Irradiation and thermal processing of silicates in the laboratory: Insights in extraterrestrial grains properties

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Outline of the talk

- Context and motivations of the study
  - Dust life-cycle
- Methodology
  - Ionic irradiations
  - Thermal annealing: Experimental protocol
- Some results
- Astrophysical implications
- Summary

Context and motivations

Dust: Responsible of starlight extinction in the lines sight towards distant stars.

Why study dust?

Dust ~ 1% of the total mass in protoplanetary discs.

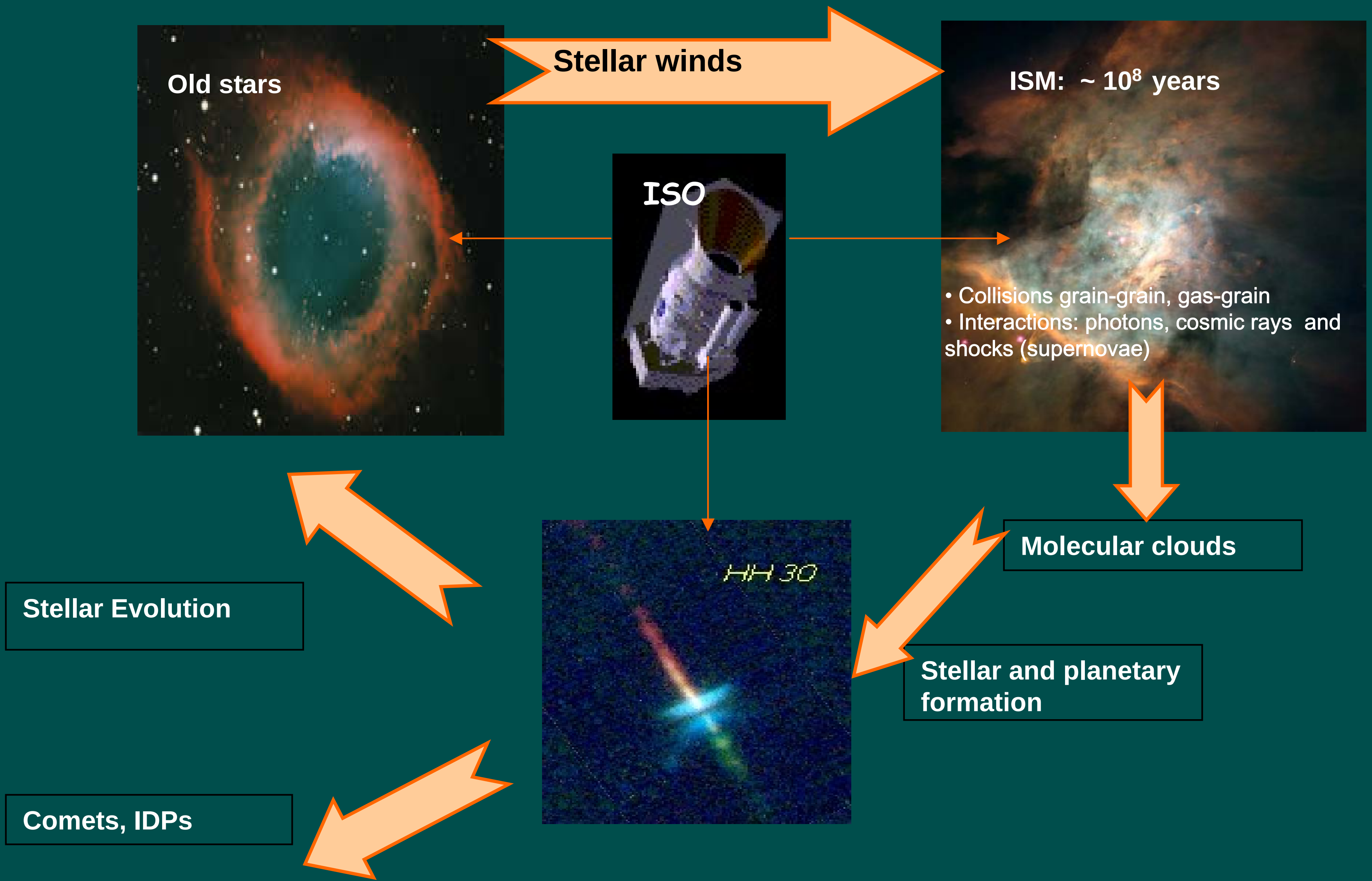
- **Represents the building blocks of planets.**
- **Probes the physical conditions in the different environments**

How is dust observed ?

Only by spectroscopy: UV, Visible, UV.

