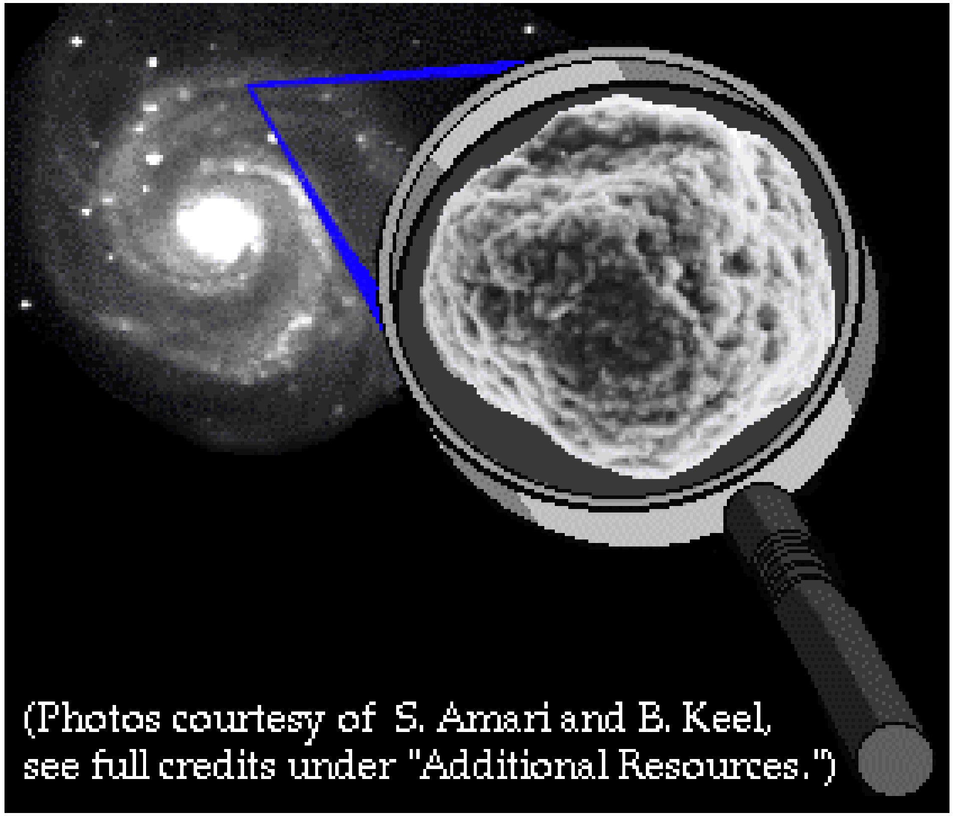
Molecules ⇒ Dust



Anja C. Andersen, Dark Cosmology Centre,

Niels Bohr Institute, Copenhagen University,

http://www.dark-cosmolgy.dk/~anja

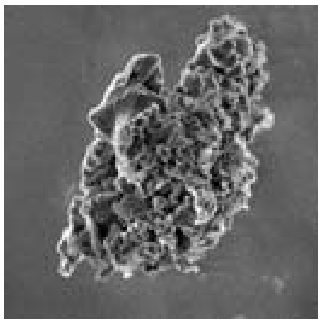
Postdoctoral positions at DARK

- Astrophysics of cosmic dust
- Star formation at high redshift
- Astrophysics of dark matter

- Deadline 2/6-2006
- See the AAS job register or http://www.dark-cosmology.dk

Stellar dust = smoke particles!

- Nano- to micron-sized solid or amorphous particles typically 10^{-7} m (~a few million atoms per dust grain)
- Must consist of the most abundant elements C, N, O, Fe, Si, or Mg.



Dust formation

- **Grain nucleation** = the step from molecule, over macromolecule to tiny solid. Need high gas super saturation pressure.
- **Grain growth** = built up of grain on top of nucleation seed.
- Interstellar grains, at least their seeds, *cannot* be made in the ISM. Grains can *only be modified* or destroyed in the ISM.
- Dust forms in the cool winds of AGB stars, Novae and SN.

Table 1. The condensation timescale for different astrophysical situations. $n_{<H>}$ total density of hydrogen in the gas, t_{typ} typical hydrodynamical timescale in the system, t_{cond} condensation timescales for SiO, Fe and C.

typical hydrodynamical timescale

dust condensation timescale

Object	Temperature [K]	log $n_{<H>}$ [cm^{-3}]	log t_{typ} [s]	log t_{cond} [s] SiO	Fe	C
interstellar medium						
H II regions	10000	$2-3$	≈ 12	∞	∞	∞
Intercloud medium	10000	≈ -1	?	∞	∞	∞
Diffuse clouds	100	≈ 2	?	> 18	> 18	> 18
Dark clouds	$10-20$	≈ 4	?	> 18	> 18	> 18
Molecular clouds	50	≈ 6	≈ 15	> 18	> 18	> 18
Compact H II reg.	$100-1000$	$3-4$	≈ 11	≈ 13	≈ 14	$13-14$
explosive ejection of matter						
Novae	from 10000 down	$\lesssim 8-10$	$6-7$	$\approx 6-8$	$7-8$	$7-8$
Supernovae	from 10000 down	$7-9$	$7-8$	$\approx 7-9$	$8-10$	$8-10$
massive winds of giant stars						
Cool winds	from 2000 down	$7-10$	≈ 8	$\approx 7-9$	≈ 8	≈ 8
Hot winds	from 20000 down	$6-8$	≈ 6	$\approx 8-10$	$\approx 9-10$	≈ 9

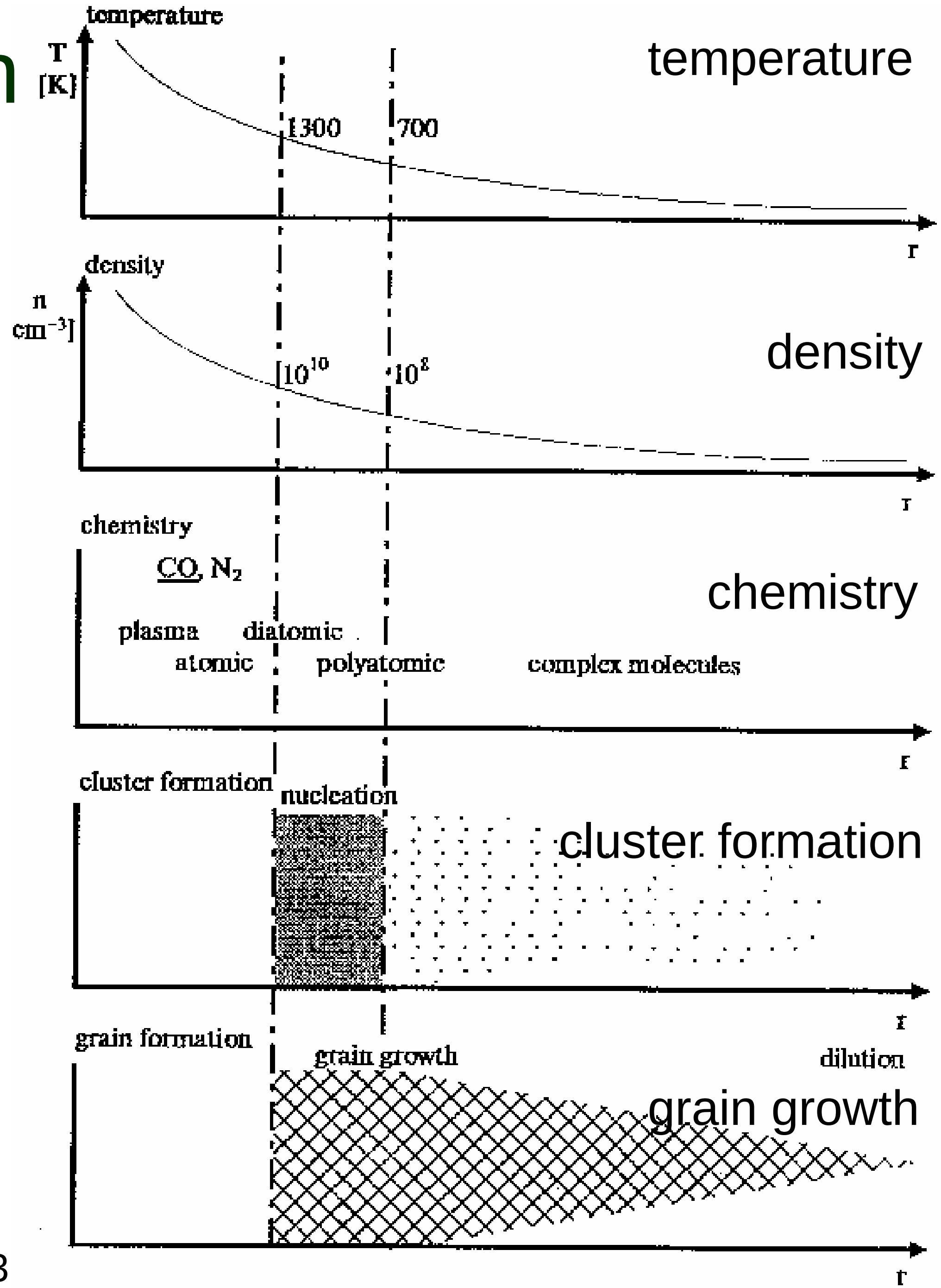
Sedlmayr 1993

Nucleation & growth

Schematic radial course of an expanding stellar wind (cool stellar winds, novae or supernovae).

Shown is the evolution of a complex chemistry, grain nucleation and grain growth.

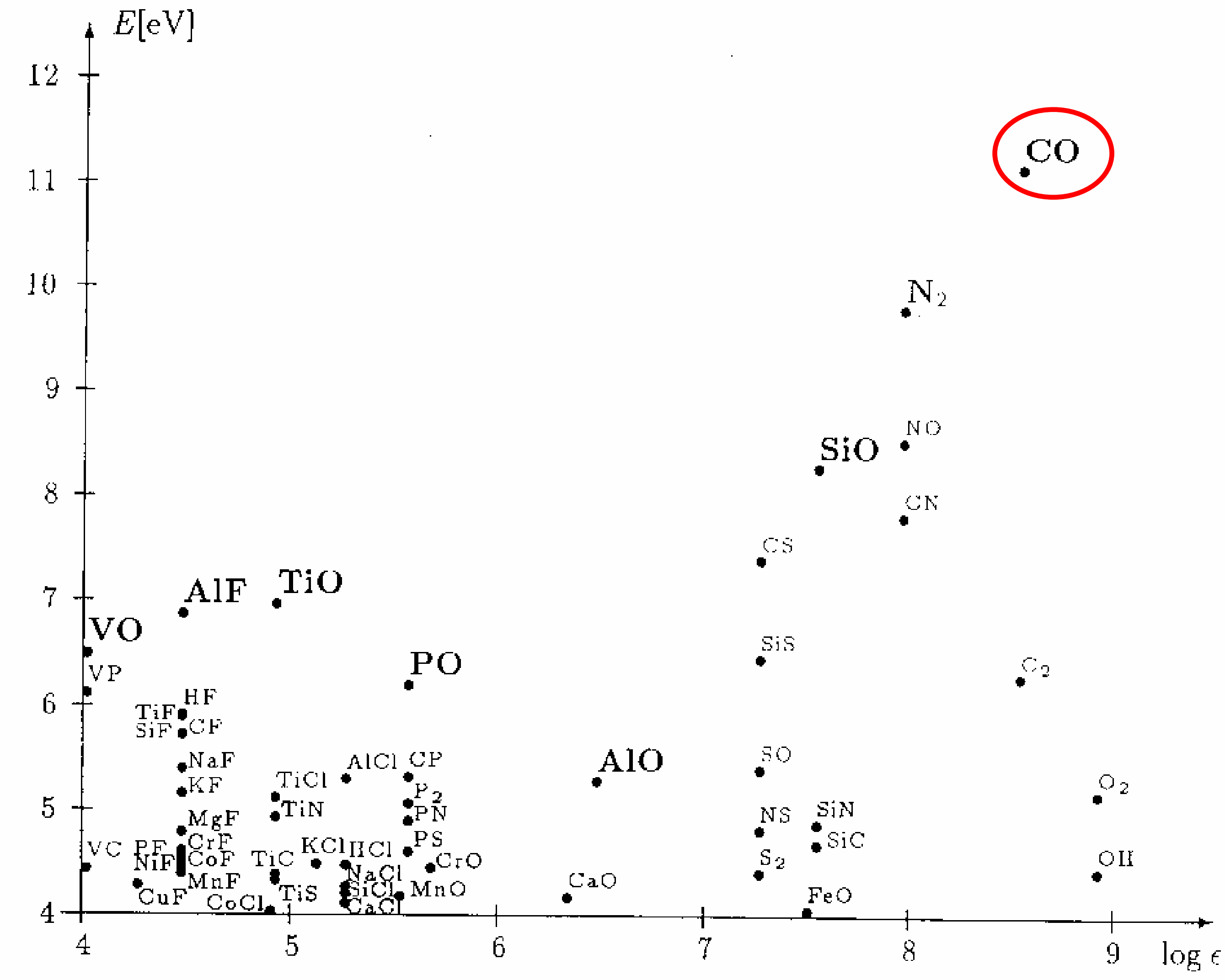
Sedlmayr 1993



An open question: is SN and/or AGB stars the major dust producers?

