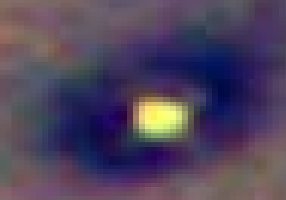
Phyllosilicate Emission from Protoplanetary Disks

Is the Indirect Detection of Extrasolar Water Possible?



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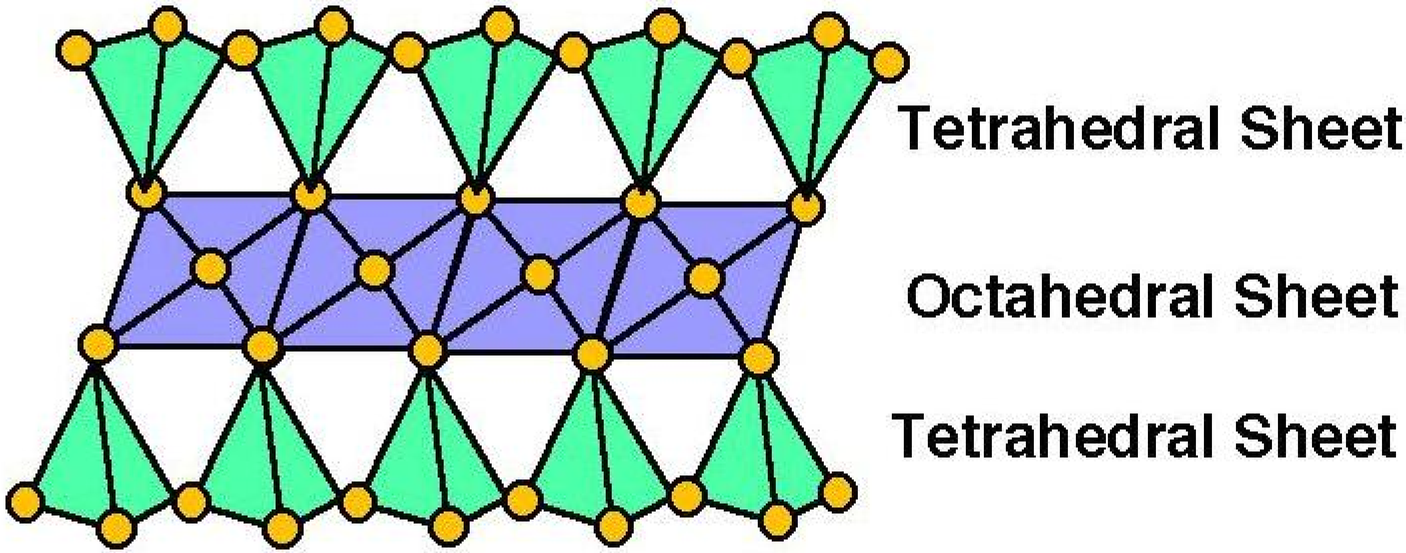
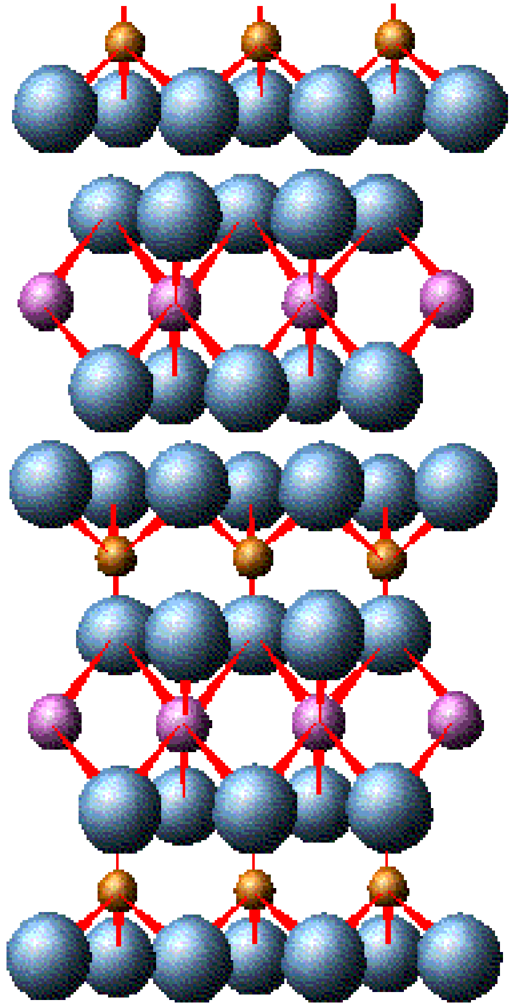
Outline

- What are phyllosilicates?
- Why are they important?
- Are phyllosilicates expected in proplyds?
- How are phyllosilicates detected?
- Can phyllosilicates be detected?

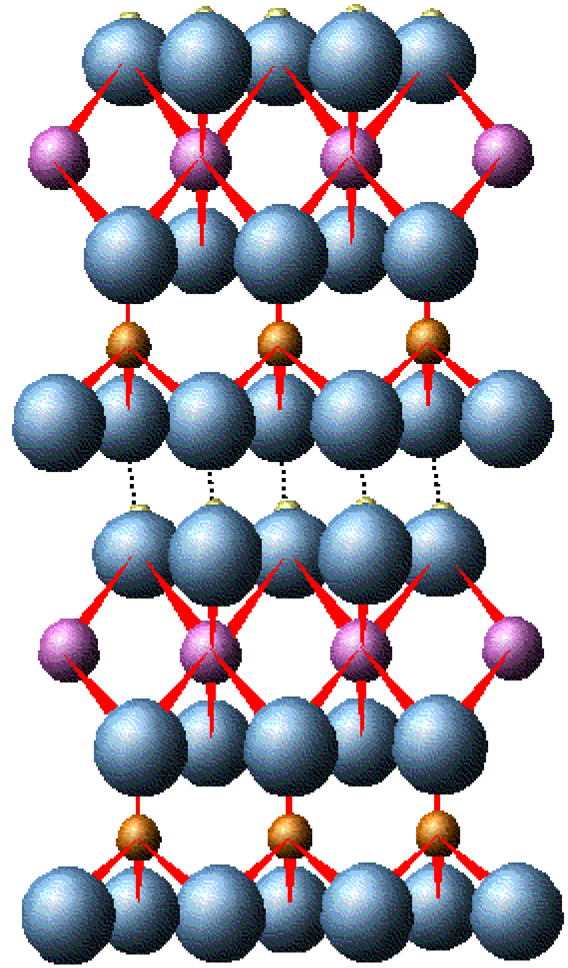
What are Phyllosilicates?

- Sheet silicates (Greek "phyllon")
- Two types
  - Octahedral *(O)* sheets
    - two planes of anionic groups
    - dioctahedral or trioctahedral
  - Tetrahedra (*T*) sheets
    - tetrahedrally coordinated cations
- *O* & *T* sheets join to form layers
  - Weakly bonded


Tetrahedral Sheet
Octahedral Sheet
Tetrahedral Sheet



chlorite



kaolinite

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What are phyllosilicates?

- Silicate rock + water at low temperature
  $\rightarrow$ clay minerals (fine-grained, < 0.002 mm)
- Mineral formed depends on
  - Parent rock
  - Temperature
  - Amount and chemistry of water
  - Time

Why Phyllosilicates?