- **UV: chemical composition (Carbon)**
- **Visible: size (modelisation of the extinction curves)**
- **IR: vibrational: chemical and structural composition (crystal/amorphous)**
- **far IR: lattice vibrations**

Dust life cycle



Silicate dust

- Definitions of Silicate:

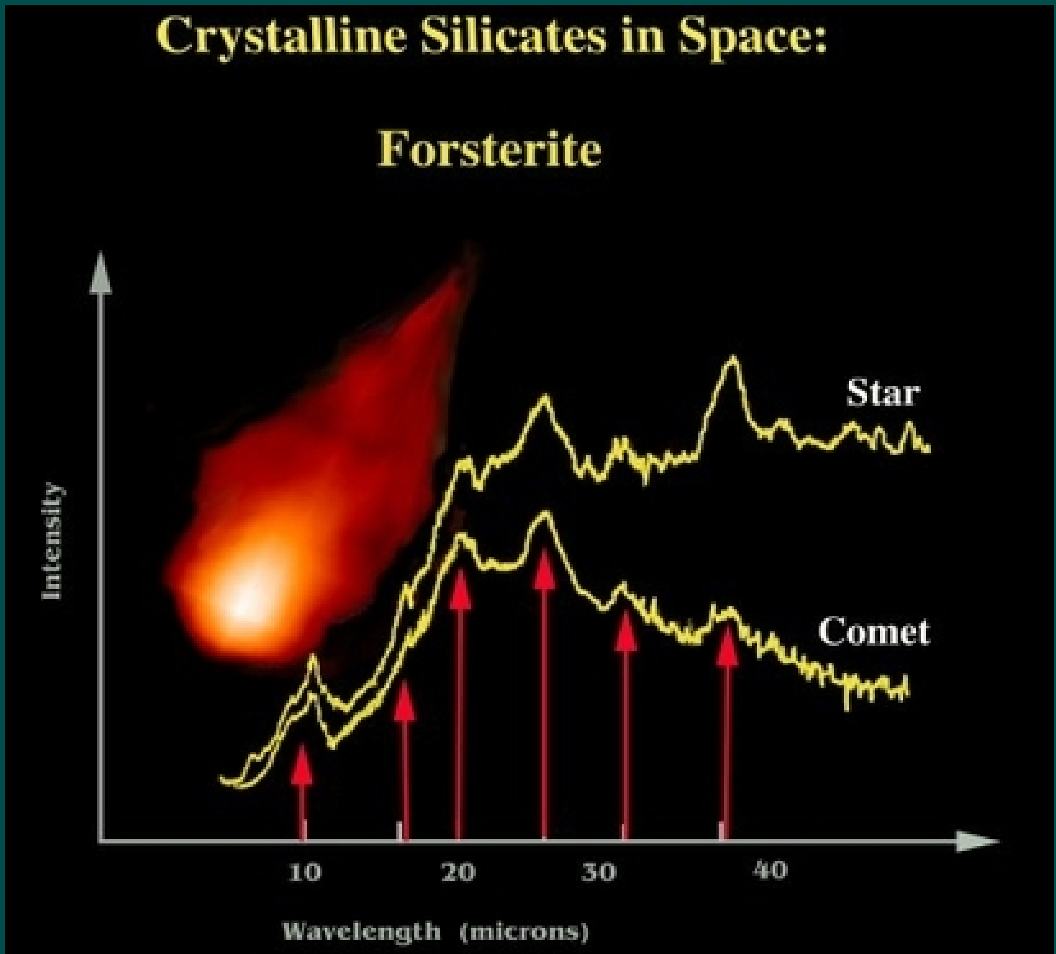
  - mineralogical = solid with base unit of Si-O bonds
  - astronomical = presence of Si-O bonds (~ 10 and 20 μm).

- Dominant forms of Silicates:

  - Olivine: $Mg_{2x}Fe_{2-2x}SiO_4$
  - Forsterite: Mg_2SiO_4
  - Pyroxene: $Mg_xFe_{1-x}SiO_3$
  - Enstatite: $MgSiO_3$

Some ISO spectra…. The crystalline revolution

Until 90's dust was always thought to be amorphous in space.
But..



