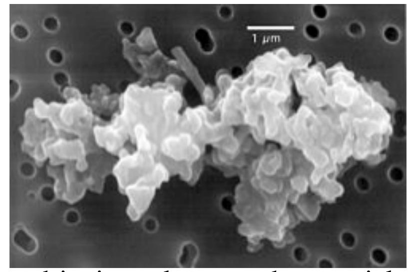
Dust

The four letter word in astrophysics

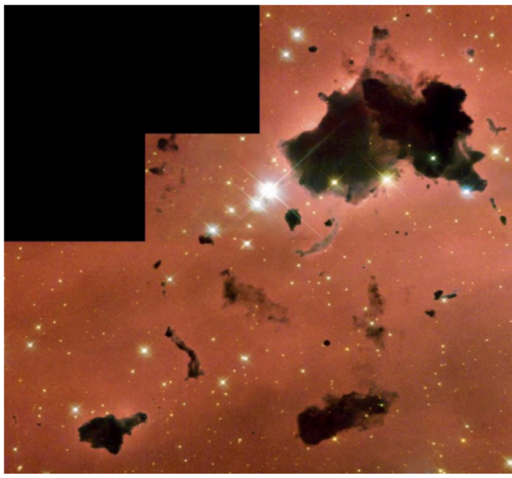
(Not too much on this in the books-MBW sec 10.3.7(b)

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

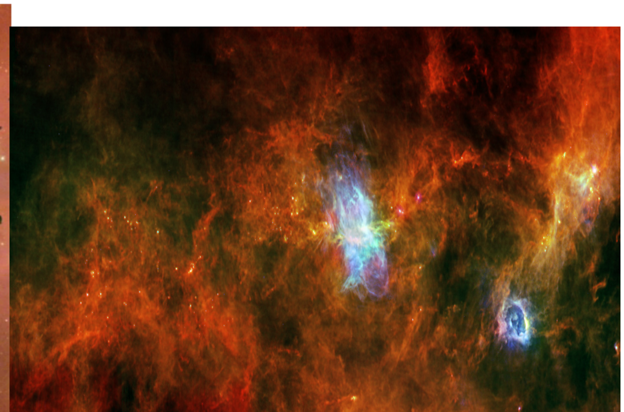


Porous chondrite interplanetary dust particle.

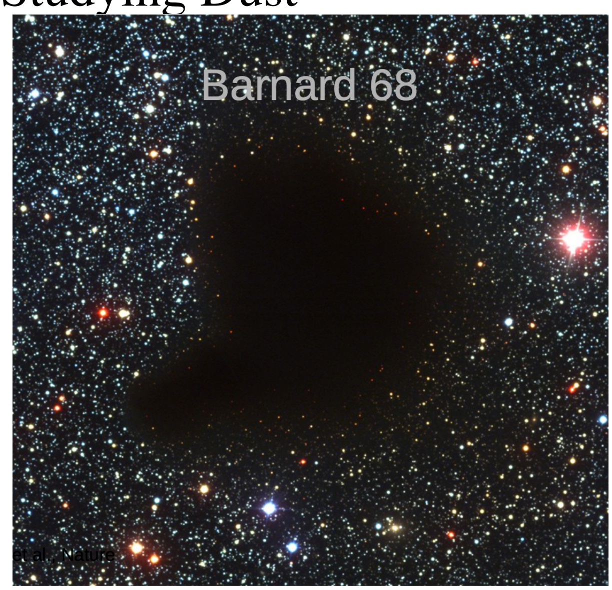
Interstellar extinction



Interstellar Emission



If We Were Studying Dust



What do we want to know about interstellar dust?

●Their composition:

–comparison between stellar and interstellar

abundances: depletion

●Their size (distribution):

–Can be constrained from:

Extinction

Emission (shape of the emission features)

Their interaction with light:

–

Absorption

Scattering: the grain shape, size, and composition are important factor

●Its role in the thermodynamics of the gas:

Photoelectric heating of the gas

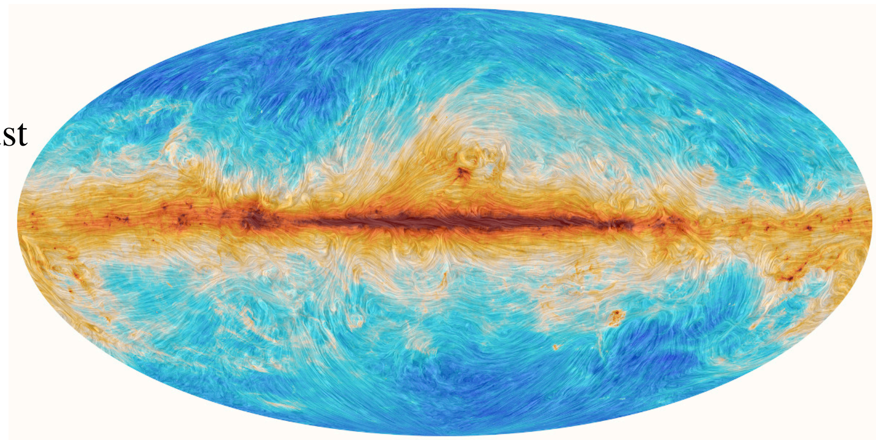
Gas-grain physics

Their role in the chemistry:

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.

