Coagulation and crystallization of silicates in protoplanetary disks : a c2d Spitzer/IRS survey

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From ISM to planetary systems

Interstellar medium

Silicates : from ISM to planetary systems

- ISM : amorphous grains (> 99%)
- ISM : sub-micronic sized grains ($\sim$ 0.1 μm)
- Olivine in Earth's crust
- High crystallinity fraction (*Mg-rich*) in comets ($\sim$40%)

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c2d/IRS sample of Class II disks

Spitzer/IRS

- Infrared spectrum (5-35 μm)
- 110 spectra of circumstellar disks (more than 70 TTauris)
- Six main star-forming clouds : Perseus, Taurus, Chamaleon, Lupus, Ophiuchus & Serpens

Composition of crystals

Enstatite

- Composition : $MgSiO_3$
- Solid-state emission features : 21.6, 23.0, 24.5, 28.2 μm

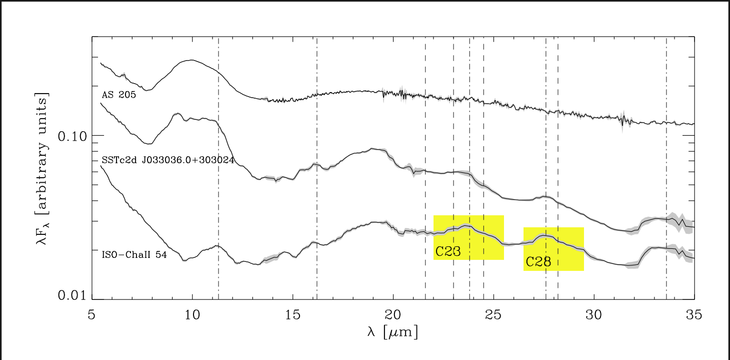
Forsterite

- Composition : Mg_2SiO_4
- Solid-state emission features : 11.3, 16.2, 23.8, 27.6 & 33.6 μm

Spectra zoology

From amorphous to crystalline

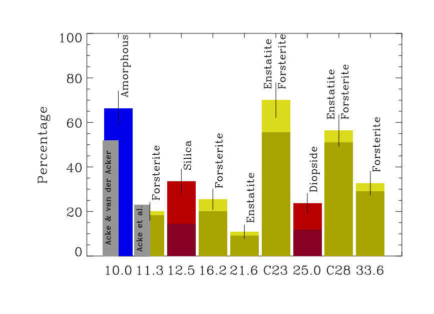
- Pristine spectra
- Crystalline spectra



Prevalence of crystalline features

Statistics

- 110 objects, mostly TTauri stars
- Herbig stars, Acke & van der Acker 2004 :
  - 52% amorphous
  - 23% 11.3 μm



Summary

- Spitzer/IRS : crystalline features at $\lambda > 15\,\mu$m.
- In our sample, $\sim$75% of the objects with at least one crystalline feature : widespread crystallinity
- Dust strongly processed at this stage of evolution

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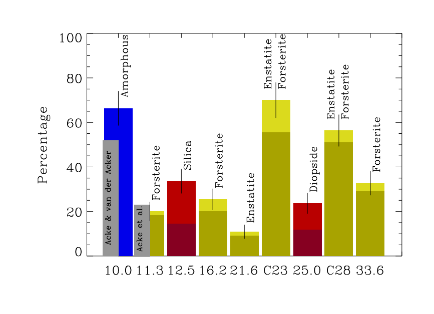

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Relationship between amorphous and crystalline silicates

10 μm vs C23

- Apparition frequency : *uncorrelated*
- Line fluxes : *uncorrelated*

10 μm vs C28

- Apparition frequency : *uncorrelated*
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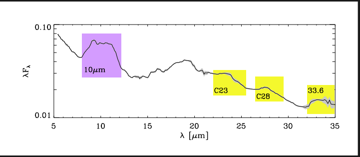
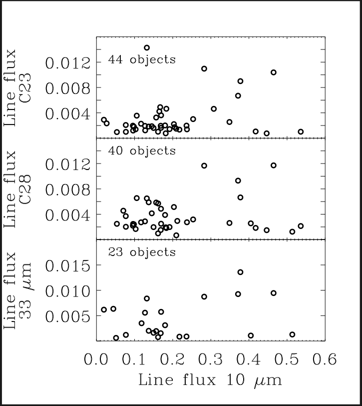
10 μm vs 33.6 μm