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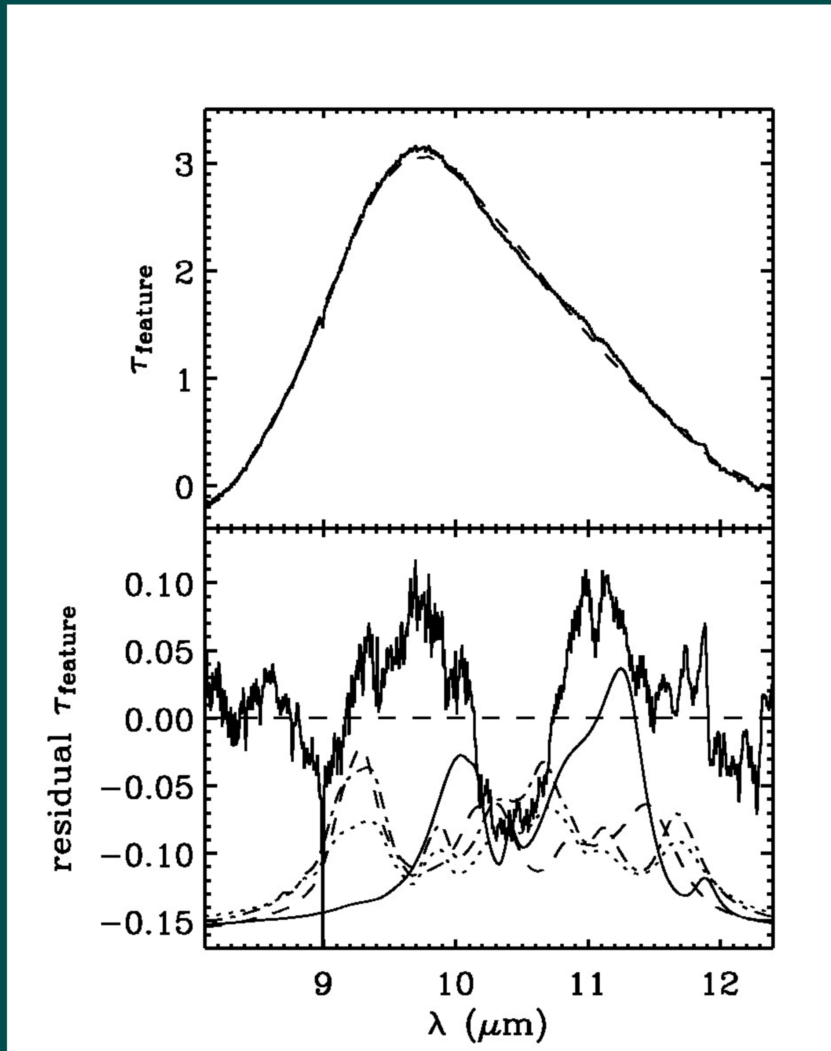


In the ISM: Kemper et al, 2004.

Nature and degree of crystallinity of silicates

	Silicate type	Structure
Old stars	Olivine Pyroxene	Amorphous ~ 15 %
Diffuse ISM	85% Olivine + 15% Pyroxene	< 0.4 %
Proto-stars	Pyroxene	Amorphous
proto planetary disks	Pyroxene type	20-25 %

Subsequent questions…..

- Why are there no crystalline silicates in the ISM?
- Since the silicates are amorphous in the ISM, how do we explain the presence of crystalline silicates in the young stars? comets? IDPs?
- How do we explain the chemical modifications of silicates in different environments.
- Is it possible to reproduce some of the microstructure of the IDPs in the laboratory.

Methodology@IAS

From astronomical observations and analyses of IDPs in the lab

↓

Laboratory experiments

- Synthesis of analogs
- Irradiations (IS), Thermal annealings (CS)
- Characterization

↓

Comparison lab results/observations

IR ⇒ Direct comparison with astronomical data and with IDPs (natural dust analyzed by IR microspectroscopy)
+ TEM, AFM ⇒ microstructure, chemical analyses.

