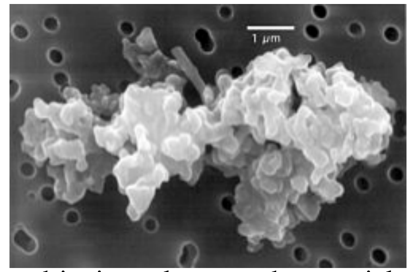
https://ay201b.files.wordpress.com/2013/03/ay201b_130305_dust.pdf

Dust

The four letter word in astrophysics

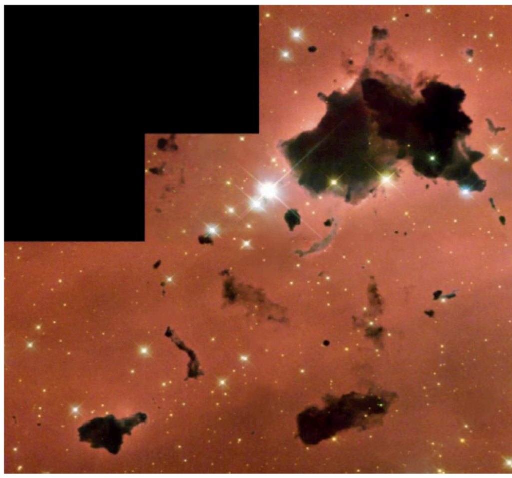
(Not too much on this in the books-MBW sec 10.3.7(b)

see ARA&A 2003 41, 241 Draine- Interstellar Dust Grains))

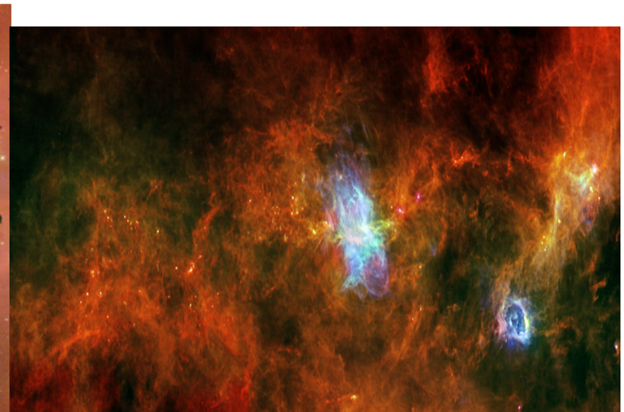


Porous chondrite interplanetary dust particle.

Interstellar extinction

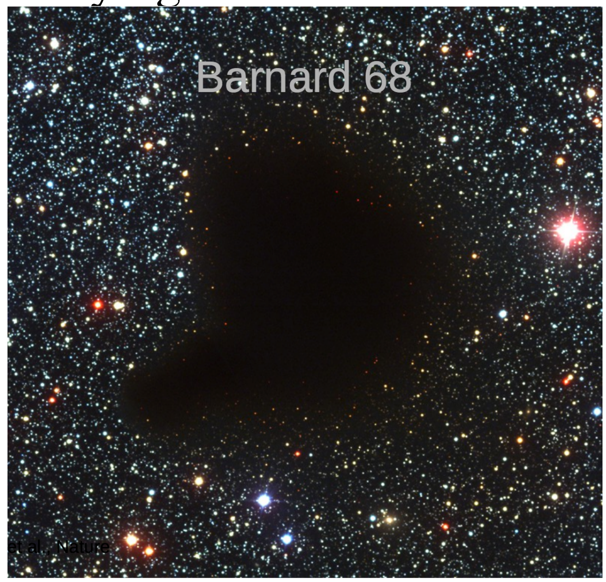


Interstellar Emission



- Mid-term is postponed to **Weds Oct 18** so I can get the 2nd homework back to you.
- Home work handed out today due Mon Oct 9
- First Homework will be handed back Weds Oct 4

If We Were Studying Dust



What do we want to know about interstellar dust?

- Its composition:

–comparison between stellar and interstellar abundances: depletion

Its size (distribution of grain sizes):

- How much extinction it causes
- Nature of the continuum emission and emission features
- Their interaction with light:
- Its role in the thermodynamics of the gas
- Their role in ISM chemistry:

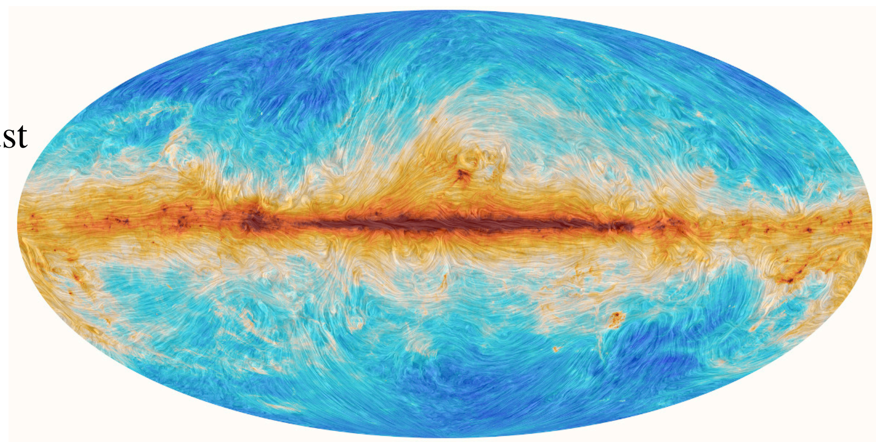
DUST From A. Goodman's Class Notes

- What it does: emits, absorbs, scatters, extincts(=absorption +scattering), polarizes - LIGHT
- What it is...silicates, carbonaceous ,"PAHs" shape and size
- Where it's found :mixed with "cold" ISM (atomic & molecular)
- Where its formed: winds from cool stars (formed there & in SNe)
- How it's used by astronomers to measure
  baryonic mass/column (~via flux conversion), temperature (via SED fitting), distance (via reddening), magnetic fields (via polarization)
- Aids in forming molecules (on grain surface), planets (in circumstellar disks)

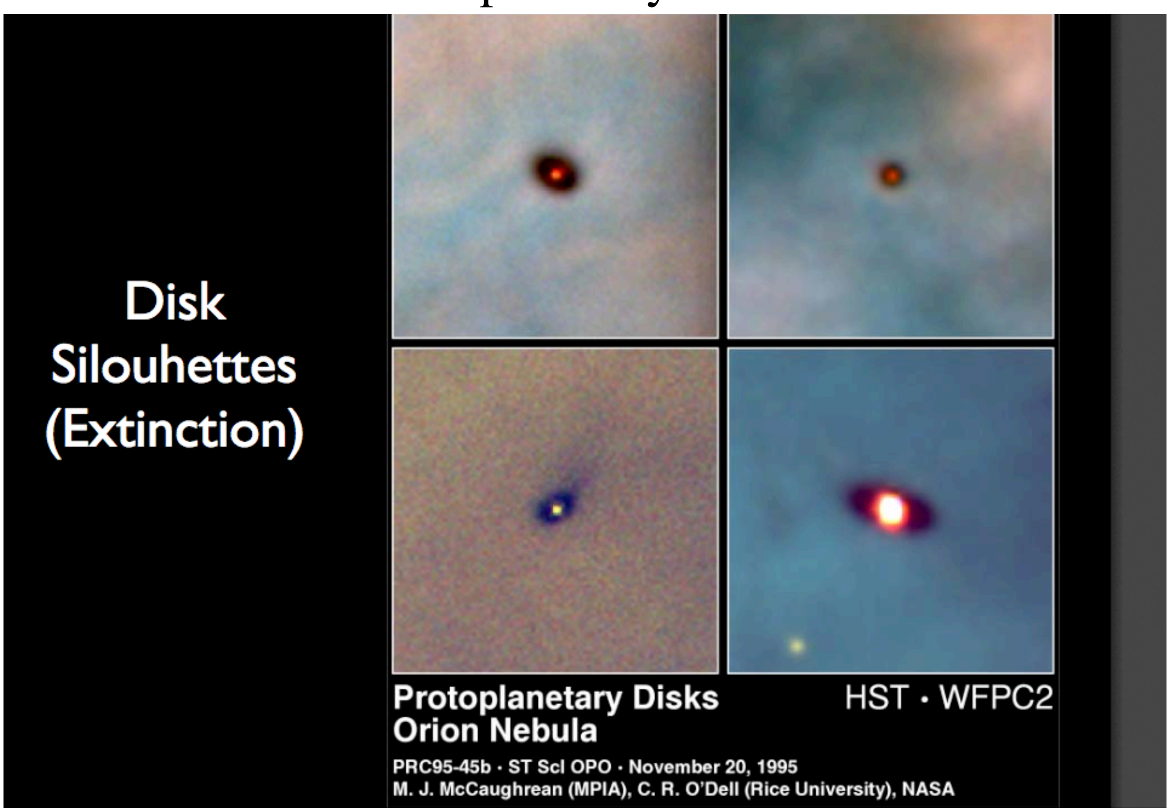
Why Study Dust?? (Draine 2003)

- Dust grains play a central role in the astrophysics of the interstellar medium, from the thermodynamics and chemistry of the gas to the dynamics of star formation.
- Dust shapes the spectra of galaxies Radiation at short wavelengths is attenuated, and energy is radiated in the infrared.
- Most of the heavy elements in the interstellar medium in spirals are in the dust
- Dust is crucial for star formation and a major noise source for the study of the CMB.
- Forms planets