- AGB stars have been *observed* to produce $1M_{Earth}$ dust per year (for how many years?).
- SNs are *predicted* to produce $\sim 1M_{Sun}$ dust.
- We *know* AGB loose up to $7M_{Sun}$ at their end stages (dependent on initial mass).
- We do *not know* how much mass a SN returns to the ISM (depend on initial mass?).
- There are many more AGB stars (today) than SN, *but* who where the most efficient dust producer over time?

Bond energies of abundant elements

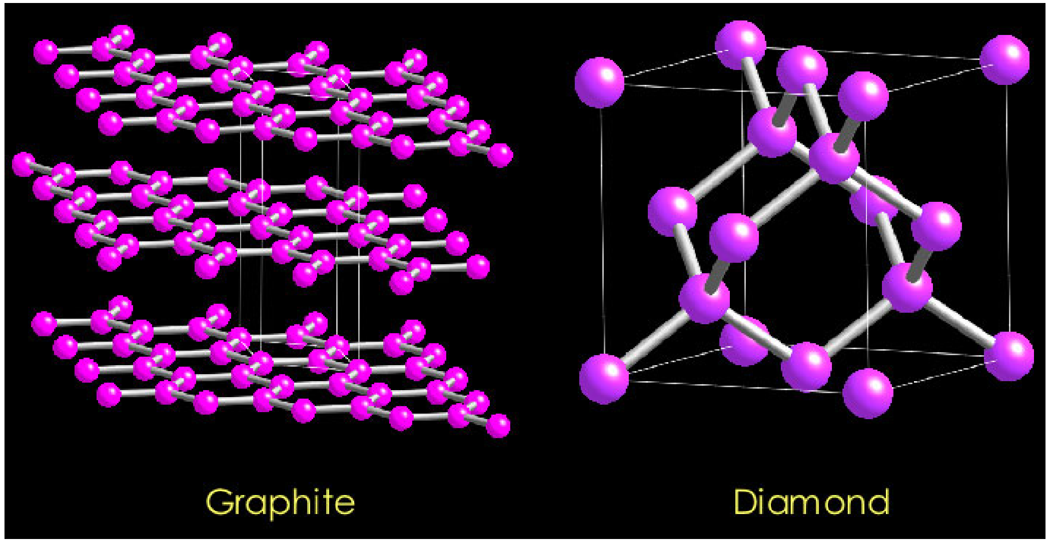


CO divides dust formation into two different chemistries

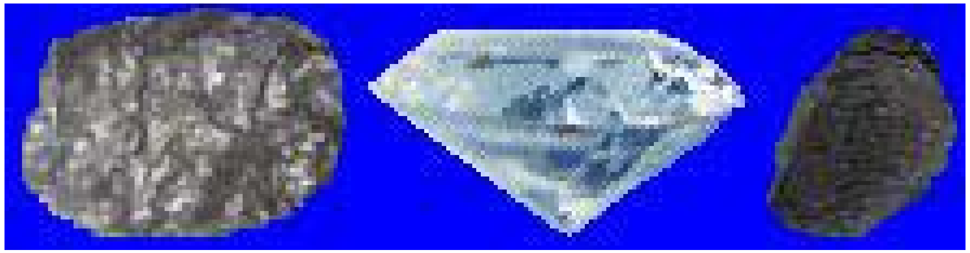
- **C/O > 1** Carbon chemistry (molecules: C_2, CN, CH, C_2H_2, C_3, HCN). *Typical dust types:* graphite (C), amorphous carbon (C), diamond (C), silicon carbide (SiC),…
- **C/O < 1** Oxygen chemistry (molecules: OH, SiO, TiO, H_2O, TiO_2, VO, ZrO, ScO, YO, LaO) *Typical dust types:* enstatite ($MgSiO_3$), olivine, ferrosilite ($FeSiO_3$), pyroxene, forsterite (Mg_2SiO_4), fayalite (Fe_2SiO_4),…

Mineralogy for astronomers

Why do geologist use all those "difficult-to-remember-names" instead of just the chemical formulae?



Graphite (C), Diamond (C), Amorphous Carbon (C)



Magnesium-iron silicates

The most stable condensate formed from the abundant elements O, Si, Mg and Fe.

$Mg_{2x}Fe_{2(1-x)}SiO_4$ with $x \in [0,1]$

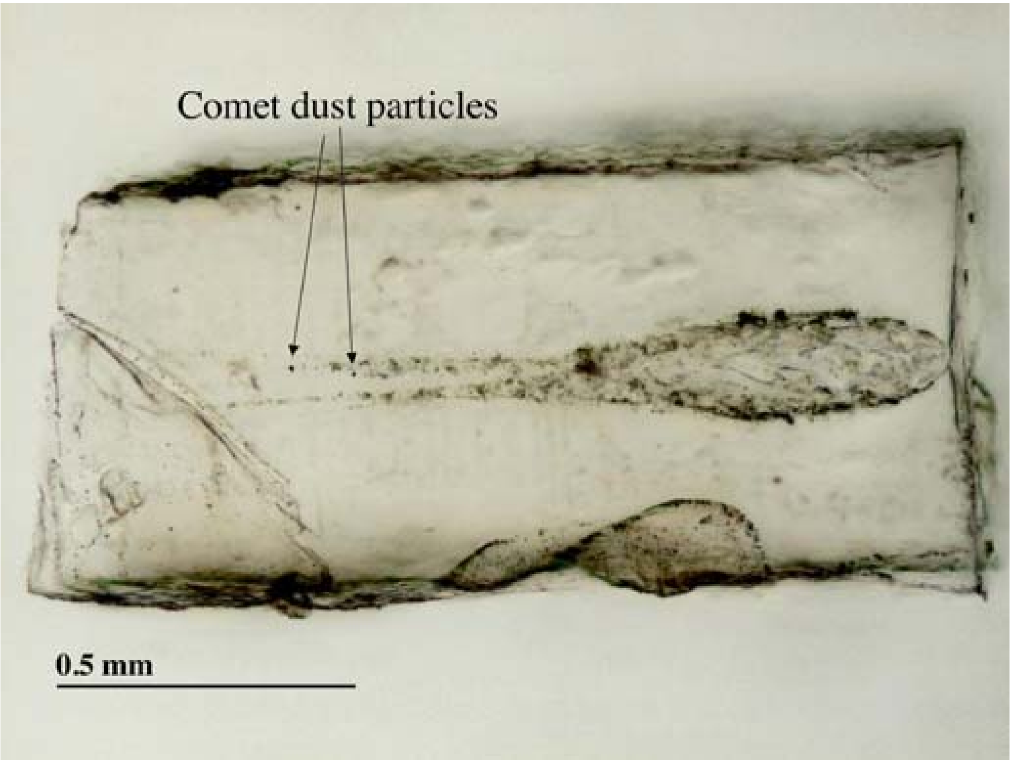
$x=1 \rightarrow$ fosterite, $x=0 \rightarrow$ fayalite, $0<x<1 \rightarrow$ olivine

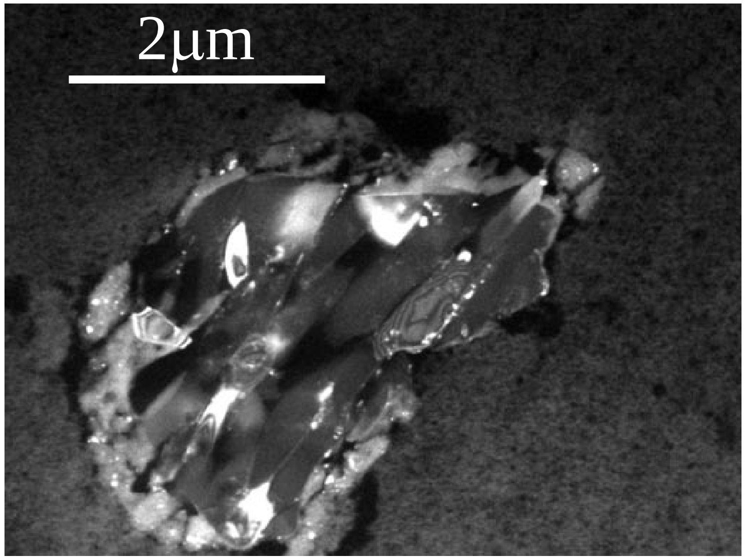
Pure fosterite is stable up to much higher temperatures, than pure fayalite.

$Mg_xFe_{(1-x)}SiO_3$ with $x \in [0,1]$

$x=0 \rightarrow$ ferrosilite, $x=1 \rightarrow$ enstatite, $0<x<1 \rightarrow$ pyroxene

Fosterite from Comet Wild 2



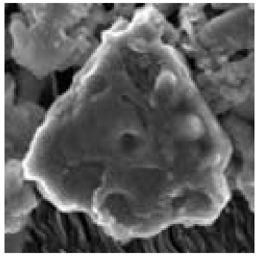


Stardust mission: Launched 7/2-99, Encounter 2/1-04 with Comet Wild 2, Returned 15/1-06.

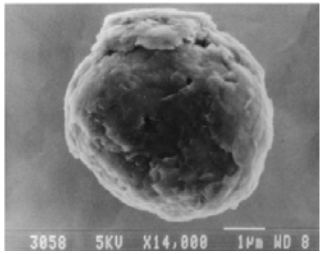
Presolar grains

Discovered in 1987 that primitive meteorites contain small quantities of presolar grains.

