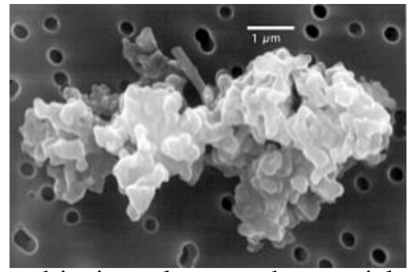
Dust

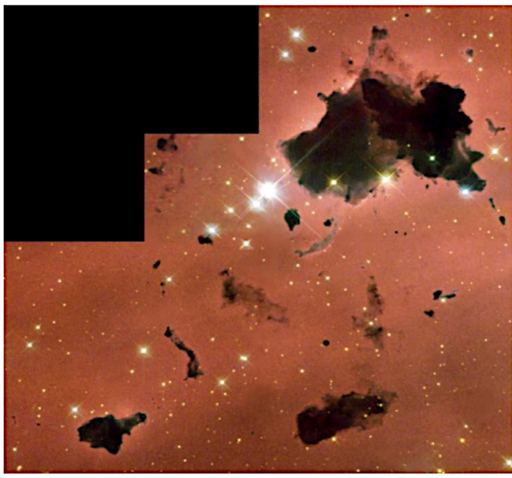
The four letter word in astrophysics

MBW sec 10.3.7 and S&G in MANY places

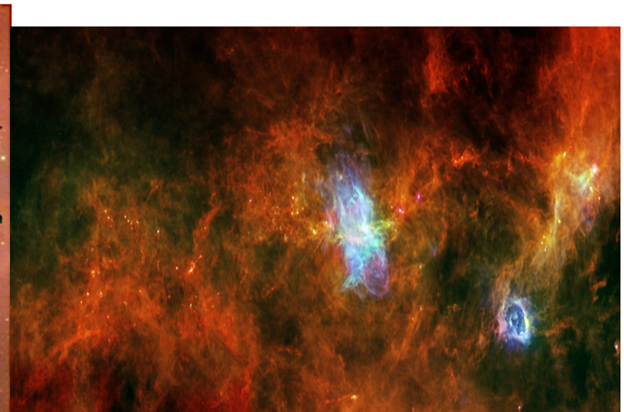


Porous chondrite interplanetary dust particle.

Interstellar extinction



Interstellar Emission



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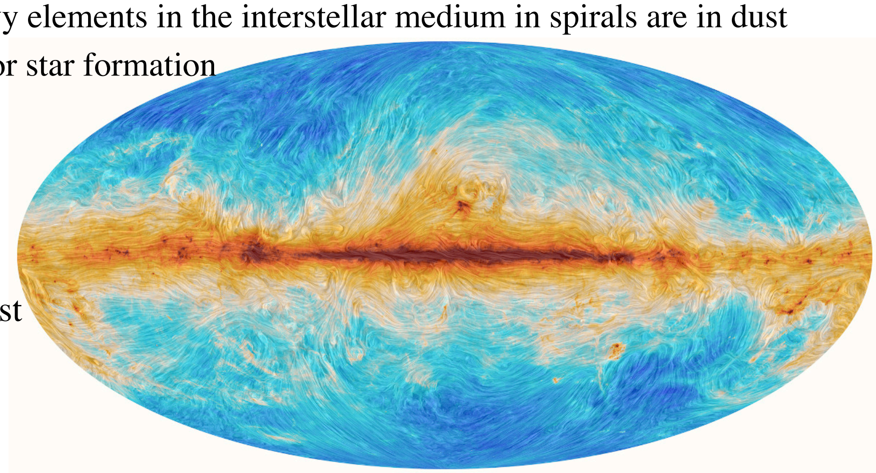
Why Study Dust?? (Draine 2003)

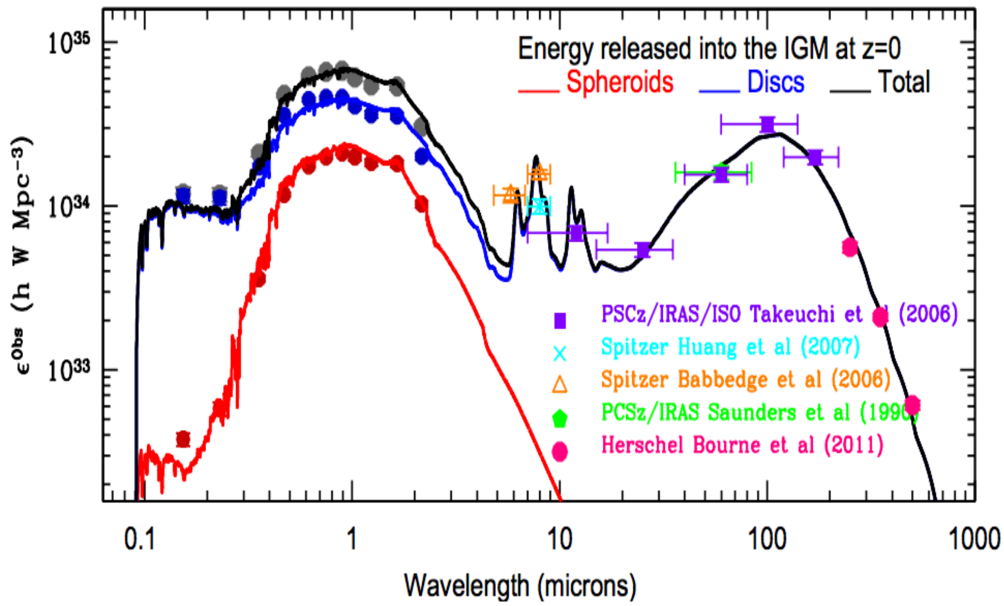
- Dust grains play a central role in the astrophysics of the interstellar medium, from the thermodynamics and chemistry of the gas to the dynamics of star formation.
- Dust shapes the spectra of galaxies Radiation at short wavelengths is attenuated, and energy is radiated in the infrared.
  - Half of the energy emitted by stars in the MW is absorbed by dust and re-radiated in the IR
- Most of the heavy elements in the interstellar medium in spirals are in dust
- Dust is crucial for star formation



Planck map of dust emission and polarization in MW

Energy Released By Galaxies

- Galaxy surveys have measured the total energy released by all low z galaxies across the UV-far IR (Driver 2012);
- **~40% of energy generated by stars is absorbed by dust and re-radiated in IR- this occurs predominately in spirals, ellipticals are relatively *dust poor***