I/ Ionic irradiations

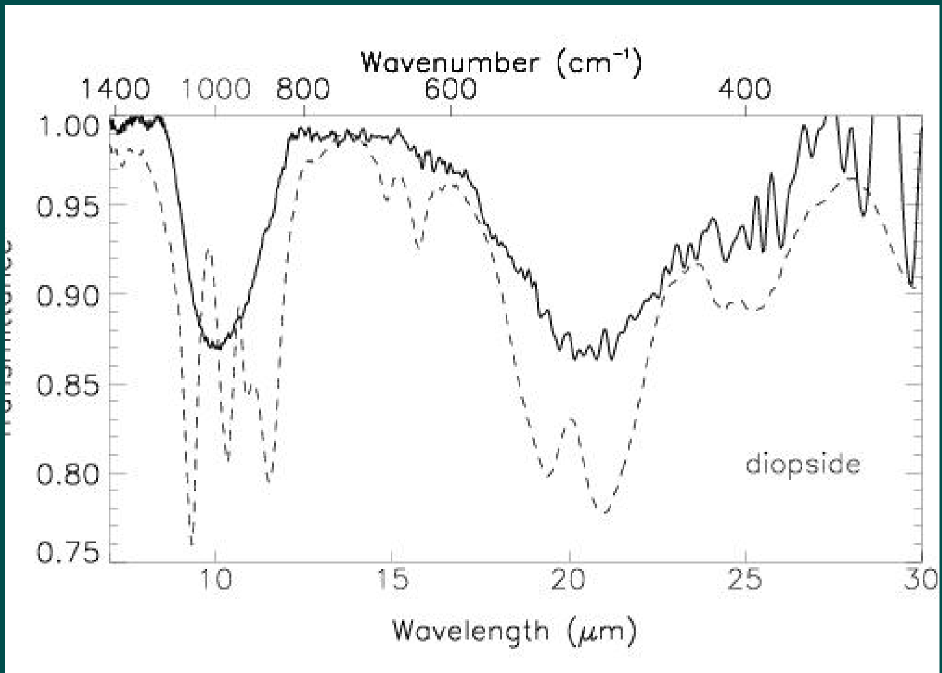
Experimental conditions

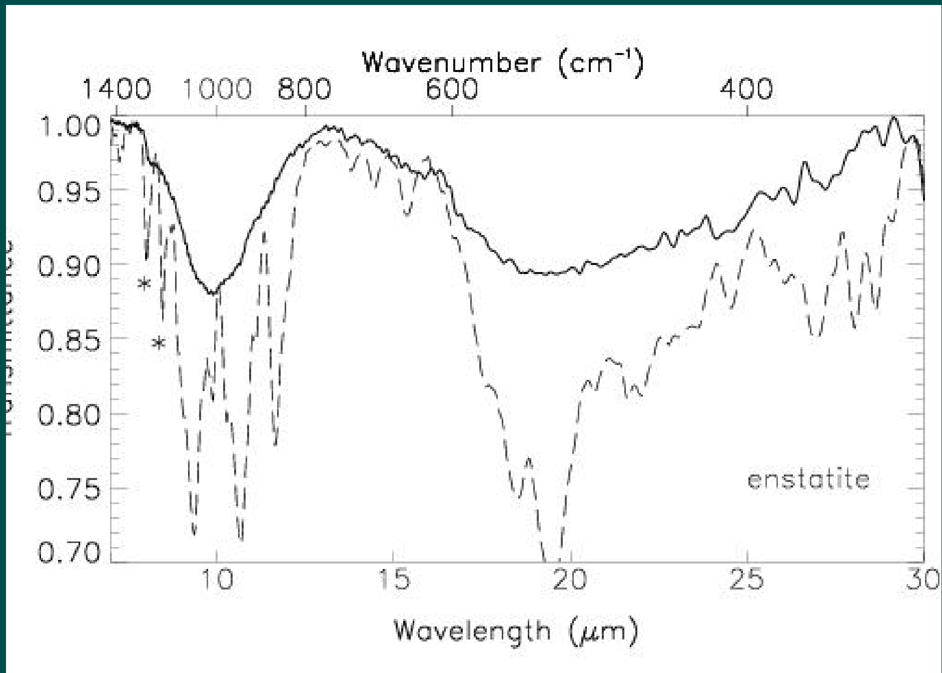
- **Silicates:** Olivine: Forsterite $MgSiO_4$
  Pyroxene: Enstatite (Mg,Fe,SiO_3), Diopside ($CaMgSi_2O_6$)
- TEM sections , powder embedded in CsI.
- Irradiations: He^+ et H^+ at energies few keV and fluences ~ 10^{16} -10^{18} ions/cm^2
- IR spectroscopy and TEM analyses

I-a/ Ionic irradiations: IR spectra

Enstatite, diopside

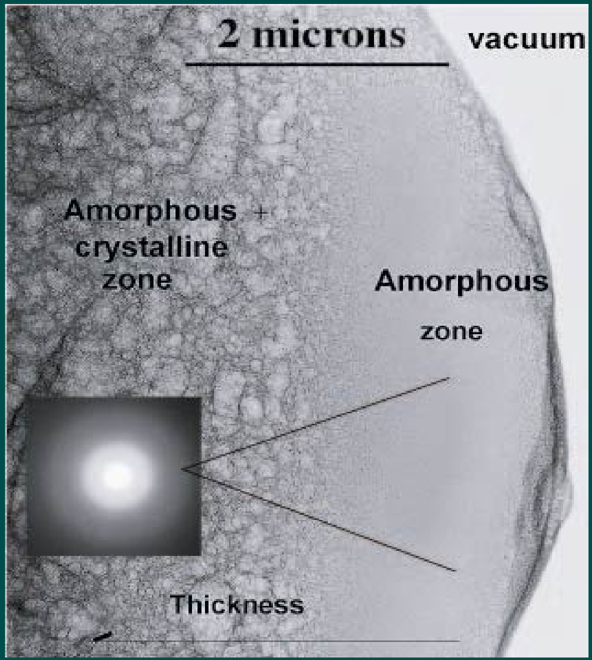
IR spectra obtained before (- - -) and after (—) irradiations

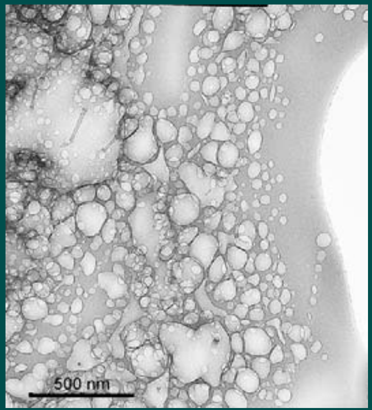




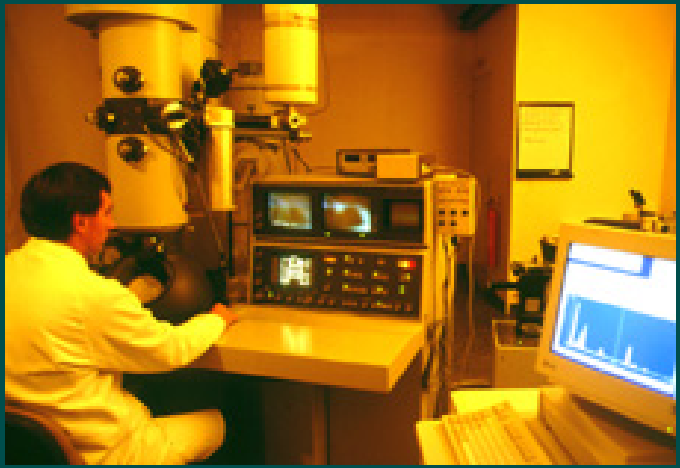
Demyk et al. A&A 2004

I-b/ Ionic irradiations: TEM results





TEM view of an olivine sample irradiated with He^+ ions at 10 keV and a fluence of 10^{18} ions/cm^2



