

Some Questions for Lab Astro

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1. Where's the Carbon?

What is $f(\text{C II}]2325 \text{ \AA})$?

2. Where's the Oxygen?

How does oxygen deplete in the diffuse ISM?

3. Where's the Iron?

What chemical form?

4. Can Amorphous Silicates Grow in the Diffuse ISM?

5. Magnetic Materials in the ISM?

Magnetism at 30–300 GHz: Mm-wave Magnetic Dipole Emission?

Where's the Carbon? Oscillator Strength for CII]2325Å

- In diffuse ISM, gas-phase carbon is almost entirely C II
- Because C II is abundant, permitted lines at $\lambda = 1335 \text{ Å}$ and $\lambda = 1026 \text{ Å}$ are saturated.
- Abundance of C II normally measured with weak intercombination line at $\lambda = 2325 \text{ Å}$:
absorption from $1s^2 2s^2 2p^2 P_{1/2}$ to $1s^2 2s 2p^2 \text{ } ^4P_{1/2}$: $f = 4.8 \times 10^{-8}$ (Morton 2003)
observed $W(2325 \text{ Å}) \rightarrow$ high gas-phase C II abundance, ~ 0.5 solar.
- Grain modellers: *we need more carbon in grains!*
- On some sightlines: can use strong $\lambda = 1334 \text{ Å}$ transition on sightlines where *damping wings* can be measured (Sofia & Parvathi 2010; Sofia et al. 2011)
Need to *increase* $f(2325)$ by factor ~ 2 to reconcile $W(2325 \text{ Å})$ with 1334 Å damping wings.
- If so:
 - $f(2325) \approx 10 \times 10^{-8}$ rather than 4.8×10^{-8}
 - reduce gas-phase abundance of C II by factor ~ 2
 - 75% of C in grains rather than 50%: *grain modelers will be happy!*.
- Problem: theorists continue to obtain $f \approx 5 \times 10^{-8}$:
 - 5.83×10^{-8} (Galavis et al. 1998)
 - 4.99×10^{-8} (Tachiev & Froese Fischer 2000)
 - 4.80×10^{-8} (Corrége & Hibbert 2002)
 - 4.86×10^{-8} (Wiese & Fuhr 2007) [critical compilation]
- Is it possible to measure $f(2325 \text{ Å})$ in the lab?

Where is the Oxygen? *How does oxygen deplete in the ISM?*

- Jenkins (2009): variation of gas-phase abundance of O with gas-phase abundance of other elements (e.g., Mg, Si, Fe): oxygen depletes surprisingly rapidly:

$$\frac{\Delta N(\text{O})}{\Delta N(\text{Mg} + \text{Si} + \text{Fe})} \approx 1.6 \text{ in regions with very low depletion}$$
$$\approx 16 \pm 5 \text{ for } \zeta\text{Oph depletion conditions}$$
$$\approx \mathbf{5} \text{ for overall change from low depletion to } \zeta\text{Oph}$$
$$= 1.5 \text{ for pyroxene } (\text{Mg, Fe})\text{SiO}_3$$

- The O depletion cannot be accounted for by silicates or metal oxides.
Further discussed by Whittet (2010) and Jenkins (2014)
- O in H₂O ice? 3.07 μm absorption feature (O-H stretch) not seen in diffuse clouds
 - could H₂O be hidden in very large ($a \gtrsim 1\mu\text{m}$) grains?
 - expect H₂O to be rapidly photodesorbed in diffuse regions (Westley et al. 1995b,a; Oberg et al. 2009)
- O in CO ice? 4.6 μm absorption feature (C=O stretch) not seen in diffuse clouds
- Carbonaceous materials incorporating substantial O?
 - Polyoxymethylene (POM): (H₂CO)_n ?
 - Some other “organic refractory” (Whittet 2010)?

Where is the O?

Need IR absorption studies of possible “organic refractory” materials that might hold the O

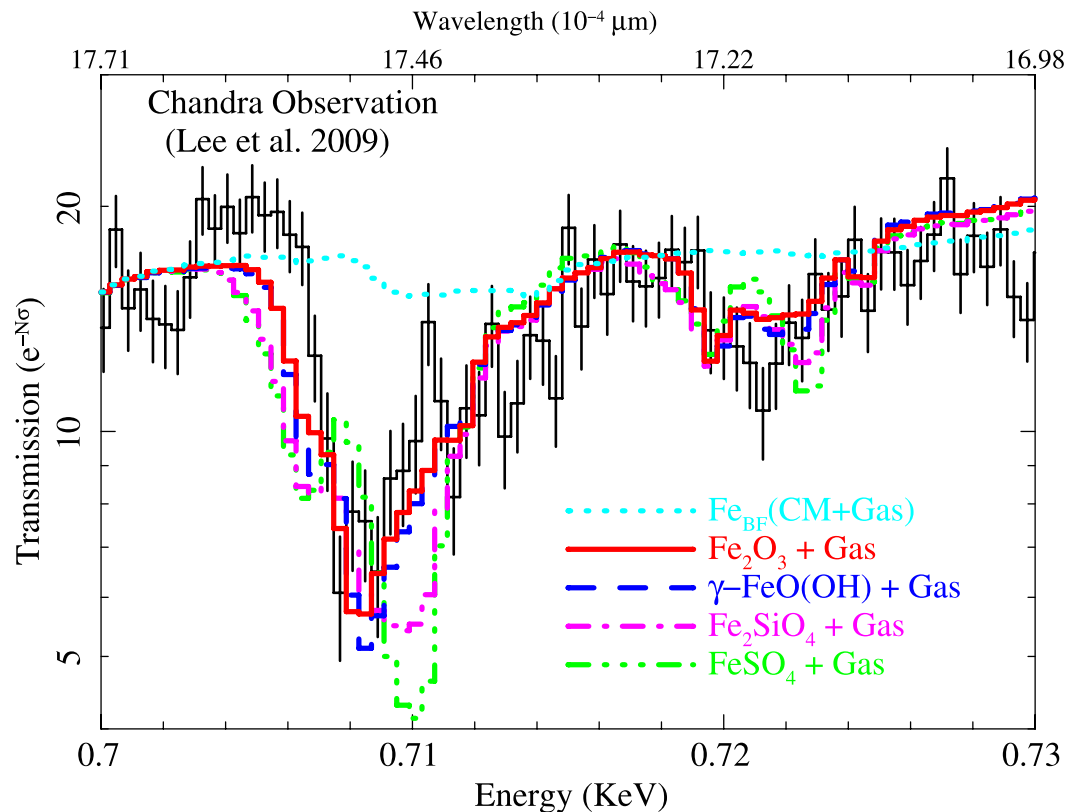
Where's the Iron?