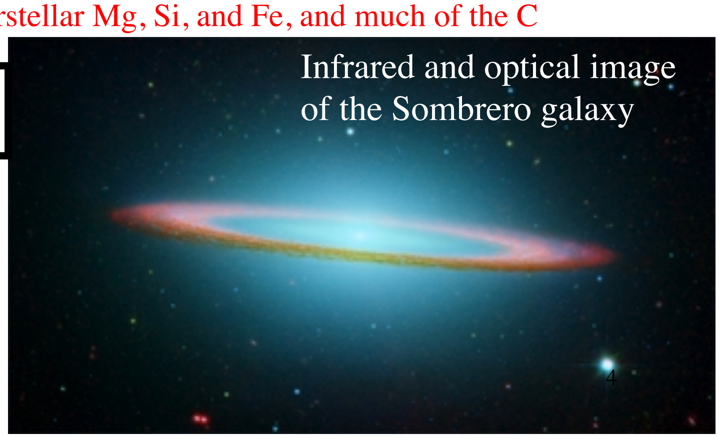


Why Dust

- 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 – dust has ~100% covering for N(H)>3x10^{21}atms/cm^2
- Attenuation ~ 1/λ (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

Most star formation occurs in cold dusty dense regions

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

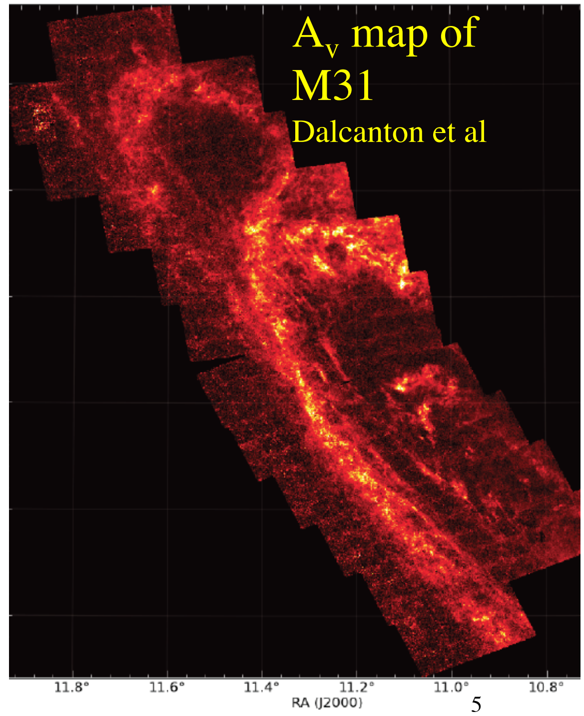


Where is the Dust

- In spirals dust 'tends' to be in the plane (edge on systems) and 'along' spiral arms.
- Most ellipticals are relatively dust free, but major exceptions (e.g. NGC5128)

- Starbursts (M82) dust all over the place

Dust Mapping in M31



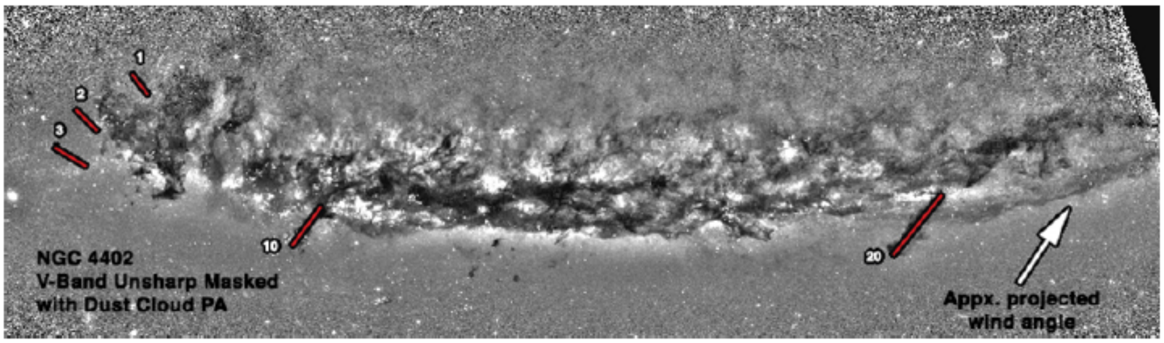
Map of the median extinction $\widetilde{A_V}$ for all analyzed regions. Some very low-level "grid" patterns are vi
ndent calibration issues with the WFC3/IR chip (Sections 4.1 & 5.3).

Dusty Facts

- Dust grains come in wide range of sizes (power law distribution of size)
  - $dn/da \sim a^{-3.5}$ with $a_{max} \sim 0.3\mu m$ over factor of 10^3
- 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
  - Dust ~ 0.7-1% (by mass) of the interstellar medium in a MW like galaxy.
- Dust explains: the λ^{-1} form of the UV/optical extinction curve (large scattering efficiency (~60%) and scattering angle)
  - Dust grains scatter and absorb radiation efficiently at wavelengths less than their own dimensions.
- Dust is destroyed at T>1300K (sublimation)
- Dust heated by diffuse stellar radiation has T ~ 10–20K and peak of emission spectrum is at ~200 µm;- dust near bright stars is hotter.
- The ISM is exceedingly dirty
  - 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

Even More Dusty Facts

- Dust is formed from SN/stellar ejecta and/or in ISM
- 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)
  - Photo-electric effect : 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)

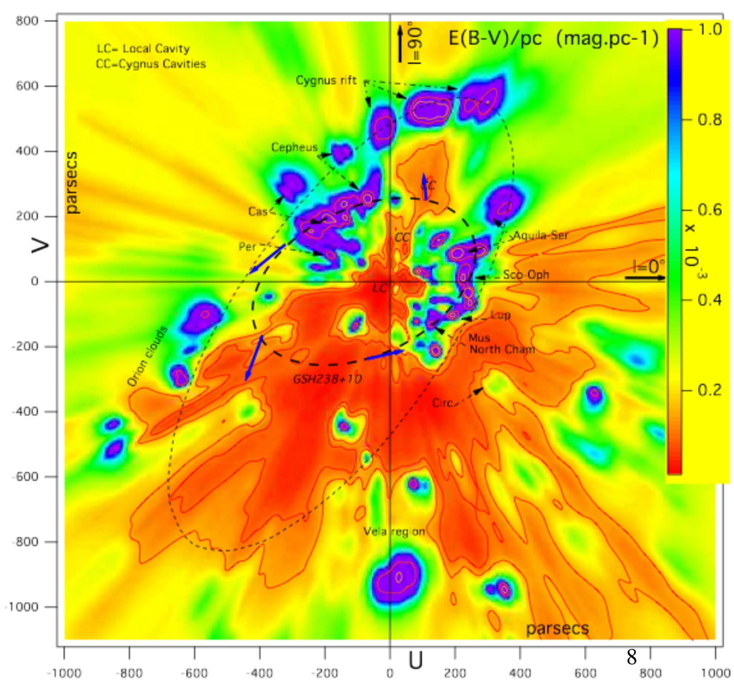


Dust is Highly Patchy

- 3-D map of the local extinction- r<1kpc

(Lallement 2014)