TEM: Lille

Microstructural & chemical study

- Amorphisation
- Composition modification
  (loss of Mg & O)
- **Induced** porosity (bubbles)

K. Demyk (IAS:2000), Ph. Carrez (Lille: 2002)

Summary of principal results of irradiation:

Olivine: Demyk et al. 2001, Carrez et al. 2002: Irradiations He+, 4-10 keV

Pyroxene: Demyk et al. 2004: Irradiations H+ (10 keV) et He+ **(20-50 keV)**

Irradiation in ISM: Amorphisation + chemical modifications.

So......

How do we explain the presence of the crystalline silicates in comets, in DPs, in protoplanetary discs. In quite cold environments in general?

Hypothesis:
Irradiation = ionic implantation $\Rightarrow$
Modification of the thermodynamical properties of the sample

Experiments for the determination of the re-crystallization activation energy of pre-irradiated samples

II/ Thermal annealing: Experimental protocol

Crystalline forsterite (San Carlos olivine)

↓ *Evaporation (in vacuum)*

Thin film (~ 100 nm) of amorphous silicate on diamond

↓ *Annealing (~1000°C, 30 min.)*

Crystalline silicate: (as observed around old stars)

ISM ↓ *Irradiation (He^+, some keV)*

Amorphous silicate

Proto stars, comets ↓ *Step heating*

Recrystallized silicate

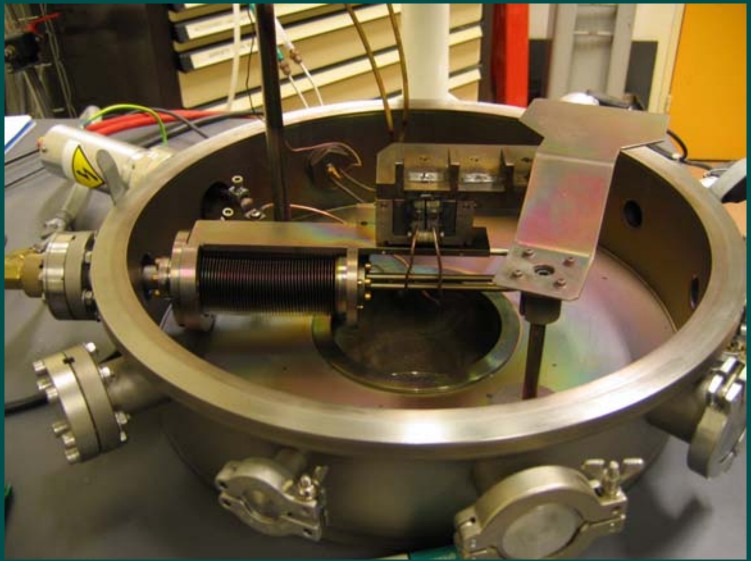
⇓

Re-crystallization activation energy

All the steps are monitored by IR spectroscopy

Analog synthesis

$Mg_{1.8}Fe_{0.2}SiO_4$



Advantages:

- Thin film ~ 100 nm on a diamond disc ~ 3 mm diameter ⇒ High surface-to-volume ratio.

- Diamond: resists to high temperatures and transparent to IR in the silicate regions.

Disadvantage

- impossible to couple IR measurements with TEM analyses.

Solution:

- remove the film from the diamond to a suitable substrat for TEM.

Annealing set-up

In a tubular furnace under vacuum (~ 10^{-7} mbar)