We know that almost all the Fe is in grains, but in what form?

- Amorphous Silicates?
 - olivine-like composition $\text{Mg}_{2-x}\text{Fe}_x\text{SiO}_4$ plausible
 - solar abundances $\text{Fe}/\text{Mg} = 0.79$, could have $x \approx 0.9$
 - some interpretations of observed $9.8\mu\text{m}$ silicate profile suggest $x \lesssim 0.4$
 - if so, where is the rest of the Fe?
- metallic Fe?
- Fe oxides? (FeO , Fe_3O_4 , Fe_2O_3)?
- FeS ?

Where's the Iron? Use X-ray Spectroscopy

X-ray absorption edges are affected by chemical state



Chandra observation of Cyg X-1 (Lee 2010) showing the Fe L edges (absorption by 2s, 2p electrons).

Challenge:

- Need high S/N, high-resolution X-ray observations (Chandra, Astro-H)
- Need lab measurements of X-ray absorption for candidate materials
- We observe *extinction*, which includes a significant contribution from *scattering* as well as *absorption*
- Need to model both absorption and scattering by realistic grain size distributions to compare to observed extinction (Draine 2003)

Can Amorphous Silicate Material Grow in the ISM?

- Amorphous silicate is abundant – strength of the $9.8\mu\text{m}$ absorption feature indicates that $\gtrsim 50\%$ of interstellar Si is in amorphous silicate
- If only source is “stardust”:
 - Even if no destruction, insufficient production of silicate stardust: $> 50\%$ of Si atoms entering ISM from stars is *not* in amorphous silicate dust
 - * winds from hot stars
 - * winds from carbon stars
 - * supernovae
 - Dust destruction in ISM by sputtering and grain-grain collisions: further reduction in fraction of interstellar Si that is incorporated in silicates
- Must be another source: growth of amorphous silicate in ISM (Draine & Salpeter 1979; Draine 1990, 2009)
 - C, Mg, Si, Fe arriving at grain surface
 - in presence of excess H and O
 - in presence of UV
 - conjecture: amorphous silicate material can grow
 - C is removed by reaction with H or O, possibly involving photodesorption of CH or CO by UV
 - conjecture: photoexcitation by UV converts admixture of {O,Mg,Si,Fe} into amorphous silicate
- **Controversy: Jones & Nuth (2011) claim that interstellar silicates *cannot* be formed in the ISM:**

Can “astrosilicate” material grow in the ISM?

Jones & Nuth (2011): No!

If refractory atoms and molecules slowly accrete onto the surfaces of surviving grains only after they have reached the comparative safety of a molecular cloud (rather than in the diffuse ISM), then such atoms may have the opportunity to react with additional adsorbed atomic and molecular species before being buried beneath the growing grain surface. The most abundant atomic species is H and the most abundant molecules are H₂, CO and H₂O. If these reactions occurred, the SiO, and Fe and Mg atoms generated by the erosion of grains in supernova shocks might never reform the initial silicate compounds observed in the ISM, but might instead form a complex ice. Experiments made with mixtures of silane (SiH₄), iron pentacarbonyl (Fe(CO)₅) and H₂O ice condensed at very low temperatures (~10 K) have demonstrated that a silicate can form from such a mixture, especially if the mixture were irradiated with cosmic-ray energy protons prior to warm-up so as to form chemical radicals in the ice (Nuth & Moore 1989). However, a major problem with the results of this study is that the IR spectrum of the warmed silicate residue does not resemble typical IR spectra observed for silicates in the ISM. Based on previous laboratory

...
Thus, any reasonable scenario for grain formation in the ISM will yield materials whose spectral properties do not match observations (Nuth et al. 1998). We suggest that the mineralogy of the majority of interstellar silicate grains is established in oxygen-rich circumstellar outflows and is only slightly modified by subsequent interstellar processes. However, the processing and recycling of carbonaceous matter may be rather fast, and more complex, in comparison.

My View: it *Must* be Possible

- Otherwise we wouldn't have enough silicate in the ISM

But How?