E(B-V) is a measure of 'reddening'

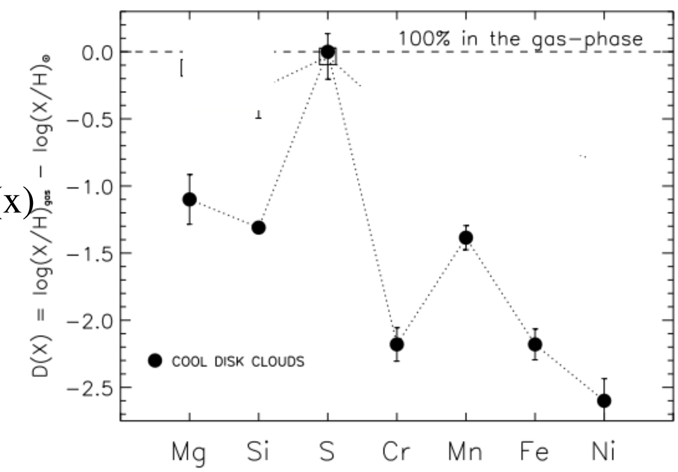


Effects of Dust on Chemical Composition of ISM

- Dust 'depletes' the ISM of 'refractory' elements
  - Mg, Si, Al, Ca, Ti, Fe (75%), Ni are concentrated in interstellar dust grains.
  - depletion caused by the atoms condensing into solid form onto dust grains- governed by the volatility of compounds that are produced: **effects can be big**

dust formation involves condensation/adsorption, & not all elements condense efficiently to dust.

D(x)

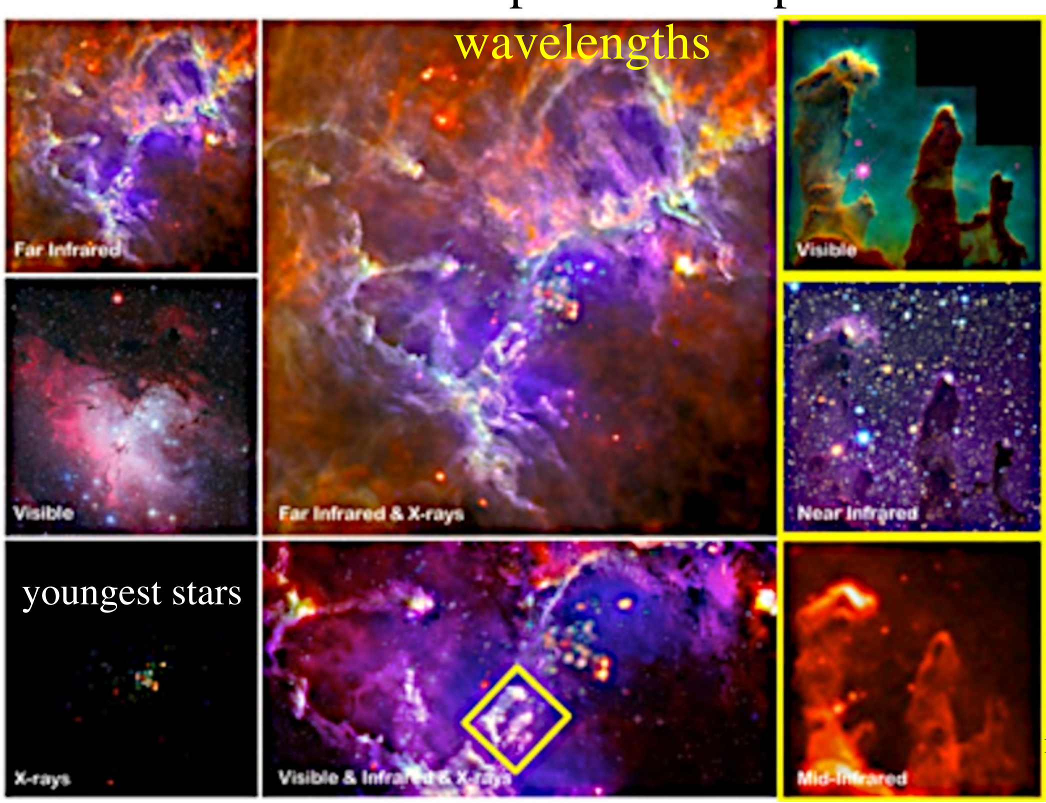


D(x)= 'depletion'- the reduction in the metallicity compared to solar

$D(X) = \log_{10}[N(X)/N(H)]_{obs} - \log_{10}[N(X)/N(H)]_{ISM}$

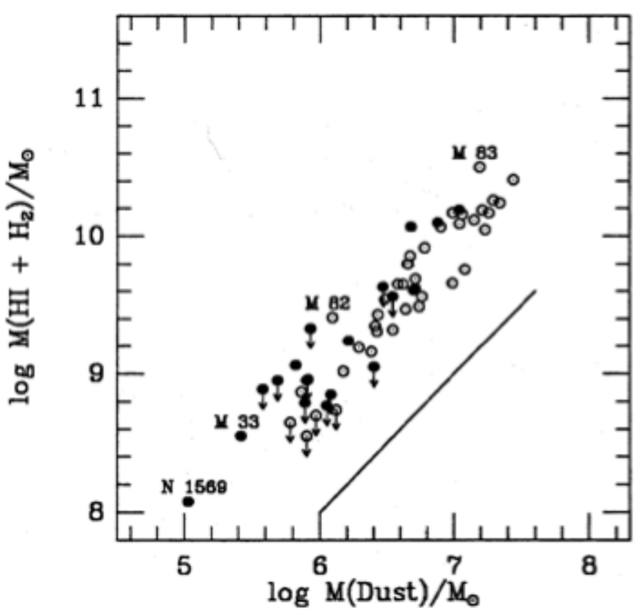
For example, D(C) = -0.7 means C/H is 20% of its expected value 80% in dust.