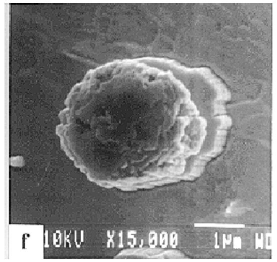
Diamond
1000 parts per million
Size ~ 1-5 nm



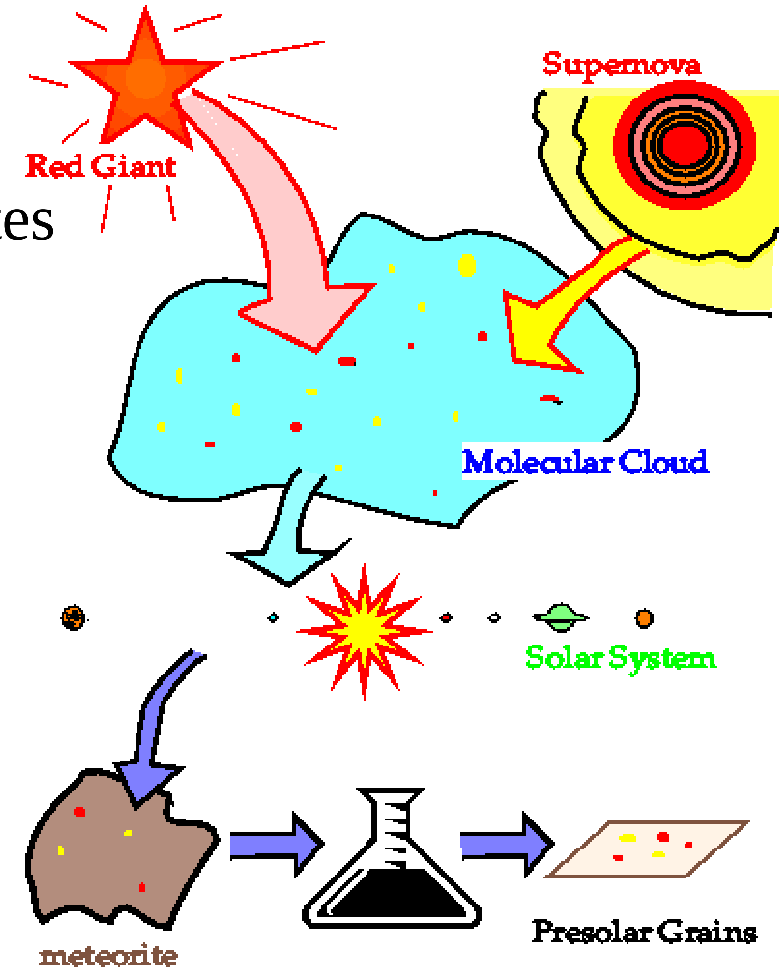
SiC
10 parts per million
Size ~0.1-10μm



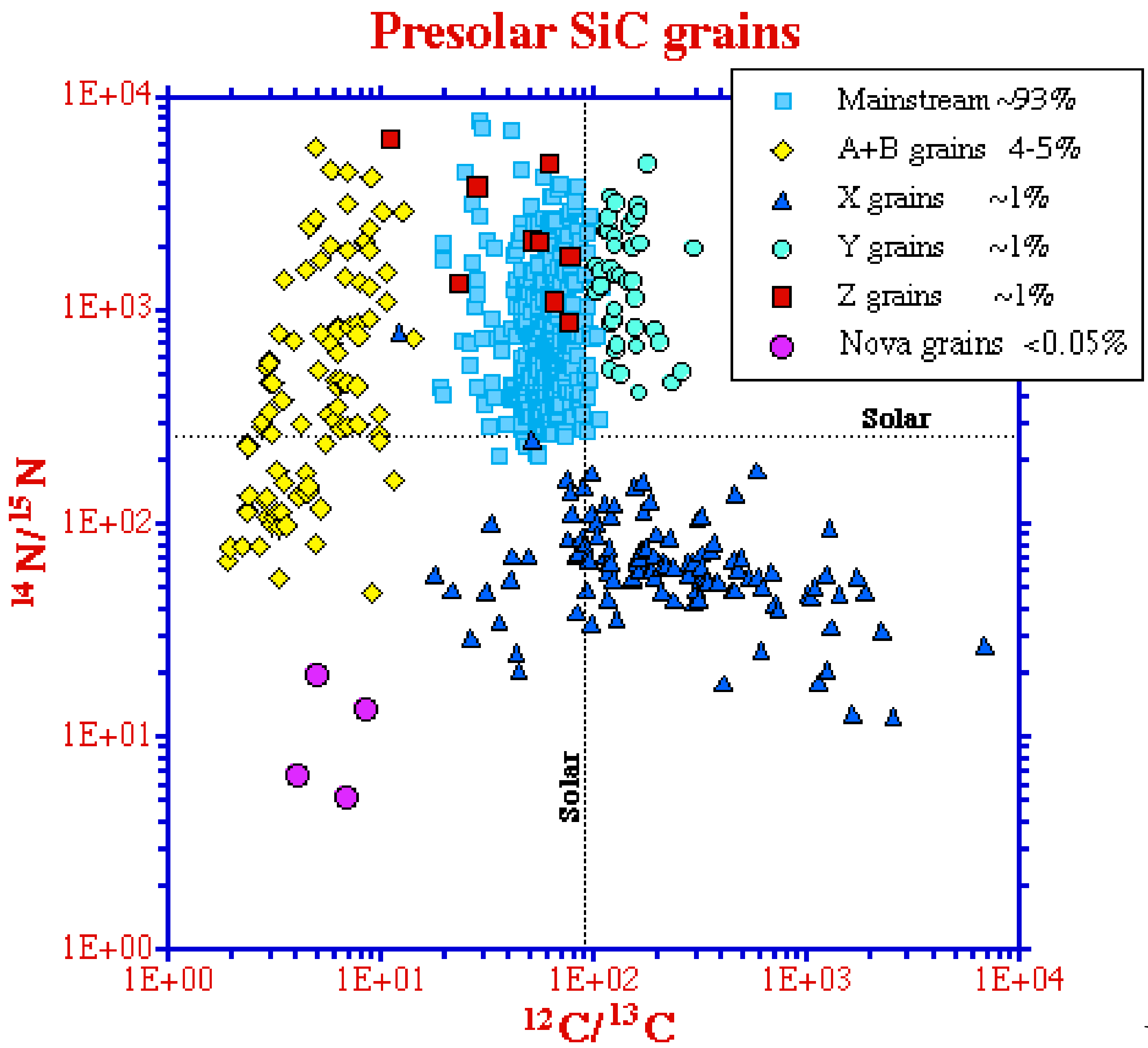
Graphite
2 parts per million
Size ~1-10μm



Al_2O_3
0.1 parts per million
Size ~ 1-5μm



Isotopic anomalies



AGB

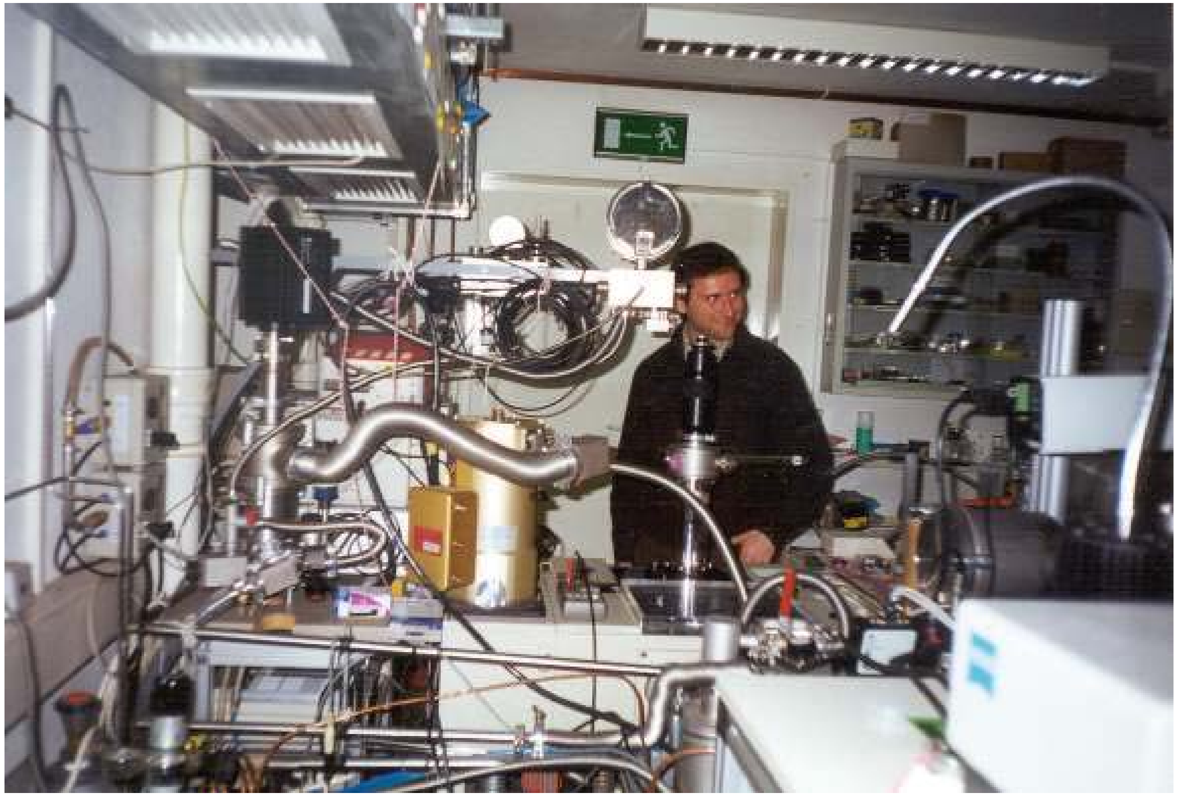
Supernova

Nova

Nittler et al.

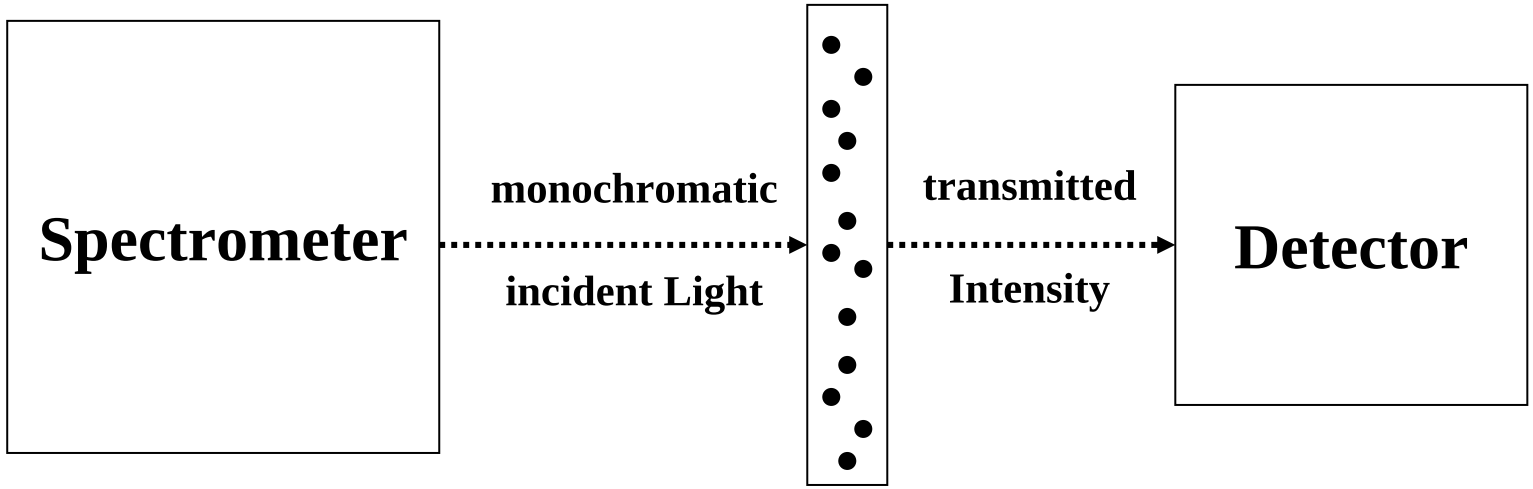
Dust spectroscopy - what we can measure

- chemical composition and bonding
- lattice structure (crystalline - amorphous)
- morphological information (shape, agglomeration)
- grain size
-grain temperature