- atoms sputtered off grains in shocks propagating in low-density regions ($n_{\text{H}} \lesssim 1 \text{ cm}^{-3}$) likely to return to grains when gas is later compressed to $n_{\text{H}} \approx 10^2 \text{ cm}^{-3}$ but “diffuse” (i.e., significant UV radiation present)
- UV irradiation will determine composition of growing material
- Amorphous silicate is observed to be abundant in the ISM, therefore this must be what forms under these growth conditions.
- (PAH material must grow separately)

Conditions for Growth of Silicates in the ISM

Consider diffuse cloud with: $n_{\text{H}} = 50 \text{ cm}^{-3}$, $T = 50 \text{ K}$, grains moving at $\sim 0.5 \text{ km s}^{-1}$
Consider one “silicate surface site”, area $A_{\text{site}} \approx 2 \times 10^{-15} \text{ cm}^2$.

- arrival rate of atoms:

$$\begin{aligned} t_{\text{arrival}}^{-1} = n_X \left(\frac{kT}{2\pi m_X} \right)^{1/2} A_{\text{site}} &\approx \frac{1}{12 \text{ yr}} \quad \text{for H} \\ &\approx \frac{1}{1 \times 10^5 \text{ yr}} \quad \text{for O} \\ &\approx \frac{1}{5 \times 10^6 \text{ yr}} \quad \text{for Mg, Si} \end{aligned}$$

- for $A_V \approx 0.5$ max, UV excitation of one of the 7 atoms in one Mg_2SiO_4 unit:

$$t_{\text{photoexc.}}^{-1} \approx 7 \times 10^{-10} \text{ s}^{-1} \approx \frac{1}{50 \text{ yr}}$$

- reactive H arrives very frequently (H_2 formation, extract excess O in form of OH?)
- $\sim 10^5$ photoexcitations between arrivals of Si atoms
- ~ 20 O atoms arrive per Si arrival: fully-oxidized chemistry likely
- 10^5 UV photoexcitations per Si arrival: photolysis will leave whatever material is stable under heavy UV irradiation

Simulation of Silicate Growth in Lab?

- Rouillé et al. (2014):
 - laser vaporization of $\text{Mg}_2\text{SiO}_4 \rightarrow$ deposition on 6K Ne ice matrix
 - while in Ne matrix, characterized composition of deposited material (Mg atoms, Si atoms, small amts of SiO)
 - evaporation of Ne at 13K
 - leaves residue with properties similar to amorphous silicate
 - very small samples: only approximate measurements of IR absorption spectrum
- Can UV effects be simulated in lab?
 - laser vaporization, deposition of **atoms** on cold non-silicate target (e.g., stainless steel)
 - simultaneous UV irradiation
 - deposit $0.1\mu\text{m}$ layer ($N_m = 200$ monolayers) in time t_{expt}
 - to have 10^5 UV excitations per site per monolayer growth time, need UV heating rate/area

$$10^5 \times \frac{N_m \times 10 \text{ eV}}{A_{\text{site}} t_{\text{expt}}} = 2.2 \text{ W cm}^{-2} \frac{1 \text{ hr}}{t_{\text{expt}}}$$

which would seem achievable, although it may be difficult to maintain sample at $\sim 20\text{K}$

If resulting residue could be well-characterized, this could settle question of whether amorphous silicates can be grown in ISM.

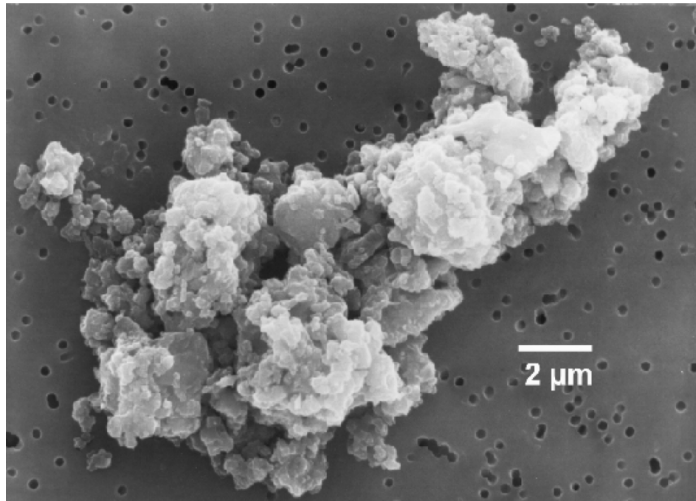
Magnetic Grains in ISM?

- Chemical form of solid-phase Fe in ISM not known – fraction in silicates is disputed.
- Metallic Fe and Fe oxides have often been considered as a grain constituent (Schalen 1965; Wickramasinghe & Nandy 1971; Huffman 1977; Chlewicki & Laureijs 1988; Cox 1990; Jones 1990)
- Metallic Fe, magnetite (Fe_3O_4), and maghemite ($\gamma\text{Fe}_2\text{O}_3$) are magnetic materials.
- McDonald et al. (2010): low-metallicity AGB stars in globular clusters sometimes produce dust that is not silicate (IR spectrum is featureless); propose that “Rusty Old Stars” produce Fe metal grains in winds.
- Fe or Fe oxide grains have been invoked to explain strong mm-wave emission from the SMC (Draine & Hensley 2013)