Planck map of dust emission and polarization in MW



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 <u>most</u> 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 $x = 2\pi |m-1| a/\lambda$

- m = n+ik

– n optical constant: real part

–k imaginary part responsible for the absorption and emission

a radius of the grain

λ= wavelength

● $Q_{ext} = Q_{abs} + Q_{scatter}$

● Rayleigh-Jeans limit when x << 1

● Geometrical optics when x>>1

● Mie theory required when x~1

Mie Theory Results

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

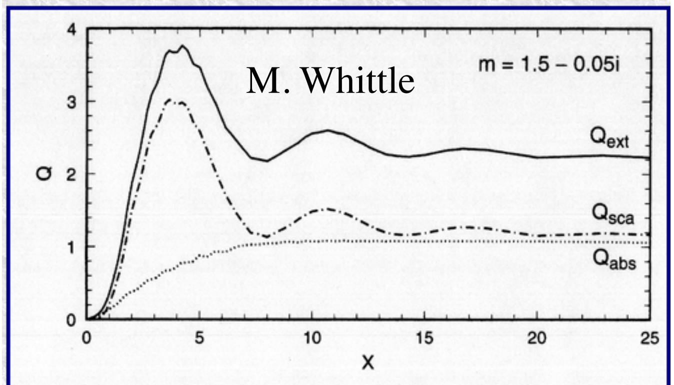


Figure 3.1. Results of Mie theory calculations for spherical grains of refractive index $m = 1.5 - 0.05i$. Efficiency factors Q_{ext}, Q_{sca} and Q_{abs} are plotted against the dimensionless size parameter $X = 2\pi a/\lambda$.

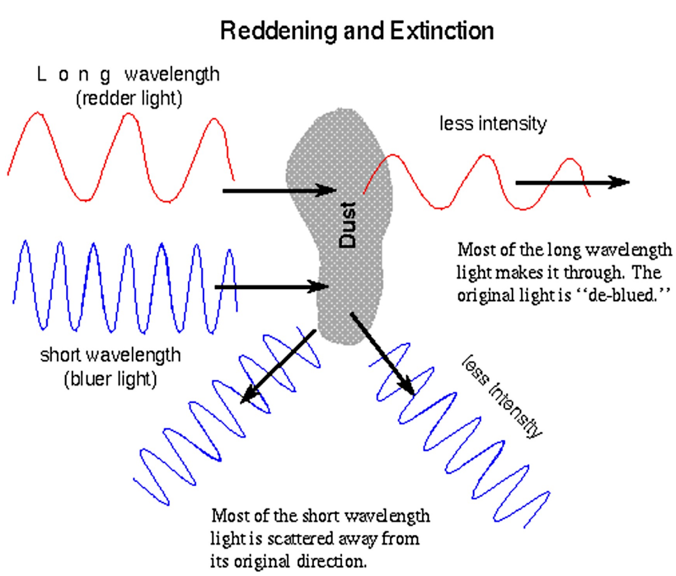
- In the limit of $\lambda >> a$ (i.e. $X = 2\pi a/\lambda << 1$), Mie theory gives:(m is the general refractive index)
- $Q_{abs} \sim 4\ X\ Im[M] \sim \lambda^{-1}$

$Im[M]$;$M = (m^2-1)/(m^2+ 2)$

Qsca 8/3 $X^4|M|^2 \sim \lambda^{-4}$

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)

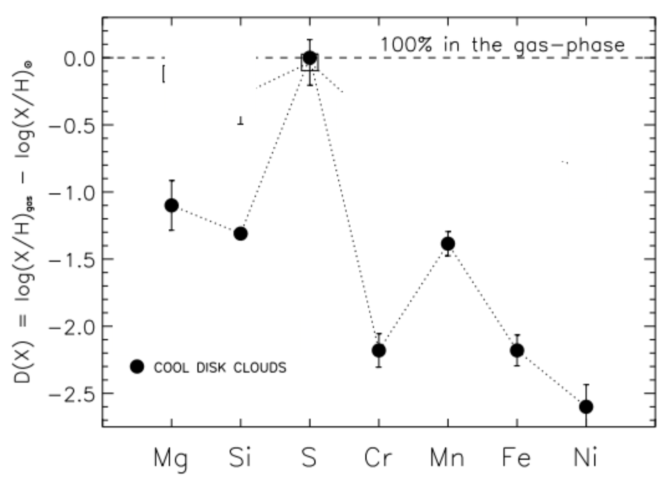
- Wing-Fai Thi MPE

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)
- Dust is the main heating mechanism 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



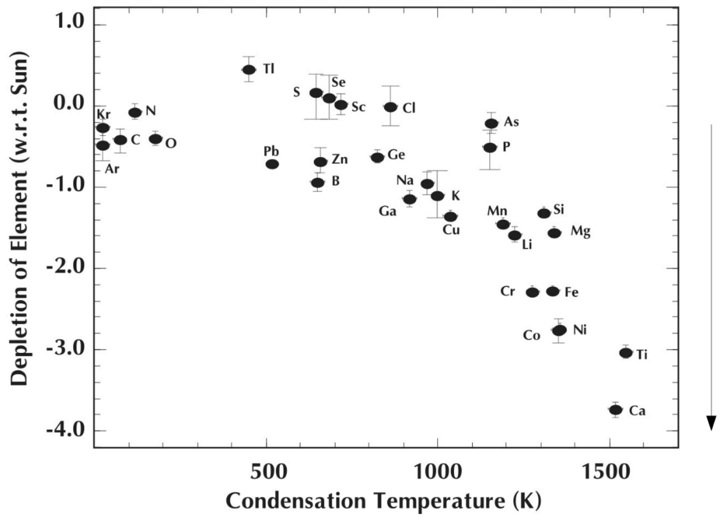
Dependence of depletion on Condensation temperature

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

it would that use up all the metals (Purcell)