Thomas Posch with the spectrograph in the Jena laboratory

The Experiment



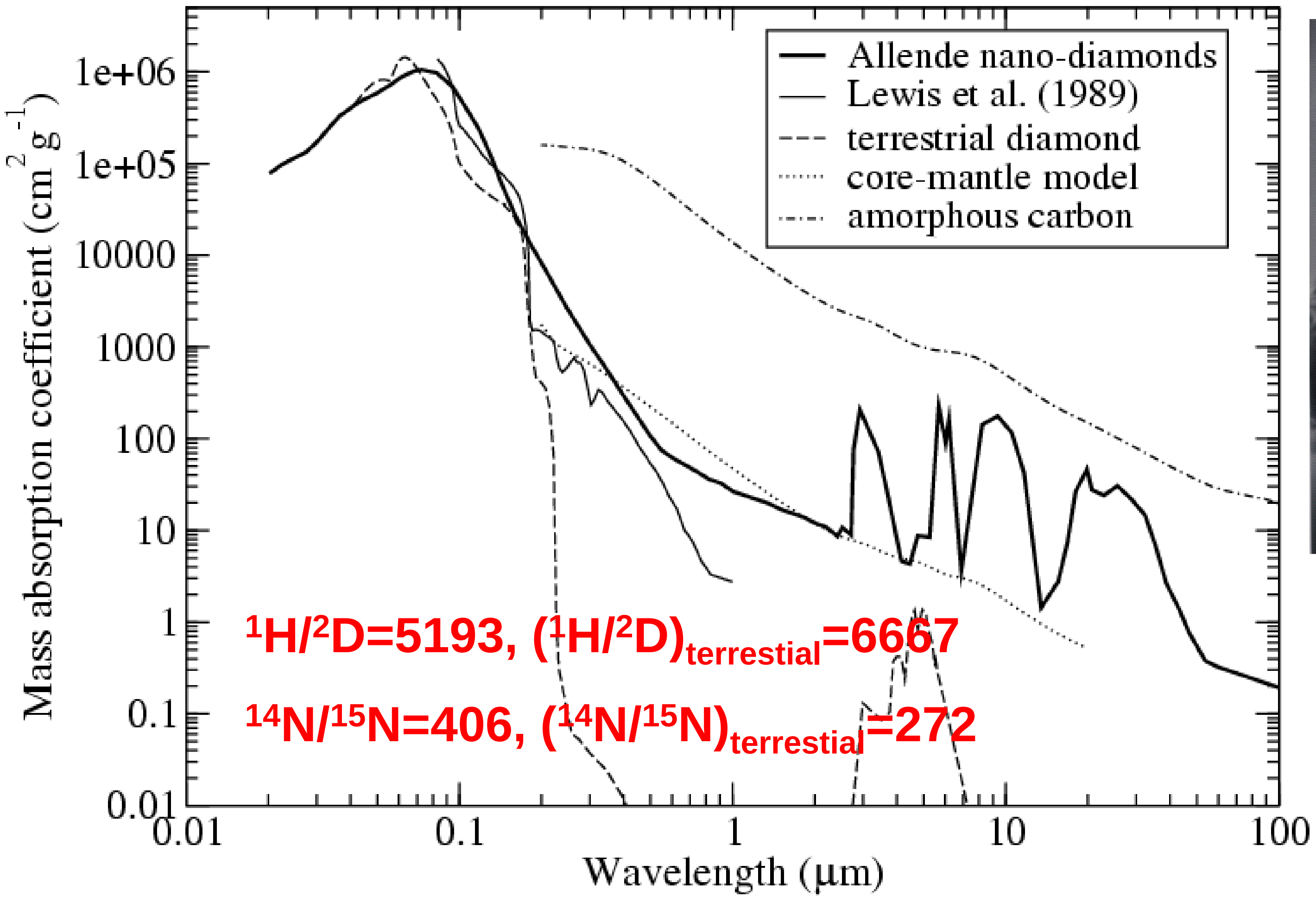
- measurement of extinction cross section (equals emission cross section)
- if necessary: scattering cross section

- always: ensembles of particles, $10^6 – 10^{18}$ cm^{-2}, embedded in or sitting on a medium

- for determination of optical constants: also reflectance measurements and electron energy loss spectroscopy

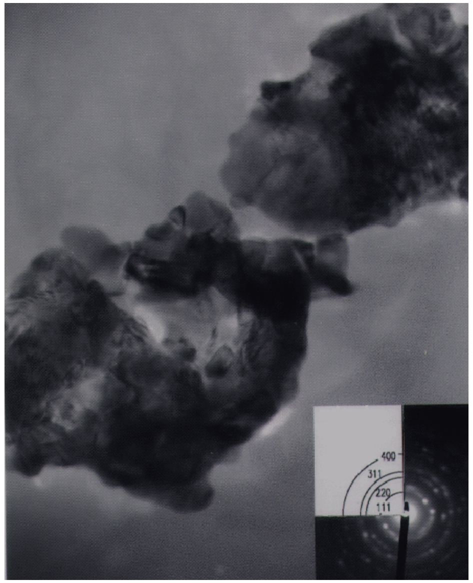
Properties of presolar diamonds

Isotopic data indicates cool red giant stars, supernova and the Solar nebular as possible formation sites. To test hypothesis the optical properties are needed.



$^{1}H/^{2}D=5193$, $(^{1}H/^{2}D)_{terrestial}=6667$

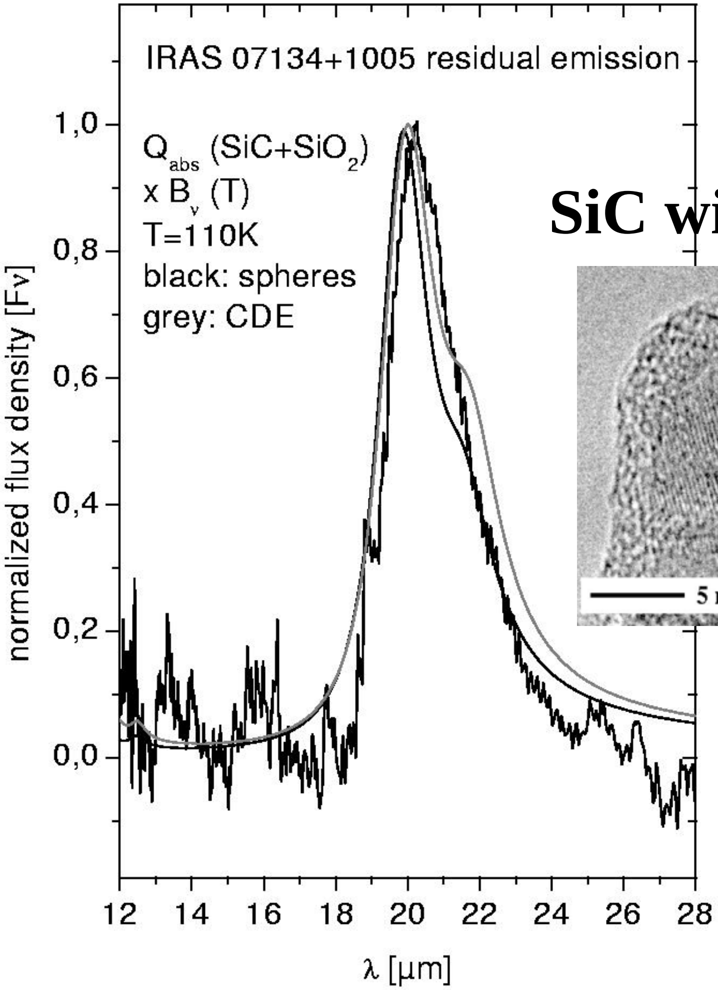
$^{14}N/^{15}N=406$, $(^{14}N/^{15}N)_{terrestial}=272$



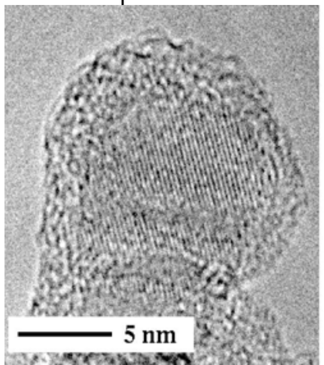
Andersen et al. 1998; Mutschke et al. 2004

Cosmic dust analogous

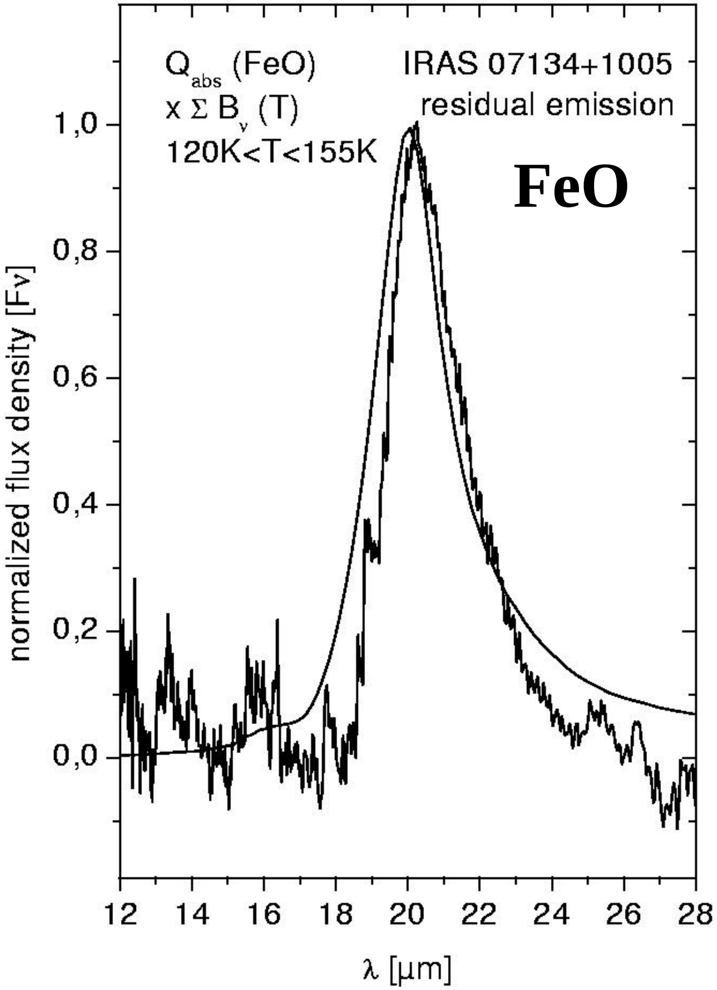
Attempt to identify the 21μm feature observed in C-rich proto-planetary nebulae.