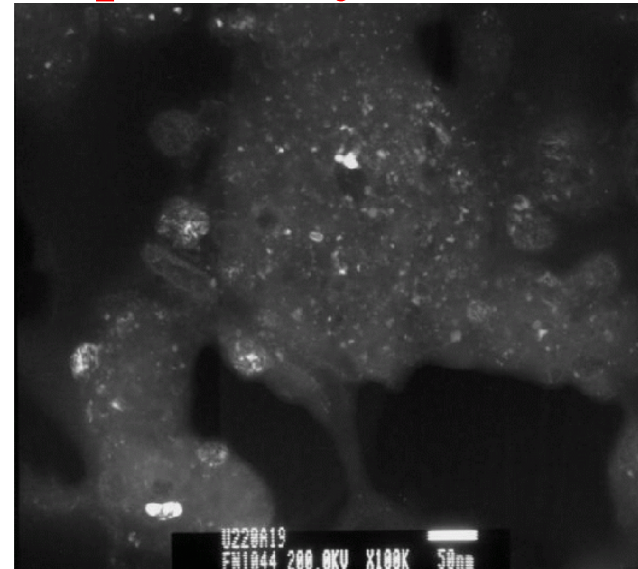
Sources of Interstellar Grain Material

- Grains do not survive long in ISM; observed abundance of solid materials requires that most of what we see was *grown in the ISM* (Draine & Salpeter 1979; Draine 1990, ...).
- Unfortunately, growth occurs far from LTE. We don't really understand the balance between different processes (reactions with impinging atoms and ions, photodesorption, UV photolysis...).
- Hints from interplanetary dust particles (IDPs) and lunar soil samples...

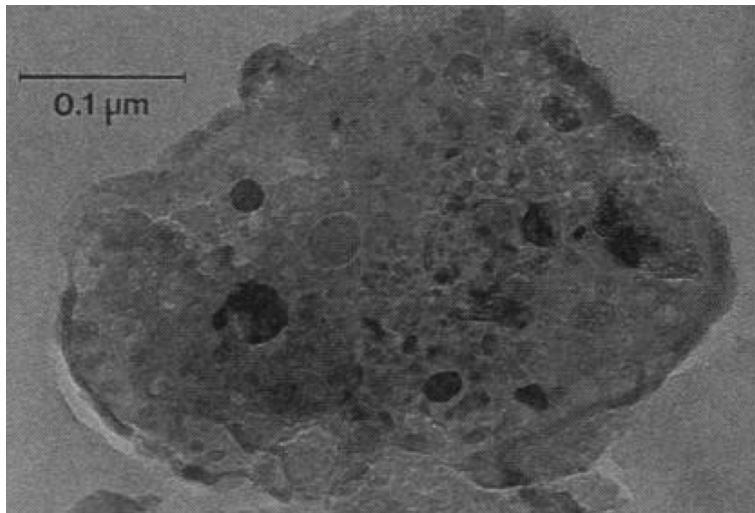
Metallic Fe nanoparticles in Interplanetary Dust Particles



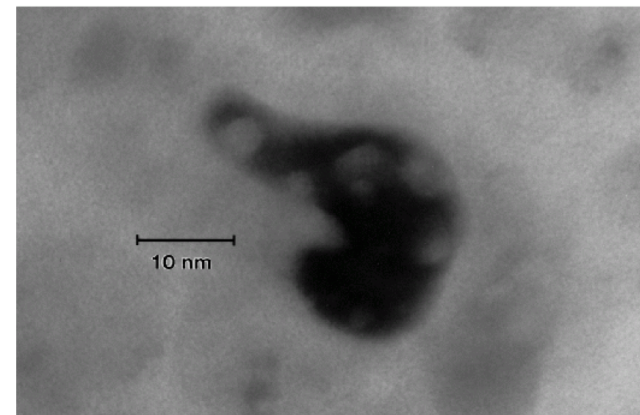
chondritic porous IDP (Bradley 2003)



Electron micrograph of GEMS in an IDP.
Bright inclusions are FeNi metal and FeNi sulfide
crystals embedded in Mg-rich silicate glass (grey)
(Bradley 2003)

