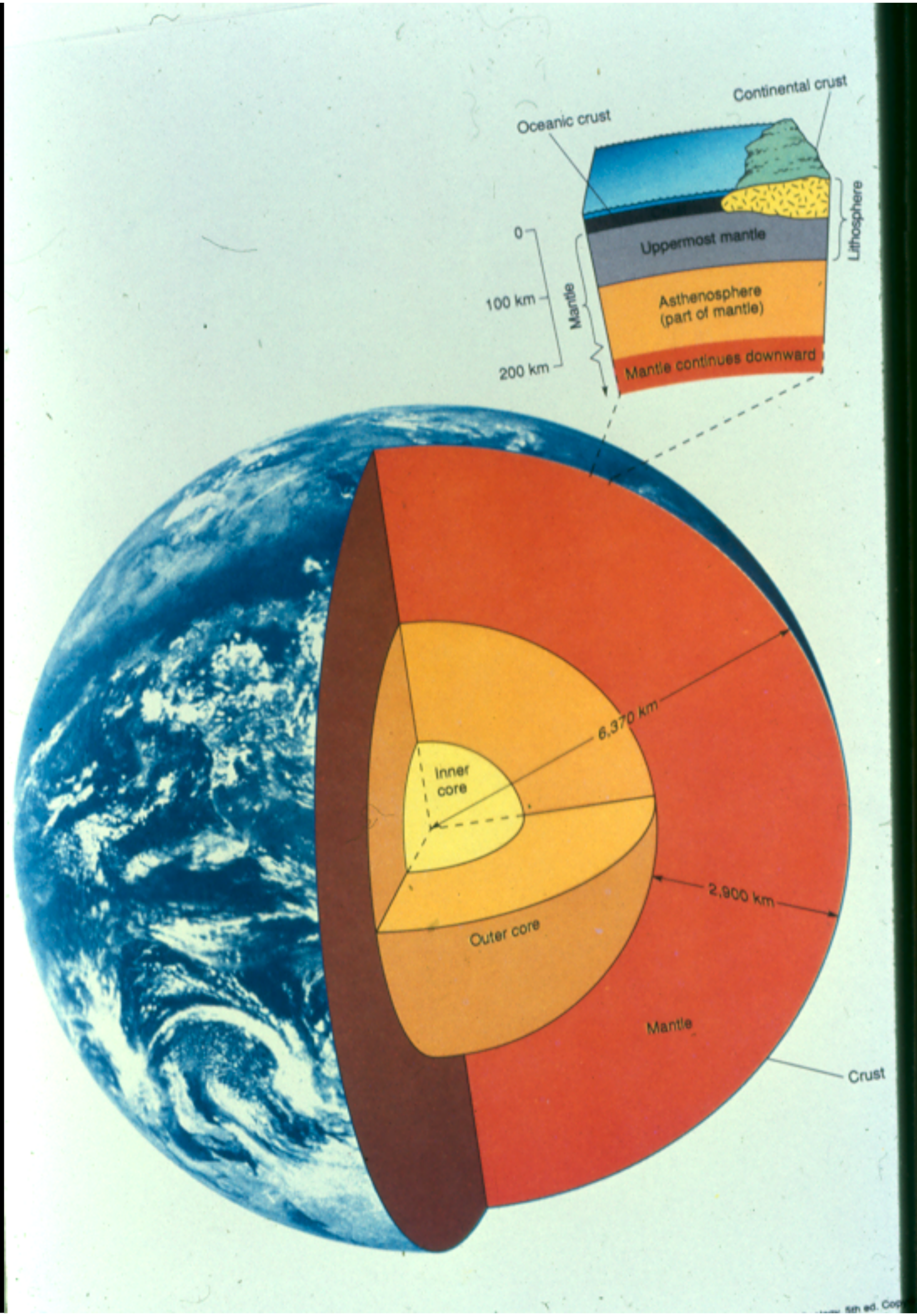


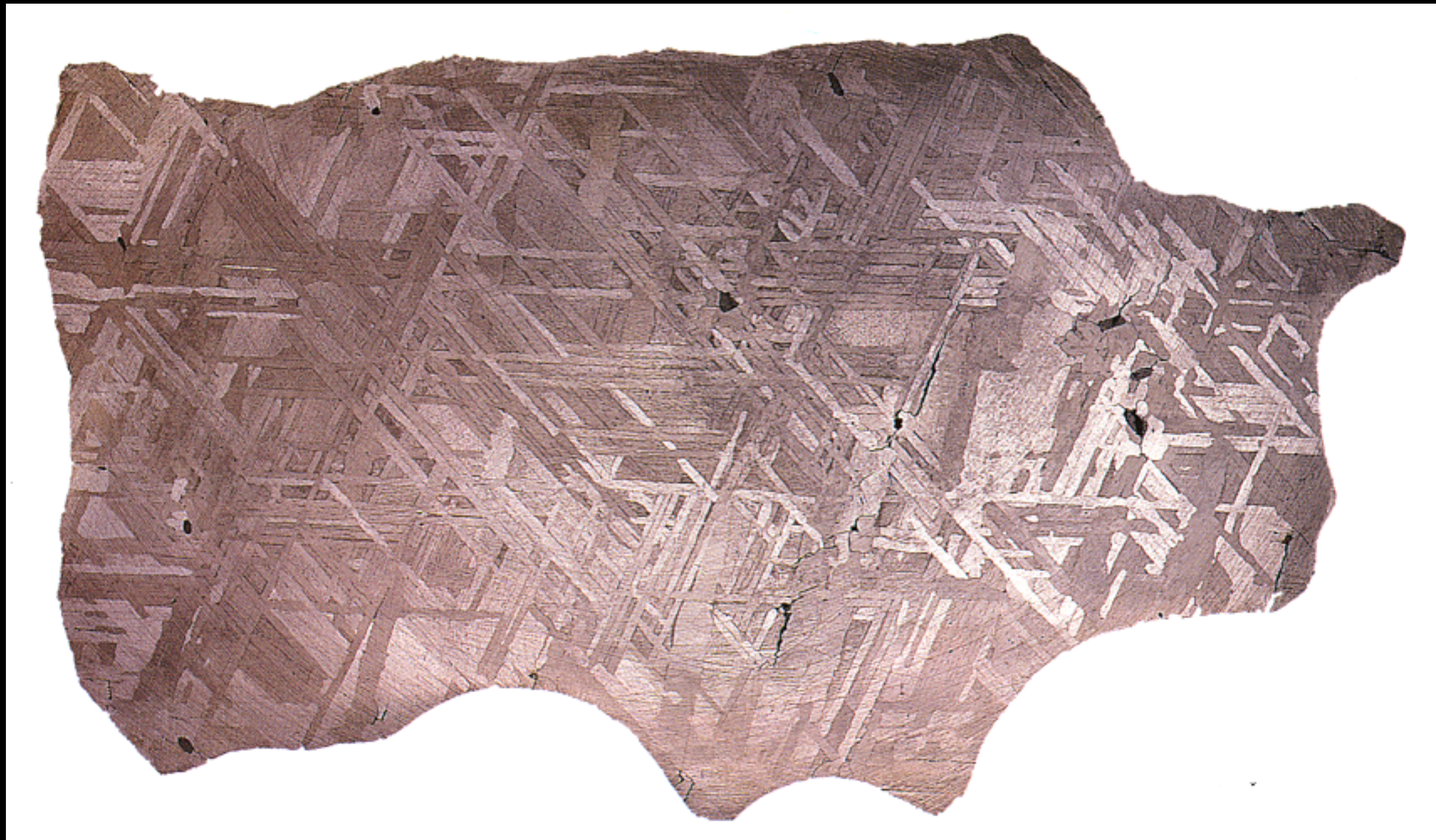
Overall classification of chondrites is based on the group (defined by Fe metal v Fe oxide, and by oxygen isotopes) and the nature of metamorphism (giving types 1 to 6).

What about iron meteorites and basaltic meteorites?

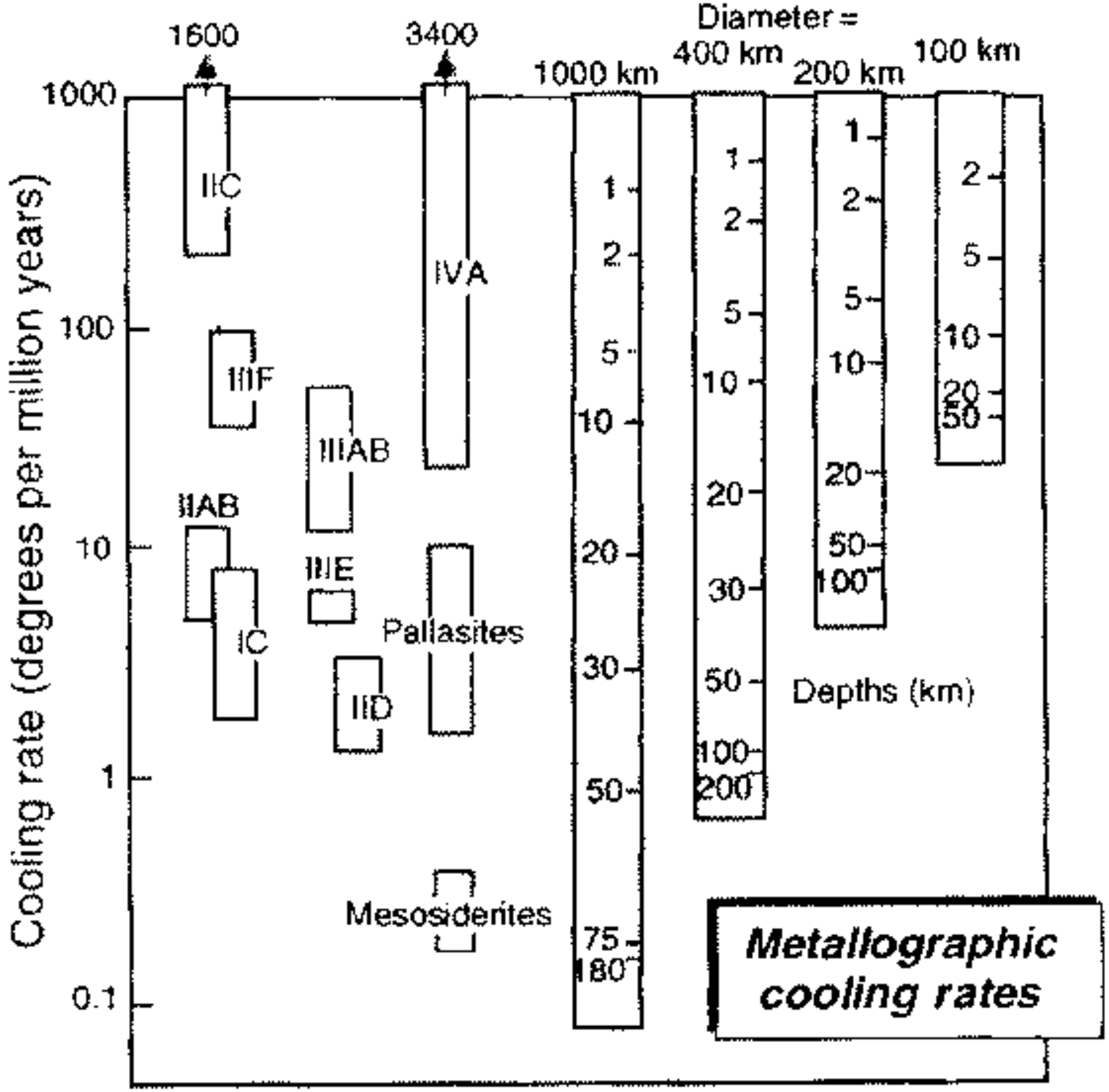


Remember - chondrites got heated

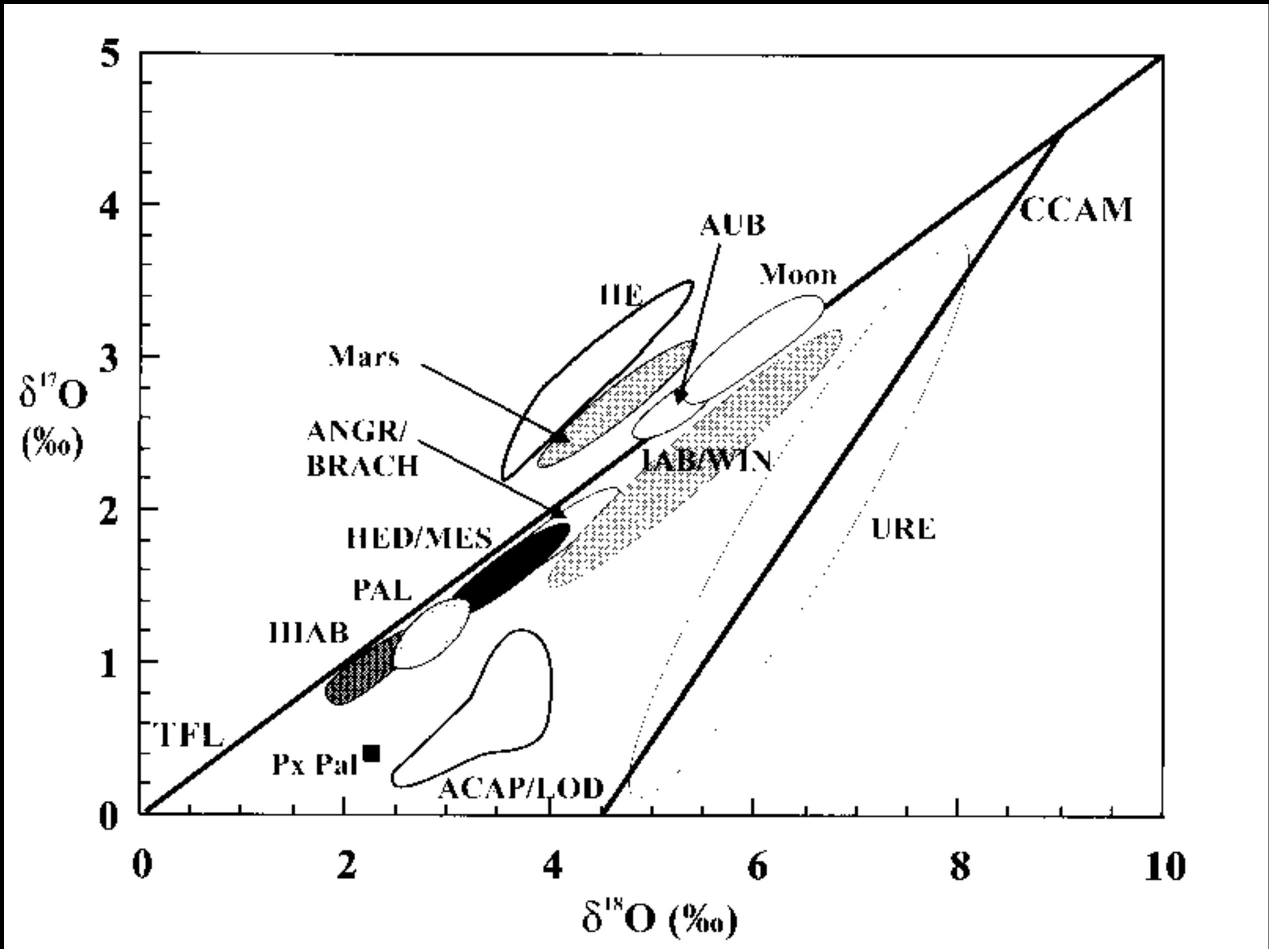

Continental crust
Oceanic crust
Lithosphere
0
Uppermost mantle
100 km
Mantle
Asthenosphere
(part of mantle)
200 km
Mantle continues downward
6,370 km
Inner
core
2,900 km
Outer core
Mantle
Crust



The pattern of bands on a polished, etched surface of an iron meteorite is called the Widmanstatten structure. Numerical simulation of the structure constrains the cooling rate.



Metallographic cooling rates
Cooling rate (degrees per million years)
1000
100
10
1
0.1
1600
3400
IIC
IIIF
IIIAB
IIAB
IIIE
IC
IID
IVA
Pallasites
Mesosiderites
Diameter =
1000 km
400 km
200 km
100 km
Depths (km)
1
2
5
10
20
30
50
75
180
1
2
5
10
20
30
50
100
200
1
2
5
10
20
50
100
2
5
10
20
50



Igneous meteorite, like chondrites, plot in discrete patches on the oxygen isotope diagram. Each patch is a group of meteorites thought to come from a single parent asteroid.

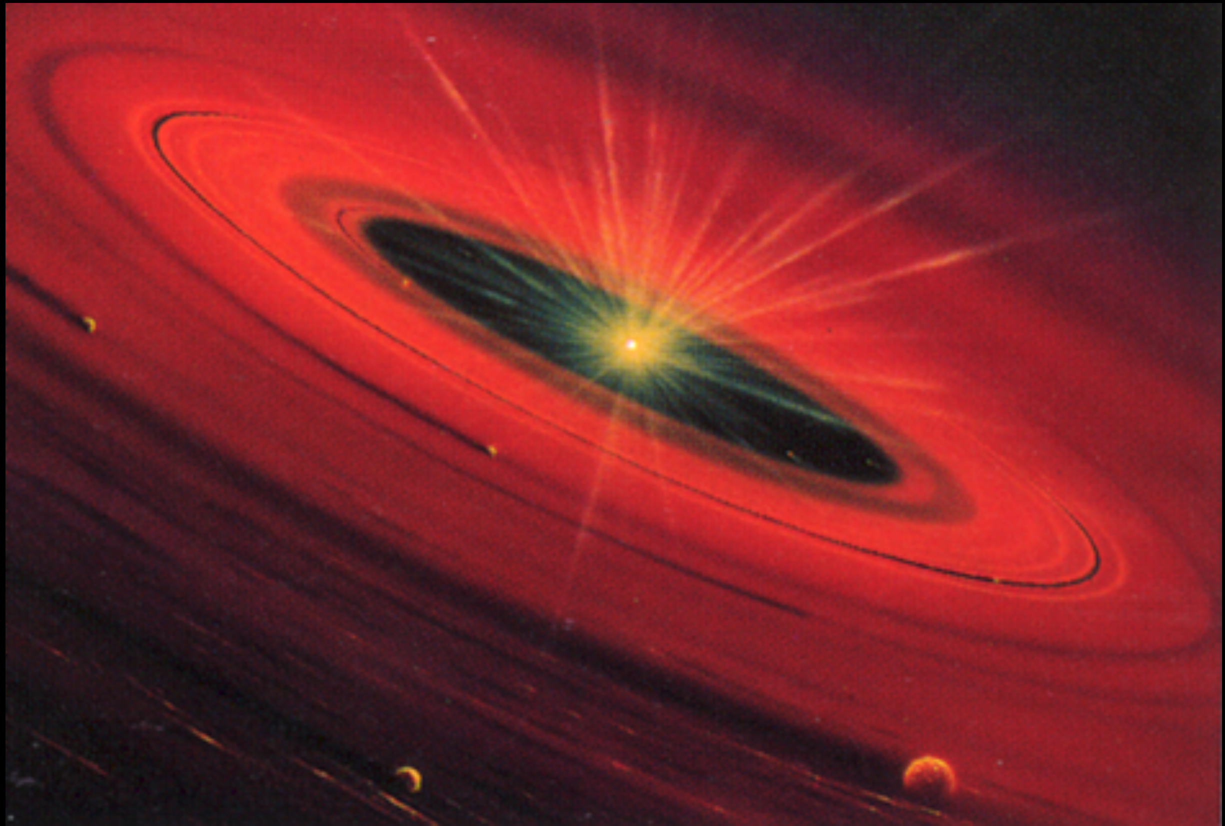
So far then:

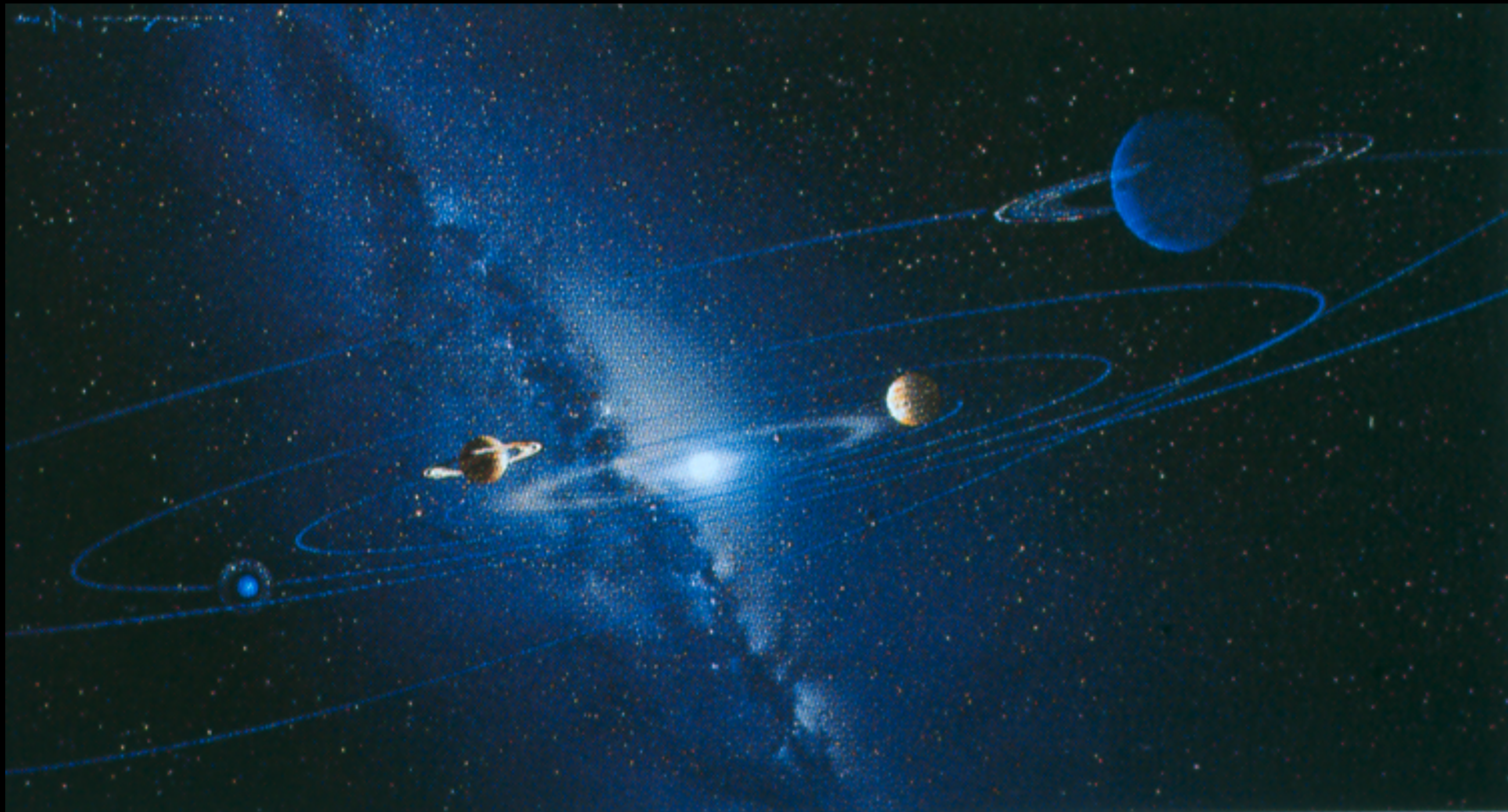
4567 million years ago, following ‘in-fall’ in a molecular cloud, radioactive dust in a disk around the infant sun became converted to chondrules, CAIs and metal grains.