Planck map of dust emission and polarization in MW



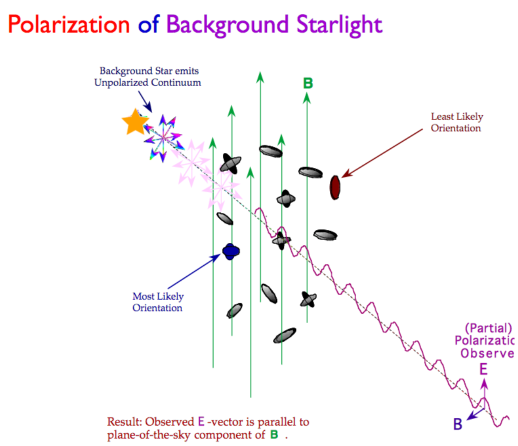
Protoplanetary Disks



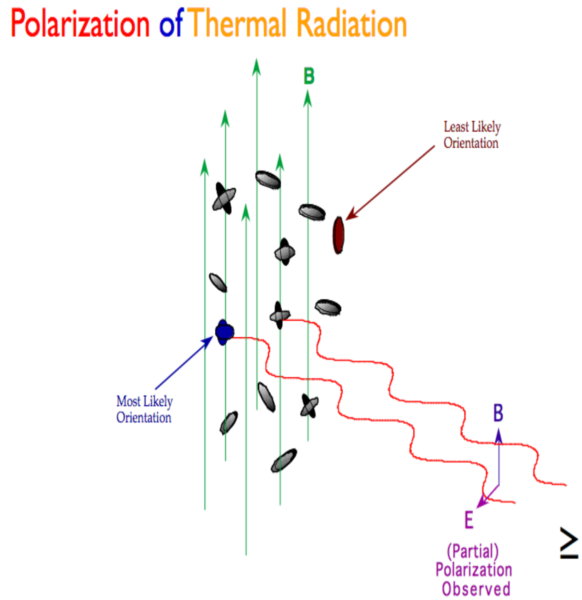
Polarization

Dust polarizes background starlight AND emits polarized thermal IR light

https://ay201b.files.wordpress.com/2013/03/ay201b_130305_dust.pdf



Observed E-vector is perpendicular to plane of sky component of B field



Observed E-vector is parallel to plane of sky component of B field

Why Dust

- Dust attenuates and scatters UV/optical/NIR

  Amount of attenuation and spectral shape depends on dust properties (grain size/type)
- Dust geometry + optical thickness crucial- many stars are embedded in the dust
- Attenuation $\tau \sim 1/\lambda$ (roughly)+ scattering
- Absorbed energy heats dust --> thermal IR emission; spectral shape of emitted radiation depends on size distribution of dust grains
- Dust contains most of the interstellar Mg, Si, and Fe, and much of the C

Infrared and optical image of the Sombrero galaxy

See Mark Whittle's web page for lots more details http://www.astro.virginia.edu/class/whittle/astr553/Topic09/Lecture_9.pdf

Dusty Facts-
see Wilson review article on class web page

- The ISM is exceedingly dirty; Cool interstellar gas contains about one grain of dust per 10^{12} hydrogen atoms: on average, one grain per 100-meter cube
  – If the ISM had the density of the earths atmosphere number density (3×10^{19} cm^{-3}) it would be a thick smog with ~1 mag/meter extinction
  – the smog is rich in carcinogenic PAHs.
- Dust grains come in wide range of sizes (power law distribution of size)
  – $dn/da \sim a^{-3.5}$ over factor of 10^3 in grain size; $a_{max} \sim 0.3\mu m$
- Dust grains have a variety of compositions: silicate grains, carbonaceous grains, amorphous carbon, and polycyclic aromatic hydrocarbons (PAHs)- grain properties not the same from galaxy to galaxy or place to place
- By mass, dust typically comprises 0.7-1% of the interstellar medium in a galaxy like the Milky Way.
- Dust explains: the λ^{-1} form of the UV/optical extinction curve (large scattering efficiency (~60%) and scattering angle) the maximum value for a_{max} comes from dust's IR transparency

Dust absorption and scattering

Lets define $x = 2\pi |m-1| a/\lambda$

λ= wavelength

- $m = n+ik$

– n optical constant: real part

–k imaginary part responsible for the absorption and emission

a radius of the grain

- Rayleigh-Jeans limit when $x << 1$
- Geometrical optics when $x>>1$
- Mie theory required when $x \sim 1$

Define dust cross section for extinction $Q(\lambda)_{ext} = \sigma(\lambda)/(\pi a^2)$ for a dust particle of 'size' a

