Laboratory studies of extraterrestrial matter: A view on the *solar* accretion disk

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Structure of the talk

1. Introduction

2. Short-lived radionuclides

3. Stellar origin for iron-60

4. Early solar system irradiation

5. A Stardust *détour*

6. Conclusions

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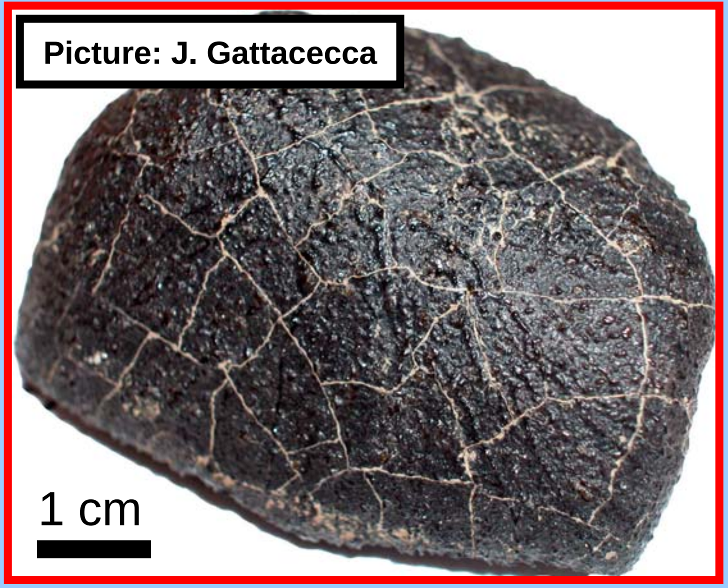
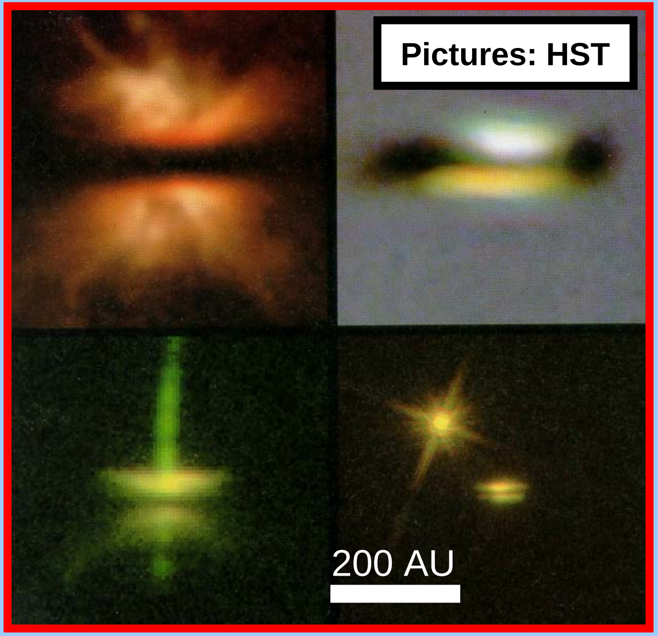
1. Introduction

Introduction

- **What do we learn on the solar accretion disk from meteorites?**
  - Astrophysical environment of the nascent Solar System
  - Physical processes in the solar accretion disk (thermal and irradiation events, primordial matter processing…)
  - Timescales of the different events (i.e. a chronology)

- **How do informations retrieved from meteorites compare with astronomical observations of low mass protostars?**





- In other words, we try to tie laboratory analyses of extraterrestrial samples with astronomical observations

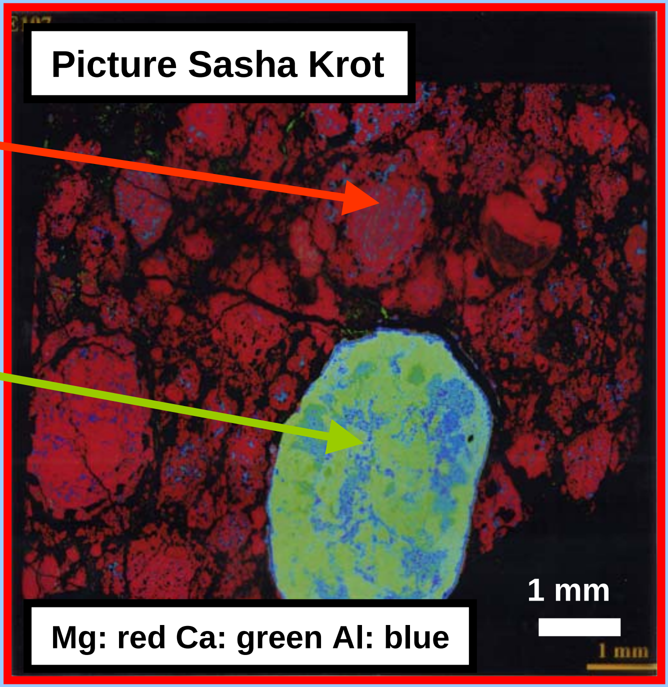
Components of chondrites

☆ This approach relies on the *assumption* that the components of primitive meteorites (chondrites) formed in the solar accretion disk

☆ *Chondrules*
  - ☆ Fe-Mg silicates, metal beads
  - ☆ Varying sizes (10 μm- few mm)

☆ *Refractory inclusions (CAIs)*
  - ☆ Contain Ca- and Al-rich minerals
  - ☆ Varying sizes (10 μm- few cm)

☆ *Matrix*
  - ☆ Silicates, oxides, amorphous
  - ☆ Fine-grained (< μm)



☆ **The common view is that CAIs are the first solids to have formed in the solar accretion disk (~ 2 Ma before chondrules)**

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2. Short-lived radionuclides

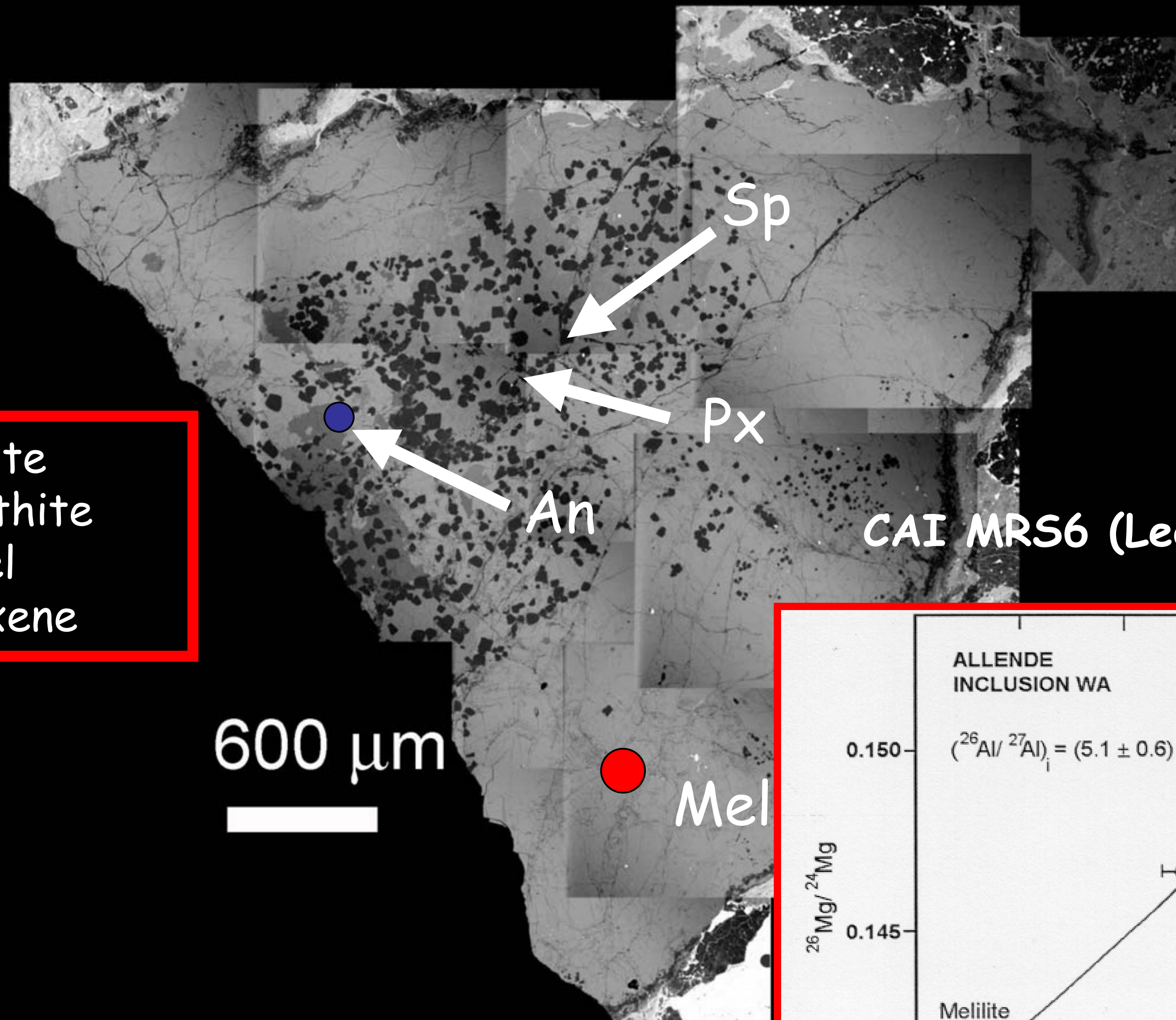
Short-lived radionuclides in the solar accretion disk

