Mineralogy of Protoplanetary Dust

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Motivation
Mineralogy of protoplanetary dust

- Infrared spectroscopic properties as a diagnostic tool (Optical depth, temperature, chemistry, growth processes, mixing, …)
- Grains: Surface for chemical reactions and opacity source (Important refractory condensates)
- Interesting structural and optical behaviour (Tunneling processes at low temperatures)

Metal Oxides –
Important Class of Materials

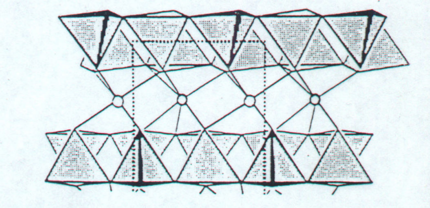
Abundances: $A_N(X) = 12 + \text{Log}\,(N_X/N_H)_{sun}$

- Oxygen: ~ 8.9
- Mg, Si, Fe: ~ 7.50
- Al, Ca: ~ 6.50

Structure of Silicates

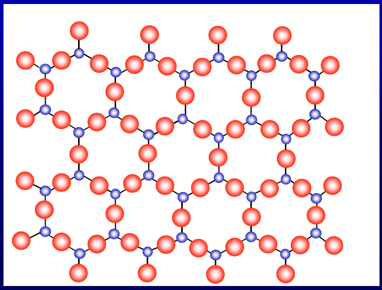
Pyroxenes: solid solution series
MgSiO3-FeSiO3

Enstatite - Ferrosilite



chain
silicates
$[SiO_3]_\infty^{2-}$

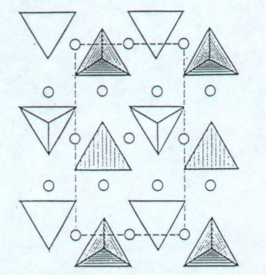
Crystalline silica



layer
silicates
SiO2

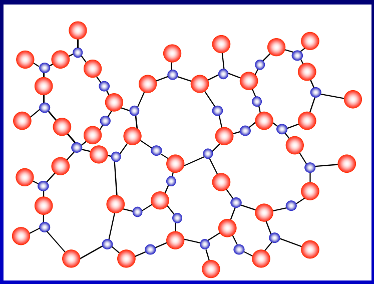
Olivines: solid solution series
Mg_2SiO_4-Fe_2SiO_4

Forsterite -Fayalite



neso silicates
$[SiO4]^{4-}$

Amorphous silica

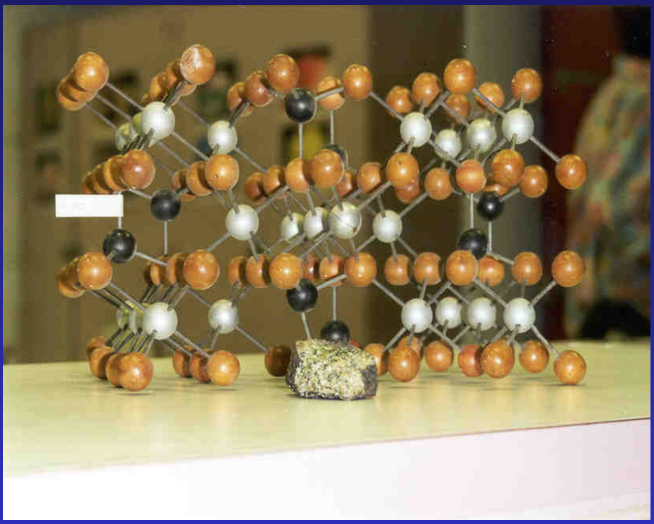


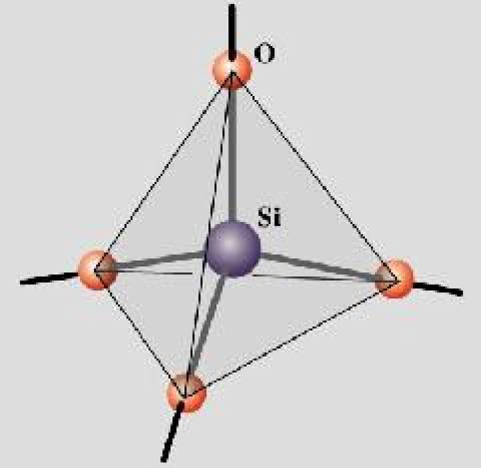
3-dim.
network

Incorporation
of modifier
cations destroys
oxygen bridges

non-bridging oxygen

Silicate Tetrahedron – A Basic Unit





- SiO_4 tetrahedron: Radius of central Si^{4+} ion is 0.041 nm
  Radius of the O^{2-} ion is 0.140 nm

The ratio of these radii is = 0.041/0.140 = 0.3 → Volume is basically filled with oxygen atoms; Number of its nearest equal neighbours (coordination number) is 4 → Nearest neighbours form a tetrahedron

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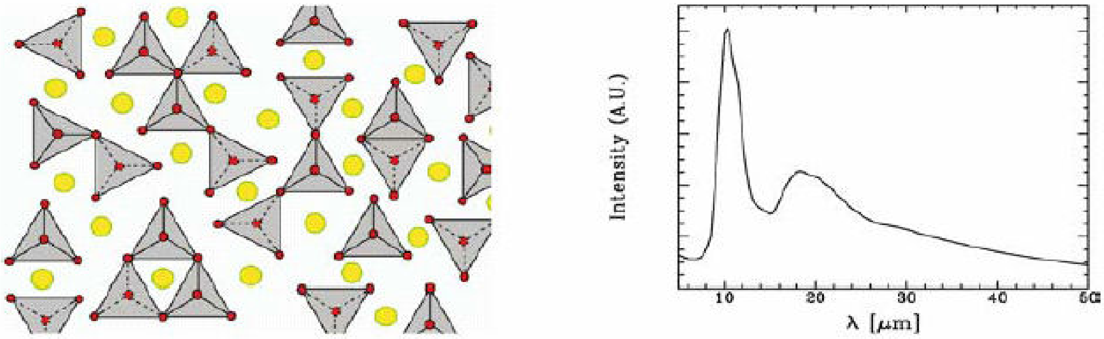
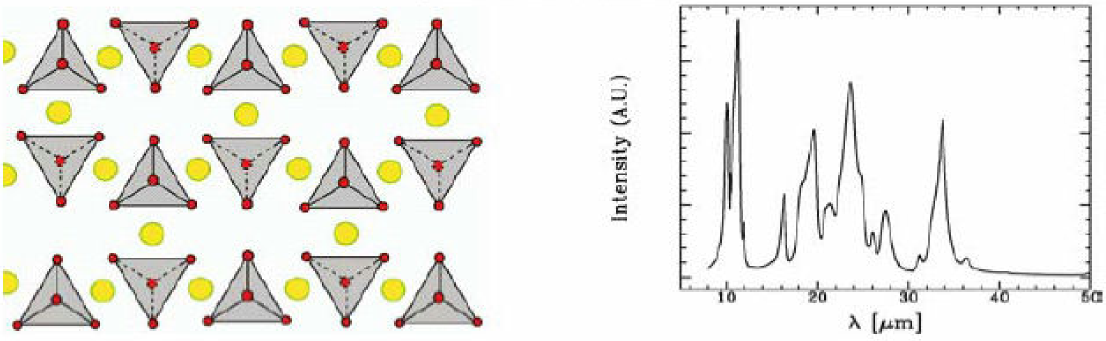
IR Properties of Silicates – Amorphous vs. Crystalline Structures

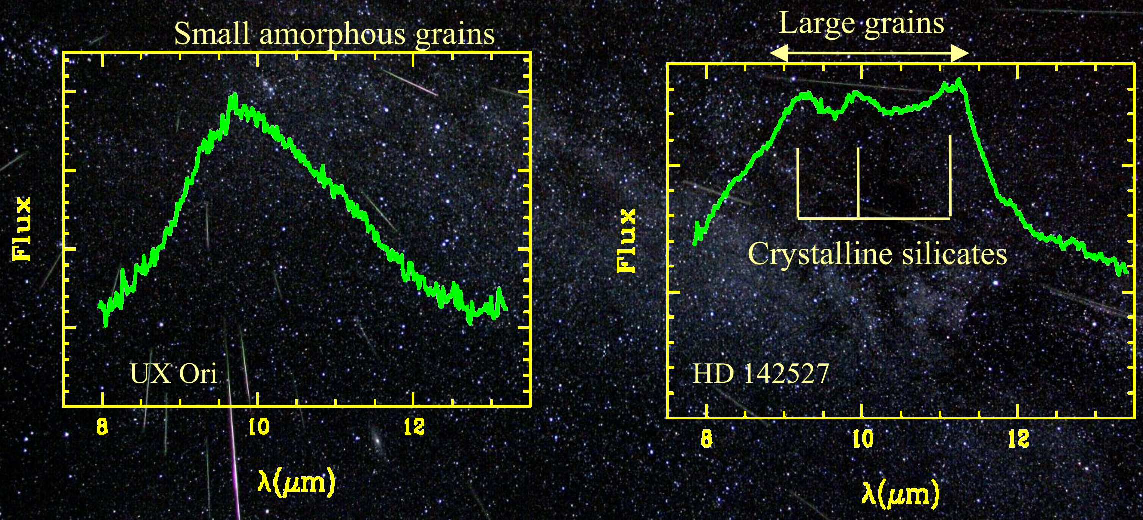
Amorphous structure



Crystalline structure



Dust processing at 10 micron



"Pristine"

"Evolved"

IR Properties of Silicates – Amorphous vs. Crystalline Structures

- **10µm band due to Si-O stretching; position depends on level of SiO_4 polymerization (e.g. band shifts from 9.0 µm for SiO_2 to 10.5 µm for $Mg_{2.4}SiO_{4.4}$ – Jäger et al. 2003)**

- **18 µm band additionally broadened (coupling of the Si-O bending to the Me-O stretching vibration)**

- **Crystalline silicates: Bands beyond 20 µm caused by translational motion of metal cations within the oxygen cage and complex translations involving Me and Si atoms**

Basic Optical Data
Cosmic Dust Analogues

- Broad Wavelength Range
- Appropriate Structure
  (Fe/Mg, am./cryst. …)
- Isolated Small Particles
- Temperature Range

Jena database of optical data (Henning et al. 1999)
http://www.astro.uni-jena.de/Group/Subgroups/Labor/odata.html

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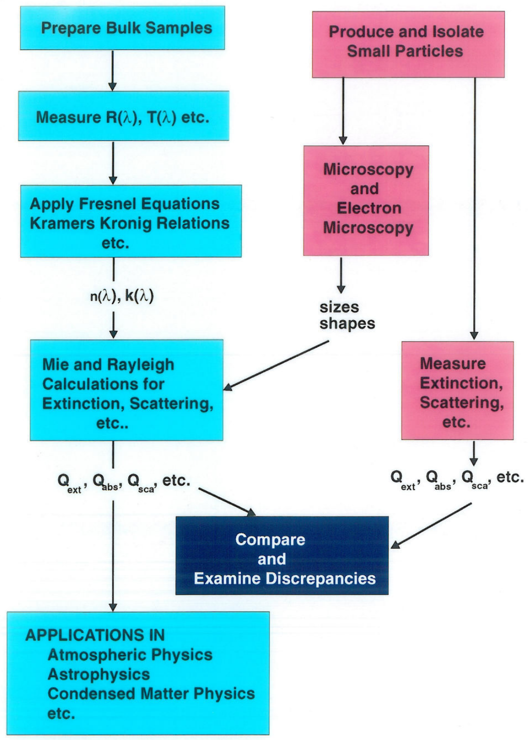
Laboratory measurements



Prepare Bulk Samples

Measure R(λ), T(λ) etc.

Apply Fresnel Equations
Kramers Kronig Relations
etc.

n(λ), k(λ)

Mie and Rayleigh
Calculations for
Extinction, Scattering,
etc..

Q_{ext}, Q_{abs}, Q_{sca}, etc.

Produce and Isolate
Small Particles

Microscopy
and
Electron
Microscopy

sizes
shapes

Measure
Extinction,
Scattering,
etc.

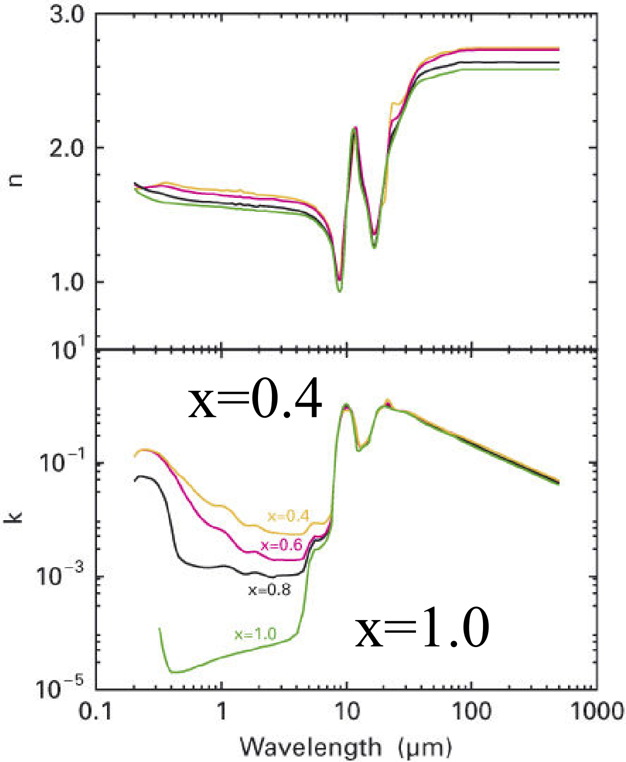
Q_{ext}, Q_{abs}, Q_{sca}, etc.

Compare
and
Examine Discrepancies

APPLICATIONS IN
Atmospheric Physics
Astrophysics
Condensed Matter Physics
etc.