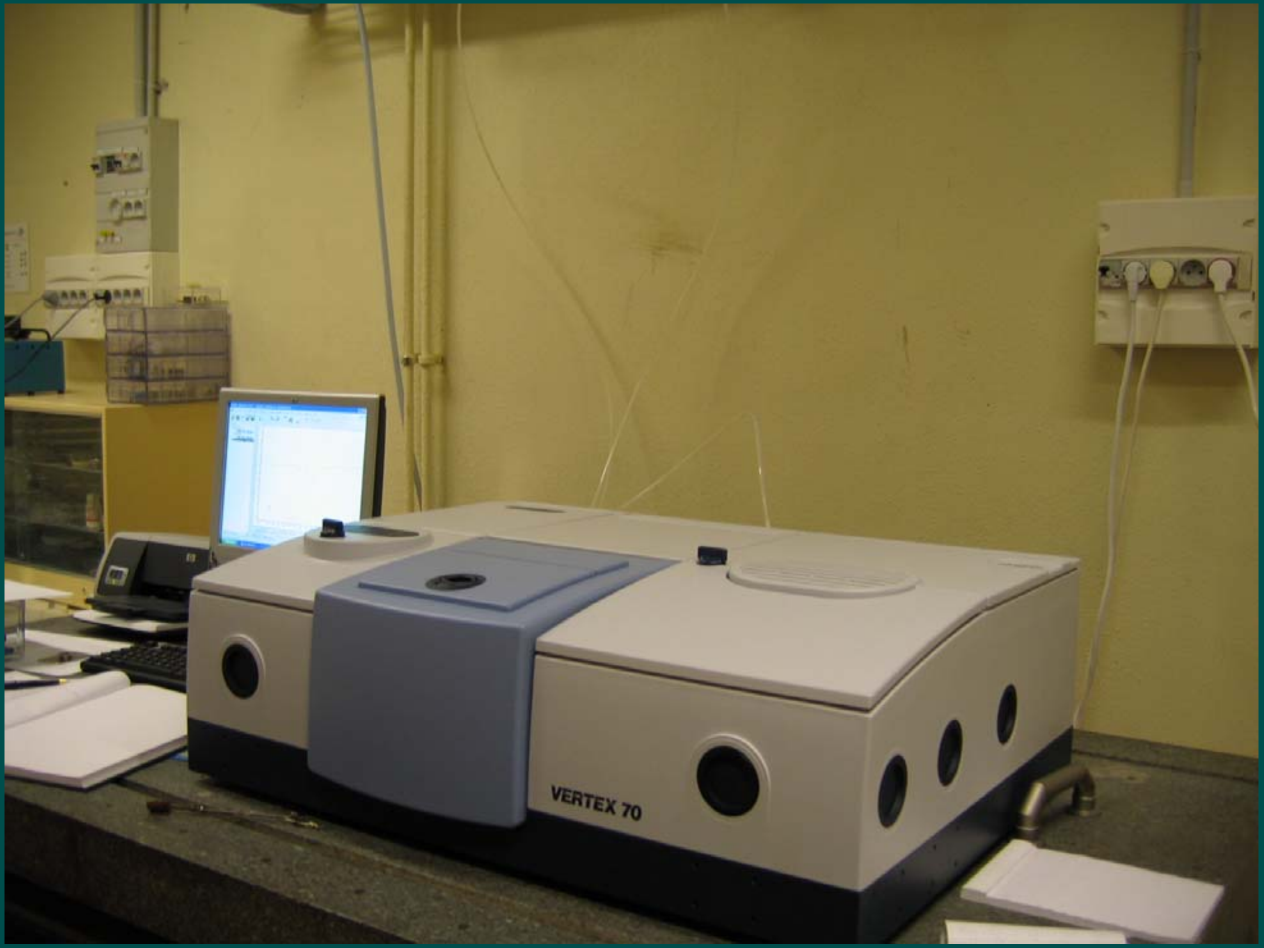
Aim: Simulation of the interstellar amorphous silicates incorporation in the protoplanetary disks.