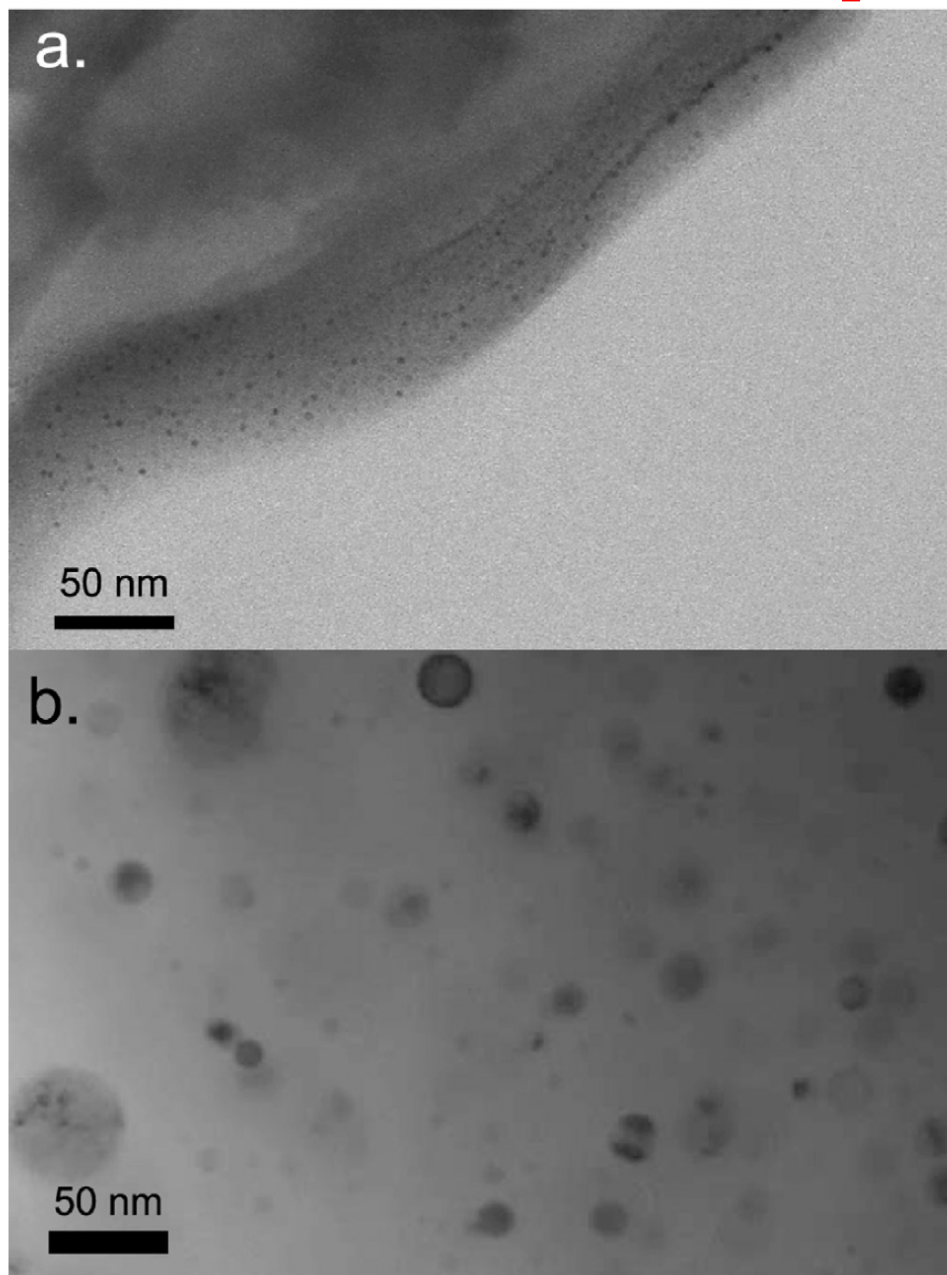


GEM (Glass with Embedded Metals and Sulfide)
from an IDP (Bradley 1994)



One FeNi inclusion (Bradley 2003)

metallic Fe nanoparticles from lunar soil



- ~ 2 nm metallic Fe nanoparticles in lunar “agglutinitic glass” (believed to be result of melting produced by micrometeorite impacts)

- ~ 10 nm metallic Fe nanoparticles in “rims” of lunar soil grains.

Noble et al. (2007)

Production of Fe Nanoparticles in the Lab

- Bombardment of olivine ($\text{Mg}_{1.8}\text{Fe}_{0.2}\text{SiO}_4$) crystals with 1 keV H^+ and 4 keV He^+ :
production of metallic Fe nanoparticles in amorphous silicate matrix
(Dukes et al. 1999; Carrez et al. 2002; Loeffler et al. 2009).
- Laser ablation of olivine ($\text{Mg}_{1.8}\text{Fe}_{0.2}\text{SiO}_4$) and redeposition of vapor on surface:
production of metallic Fe nanoparticles in amorphous silicate matrix
(Loeffler et al. 2008).

*Metallic Fe nanoparticles should be considered
as possible constituents of interstellar grains.*

*If present in ISM: millimeter and cm-wave emission
due to thermal fluctuations in magnetization*

Response of Material to Applied EM Field

Electric Field

- Applied \vec{E} :
 - polarization \vec{P}
(*displacement of bound charge*)
 - electric current $\vec{J} = \sigma \vec{E}$
(*displacement of free charge*)
- In linear regime, describe response to
 $\vec{E}(t) = \vec{E}_0 e^{-i\omega t}$
by complex dielectric tensor $\epsilon(\omega)$:

$$\vec{D} = \vec{E} + 4\pi\vec{P} = \epsilon \cdot \vec{E}$$

Magnetic Field

- In absence of applied \vec{H} :
ferromagnetic material has spontaneous magnetization \vec{M}_0 due to aligned electron spins
- Applied $\vec{B} \rightarrow$ torque on spins
 - \rightarrow spin precession
 - \rightarrow precession of magnetization \vec{M}
- In linear regime, describe response to
 $\vec{H}(t) = \vec{H}_0 e^{-i\omega t}$
by complex permeability **tensor**
 $\mu(\omega) \equiv 1 + 4\pi\chi(\omega)$:

$$\vec{B} = \vec{H} + 4\pi\vec{M} = \mu \cdot \vec{H}$$

Can we model $\mu(\omega)$?

High Frequency Magnetism

Ferromagnetism

- Lowest energy state of metallic Fe:
 - unpaired spins are **parallel** (magnetized) because this minimizes the Coulomb energy
 - magnetization \vec{M}_0 is aligned with one of the crystal axes
 - $4\pi M_0 = 22 \text{ kG}$ for Fe
- Fictitious “crystalline anisotropy field” H_K to describe the variation of energy with direction of \vec{M} relative to crystal axes
$$\Delta E = \Delta(\vec{M}_0 \cdot \vec{H}_K)$$
$$(H_K = 548 \text{ gauss for Fe})$$
- Spins **precess** around “effective field” $\vec{H}_T = \text{actual field} + \vec{H}_K$
- Must be dissipation associated with spin precession.
- Seek to model absorption of energy from oscillating \vec{B} .
i.e., model for tensor $\mu(\omega)$