SiC with SiO_2

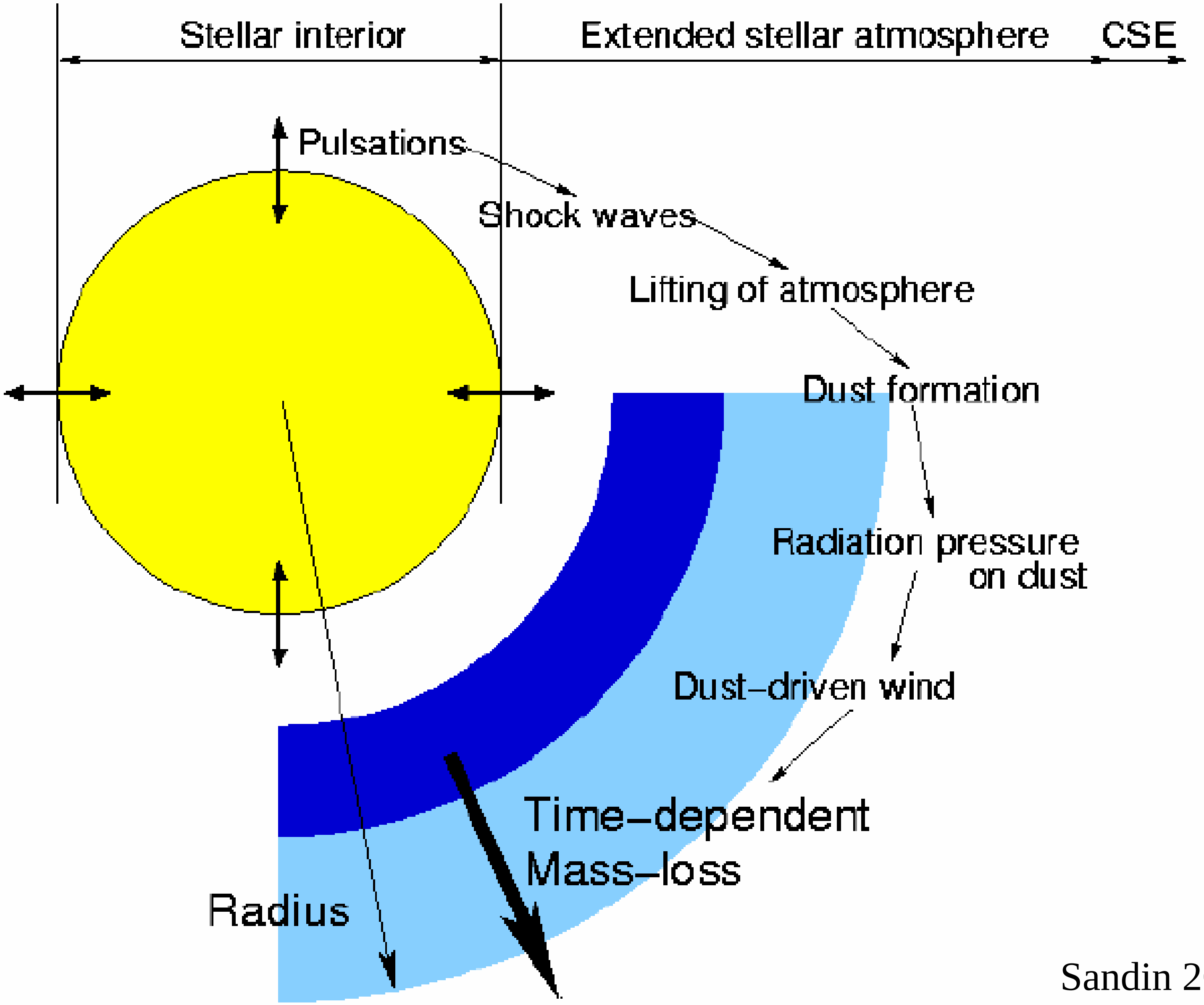


FeO



Posch et al. 2005

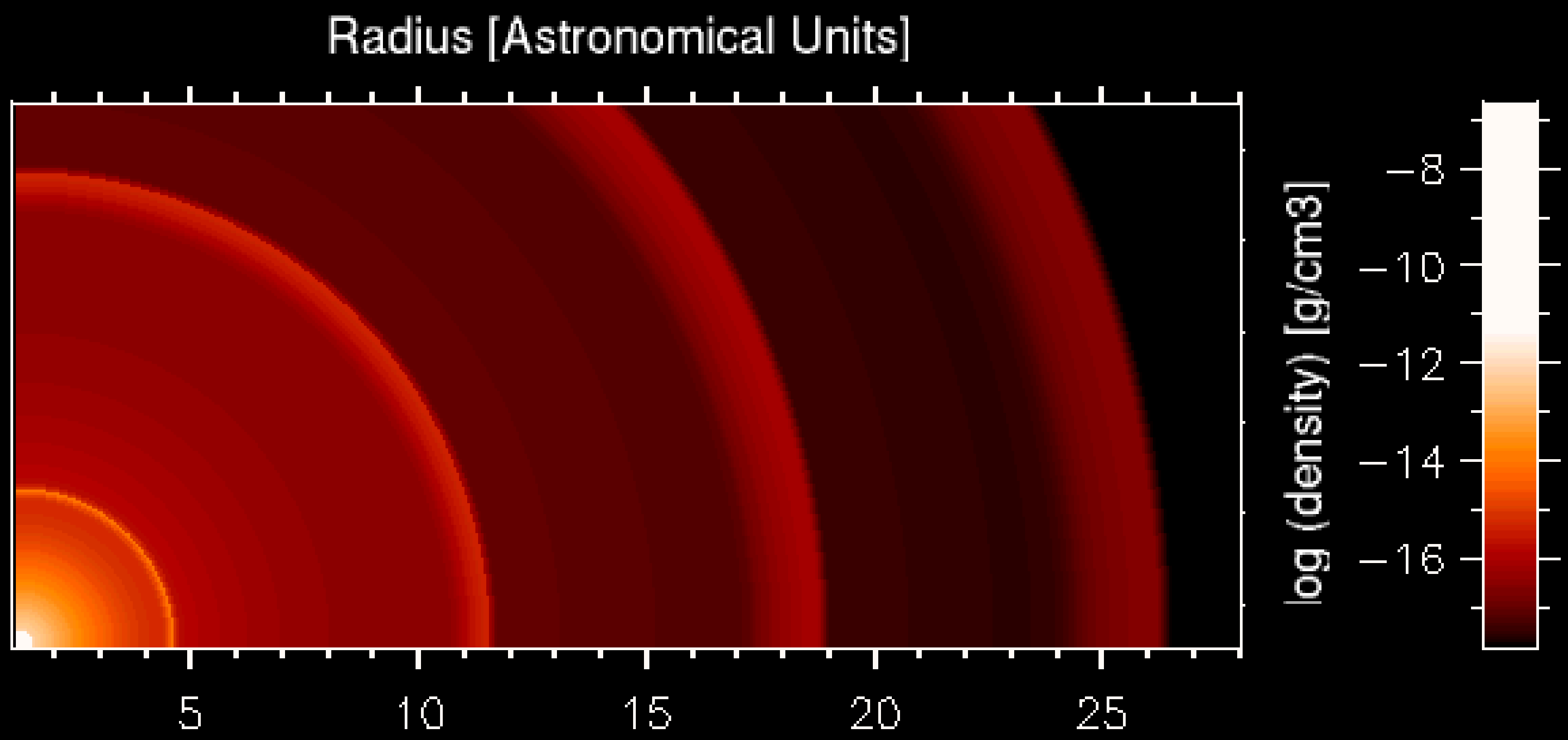
AGB star mass loss models



Sandin 2003

Red giant stars provides > 90% of the Galactic stellar mass-loss.

Model illustrates the wind properties of an AGB star.