- **Short-lived radionuclides are radioactive elements with half-life < 5 Ma that were alive in the solar accretion disk**
  - Detected in CAIs, chondrules and differentiated meteorites
  - Now extinct (detected through excesses of their daughter isotopes)

- **Because short-lived radionuclides have short half-lives compared to molecular cloud cores evolution timescales, they have a late minute origin**
  - Made close to the disk or within the disk

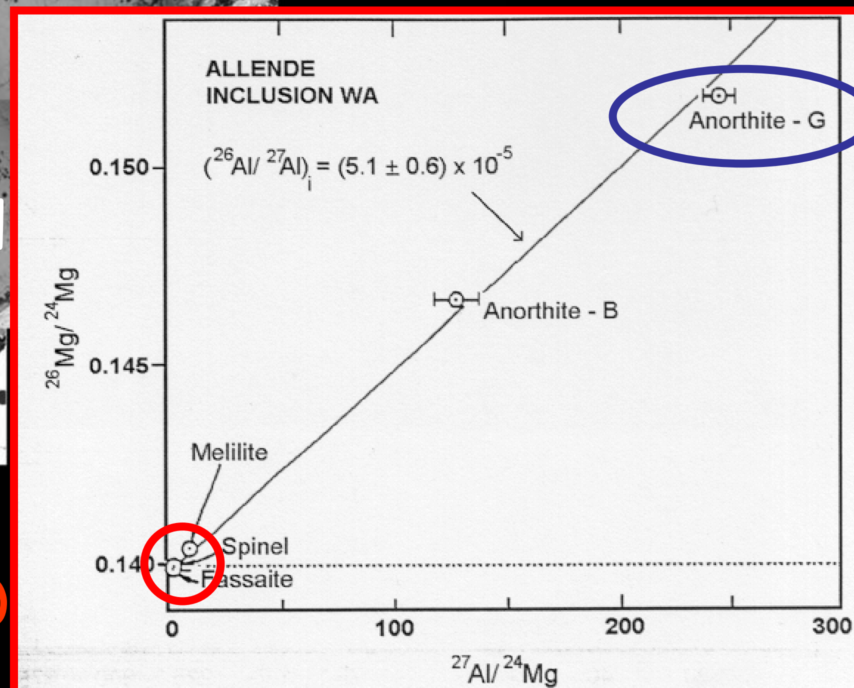
- **Understanding the origin (as well as initial abundance and spatial distribution) of extinct short-lived radionuclides is a key task for cosmochemists and astrophysicists**
  - It constrains the **astrophysical environment** of the protosun
  - It constrains the **irradiation conditions** in the solar accretion disk
  - SRs offer the possibility to build a **chronology** for the radionuclides whose initial distribution is well known
  - γ-ray emitters SRs (^{26}Al and ^{60}Fe) are a potential **heat source** for planetesimals

How does one detect a short-lived radionuclide?



Melilite
Anorthite
Spinel
Pyroxene

CAI MRS6 (Leoville, CV3)



Isotopic measurements at the mineral scale
(Secondary Ion Mass Spectrometry - SIMS)

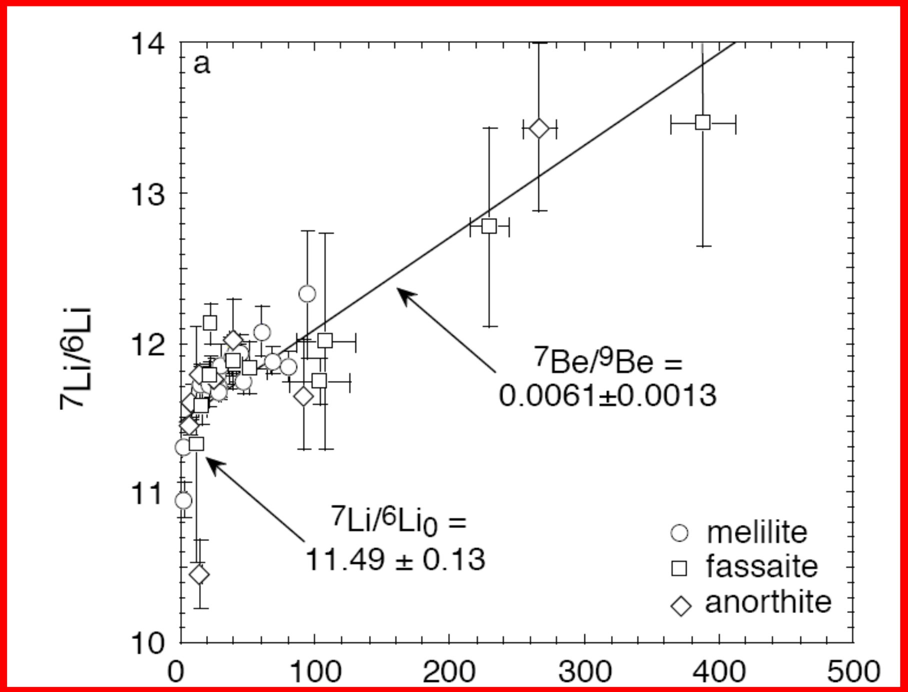
Key radionuclides

- Some key radionuclides have been recently (re)discovered
  - **Beryllium-7** decays to lithium-7 (T = 53 days) Chaussidon, McKeegan and Robert (2006)
  - **Beryllium-10** decays to boron-10 (T = 1.5 Ma) McKeegan, Chaussidon and Robert (2000)
  - **Chlorine-36** decays to argon-36 and sulfur-36 (T = 0.1 Ma) Lin et al. (2005)
  - **Iron-60** decays to nickel-60 (T = 1.5 Ma) Tachibana et al. (2006)
- What was their initial value in the solar system?

The initial value of beryllium-7

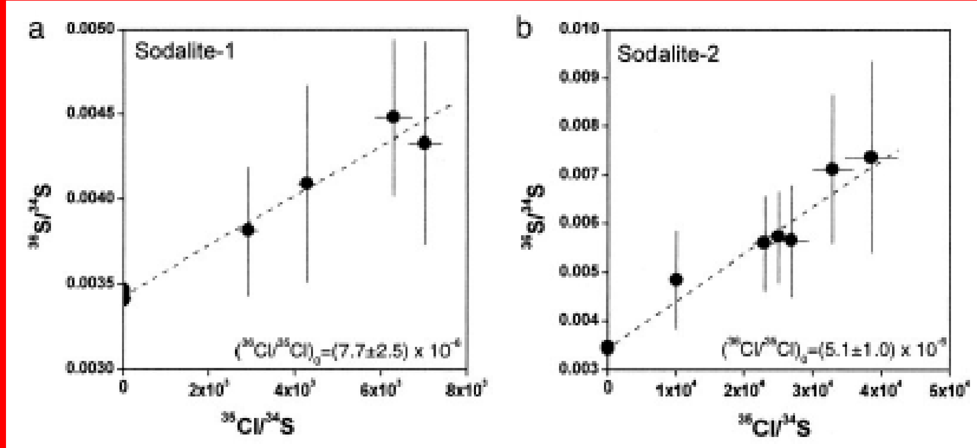
- ☆ The past presence of beryllium-7 ($T_{1/2}$= 53 days) has been demonstrated in CAI Allende 3529-41
- ☆ $^7Be/^9Be = (6.1 \pm 1.3) \times 10^{-3}$ in CAI Allende 3529-41
- ☆ So far demonstrated in *one* CAI only

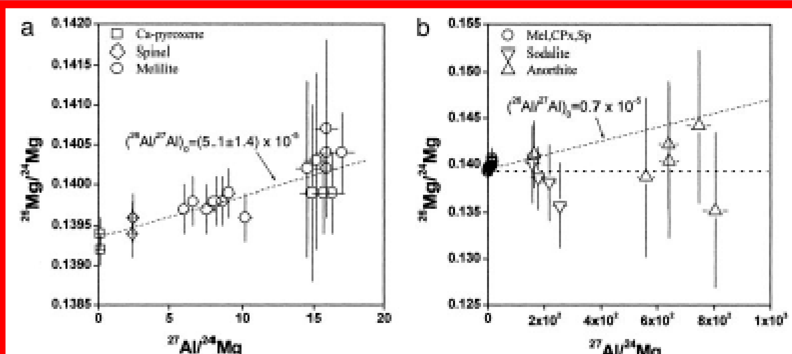
Chaussidon, Robert & McKeegan, GCA, 2006