- Phyllosilicates
  - product of aqueous alteration of silicate rock
    - diagnostic of liquid water
    - LAWKI (requires source of free energy, carbon, liquid water)
  - found in meteorites-mass fraction up to 40-90%

    (Tomeoka & Buseck 1990; Buseck & Hua 1993; Rubin 1997)
    - Matrix (Fe-rich)
    - Rims around chondrules (Mg-rich)
  - zodiacal dust modeled with 20% (Reach et al. 2003)

Table 1. Phyllosilicates found in chondrites

Saponite	Serpentine	Montmorillonite	Cronstedtite
CI	CM	CI	CM
CV	CO		
CR	CR		
ord. chond.			
IDPs			

- Saponite ($[Ca/2,Na]_{0.33}[Mg,Fe^{2+}]_3[Si,Al]_4O_{10}[OH]_2 \cdot 4H_2O$)
- Serpentine ($[Mg,Fe]_3Si_2O_5[OH]_4$)
- Montmorillonite ($[Na,Ca]_{0.33}[Al,Mg]_2Si_4O_{10}[OH]_2 \cdot n[H_2O]$)
- Cronstedtite ($Fe^{2+}Fe^{3+}[Si,Fe^{3+}]O_5[OH]_4$)

Are Phyllosilicates Expected?

- Majority of Earth's water delivered by planetesimals (Morbidelli et al. 2000; Raymond et al. 2004; Mottl et al 2007)
  - at most 10% from comets (Morbidelli et al. 2000)
- D/H ratio in VSMOW ~ carbonaceous chondrites (Drake & Righter 2002)
  - D/H ratio in comets too high (Eberhardt et al. 1995; Bockelee-Morvan et al. 1998; Meier et al . 1998; Drake & Righter 2002)
  - Probability of comet collisions too low (Levison 2001; Morbidelli et al. 2000)
  - Comets introduce too much Ar and other noble gases (Swindle & Kring 1997, Owen & Bar-Nun 1995, Morbidelli et al. 2000; Drake & Righter 2002)
- Carbonaceous chondrites ~ 10 wt% water
  - formed in outer asteroid belt (Gradie & Tedesco 1982)
- Ordinary chondrites ~ 0.5-0.1 wt% water
  - formed in inner asteroid belt (Gradie & Tedesco 1982)
- Water in chondrites mainly in hydrous minerals
  - phyllosilicates

Are Phyllosilicates Expected?

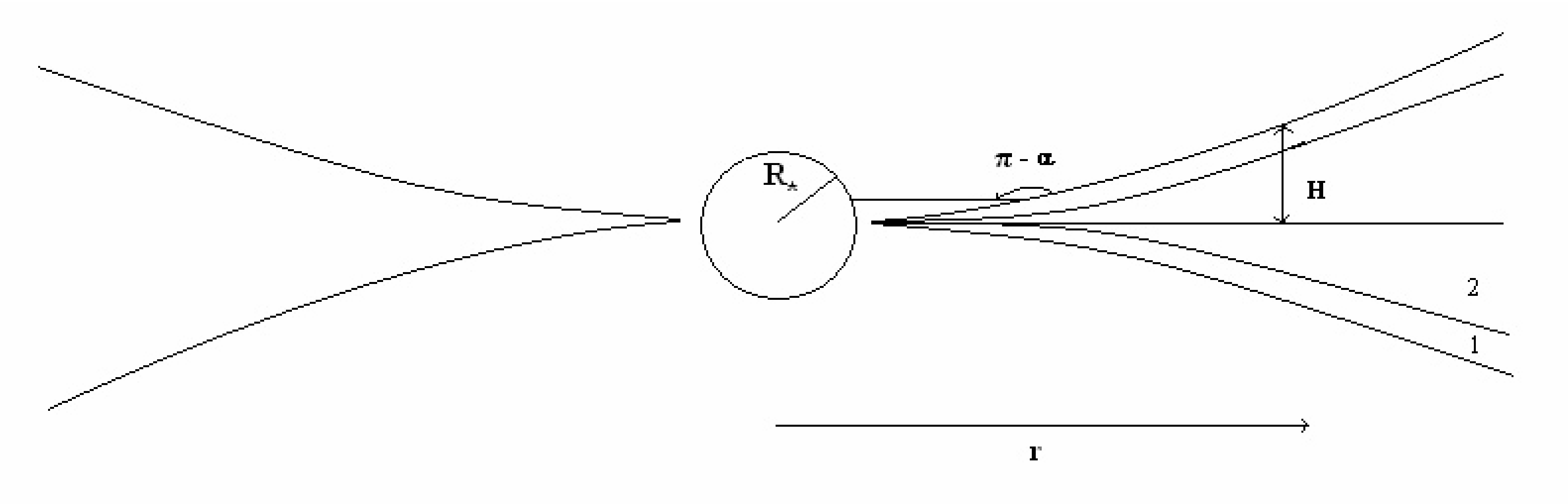
- Protoplanetary disks
  - Disk lifetimes ~ 3-10 Myr (Haisch et al. 2001)
  - Formation of km-sized bodies 10^4 – 10^5 yrs (Weidenschilling 2000; Woolum & Cassen 1999)

    → planetesimals in T Tauri disks
- Numerical simulations of coagulation of dust and accretion of larger bodies (Weidenschilling 2000)
  - Planetesimals built up and torn down in < 1 My
  - Half the mass in planetesimals
  - Half in dust eroded from larger planetesimals
- Dust shed from asteroids
  - Present asteroid belt: 10^{20} g (Nesvorny et al. 2006)
  - In primordial belt: ~ 10^{27} g after 10^5 yr
- Estimate of 3% phyllosilicate abundance
  - Mass fraction of phyllosilicates of 30%
  - Produced in 10% of the disk (2-4 AU)

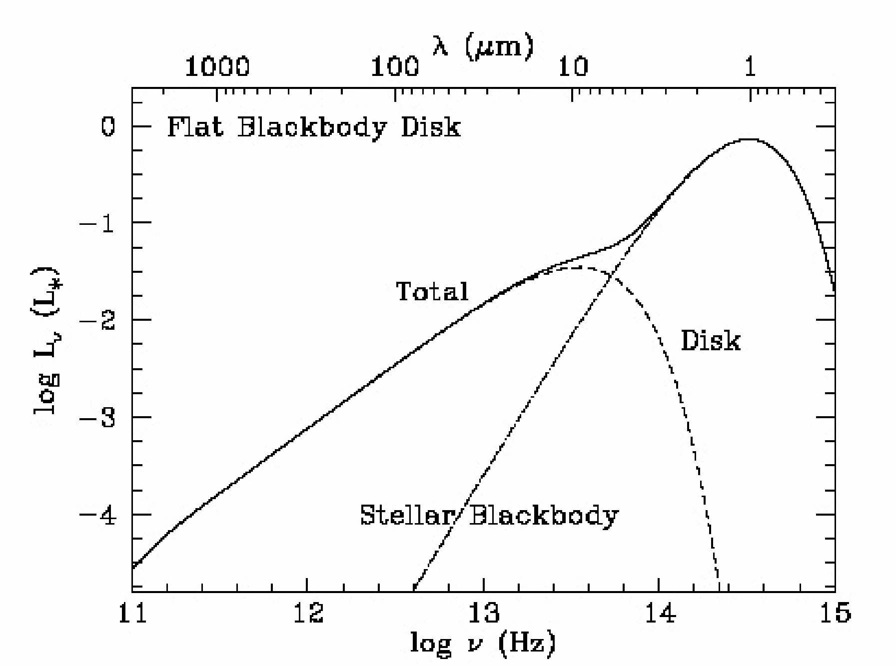
Are Phyllosilicates Expected?