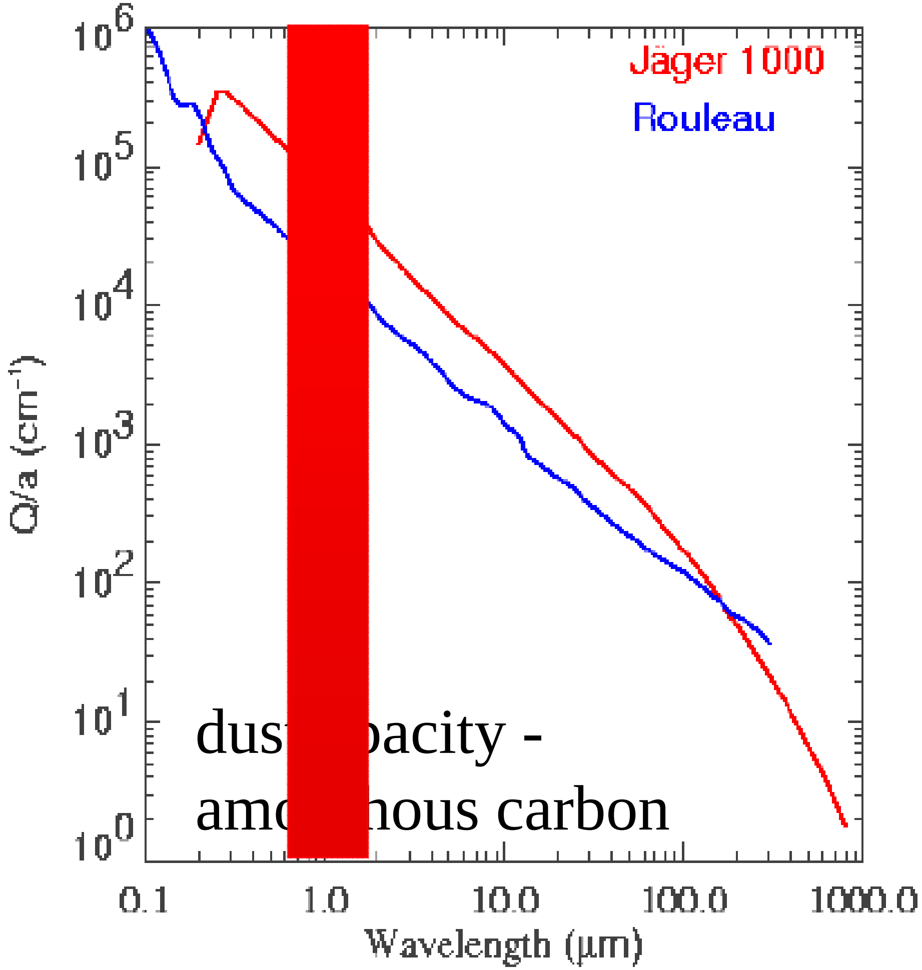


Höfner 2003

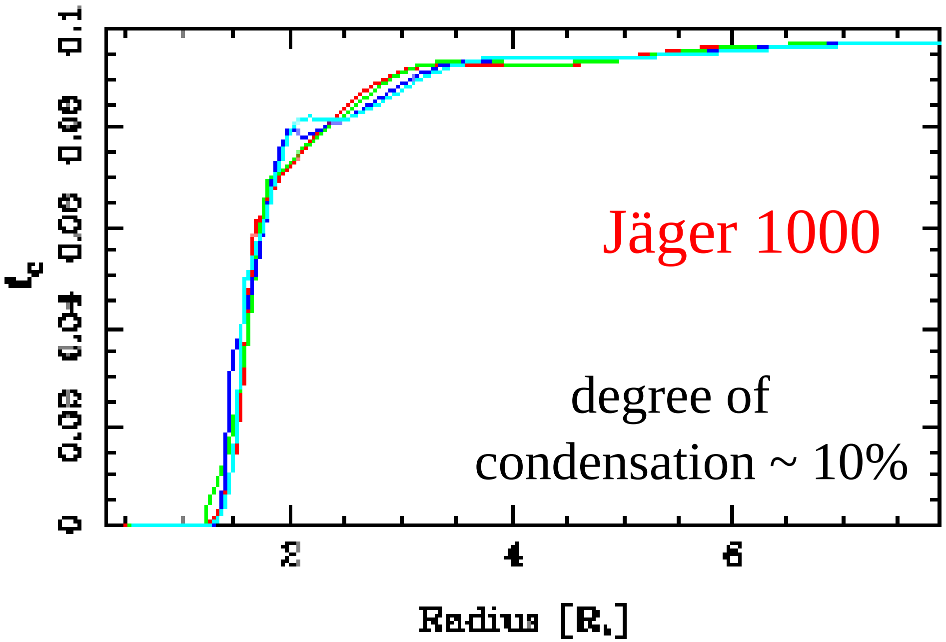
Dynamic models

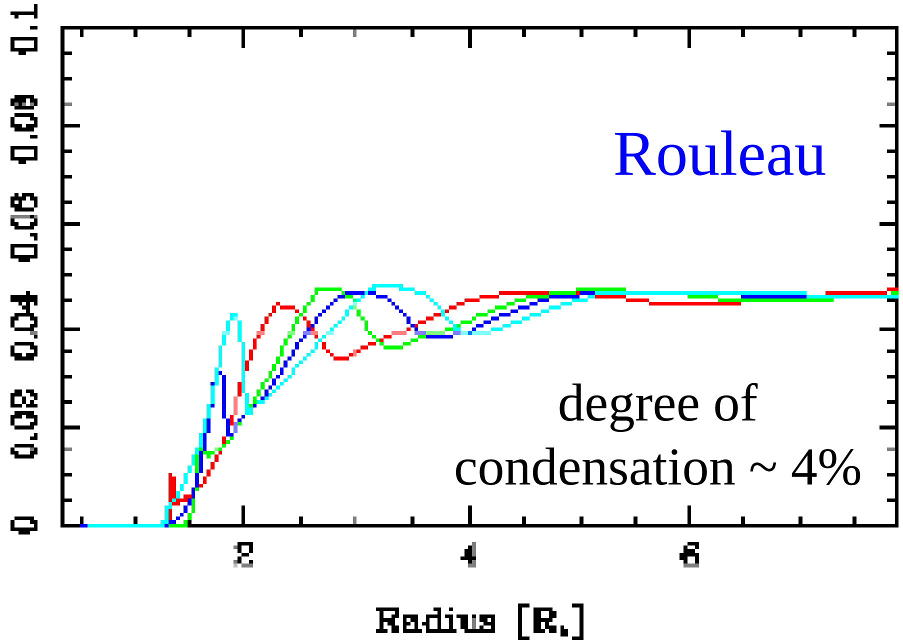
Radial structure at 4 phases

$L_* = 13000 L_\odot$, $T_* = 2700$K,
$M_* = 1 M_\odot$, C/O=1.4, P=650d

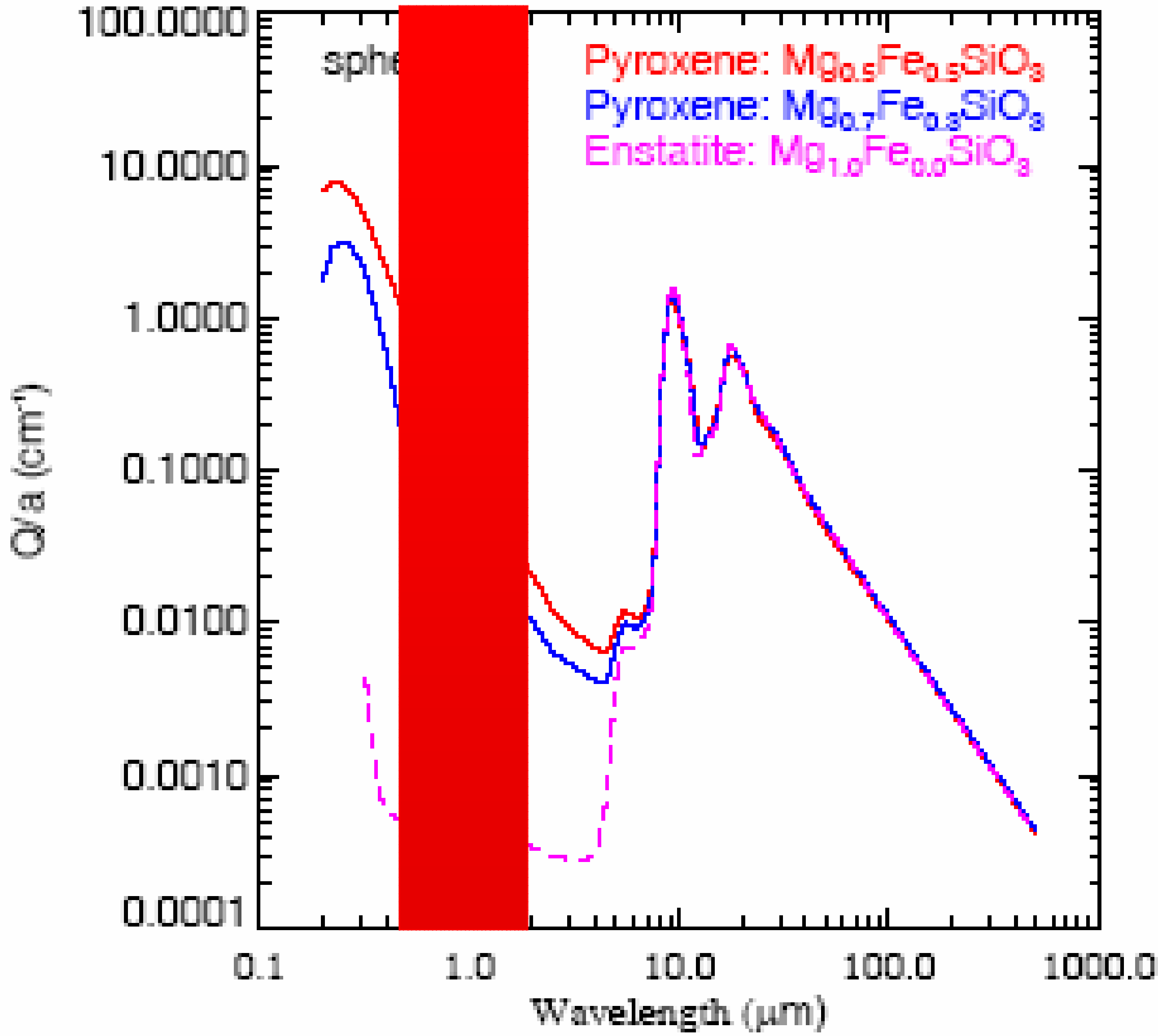


Laboratory dust mesurement





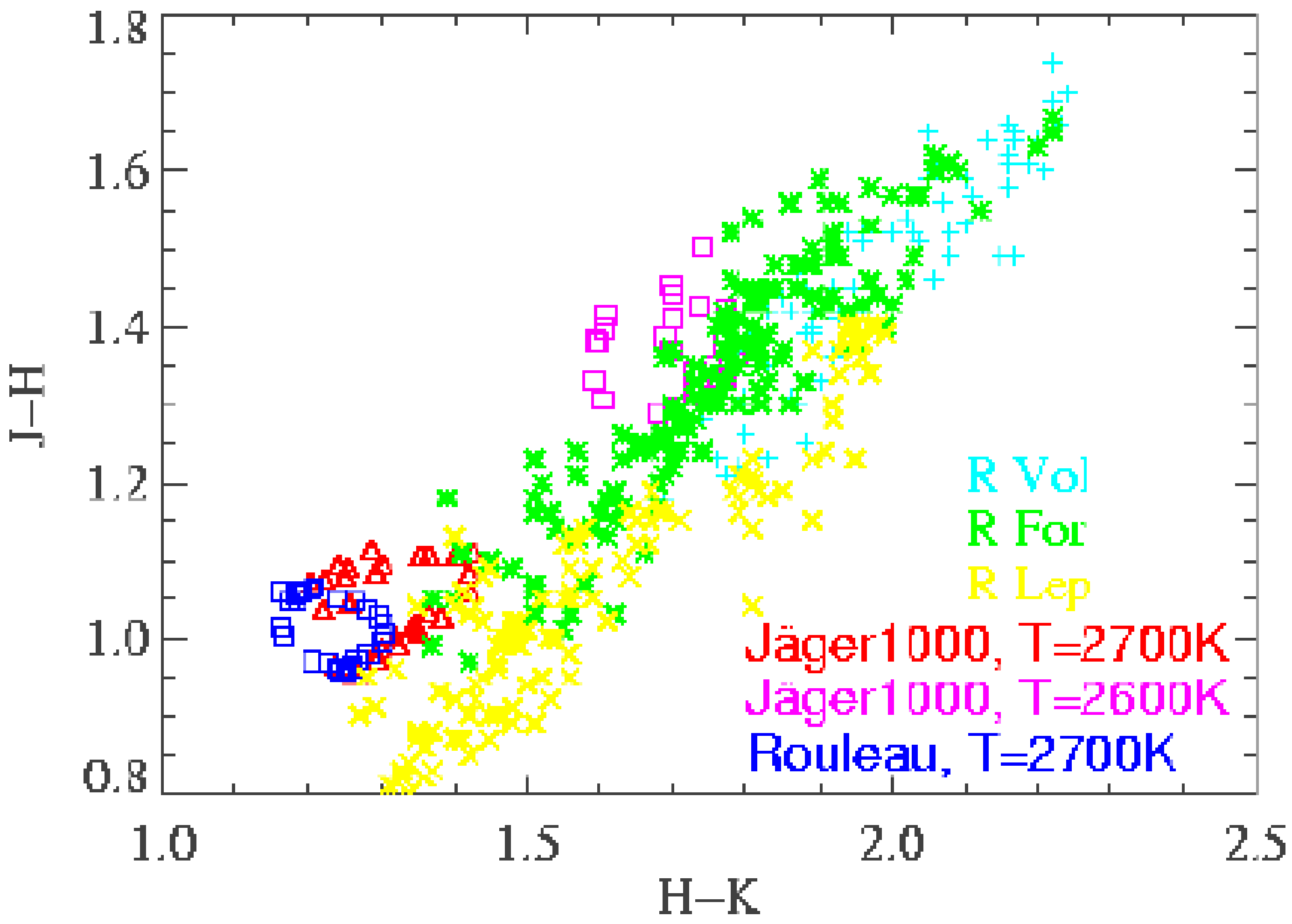
Numerical stellar models



Pyroxene: Mg0.5Fe0.5SiO3
Pyroxene: Mg0.7Fe0.3SiO3
Enstatite: Mg1.0Fe0.0SiO3
100.0000
10.0000
1.0000
0.1000
0.0100
0.0010
0.0001
Q/a (cm-1)
0.1
1.0
10.0
100.0
1000.0
Wavelength (μm)

Comparison with observations

Models vs. three carbon Miras with **moderately** thick dust shells and comparable outflow velocities.



Models: Andersen et al. (2003)
Observations: Whitelock et al. (1997)

IAU XXVI GA JD 11: Presolar Grains as Astrophysical Tools
Monday 21/8-2006 in Prague

Session 1: Introduction and Overview

Overview: Opportunities from Grains Uli Ott

Abundances in Grains, Stars and the Galaxy Larry Nittler

New Science from New Technology: Nano-SIMS and RIMS Peter Hoppe

Session 2: Nucleosynthesis

Pre-Solar Grains and AGB Stars Maria Lugaro

Pre-Solar Grains: WR Stars, novae and supernovae Sachiko Amari

Session 3: Grain Formation

Condensation of Grains Katherina Lodders

Mass-loss: the role of Grains Susanne Hoefner

Session 4: Grains in Space

Life Story of a Grain: from Formation to the Lab Bruce Draine

Constraints on the Solar Nebula from Presolar Grains Gary Huss

STARDUST Mission Update Scott Messenger

Overview: Agenda for the Future Conel Alexander

"Sure it's beautiful, but I can't help thinking about all the interstellar dust out there."

Dust spectroscopy - what do we see?

1. **Observationally**

- UV to IR absorption bands of interstellar dust (diffuse medium and molecular clouds)
- Far IR (sub-mm) continuum emission from cold dust
- Photoluminescence bands of very small grains (extended red emission, aromatic IR bands)
- IR emission (absorption) bands from warm (circumstellar) dust

2. **Physically**

- electronic interband transitions,
- single and multi-phonon bands,
- plasmons (conducting – semicond. materials),
- surface species, defect states (electronic and vibrations)
- low-energy two-level tunnelling systems

Types and characteristics of presolar grains found in meteorites.