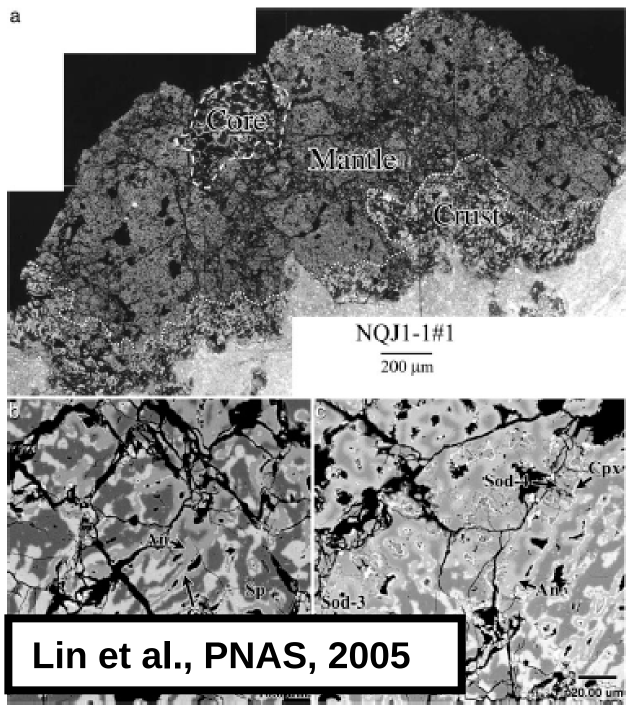


The initial value of chlorine-36

- **Past presence of chlorine-36 (<u>$T_{1/2}$ = 0.3 Ma</u>) was detected in sodalite from *one* Ningqiang CAI**
  - $^{36}Cl/^{35}Cl = 5 \times 10^{-6}$
- **Sodalite is a secondary phase made by hydrothermal alteration**
  - $^{26}Al/^{27}Al < 0.7 \times 10^{-5}$ for the altered phase and $^{26}Al/^{27}Al = (5.1 \pm 1.4) \times 10^{-5}$ for the unaltered CAI
- **Combining ^{26}Al and ^{36}Cl data on the same CAI, one infers the initial value of $^{36}Cl/^{35}Cl$**
  - **Using the exponential decay law**
  - **$^{36}Cl/^{35}Cl > 1.6 \times 10^{-4}$ in CAIs**





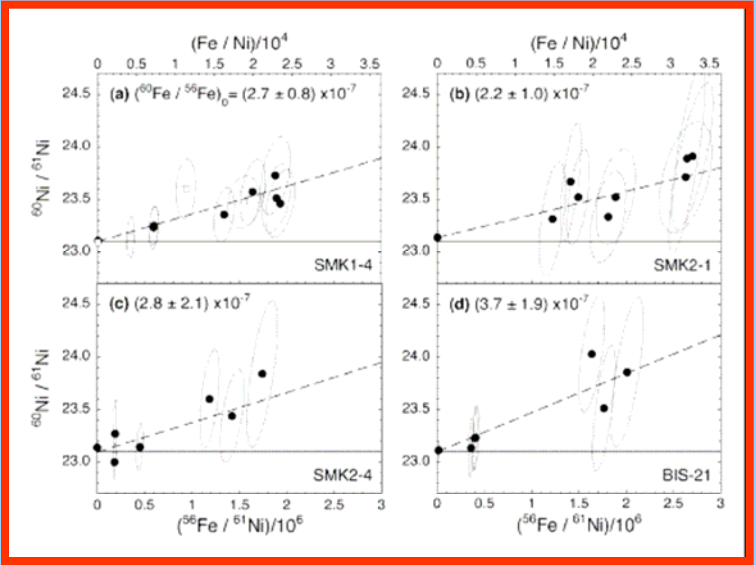


Lin et al., PNAS, 2005

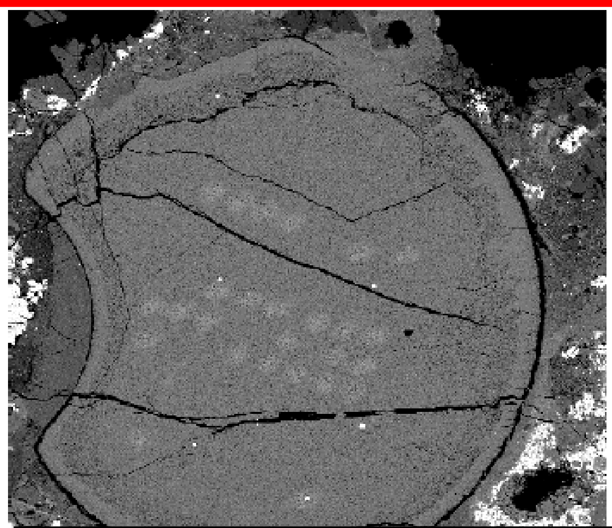
The initial value of iron-60

☆ The presence of ^{60}Fe <u>($T_{1/2}$ = 1.5 Ma)</u> has been demonstrated in several chondrules from unequilibrated ordinary chondrites

- $^{60}Fe/^{56}Fe = (2.5 \pm 0.8) \times 10^{-7}$ Semarkona 1-4
- $^{60}Fe/^{56}Fe = (1.9 \pm 1.3) \times 10^{-7}$ Semarkona 2-1
- $^{60}Fe/^{56}Fe = (3.4 \pm 2.1) \times 10^{-7}$ Semarkona 2-4
- $^{60}Fe/^{56}Fe = (5.1 \pm 2.5) \times 10^{-7}$ Bishunpur 21



- If CAIs formed 1-2 Ma after CAIs
  - **$^{60}Fe/^{56}Fe = 5\text{-}10 \times 10^{-7}$ in CAIs**



Tachibana et al. ApJ, 2006

☆Note that the initial abundance of iron-60 in CAIs is *inferred* from the chondrule value and the putative time difference between CAIs and chondrules

Inventory of short-lived radionuclides

Radioisotope (R)	T (Ma)	Isotope fils	Isotope stable (S)	R/S	Detection
^{7}Be	52 jours	^{7}Li	^{9}Be	6.1×10^{-3}	CAIs
^{41}Ca	0.1	^{41}K	^{40}Ca	1.5×10^{-8}	CAIs
^{36}Cl	0.3	^{36}S	^{35}Cl	$> 1.6 \times 10^{-4}$	CAIs
^{26}Al	0.74	^{26}Mg	^{27}Al	4.5×10^{-5}	CAIs, CHs, DIFF
^{10}Be	1.5	^{10}B	^{9}Be	$5\text{-}10 \times 10^{-4}$	CAIs
^{60}Fe	1.5	^{60}Ni	^{56}Fe	$5\text{-}10 \times 10^{-7}$	CHs, DIFF
^{53}Mn	3.7	^{53}Cr	^{55}Mn	$3\text{-}10 \times 10^{-5}$	CAIs, CHs, DIFF

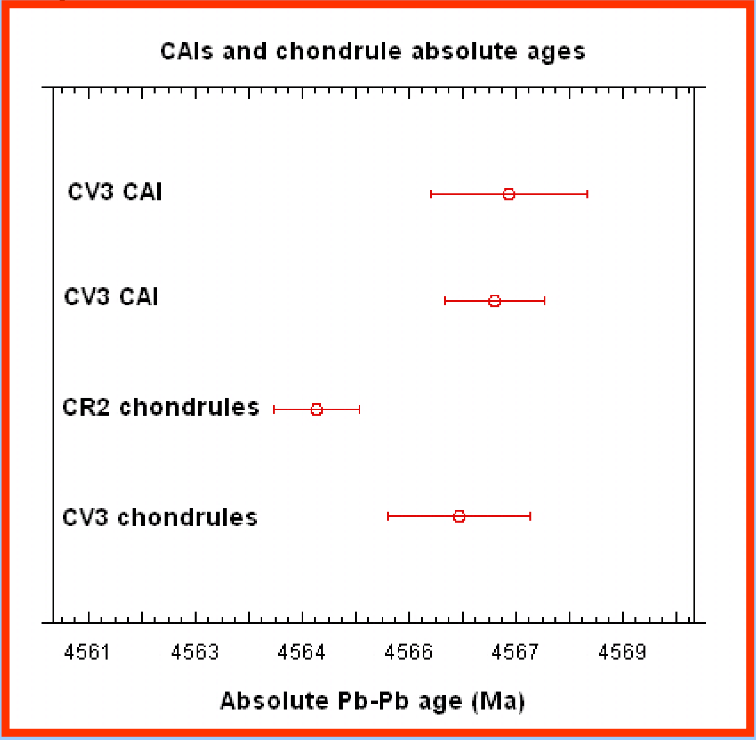
CAI = CAI, CH = chondrule, DIFF = differentiated meteorite

Note: Other "short"-lived radionuclides with T> 5 Ma exist such as Hf-182 (T = 9 Ma) but they do not request a last minute origin, and therefore are not discussed here

The initial value of radionuclides in question

- **Recent data question the fact that CAIs are the solar system oldest objects**
  - Some iron meteorites have ^{182}Hf-^{182}W ages older than those of CAIs (Kleine et al. *GCA* 2005)
  - Some achondrites have Pb-Pb ages comparable to that of CAIs (4566.2 ± 0.2 Ma vs 4567.2 ± 0.6 Ma) (Baker et al. 2005)
  - Some chondrules have absolute ages comparable to that of CAIs

Krot et al. Nature 2005 ; Amelin et al. Science 2002



☆Keep that in mind when models are discussed

The origin of short-lived radionuclides in Solar System

3. Stellar delivery of iron-60

Stellar production of radionuclides

- ☆ Iron-60 cannot be made by irradiation
  - ☆ No neutron-rich target to make this neutron-rich isotope