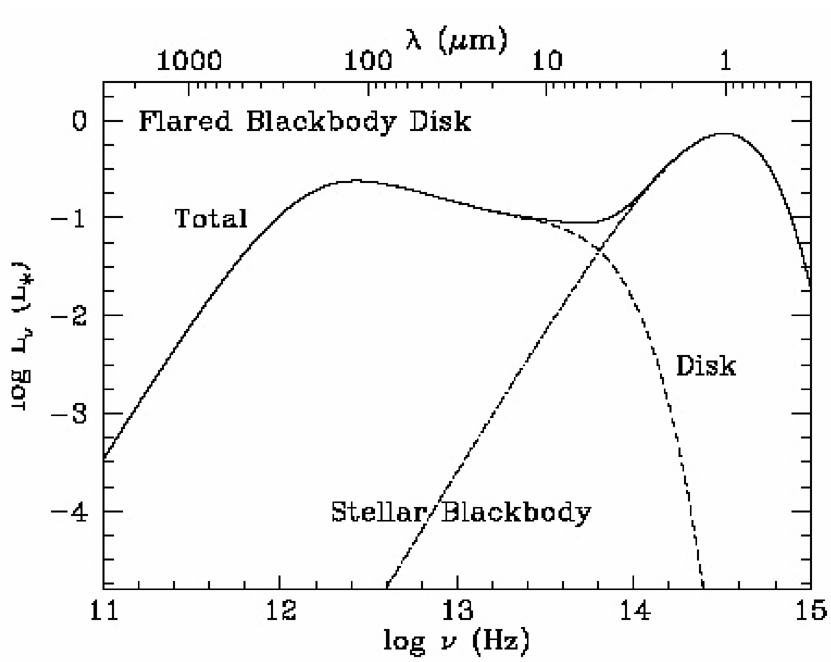
- Debris disks too faint (Morris & Desch 2009)
  - Column density of debris disks ~ 10^{-4} - 10^{-7} g cm^{-2}
  - Column density of protoplanetary disks ~ 10^{-3} g cm^{-2}
  - Flux difference in excess of ~ 10^{3}
- "Waterworlds" hyposthesis (Desch & Leshin 2004)
  - Water abundance dependent on amount of ^{26}Al
  - Planetesimals with less ^{26}Al would never melt ice
    - No phyllosilicates produced on planetesimals
    - Would not be detected in exozodiacal dust

How are Phyllosilicates Detected?



How are Phyllosilicates Detected?

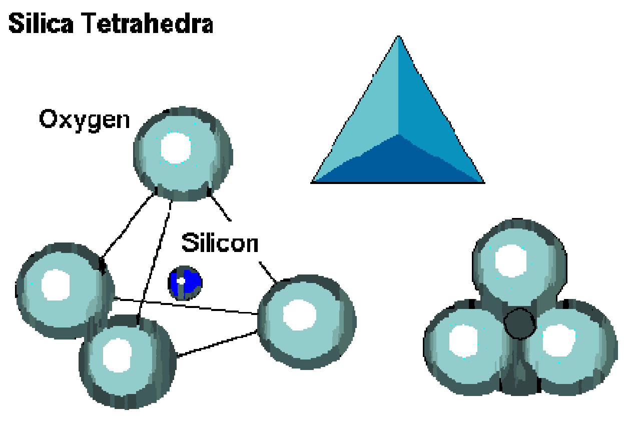




Model SEDs of a flat, blackbody disk and a flared, blackbody disk from Chiang & Goldreich (1997). Note the flattish spectrum of the flared disk (from 1 - 300 µm) compared to the much steeper spectra of the flat disk. This results because flared disks capture and reprocess more stellar radiation, although typically at lower T and larger .

MIR Spectra of Silicates

- SiO_4 tetrahedral structures
- 10 μm feature due to Si-O vibration mode
- 20 μm feature due to Si-O-Si bending mode
- Features seen in both absorption/emission
  - depends on optical depth and grain temperature
- Amorphous (glassy) silicates
  - broad, smooth spectral profiles
- Crystalline silicates
  - substructure with sharp/distinct features
- Diagnostic of stoichiometry



How are Phyllosilicates Detected?

- Characteristic emission features in the MIR
- 10 µm and 20 µm features
- Absorption feature at 6 µm due to H_2O
- Differences between Fe-rich and Mg-rich
- *Distinctive substructure particular to mineral*

Model SED

- Minerals (other than phyllosilicates) based on models of Pollack et al. (1994) & Gail (2003, 2004)
- Phyllosilicates based on meteorite abundances
  - Optical constants measured for phyllosilicates
  - Opacities calculated using Mie theory
  - Distribution of Hollow Spheres (best fit - Min et al. 2003)
- Disk model based on Chiang & Goldreich (1997)
  - Corrected effective temperature (factor of $2^{1/4}$)
  - Actual dust opacities used
  - 1993 Kurucz models used for central star

Absorption Properties

- Homogeneous spheres, where |m|x << 1 (x = 2πa/λ)

$$Q_{abs} = 4x \,\mathrm{Im}\left\{\frac{m^2-1}{m^2+2}\right\}\left[1 - \frac{4x^3}{3}\,\mathrm{Im}\left\{\frac{m^2-1}{m^2+2}\right\}^2\right]$$

- Long λ limit, where |m|x << 1 *and* x << 1

$$Q_{abs} = 4x \,\mathrm{Im}\left(\frac{m^2-1}{m^2+2}\right)$$

- If scattering small compared to absorption (k= 2π/λ)

$$C_{abs} = k \,\mathrm{Im}\,(\alpha)$$

Absorption Properties

- Ellipsoids, Rayleigh approximation

$$C_{abs} = kV \, \mathrm{Im} \left(\alpha_1 + \alpha_2 + \alpha_3 \right)$$

- Polarizability per unit volume

$$\alpha_i = \frac{m^2 - 1}{3 + 3L_i \left(m^2 - 1 \right)}$$

- $L_1 + L_2 + L_3 = 1$, for homogeneous spheres, $L_i = ⅓$

$$\alpha_i = \frac{m^2 - 1}{m^2 + 2}$$

Shape Distributions

- Collection of randomly oriented ellipsoids

$$\langle C_{abs} \rangle = kV \int_0^1 dL_1 \int_0^{1-L_1} dL_2 \, \mathrm{Im}\,(\alpha_1 + \alpha_2 + \alpha_3)\, \mathcal{P}(L_1, L_2)$$
$$= kV \, \mathrm{Im}\,(\bar{\alpha})$$

- Continuous Distribution of Ellipsoids (CDE) $\mathcal{P}(L_1, L_2) = 2$

$$C_{abs} = 2kV \; \mathrm{Im} \left(\frac{m^2}{m^2 - 1} \ln m^2 \right)$$

- Continuous Distribution of Spheroids (CDS) $\mathcal{P}(L)=1$
  - Used outside the Rayleigh limit
- Uniform Distribution of Spheroids (UDS)
  - Not possible to find an analytic expression for $\bar{\alpha}$

Distribution of Hollow Spheres

- Inhomogeneity in composition or porous inclusions
- Particles with vacuum inclusions (with m = 1)

$$V = \tfrac{4}{3}a^3 (1 - f)$$

$$\alpha = \frac{(m^2 - 1)(2m^2 + 1)}{(m^2 + 2)(2m^2 + 1) - 2(m^2 - 1)^2 f}$$

$$\begin{aligned} \langle C_{abs} \rangle &= kV \, \mathrm{Im}(3\alpha) \\ &= 4\pi a^3 k \, \mathrm{Im}\left[\frac{(1 - f)(m^2 - 1)(2m^2 + 1)}{(m^2 + 2)(2m^2 + 1) - 2(m^2 - 1)^2 f} \right] \end{aligned}$$