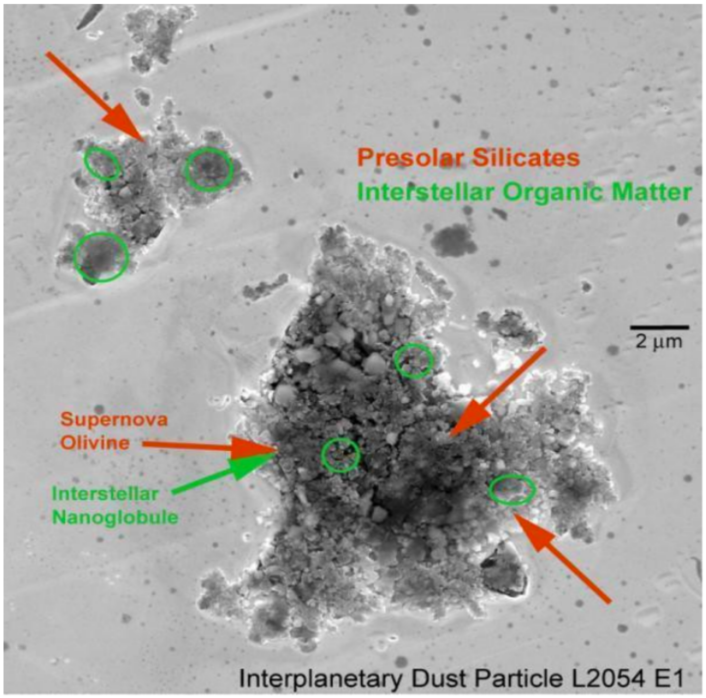
- If condensation temperature is >100k element is depleted in the ISM as are O and C (slightly)
- Dust composition

Dust grain composition from elemental depetion (missing from the gas-phase)



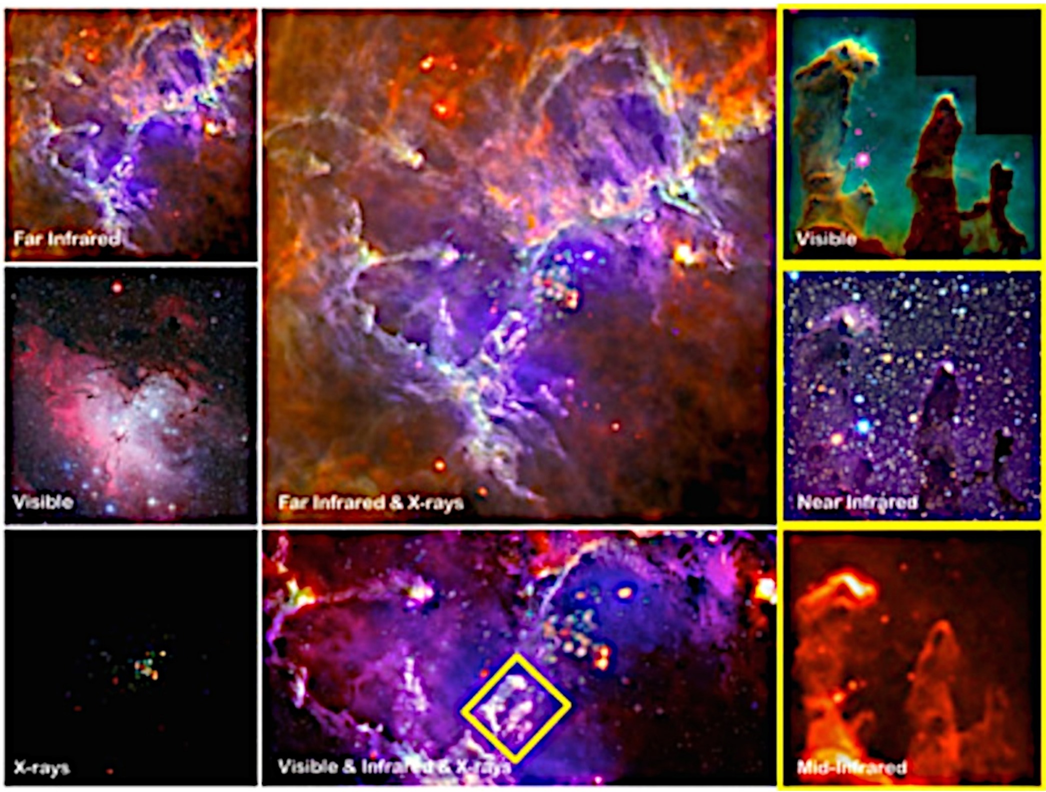
Wing-Fai Thi

Interstellar Dust in Solar System (!)



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

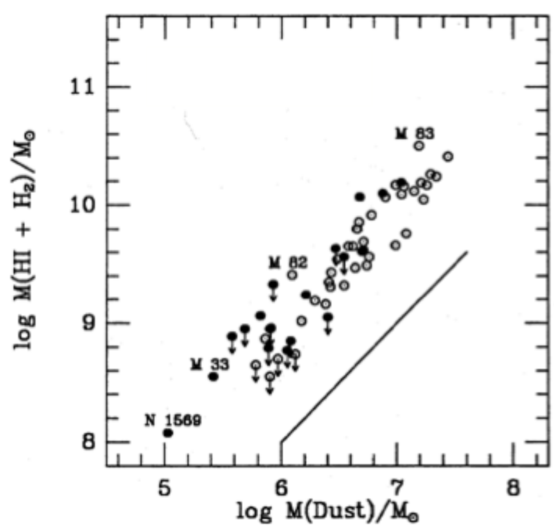
Emission and Absorption



Strong correlation of Dense Gas and Dust

- for column densities in excess of $N_{HI} > 4 \times 10^{20}$ 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')
- $Q_{\lambda} \sim \lambda^{-\beta}$