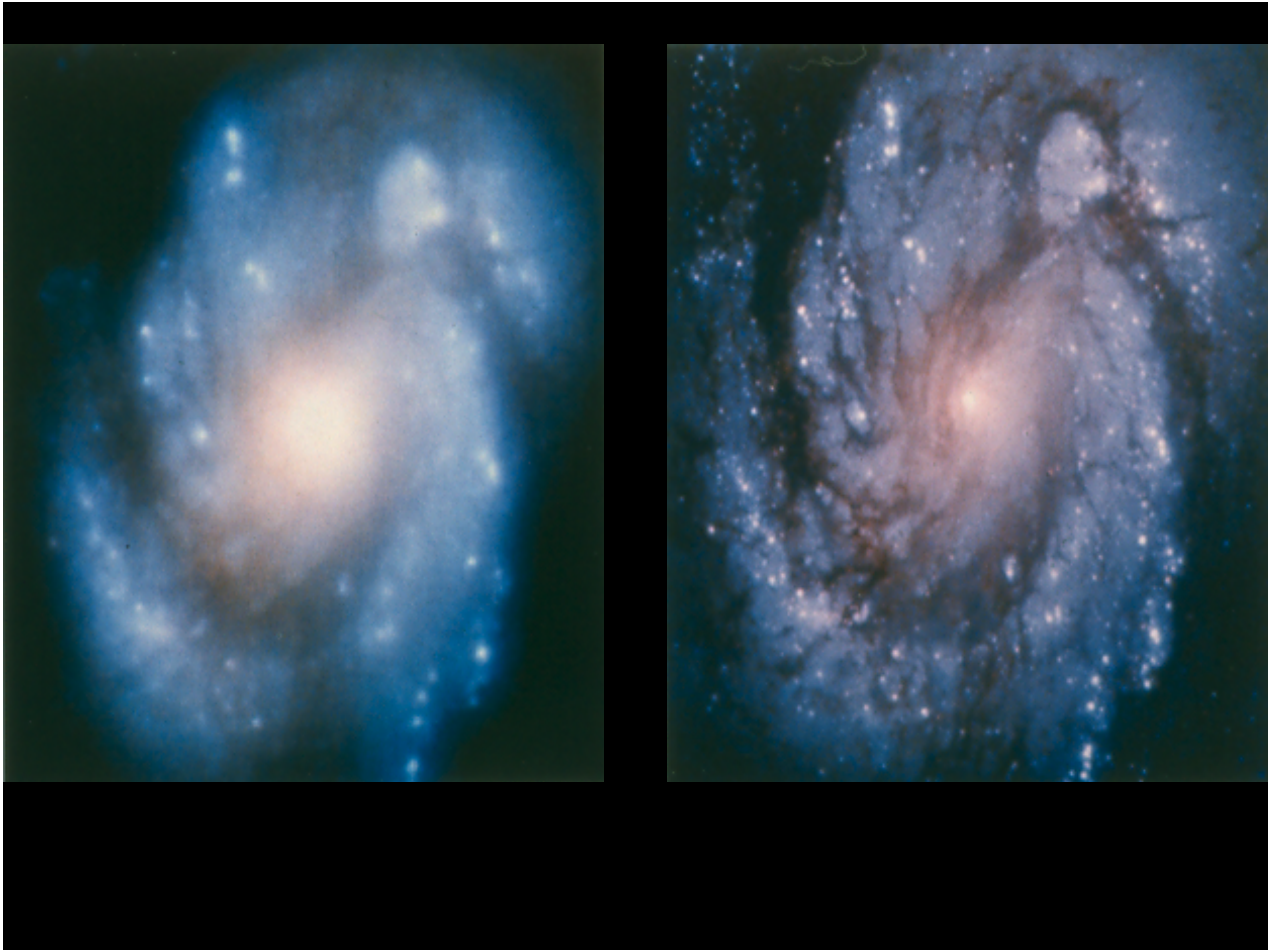
These grains, plus some dust with original pre-solar grains, accreted into planetesimals.

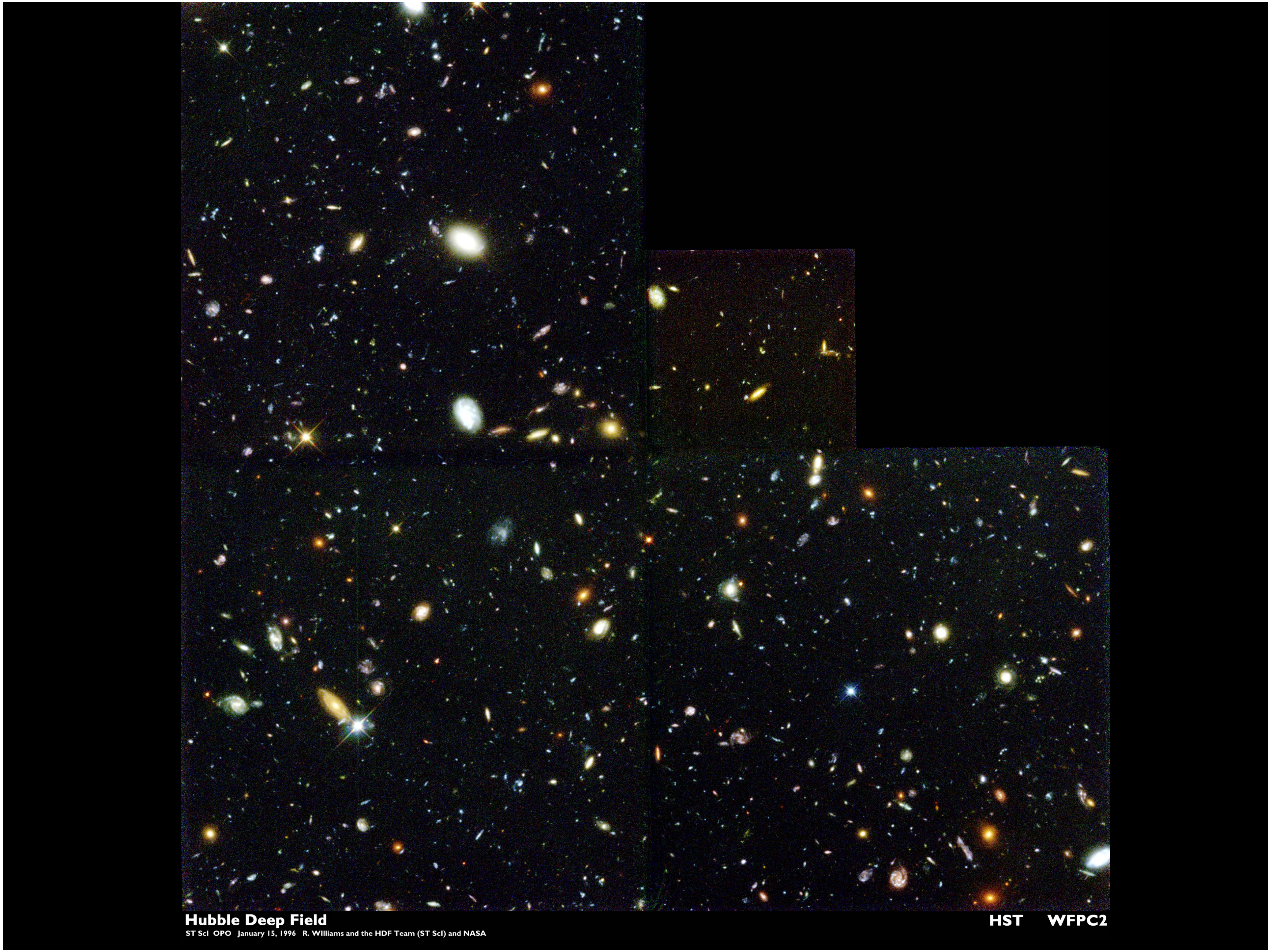
The planetesimals got hot and some of them melted.

Where did the disk come from?
Or, what is the origin of the solar system?

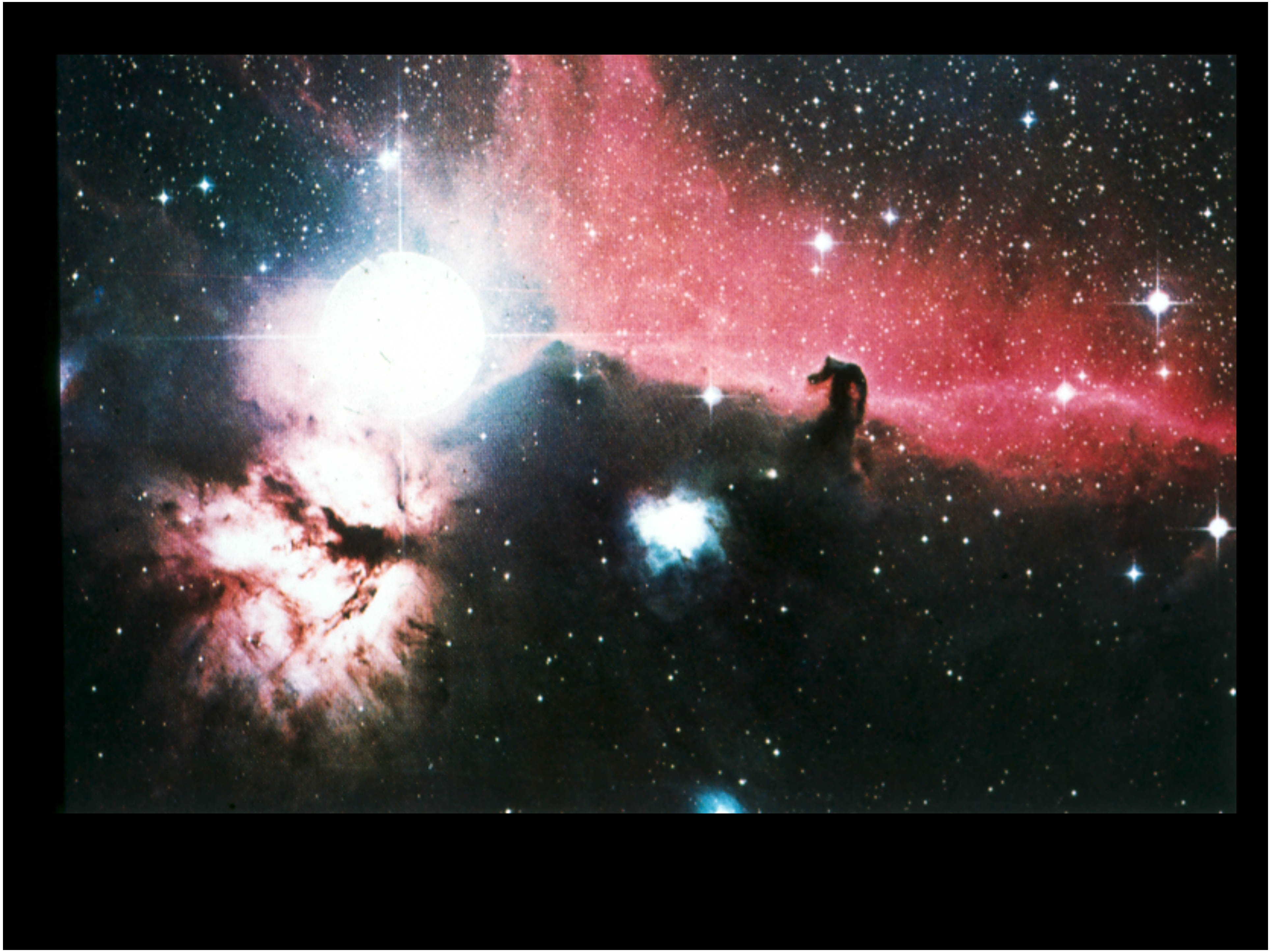


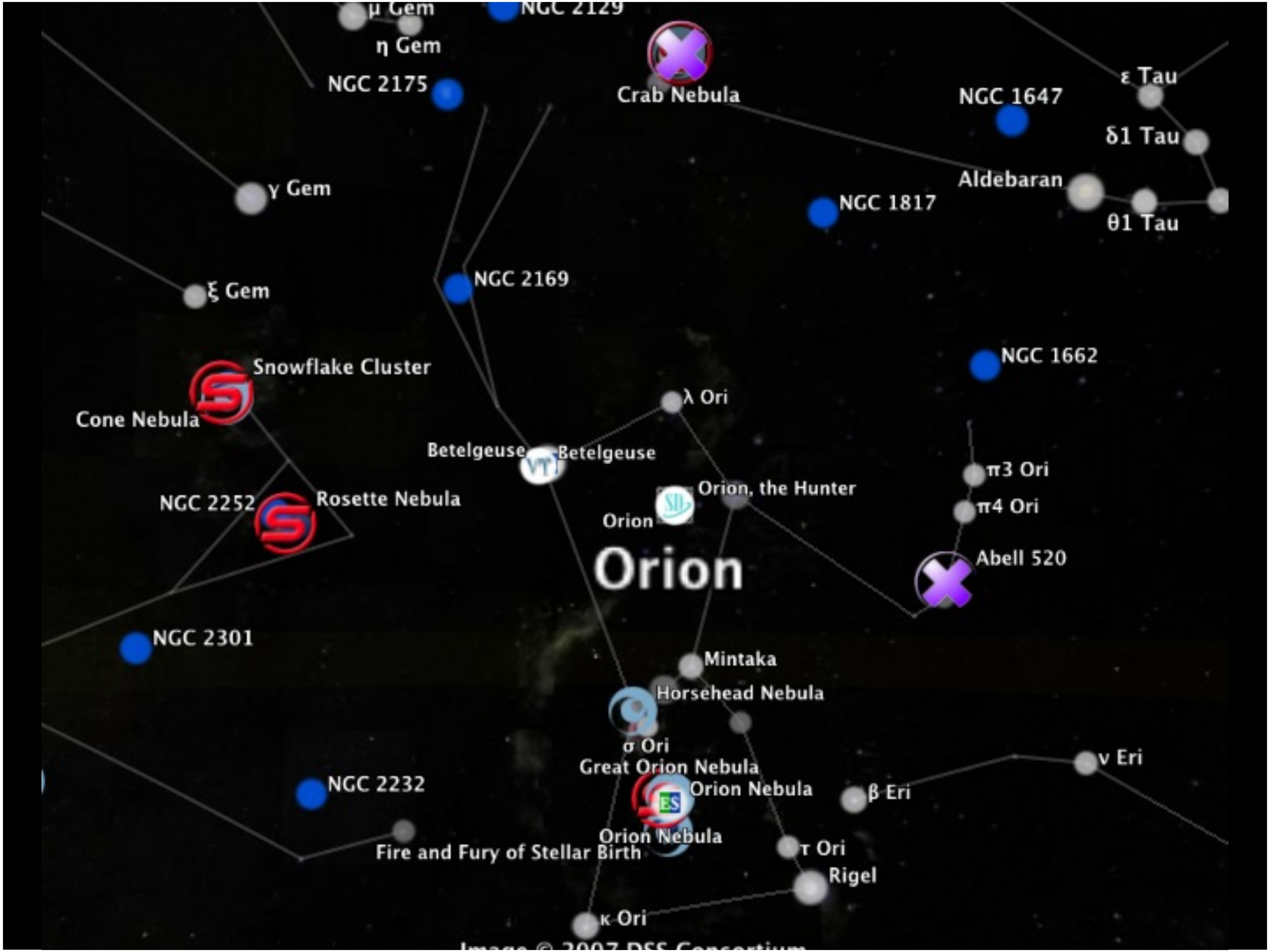




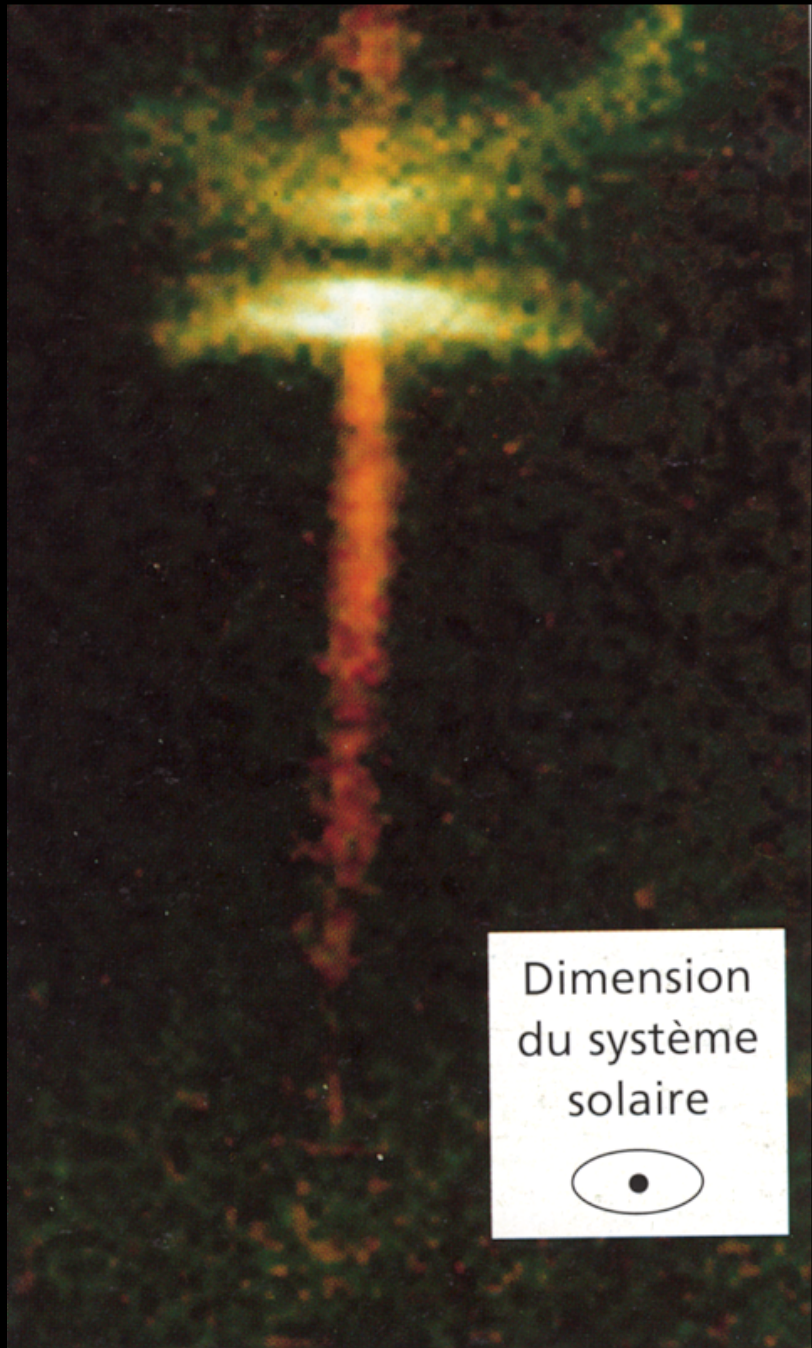

Hubble Deep Field
ST ScI OPO January 15, 1996 R. WIlliams and the HDF Team (ST ScI) and NASA
HST WFPC2

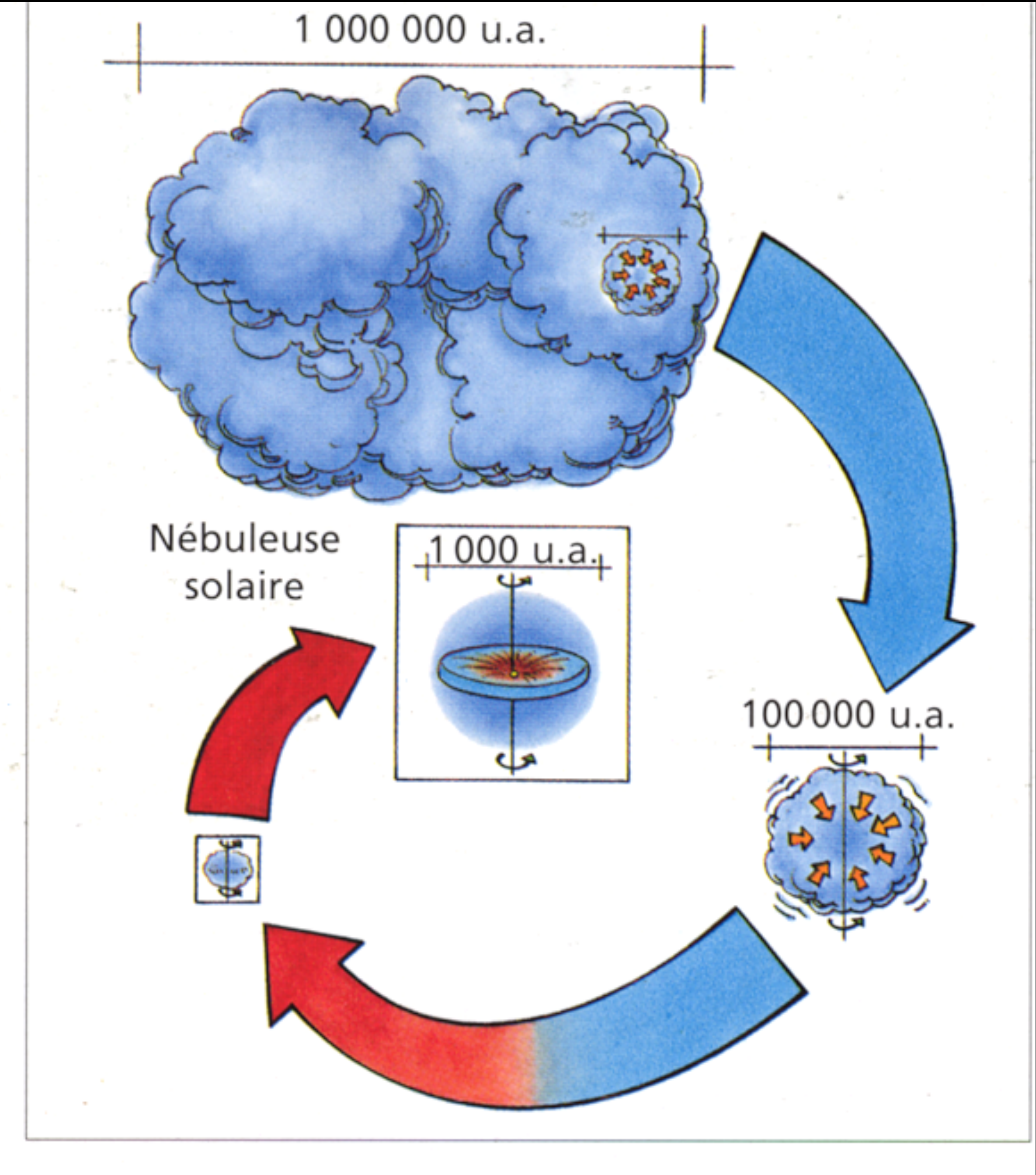
Question:
Are there more atoms in 12 grams of carbon than there are stars in the entire universe?