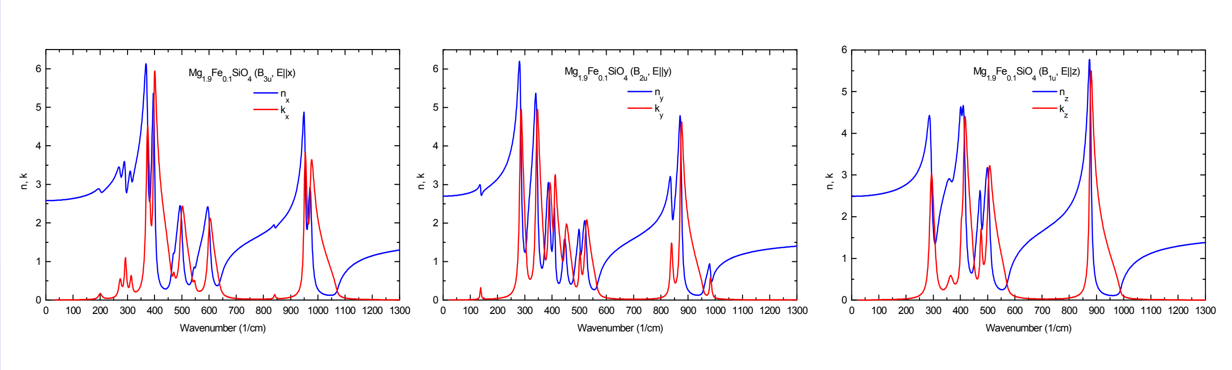
Optical data of Amorphous Pyroxenes $Mg_xFe_{1-x}SiO_3$

Increase
of NIR absorptivity
with Fe content



(J. Dorschner, B. Begemann, Th. Henning, C. Jäger and H. Mutschke, A&A 1995)

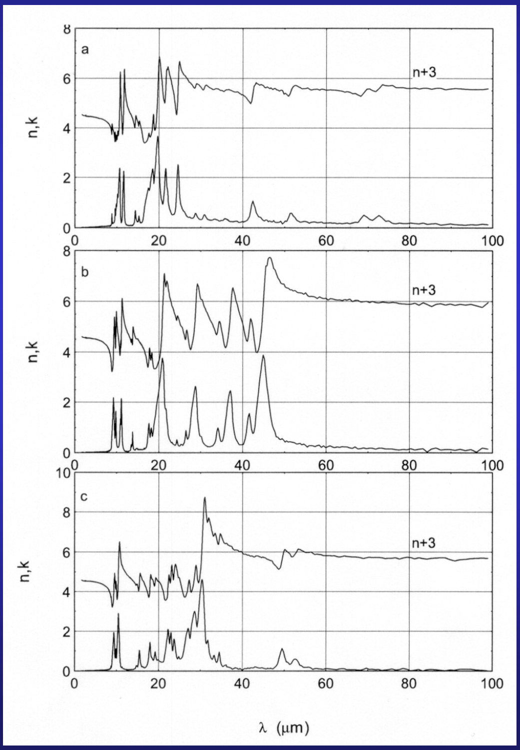
Complex refractive index *n* + *ik*: Olivine Crystal



Fabian, Henning et al. (2001)

Basic Optical Data for Silicates

Enstatite



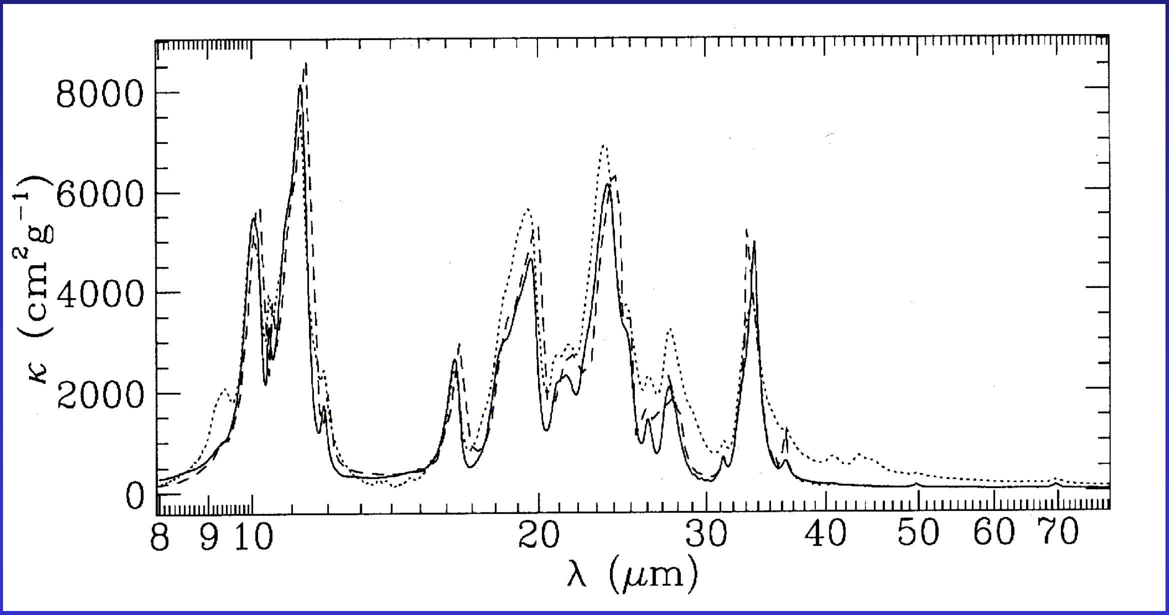
Jäger et al. (1998)

Steps toward interstellar silicate mineralogy
Jena 1994-2003

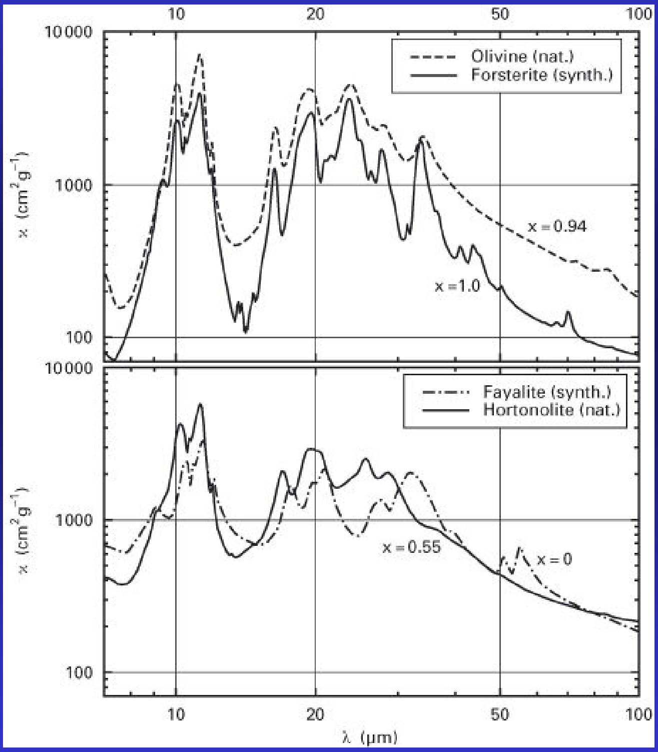
See also:
Papers by Neaples and Kobe Groups

Forsterite Mg_2SiO_4

- Two strong features in the 10 micron region
- Two prominent features in the 18 micron region
- A strong band in the 23 micron complex
- Strong band in the 33 micron complex



$Mg_{2x} Fe_{2-2x} SiO_4$ (Olivines)



Jäger et al. (1998)

Increase of iron content

Olivines $Mg_{2x} Fe_{2-2x} SiO_4$

(1) Strengths of 10 and 20 μm bands relative to the underlying continuum decrease

(2) Band peak positions are shifted to longer wavelengths ($\Delta\lambda \alpha \lambda^2$; bands are shifted by the same amount in wavenumber) – growing metal-oxygen distances

(3) 33.6 and 33.8 μm features: only shoulders in hortolonite (x = 0.55), disappear for fayalite (x = 0.0)

Pyroxenes $Mg_x Fe_{1-x} SiO_3$

(1) Similar behaviour as olivines with the exception of the 10 μm region (Si-O stretching modes not sensitive to Fe incorporation)

LOW-TEMPERATURE EFFECTS

Henning and Mutschke (1997)

Crystalline Dielectric Solids

- IR bands (single phonon transitions):
  Sharpening because of decreased damping, shift to shorter wavelengths
- FIR absorption (phonon difference processes):
  significant reduction because of decreasing phonon number

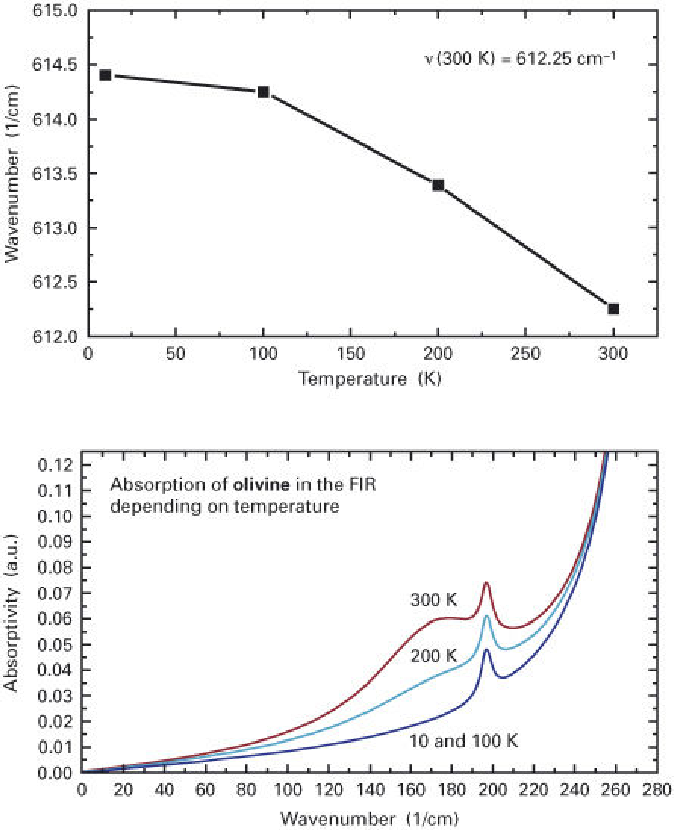
Amorphous Dielectric Solids

- FIR absorption:
  Dominated by disorder-induced single phonon processes, no temperature dependence
- Millimeter range:
  highly temperature-dependent low energy processes, e.g. tunneling transitions in glasses

Semiconductors

- free charge carrier absorption:
  vanishes because conduction band is depopulated

Temperature Behaviour of Optical Properties (Olivine)



What is expected ?

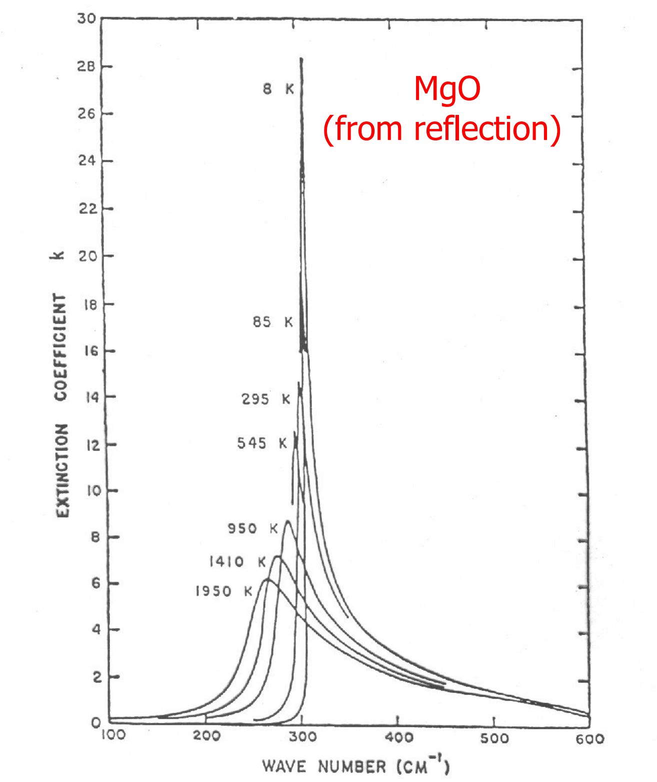


Fig. 9. Computed extinction coefficients of MgO as functions of wave number and temperature. (From Jasperse *et al.* [12].) 1966

=>Bands are broadened and shifted to lower frequencies with higher temperature

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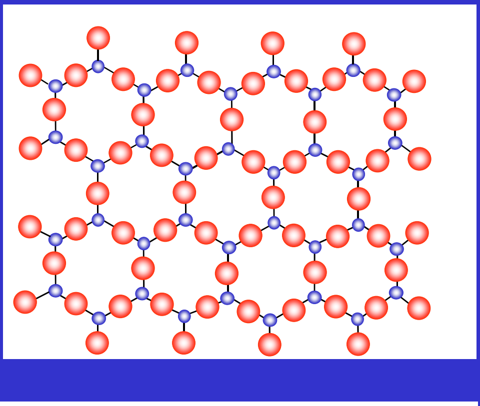
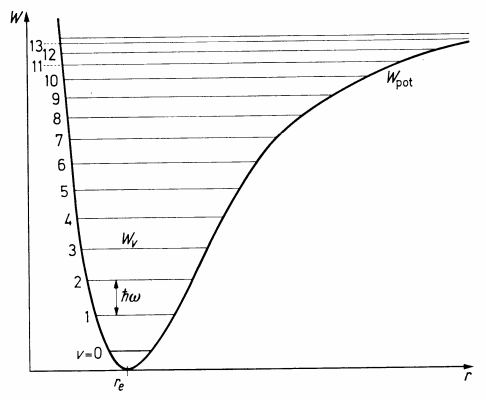
Henning & Mutschke 1997, Mennella et al. 1998, Bowey et al. 2001, Chihara et al. 2001, Koike, Mutschke et al. 2005