$\beta=0$ for a BB

$\beta=1$ for amorphous material

$\beta=2$ for metal and crystals

The peak of Black body is at $\lambda=2900\mu$m/T(K)in $F(\lambda)$

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

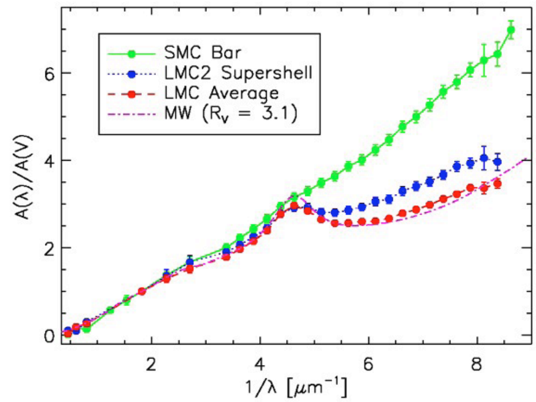
Temperature and luminosity in dust diagnostic of fraction of light absorbed, spatial distribution of sources and dust

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

Reddening and Extinction

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

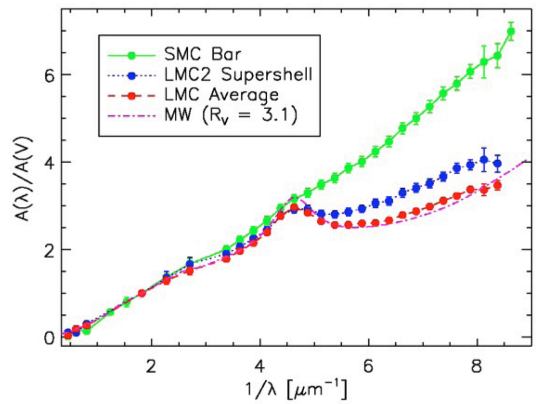
•$m-M=5\log d-5+A_v$

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 $k(\lambda$ is that they are insensitive to the total amount of dust along a line-of-sight.



Reddening/Extinction MBW pg 479

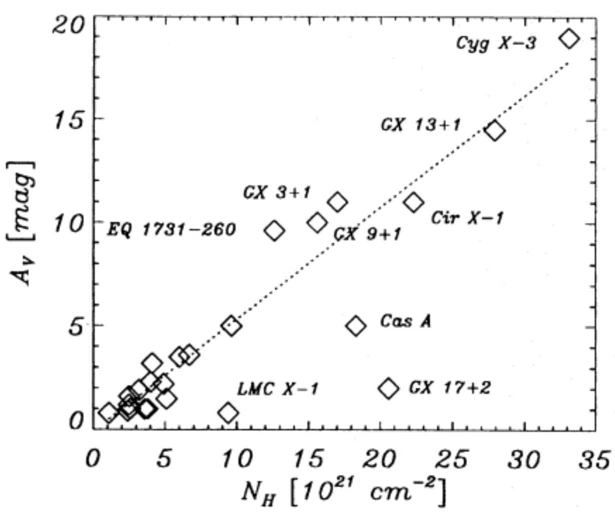
- Often reddening is easier to measure than extinction
- so another useful parameter is :
- $E(B\text{-}V) = (B\text{-}V)-(B\text{-}V)_0 = A_B - A_V$ or its generic relative $E_{\lambda-x} = A_\lambda - A_x$

- E values are differences in color and are therefore easier to measure
- optical depths are additive, E_{B-V} and A_V are proportional

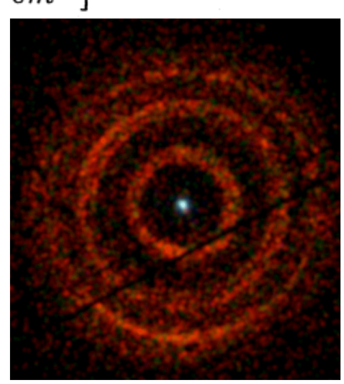
Dust to Gas Ratio

- 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 .
- $E(B\text{-}V)/N_H = 1.45\times10^{-22}$ mag cm^2/atoms

  or $N(H) = 1.8\times10^{21} A_v$
- 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



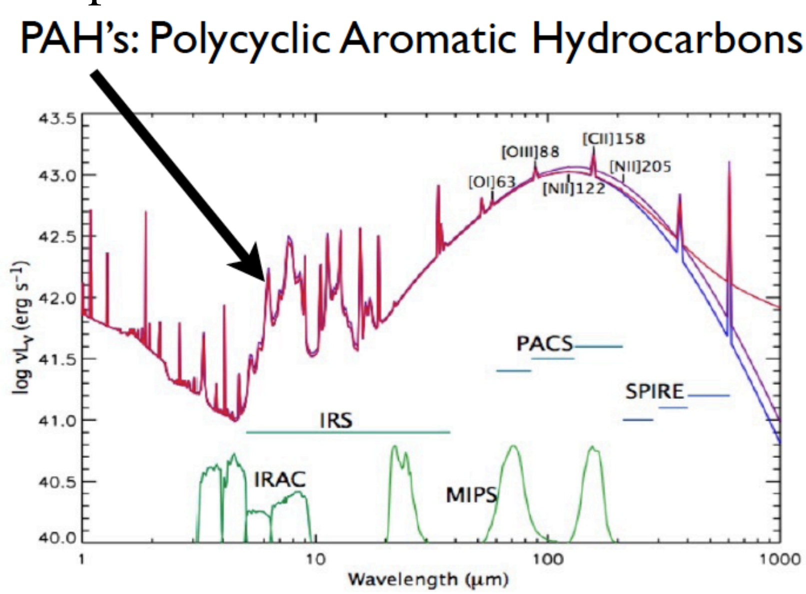
today arXiv:1509.08987 X-Ray Absorption and Scattering by Interstellar Grains John A. Hoffman, Bruce T. Draine