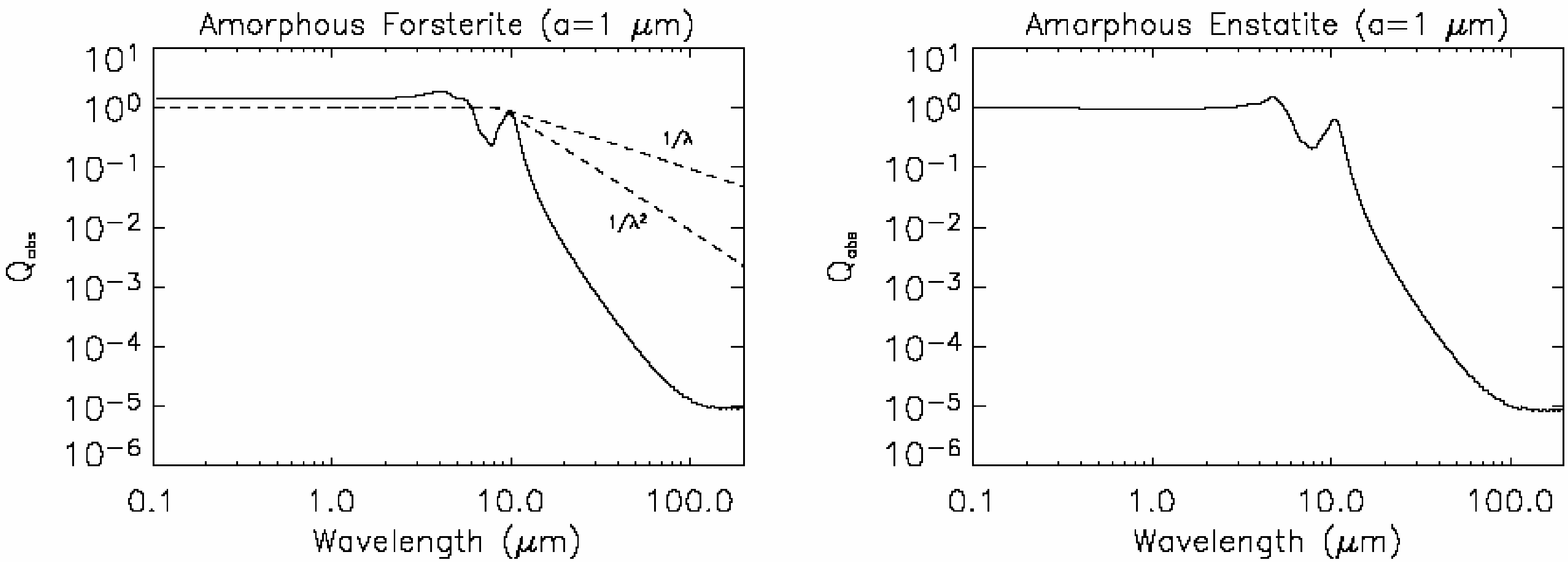


Fig. 1. Q_{abs} for 1 μm grains of amorphous forsterite and amorphous enstatite, calculated from n and k from Jäger et al. (2003). Note that Q_{abs} decreases much more rapidly than $1/\lambda$.

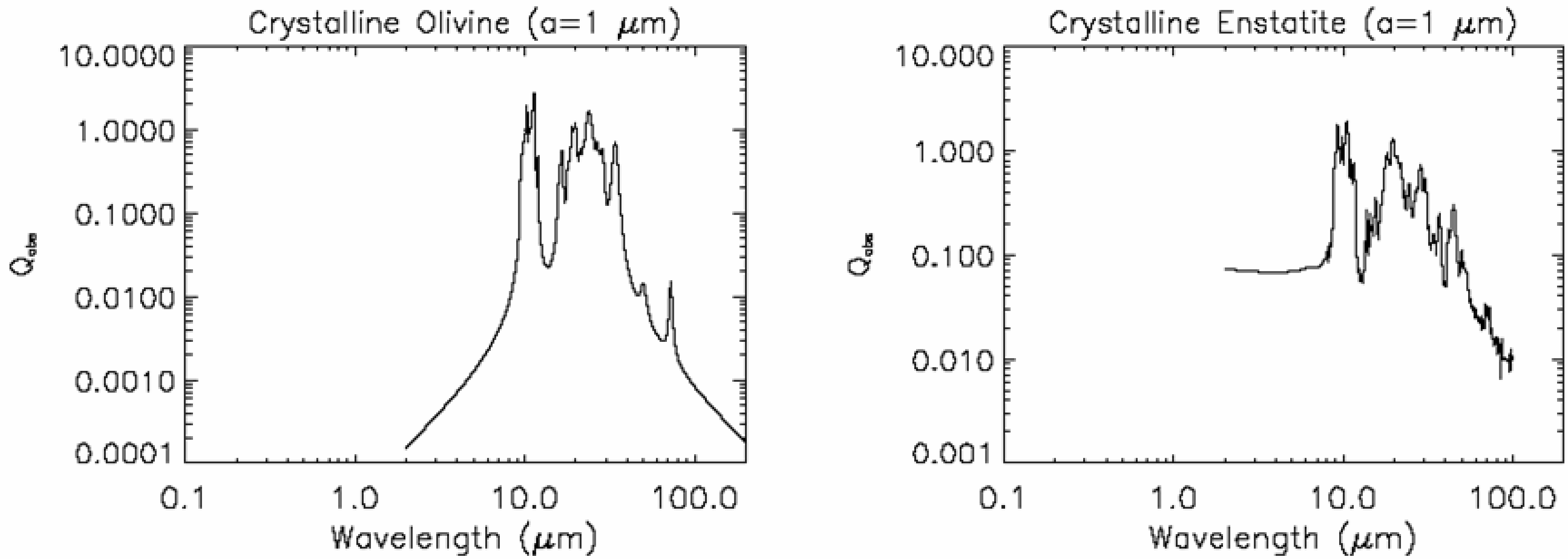


Fig. 2. Q_{abs} for for 1 μm grains of crystalline olivine and crystalline enstatite, calculated from n and k from Fabian et al. (2001) and Jäger et al. (1998), respectively.