Explanation (higher T):



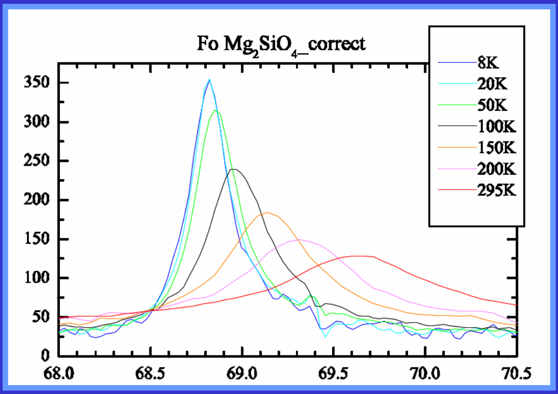
- **Lattice expansion => smaller forces => lower excitation frequencies**
- **Moving atoms => broader frequency range for excitation**

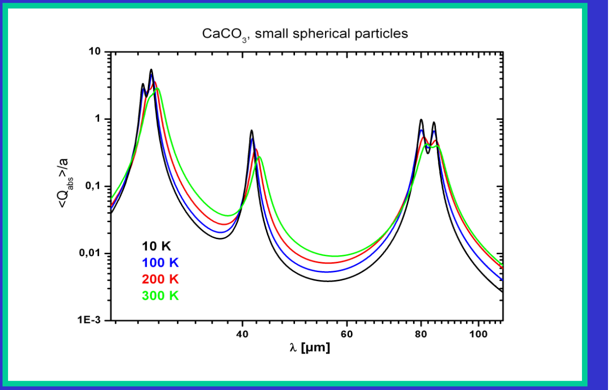


- **physically: anharmonicity of potential**
  + scattering at other phonons (shorter lifetime – broader levels)

Band changes at low temperatures

Prominent examples:
69µm forsterite (Mg_2SiO_4) band
41-43µm [spher. grains] calcite ($CaCO_3$) band

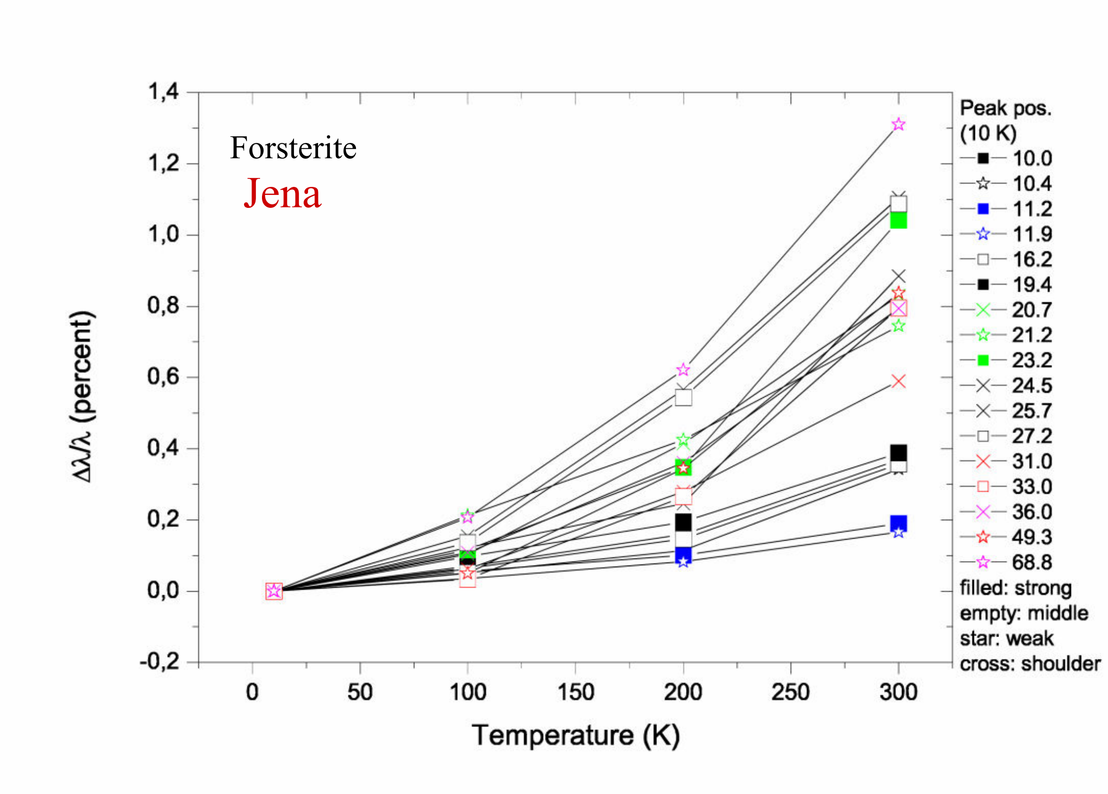


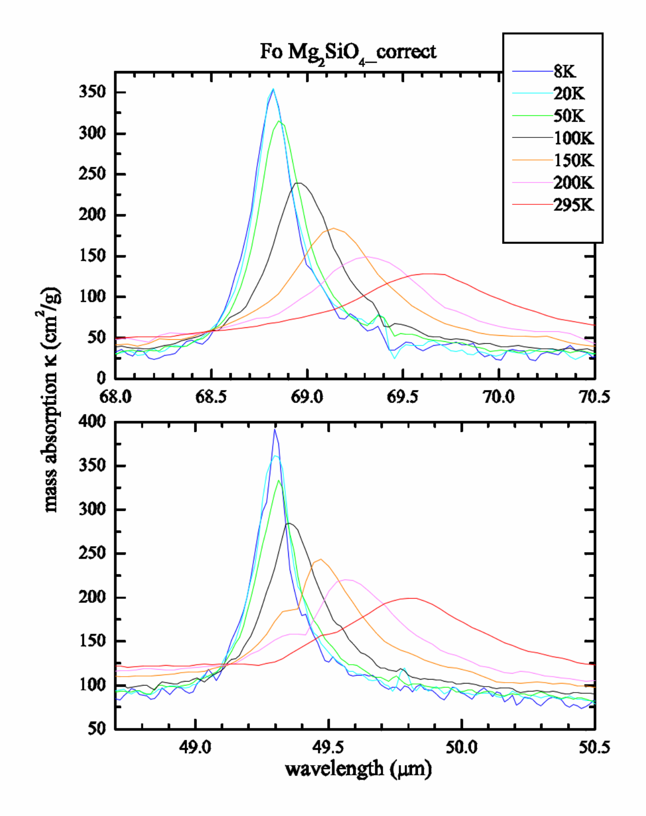


Koike, Mutschke et al. (2006)

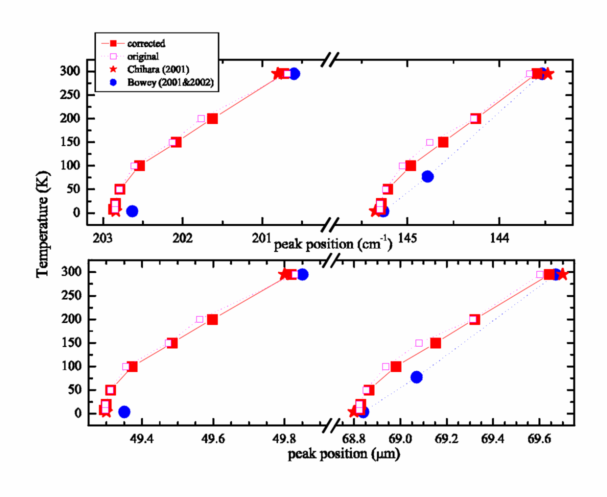
Posch, Mutschke et al. (2006)

How big is the relative peak shift ?

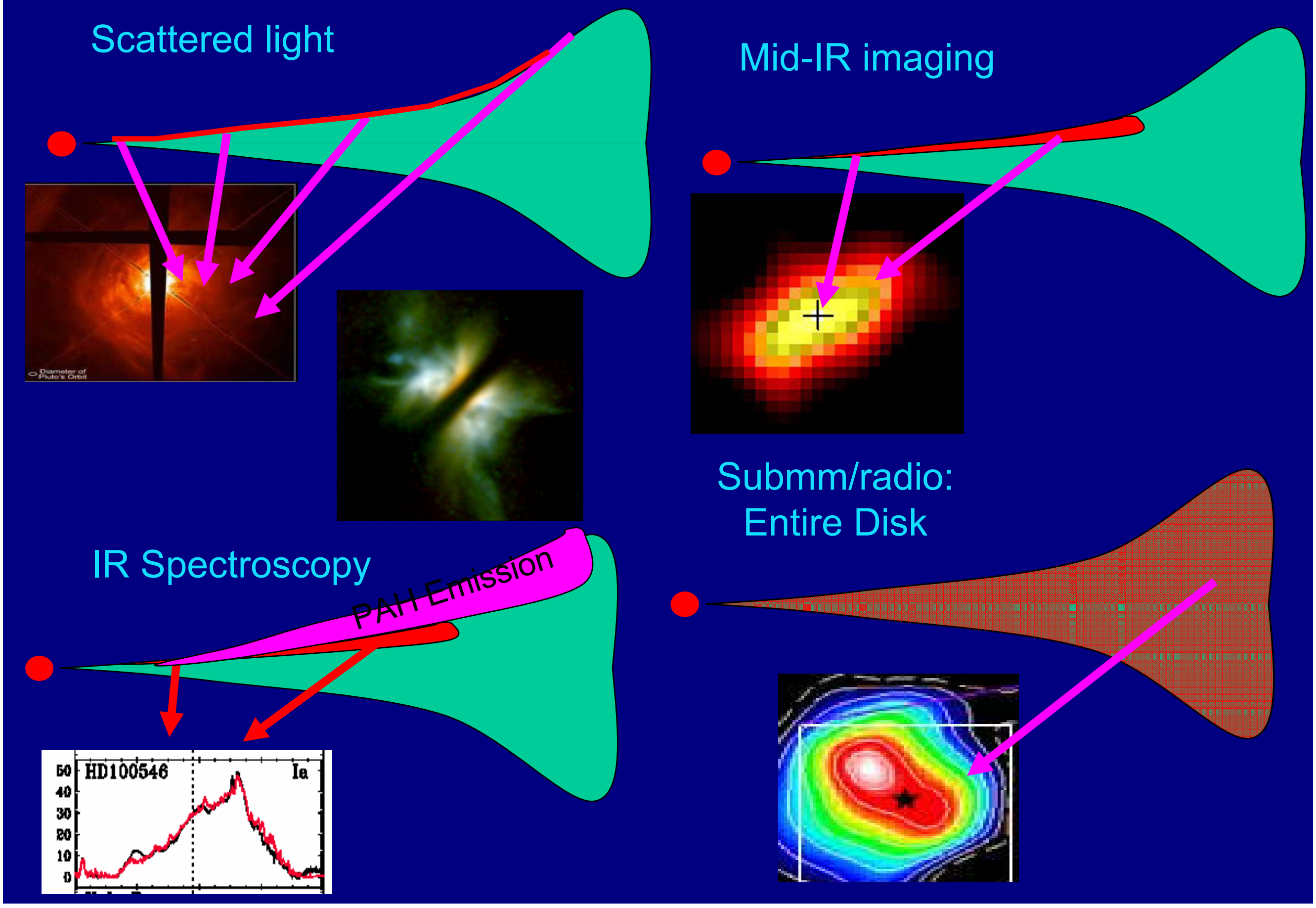




Long-wavelength forsterite bands as thermometer



Which observations probe which grains?