IR spectroscopy

IR spectroscopy by transmission

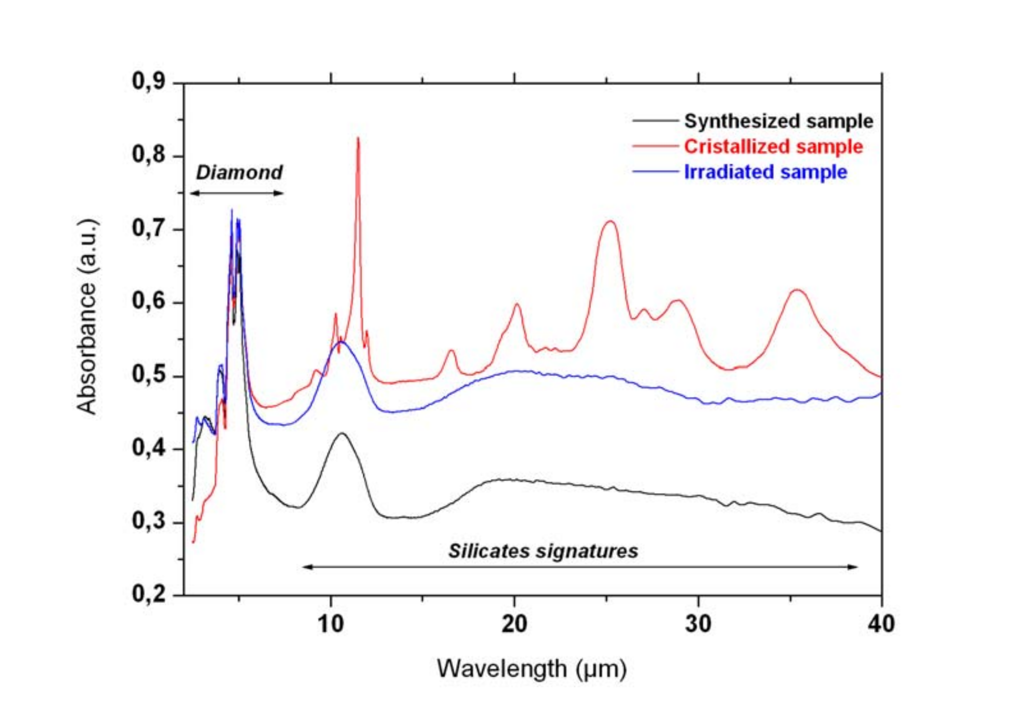
[7000, 400] cm^{-1}

1.5-25 µm

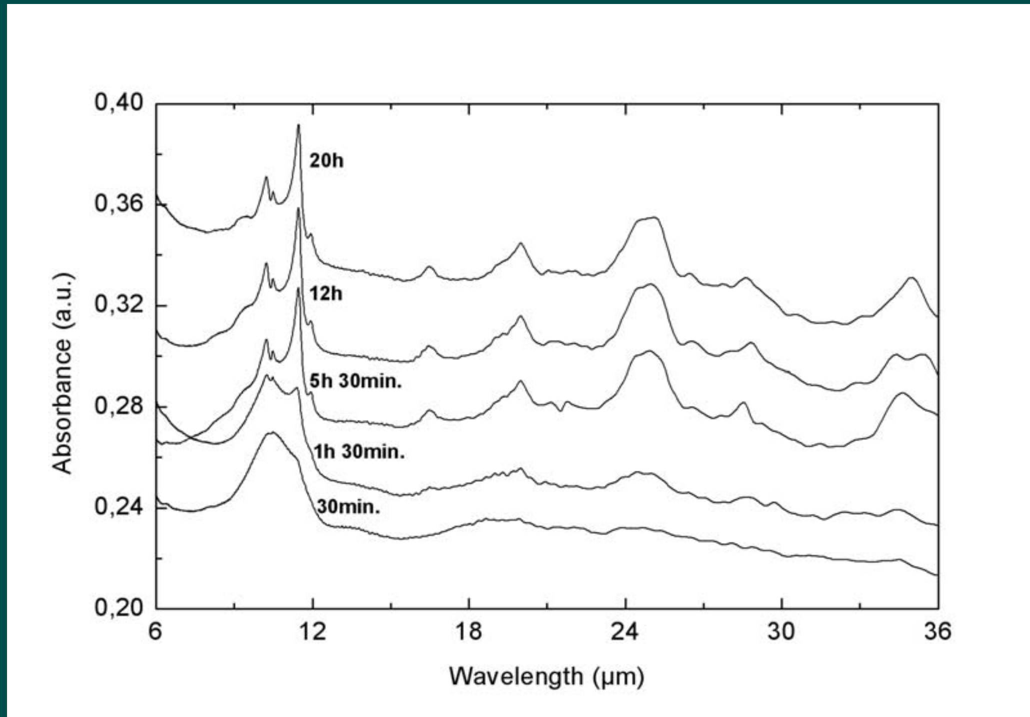


II-a/ Thermal annealing: IR spectra

Typical IR spectra



Bands evolution with annealing time: 750°C



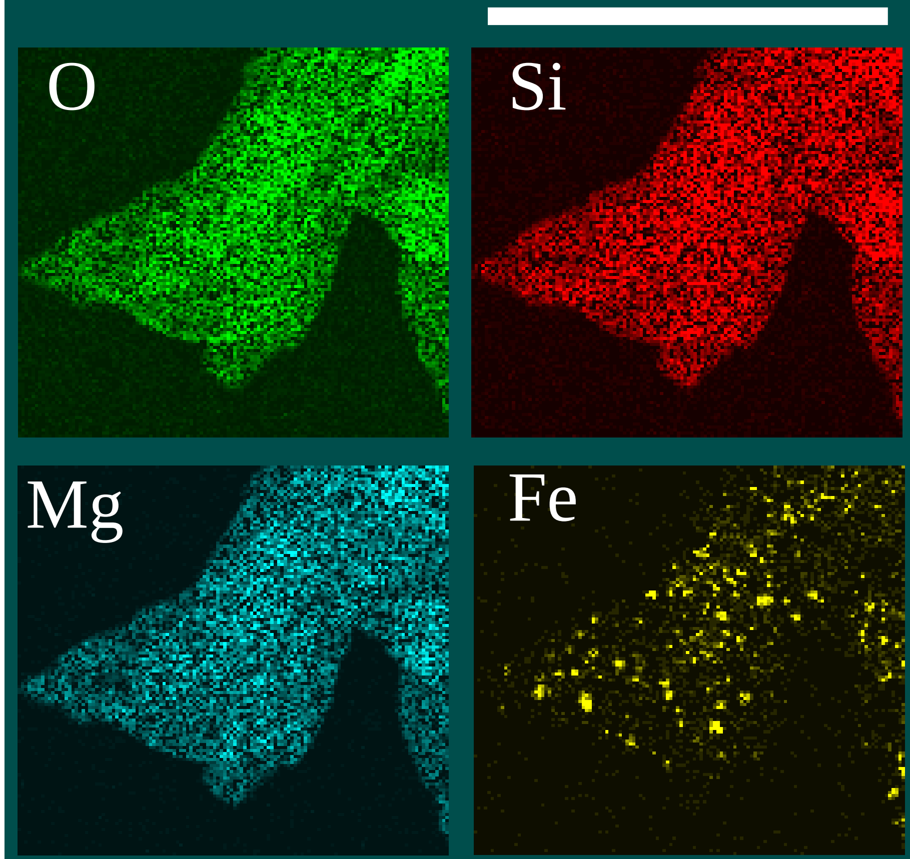
$$t = \nu^{-1} \exp\left(\frac{E_a}{kT}\right)$$

Fabian et al. *(A&A, 364, 282, 2002)*	39100 K
Brucato et al. *(Planet. Space Sci., 50, 829, 2002)*	40400 K
Djouadi at al. *(A&A, 440, 179, 2005)*	(41700 ± 2400) K

⇒ The crystallization of silicate dust is independent of its history.