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

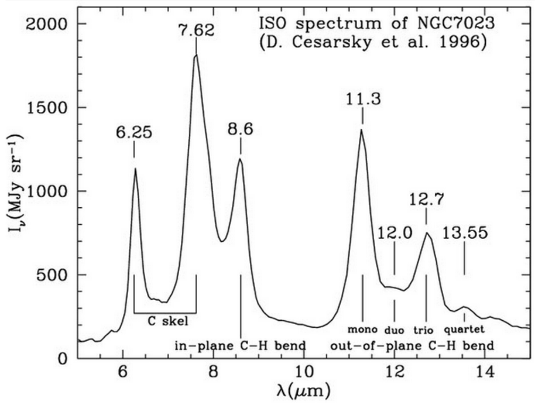
Strongest Spectral Features Due to Dust

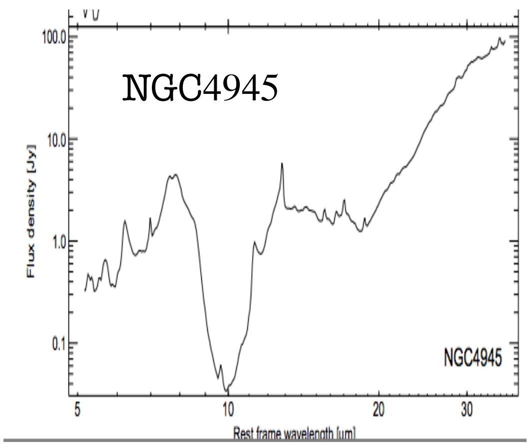


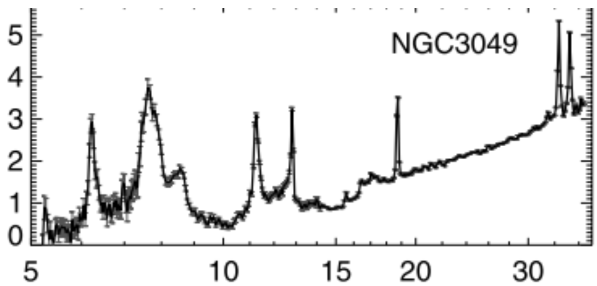
Green are the bands in the 2 IR
instruments which were flown on Spitzer and Herschel

Dust Spectral Features

- PAH features carry 5-20% of the mid-IR energy
- Strong 10μ Si absorption occurs when a bright continuum source has lots of Si dust in front of it





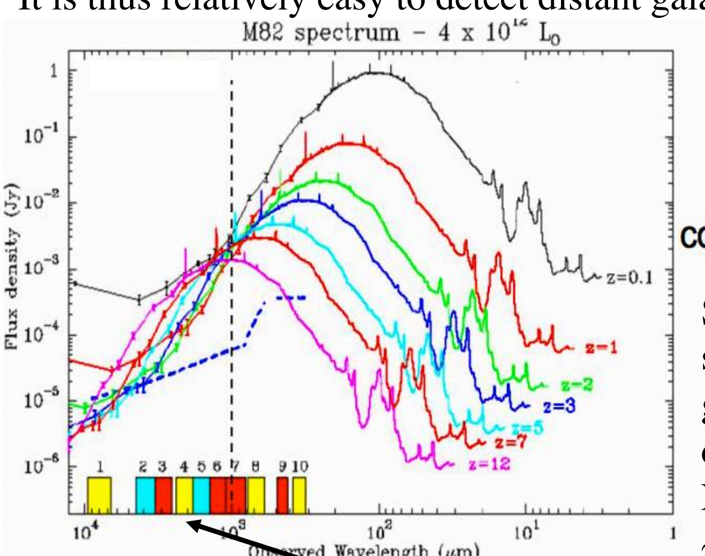


λ (μ)

λ (μ)

In the High Z Universe Dust is Our Friend

- FIR emission from dust has a negative 'K' correction (the observed flux is only weakly dependent on distance)
- It is thus relatively easy to detect distant galaxies in the FIR



The steep submm SED counteracts the $1/D^2$ cosmological dimming

Spectrum of the rapidly star forming galaxy M82 observed at different redshifts- Notice that the flux at ~1000μ remains constant!

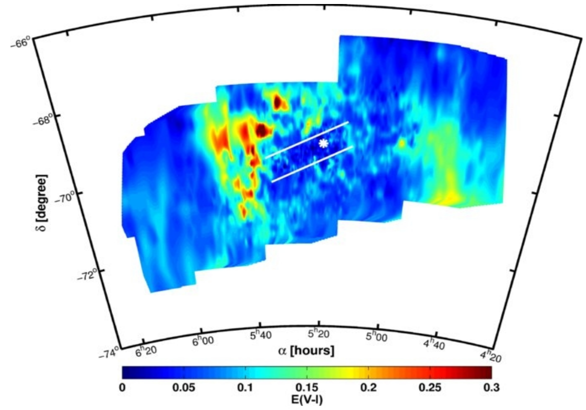
R. Maiolino

ALMA bands

Dust and Reddening

- The effects of reddening can be complex.
- reddening law for isolated stars
  - not the same for all galaxies; e.g. MW and SMC are rather different in the UV but not in the optical
    - due to different dust grain size distributions and composition (graphite, silicates etc etc)
- It depends on how the stars and the dust are intermixed
- Since star formation occurs in dusty molecular clouds regions of high SFR show high reddening - thus rapidly star forming galaxies are more reddened and more of their luminosity is reprocessed into the IR.