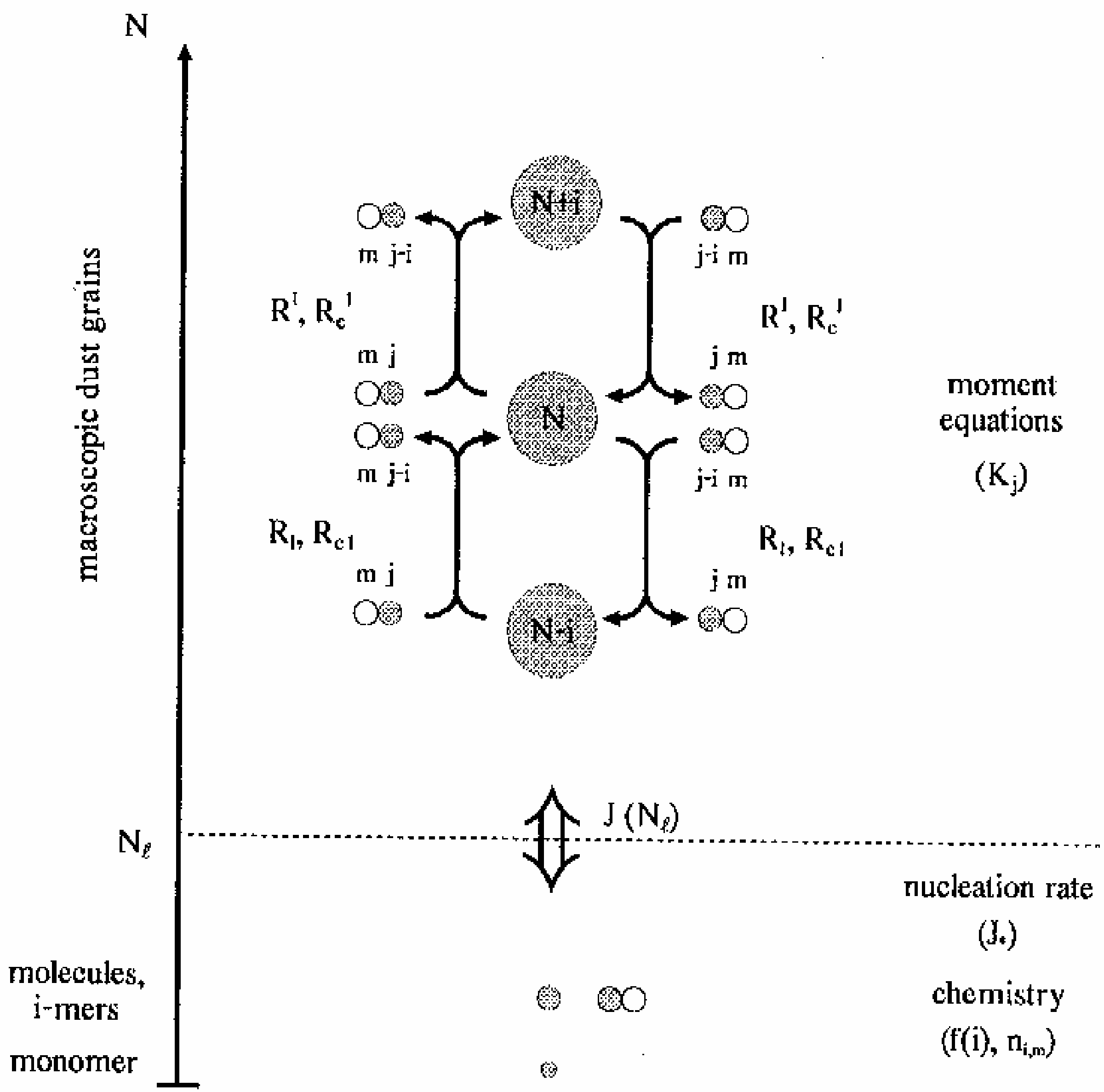
Type	Size	Concentration in Meteorites	Sources
Diamond (C)	1-5 nanometers	1000 parts per million	Supernovae
Silicon carbide (SiC)	0.1-10 micrometers	10 parts per million	Carbon-rich giant stars, or supernovae
Graphite (C)	1-10 micrometers	2 parts per million	Supernovae and carbon-rich giant stars
Aluminum oxide (Al_2O_3)	1-5 micrometers	0.1 parts per million	oxygen-rich giant stars
Spinel ($MgAl_2O_4$)	1 micrometer	2 parts per billion	oxygen-rich giant stars
Silicon nitride (Si_3N_4)	1 micrometer	2 parts per billion	Supernovae

Table adapted from a 1993 *Meteoritics* review by Edward Anders and Ernst Zinner, and Conel Alexander's *Carnegie Institution Yearbook 95*, report "Stardust in the Laboratory."

The Moment method describes the time evolution of an ensemble of macroscopic dust grains of various sizes.

Gail et al. 1984
Gail & Sedlmayr 1988
Gauger et al. 1990

Input: nucleation rate, dust opacity, intrinsic dust density, sticking coefficient.

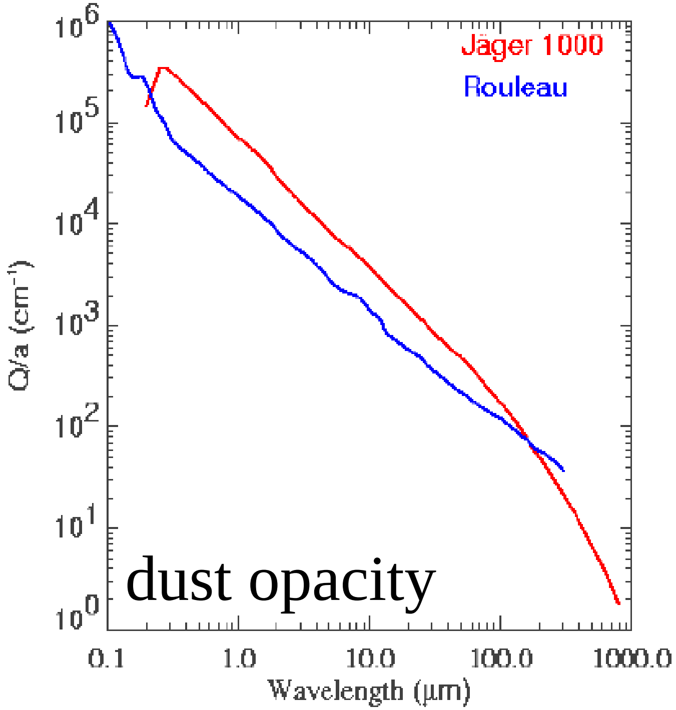


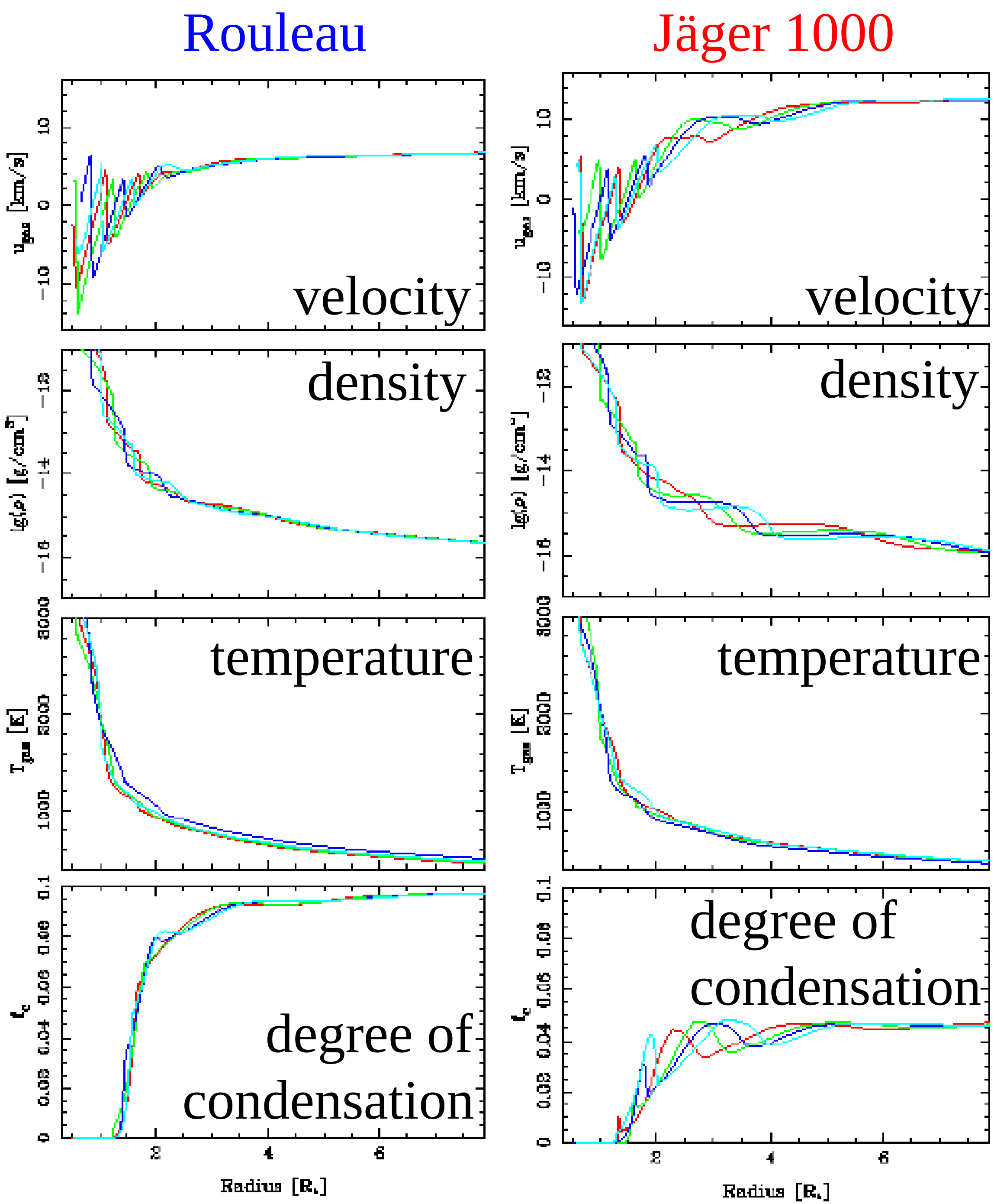
Nucleation, growth and destruction of dust grains are supposed to proceed by reactions involving C, C_2, C_2H and C_2H_2.