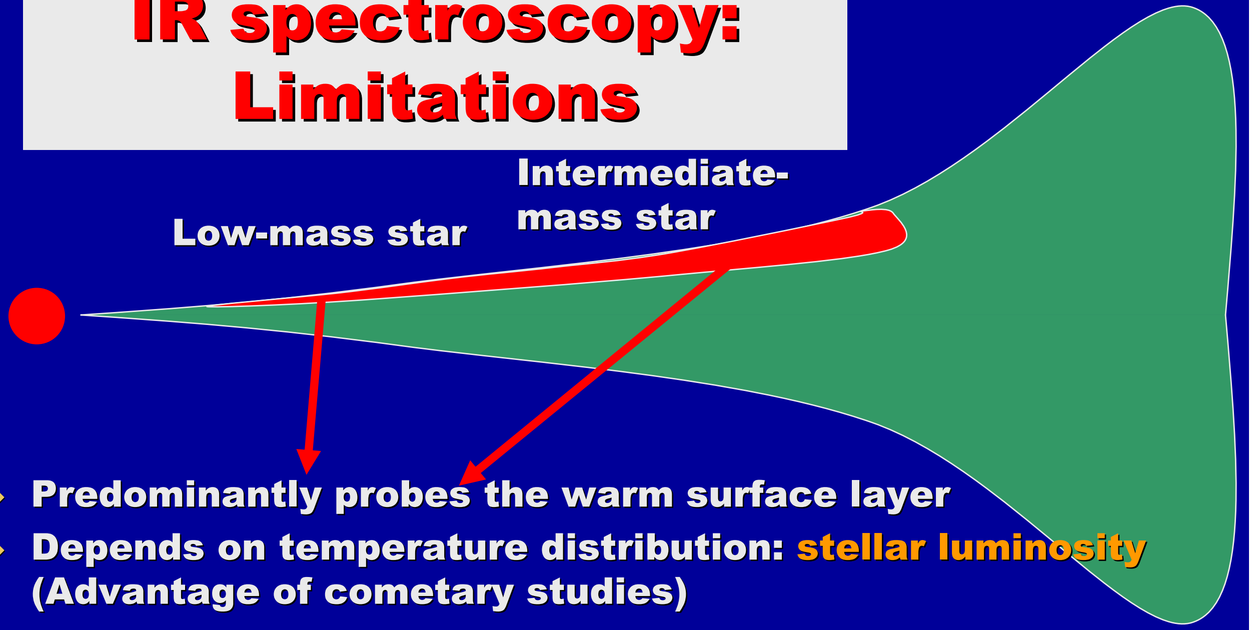
Scattered light

Mid-IR imaging

IR Spectroscopy

Submm/radio: Entire Disk

IR spectroscopy: Limitations



Low-mass star

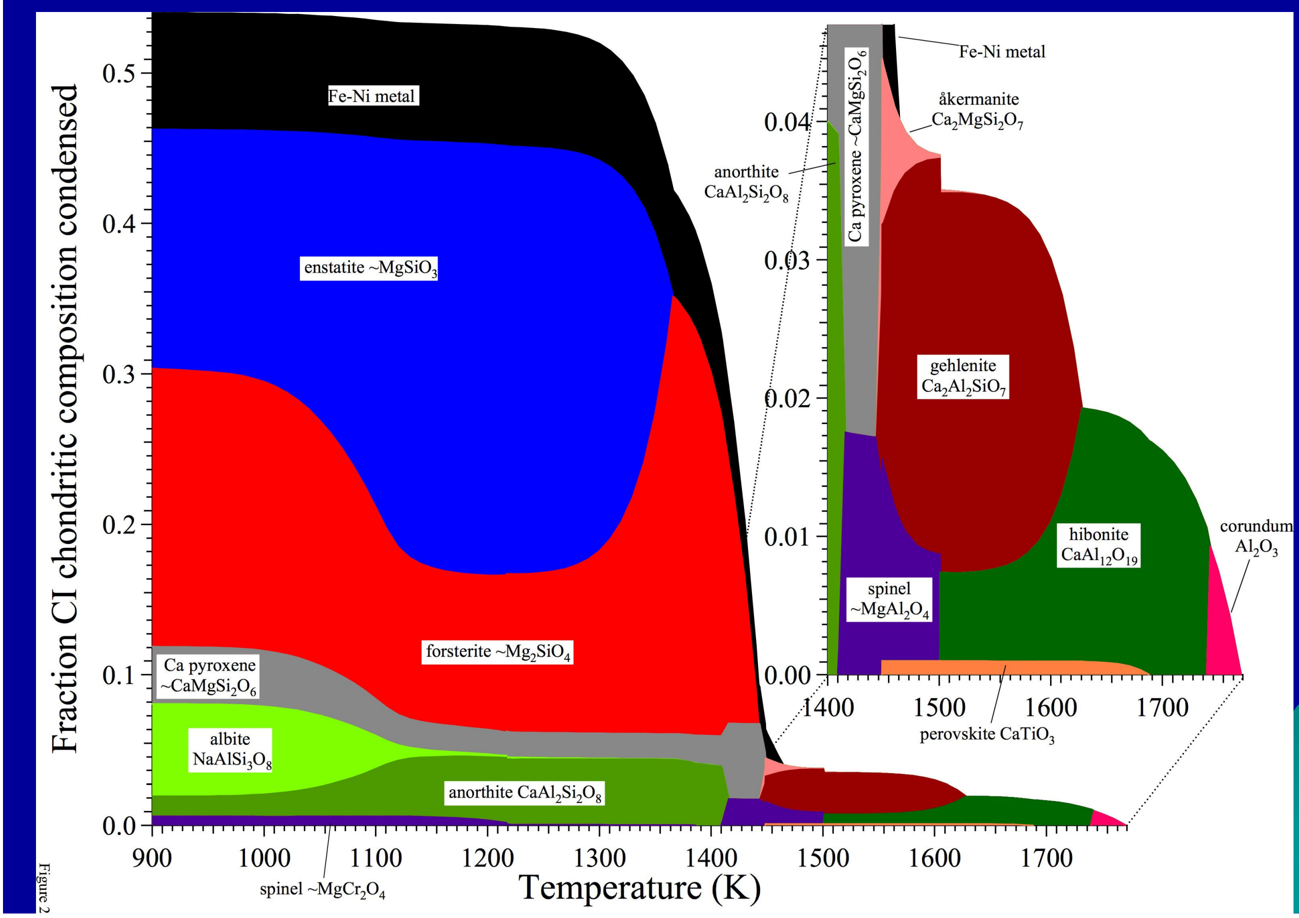
Intermediate-mass star

- **Predominantly probes the warm surface layer**
- **Depends on temperature distribution: stellar luminosity (Advantage of cometary studies)**

- **Trace grains only up to micron sizes**
- **Lower sensitivity compared to millimeter spectroscopy**

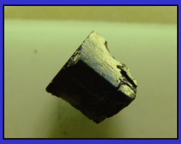
- **Ground-based: Small wavelength range**
- **Space-based: Low spatial resolution**

Dust condensation sequence



Metal Oxides in the Dust Condensation Sequence

For solar elemental abundances and a pressure of $5*10^{-9}$ bar, the following *stability limits* of oxides and silicates containing abundant elements are currently predicted:



Corundum α-Al_2O_3: ~ 1420K

Hibonite $CaAl_{12}O_{19}$: ~ 1320K

Perovskite $CaTiO_3$: ~ 1300K

Gehlenite $Ca_2Al\ [(Si,Al)_2O_7]$:~ 1200K

Grossite $CaAl_4O_7$: ~ 1200K

Spinel $MgAl_2O_4$: ~ 1150K

Forsteríte Mg_2SiO_4: ~ 1090K

(Gail 2003;
Ebel&Grossman 2000)

$CaCO_3$?

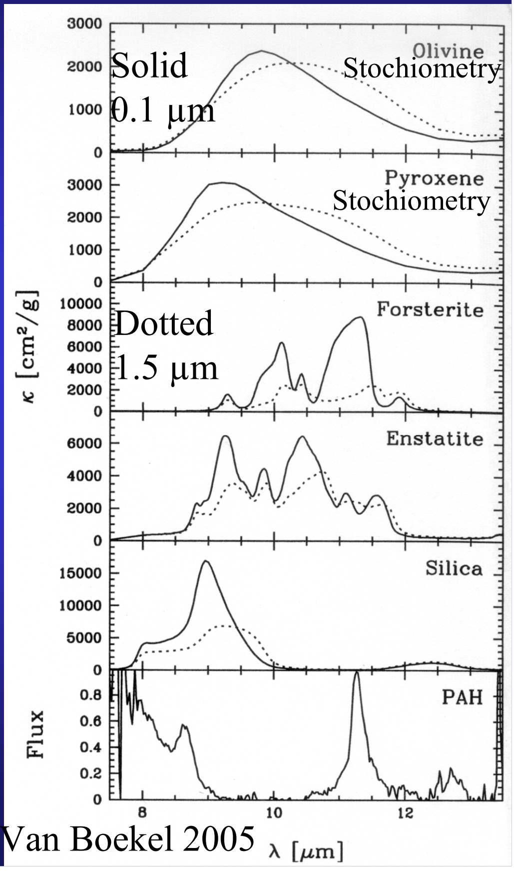
Dust Disk Mineralogy - Wavelength Positions

Forsterite	10.0, 11.3, 16.3, 23.5, 27.5, 33.5, 69.7 µm
Enstatite	9.4, 9.9, 10.6, 11.1, 11.6, 18.2, 19.3, 21.5 µm

(strong features, exact positions vary with material + temp.)

Koike et al. (1993, 2000, 2003),
Colangeli et al. (1995),
Jäger et al. (1994, 2003),
Fabian et al. (2001),
Chihara et al. (2002), ….

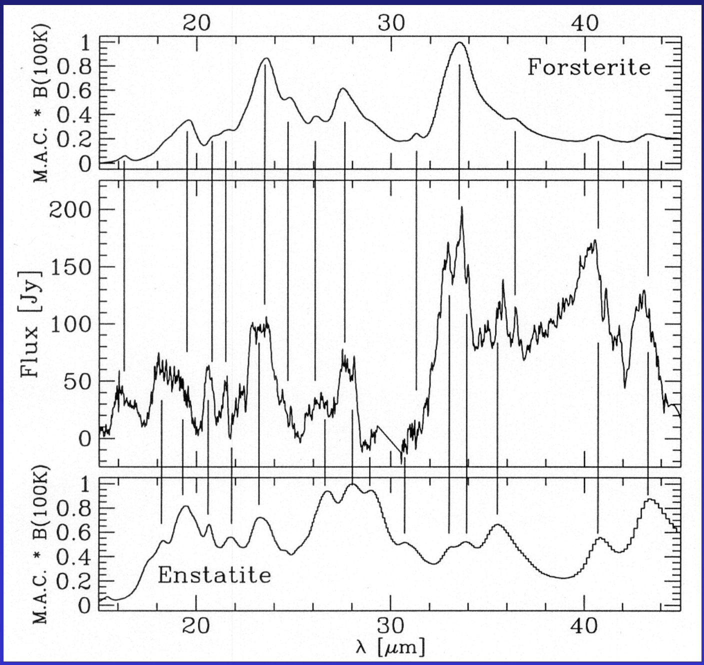
Database: Henning et al. (1999)



Van Boekel 2005

Crystalline Revolution (ISO and Spitzer)

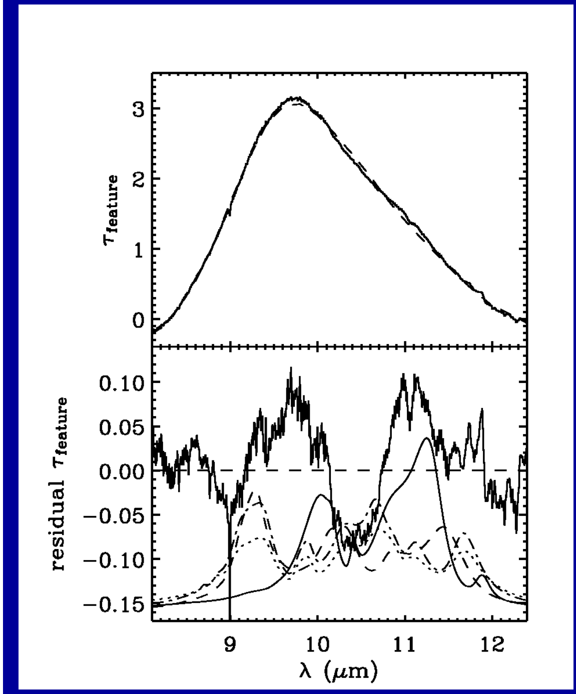
AFGL 4106



T=100 K

Jäger et al. (1998)

Crystalline silicates in the ISM



Composition of amorphous silicates:

- **Olivine (MgFeSiO4): 85%**
- **Pyroxene (MgFeSi$_2$O$_6$):15%**

Crystallinity

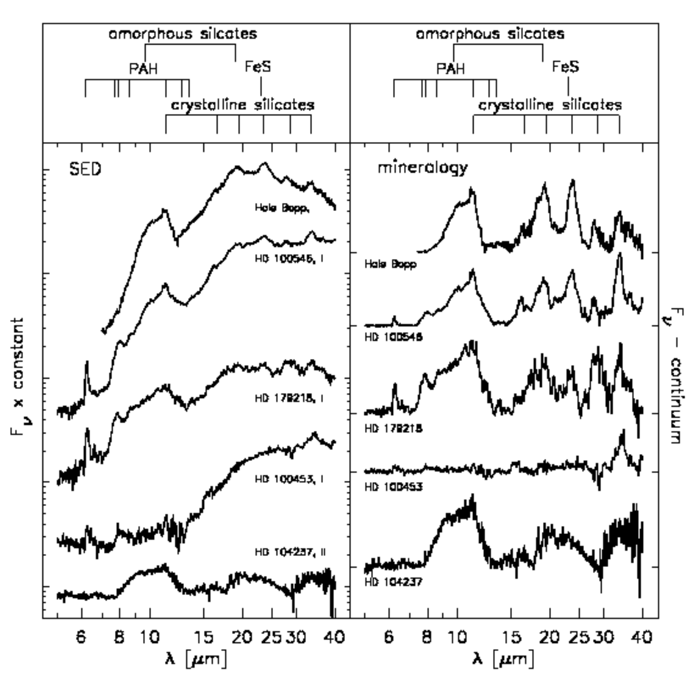
- **<0.4 % of silicates in diffuse ISM are crystalline**
- **Crystallinity of 0.2%(±0.2%) gives best fit to the 10 micron absorption feature**

But:

Stellar ejecta are 10-20% crystalline!