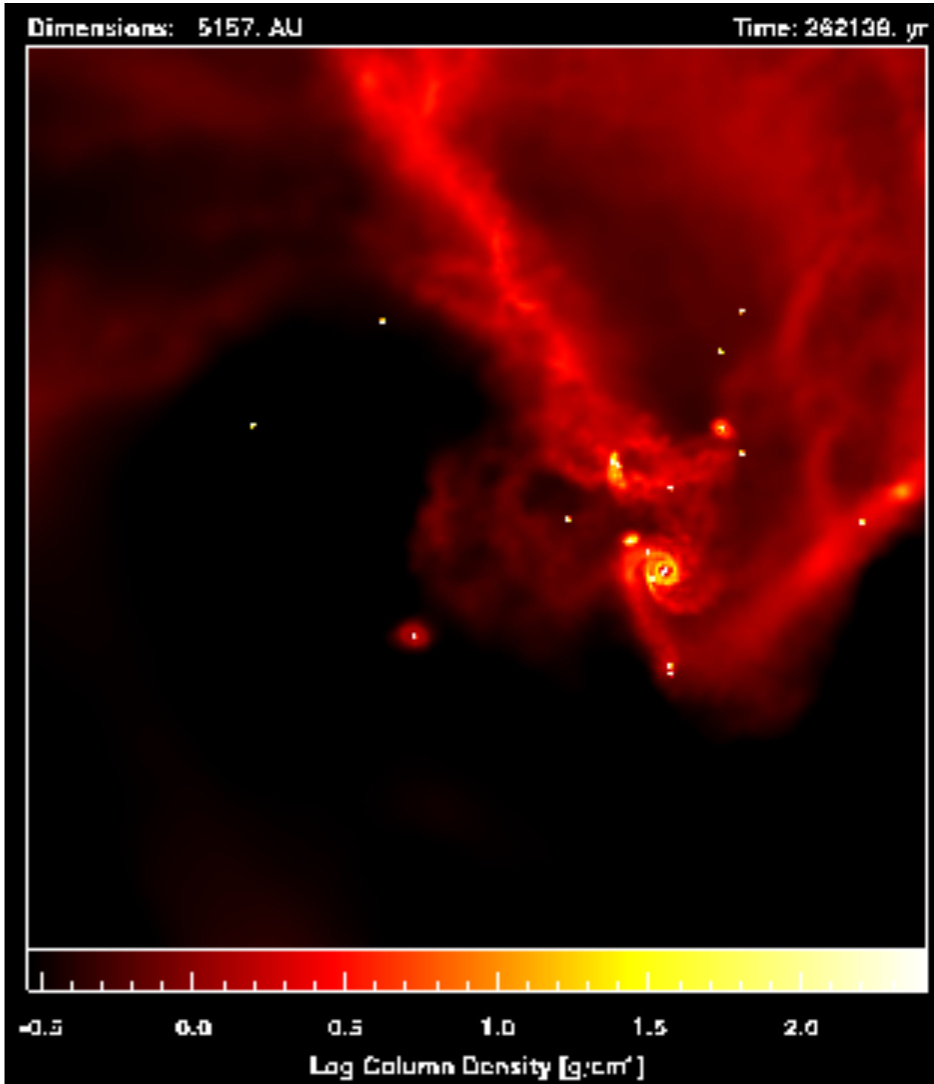


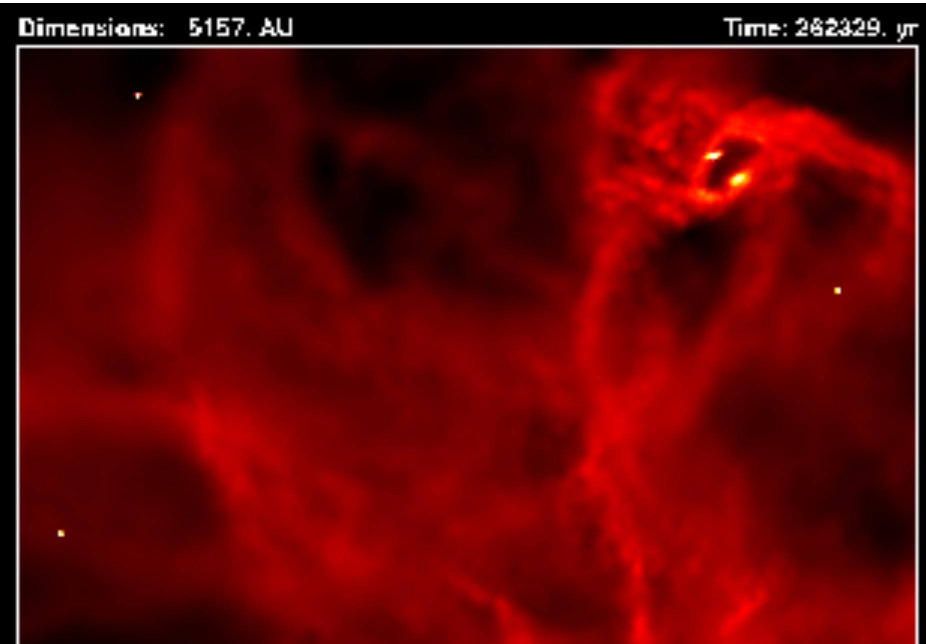

μ Gem
NGC 2129
η Gem
NGC 2175
Crab Nebula
NGC 1647
ε Tau
δ1 Tau
Aldebaran
γ Gem
NGC 1817
θ1 Tau
NGC 2169
ξ Gem
Snowflake Cluster
NGC 1662
Cone Nebula
λ Ori
Betelgeuse
Betelgeuse
π3 Ori
Orion, the Hunter
NGC 2252
Rosette Nebula
π4 Ori
Orion
Orion
Abell 520
NGC 2301
Mintaka
Horsehead Nebula
σ Ori
Great Orion Nebula
ν Eri
NGC 2232
Orion Nebula
β Eri
Orion Nebula
Fire and Fury of Stellar Birth
τ Ori
Rigel
κ Ori


PROPLYD

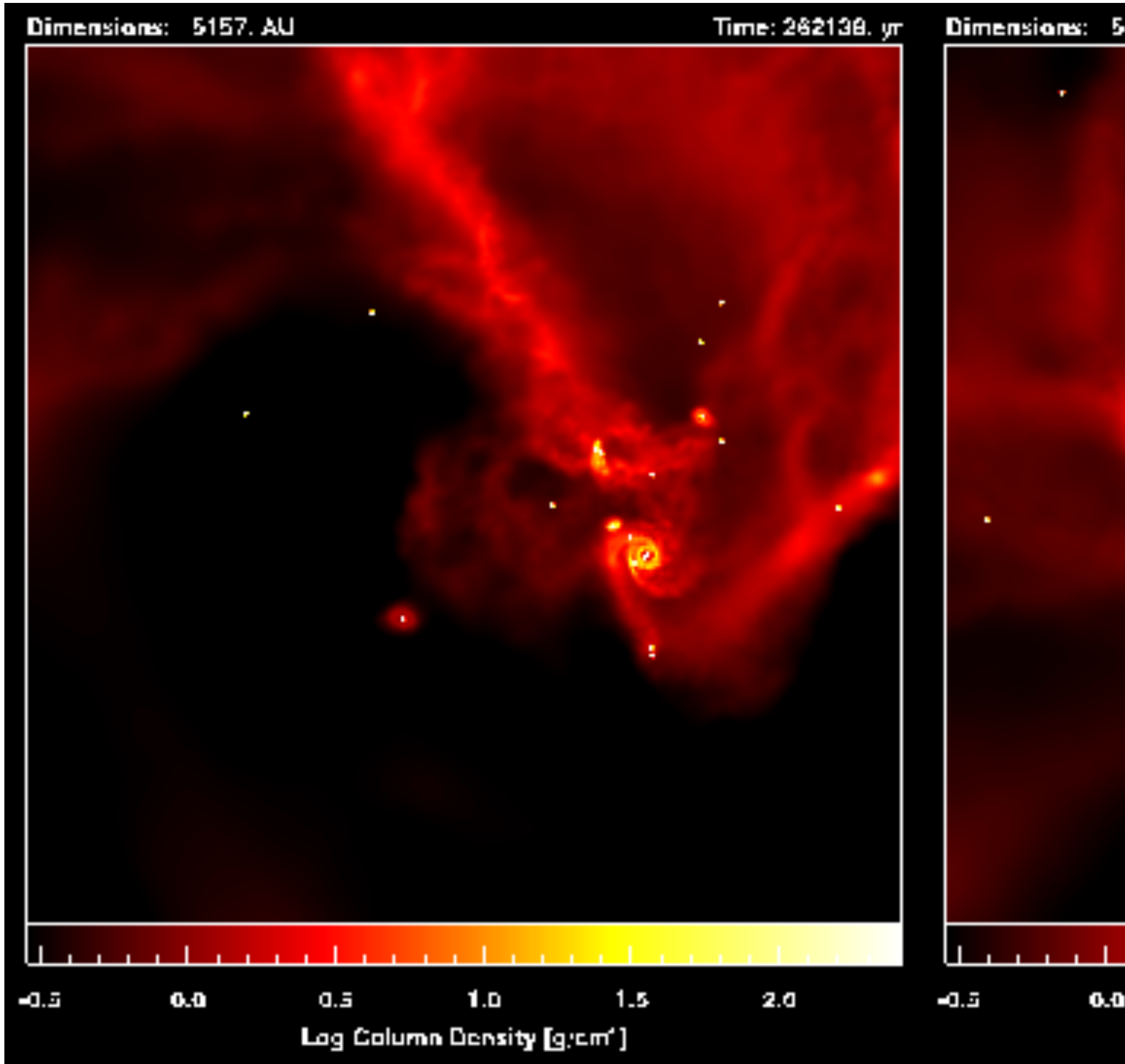

Dimension
du système
solaire


1 000 000 u.a.
Nébuleuse
solaire
1 000 u.a.
100 000 u.a.