Emission and Absorption- Same place different wavelengths

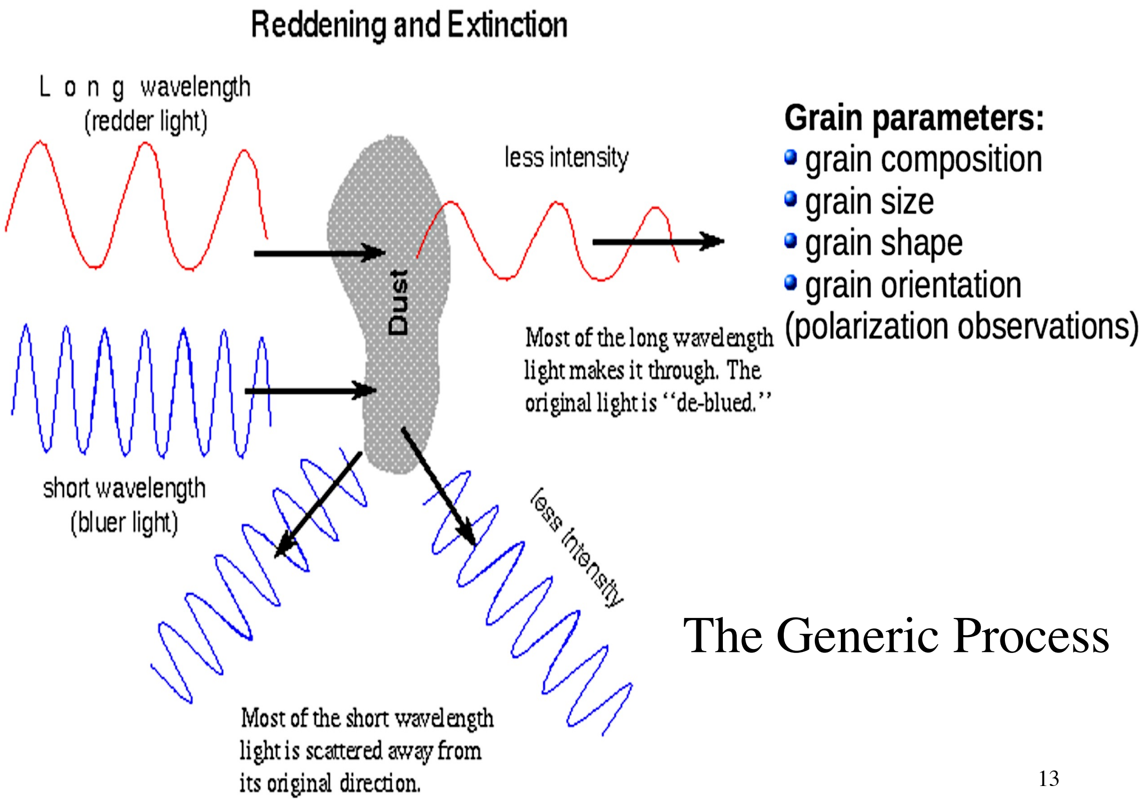


Strong correlation of Gas and Dust

- To first order the ratio of dust to gas is the same (e.g linear relation)
  - Dust shields the gas from the UV radiation field, allowing it to be cool.
  - The coldest dust is heated by 'normal' stars and is not associated with molecular clouds
- Warm dust (T~20-100k) 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



The Generic Process

Continuum Emission from Dust

- Emissivity from dust is 'quasi-black body like'- (grey body)
- $F_\lambda = N_a \pi a^2 \mathbf{Q_\lambda} \mathbf{B_\lambda(T)}/D^2$ (from a grain)
  - where a is the size of the grain, D is its distance, B$_\lambda$ is the black body function , N_a is the number of grains and Q_λ is the emissivity in the IR (grain is not 'black') ; $Q_\lambda \sim \lambda^{-\beta}$
  - In R-J limit $F_\nu \sim \nu^{\beta+2}$

$\beta=0$ for a Black Body, $\beta=1$ for amorphous material, $\beta=2$ for metal and crystals

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

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

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

Reddening and Extinction

- Dust effects the transfer of radiation through a galaxy

- In general the extinction due to dust can be parameterized by
  - $I_\lambda = I(o)e^{-\tau(\lambda)}$
  - $dI_\lambda/dx = -k(\lambda)I_\lambda$; $k(\lambda) \sim \lambda^{-1}$

    (S+G pg 33-34);MBW pg 478-482

- 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)
- **$E(B-V) = (B-V) - (B-V)_0$**

Reddening and Extinction

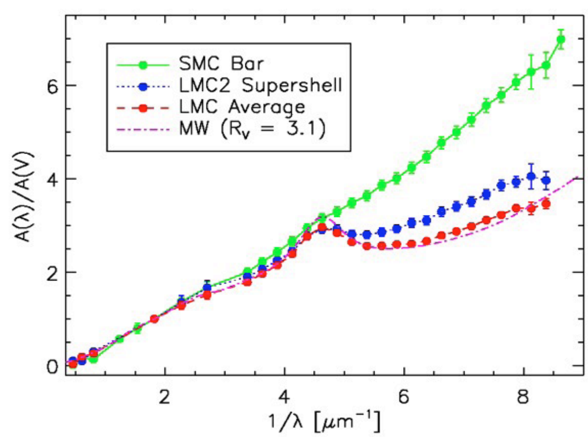
Extinction and reddening are linked

$A_V = R*E(B-V)$;

R~3.1 for MW, 2.7 for SMC

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

- $R_V = A_V/E(B-V)$
- $m_v - M_v = 5\log d - 5 + A_v$



$A_\lambda - A_v$ is a function of wavelength and can differ from place to place

Reddening/Extinction

- Often reddening (change in color) is easier to measure than extinction (reduction in intensity)
  - dust absorbs and scatters blue light more than red light, making stars appear redder.
- so another useful parameter is :
  - $E(B-V) = (B-V)-(B-V)_0 = A_B - A_V$ or its generic relative $\mathbf{E_{\lambda-V} = A_\lambda - A_V}$
- $E_{\lambda-V}$ values are differences in color and are therefore easier to measure
- optical depths are additive, E_{B-V} and A_V are proportional (e.g. in magnitudes)

Extinction can be a very large effect

towards the galactic center A ~30 mags in the optical

On average A_V~ .8mag/kpc- e.g. factor of 2 reduction in brightness for each kpc in distance (V band) can invert this to get estimates of distances

Alternatively

- $I_\lambda = I_\lambda(0)e^{-\tau_\lambda}$, *where* I_λ *is the observed spectrum and* $I_\lambda(0)$ *is the emitted*
- $k(\lambda) \equiv A_\lambda/E(B-V) \equiv R_V A_\lambda/A_V$ *eq* (10.100 in MBW)
  - $k(\lambda)$ is the extinction form
- 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 $R_V \equiv A_V/E(B-V)$
- $R_V = A_V/E_{B-V}$ ~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 (e.g B and V)
- bigger values of R_V mean shallower slope and less UV extinction for a given A_V.