(Kemper et al. 2004)

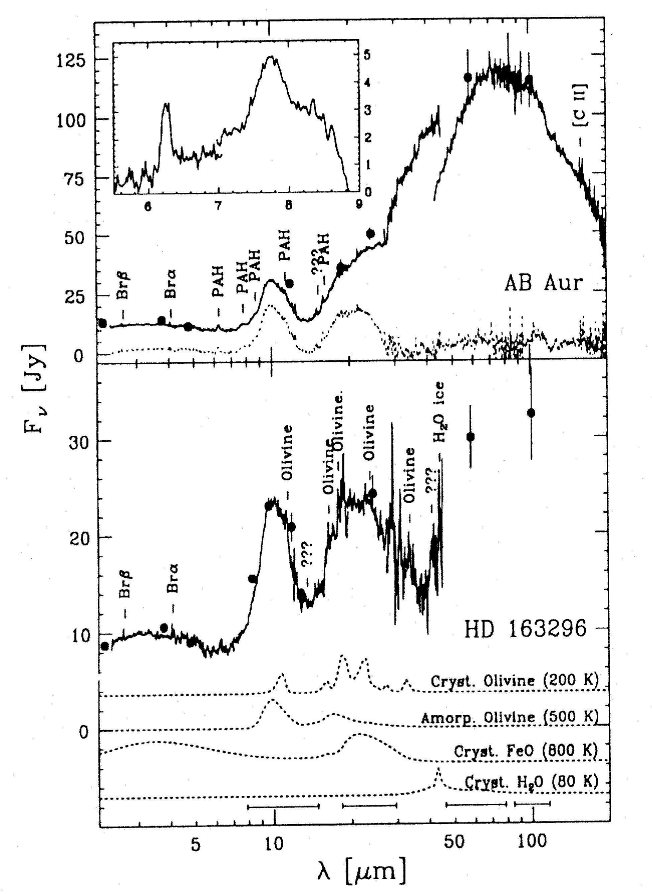
ISO: Dust in Herbig Ae systems



- **Dust mineralogy**
  - **Forsterite**
  - **Enstatite**
  - **FeS ???**
  - **Amorphous Silicates**
  - **PAH**
  - **Silica**
- **Slope change**
- **Grain growth**

See Meeus et al. 2001, van den Ancker et al. 1999, Malfait et al. 1998, Bouwman et al. 2001, VandenBusche et al. 2002

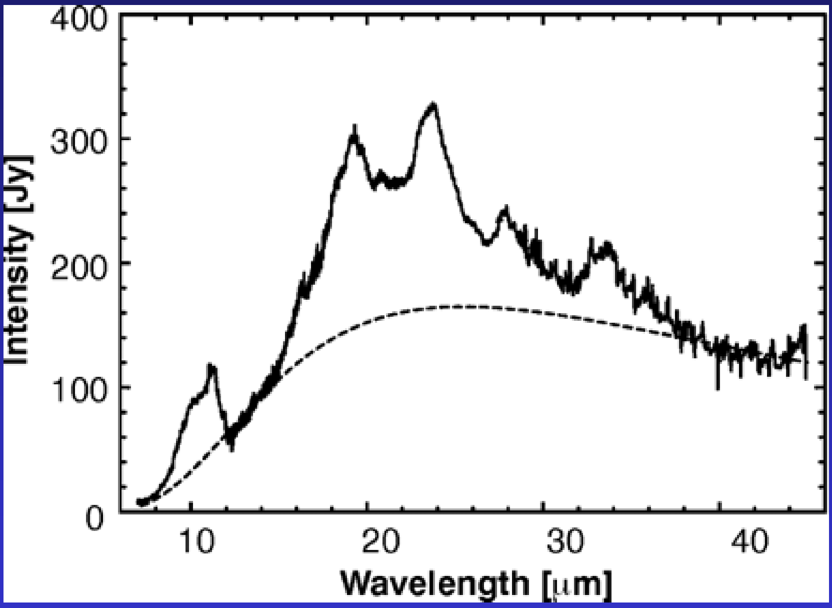
A few more examples



van den Ancker et al. (1999)

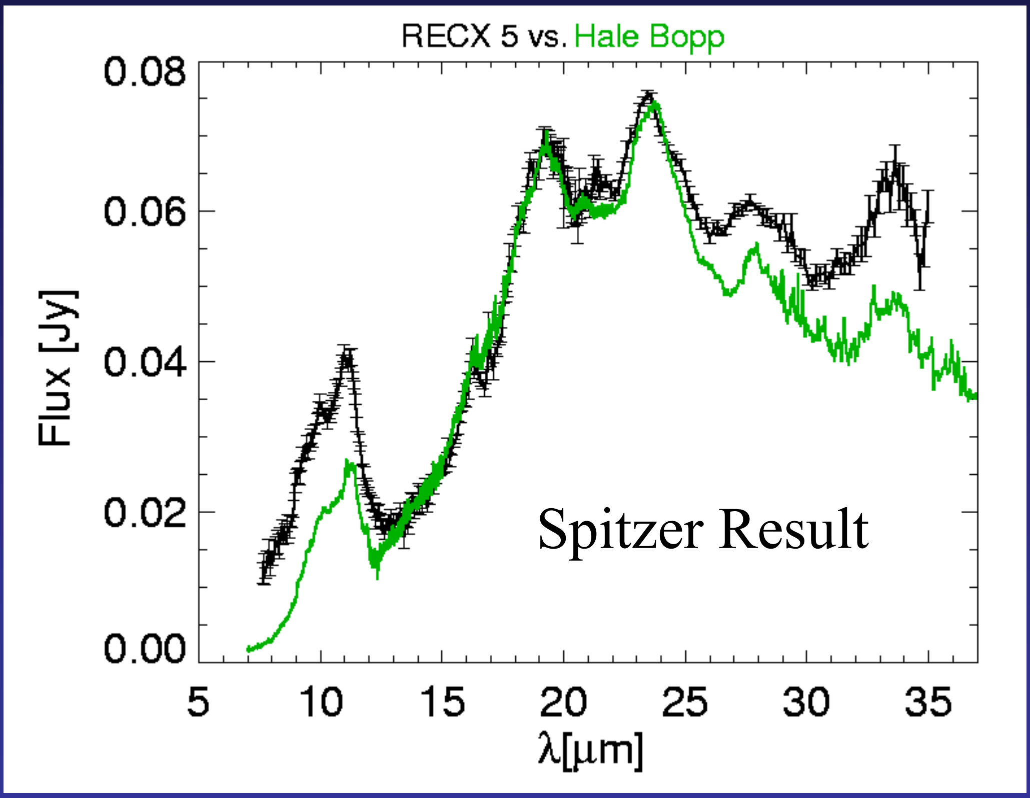
Comet Hale-Bopp (C/1995 O1)

Crovisier et al. (1997), see also Wooden et al. (1999, 2000)



Evidence for crystalline Mg-rich olivines (forsterite)
(e.g. 11.3, 16.5, 19.8, 24.0, 27.6, 33.9 micron bands)

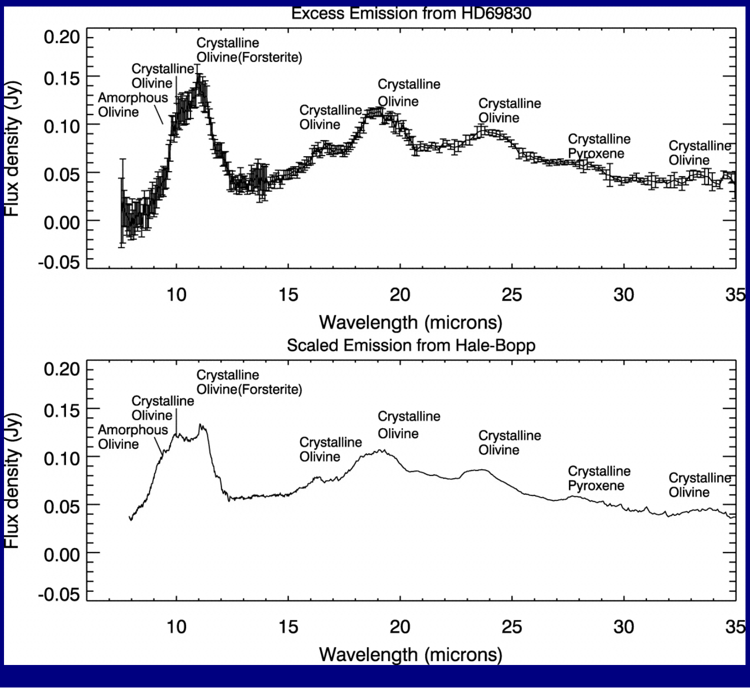
RECX5: Hale Bopp Formation around an M4 star?



Bouwman, Lawson, Henning et al. (2006, in prep.)

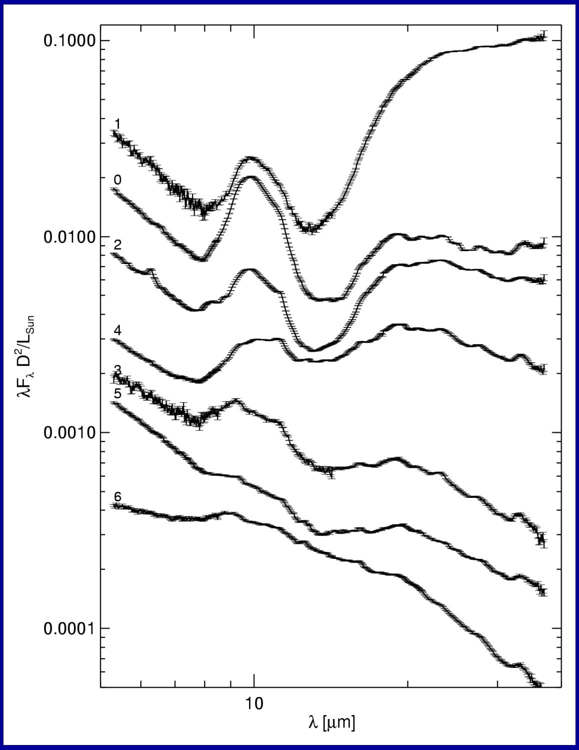
Large Excess and Crystallinity in HD 69830
A Rare Case

(12.6 pc, K0V, 0.6-2 Gyr with higher age more probable)



Beichman
et al. (2005)

FEPS: 3-15 Myr old TTS stars

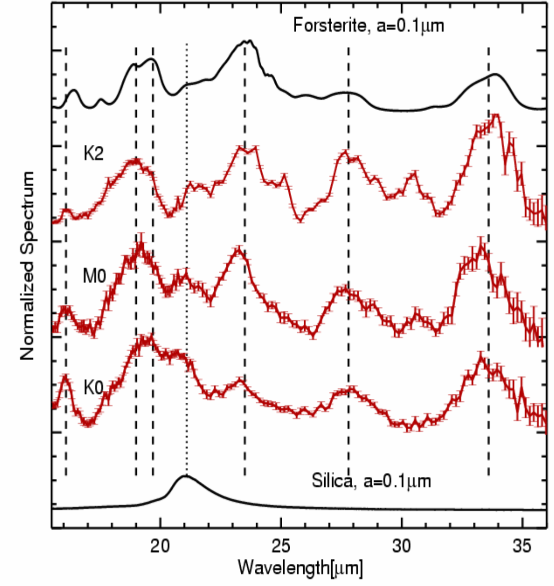


- Same as HAEBEs
- Strong variation in amorphous silicate band strength
- Changing SED slopes
- Unambiguous detection of PAHs

(Bouwman, Henning et al. 2006)

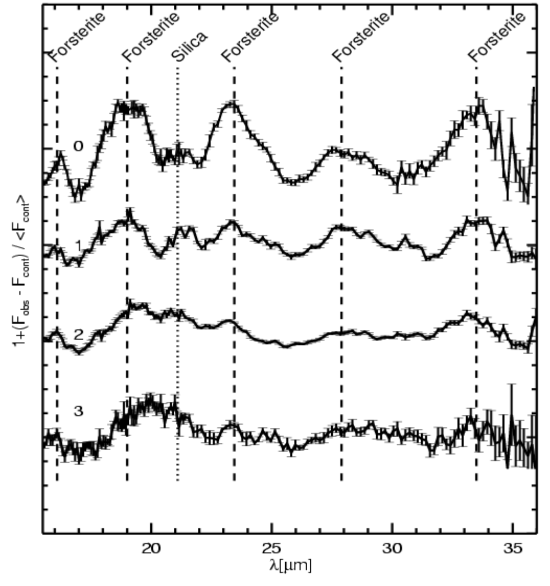
Long-wavelength Observations of Disks

FEPS:TTS



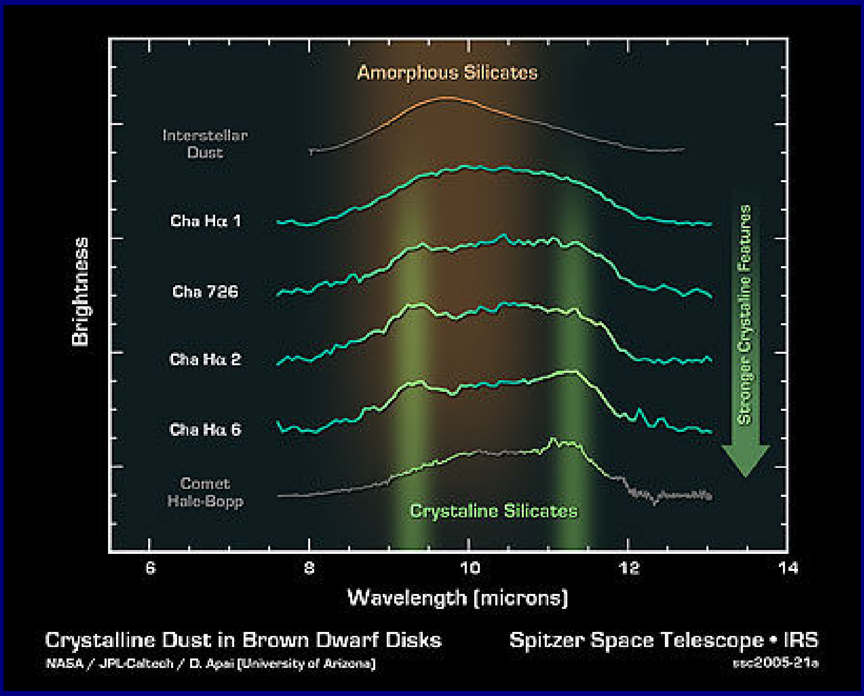
D=140 pc
Age=5-10 Myr

Eta Cha: M stars



D=100 pc
Age=8 Myr

Crystalline Dust in Brown Dwarf Disks

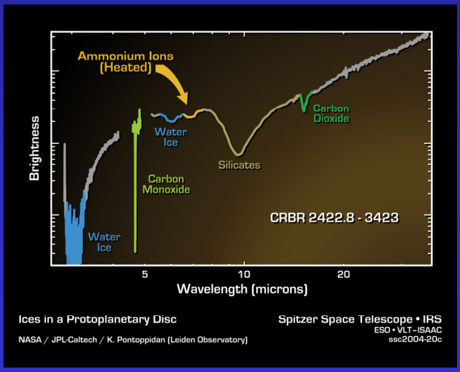


Crystalline Dust in Brown Dwarf Disks
Spitzer Space Telescope • IRS
NASA / JPL-Caltech / D. Apai (University of Arizona)
ssc2005-21a