Dynamic models

Radial structure at 4 phases

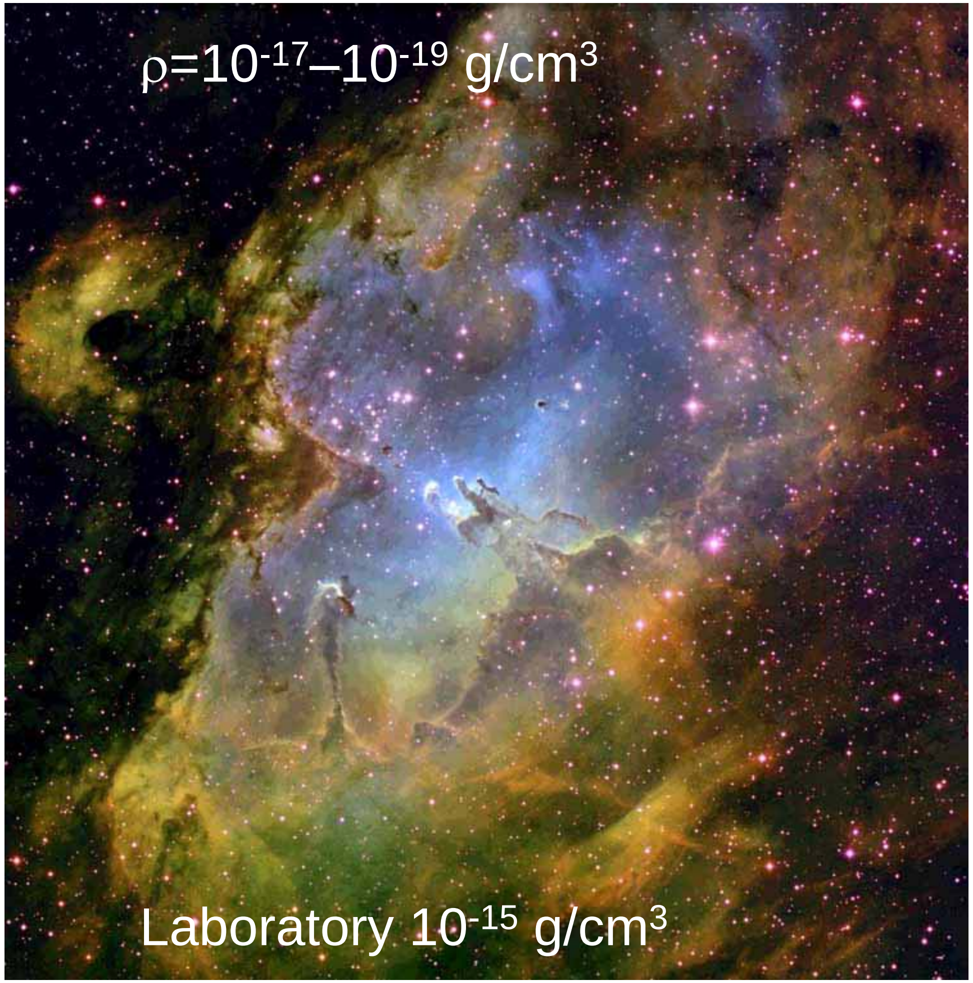
$L_* = 13000 L_\odot$, $T_* = 2700K$,
$M_* = 1 M_\odot$, C/O=1.4, P=650d





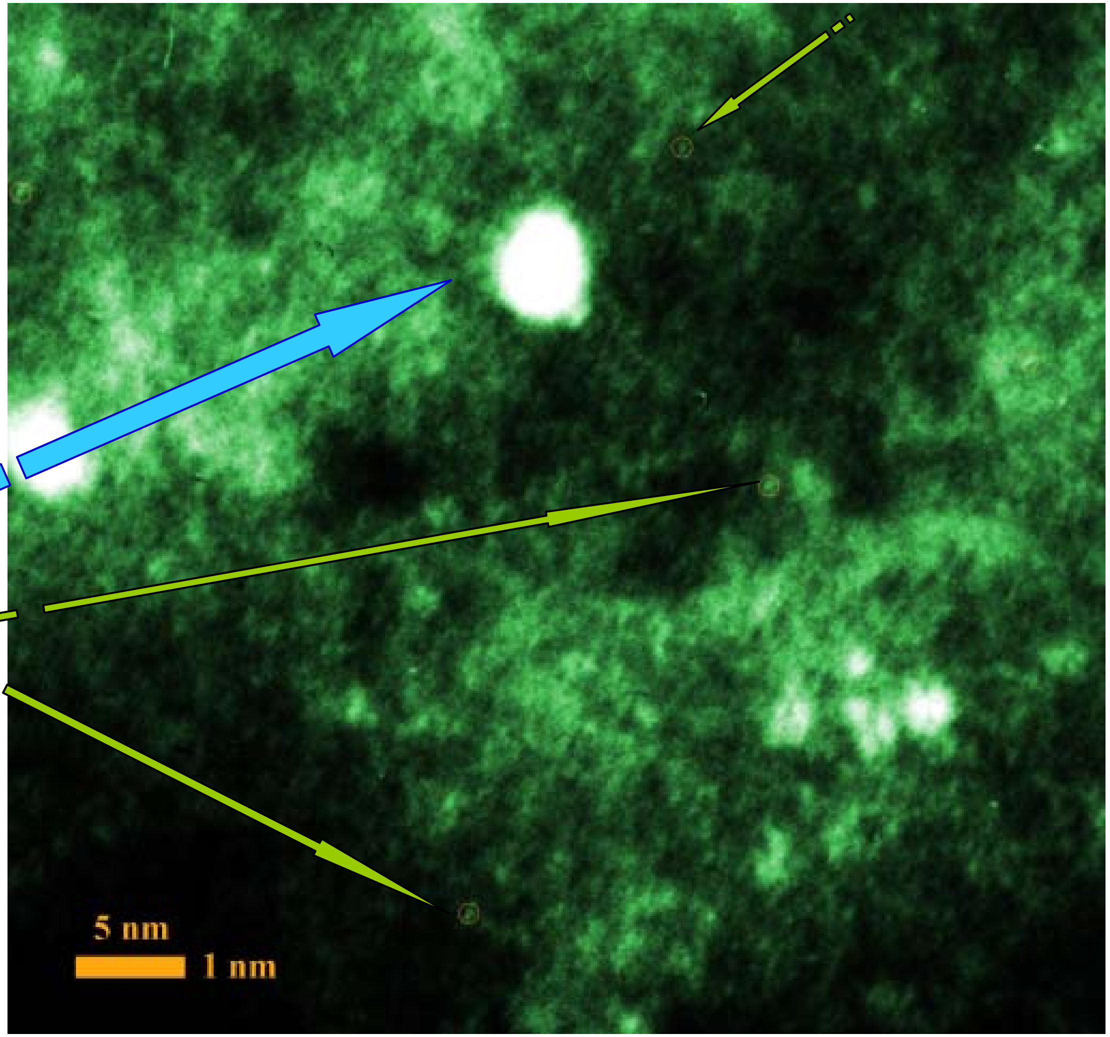
Dust in the ISM

If the Earth atmosphere had the same relative dust content as the ISM the optical depth τ would become unity at l=10 cm and we could not see our feet!



Nanodiamonds: electron spectroscopy

- Meteorite Murray. Single crystals may show up as bright dots only if their carbon-atom planes are oriented to reflect electrons into the camera.
- Although a few of the nanodiamonds are 5 nm (25 atoms) across, most of them are under 1 nm (5 atoms) across.

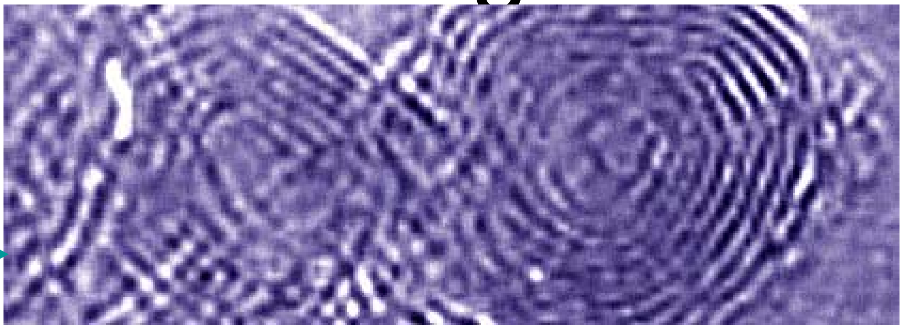


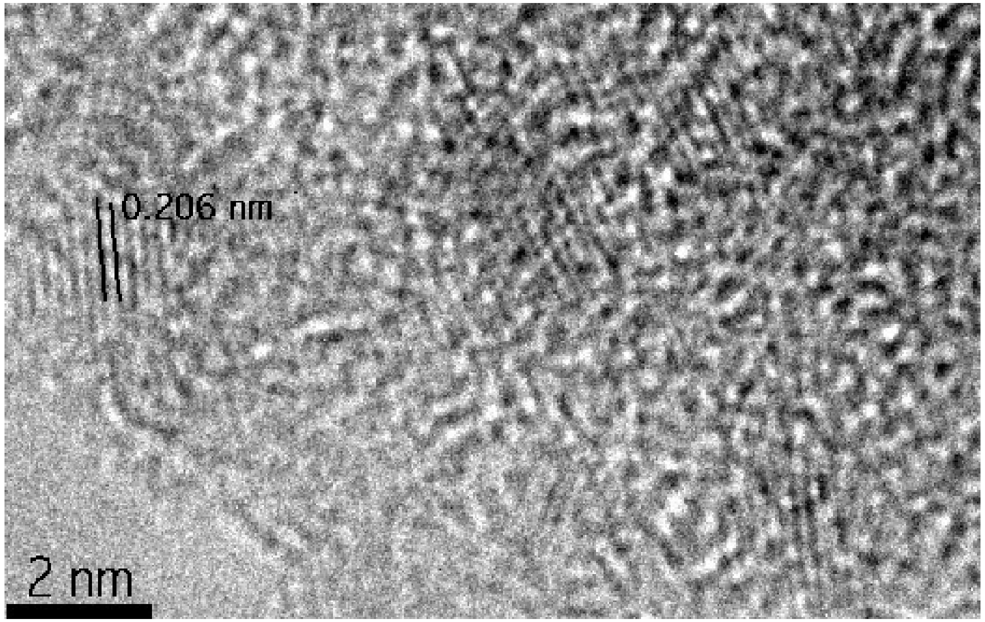
Fraundorf et al. (1989)

Fringes

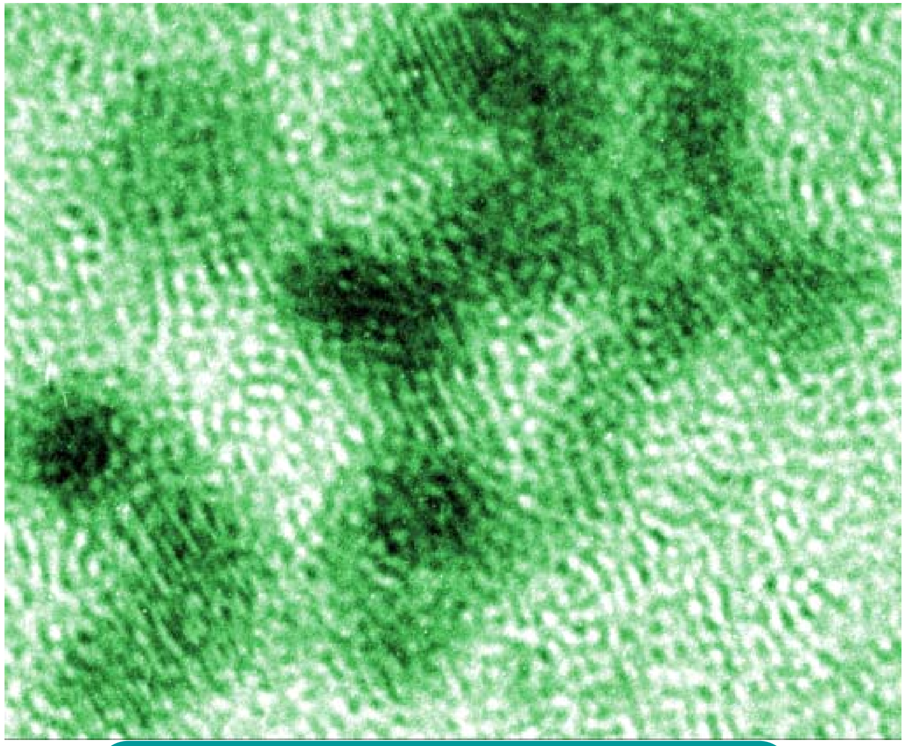
Nanodiamonds: lattice fringes

Bucky diamonds
within fullerenes
A. S. Banard
& coworkers





Allende meteorite
Mutschke et al. (2004)



Murray meteorite
Fraundorf et al. (1989)