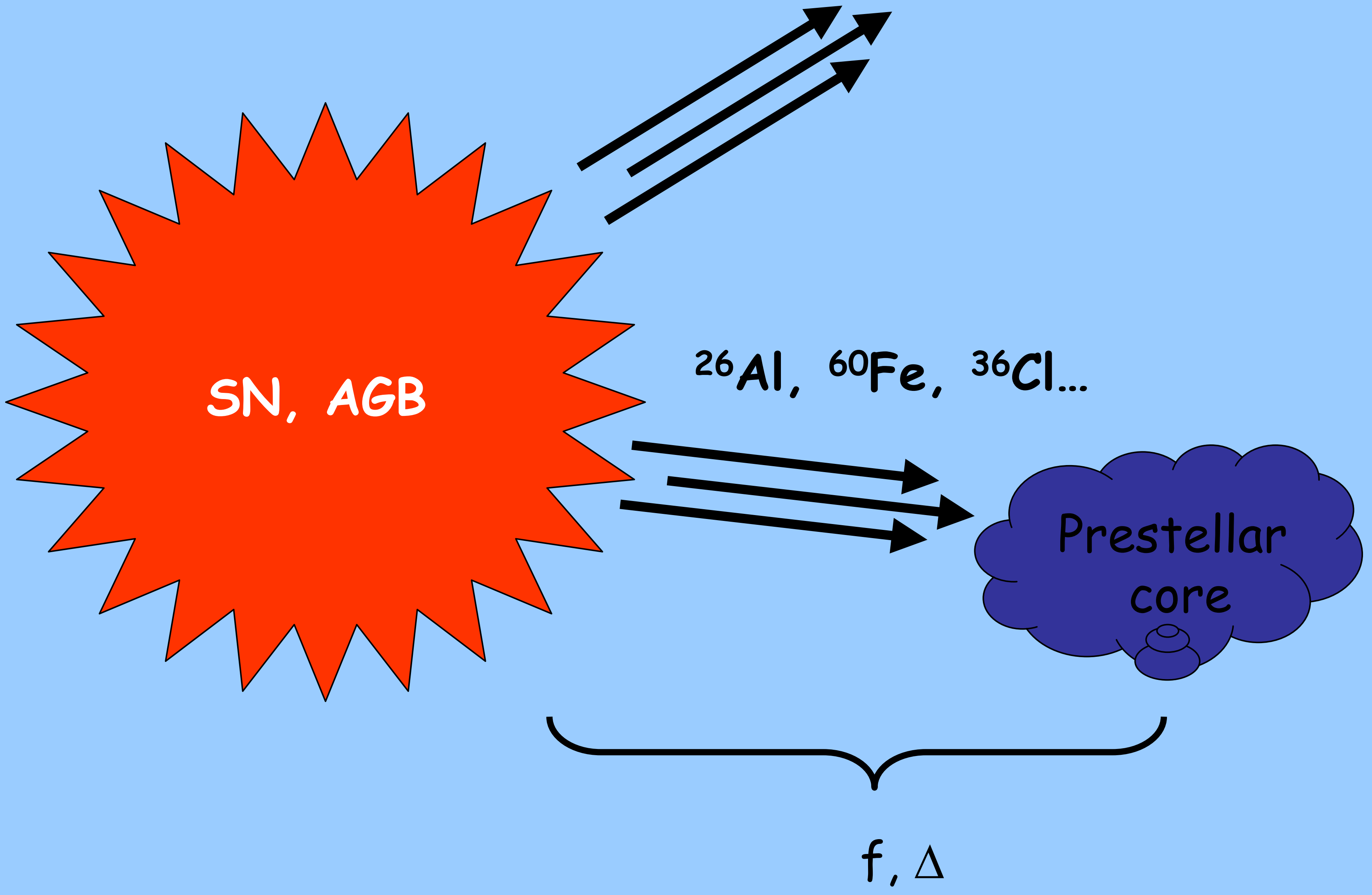
- ☆ Iron-60 has a stellar origin

- ☆ Candidates are AGB stars or supernovae

- ☆ <u>Questions</u>
  - ☆ **Did the star that delivered ^{60}Fe, co-delivered other short-lived radioactivities?**
  - ☆ How far was the star?
  - ☆ Physics of injection

- ☆ Stellar models for the origin of short-lived radionuclides are parametrized by the fraction (f) of the ejecta incorporated in the protosolar system and the delay (Δ) between the end of nucleosynthesis and the incorporation within the first solids. They also depend on stellar nucleosynthesis yields.

Delivery of radionuclides by a nearby star



AGB delivery of radionuclides

- <u>AGB stars</u> are a possible source for delivering short-lived radionuclides in the early Solar System (Wasserburg et al. 1994)

Table 2
Short-lived nuclei from a low mass star with cool bottom processes

Rad.	Ref.	$\frac{q_{S,w}}{q_0}$	$(N_R/N_S)_w$	$(N_R/N_S)_{\Delta_1}$
^{26}Al	^{27}Al	1.02	2.0×10^{-2}	5.0×10^{-5}
^{41}Ca	^{40}Ca	0.99	4.5×10^{-4}	1.4×10^{-8}
^{60}Fe	^{56}Fe	0.99	1.6×10^{-5}	5.7×10^{-8}
^{107}Pd	^{108}Pd	1.02	9.9×10^{-3}	4.6×10^{-5}
^{36}Cl	^{35}Cl	0.99	2.7×10^{-3}	2.4×10^{-6}
^{93}Zr	^{92}Zr	1.01	1.1×10^{-2}	4.0×10^{-5}
^{99}Tc	^{100}Ru	1.02	7.0×10^{-3}	3.2×10^{-6}
^{135}Cs	^{133}Cs	0.99	1.9×10^{-2}	9.1×10^{-5}
^{205}Pb	^{204}Pb	$\leqslant 1.07$	1.0×10^{-1}	$\leqslant 5.1\times10^{-4}$

$M = 1.5\ M_\odot$, $Z = 0.02$, $f_0 = 5.1\times10^{-3}$, $\Delta_1 = 0.76$ Myr.

Dilution factor f

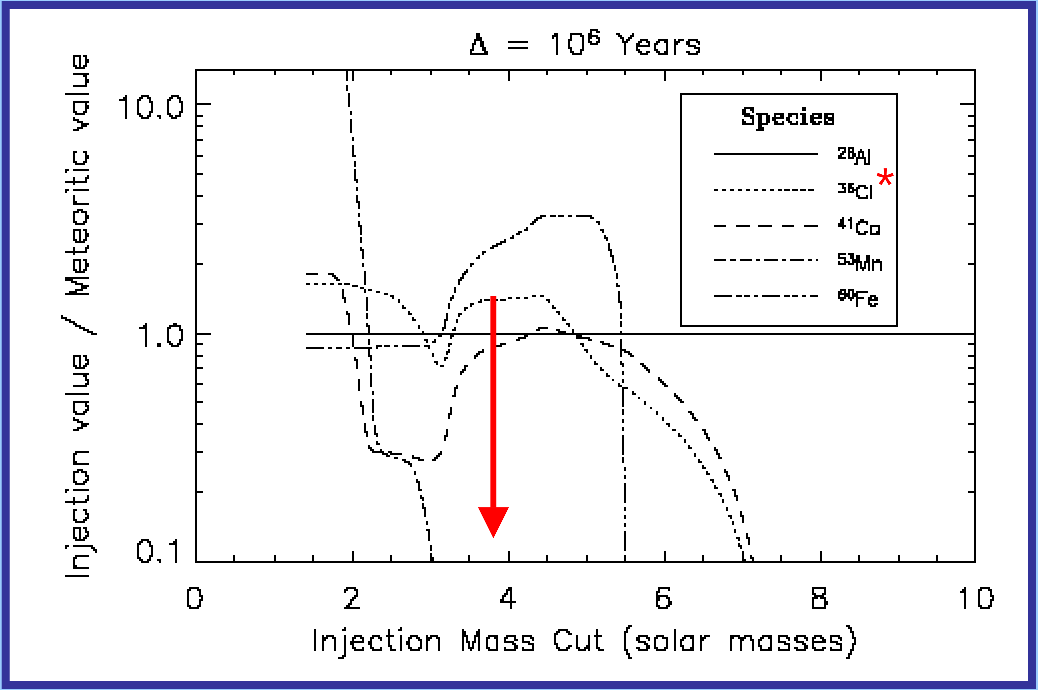
Decay interval Δ

Gallino et al., NAR, 2004

- <u>Choosing f_0 and Δ1</u> makes it possible to reproduce ^{26}Al and ^{41}Ca in the right amount
- ^{53}Mn is not produced by AGB stars
  - Possible origin via continuous galactic nucleosynthesis
- ^{60}Fe and ^{36}Cl underproduced by two orders of magnitude
  - A possible solution for ^{60}Fe is to increase metallicity (if $Z = Z_\odot/6$, ^{60}Fe/^{56}Fe ~ 3×10^{-7})
  - ^{36}Cl ?
- The encounter probability between an AGB star and a molecular cloud core is very low (Kastner and Myers 1994)