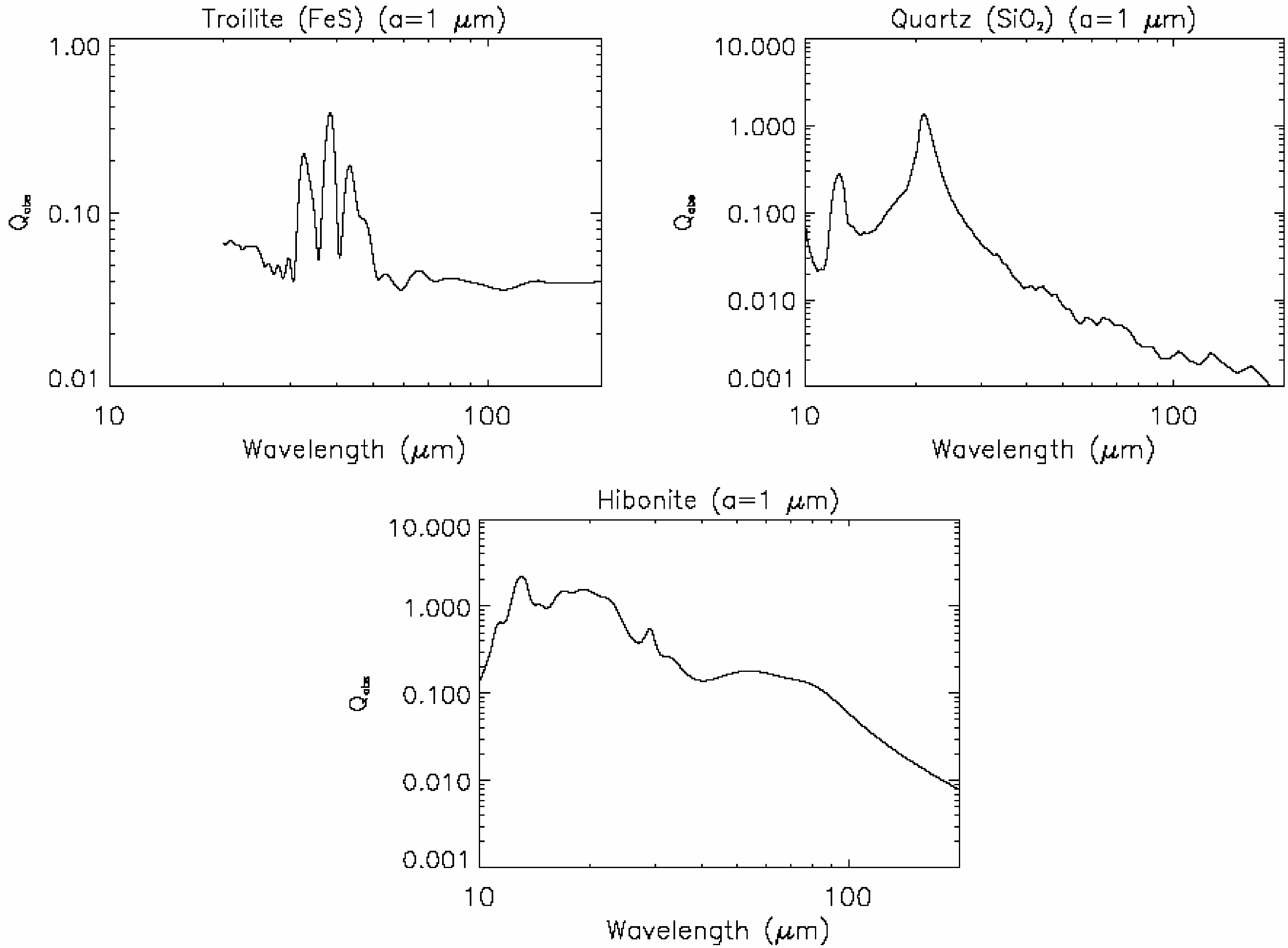


Fig. 3. Q_{abs} for 1 μm grains of troilite, quartz, and hibonite, calculated from n and k from Begemann et al. (1994), Henning & Mutschke (1997), and Mutschke et al. (2002), respectively.

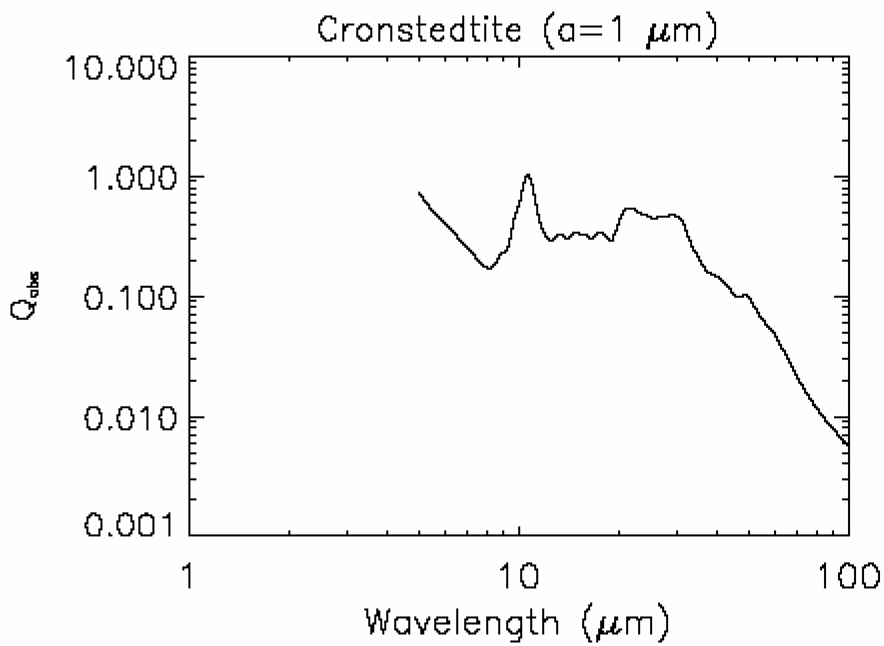
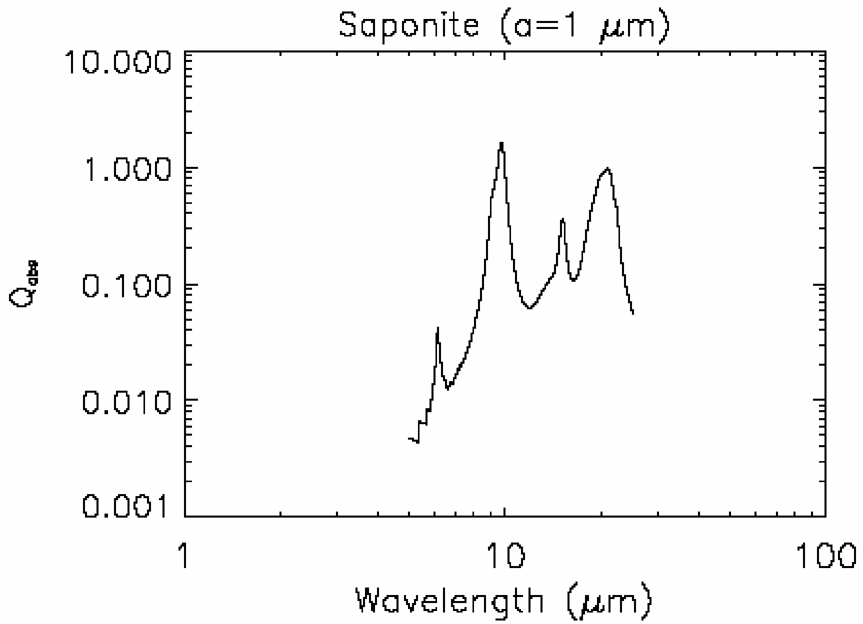
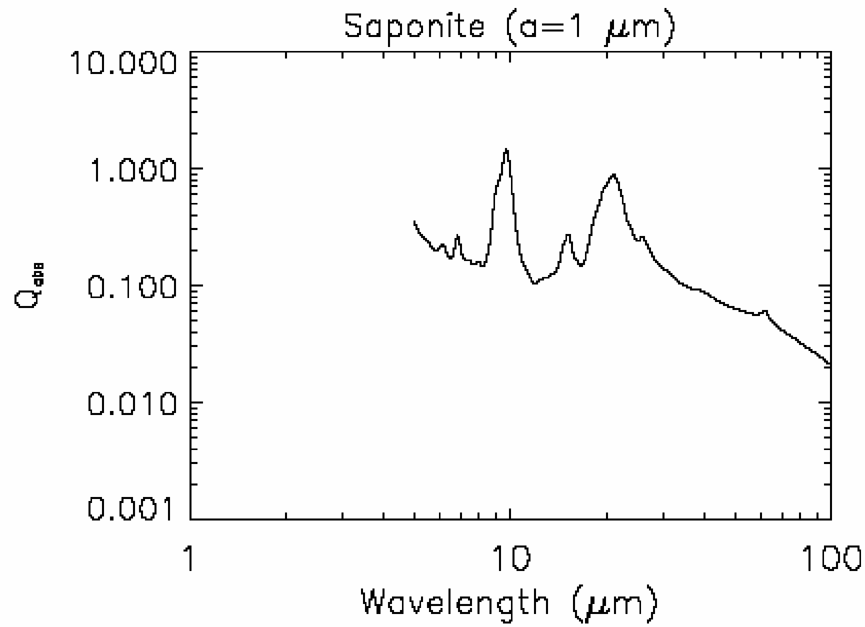
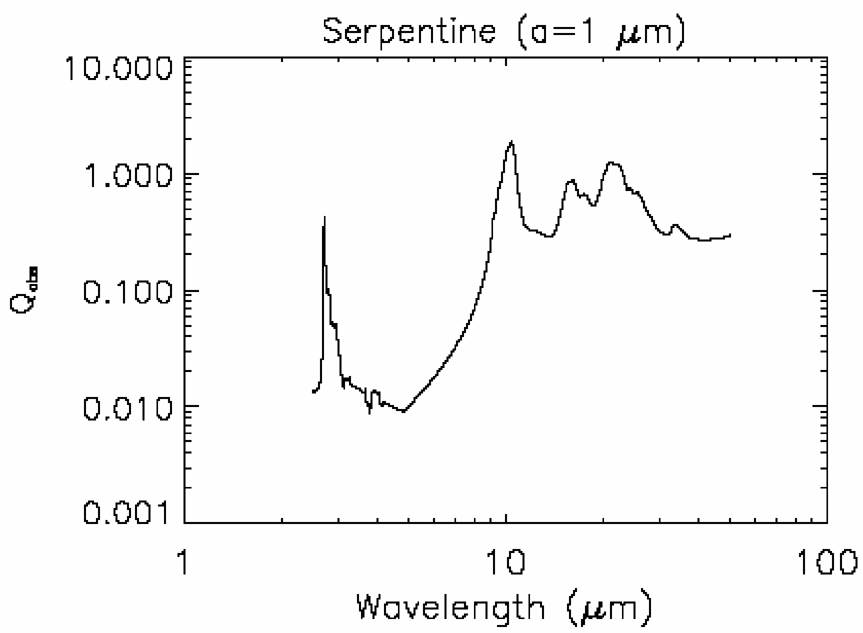
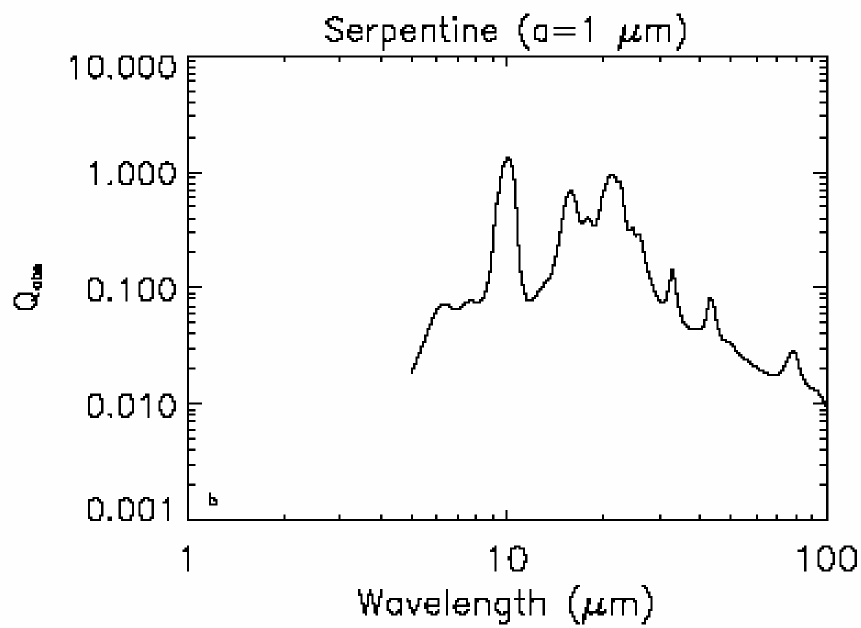