Dust is Crucial in ISM Chemistry

• **Dust formation models**
all 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 doesn't work

Lots of dust forms in supernova remnants shell and stellar winds

Extinction as a Function of Position in MW (Majewski et al 2016)

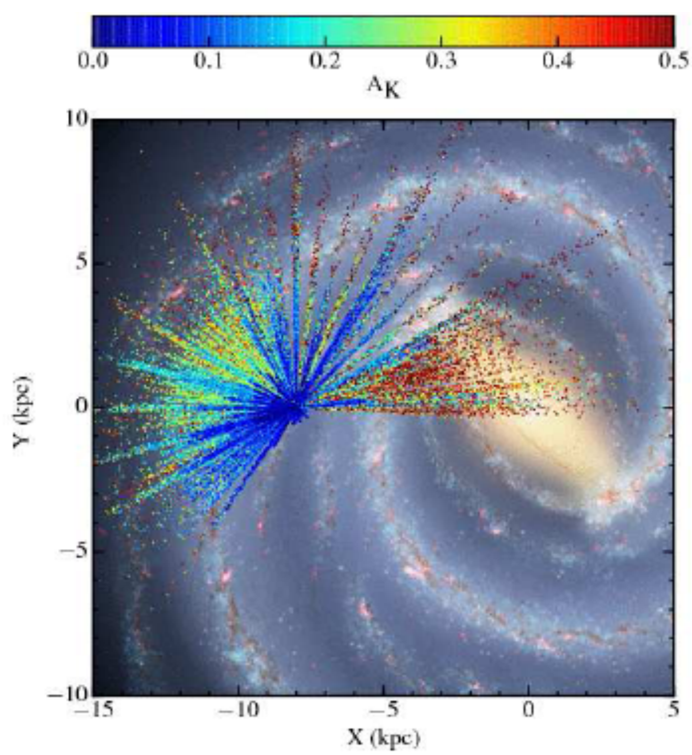
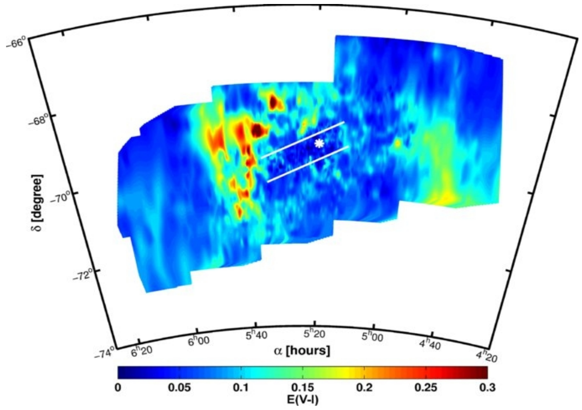


FIG. 31.— Distribution of extinction across the Galactic plar

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
    - due to different dust grain size distributions and composition (graphite, silicates etc etc)

Reddening Map of the LMC



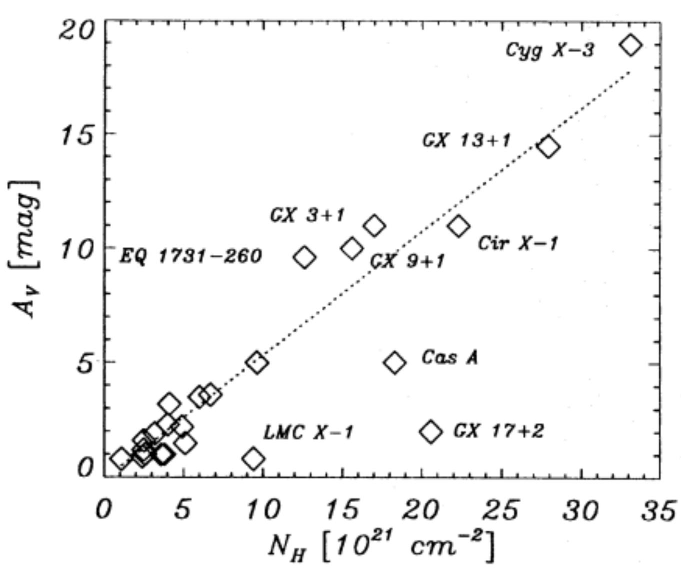
E(V-I)

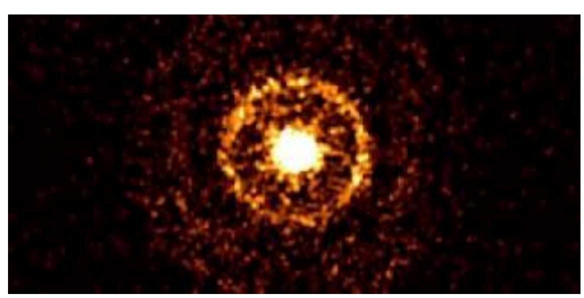
It depends on how the stars and the dust are intermixed
Since star formation occurs in dusty molecular clouds, regions of high SFR show high reddening - thus rapidly star forming galaxies are more reddened and more of their luminosity is reprocessed into the IR.