Then the optical depth $\tau(\lambda)$ along a line of sight with N_D dust grains of size a is

$\tau(\lambda) = \pi a^2 N_D Q(\lambda)_{ext}$

The extinction is then for an input spectrum $I(\lambda) = I_0(\lambda)\exp(-\tau(\lambda))$
and in magnitudes
$A(l) = -2.5 \log_{10} [I(\lambda)/I_0(\lambda)] = 1.086\tau(\lambda)$

Blue and ultraviolet radiation is more strongly scattered and absorbed by dust than red light, so dust between us and a star makes it appear both dimmer and redder.
https://ned.ipac.caltech.edu/level5/Sept07/Li1/Li2.html

Mie Theory Results

- In the limit of λ<< a, Mie theory gives:
- $Q_{abs} = 1$ (ie πa^2 as expected, independent of wavelength)
- $Q_{scat} = \pi a^2$, (from diffraction)
- $Q_{ext} = Q_{abs} + Q_{scat} = 2$, double the simple geometrical cross section.

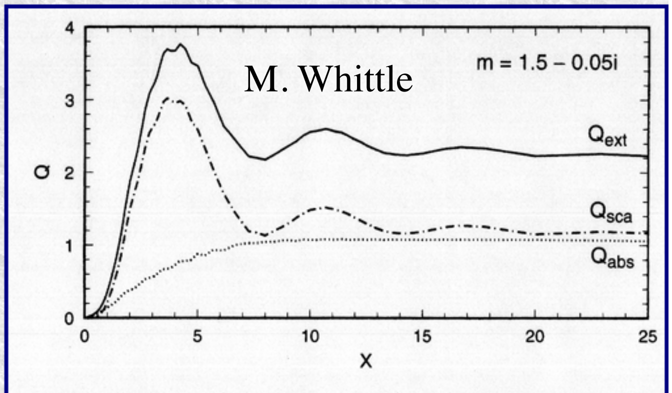
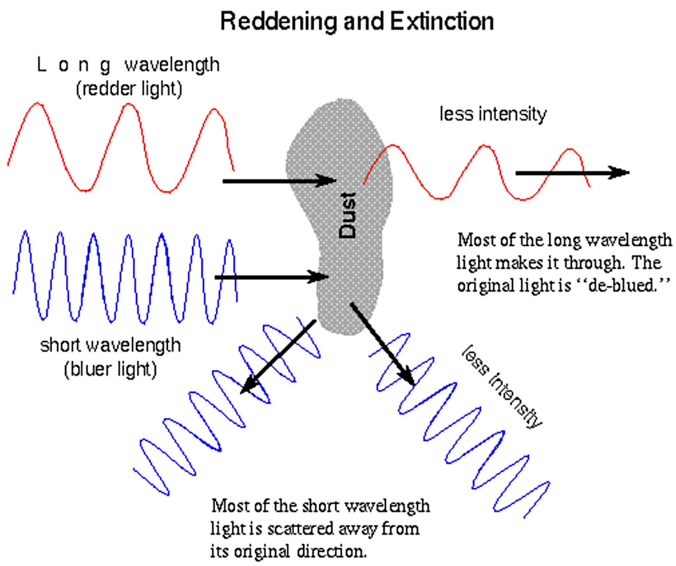


Figure 3.1. Results of Mie theory calculations for spherical grains of refractive index $m = 1.5 - 0.05i$. Efficiency factors Q_{ext}, Q_{sca} and Q_{abs} are plotted against the dimensionless size parameter $X = 2\pi a/\lambda$.

The **Mie solution** to Maxwell's equations describes the scattering of electromagnetic radiation by a sphere- as a truncated multipole expansion of the full solution to the scattering problem.
As grain radius *a* increases, the number of multipole terms required also increases.
For grain sizes that are much larger than the incident wavelength, Mie theory becomes computationally demanding- Hoffman and Draine 2015

Interaction of Dust with Light



Grain parameters:
- grain composition
- grain size
- grain shape
- grain orientation

(polarization observations)

- Wing-Fai Thi MPE for lots more detail see

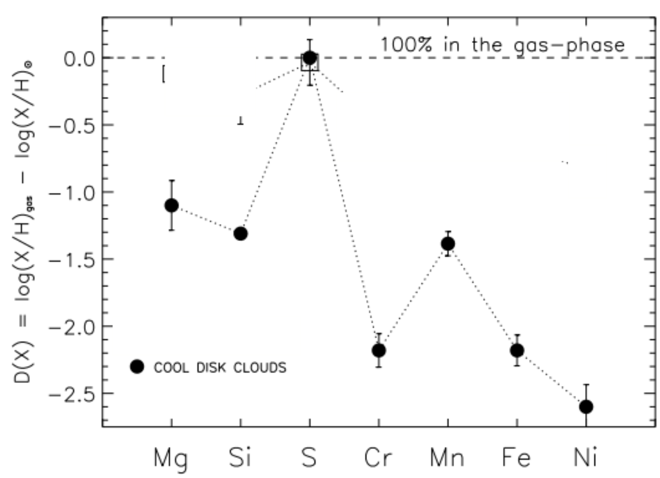
http://w.astro.berkeley.edu/~ay216/08/NOTES/Lecture05-08.pdf