www.astro.ex.ac.uk/people/mbate



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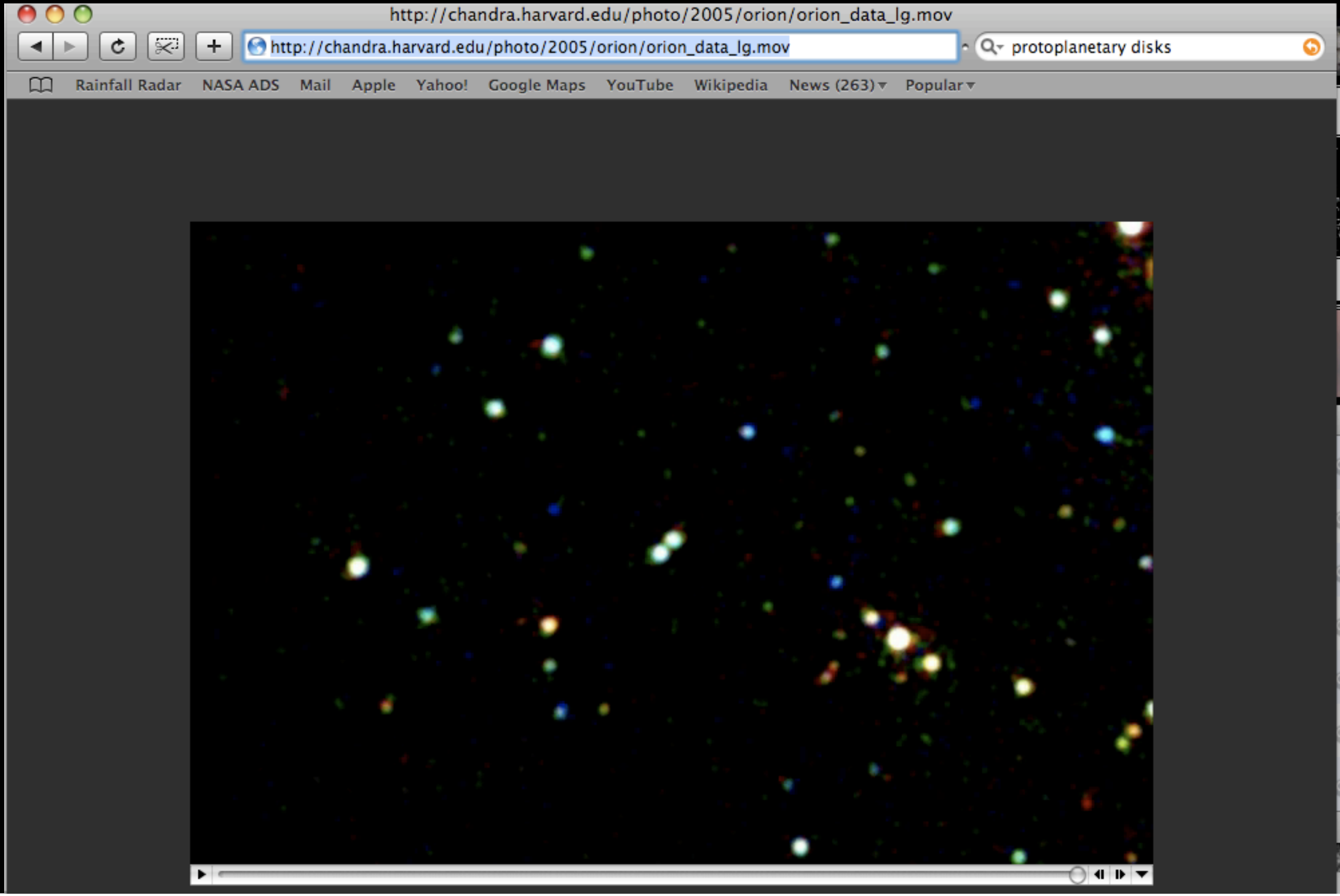
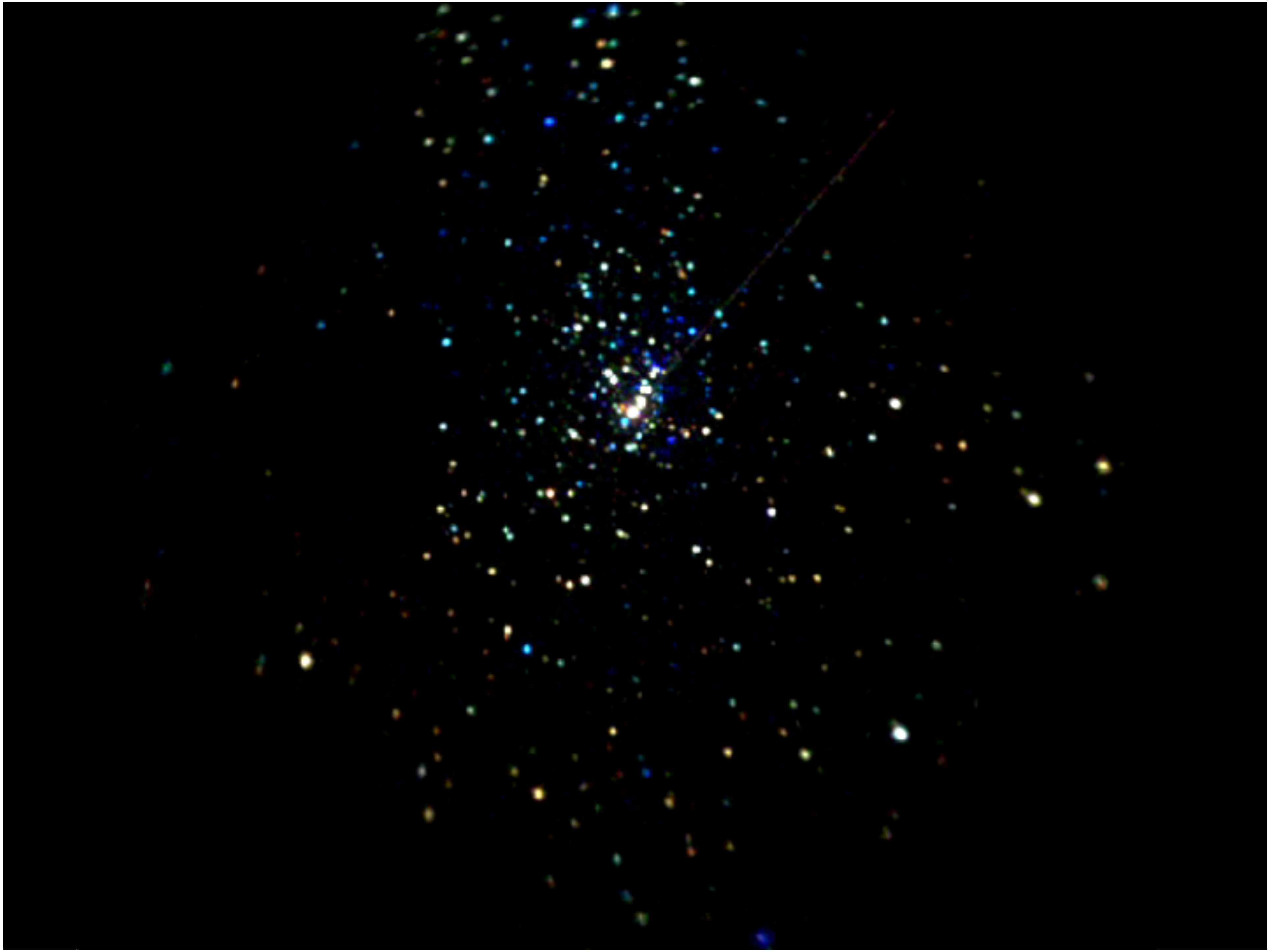
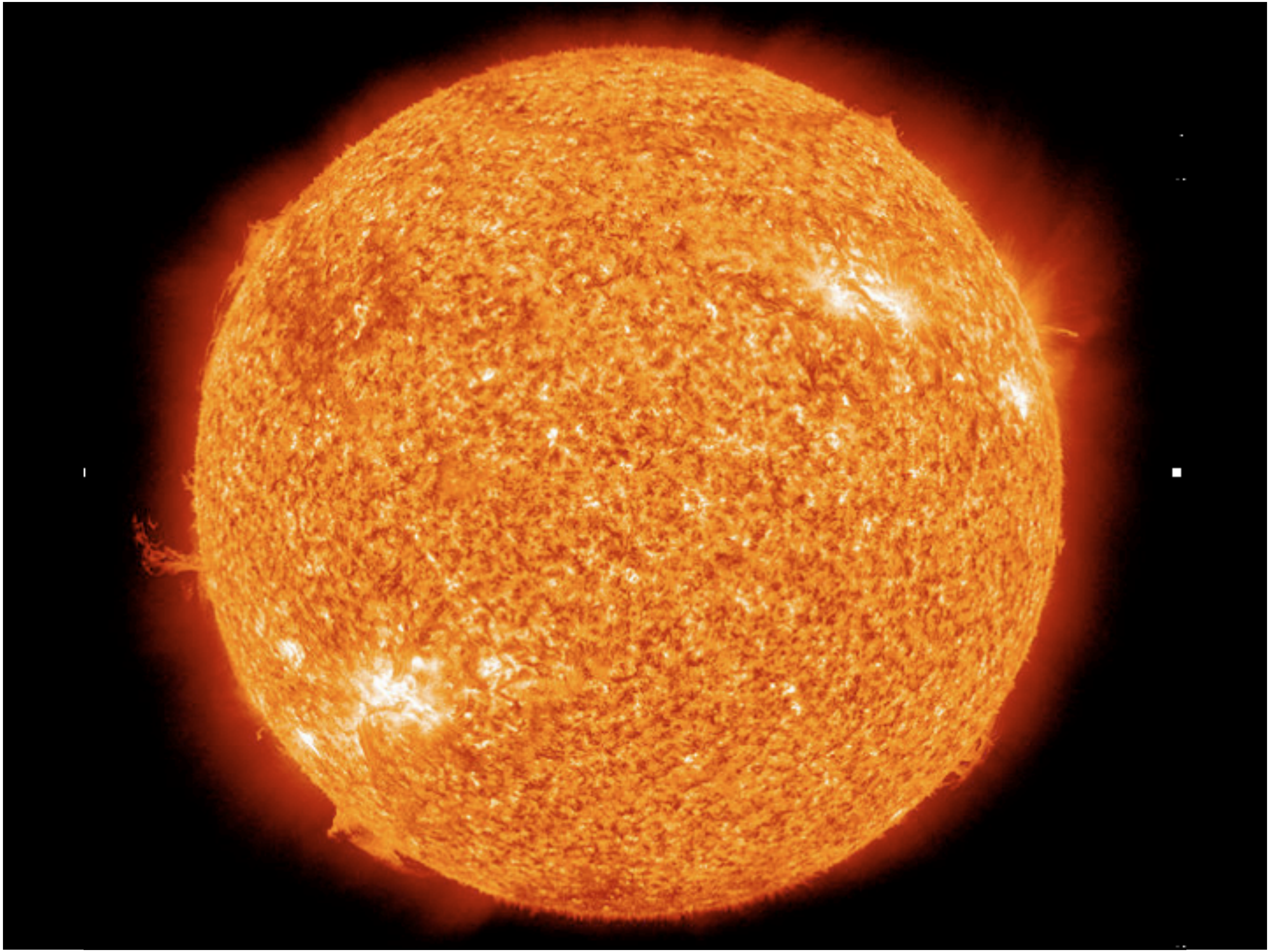
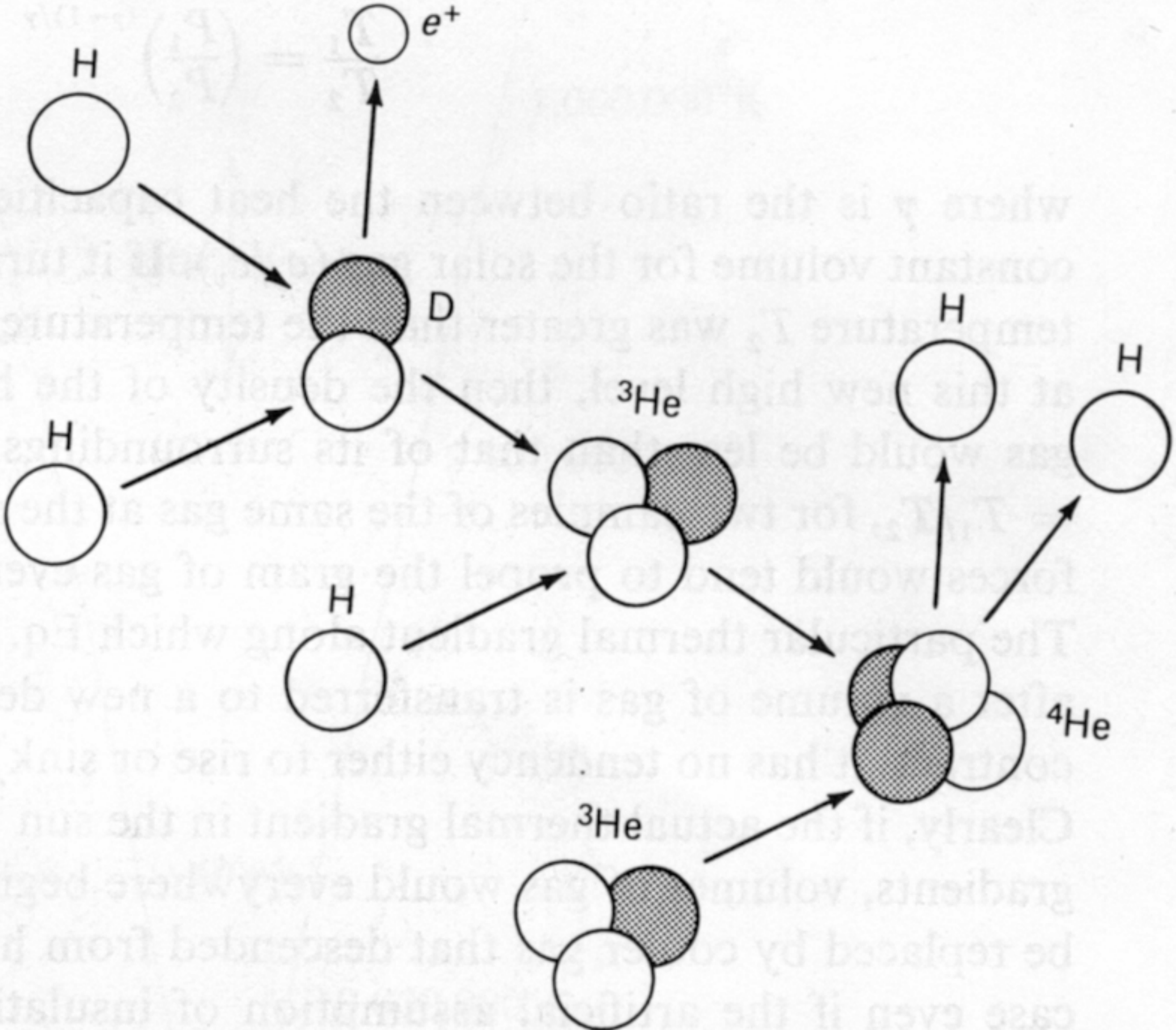
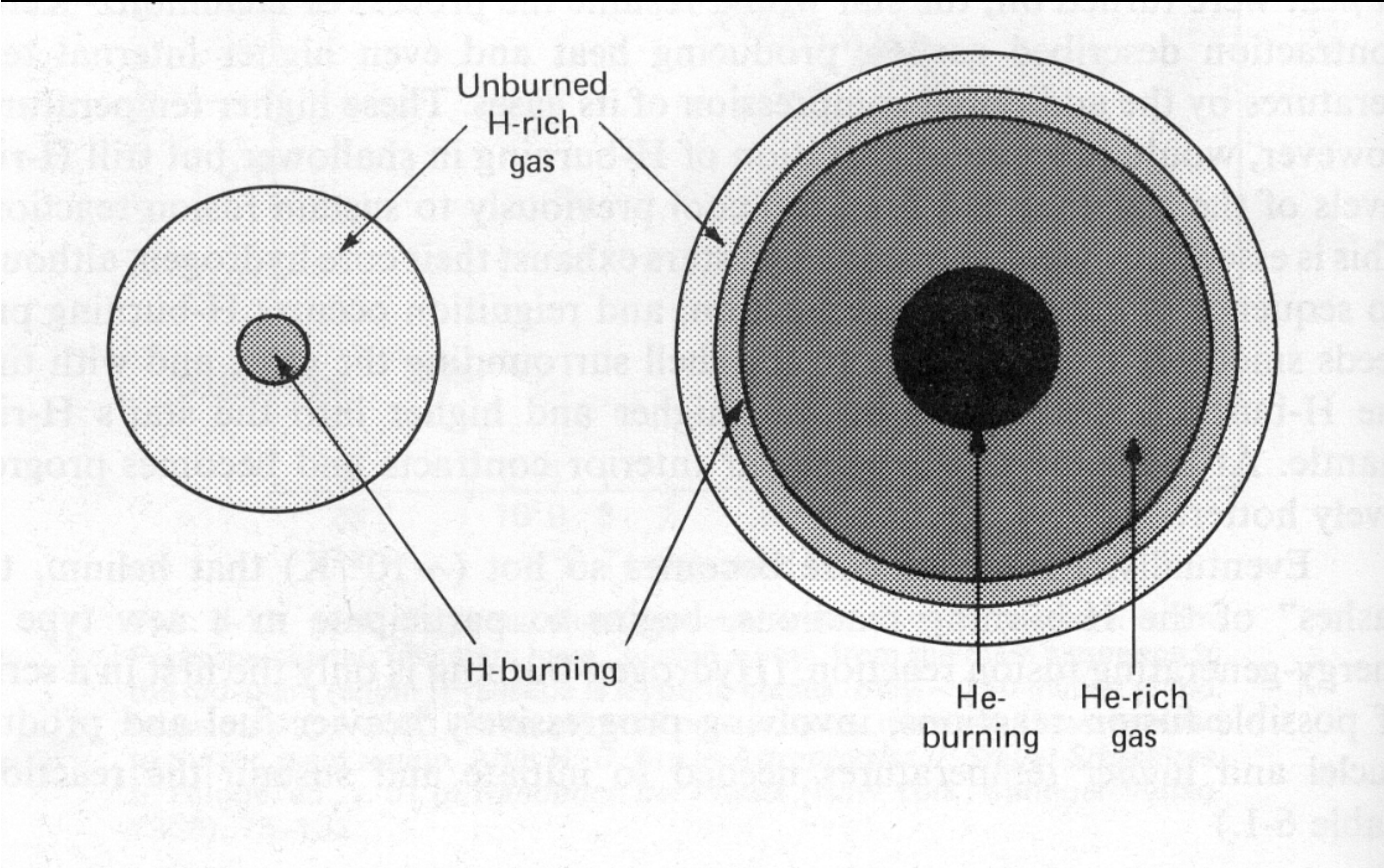