- Apparition frequency : *uncorrelated*
- Line fluxes : *uncorrelated*





Relationship between crystalline features

C23 vs 33 μm

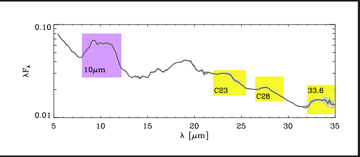
- Apparition frequency : *correlated*
- Line fluxes : *correlated*

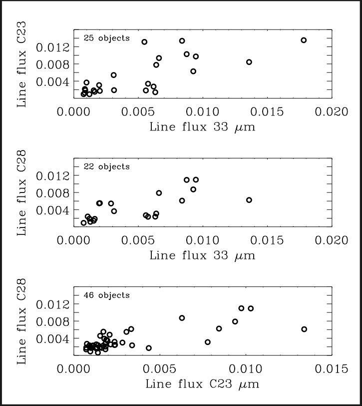
C28 vs 33 μm

- Apparition frequency : *correlated*
- Line fluxes : *correlated*

C23 vs C28

- Apparition frequency : *correlated*
- Line fluxes : *correlated*





Crystalline population

Summary

- 10 μm feature and C23, C28 & 33.6 features are probing *two independent dust populations*
- C23, C28 and 33.6 μm forsterite feature probably probe one single dust population

Emission at 10 μm
"Warm component"

Emission C23, C28 & 33.6
"Cold component"

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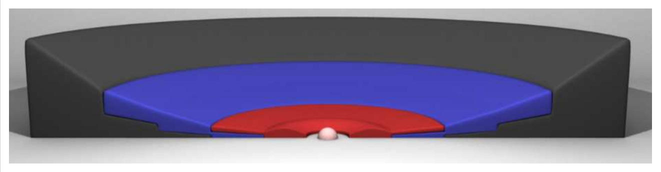

Emission at 10 μm
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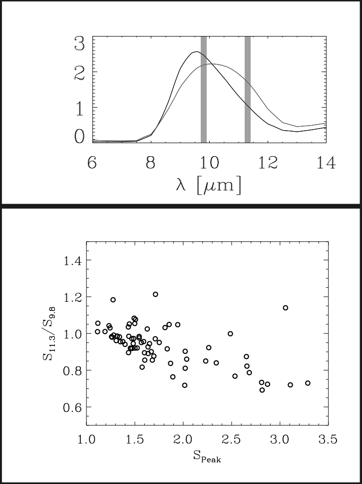
Growth of amorphous silicates

Shape versus strength

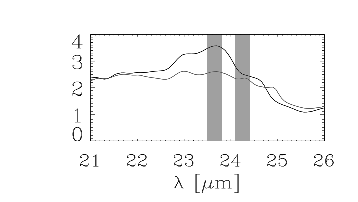
- Known correlation : shape vs. strength of the amorphous 10 μm
- Used as a proxy for amorphous grain size
- Typical grain size is μm-sized

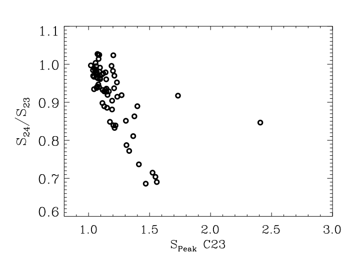


What about growth of crystalline silicates ?

C23 complex

- Similar study : shape vs. strength for C23
- Proxy for crystalline grain size
- Typical grain size is μm-sized





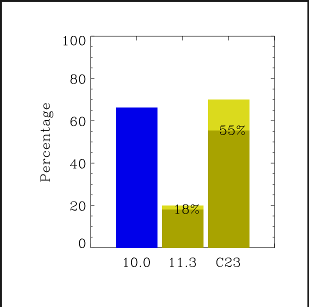
Lower crystallinity of the warmer component?

Contrast effect ...

- Amorphous features can hide crystalline features
- Theoretical grain opacities
- Detectability of crystalline features as a function of the crystallinity fraction

... is not enough

- Lower crystallinity in the warmer component?
- Models characterizing the distribution of objects as a function of crystallinity



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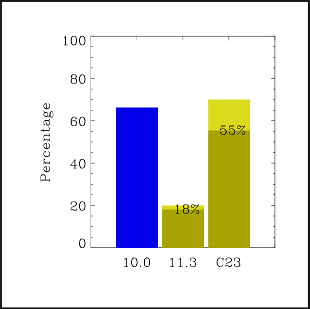