Reddening Map of the LMC

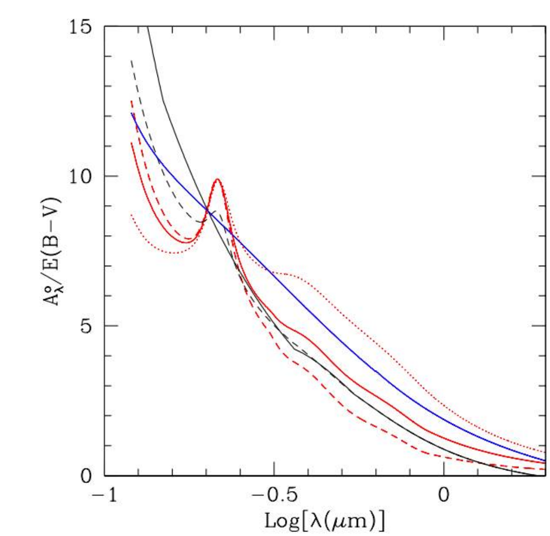


E(V-I)

$R_V = A_V/E_{B-V}$ ~3.1 for the standard extinction law.
$1/R_V = (A_B-A_V)/A_V = (A_B/A_V) - 1$
the slope of the extinction curve in the 4500A - 5500A region
bigger values of R_V mean shallower slope and less UV extinction for a given A_V.

Examples of extinction curves in local galaxies.

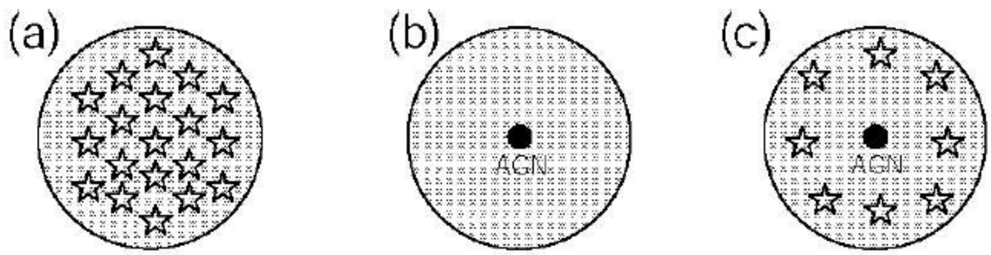
- Milky-Way extinction law for **three different values of R_V,** 3.1 (continuous red line), 5.0 (dashed red line), and 2. (dotted red line)
- the Large Magellanic Cloud's 30 Doradus region (dashed black line) and of the Small Magellanic Cloud's bar (continuous black line) have R_V=2.7
- **The starburst obscuration curve- blue**
- when integrated over a galaxy things get complex, with the geometry of the stars and dust strongly affecting the resulting spectrum.
- the effects of varying amounts of extinction of the different stellar populations due to the spatial distribution of stars and clumpy dust, creates an attenuation law, different than that seen for any individual star



Dust and Geometry

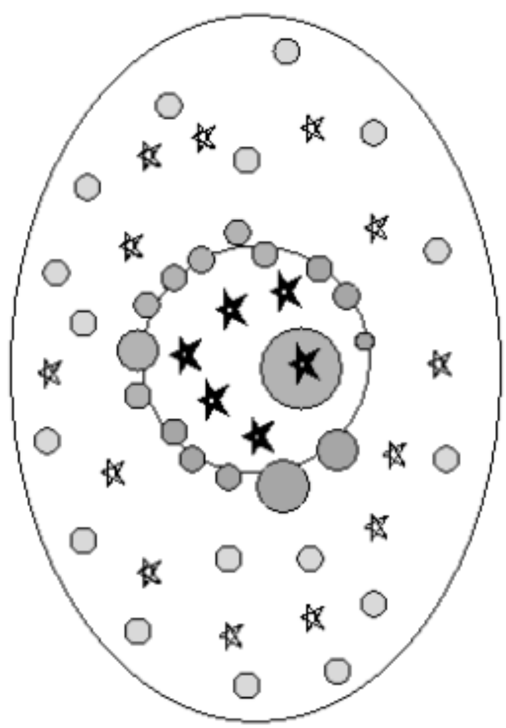
- The effect of dust depends on the relative geometry of the sources and the dust.
- in (a) the stars near the surface of the dust cloud have much less extinction and thus dominate the UV light
  - stars near the center are more absorbed and thus dominate the IR light
- In case (B) we have the classic case of a simple absorber and one star
  - in case (C) we have one very luminous object (AGN) and stars