Magnetization Dynamics

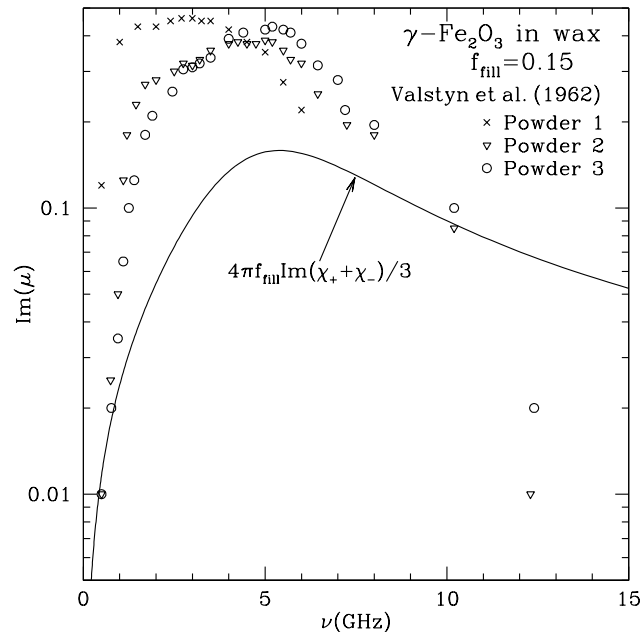
Three approaches:

- Landau-Lifshitz equation (Landau & Lifshitz 1935)
one phenomenological damping parameter
- Bloch-Bloembergen equation (Bloch 1946; Bloembergen 1950)
two phenomenological damping times τ_1, τ_2 .
Problem: *non-physical behavior!!*
- Gilbert equation (Gilbert 1955, 2004)
One phenomenological damping parameter α_G .

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{H}_T + \alpha_G \frac{\vec{M}}{|\vec{M}|} \times \frac{d\vec{M}}{dt}$$

Lab measurements of magnetic absorption

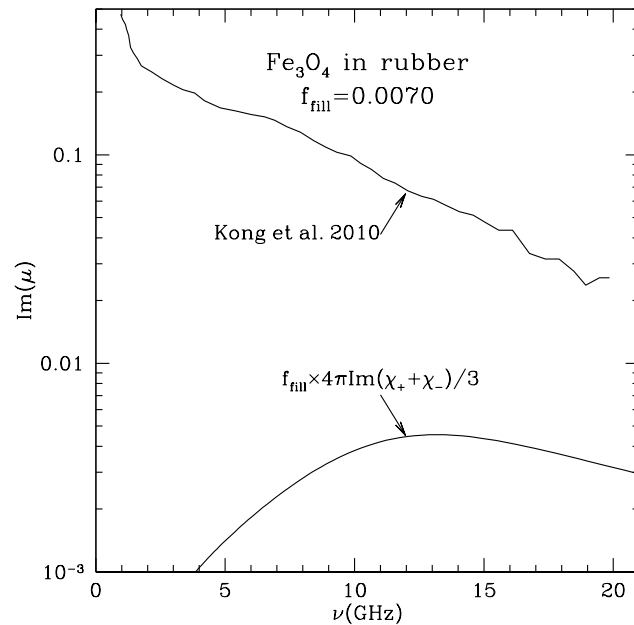
Very little data in literature for 10–300GHz



~120–500 nm maghemite $\gamma\text{-Fe}_2\text{O}_3$ in wax matrix (Valstyn et al. 1962)

Model with $\alpha_G = 0.2$:

- *under*predicts $\nu \lesssim 8$ GHz absorption
- *over*predicts ~ 13 GHz absorption near



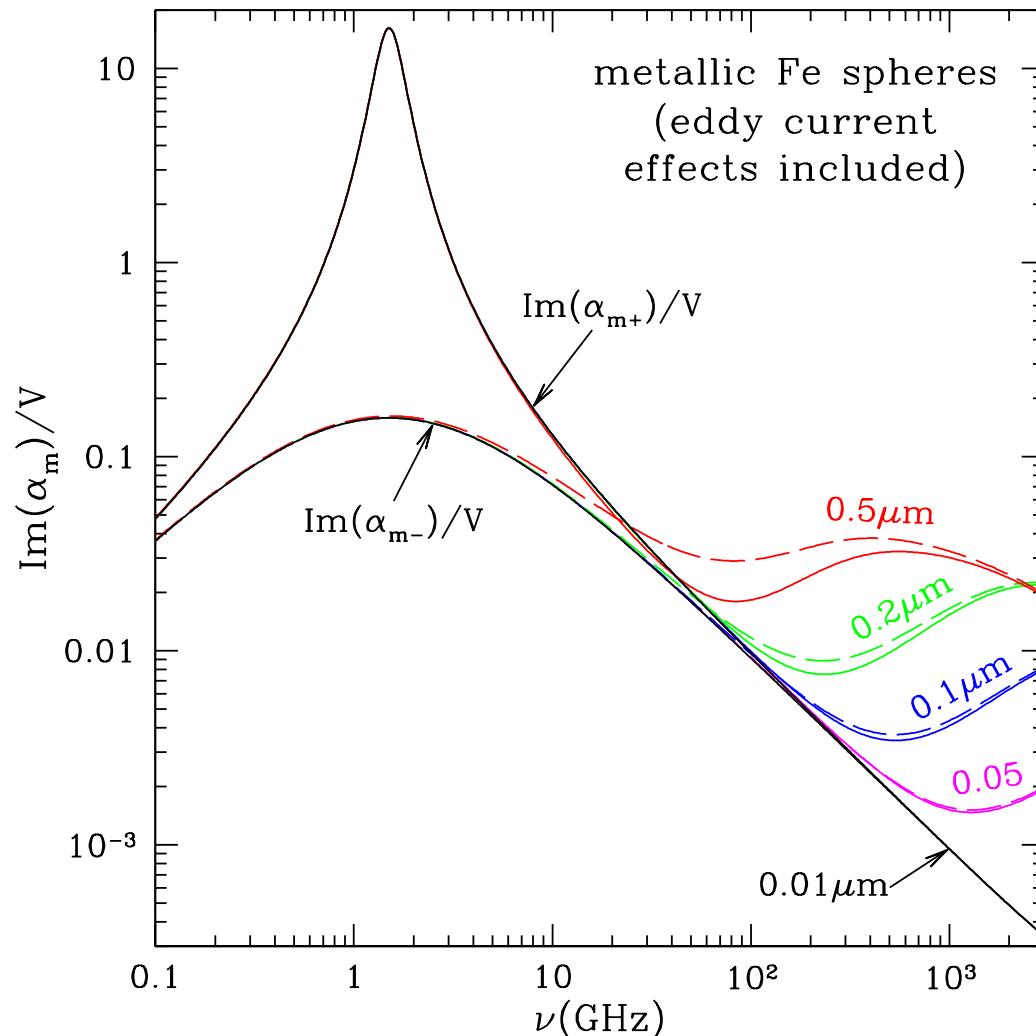
~25 nm magnetite Fe_3O_4 in rubber matrix (Kong et al. 2010)