Supernova delivery of radionuclides

- Type II supernovae are more likely candidates



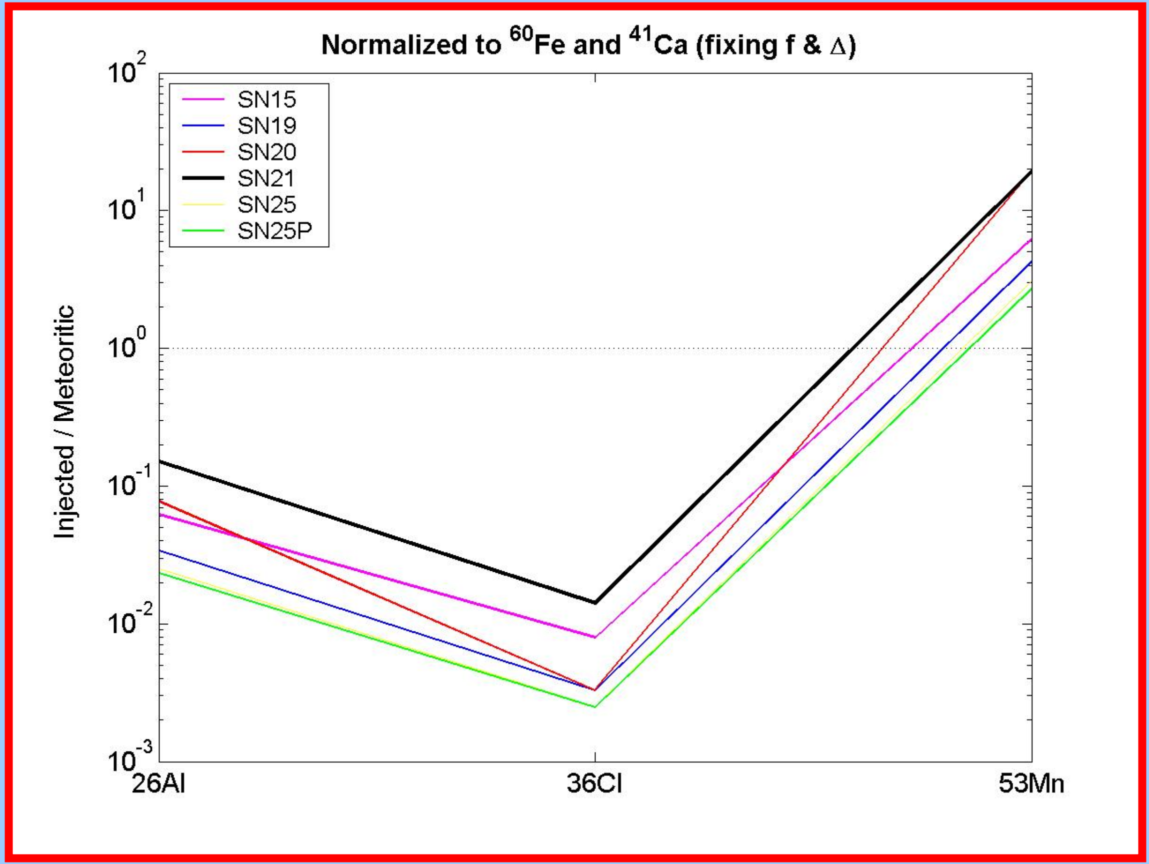
- 25 M_o star
- Clemson/Beyruth stellar evolution code
- Injection in a 1 Mo presolar nebula

Meyer (2005) *In* Chondrites and the protoplanetary disk, PASP, Krot, Scott, Reipurt Eds

* The meteoritical value is underestimated by ~40

- **For injection mass cut < 5.5 Mo**
  - ^{26}Al, ^{60}Fe, ^{41}Ca delivered at the solar system abundance
  - ^{36}Cl underproduced by a factor of at least 20
- **For injection mass cut > 6 Mo**
  - No delivery!

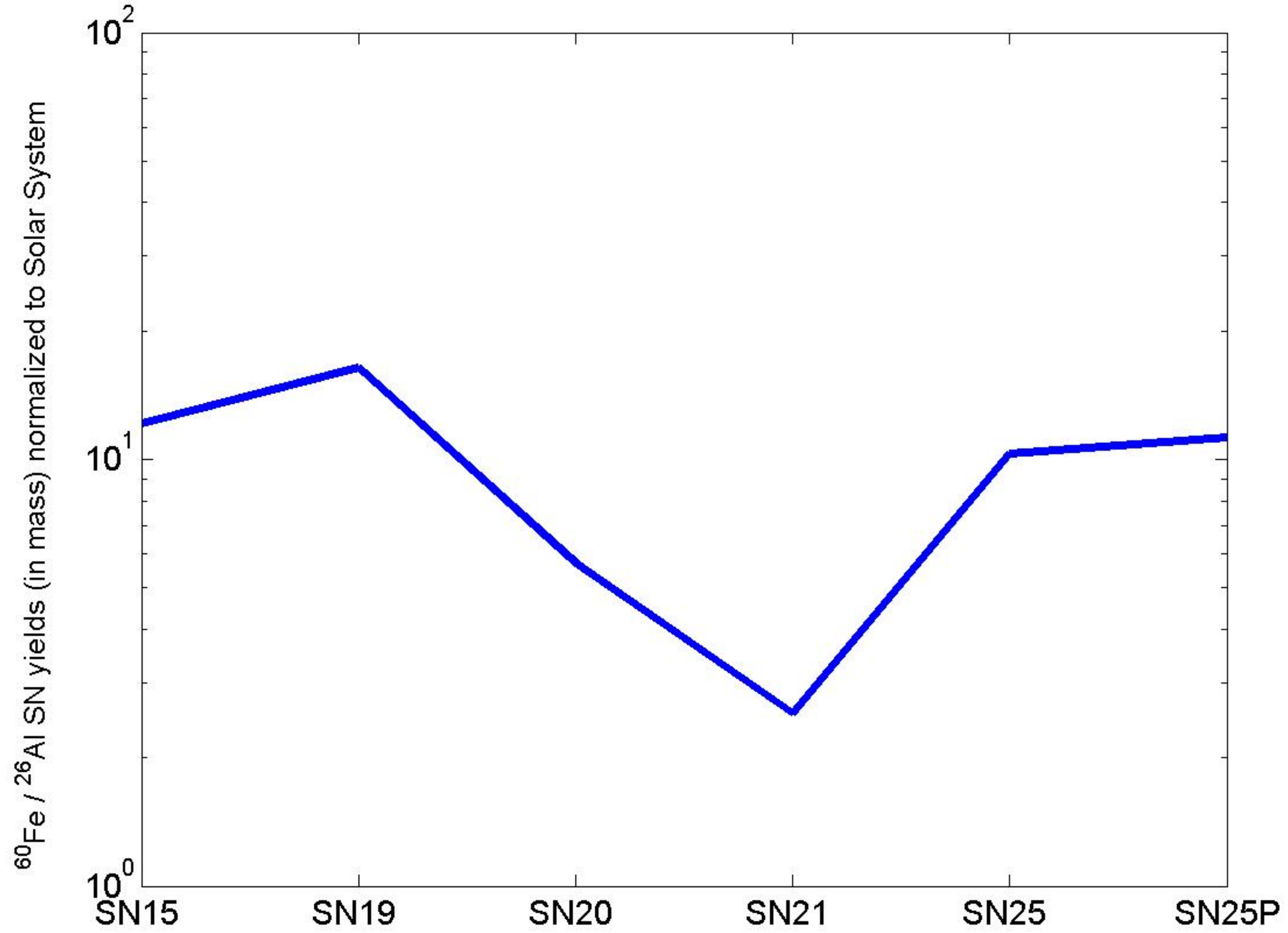
Supernova delivery of radionuclides



- ☆ Nucleosynthesis yields from Rauscher et al. ApJ 2002
- ☆ f varies between 0.8×10^{-5} to 5.5×10^{-5}. Δ varies between 0.57 and 1.37 Ma

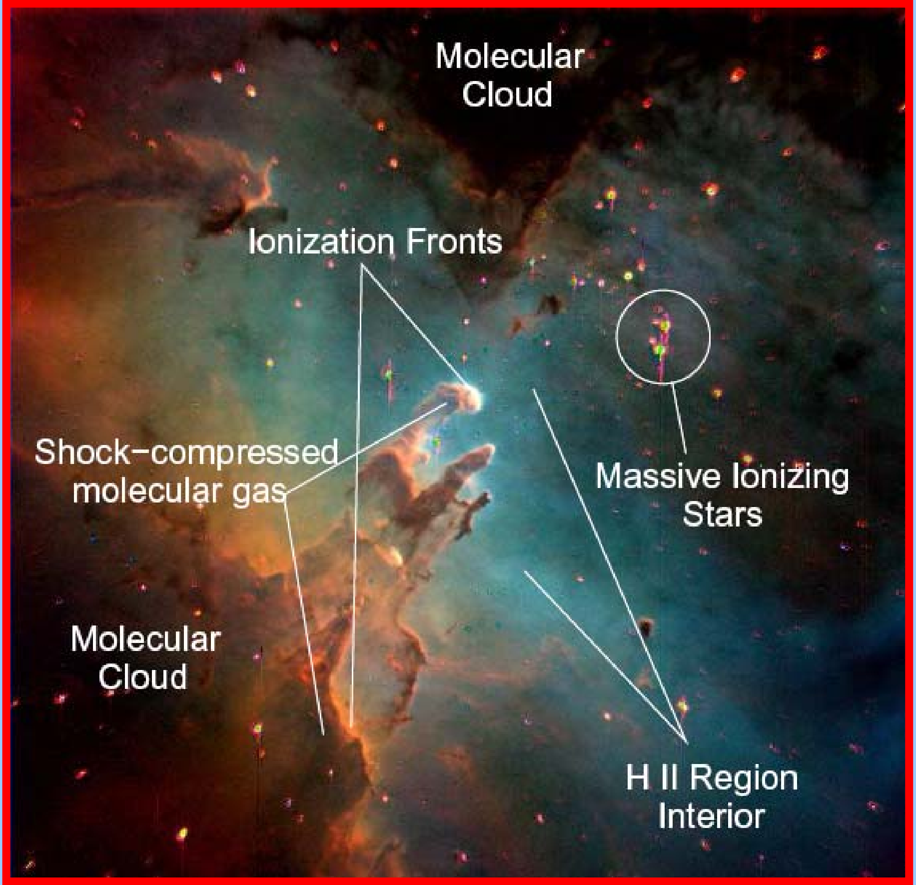
- ☆ ^{26}Al, ^{36}Cl underproduced, ^{53}Mn overproduced
- ☆ ***If a supernova delivered ^{60}Fe (and ^{41}Ca), unlikely it delivered ^{26}Al and ^{36}Cl***

Supernova delivery of radionuclides



An Orion-like environment for the formation of low-mass stars ?