Apai et al. (Science, 2005)

Chemical composition

- PAHs in some of the systems
- Amorphous silicates present
- Mg-rich crystalline silicates exist (radial variation in structure)
- Silica exists
- No (strong) evidence for FeS
- No evidence for „organics“
- Evidence for simple molecular ices



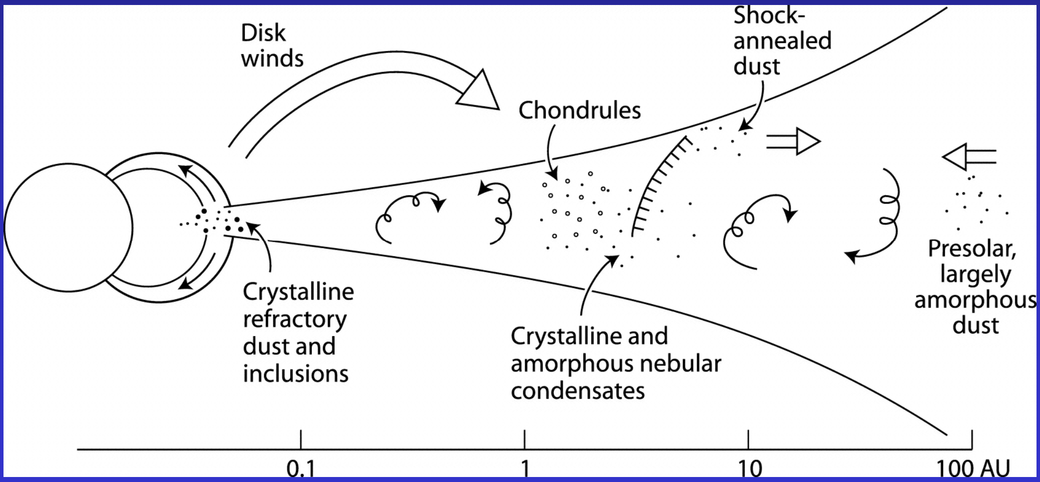
Ices in a Protoplanetary Disc

Spitzer Space Telescope • IRS
ESO • VLT-ISAAC
ssc2004-20c

NASA / JPL-Caltech / K. Pontoppidan (Leiden Observatory)

Origin of Crystalline Silicates in Protoplanetary Disks

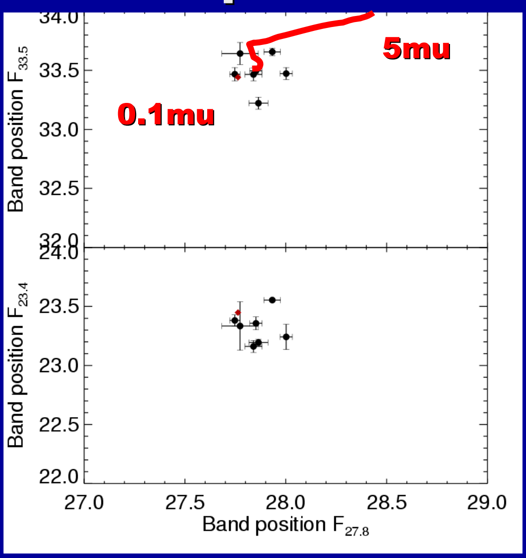
- Annealing/transport of amorphous silicates in/from inner disk or/and shock heating in the outer disk (annealing and/or condensation from the gas phase)
- Pre-solar stardust (???)



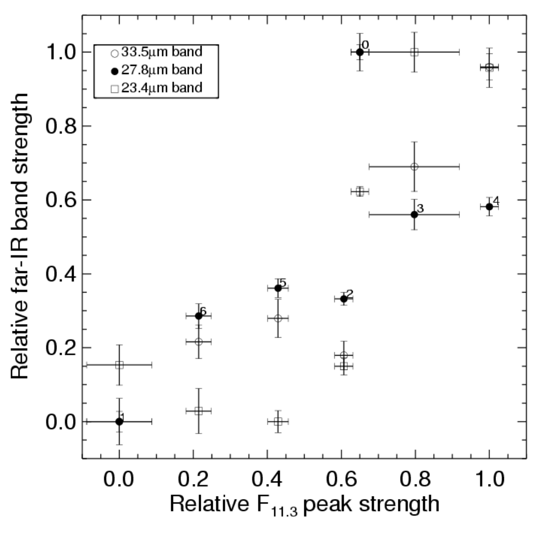
Scott & Krot (2005)

The nature of the crystalline silicates

Band position



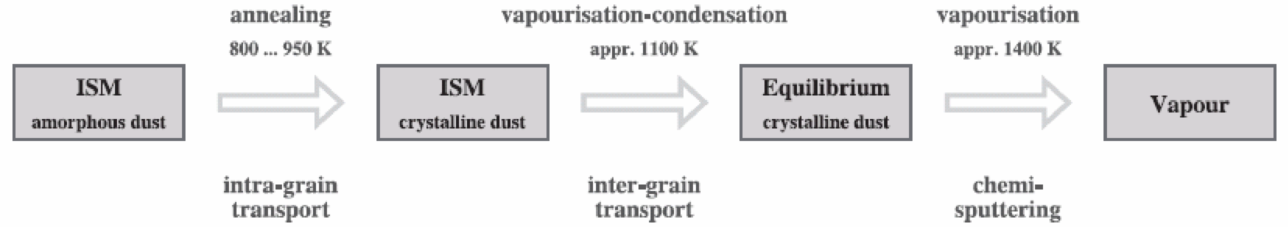
Band strength



Inner (1AU) and outer (~5-10AU) disk connected: Entire planet formation zone becomes crystalline

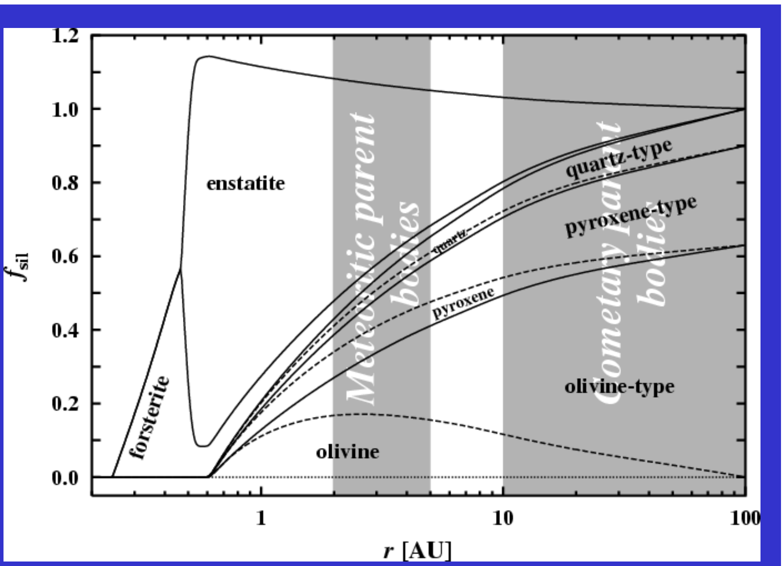
Crystalline silicates do not grow, but may get incorporated into larger aggregates (left)!

Mineralogy of Protoplanetary Disks



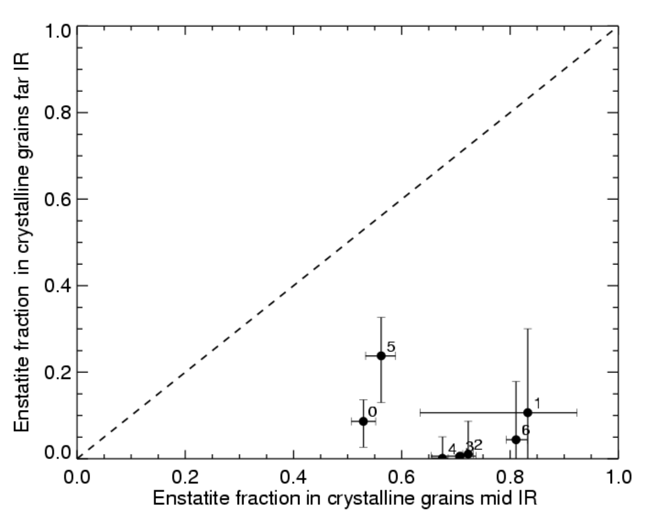
ISM amorphous dust ⇨ annealing 800 ... 950 K, intra-grain transport ⇨ **ISM** crystalline dust ⇨ vapourisation-condensation appr. 1100 K, inter-grain transport ⇨ **Equilibrium** crystalline dust ⇨ vapourisation appr. 1400 K, chemi-sputtering ⇨ **Vapour**

- ⇨ Different dust material in the inner and outer disk
- ⇨ Processing of (am.) quartz, olivine and pyroxene
- ⇨ Formation of crystalline Mg-rich end members and iron
- ⇨ Forsterite – dominant material in the inner disk



Gail (2004)

Origin of crystalline silicates: Annealing or condensation/shocks?

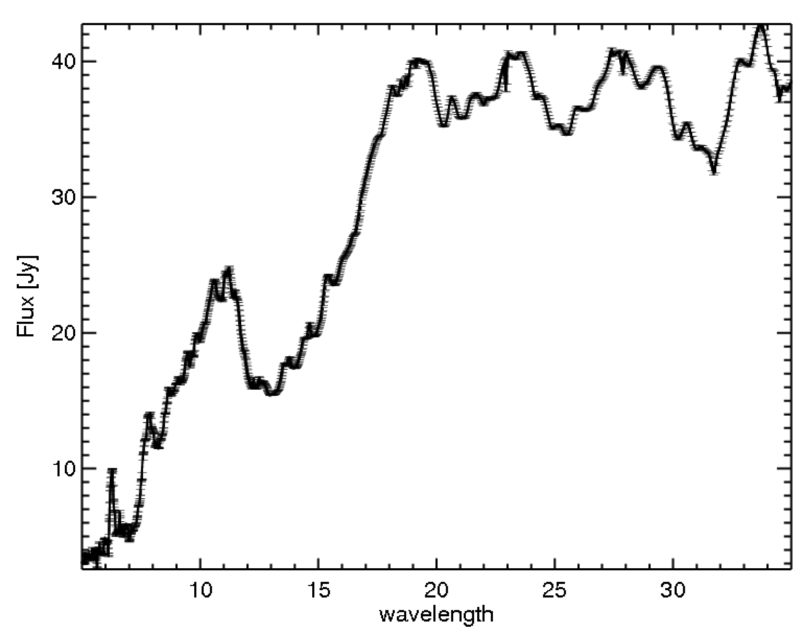


TTS systems

Enstatite dominates in the inner disk (10 μm)
Forsterite in the outer disk (20-30 μm) !!

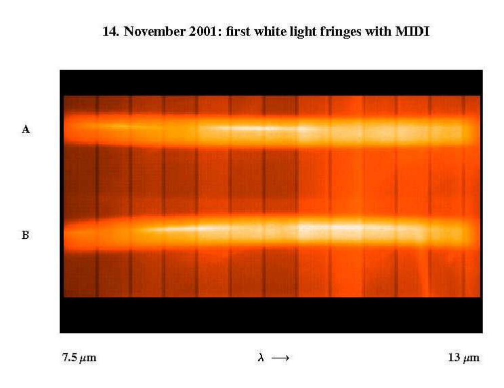
Bouwman, Henning et al. and FEPS team (2006)

Enstatite in outer disk: The HAEBE star HD179218 exceptional case



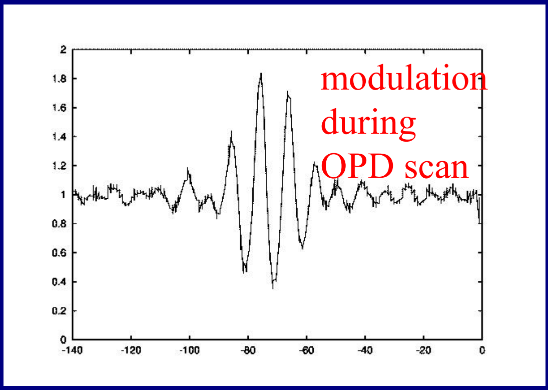
Spectroscopy plus Interferometry
- A New Frontier in Disk Studies -