Model with $\alpha_G = 0.2$:

- *under*predicts 1–20 GHz absorption

from Draine & Hensley (2013)

Metallic Fe: theoretical model

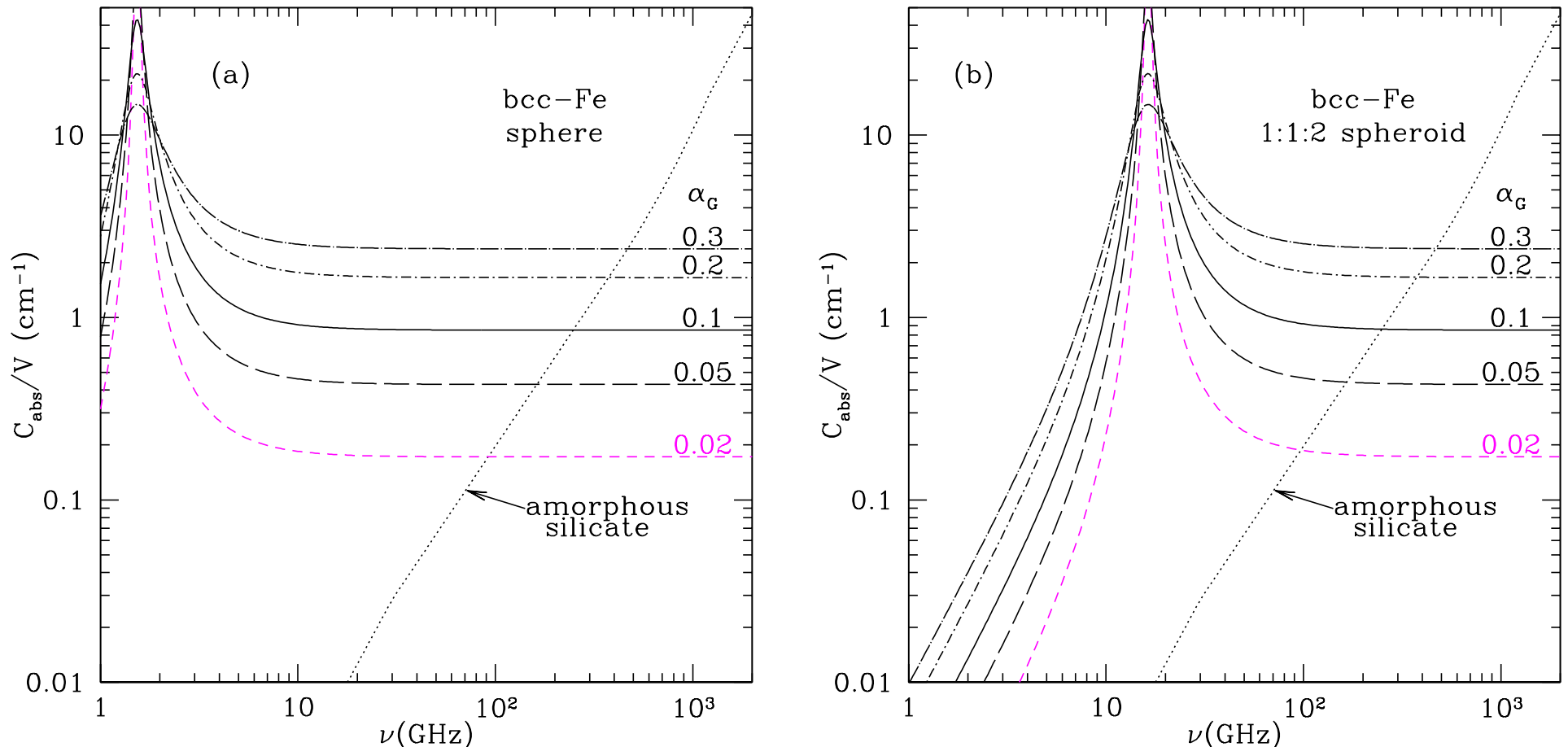


α_m = magnetic polarizability of Fe sphere
assuming Gilbert equation with $\alpha_G = 0.2$
(Draine & Hensley 2013)

- Resonance near 1.5 GHz for spheres
- Near resonance: absorption different for two circular polarization modes
- For large particles, eddy current absorption dominates
- For $a < 100\text{nm}$, eddy current effects are minor for $\nu < 200\text{GHz}$
- To study in lab: disperse Fe nanoparticles in insulating matrix. (must avoid clumping!)