- ☆ Most (?) low-mass stars form in the vicinity of massive stars (Orion vs Taurus)
- ☆ Not clear yet if our solar system did
  - ☆ Not have enough short-lived radionuclides that have a *certain* stellar origin
  - ☆ Difficult to estimate the distance of the supernova
  - ☆ Difficult to estimate the size of the molecular cloud core



Hester & Desch (2005) ***In*** **Chondrites and the protoplanetary disk, PASP, Krot, Scott, Reipurt Eds**

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4. Early solar system irradiation

Irradiation production of radionuclides

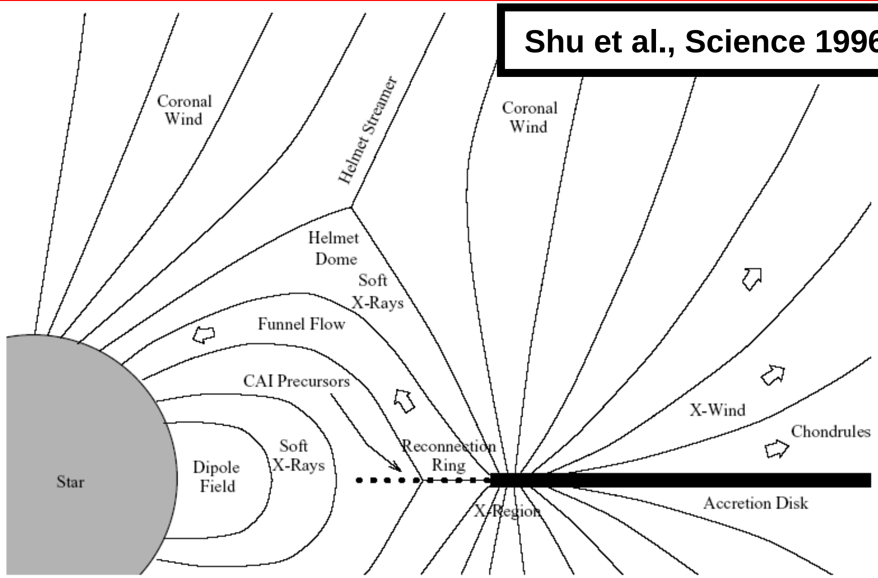
- Because of its short half-life (53 days), beryllium-7 has an irradiation origin
- Beryllium-10 also likely formed by irradiation (McKeegan et al. 2001; Gounelle et al. 2001 2006)
- Questions
  - Irradiation physics (nature, energy distribution, abundance… of accelerated particles)
  - Location of irradiation
  - Can irradiation coproduce other short-lived radionuclides?
- Irradiation models depend on the chemistry of target, the irradiation time, the nature of the cosmic-rays, nuclear cross sections…

Irradiation in the context of the x-wind

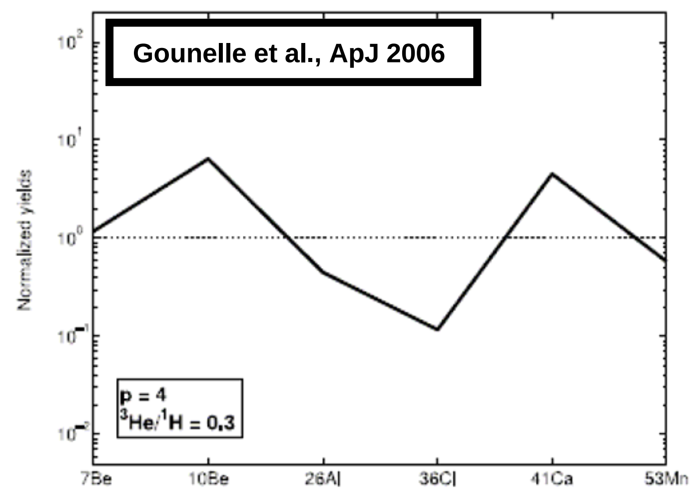
- Irradiation close to the Sun (~0.06 AU) of a solid target
  - Where baryons are accelerated and confined (reconnection ring)
- Transport of irradiated protoCAIs to asteroidal distances by the x-wind
- To produce beryllium-7 and beryllium-10
  - Short irradiation times needed (1-10 yr)
  - Elevated energetic particles fluxes ($F_p \sim 2 \times 10^{10}$ $cm^{-2}.s^{-1}$)
- Other short-lived radionuclides co-produced if **impulsive events (flares)** are considered (steep energy spectra and elevated abundances of helium-3)

Lee et al., ApJ 1998 ; Shu et al., ApJ 2001 ; Gounelle et al., ApJ 2001; Gounelle et al. ApJ 2006

Shu et al., Science 1996



Gounelle et al., ApJ 2006



X-ray observations of protostars

- COUP
  - Chandra Orion Ultradeep Project (PI: E. Feigelson)
  - X-ray [0.5-8 keV] observation of the Orion Nebular Cluster (ONC)
  - Detection of 1400 young stars during **13.2 days**
  - Specific study of **28 solar masses stars** (0.9 Mo < M < 1.2 Mo)
  - The unprecedented long observation time is ideal to study flaring

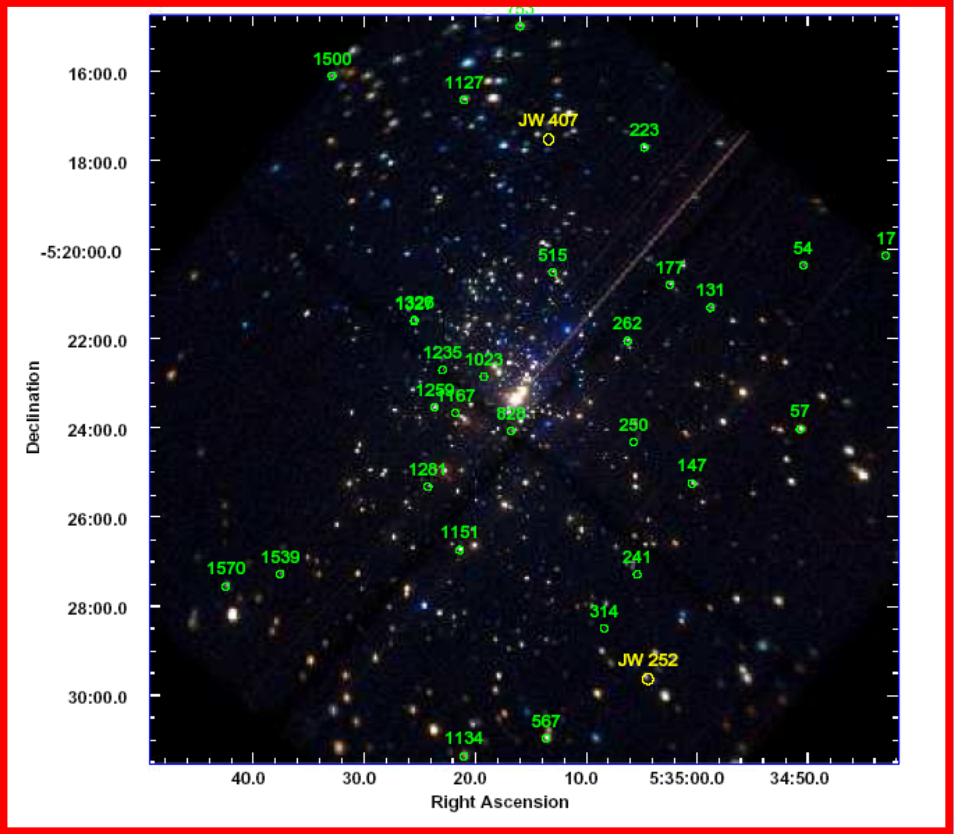
Table 1. Near-infrared and Optical Properties of Solar Mass Orion Nebula Cluster Stars