Full detector



14. November 2001: first white light fringes with MIDI

One wavelength bin



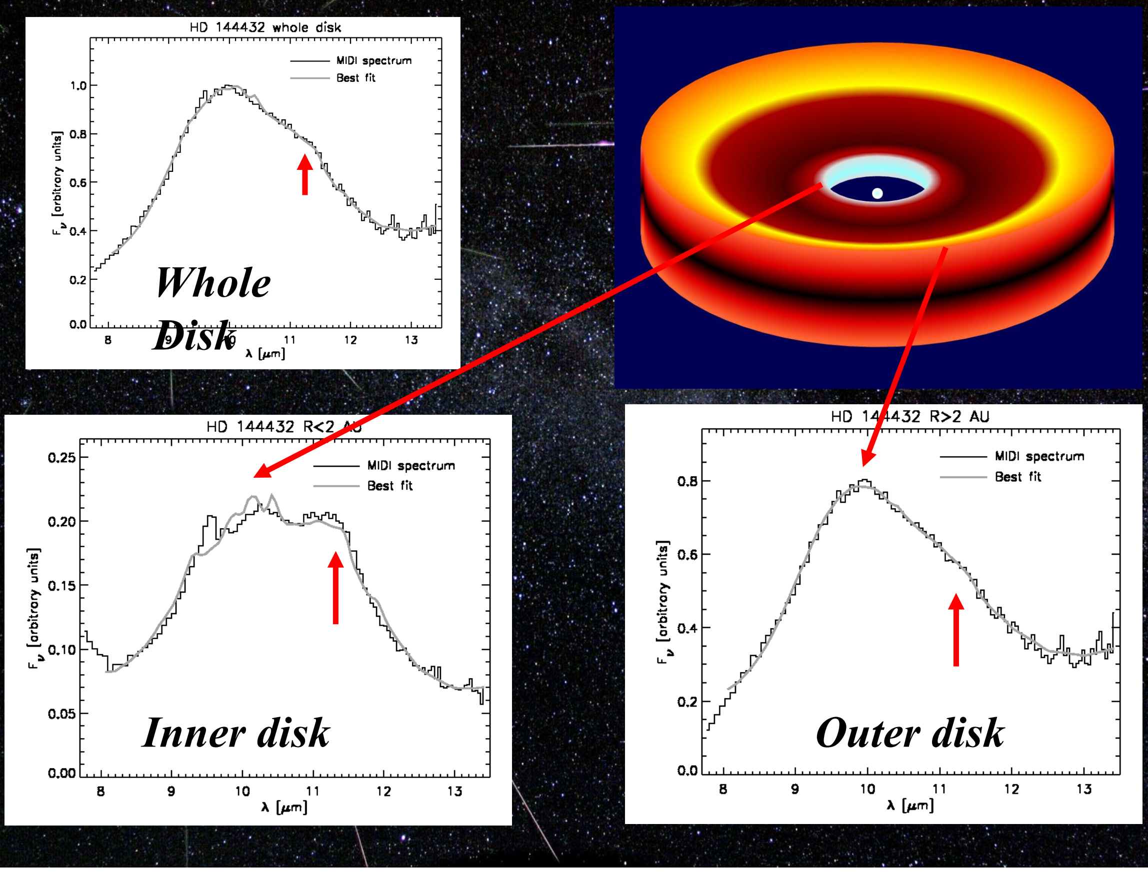
modulation during OPD scan

The two aspects of dispersed interferometric measurements

Visibility V = correlated flux / total flux = $I\,(x;y)$ at $(u,v) = \vec{B}_{eff}/\lambda$
van Cittert – Zernike – Theorem
→ **a size indicator**

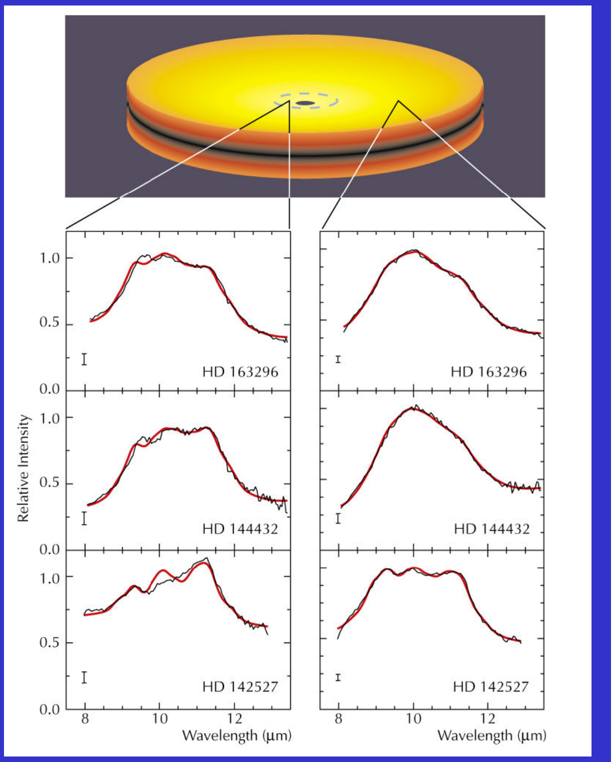
Correlated flux = V · total flux = I_ν of interferometrically selected region of characteristic size λ/B_{eff}
→ **probes physical conditions**

Spatially resolved HAe spectroscopy (MIDI)



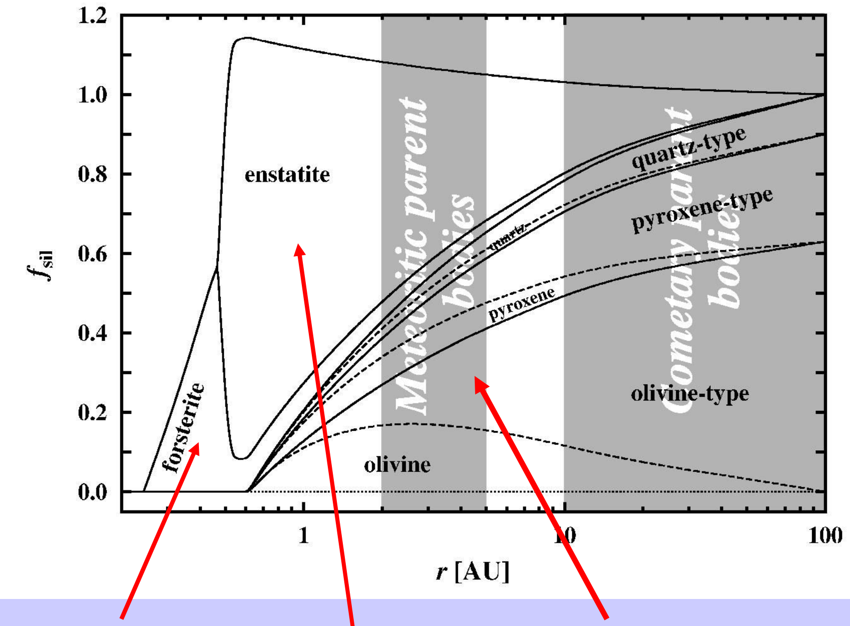
Spatial distribution of the dust

- Crystalline grains concentrated in central disk regions
- Outer disks can be "pristine" while inner disks are "evolved"
- In disks with low crystallinity, crystals seem restricted to innermost disk region
- In disks with high crystallinity, crystals are present also further out.
- HD 142527: inner disk mostly forsterite, further out more enstatite



MIDI @ VLTI Nature, **432**, 479

Radial Distribution of Silicates

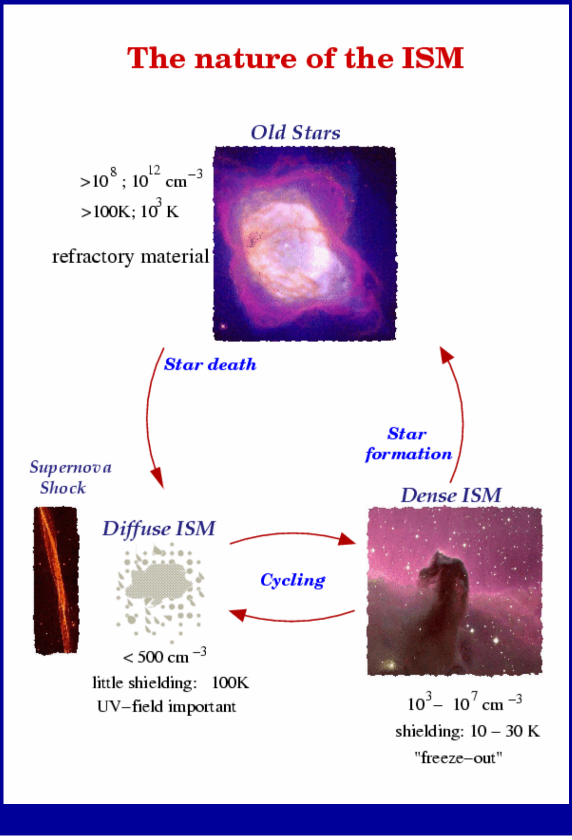


Gail (2004)

Forsterite Enstatite

Fe-rich amorphous olivines,pyroxenes

The Lifecycle of Dust: Crystalline vs. Amorphous Dust

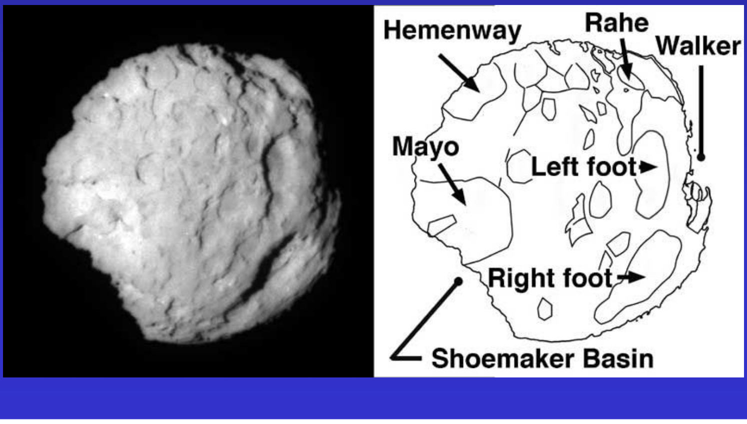


crystallinity *x*

Evolved (AGB, PN, RSG)	**11-18 %**
Evolved (SN)	**?**
diffuse ISM	**<0.4 %**
Star-forming regions	**Small**
Herbig Ae/Be, T Tau stars	**5-8 %**
Debris disks	**?**
Solar system	**Very high**

In-situ studies of primitive material in the solar system

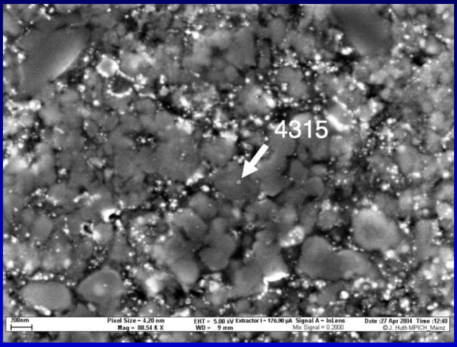
- **Detailed chemical, mineralogical, and isotopic analysis**
- **Properties of the „initial“ grain population**
- **Comparative studies with protoplanetary disks**



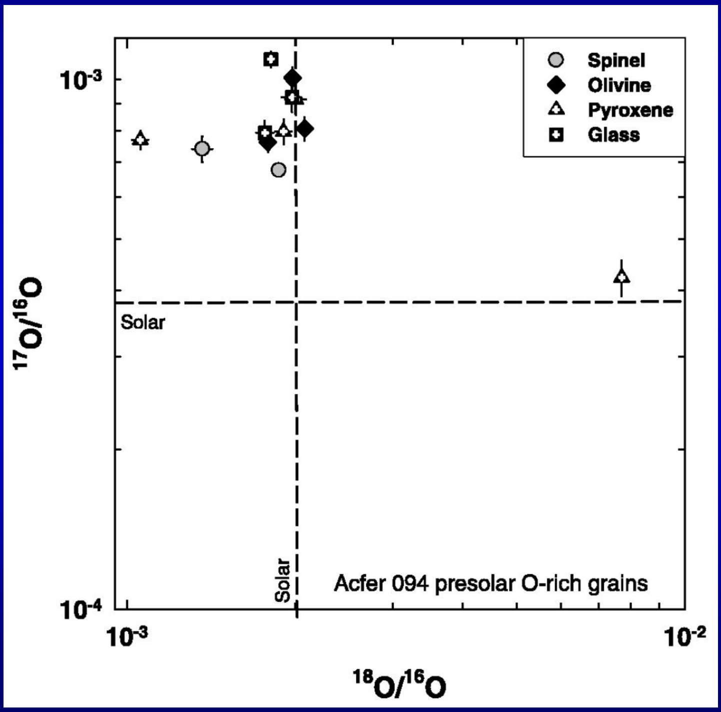
Stardust probe
Closest encounter
July 2, 2004

Silicates from Space

SEM Image



Scale bar: 200 nm



AGB or RGB origin

- 3 Olivine grains
- 4 Pyroxene grains
- 3 Glass-like grains

Hoppe et al. 2005

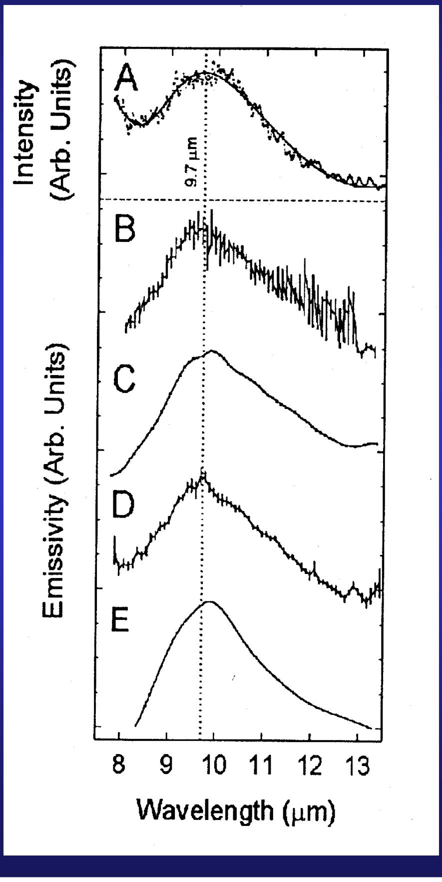
(see also Messenger et al. 2003)

Glass with embedded metals and metal sulphides GEMS

Bradley (1994)

- Abundant component of anhydrous interplanetary dust particles (IDPs)
- Silicate glasses with inclusions of iron-nickel metal and iron-rich sulfides
- Extended ion irradiation history

Comparison of the 10 µm Si-O stretch band



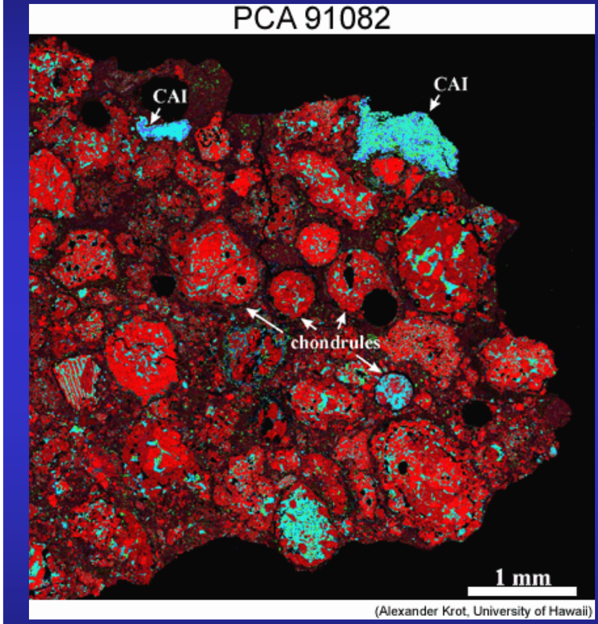
Spectral ambiguity ….