⇒ The crystalline silicates observed in the vicinity of cold environments (around young stars and some comets) have probably been crystallized before their injection into these environments.

II-b/ Thermal annealing: TEM analyses



1/ Presence of metallic beads of ~ 2-50 nm.

2/ Formation of amorphous silicates free of iron. (in accordance with the observations)

3/ For the samples partially crystallized: formation of forsterite cristals+Fe beads.

$\Rightarrow$ The Fe initially present in form of FeO has been reduced.

$$\left.\begin{aligned} FeO &\rightarrow Fe + \frac{1}{2}O_2 \\ C + \frac{1}{2}O_2 &\leftrightarrow CO \end{aligned}\right\} \Rightarrow FeO + C \rightarrow Fe + CO$$

C. Davoisne, Z. Djouadi et al. *(A&A, 448, L1, 2006)*

Summary of principal results of annealing:

• Crystallization enthalpy is not modified after ionic irradiation ⇒ Redistribution of the matter between inner hot regions and outer cooler ones.

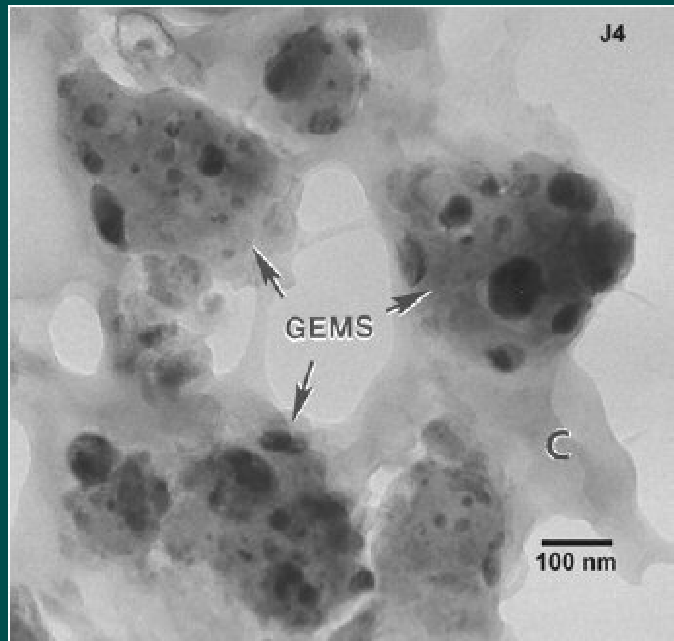
• Formation of forsterite (Mg rich silicates) in accordance with the observations

• Locking iron as metallic particles within the silicates explains why astronomical silicates always appear observationally Fe-poor (metallic Fe has no IR signature)

Astrophysical implications:

a/ GEMS formation scenario

- GEMS= Glass Embedded with Metal and sulfides: 'intrigious' metallic inclusions in anhydrous IDPs.
- No consensus to explain their origin, and their formation process.
- We propose a possible simple scheme for their formation : they are probably modified in the protoplanetary disks in reducing conditions.



Astrophysical implications:

b/ Grain alignment (?)

• Polarized signal of the starlight ⇒ IS grains are aspherical and aligned by a local magnetic field

• 1951: DG model of spinning interstellar grains but considering the random collisions with molecules, gas atoms.. Impossible to maintain the grain alignment in a ~ μG.

• 1969: Jones & Spitzer and 1978: Duley argued DG efficient if « Fe inclusions» are present. SPFM alignment.

• 1985: Mathis. IS grains = aggregates of tinier particles, some of them SPFM.

• 1995: P.G. Martin, GEMS = solution to this old and mystery problem..
  - Fe(Ni)S inclusions (due to irradiation (Bradley 1994)) = SPFM.
  - Any C-rich IS grain wouldn't be aligned (Ok with Mathis 1986).
  - GEMS are aspherical 1.4:1 (kim & Martin 1995)

The problem of IS grains alignment is still unresolved !!. We propose that these grains contain appreciable amounts of metallic Fe nano-phase

Summary

- Experimental set-up to process synthetic grain materials

    - Simulation in the laboratory of interstellar and circumstellar physical conditions

    ⇒ Reproduction of some physical and structural properties of dust

- Formation of Fe-Ni beads (GEMS-like structure)

    ⇒ Possible explanation for the grain alignment.

The magnetic susceptibility measurements in our sample are under progress

The end, and ……

Thanks for your attention !!