COUP	COUP J	JW[a]	offset(″) Optical	offset(″) 2MASS	V	I	J	H	K_s	L	Spec.Type	A_V
17	053443.0-052007	63	1.37	1.13	14.81	12.75	11.17	10.37	10.09	—	K6	1.58
54	053450.4-052020	113	0.03	0.43	16.43	14.20	11.96	11.03	10.44	—	K6	2.02
57	053450.7-052401	116	0.09	0.34	13.56	12.12	11.01	10.53	10.28	—	K5	0.33
131	053458.8-052117	187	0.29	0.19	17.12	14.27	11.98	10.95	10.24	—	K5	3.95
147	053500.4-052514	198	0.15	0.21	15.43	13.80	12.19	11.19	10.40	—	K6	0.48
177	053502.4-052046	223a	0.08	0.19	16.06	13.64	11.54	10.52	10.10	—	K5	2.85
223	053504.7-051742	253	0.32	0.23	17.35	14.22	11.53	10.10	9.34	—	K5	4.66
241	053505.4-052717	268	0.14	0.12	14.49	12.88	11.8	11.08	10.84	—	K5-K6	0.43
250	053505.7-052418	278	0.22	0.22	15.6	13.66	11.62	10.30	9.33	8.19	K2-K7	1.61
262	053506.2-052202	286	0.12	0.18	17.69	14.91	11.66	10.07	9.30	8.59	K5	3.77
314	053508.4-052829	320	0.18	0.24	17.1	14.73	13.27	11.78	10.82	—	K2	3.52
515	053513.0-052030	394	0.20	0.23	18.82	14.98	12.29	10.96	10.43	10.09	K6	6.15
567	053513.6-053057	421	0.07	0.26	12.94	11.48	10.18	9.26	8.62	—	K5[b]	0.38
753	053515.9-051459	487	0.16	0.21	14.57	12.79	11.63	10.77	10.32	—	K6	0.87
828	053516.7-052404	526b	0.35	0.16	13.77	11.87	10.01	9.18	8.89	8.84	K2-K6	1.17
1023	053519.2-052250	9250	0.64	0.19	17.03	14.23	11.98	10.86	10.36	9.88	K5	3.82
1127	053521.0-051637	664	0.14	0.23	16.93	14.05	12.08	11.03	10.64	—	K5.5-7	3.69
1134	053521.0-053121	673	0.17	0.30	14.9	13.07	11.57	10.62	10.03	—	K5	1.33
1151	053521.3-052644	683	0.10	0.21	13.61	11.76	10.48	9.64	9.40	—	K6	1.05
1167	053521.7-052339	694	0.29	0.23	17.73	14.74	12.54	11.42	10.80	9.83	K5-K7	3.97
1235	053522.9-052241	726	0.23	0.20	19.24	15.35	12.5	11.03	10.33	9.95	K5-K7	6.28
1259	053523.6-052331	738	0.15	0.18	15.7	13.84	11.97	10.92	10.45	10.09	K5	1.41
1281	053524.2-052518	750	0.28	0.03	14.85	12.87	11.53	10.54	9.94	9.25	K0-K5	1.72
1326	053525.4-052134	777	0.64	0.02	18.46	15.15	12.72	11.40	10.58	—	K6	4.79
1327	053525.4-052135	777	0.59	0.02	18.46	15.15	12	10.90	10.53	9.86	K6	4.79
1500	053532.9-051605	892	0.18	0.30	16.21	13.99	11.62	10.49	10.06	—	lateK	2.00
1539	053537.5-052716	930	0.03	0.06	16.64	14.08	12.71	11.94	11.71	—	K5-K7	2.87
1570	053542.4-052733	962	0.08	0.05	15.23	13.26	11.39	10.57	10.12	—	K6	1.35

[a] Jones, B. F. & Walker, M. F. 1988, AJ, 95, 1755

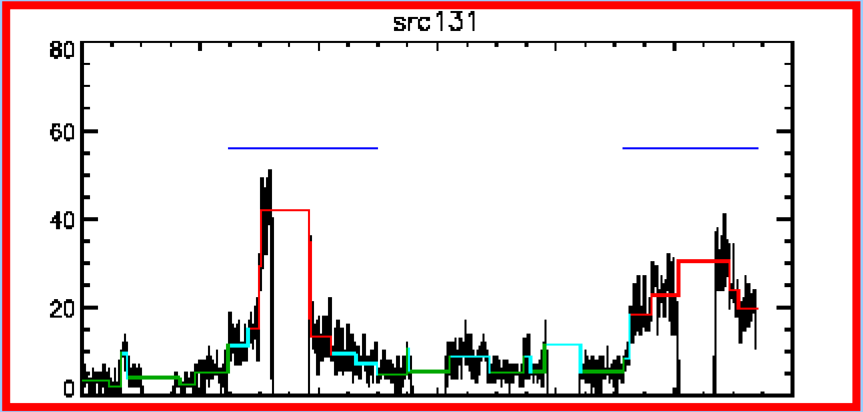
[b] Hillenbrand (1997) list this as a K5 (as measured by Hillenbrand) with a previous spectral type of F8-G0III-IV with an unknown reference

Wolk et al., ApJS, 2005



X-ray observations of protostars

- <u>COUP Results: General</u>
  - The solar mass stars have a *non constant* X-ray activity at a confidence of 99 %
  - Blocks of observations are classified as
    - Characteristic [green]
    - Elevated [cyan] and very elevated [red]
    - Flares [fast rise and exponential decay, blue]

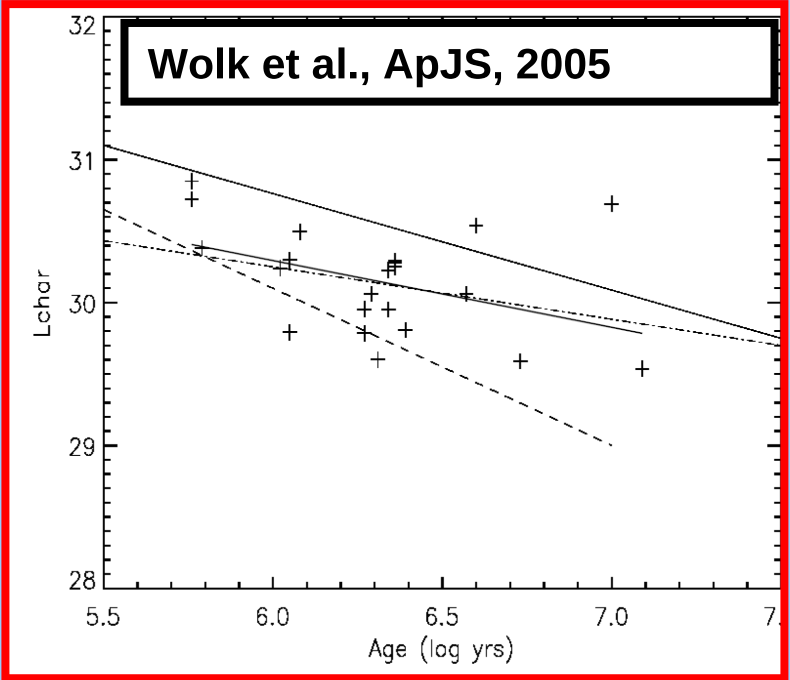


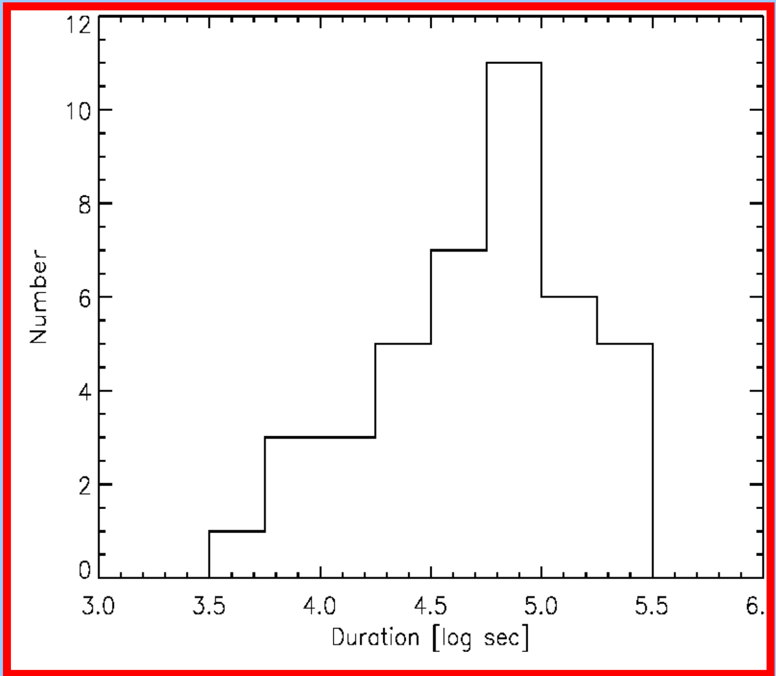
Wolk et al., ApJS, 2005

- <u>COUP Results: characteristic activity</u>
  - Sources spend 75 % of their time at the characteristic level
  - The characteristic activity of all low-mass young stars is extremly high
    - $\langle L_X \rangle = 1.8 \times 10^{30}$ erg.s^{-1} (SUN: $\langle L_X \rangle = 2 \times 10^{25}$ erg.s^{-1})
  - There is no apparent correlation with age
  - **The characteristic level could be the result of micro/nanoflaring**

X-ray observations of protostars

- COUP Results: Flaring
  - 41 flares were detected at 95 % confidence
  - Flare duration is vast: 1 hour to three days
    - $\langle L_X \rangle = 6.5 \times 10^{30}$ erg.s^{-1}
  - 90 % of flares rise to less than 10 times the characteristic level
  - COUP 1259 has $L_X = 4.0 \times 10^{32}$ erg.s^{-1} [most powerful flare]
  - One flare every 4 days
  - No dependence of flares on the presence of dusty disks or accretion





X-ray interactions with protoplanetary disks

- Ionization, shock-wave generation etc (Glassgold et al. 2005)