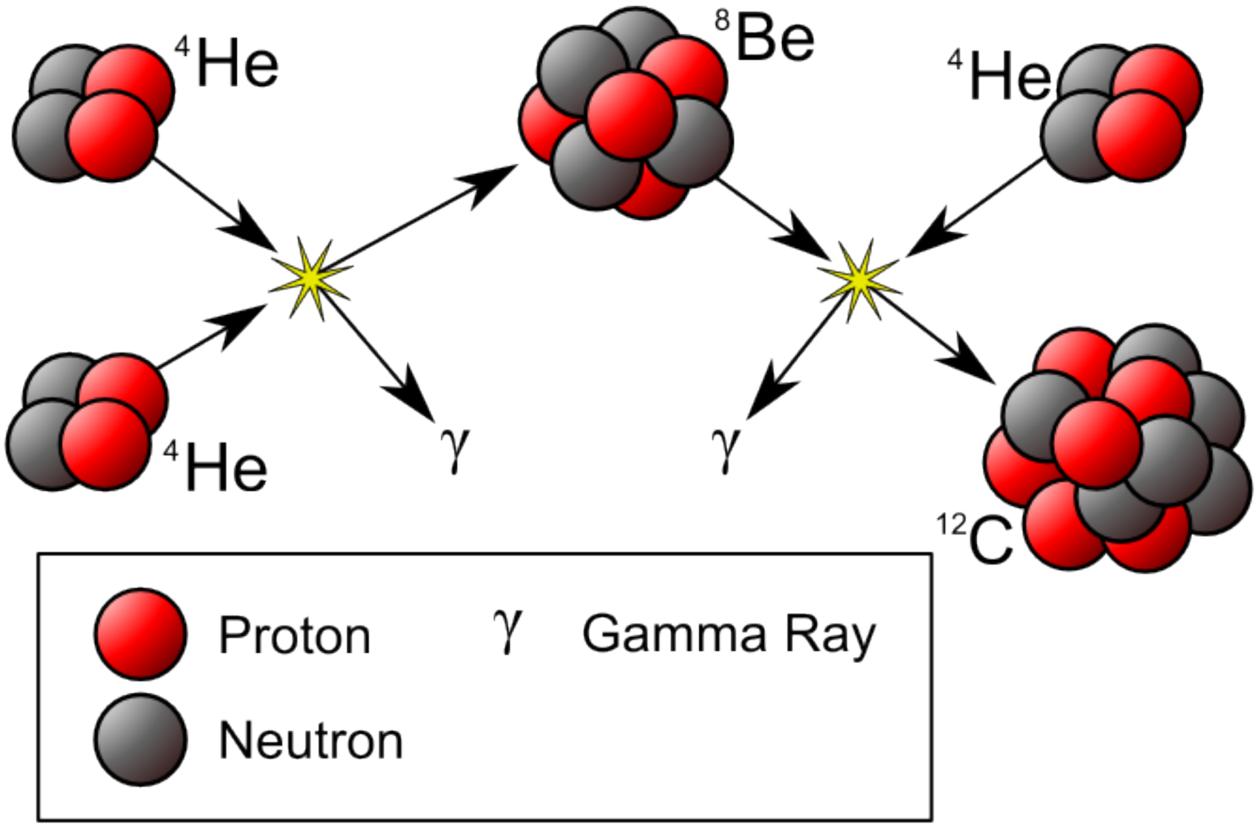




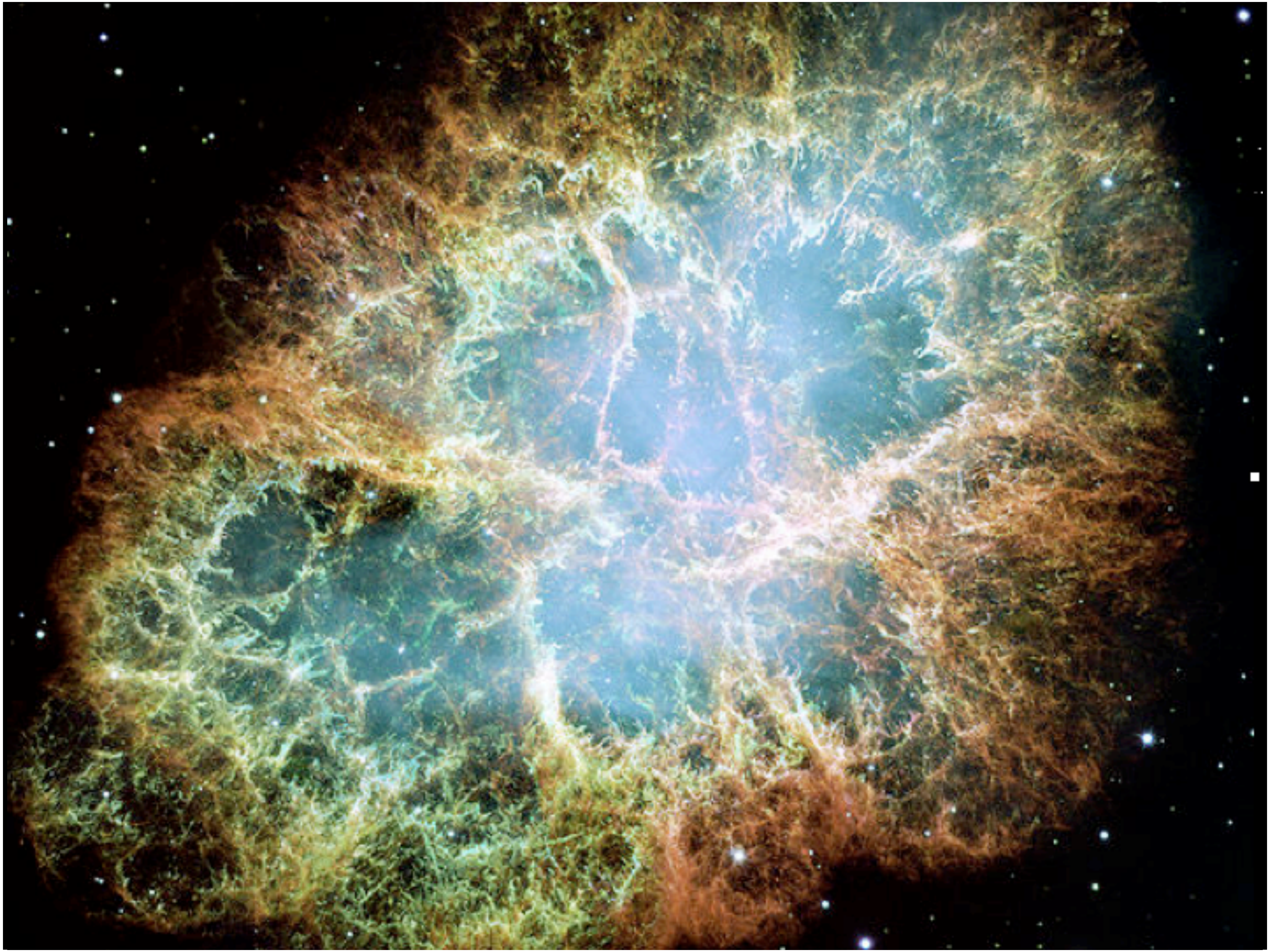
e^+
H
D
H
^{3}He
H
H
H
^{4}He
^{3}He

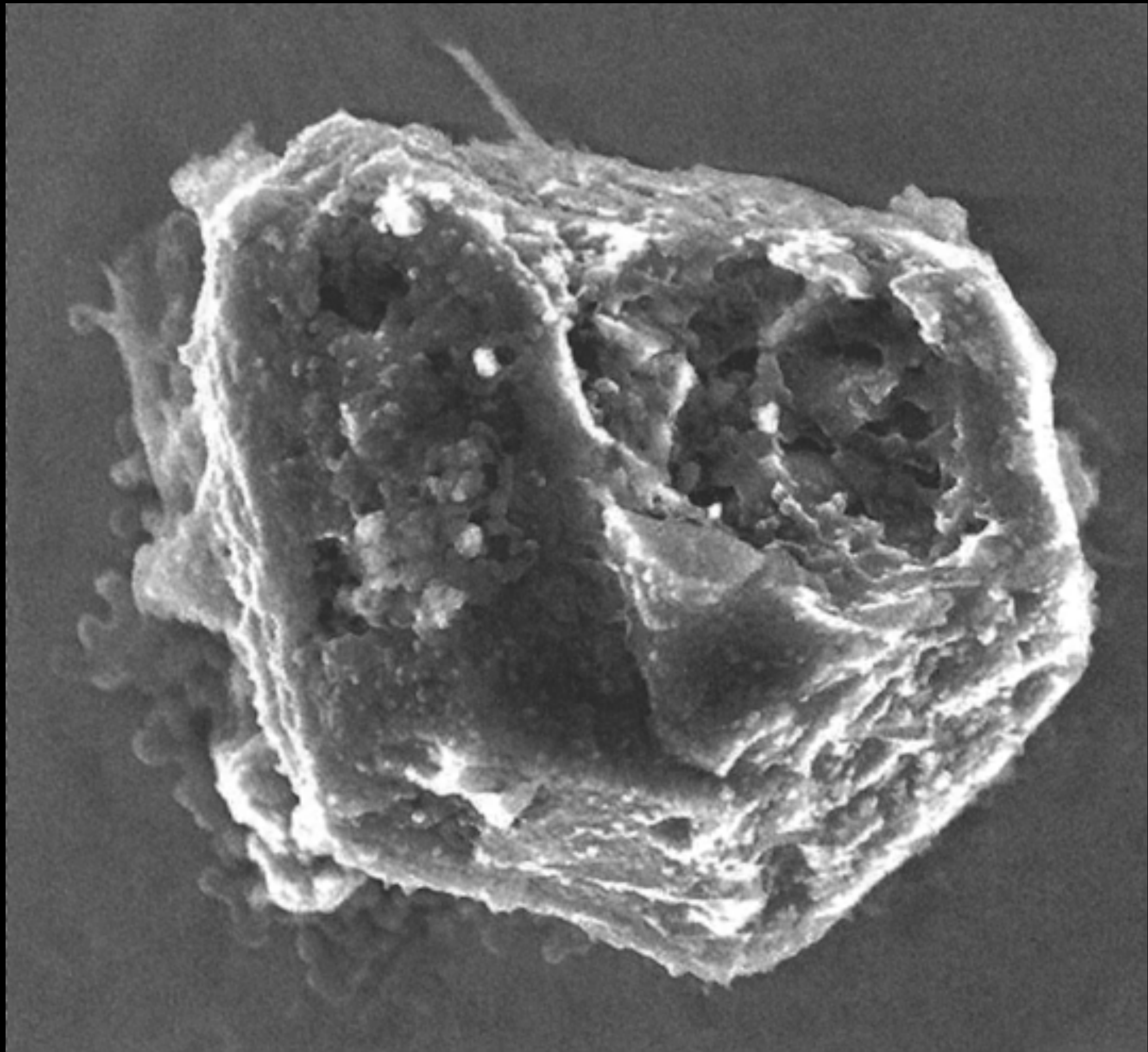

Unburned
H-rich
gas
H-burning
He-
burning
He-rich
gas

Sir Fred Hoyle FRS 1915-2001



^{4}He
^{8}Be
^{4}He
^{4}He
γ
γ
^{12}C
Proton
γ Gamma Ray
Neutron

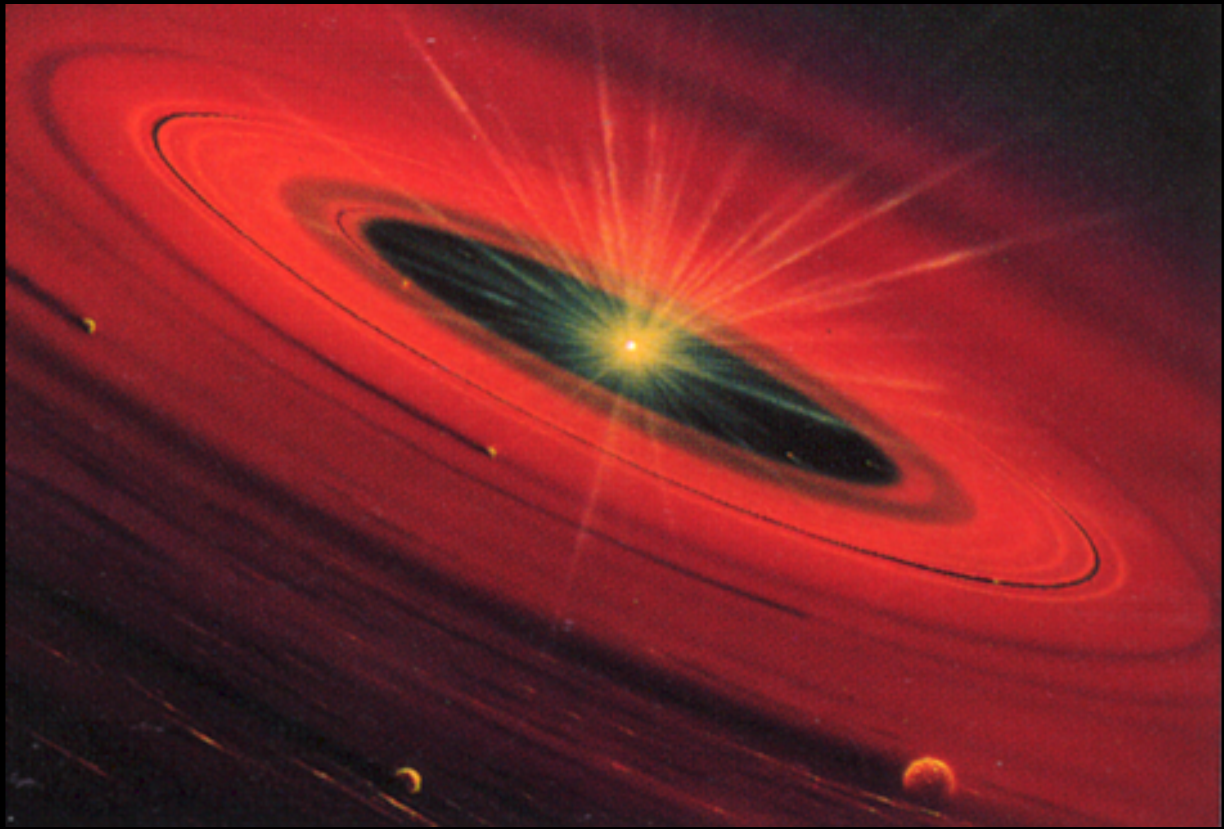




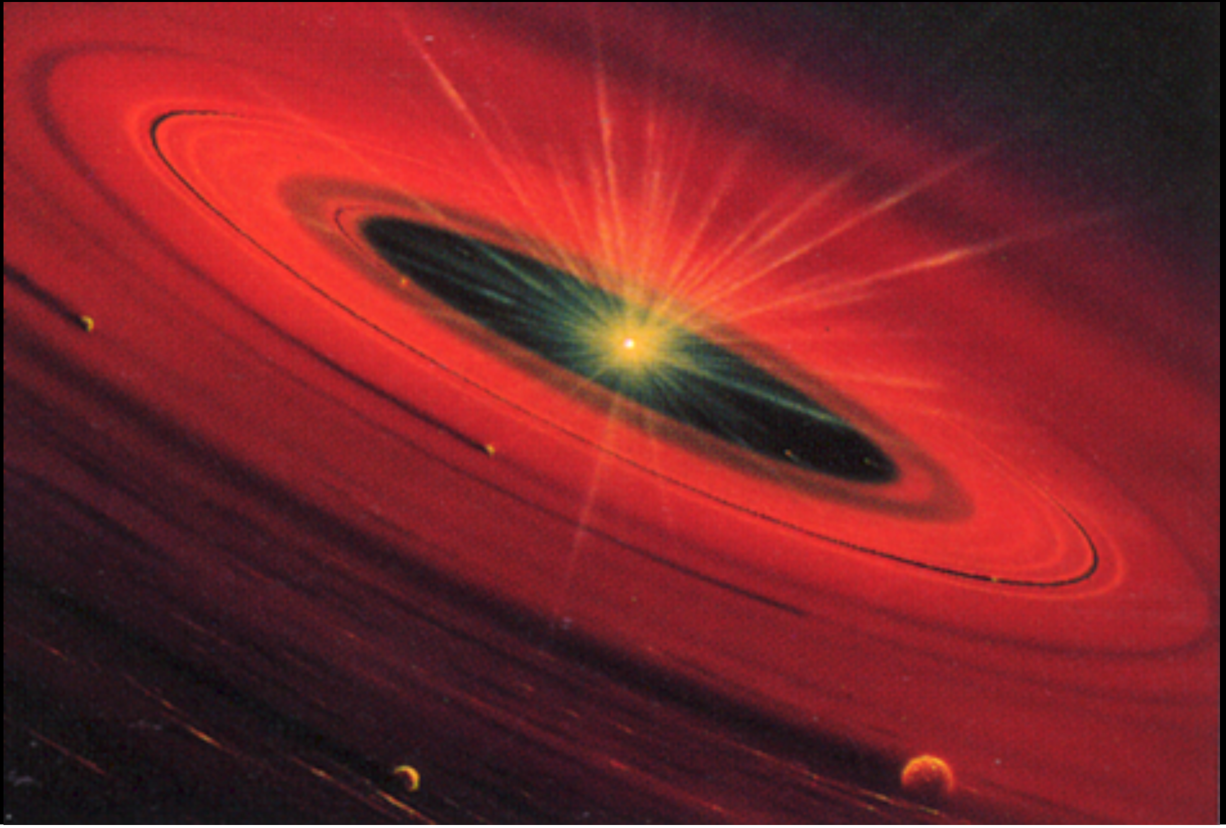
In this 5 micron SiC grain $^{12}C/^{13}C$ is only 39

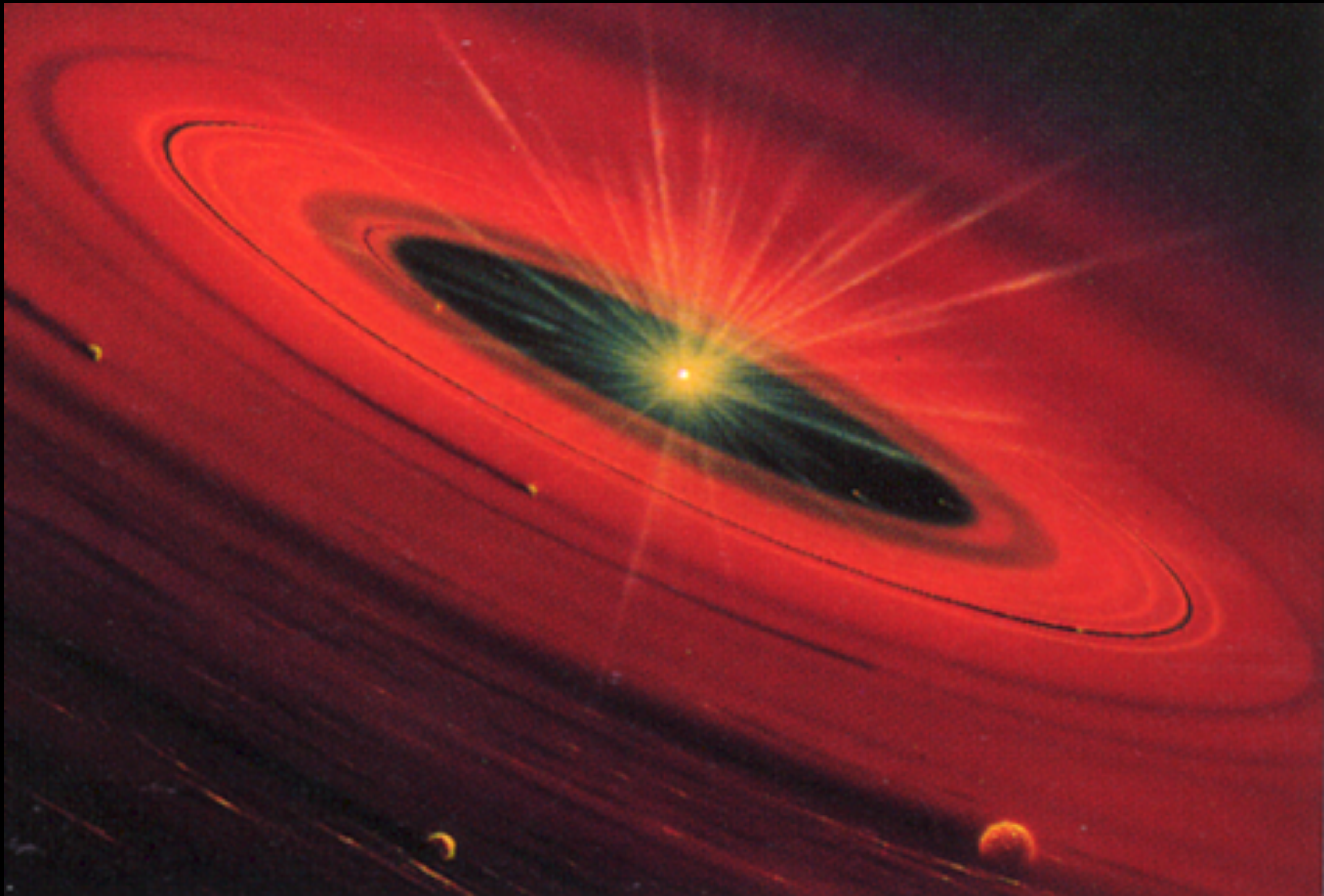
(Normally it is 89)

Chondrules are NOT stardust - they have Solar System isotope ratios, so were melted (by some unknown process) in the disk, before they accreted



So, chondrules, CAIs, bits of metal and matrix dust were made in the disk, then accreted onto growing planetesimals (with rare presolar grains). Fragments of those planetesimals arrive on Earth as chondrites.





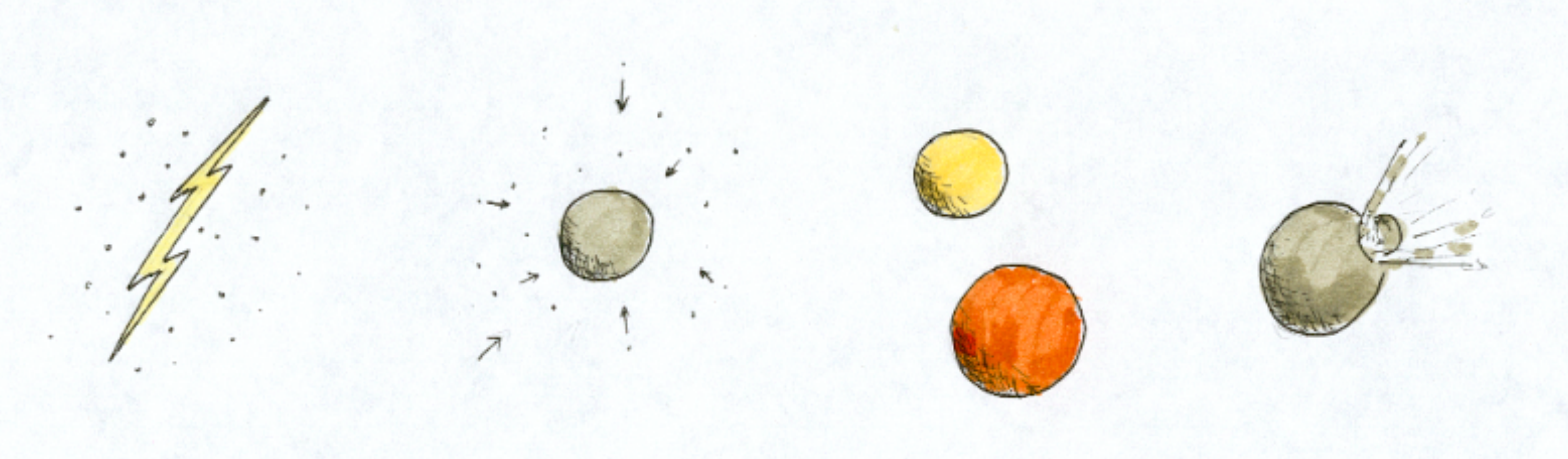
[redacted]

A new paradigm

Chondrules, chronology and recycled planetesimals: an emerging new view of the early solar system

So far then:
4567 million years ago, following 'in-fall' in a molecular cloud, radioactive dust in a disk around the infant sun became converted to chondrules, CAIs and metal grains. These grains, plus some original dust with pre-solar grains, accreted into planetesimals. The planetesimals got hot and even melted.

Popular view of events in the disk



1) CAIs and chondrules were made as flash-melted dust clumps

2) The 'bits' accreted to make chondrite parent bodies

3) The bodies got hot and some even melted to make iron and basalt

4) Impacts, shock and brecciation followed after cooling

But this popular view of early disk evolution is at odds with four items of evidence.

1. Basalt clasts are found in some chondrites

Earth and Planetary Science Letters, 113 (1992) 191–205
Elsevier Science Publishers B.V., Amsterdam

[UC]

A unique high Mn/Fe microgabbro in the Parnallee (LL3) ordinary chondrite: nebular mixture or planetary differentiate from a previously unrecognized planetary body? *

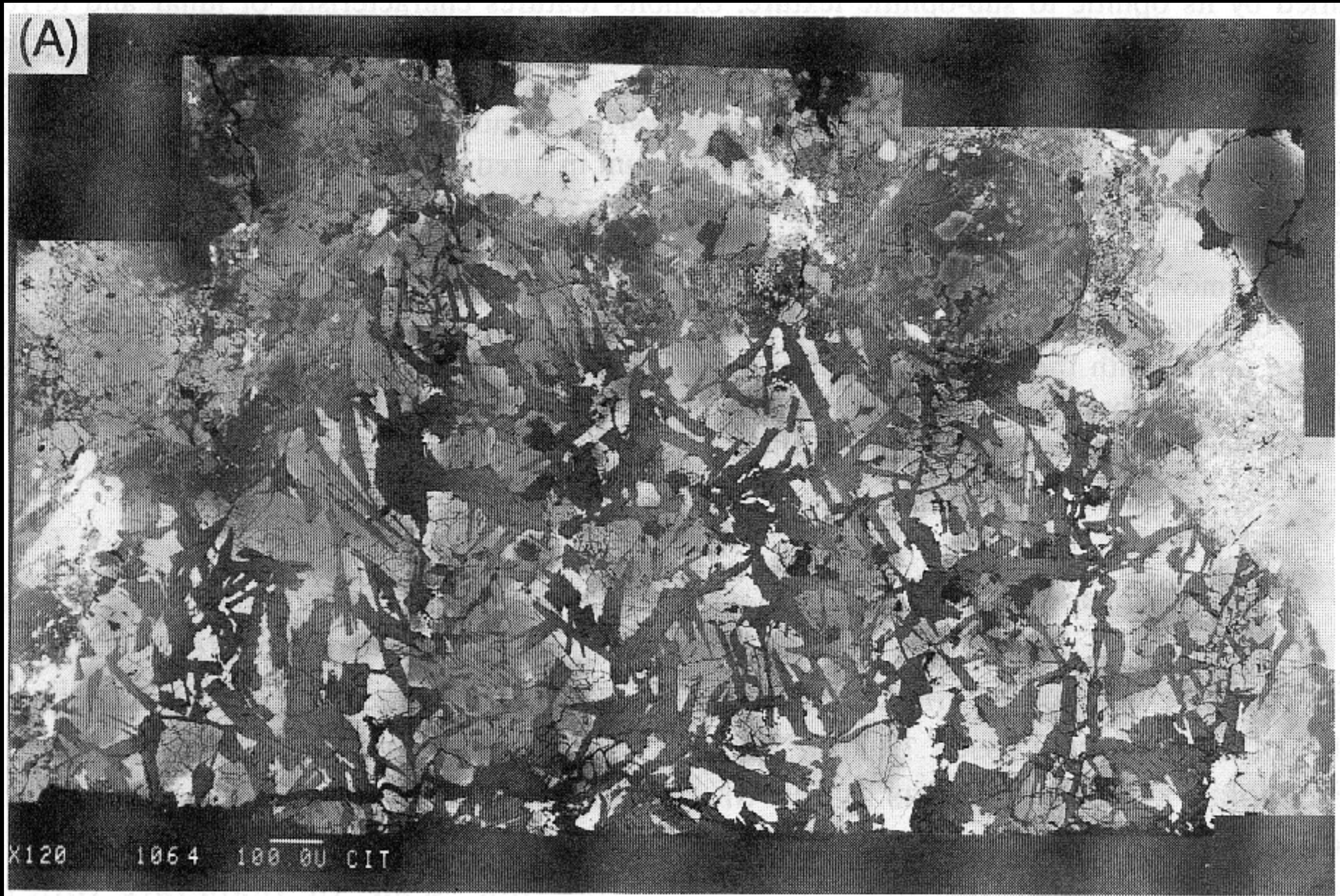
A.K. Kennedy [a], R. Hutchison [b], I.D. Hutcheon [a], and S.O. Agrell [c]

[a] *The Lunatic Asylum of the Charles Arms Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA*
[b] *The Natural History Museum, Cromwell Road, London SW7 5BD, UK*
[c] *Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK*

Received October 14, 1991; revision accepted July 1, 1992

ABSTRACT

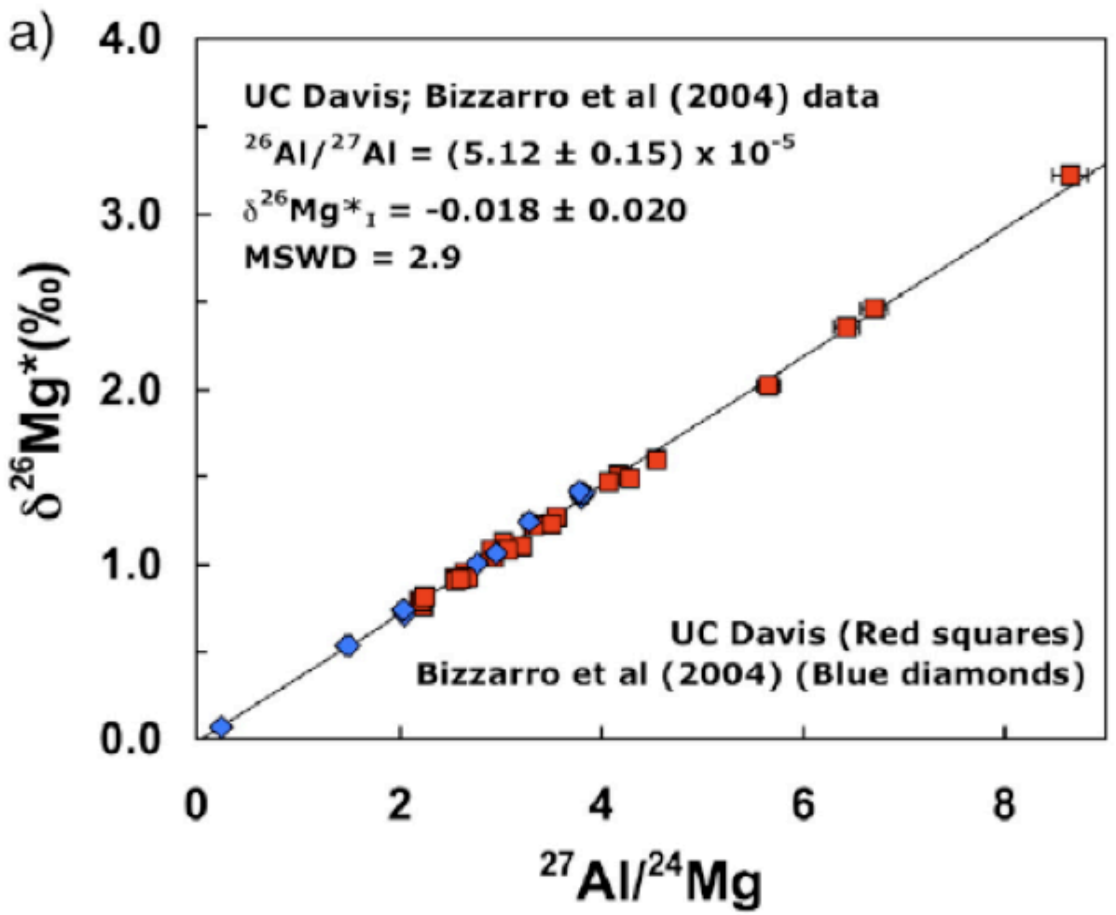
The study of planetary materials in chondritic meteorites constrains the compositional diversity of materials in different nebular environments and provides information on the degree of differentiation of early planetary bodies. We studied a


(A)
X120 1064 100.0U CIT

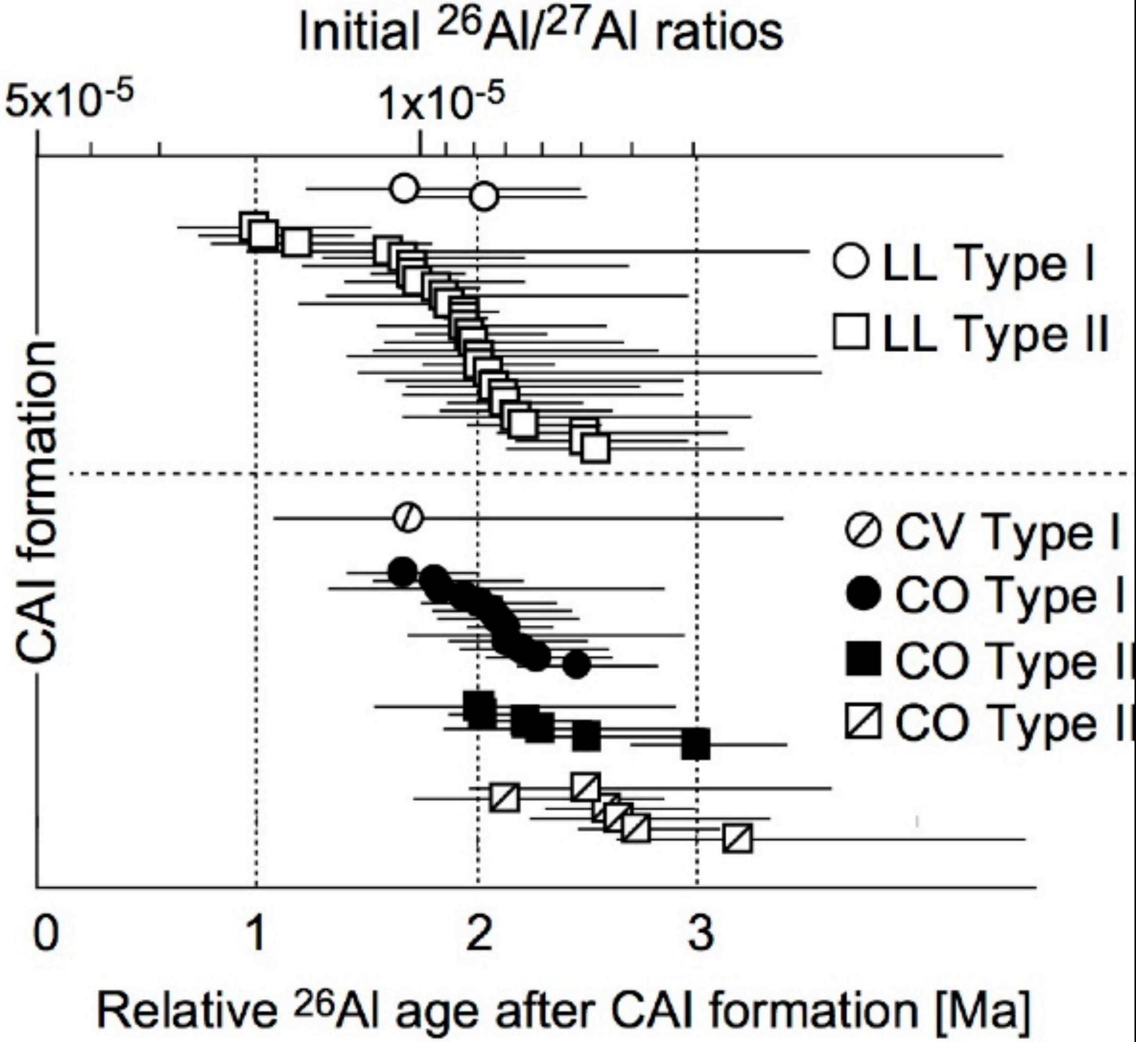
Robert Hutchison
1938 - 2007

But this popular view of early disk evolution is at odds with four items of evidence.