So it ain't simple



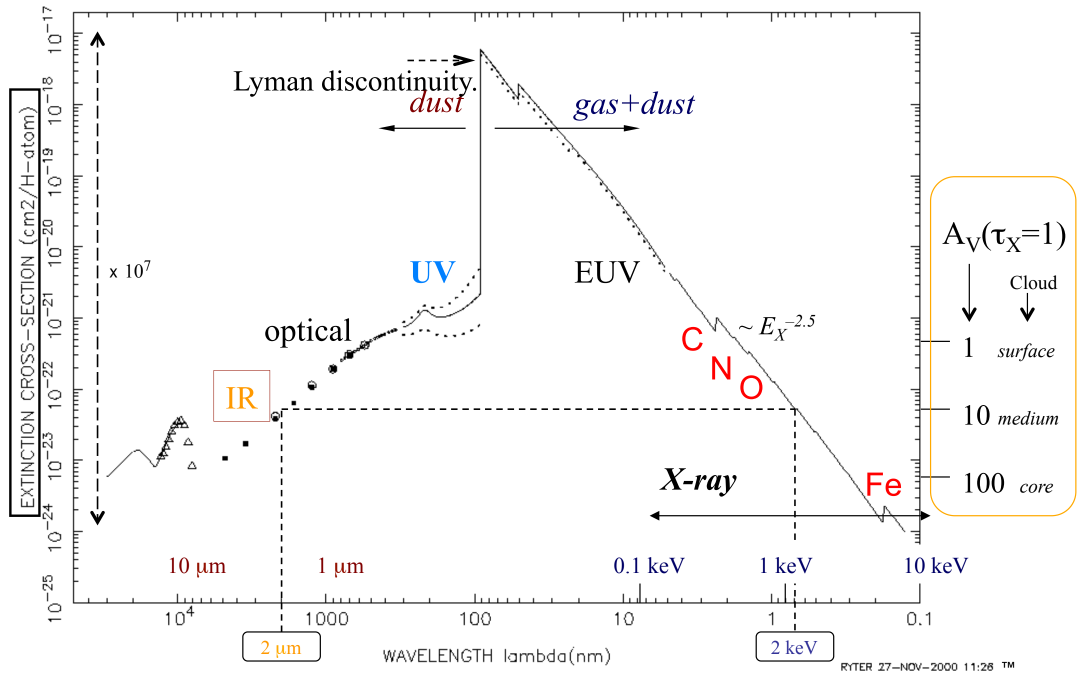
Picture of A Rapidly Star Forming Galaxy

- The starburst region (center of figure) has a newly formed stellar population, (dark starred symbols), some still embedded in the parental clouds.
- dust and gas (dark-gray circles) from the previous generation of stars to the edges of the region is further out.
- The galaxy's diffuse ISM (light-gray circles) surrounds the starburst.
- Both the galactic and the starburst-associated dust are clumpy
- stellar light will often emerge from regions that are not necessarily spatially coincident (in projection) with those of the dust and ionized gas



Taken from Calzetti 2000

Extinction - the Big Picture



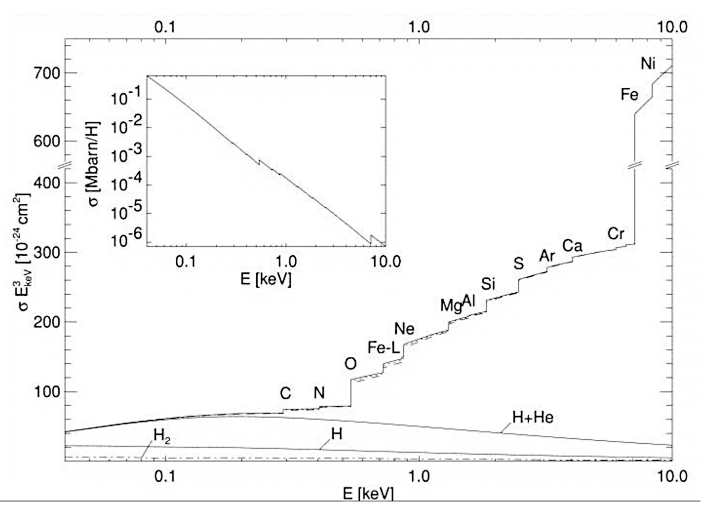
T. Montmerle

Extinction in the X-ray Band

- X-rays are absorbed by the K shell electrons of all elements and thus there can be significant x-ray absorption if the line of sight column density of material is large enough.

- Many rapidly star forming galaxies and active galaxies exhibit strong x-ray absorption .

$I(E)=\exp(-\sigma_{ism}(E)N_H)I_{source}(E)$ while this scales with the hydrogen column density N_H, at E>0.5 keV all the opacity is due to metals



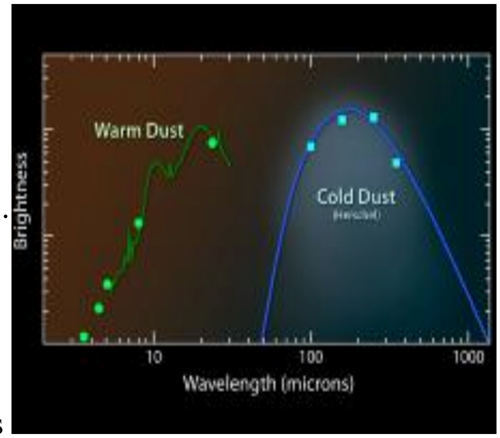
σ_{ism}(E) x-ray abs cross section x E^3

Wilms et al 2000

Dust Formation

There are several sites of dust formation

1. winds from evolved RG and AGB stars(most important)
2. winds from young massive stars (e.g. ηCarina).
3. nova ejecta
4. supernova ejecta (Important in early universe.. recent Herschel results on 1987A)
5. gas phase condensation operating on pre-existing cores



- All these processes involve outflowing winds with decreasing density and temperature
- Refractory seeds form and grow by adsorption
- The growth rate depends on the wind density, temperature, velocity, and time in the flow.
- The growth is non-equilibrium -- simple condensation tracks wont work