Dusty Facts

- Dust mass insignificant (~1% of total HI gas mass)
- Dust is formed from SN/stellar ejecta and/or in ISM
- Dust grains come in wide range of sizes (power law distribution of size)
- Dust grains are mainly: silicates (Mg/Fe-rich) or graphites (C) with a bit of ice
- Grains provide surface for complex astrochemistry (and H_2 formation-MBW 9.2.1)
- Dust is one of the main heating mechanisms of the molecular gas (through photo-electric effect)- this ionizes even molecular clouds a tiny bit (enough to couple to B field)
  - Photoeffect :photon liberates e- from solid (e.g. dust).
  - Mostly working on PAHs and small dust grains.
- Spectral features due to dust
  - PAH (poly-cyclic aromatic hydrocarbons) produce characteristic spectral features
  - Silicates can produce strong absorption features (10μ)
- Effective temperature of dust in emission ranges from ~10-100k depending on energy sources and geometry
- Wide range of dust in galaxies

Effects of Dust on Chemical Composition of ISM

- Dust 'depletes' the ISM of 'refractory' elements
  - Elements with high evaporation temperatures Mg, Si, Al, Ca, Ti, Fe, Ni are concentrated in interstellar dust grains.
- These depletions are caused by the atoms condensing into solid form onto dust grains. Their strengths are governed by the volatility of compounds that are produced: **effects can be big**
  - dust grains contain approximately 70% of the Mg, 45% of the Si, and 75% of the Fe



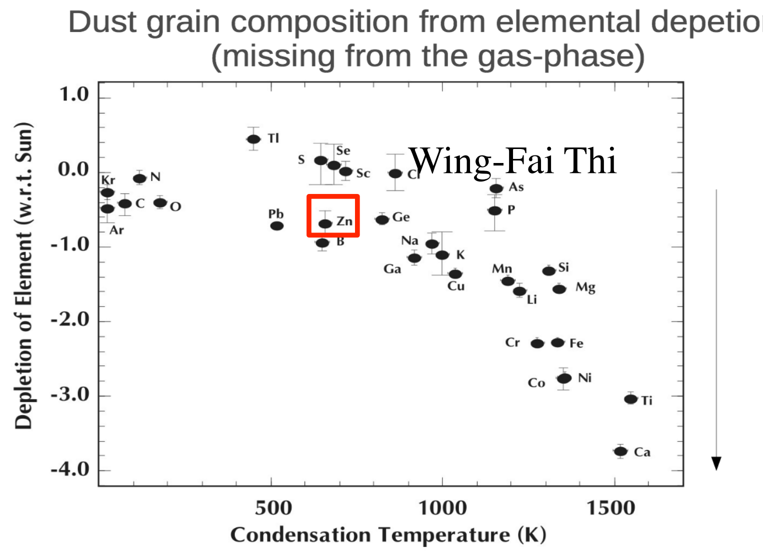
ISM abundances have to be adjusted for this effect

Dependence of depletion on Condensation temperature

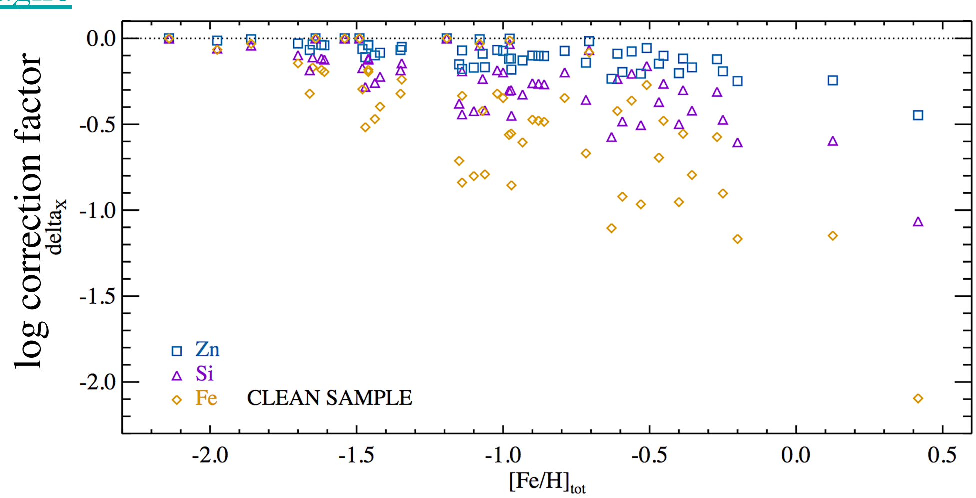
- mass gas/mass dust ~ 100
  - There cannot be much more dust than 0.01 M_H

since it would that use up all the metals (Purcell)