2. Chondrules are NOT the same age as CAIs, but about 2 Myr younger.

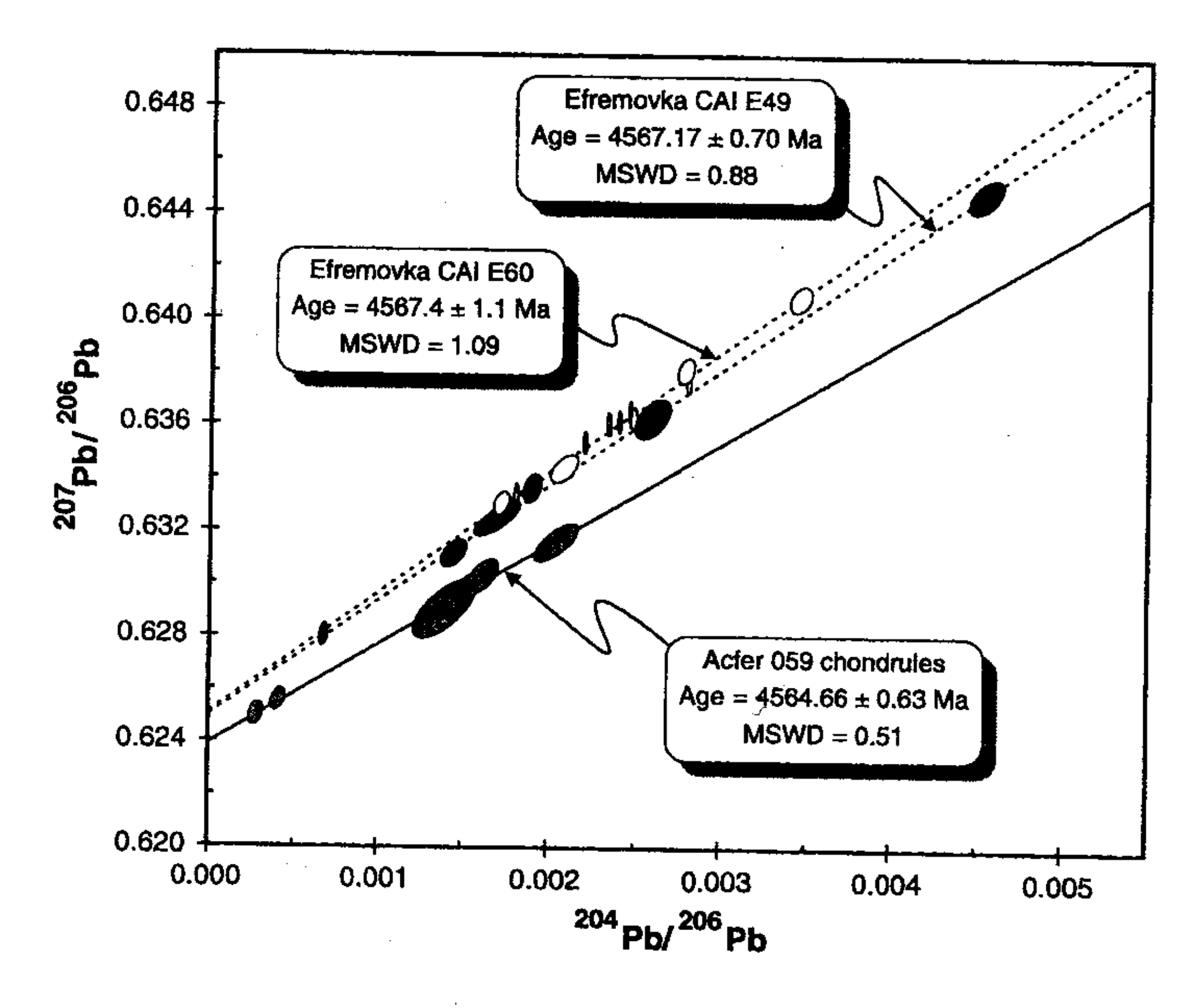


CAIs contained 5 atoms of radioactive ^{26}Al for every 100,000 atoms of ^{27}Al.
i.e. when CAIs were made, $^{26}Al/^{27}Al$ was 5×10^{-5}



But chondrules have $^{26}Al/^{27}Al = 1 \times 10^{-5}$

This is 2 to 3 half lives, or 2 Myr, after CAIs



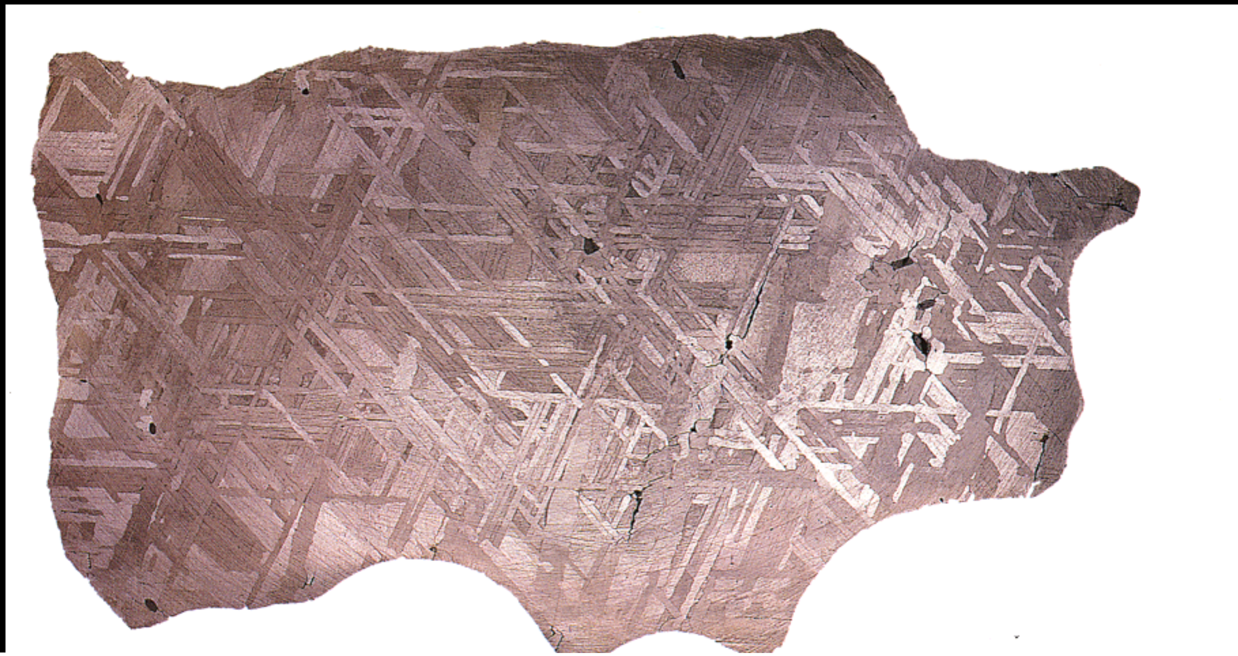
Pb-Pb dating from Amelin et al. (2002)

The y-axis is a measure of age. Top lines are for CAIs. They cut the y-axis at 0.625 (=4567 Myr). The chondrule line below cuts at 0.624 (=4565 Myr)

But this popular view of early disk evolution is at odds with four items of evidence.

3. Iron meteorites (the separation of metal from rock) happened at the same time as CAIs based on low eps^{182}W.

^{182}Hf (lithophile) was decaying to ^{182}W (siderophile) with a half-life of ~ 10 Myr. So ^{182}W/ ^{184}W in the disk was increasing. Now ^{182}W/ ^{184}W in irons is really low and shows that molten cores separated, leaving ^{182}Hf parent isotope in the mantle, at the same time as CAIs were made.



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Hf–W mineral isochron for Ca,Al-rich inclusions: Age of the solar system and the timing of core formation in planetesimals

Christoph Burkhardt [a,b,*], Thorsten Kleine [a], Bernard Bourdon [a], Herbert Palme [b], Jutta Zipfel [c], Jon M. Friedrich [d], Denton S. Ebel [c]

[a] *Institute of Isotope Geochemistry and Mineral Resources, ETH Zurich, Clausiusstrasse 25, CH-8092 Zurich, Switzerland*

[b] *Institut für Geologie und Mineralogie, Universität zu Köln, Zülpicherstrasse 49b, D-50674 Köln, Germany*

[c] *Naturmuseum und Forschungsinstitut Senckenberg, Frankfurt, Germany*

[d] *Department of Chemistry, Fordham University, Bronx, NY 10458, USA*

[e] *Department of Earth and Planetary Sciences, The American Museum of Natural History, Central Park West at 79th Street, NY 10024-5192, USA*

Received 22 January 2008; accepted in revised form 29 October 2008; available online 5 November 2008

Abstract

Application of ^{182}Hf–^{182}W chronometry to constrain the duration of early solar system processes requires the precise knowledge of the initial Hf and W isotope compositions of the solar system. To determine these values, we investigated the Hf–W isotopic systematics of bulk samples and mineral separates from several Ca,Al-rich inclusions (CAIs) from the [redacted]

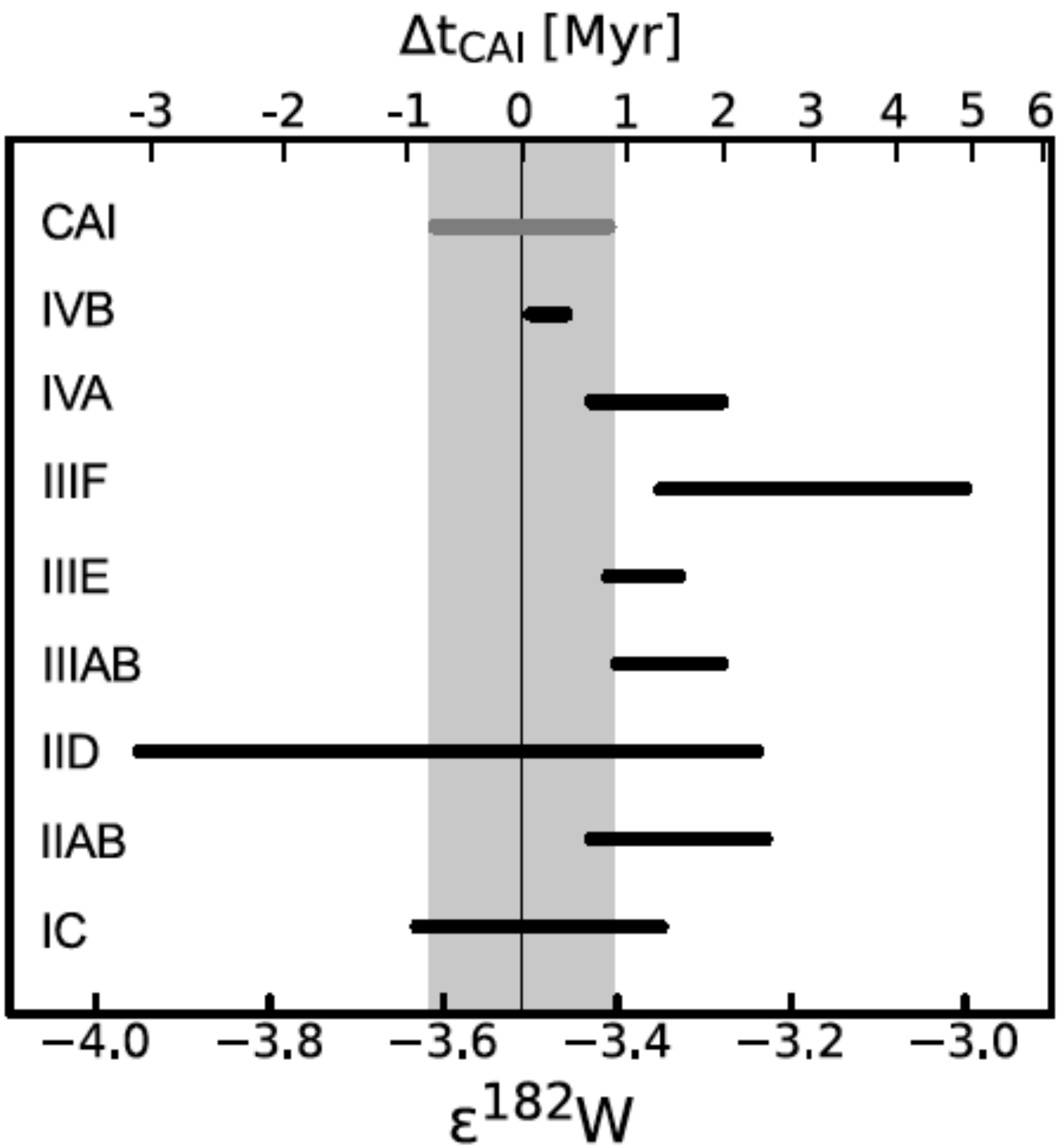


Figure 4. Hf–W model ages for core formation in iron meteorite parent

So:

The first planetesimals formed at the same time as CAIs, and soon melted (iron cores).

Chondrules were made up to 2 Myr later.

Later still chondrules aggregated, along with some basalt and other ‘planetary’ bits to make chondritic planetesimals.

How is this so?


26


26


JOHN WEST
Pink Salmon
418 g

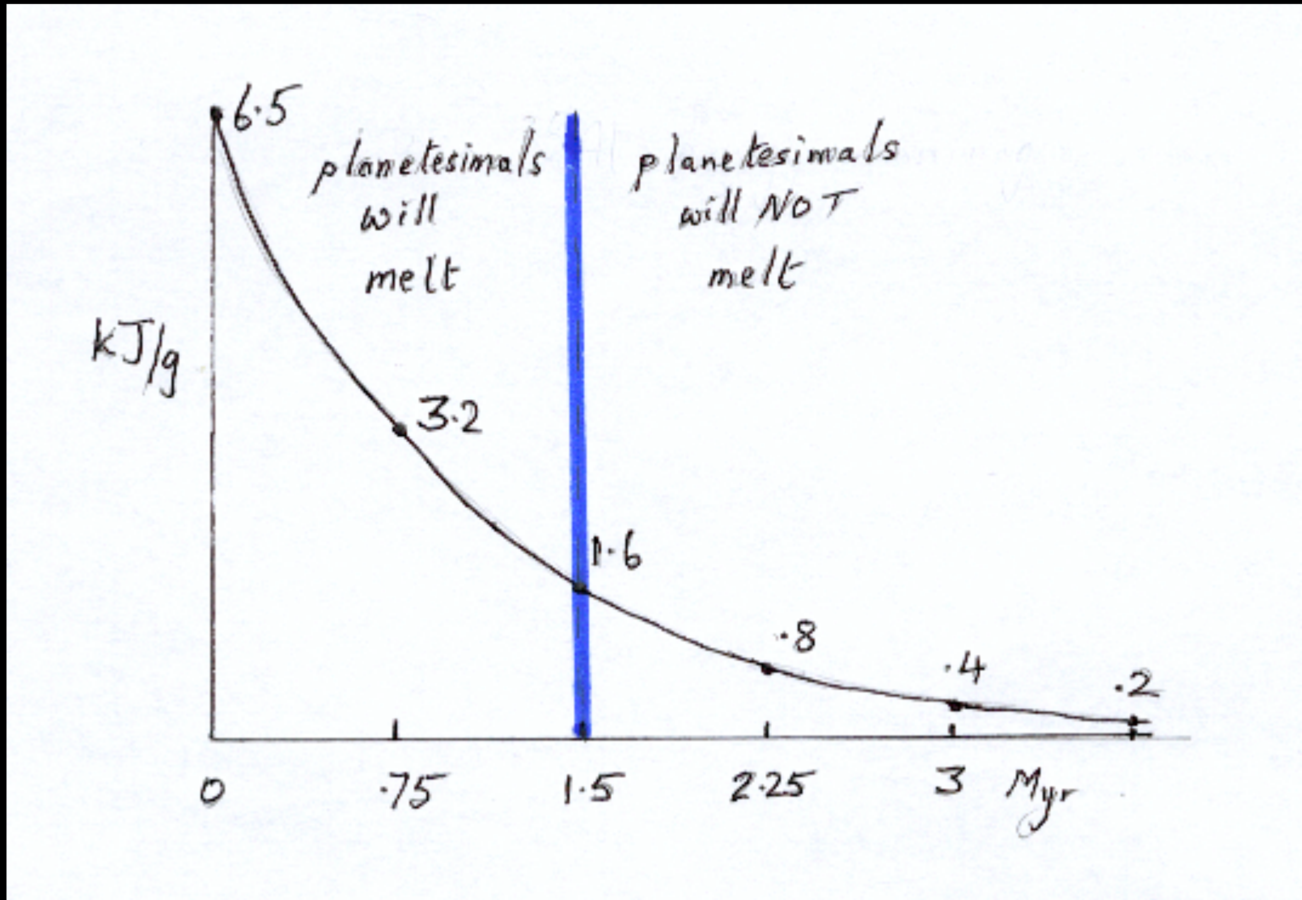
JOHN WEST
Pink Salm on
Pink Salmon is the smallest speci Pacific
Salmon, quite distinct from Red Salm it contains
very little oil which makes it ideal only for
delicious sandwiches but for a var of recipes
when you want the great taste of Sal John West
Pink Salmon contains no artific lavour,
added colour or preserva
John West selects only the
For more information about our r of Salmon
Products write to The Marketing rtment,
John West Foods Ltd. at the add below.
INGREDIENTS:
PINK SALMON, SAL
5 000171 001450
NUTRITIO INFORMATION
Energy 155 Kcal/650 kJ
Protein 23 g
Carbohydrate Trace
Fat 7 g
PRODUCED IN U.S.A. FOR
JOHN WEST FOODS LTD.,
LIVERPOOL. L3 9SR
ENGLAND.

Assumptions: 3 MeV per ^{26}Al atom

1.2 wt% Al in dry primitive dust

^{26}Al/^{27}Al initial is 5.25 x 10^{-5}

This amounts to about 6.5 kJ per gram of ^{26}Al energy.



Nebular dust began with about 6.5 kJ per gram of ^{26}Al energy. Only 1.6 kJ per gram is needed to induce total meltdown. So two half lives - 1.5 Myr - is a watershed in the early solar system, dividing planetesimals that will melt from those that will not.

The first crop of planetesimals were so radioactive that they suffered meltdown.

Chondrules may have been made throughout the first 2 or 3 Myr.

If so, during the first 1.5 Myr the chondrules mostly accreted to planetesimals that were later to melt, and so were destroyed.

After this period, the potency of ^{26}Al had declined, so newly accreted chondrules survived melting, producing chondritic planetesimals.