M. Whittle .

What Heats the Dust

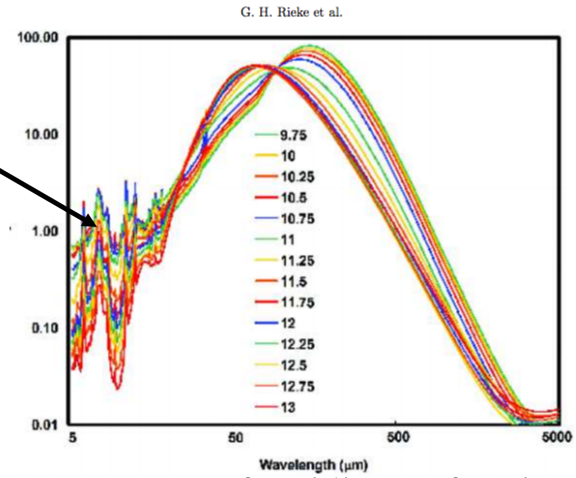
- in most galaxies, evolved stars (e.g ages above 100–200Myr) contribute significantly to the dust heating, which tends to cause the IR luminosity to overestimate the SFR.
- The fraction of dust heating from young stars varies by a large factor among galaxies; in extreme circumnuclear starburst galaxies or individual star-forming regions, nearly all of the dust heating arises from young stars,
- in evolved galaxies with low specific SFRs, the fraction can be as low as ~10%
- **Don't forget AGN- black hole heated dust !**

What Photons Does the Dust Emit

- It all depends...
  - 5-20μ dominated by molecular bands arising from polycyclic aromatic hydrocarbons (PAHs).

    λ> 20 μ, emission dominated by thermal continuum emission from the main dust grain population.
  - at λ> 60 μ, emission from larger grains with steady state temperatures dominates

(Kennicutt and Evans 2012)



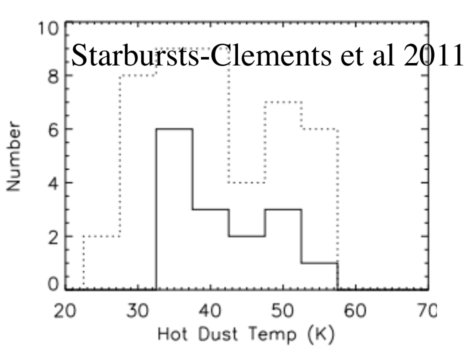
IR spectra of rapidly star forming galaxies over range of $10^{3.25}$ in luminosity Rieke et al 2008

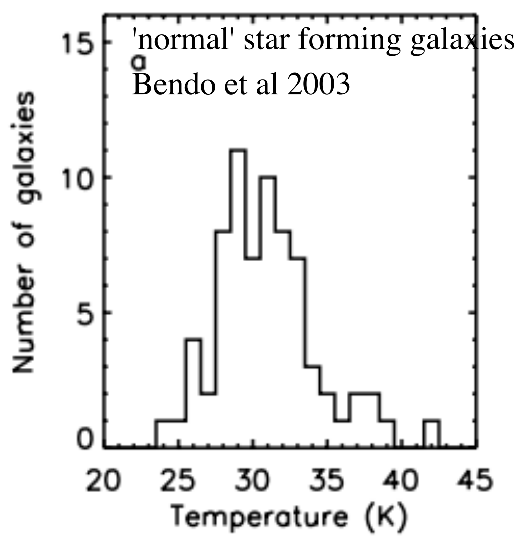
Peak varies from ~40-200μ

If use BB formula T varies by 5 ($\lambda_{max} \sim 1/T$)

Dust Temperatures

- In 'normal' star forming galaxies dust temperatures are low ~30k
- In rapid star forming galaxies in starburst galaxies, the peak of the SED shifts from 100-200 μm to the 60-100 μm
- Remember **L ~AσT⁴** so need a lot of area to get high luminosity at low temperatures-factor of 2 in T**>** 16 in L





But spectra often not well described by single temperature (sum over many emission regions)

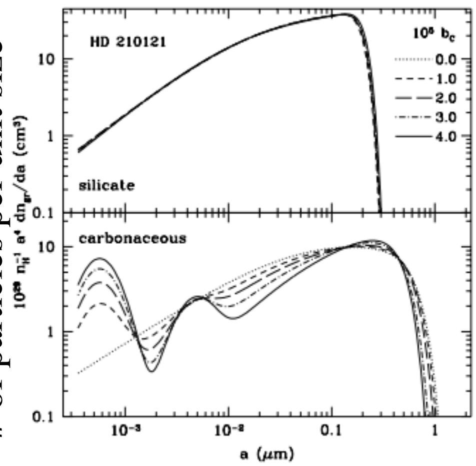
Size of Dust

http://ay201b.wordpress.com/2011/02/19/dust-grain-size-distributions-and-extinction-in-the-milky-way-large-magellanic-cloud-and-small-magellanic-cloud/

- Its all sizes :The size of dust grains along with composition and geometry determines
  - the extinction of light as it travels through a dust cloud
  - the emissivity of the grain for IR radiation.
- two main species of grains, silicate and carbonaceous. Silicates are produced in supernovae and carbonaceous grains in the winds of hot AGB stars.
- small grains come together to form large grains in dense clouds. collisions in shock waves can shatter the large grains and replenish the small grain population.
- the cutoff in the size distribution is limited by the timescales of coagulation, shattering, accretion, and erosion along with the proportion between PAH molecules (small grains) and graphite (large grains).

$dn/da \sim a^{-3.5}$

\# of particles per unit size



size of particles microns

Weingartner and Draine 2001