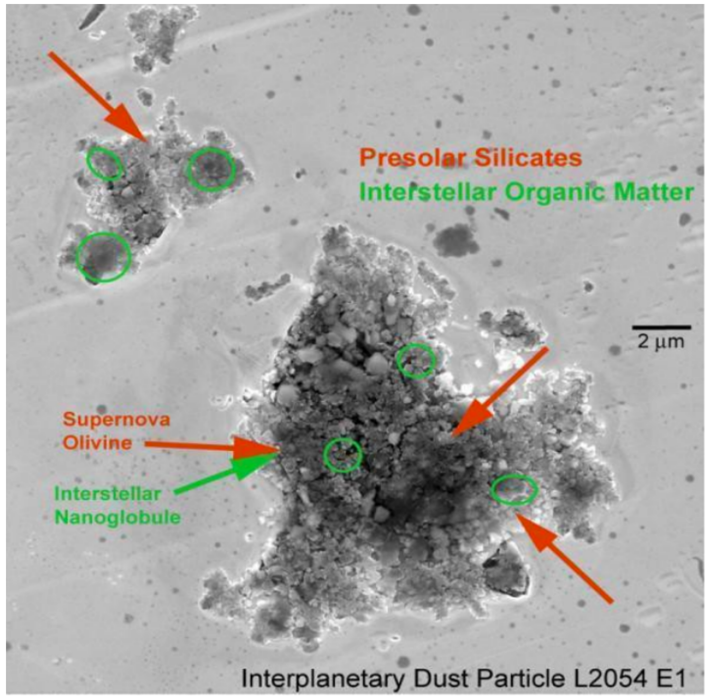
- If condensation temperature is >100k element is depleted in the ISM as are O and C (slightly)
- Dust composition



- Dust depletion as a function of element and [Fe/H] for high redshift galaxies
- for the effect on estimate evolution of abundances over cosmic time see arXiv:1709.06578 The cosmic evolution of dust-corrected metallicity in the neutral gas A. De Cia, C. Ledoux, P. Petitjean, S. Savaglio

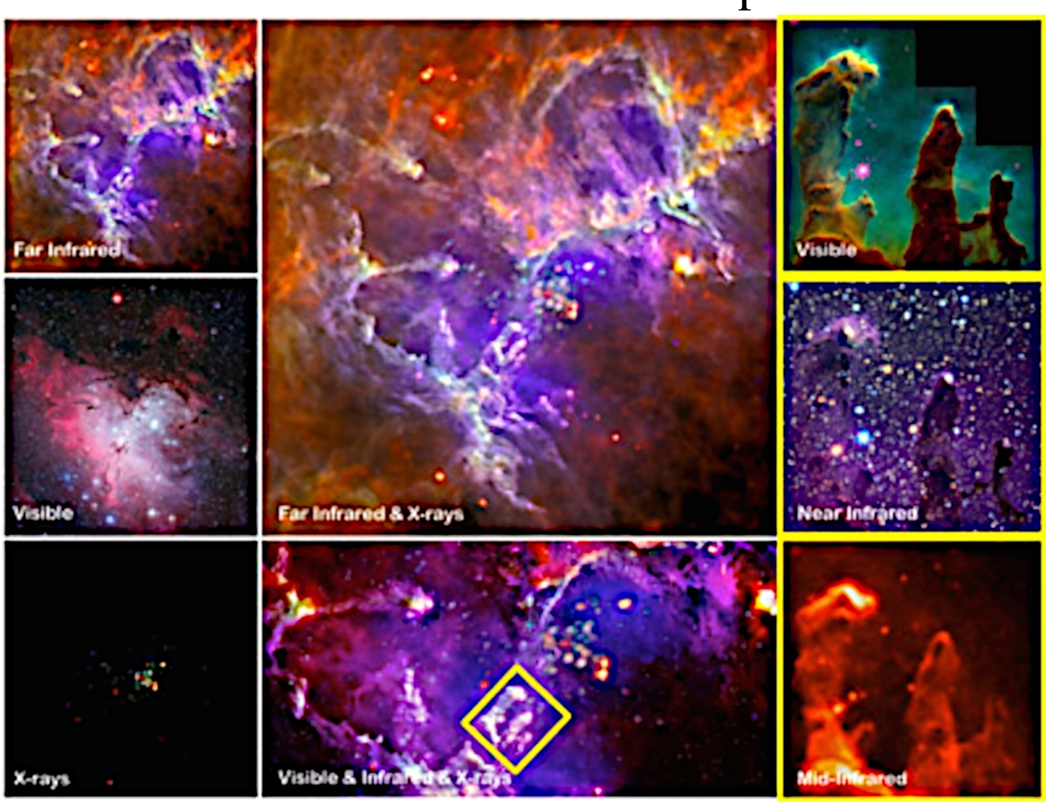


Interstellar Dust in Solar System (!)