A	GEMS in IDP L2011*B6
B	Elias 16
C	Trapezium
D	DI Cep (T Tauri star)
E	µ Cep (M supergiant)

GEMS: (Mg+Fe)/Si~0.7
(Keller & Messenger 2004)

Bradley et al. (1999)

Calcium-Aluminium Rich Inclusions (CAIs)

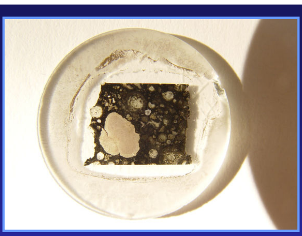


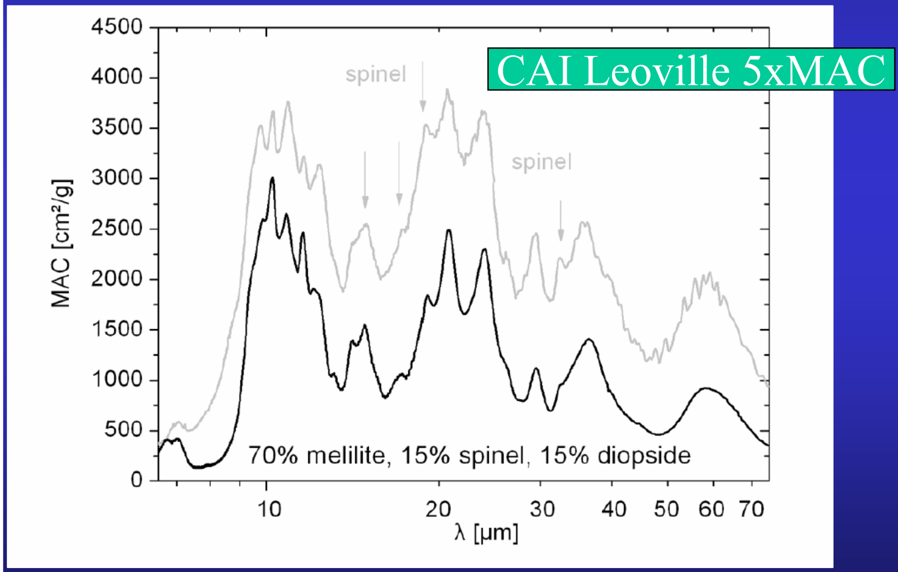
(Alexander Krot, University of Hawaii)

- Oldest known objects in the solar system; age 4.57 billion years (Amelin et al. 2002)
- Consist of high-temperature minerals

X-ray elemental map
Mg – red, Ca – green, Al - blue

Spectroscopy of CAIs

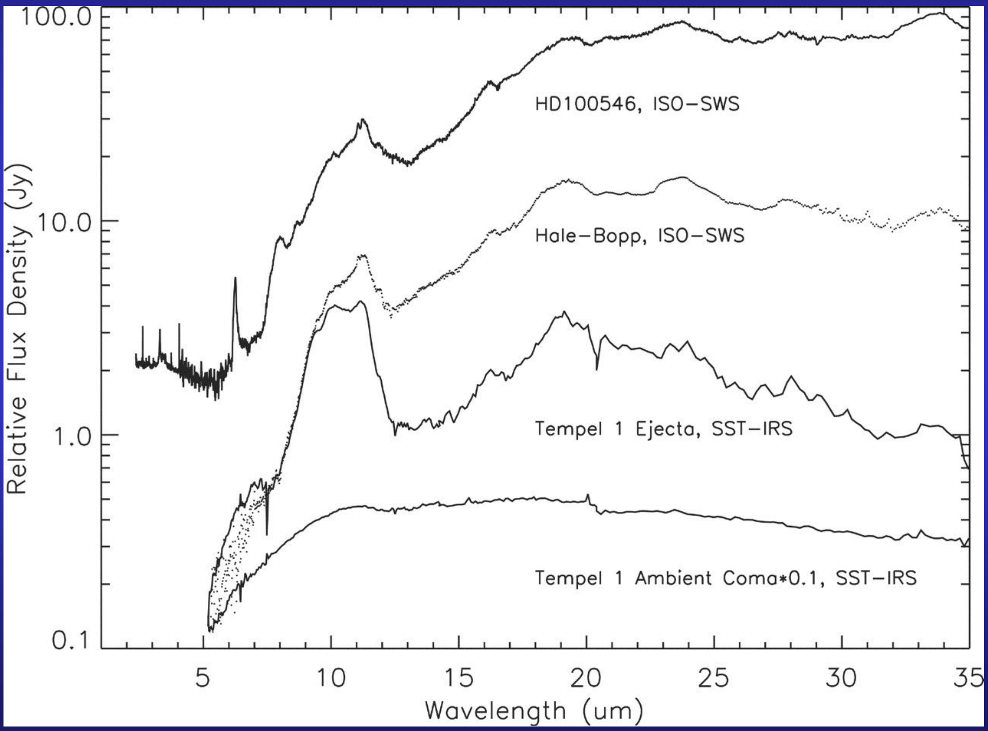




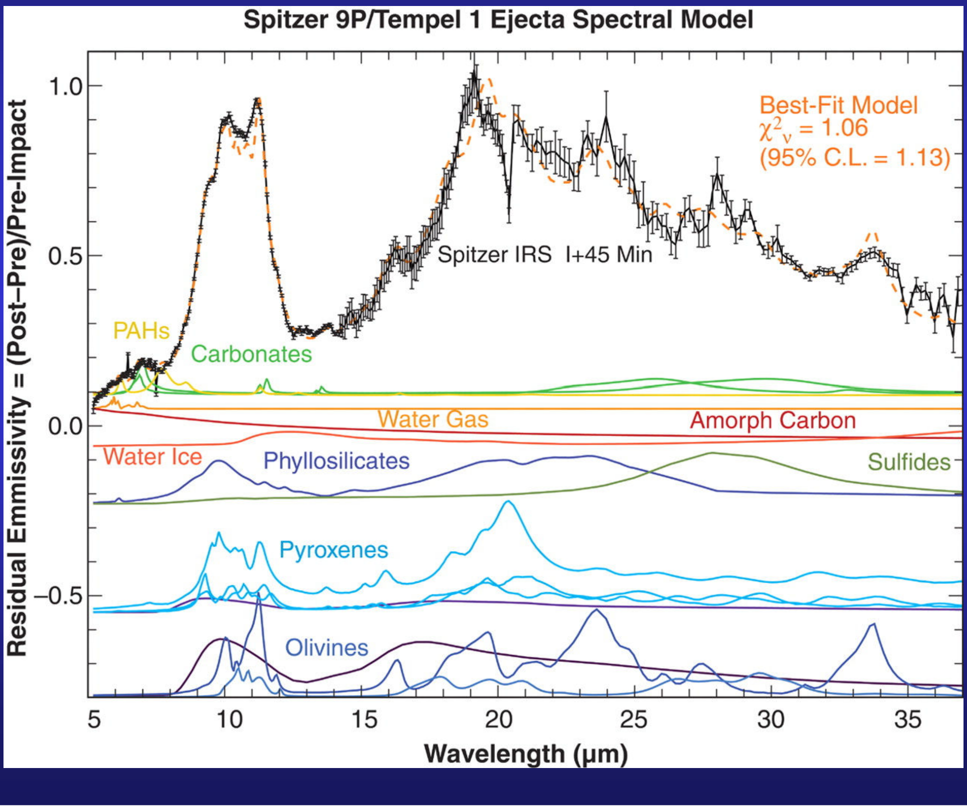
Posch et al. (2006, submitted)

- Diopside $CaMgSi_2O_6$
- Spinel $MgAl_2O_4$
- Melilite – Solid solution of gehlenite ($Ca_2Al_2SiO_7$) åkermanite ($Ca_2MgSi_2O_7$)

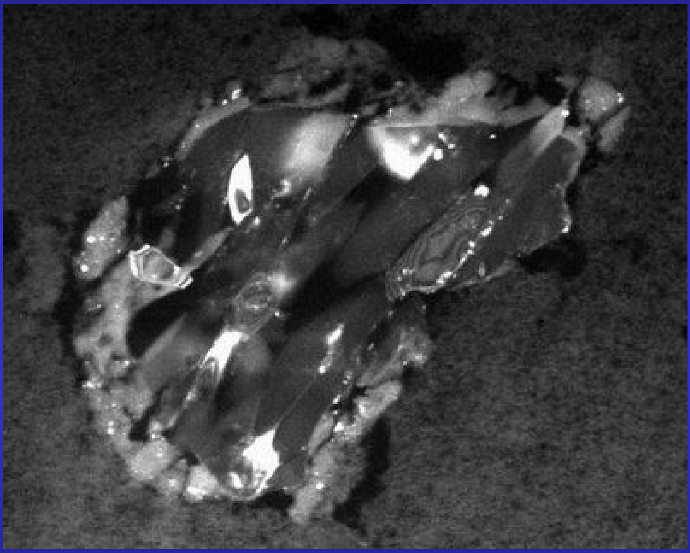
Spitzer Results – Deep Impact Ejecta of Comet 9P/Tempel 1



Spitzer Results – Deep Impact Ejecta of Comet 9P/Tempel 1


Spitzer 9P/Tempel 1 Ejecta Spectral Model

First Stardust Results –
Mg-rich olivine crystals from comet Wild 2



Scale
2 microns

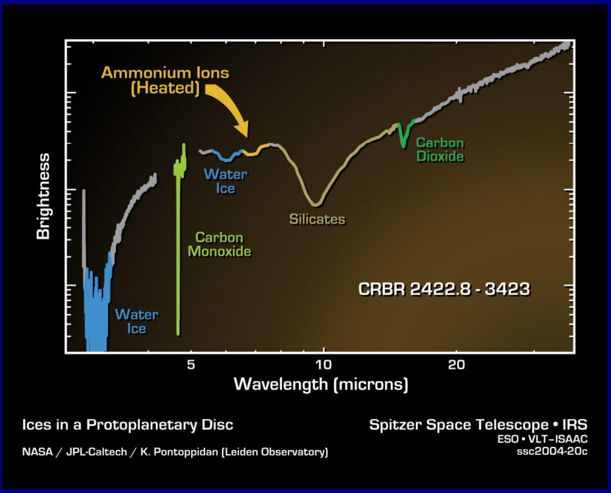
Other high-temperature crystals rich in Ca, Al, Ti

Summary

- Amorphous silicates present
- Crystalline Mg-rich olivine and pyroxene detected
- No evidence for iron sulphides
- Spatially resolved data are becoming available
- In-situ study of primitive material in solar system

Open questions

- How are the crystalline silicates produced?
- Do we see other high-temperature solids?
- Where is the iron?
- What is the structure of grain mantles?



Ices in a Protoplanetary Disc

NASA / JPL-Caltech / K. Pontoppidan (Leiden Observatory)

Spitzer Space Telescope • IRS
ESO • VLT–ISAAC
ssc2004-20c

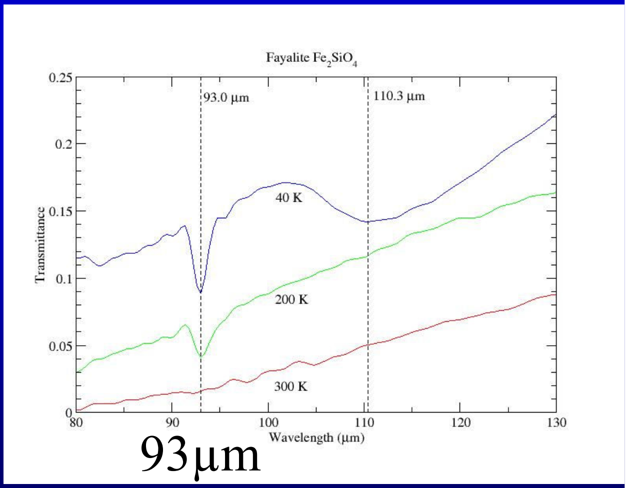
Stay tuned for Spitzer and Stardust results …

Herschel – The future ?

FIR: Lattice vibrations of heavy ions or ion groups with low bond energies (example KBr: transverse optical mode at 86 µm)

PACS: 57-210 µm

- Forsterite 69 µm band
- Fayalite 93-94 µm and 110 µm band
- Hydrous silicates 100-110 µm (e.g. montmorillonite)



93µm

> Absorption, scattering, and emission by interstellar material produces enough puzzles, even of identification, to keep the proverbial seven spectroscopists with seven brooms busy for at least seven years.

Trimble & Aschwaden (1998)

Collaborators and Reviews

F. Huisken, C. Jäger, H. Mutschke (Lab AIU Jena/MPIA Heidelberg)

R. van Boekel, J. Bouwman (ISO/Spitzer/MIDI, MPIA Heidelberg)

Reviews:

Henning, Th. (ed.): Astromineralogy. Springer 2003.

Henning, Th., Mutschke, H.: Optical Properties of Cosmic Dust Analogs. In: ASP Conf Series. 2000. p.253

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