Magnetic Dipole Absorption Cross Section for Fe Nanoparticles

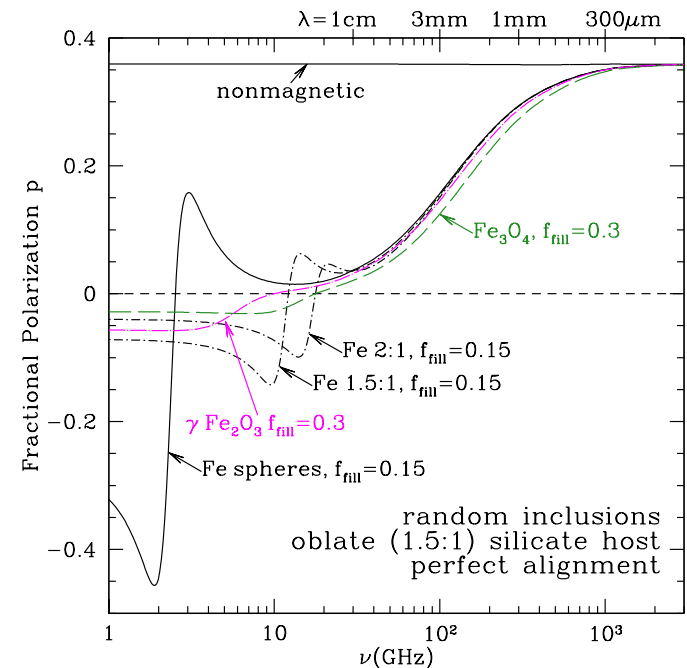
theoretical estimates (Draine & Hensley 2013)



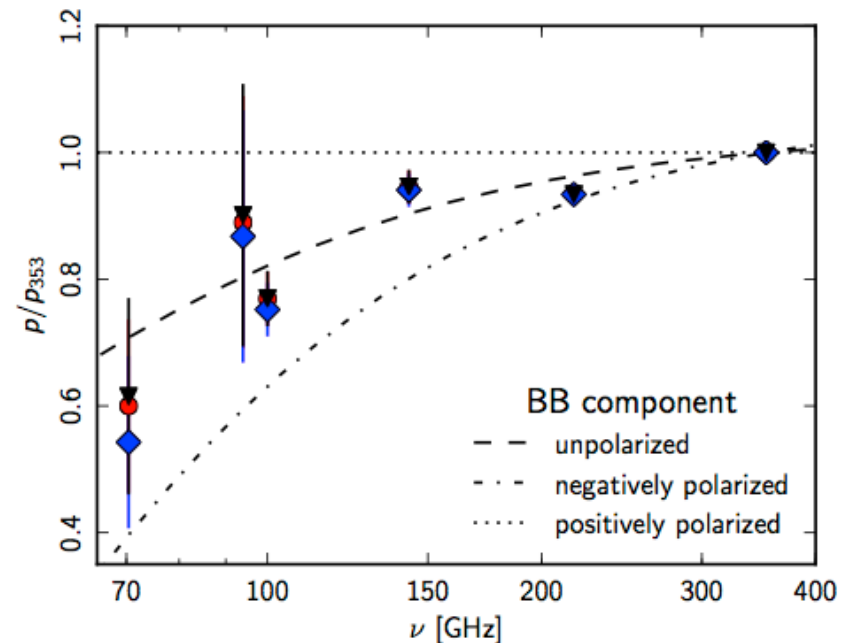
- Resonance frequency depends on particle shape.
- Absorption depends on uncertain “Gilbert damping parameter” α_G .
 $\alpha_G \approx 0.2$ may be realistic.
- **Absorption/volume C_{abs}/V exceeds value adopted for “astrosilicate” for $\nu \lesssim 300$ GHz.**
→ “excess” emission for $\nu < 300$ GHz (e.g., 150 GHz BICEP2?)

Why are we so interested in possibility of magnetic grains?

- metallic Fe and Fe oxides are plausible grain constituents
- magnetic grains may be able to explain strong 1–3 mm emission from dust in the SMC (Draine & Hensley 2012)
- Predicted polarization signature: if magnetic material is present as randomly-oriented inclusions in amorphous silicate grains, then expect the polarization fraction to *decrease* with decreasing frequency in mm region. This is consistent with most recent *Planck* papers on polarized Galactic foregrounds.



from Draine & Hensley (2013)



Planck int. results. XXII (arXiv:1405.0874)

Summary

- *Where's the carbon?*

Establish value of $f(CII]2325 \text{ \AA})$ used to determine gas-phase abundance of carbon.

- *Where's the oxygen?*

Lab studies of candidate materials (hydrocarbons?) that could hold the missing oxygen

- *Where's the iron?*

X-ray spectroscopy may be able to tell us

- *Can amorphous silicates grow in the diffuse ISM?*

simulate formation of silicates on cold surfaces:

- from atoms
- in presence of UV

- *Magnetic materials in the ISM?*

Lab measurements of absorption by candidate magnetic materials (metallic Fe, magnetite, maghemite) at $10 < \nu < 500 \text{ GHz}$

- test validity of Gilbert equation
- determine value of damping parameter α_G



THANK YOU

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