Fig. 4. Q_{abs} for cronstedtite calculated from n and k determined by Tim Glotch.


Saponite (a=1 μm)
10.000
1.000
0.100
0.010
0.001
Q_{abs}
1
10
100
Wavelength (μm)


Saponite (a=1 μm)
10.000
1.000
0.100
0.010
0.001
Q_{abs}
1
10
100
Wavelength (μm)





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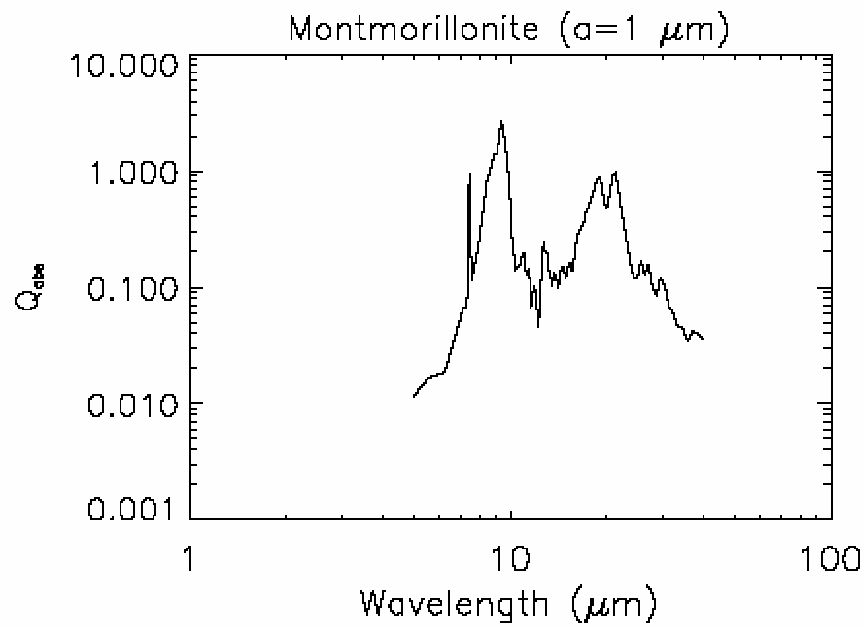
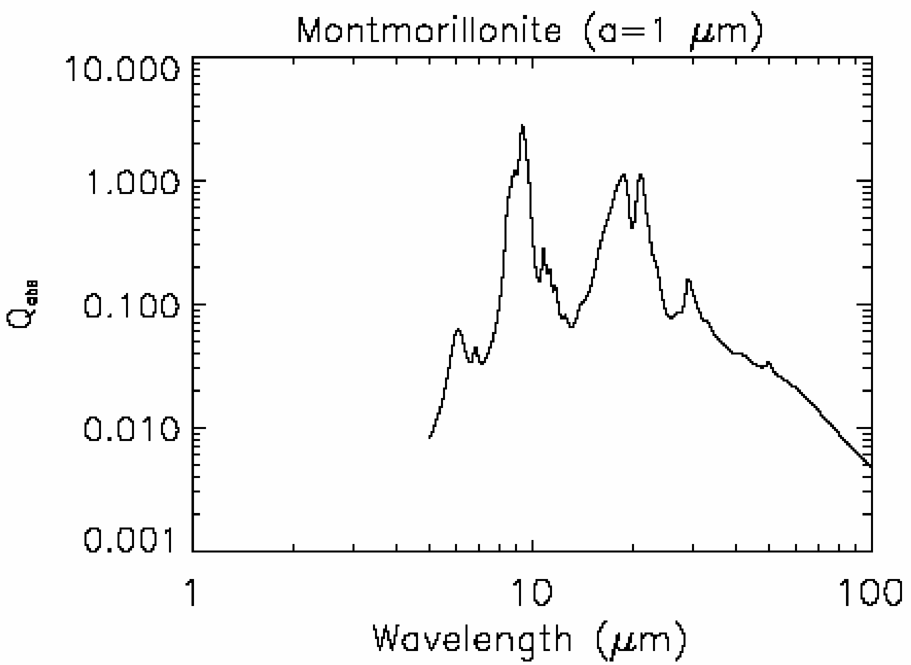

Montmorillonite (a=1 μm)
10.000
1.000
0.100
0.010
0.001
Q_{abs}
1
10
100
Wavelength (μm)