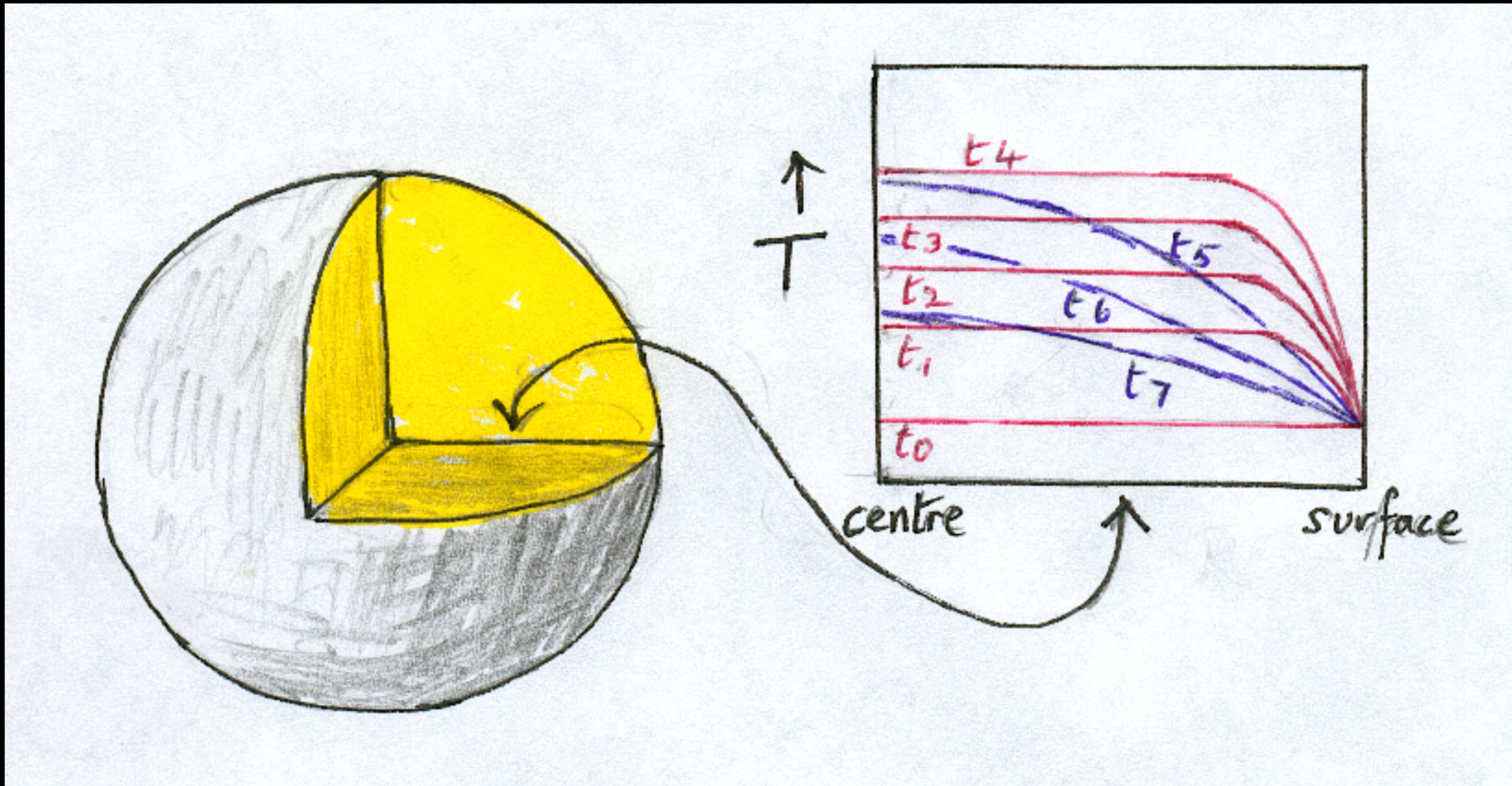
Energy release from ^{26}Al ?
Half life is 0.73 Myr

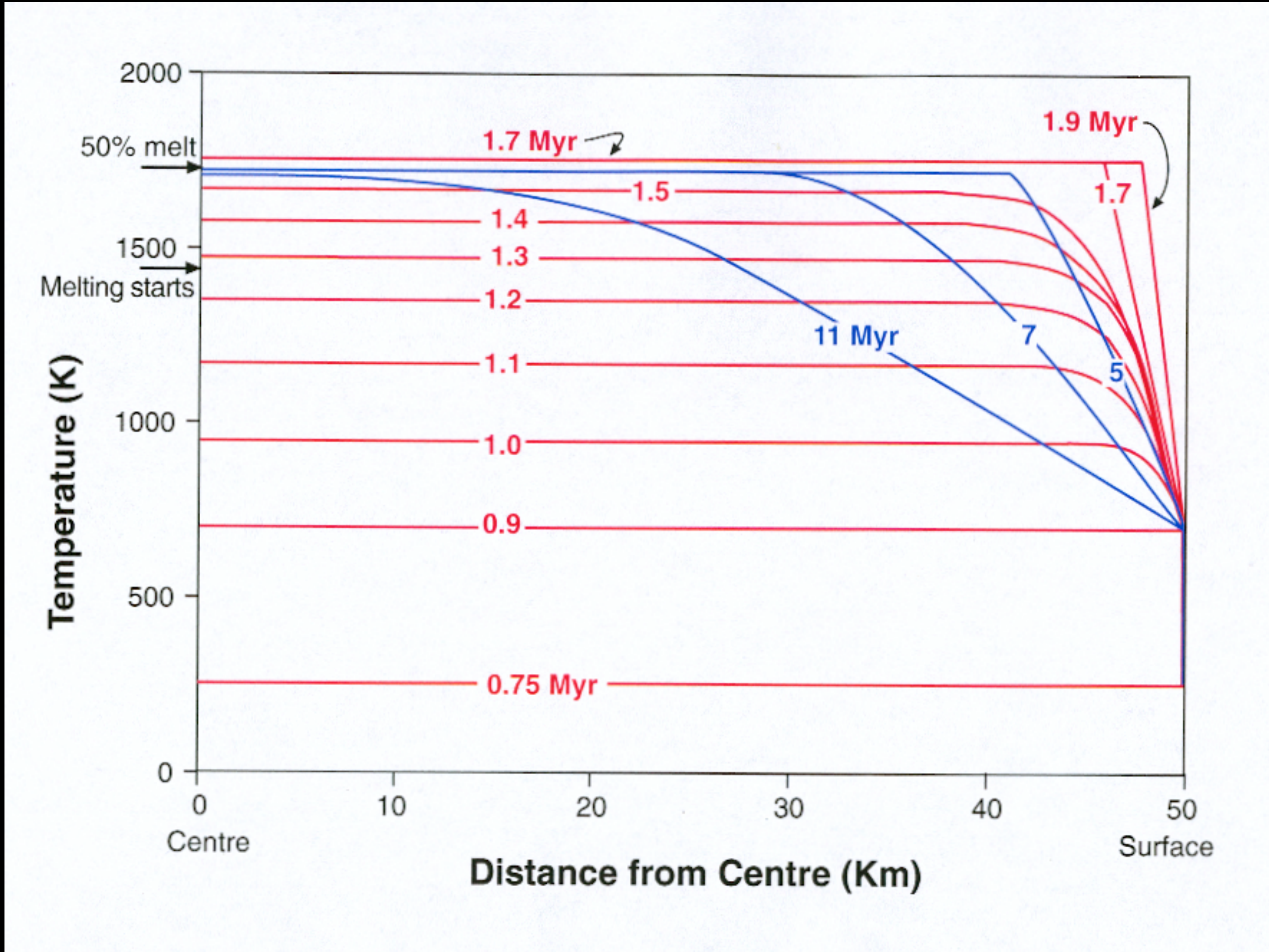
after one half life
(half the beer has gone)

after two half lives
(not enough left to get merry)

In a similar way, ^{26}Al in the disk had lost its potency to cause melting after two half lives, or roughly 1.5 Myr

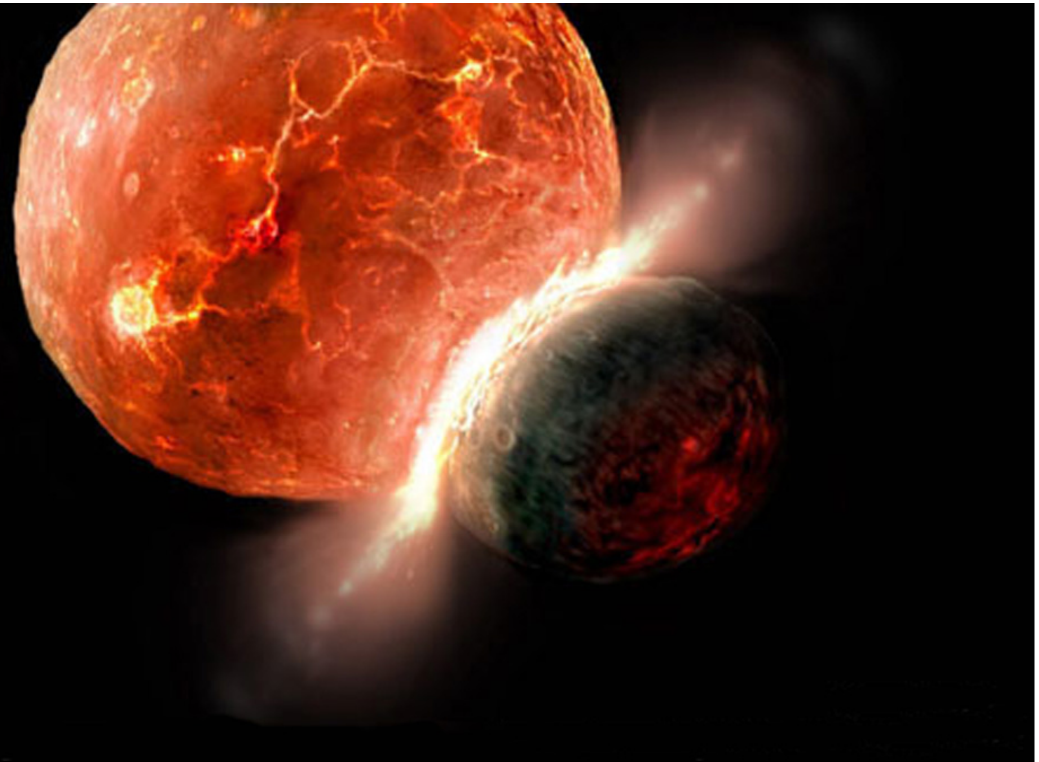
From computer simulations it is envisaged that very rapid heating led to near total melting and turbulent convection below a thin conducting crust from as early as 300 kyr after CAIs. (Hevey and Sanders 2006 Meteoritics and Planetary Science)


T
t4
t3
t5
t2
t6
t1
t7
t0
centre
surface



2000
1500
1000
500
0
50% melt
Melting starts
Temperature (K)
1.7 Myr
1.9 Myr
1.7
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.75 Myr
11 Myr
7
5
0
10
20
30
40
50
Centre
Surface
Distance from Centre (Km)

About 130 separate parent bodies are sampled by meteorites. Over 100 of them melted and supply igneous meteorites (irons, basalt etc.). These bodies melted, probably soon after CAIs were made, so the 2 Myr old disk was populated with molten bodies. (Note that the supply of igneous meteorites, just 14% of falls, is not representative of parent body numbers)

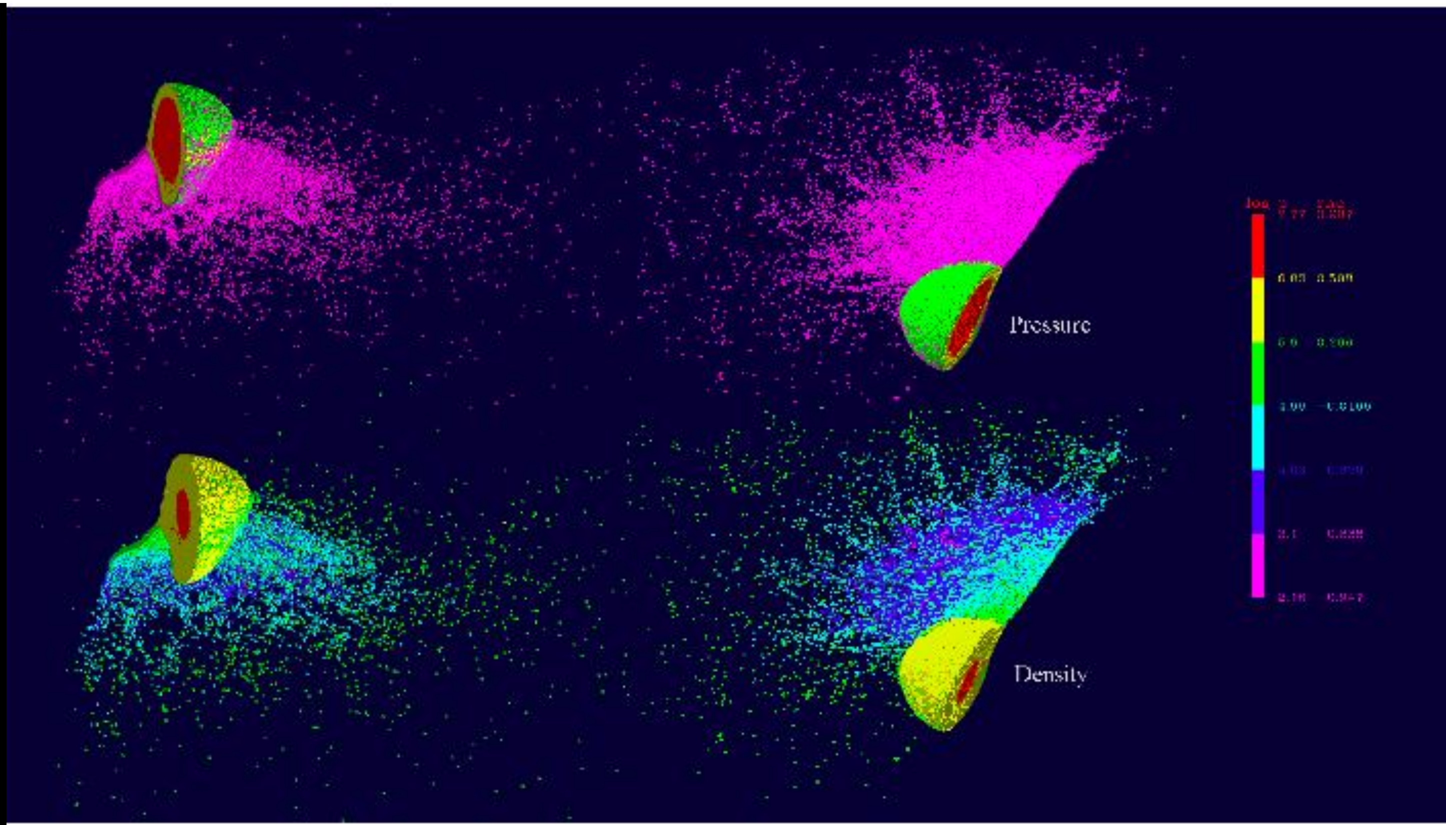


And how were chondrules made?

Could mergers of the molten planetesimals have released impact plumes of incandescent spray? No better way to make droplets of liquid than to collide one body into another body of liquid…

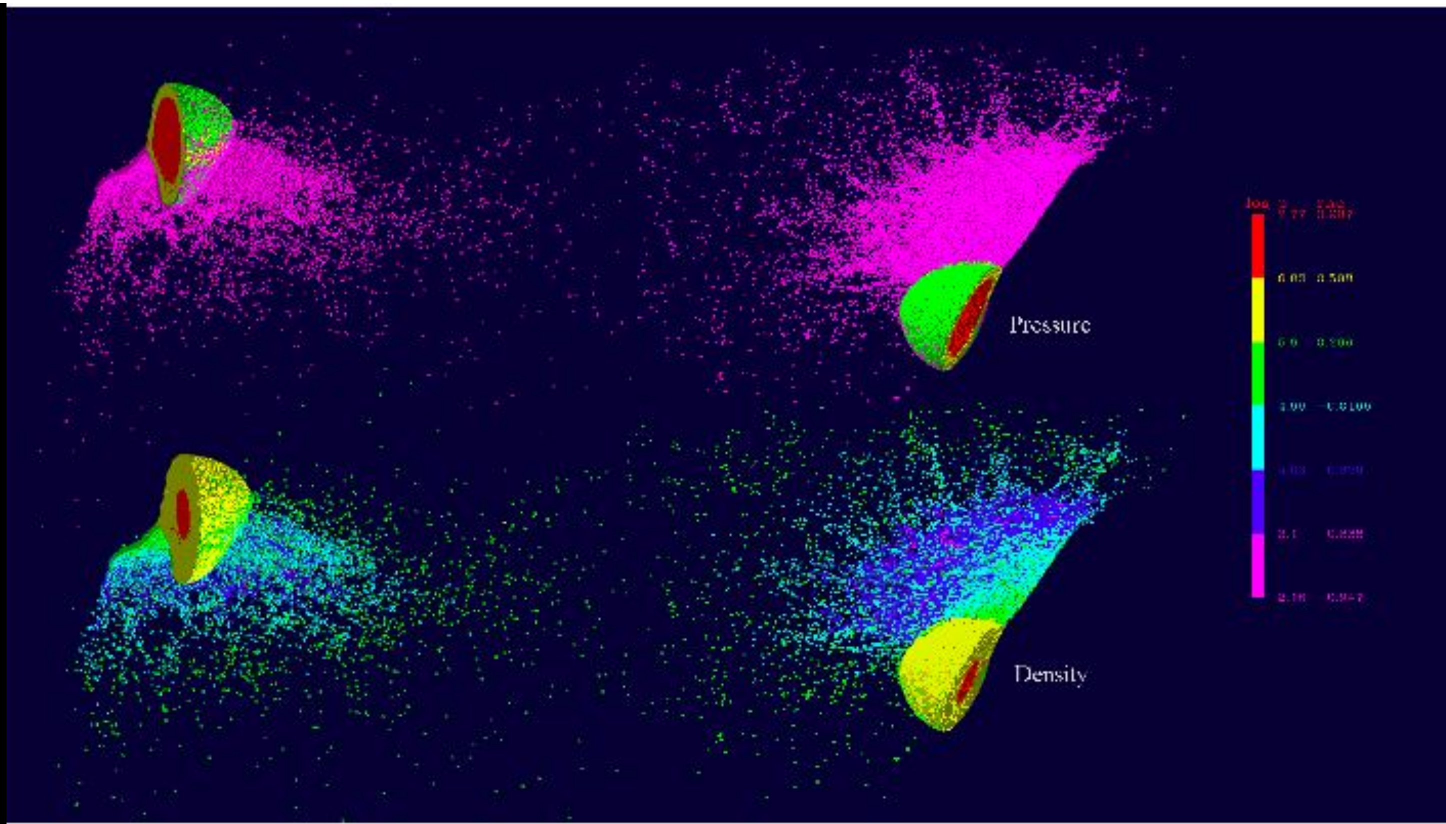
Making chondrules this way seems rather obvious. Even so, most researchers still reject the idea, and cling religiously to the conventional wisdom of chondrules being shock-melted clumps of dust.

The idea was mooted by Herb Zook (1981), and supported by a handful of people over the years since. It had a major boost, however, in 2011 when Erik Asphaug modelled the process numerically.



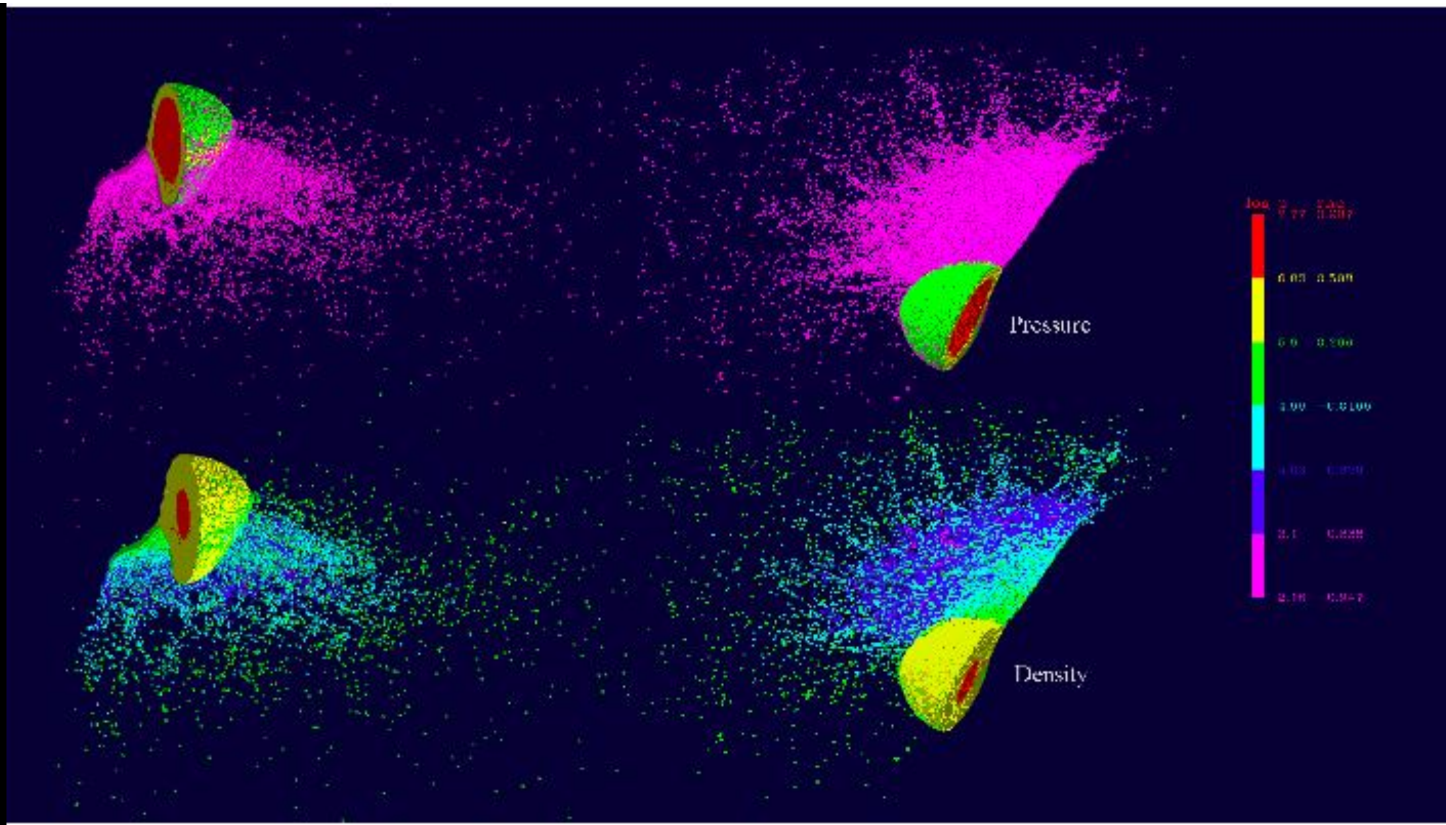
Asphaug et al. (2011) made a computer simulation of such a collision. In an oblique low velocity merger, the overshooting molten impactor expands downstream into a fan-shaped plume of closely-spaced molten droplets.