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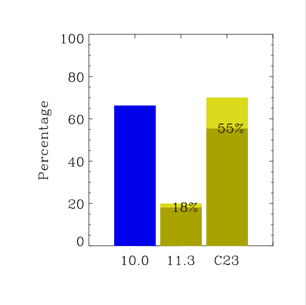

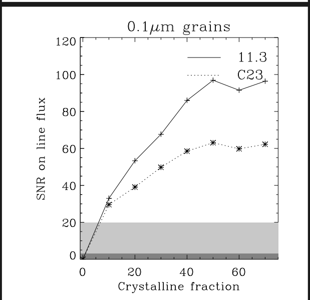

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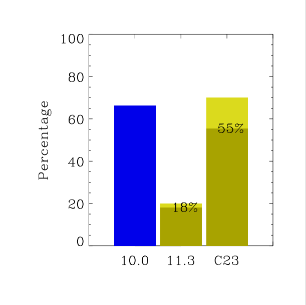

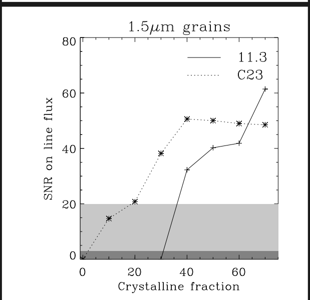

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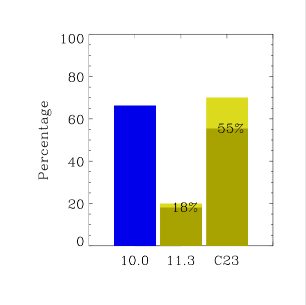

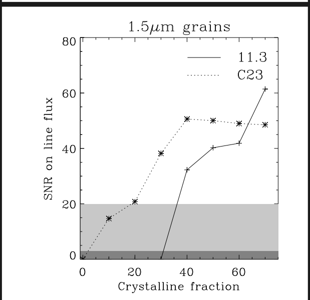

Overview of crystalline silicates from the c2d/IRS sample

Dust mineralogy

- ISM mineralogy : typical grain size micronic, widespread crystallinity
- Two independent grain populations (Warm component vs. Cold component)
- Systematic presence of μm-sized grains in disks upper layers : efficient vertical mixing (turbulence ?), compensating for grain sedimentation
- Presence of crystalline grains in cold regions : (1) radial transportation mechanisms : turbulence, winds (2) crystallization process at cold temperatures

Going further

- Spitzer/IRS : new observational constraints on protoplanetary disks, strong needs for :
  - Modeling
  - Complementary observations of the inner disk regions

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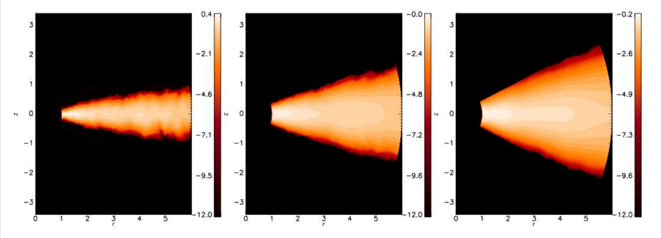
MHD simulations, Fromang & Nelson, submitted

MHD simulations of protoplanetary disks



a $\sim$1 mm

a $\sim$100 μm

a $\sim$10 μm

Sedimentation

Global MHD simulations of protoplanetary disks, using different grain sizes : help us understanding the sedimentation process

Detailled mineralogic analysis

Compositional fitting

- Goal : deriving silicate mineralogy by fitting spectra
  - Two independent dust populations
  - 5 compositions and 2 grain sizes
- Returns compositions, grain sizes and temperatures for each population

Bouy et al. 2008

- Warm component : $\sim$5% crystalline
- Cold component : $\sim$40% crystalline

Merìn et al. 2007

- Warm component : $\sim$10% crystalline
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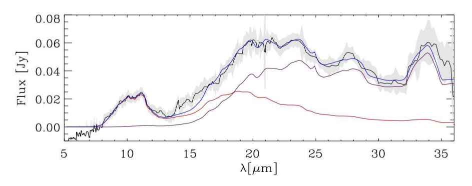