Dust to Gas Ratio

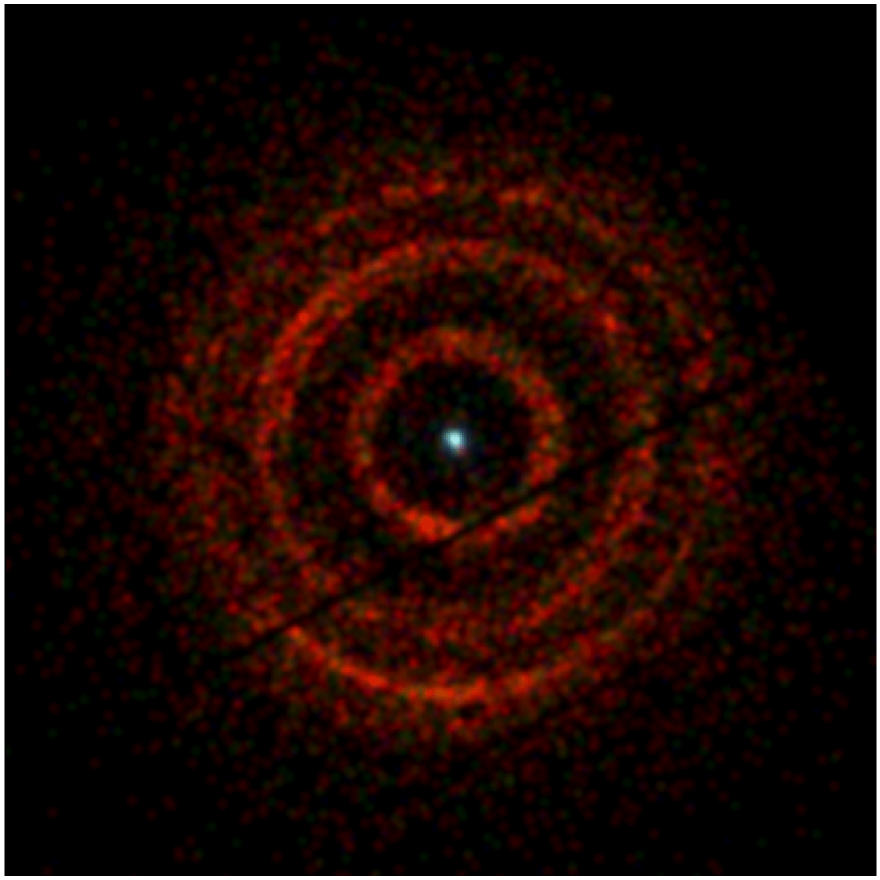
- In the MW the average dust to gas ratio (by mass) is ~100
- This gives a relationship between A_V and N(H), the gas column density
- $E(B-V)/N_H \sim 1.45 \times 10^{-22}$ mag cm^2/atoms

  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 photons





- Rings in the x-ray from dust scattering



Dust is Crucial in ISM Chemistry

- Most Si and Fe, and 50% of C and 20% of O get locked up in dust grains cores
  - 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- stuff of life

Dust Formation

There are several sites of dust formation

- **winds from evolved RG and AGB stars** (most important)
- supernova ejecta (Important in early universe....)

- 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

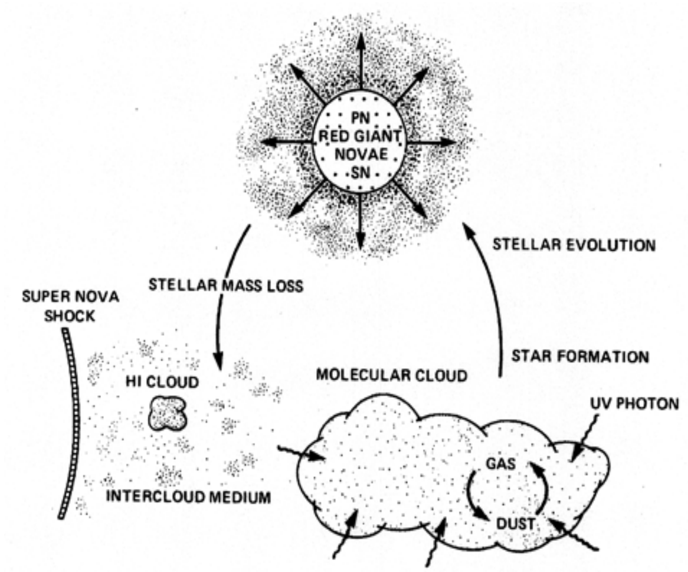
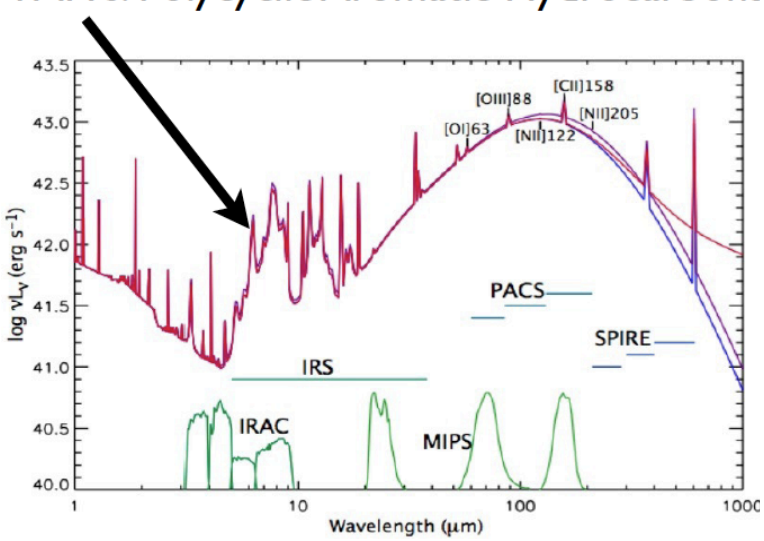


Figure 8.1. Schematic representation of the lifecycle of cosmic dust. Grains of 'stardust' originating in the atmospheres and outflows of evolved stars (red giants, planetary nebulae, novae and supernovae) are ejected into low-density phases of the interstellar medium, where they are exposed to ultraviolet irradiation and to destruction by shocks. Within molecular clouds, ambient conditions favour the growth of volatile mantles on the grains. Subsequent star formation leads to the dissipation of the molecular clouds. (From Tielens and Allamandola 1987b; reprinted by permission of Kluwer Academic Publishers.)

Strongest Spectral Features Due to Dust

- found in coal and in tar deposits -combustion of organic matter (e.g. in engines and incinerators forest fires, etc.).
- PAH are abundant in the universe, in association with formation of new stars and exoplanets.
- PAHs are possible starting materials for abiologic syntheses of materials required by the earliest forms of life.