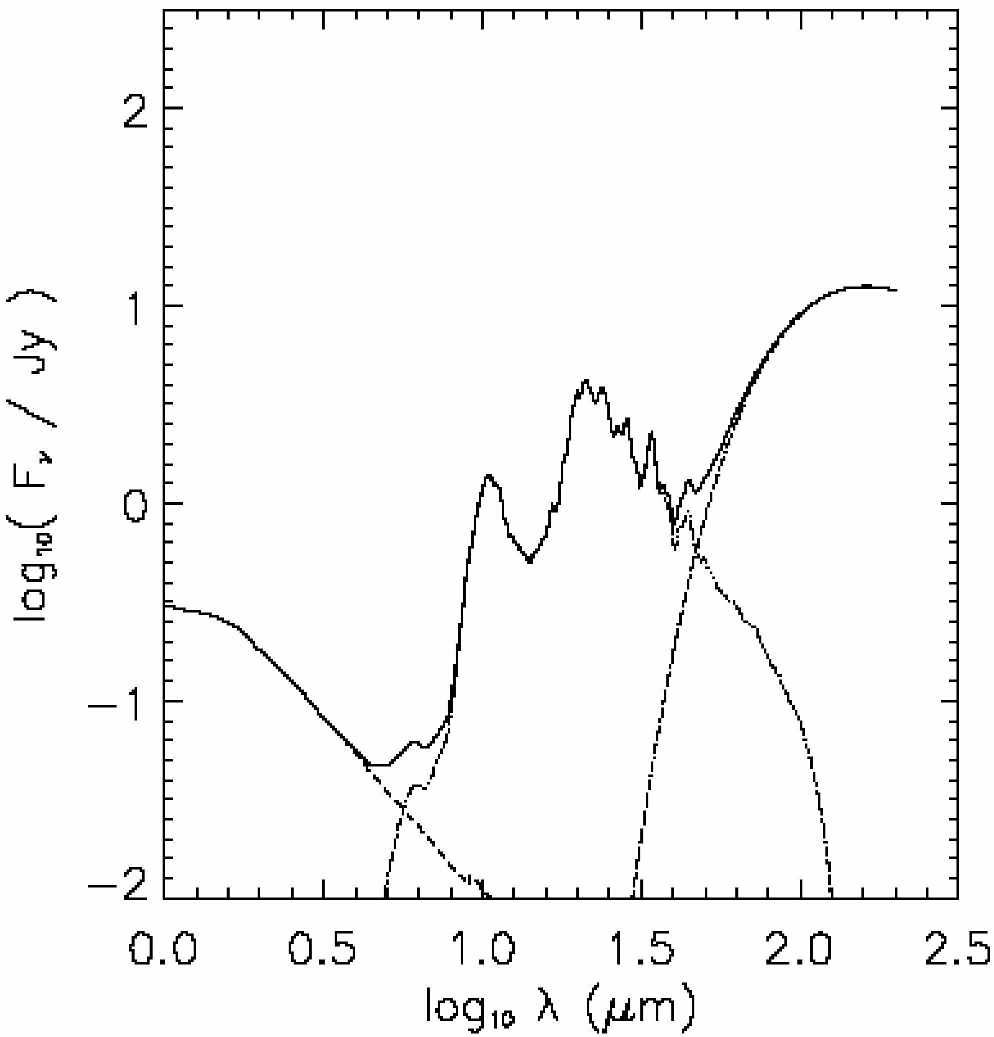

Montmorillonite (a=1 μm)
10.000
1.000
0.100
0.010
0.001
Q_{abs}
1
10
100
Wavelength (μm)

Grain Composition

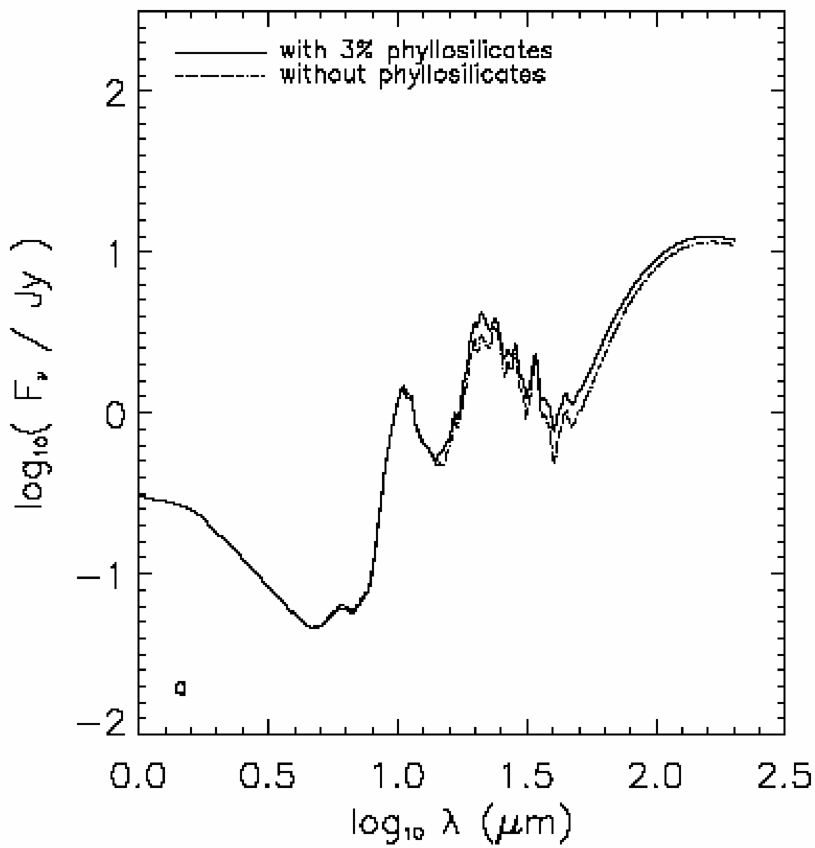
(Grain size of 0.1 μm)

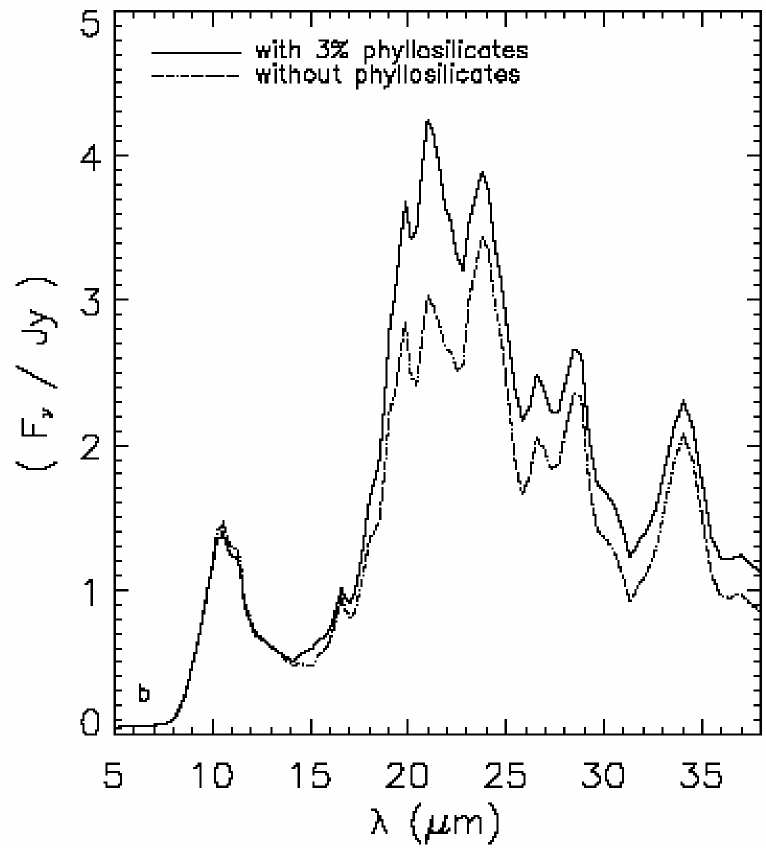
Table 4. Relative percentages of the minerals used in modeled SEDs.