(see G. Munoz Caro, 2006 A&A)

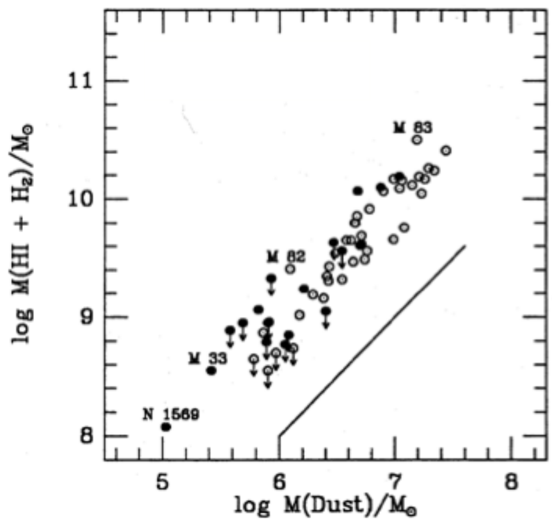
Emission and Absorption



Strong correlation of Dense Gas and Dust

- for column densities in excess of $N_{HI} > 4 \times 10^{21}$ cm^{-2}, gas transitions from atomic to molecular gas.

- Dust shields the gas from the UV radiation field, allowing it to be cool.
- In molecular clouds mean gas-to-dust mass ratios of ~ 600 (compared to 100 for galaxy as a whole)
- The coldest dust is heated by 'normal' stars and is not associated with molecular clouds
- Warm dust is associated with star forming regions and thus molecular gas



•MOLECULAR GAS IN GALAXIES

J.S. Young &N.Z. Scoville Annu. Rev. Astron. Astrophys. 1991. 29: 581-625

Continuum Emission from Dust

- Emissivity from dust is 'quasi-black body like'- (grey body)
- $F_\lambda = N_a \pi a^2 Q_\lambda B_\lambda(T)/D^2$ (from a given grain)
- where a is the size of the grain, D is its distance, B_λ is the black body function and Q_λ is the emissivity in the IR (grain is not 'black')
- $Q_\lambda \sim \lambda^{-\beta}$

β=0 for a BB

β=1 for amorphous material

β=2 for metal and crystals

The peak of Black body is at λ=2900μm/T(K)in F(λ)

In R-J limit $F_\nu \sim \nu^{\beta+2}$

Temperature and luminosity in dust diagnostic of fraction of light absorbed, spatial distribution of sources and dust

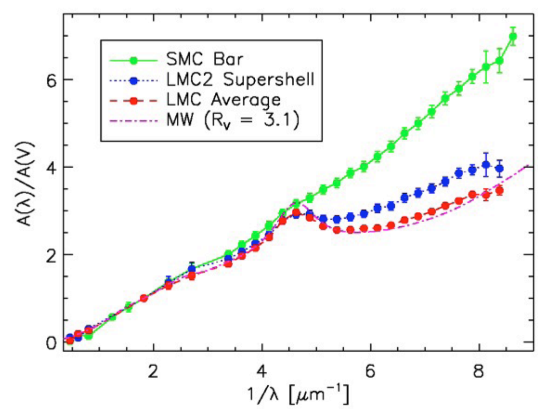
- In most galaxies, the bulk is in the FIR, ~60 - 200μm
- the majority of dust has T_d~ 10 - 50K

Reddening and Extinction

MBW pg 478 -482

- Dust and gas strongly effect the transfer of radiation through a galaxy
- Dust and gas clouds are where stars form
- Dust and gas interact
- In general the extinction due to dust can be parameterized by
- $I_\lambda = I(o)e^{-\tau(\lambda)}$
- $dI_\lambda/dx = -k(\lambda)I_\lambda$;$=-k(\lambda) \sim \lambda^{-1}$