PAH's: Polycyclic Aromatic Hydrocarbons

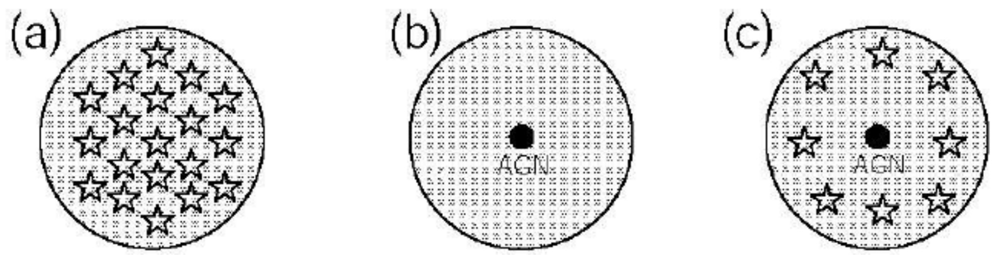


Green are the bands in the 2 most sensitive IR instruments Spitzer and Herschel

Dust and Geometry

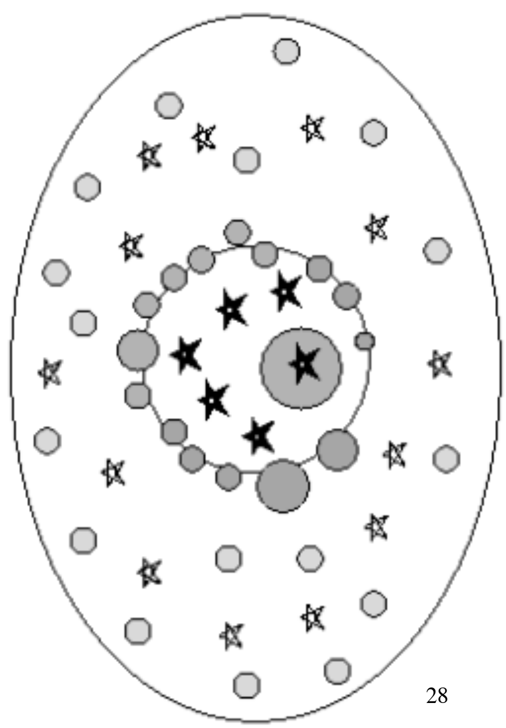
- The effect of dust depends on the relative geometry of the sources and the dust.
- in (a) the stars near the surface of the dust cloud have much less extinction and thus dominate the UV light
  - stars near the center are more absorbed and thus dominate the IR light
- In case (B) we have the classic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

So it ain't simple



Picture of A Rapidly Star Forming Galaxy

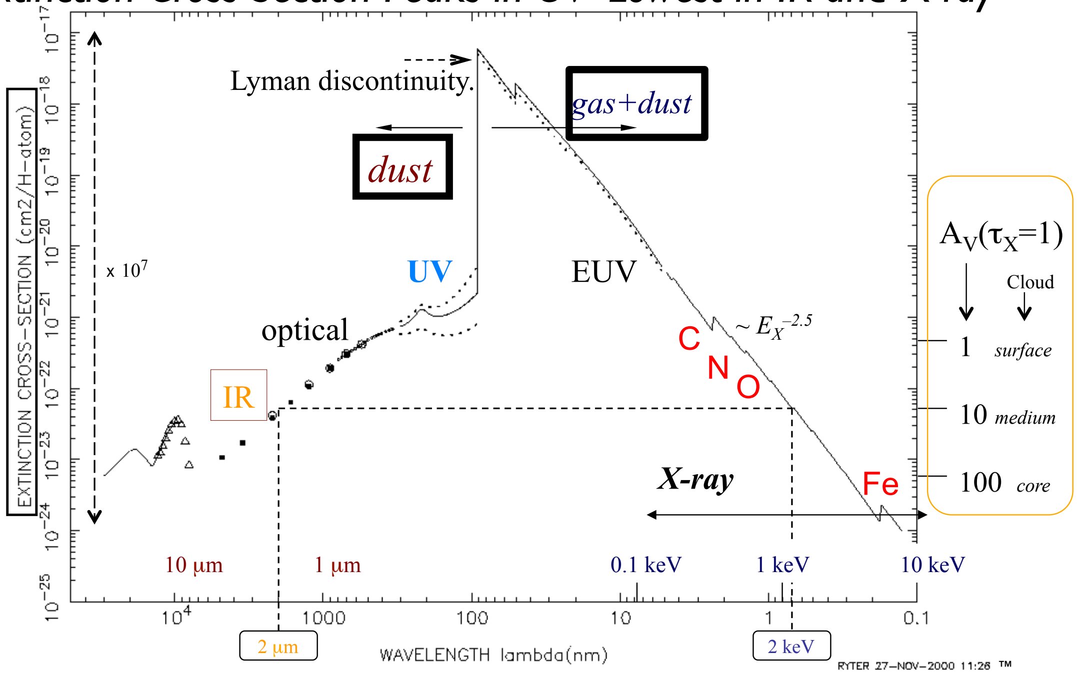
- The starburst region (center of figure) has a newly formed stellar population, (dark starred symbols), some still embedded in the parental clouds.
- dust and gas (dark-gray circles) from the previous generation of stars to the edges of the region is further out.
- The galaxy's diffuse ISM (light-gray 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

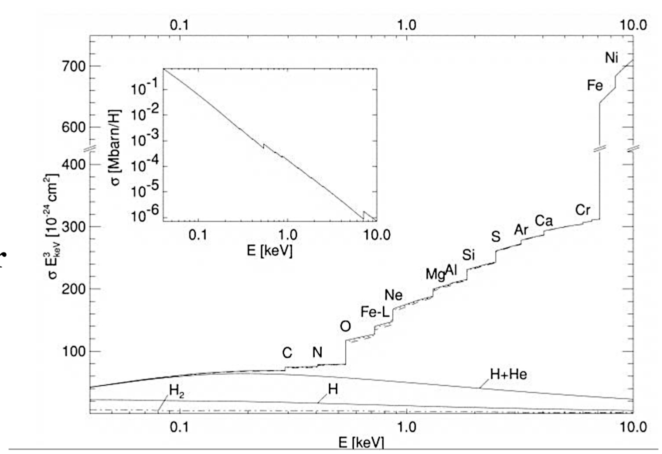
Extinction Cross Section Peaks in UV- Lowest in IR and X-ray



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.
  - absorption is largest at **lower** x-ray energies
- Many rapidly star forming galaxies and active galaxies exhibit strong x-ray absorption .
- $I(E)=\exp(-\sigma_{ism}(E)N_H)I_{source}(E)$