Gujba, a rare kind of meteorite with 'ball bearings' - widely viewed as a collision product.

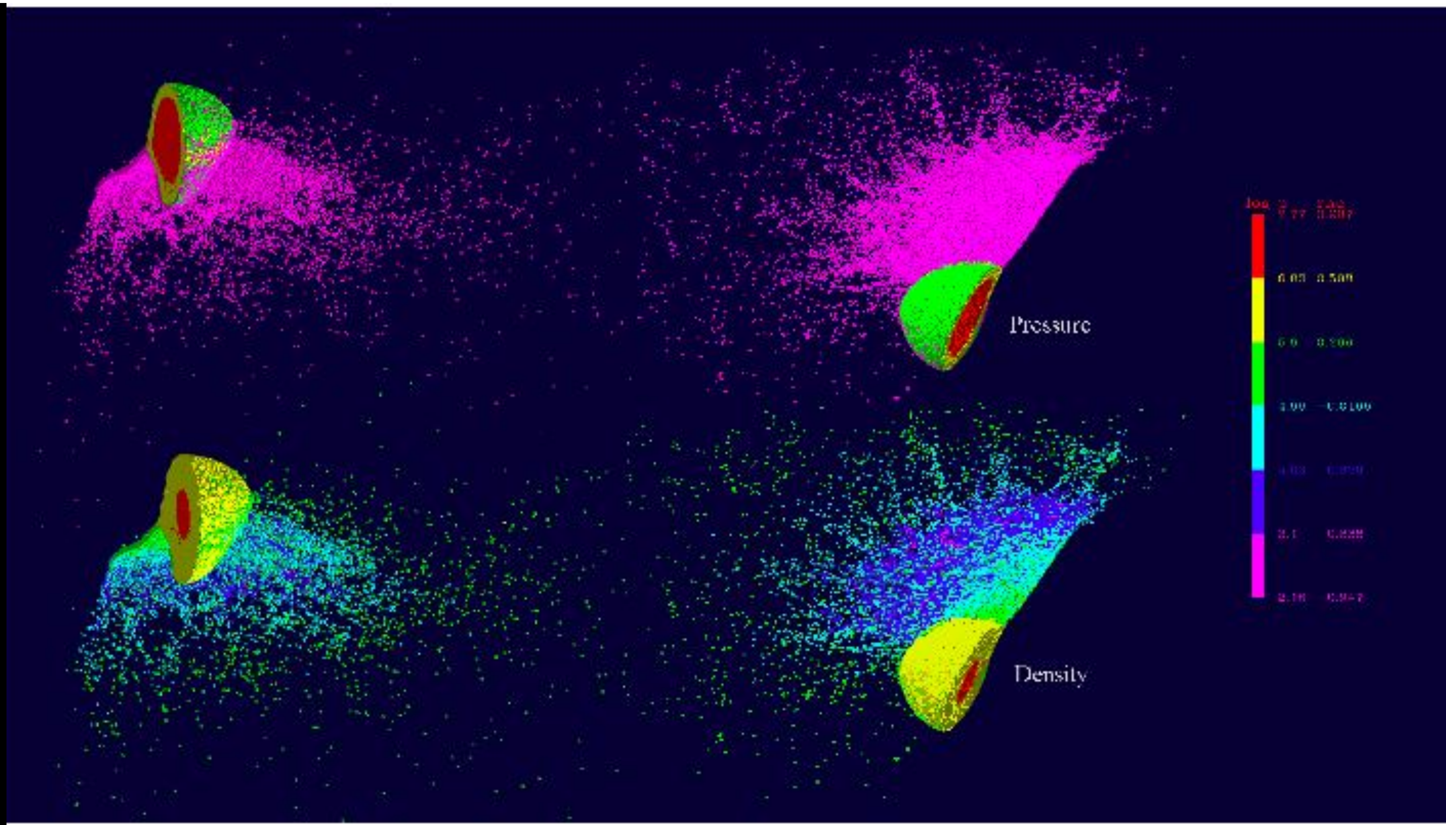


Can chondrule features be reconciled with formation in this kind of setting?

Yes



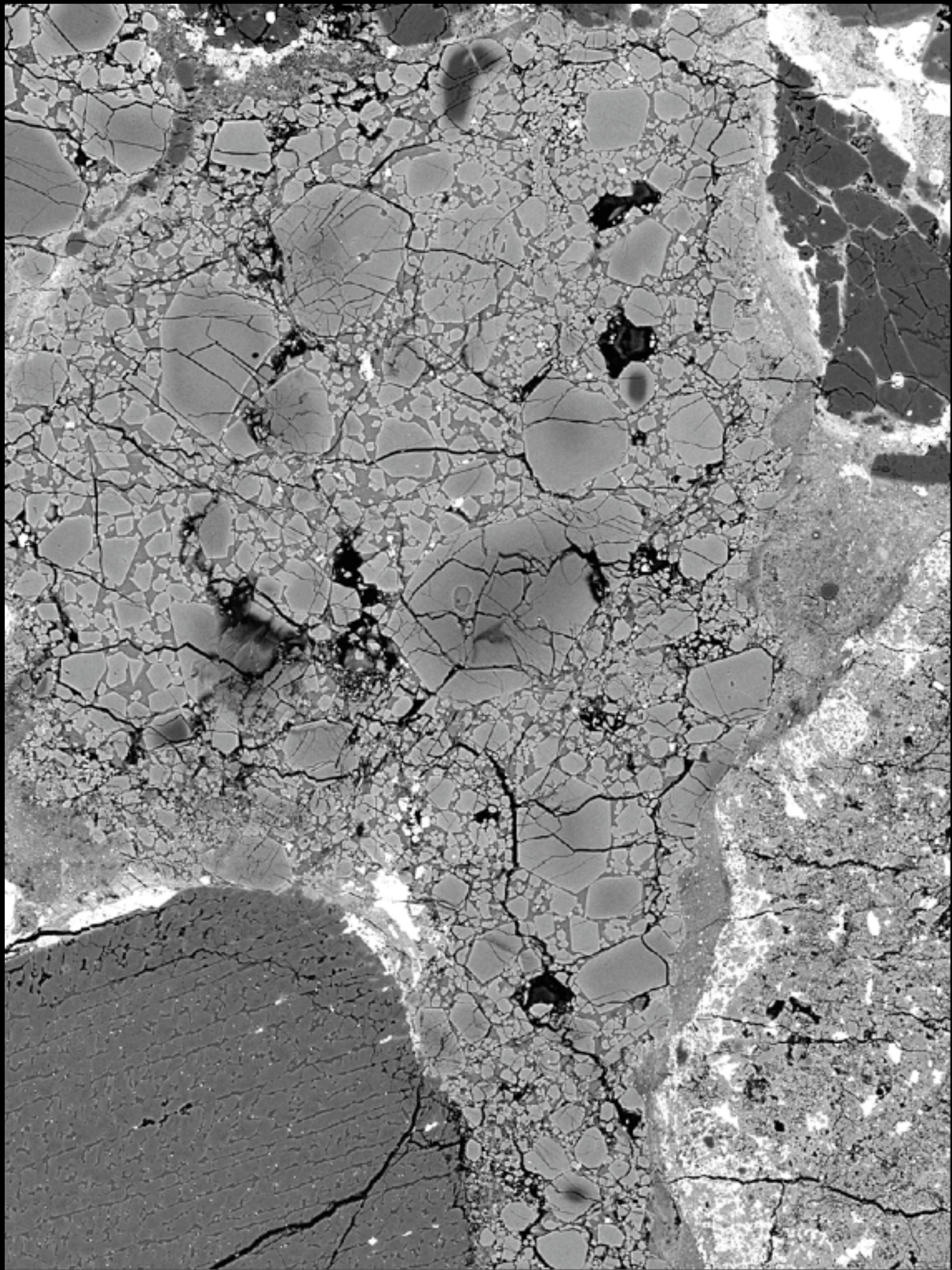
1) Chondrules took hours to cool down, not seconds as they would have done as isolated droplets radiating to cold space. Clouds of droplets were optically thick, so chondrules were immersed in a 'thermal bath'.



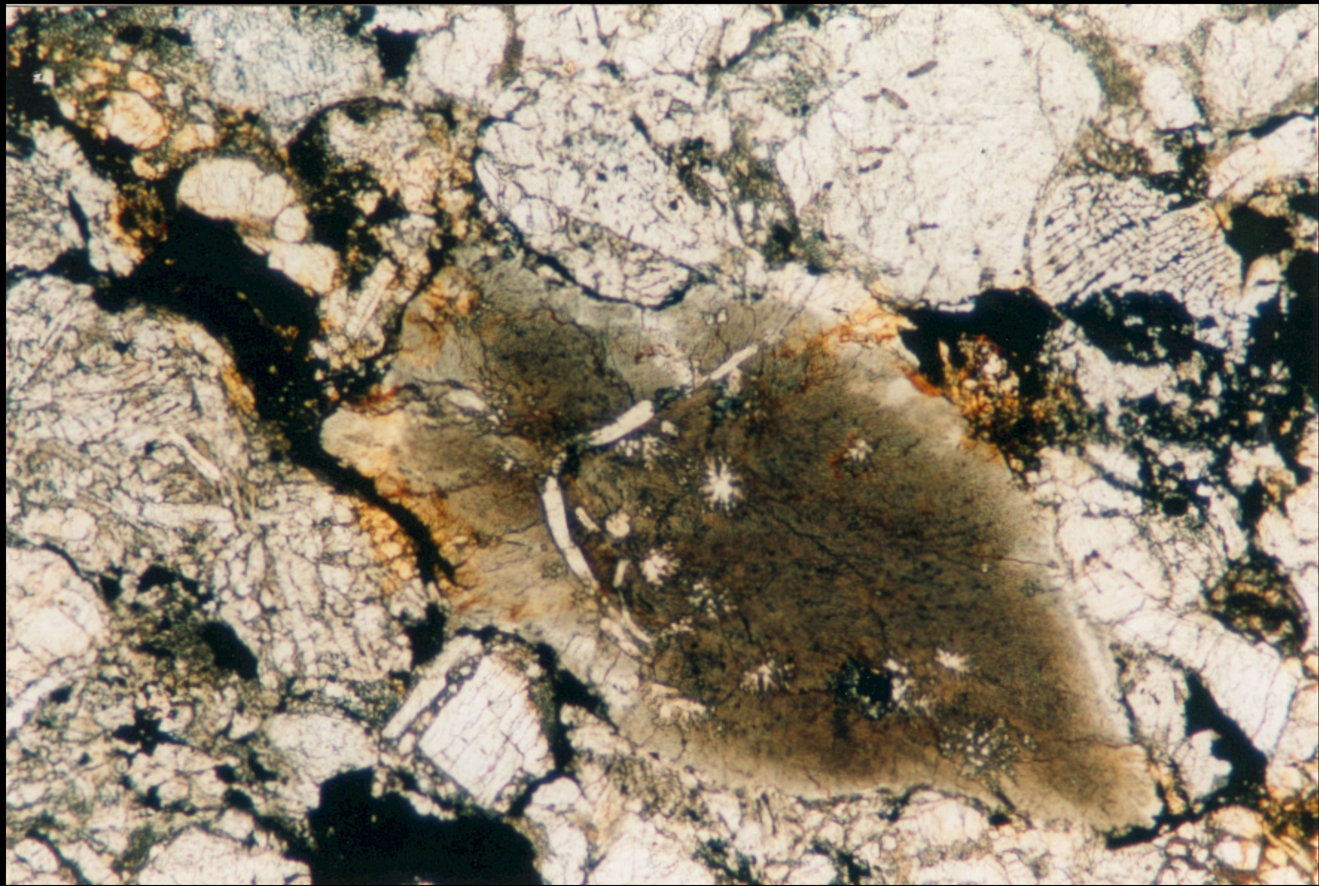
2) Na is volatile but is present in chondrules. (Alexander et al. 2008, Hewins et al. 2012). It did not evaporate significantly, so the gas between chondrules must have been saturated in Na, and chondrules must have been close to each other.

multiple compound chondrule from Bovedy L3

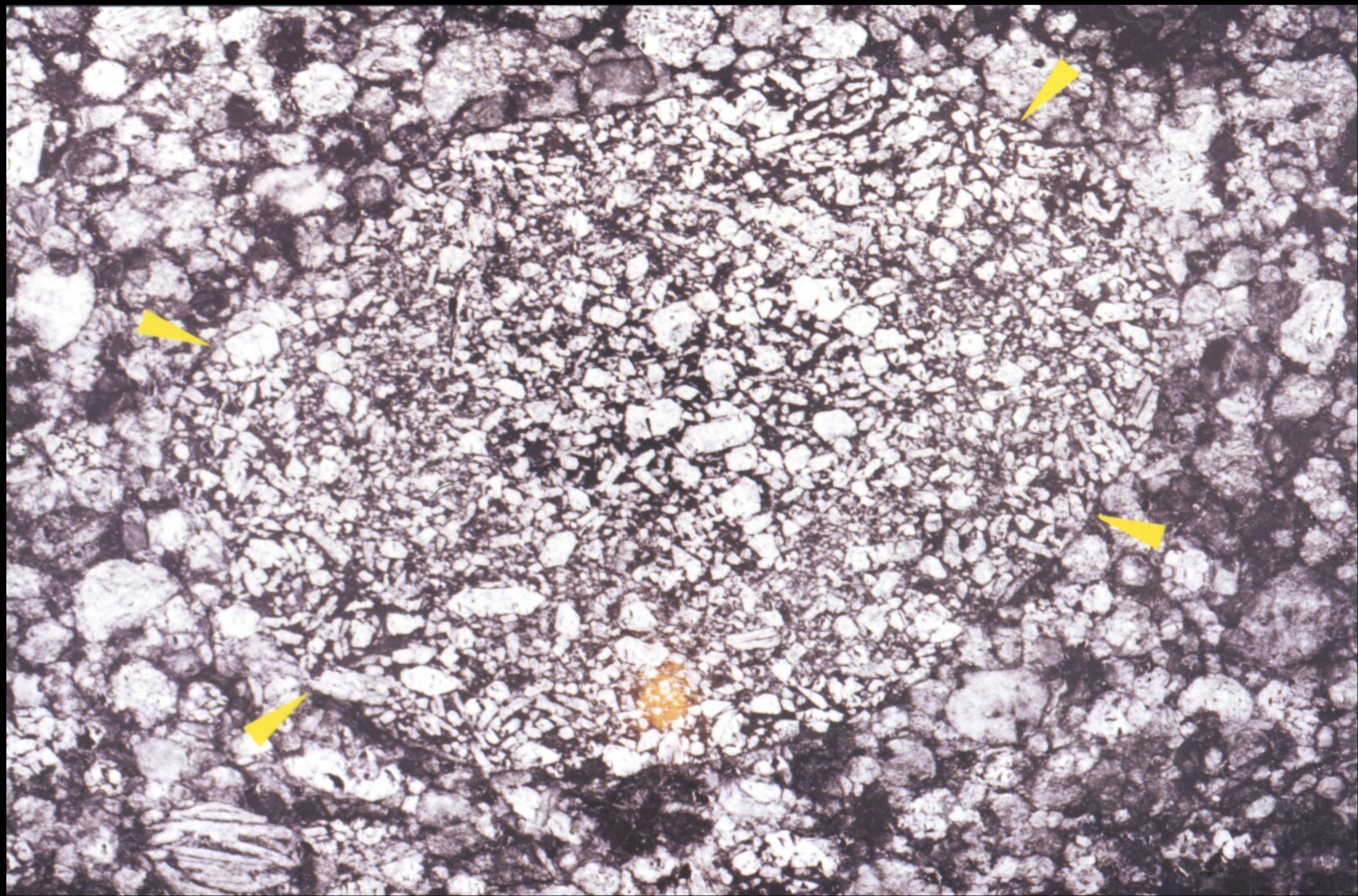
3) Compound chondrules are common - they imply closely-spaced chondrules, close enough to collide and stick during the cooling interval.



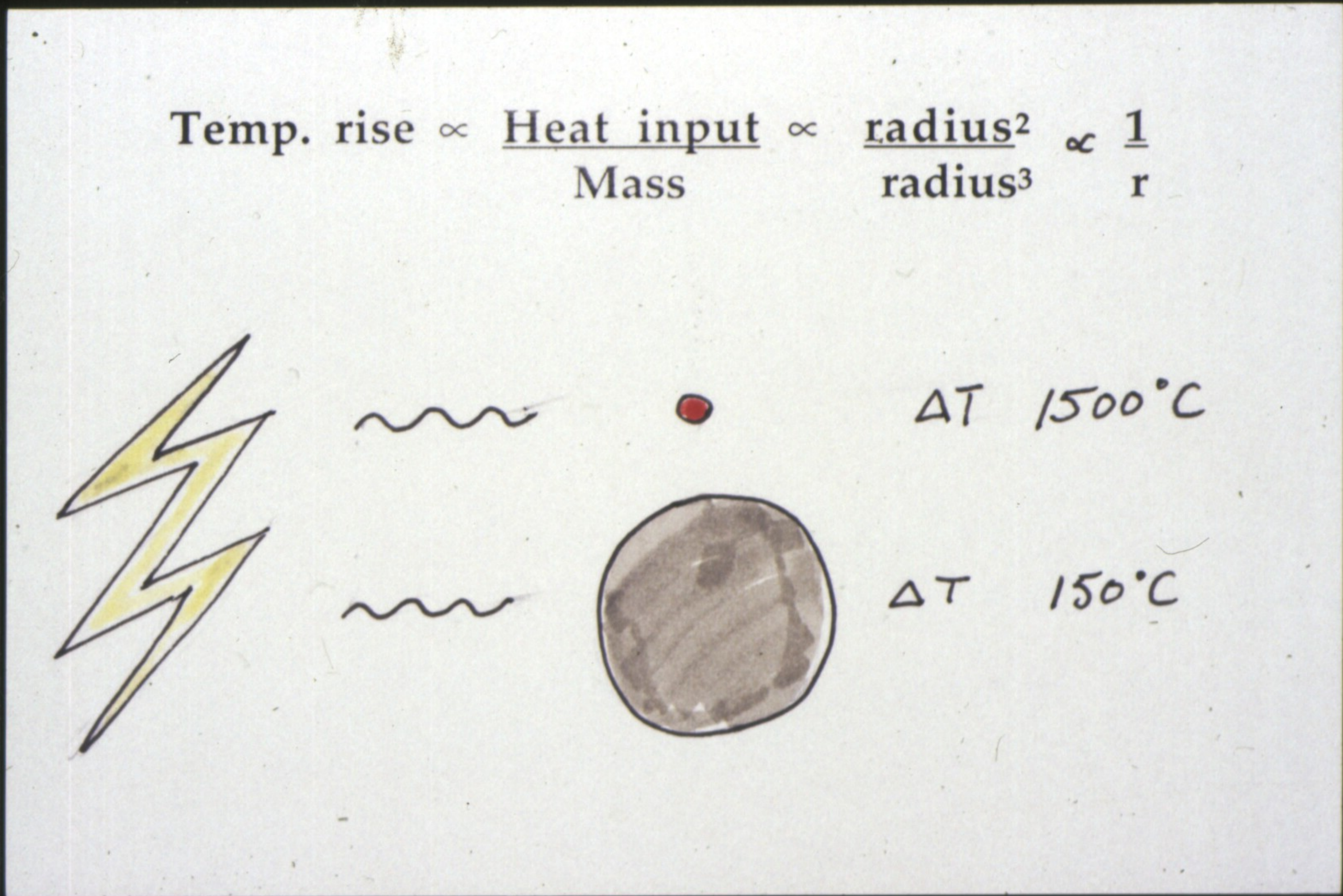
4) Molded chondrules were still molten when they met. They stuck and formed clusters. The clusters are a bit like multiple compound chondrules up to 10 cm across.



Flattened molded chondrule from Bovedy L3
Is the flattening parallel to the accreting surface of the planetesimal?



5) Megachondrules. This one is 1 cm wide - a big blob of splashed melt.



Temp. rise ∝ Heat input / Mass ∝ radius² / radius³ ∝ 1 / r
ΔT 1500°C
ΔT 150°C

6) Molten slurry has near-primitive silicate chemistry, just like that in chondrules

7) Droplet ‘peak’ temperatures are sub-liquidus

8) Already molten. No need to invent a ‘flash melting’ process.

9) Mechanism explains why most chondrites are depleted in metal. Metal gets concentrated in the core of the target body, and so plume of droplets is short of metal.

Summary:

The popular view of disk evolution (i.e. chondrules as nebular ‘flash-melted’ dust clumps, followed by planetesimal accretion, heating and melting) is not consistent with current chronological evidence.

Instead, planetesimals accreted from the outset. Those formed before 1.5 million years melted rapidly due to intense ^{26}Al heating. Those formed after 1.5 million years got hot but did not melt; they were the chondrite parent bodies.

Chondrules are probably frozen droplets splashed in cascades when the molten planetesimals were disrupted by impact or close encounter as they merged in the first steps towards planet formation