- Astronomers use magnitudes (ugh)
- We can determine the degree of reddening by measuring the color index (B-V) of the object and comparing that to its true color index $(B-V)_0$: (where the units are magnitudes...sigh)
- $E(B-V) = (B-V) - (B-V)_0$



with extinction and reddening linked $A_V = R*E(B-V)$; R~3.1 for MW, 2.7 for SMC

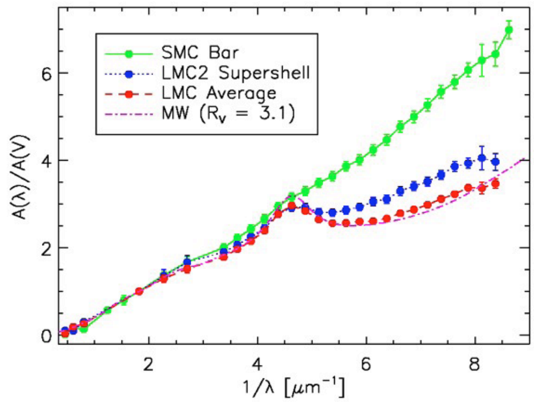
•so $k(\lambda)=A_\lambda/(E(B-V)=R_V A_\lambda/A_V$ and $A_\lambda = (2.5\log e)\tau(\lambda)$ -change in magnitude at wavelength λ due to extinction

• $E(B-V)=A_B-A_V$ is the color excess

and $R_V=A_V/E(B-V$

•$m-M=5\log d-5+A_v$

Reddening and Extinction



- *Extinction law*
  - $k(\lambda) \equiv A_\lambda/E(B-V) \equiv R_V A_\lambda/A_V$
  - where $A_\lambda = (2.5\log e)\tau_\lambda$ is the change in magnitude at wavelength λ due to extinction,
- $E(B-V) \equiv A_B - A_V$ is the color excess measured between the *B* and *V* bands, and
- $R_V \equiv A_V/E(B-V)$
- *This is of course generalizable to any pair of wavelengths*
- The advantage of working with R_V and k(λ is that they are insensitive to the total amount of dust along a line-of-sight.

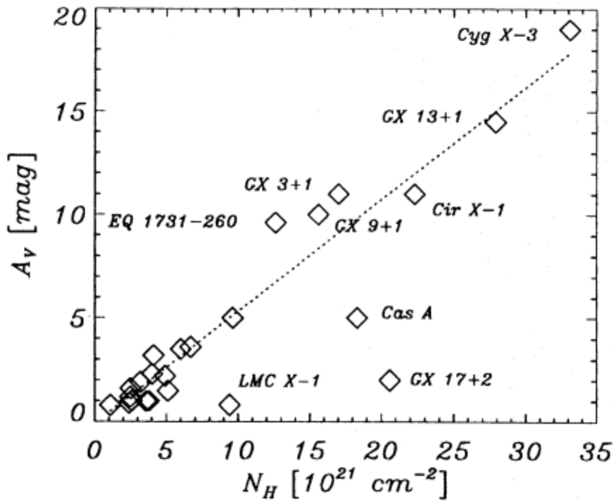
Reddening/Extinction MBW pg 479

- Often reddening is easier to measure than extinction
- so another useful parameter is :
- $E(B-V) = (B-V)-(B-V)_0 = A_B - A_V$ or its generic relative $E_{\lambda-x} = A_\lambda - A_x$
- E values are differences in color and are therefore easier to measure
- optical depths are additive, E_{B-V} and A_V are proportional

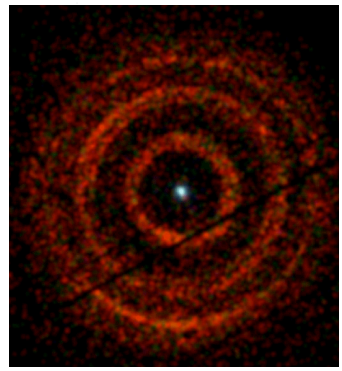
Dust to Gas Ratio

- In the MW the average dust to gas ratio (by mass) is ~100
- This gives a relationship between A_V and N(H) the column density for a given dust size distribution and composition .
- $E(B-V)/N_H = 1.45 \times 10^{-22}$ mag cm^2/atoms

  or $N(H) = 1.8 \times 10^{21} A_v$
- This has been tested using dust halos seen in x-rays- the dust scatters x-rays according to the size and position of the grains and the energy of the incident photons and x-ray photoelectric absorption measures the gas column density



arXiv:1509.08987
X-Ray Absorption and Scattering by Interstellar Grains
John A. Hoffman,
Bruce T. Draine



Dust is Crucial in ISM Chemistry

- Most Si and Fe, and 50% of C and 20% of O get locked up in dense dust grain cores
- interstellar chemistry is carbon-dominated
- Dust grain surfaces: shield molecules from UV radiation field, produce H_2 through catalysis: H+H+grain-->H_2+grain drives much of gas-phase chemistry
'Stuff' sticks to dust grains, provides sites for chemistry to occur- add UV light to get complex molecules