	Mineral Percentages	
	Without Phyllosilicates	With Phyllosilicates
amorphous forsterite	58	55
amorphous enstatite	32	32
crystalline olivine	3	3
crystalline enstatite	2	2
FeS (troilite)	2	2
quartz	2	2
hibonite	1	1
saponite	0	3



2
1
0
−1
−2
0.0
0.5
1.0
1.5
2.0
2.5
log₁₀(F_ν / Jy)
log₁₀ λ (μm)





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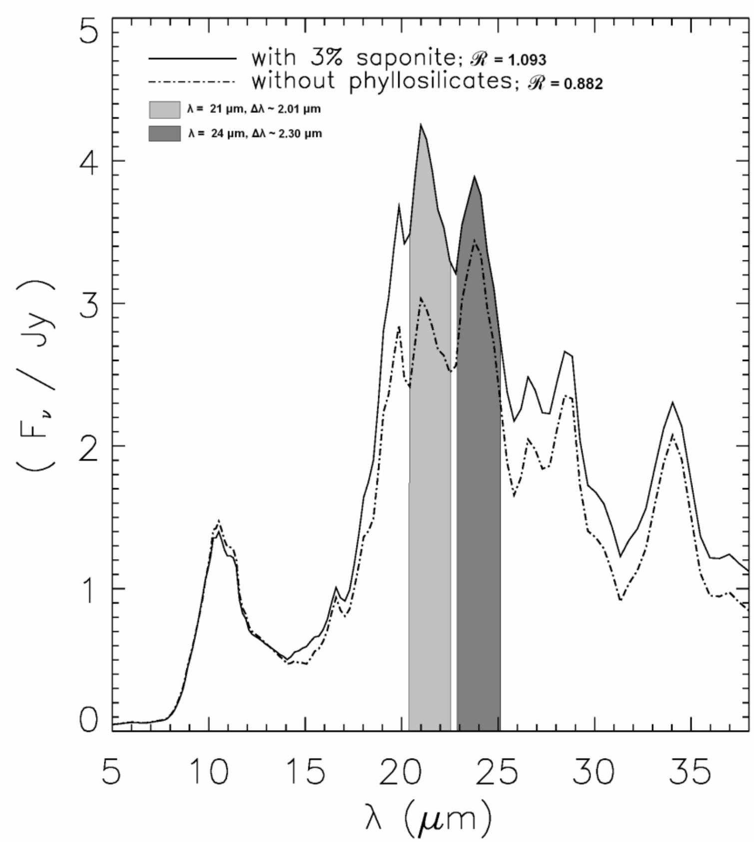
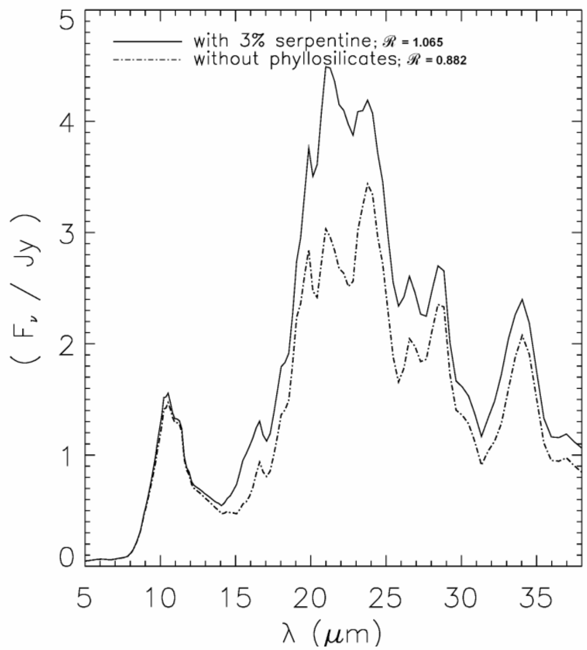
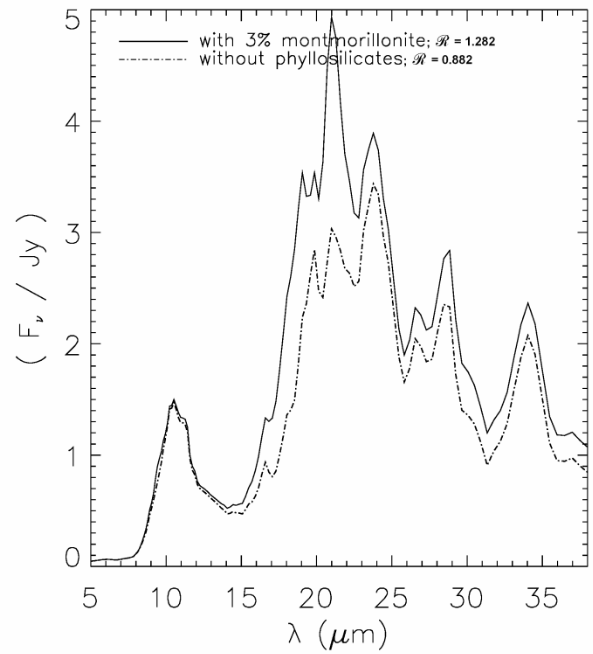
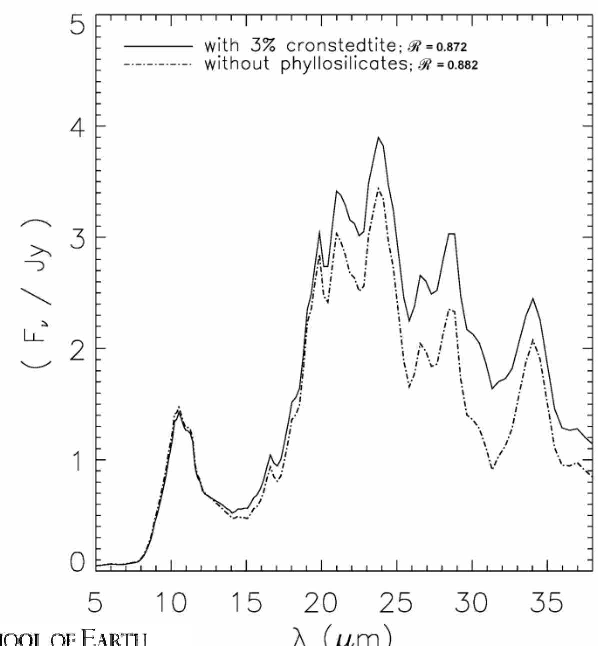
Is Detection Possible?

- Although significant difference with and without inclusion of phyllosilicates, broad differences are difficult to detect.
- Easier and more reliable to compare distinct features that can be isolated from background.
  - Higher emission at 21 μm than 24 μm with phyllosilicates
  - Higher emission at 24 μm than 21 μm without phyllosilicates









Seems to hold true for most other phyllosilicates (other than cronstedtite)

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Telescope	Instrument	R[1]	Sensitivity[2]	t[3]
Spitzer	IRS	600	0.4 mJy	21.8 s
SOFIA	EXES	3000	2.7 Jy	59.8 s
Gemini North	Michelle	110	14 mJy	920.9 s
IRTF	MIRSI	100	100 mJy	383.8 s
JWST	MIRI	3000	5×10^{-20} Wm^{-2}	8.3×10^{-5} s

- [1]Spectral resolution, R = λ/Δλ, is given at the relevant wavelengths (21 and 24 μm). [2]Sensitivities listed for IRS, EXES, Michelle, MIRSI, and MIRI are, 1σ for an integration time of 512s, 4σ for an integration time of 900s, 5σ for an integration time of one hour, 1σ for an integration time of 60s, and 10σ for an integration time of 10,000s. [3]Minimum integration times necessary to achieve a 1σ detection of ratio.
- Assumptions
  - Shot-noise limited
  - Difference in emission due to phyllosilicates small compared to total
  - Source is bright compared to the background
  - Dark current is negligible

Conclusions and Implications

- The most common phyllosilicates found in meteorites should be detectable in protoplanetary disks, at a level of 3%, by examining the ratio of the emission at 21 μm to the emission at 24 μm.
- Detection of phyllosilicates
  - Identification of a new mineral in disks
  - First indication of liquid water outside Solar System
  - Indicate similarity to Solar System
- Use improved disk model (Desch research group) to produce SEDs
- Large amounts of archived data on protoplanetary disks as a part of the Spitzer Legacy Science Program.
  - MSU NASA MO Space Grant intern, Aron McCart, currently mining data
- Results could be used in planning future observations with SOFIA and JWST
- Provide a test for the "waterworlds" hypothesis

Thank You!