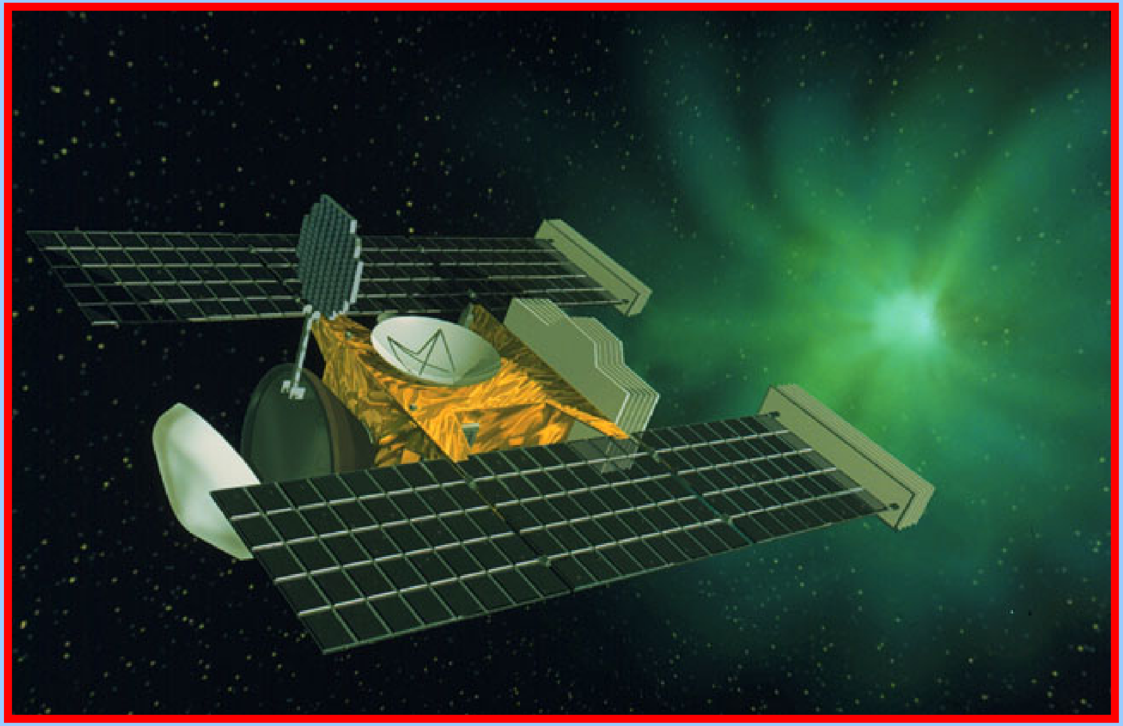
- Particle acceleration is associated with X-ray emission
  - Directly observed for the SUN [L_p (E>10 MeV) ~ 0.09 L_X]
  - Detection of radiosynchrotron radiation from MeV electrons accelerated by magnetic flares in YSOs

- Comparison with the x-wind irradiation model
  - The average characteristic value is within a factor of 3 of that adopted by Lee etal. (1998) and Gounelle et al. (2001) using very preliminary data (ROSAT & ASCA)
  - Fluence calculated by Wolk et al. (2005) similar to that estimated by Lee et al. (1998)
  - The impulsive phase is often present (Wolk et al. 2005)
    - Difficult to quantify at present
  - Stars considered by COUP are 2 Ma old stars (revealed TTauri/class 3)
    - Stars considered in the context of the x-wind model are protostars (class 0) and embedded TTauris (class 1)

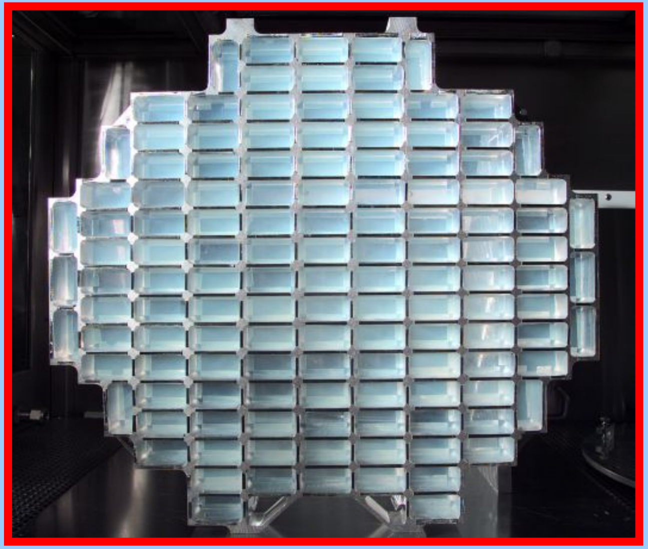
Laboratory studies of extraterrestrial matter: A view on the *solar* accretion disk

5. A Stardust *détour*

NASA Stardust Mission



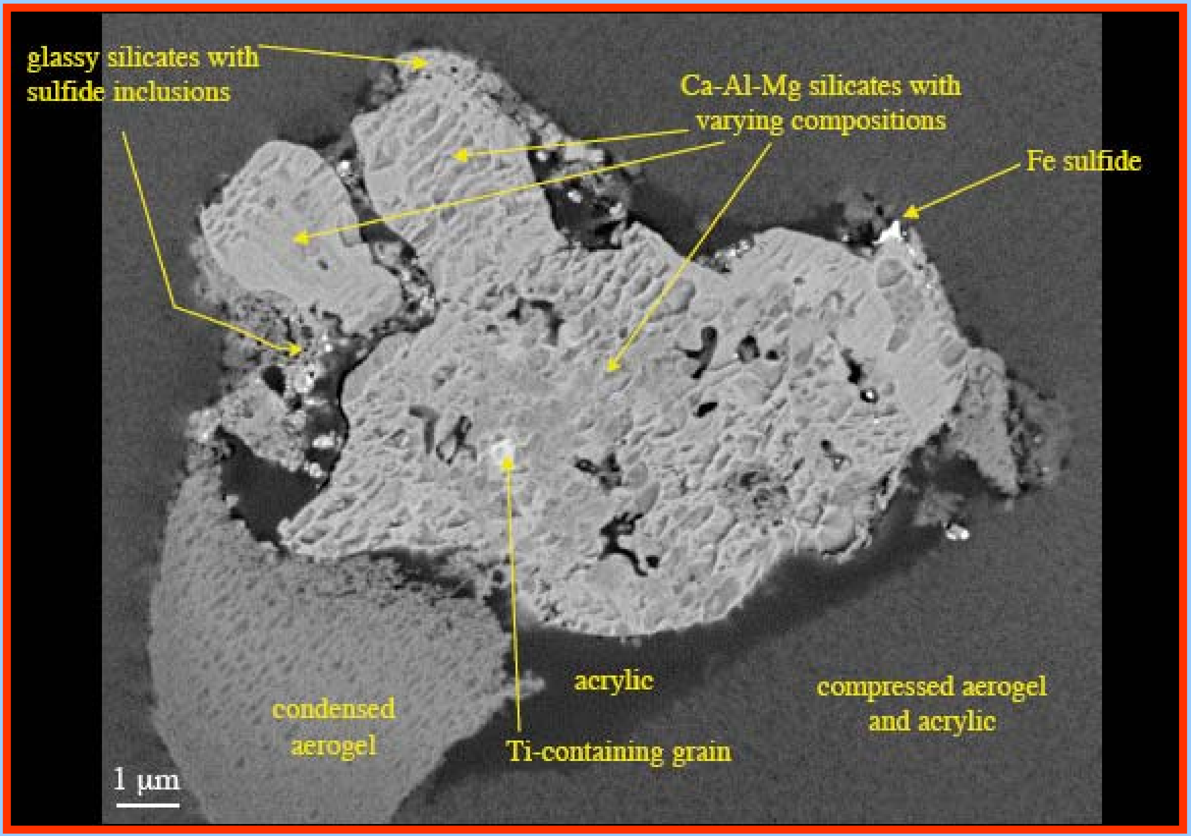
- ☆ Encounter with comet Wild 2: January 2nd 2004
- ☆ Jupiter Family Comet
- ☆ Capture of cometary dust in aerogel
- ☆ Back to Earth (Utah desert): 2006 January 15th



☆Samples from *one* comet!

☆As asteroids differ one from the other, so probably do comets

NASA Stardust Mission



☆ CAIs found among Stardust samples

☆ Unexpected for most cometary scientists

☆ Prediction of the x-wind model

Toward an Astrophysical Theory of Chondrites

Frank H. Shu,* Hsien Shang, Typhoon Lee

at all distances from the sun. Thus, comets should also contain CAIs and chondrules.

SCIENCE • VOL. 271 • 15 MARCH 1996

☆**Since CAIs likely formed close to the Sun, this finding demonstrates extensive mixing in the protoplanetary disk**

- ☆Via the x-wind
- ☆Via turbulence

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

Laboratory studies of extraterrestrial matter: A view on the *solar* accretion disk

6. Conclusions

Conclusions

- ☆ **Meteorites' components record processes in the protoplanetary disk**

- ☆ **Short-lived radionuclides are a key tool for**
  - ☆ Constraining the astrophysical environment of our solar system birth
  - ☆ Constraining the irradiation conditions of the protoplanetary disk
  - ☆ Building a chronology of the disk history

- ☆ **Note that the initial value of short-lived radionuclides is not that well known**

- ☆ **Recent measurements of short-lived radionuclides have revealed that**
  - ☆ The sun formed "close" to a supernova
  - ☆ If iron-60 delivered by a supernova, unlikely other radionuclides were (my view)
  - ☆ Irradiation took place at high fluxes

- ☆ **If aluminium-26 has an irradiation origin, a *chronology* based on an heterogeneous distribution of ^{26}Al is needed** (Gounelle & Russell 2005a,b)

- ☆ **Stardust samples reveal intense processing of interstellar matter and active mixing between the inner and the outer solar system**

- ☆ **Comparison with astronomical observations and astrophysical model is key in interpreting meteorites'data**