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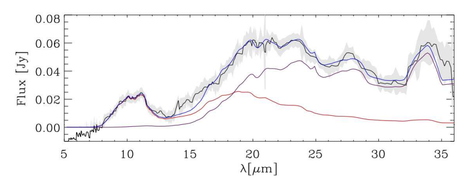
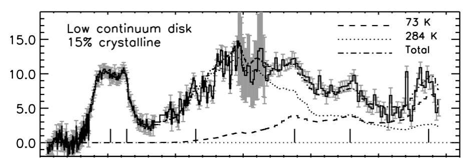
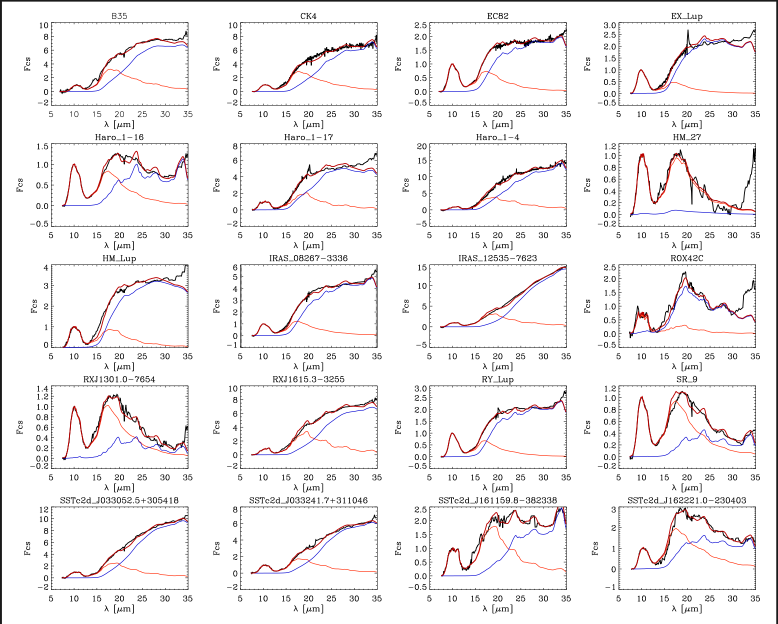


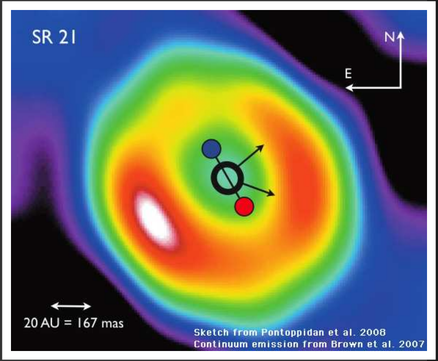



B35
CK4
EC82
EX_Lup
Haro_1−16
Haro_1−17
Haro_1−4
HM_27
HM_Lup
IRAS_08267−3336
IRAS_12535−7623
ROX42C
RXJ1301.0−7654
RXJ1615.3−3255
RY_Lup
SR_9
SSTc2d_J033052.5+305418
SSTc2d_J033241.7+311046
SSTc2d_J161159.8−382338
SSTc2d_J162221.0−230403
Fcs
λ [μm]

Spatially resolving Class II disks : near-IR interferometry

AMBER/VLTI

- Spatial informations on the inner regions
  - TTauri SR21 (reduction : Eric Tatulli)
  - Resolved : $V^2 \sim 0.5$ (<1)
  - No strong spectral dependency
- Constrain the inner disk morphology



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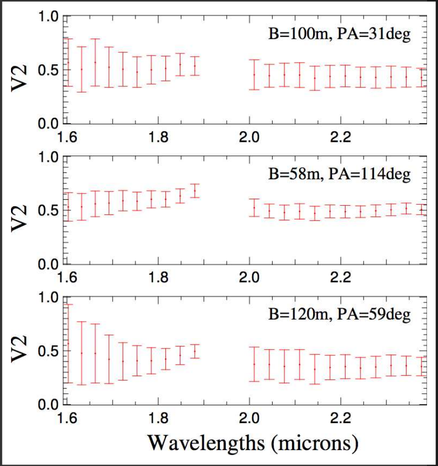

Thank you for your attention

Publications

- Olofsson et al. in prep, *“C2D Spitzer-IRS spectra of disk around T Tauri stars. IV Crystalline silicates”*
- Lahuis et al. 2007, *“C2D Spitzer-IRS spectra of disk around T Tauri stars. III [Ne II], [Fe I] and H_2 gas phase lines”*
- Geers et al. 2006, *“C2D Spitzer-IRS spectra of disk around T Tauri stars. II PAH emission features”*
- Kessler-Silacci et al. 2006, *“C2D Spitzer-IRS spectra of disk around T Tauri stars. I Silicate emission and grain growth”*
- Merín et al. 2007, *“Abundant crystalline silicates in the disk of a very low mass star”*