$\sigma_{ism}(E)$ x-ray abs cross sectionxE^3

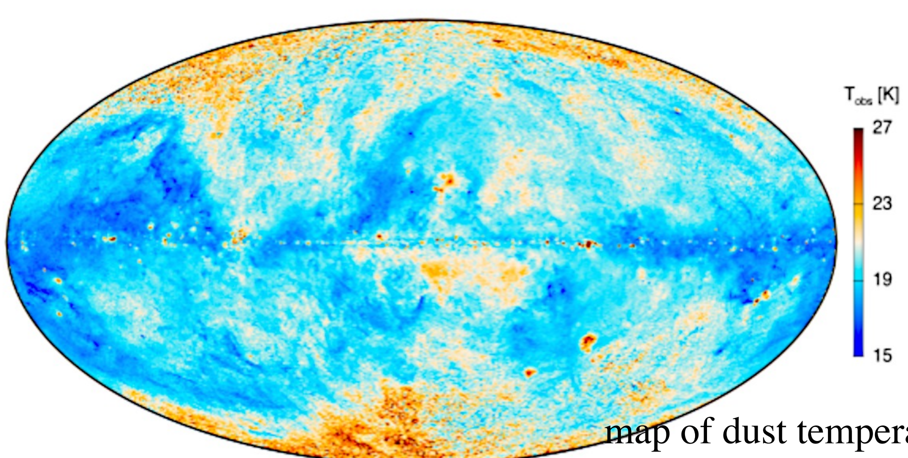
Wilms et al 2000

Connection Between Reddening and Extinction

- It is only in the optical and UV that reddening and extinction are simply connected- that is because of the wavelength dependence ($1/\lambda$) of extinction in that band.
- In the x-ray dust is much less important than gas is for extinction.

What Heats the Dust

- The fraction of dust heating from young stars varies by a large factor among and inside galaxies; in extreme circumnuclear starburst galaxies or individual star-forming regions, nearly all of the dust heating arises from young stars,
- In galaxies with low specific Star Formation Rates, a lot of the heating comes from evolved stars

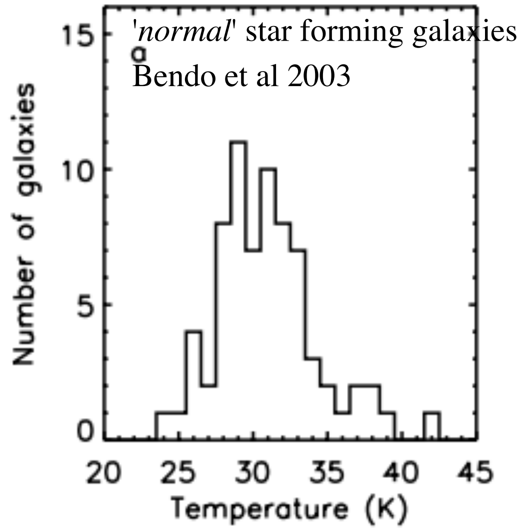


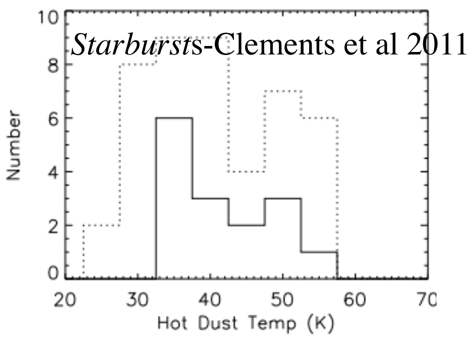
map of dust temperature of MW
Planck data

Dust Temperatures

- In 'normal' star forming galaxies average dust temperatures are ~30k
- In rapid star forming galaxies (starburst galaxies) the dust is hotter, the peak of the SED shifts from 100-200 μm to 60-100 μm

- Remember **L ~AσT^4** 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)

Reminder Black Bodies

λ_{peak}~29μ/T_{100} ; λ_{peak} in units of microns and T in units of 100k

T~λ^{-1} but L~AT^4 so to get a lot of luminosity at long wavelengths needs a large emiting area, A

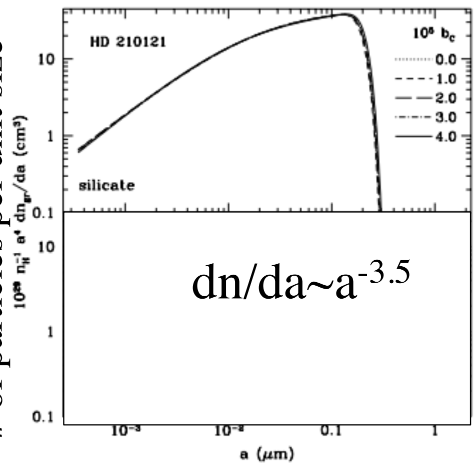
Temperature is set primarily by equilibrium; energy absorbed=energy emitted and physics of dust grains (grains cool very fast).

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.
- 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).

# of particles per unit size



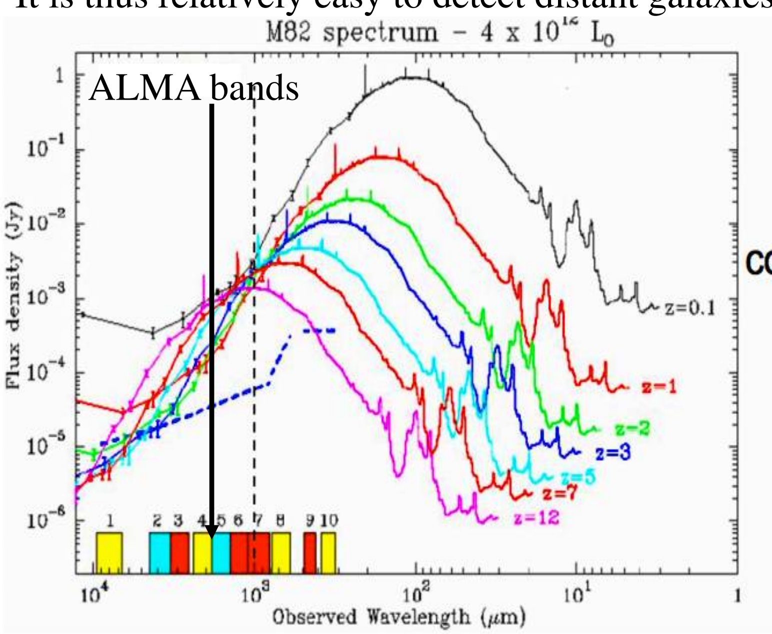
$dn/da \sim a^{-3.5}$

size of particles microns

Weingartner and Draine 2001

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

R. Maiolino

Summary of Dust

- Strong influence on
  - observational properties of galaxies (extinction, reddening, reprocessing)
  - physics of galaxies:
    - star formation
    - ISM
- Observed via
  - emission in IR
  - absorption in UV/optical
- Observational properties depend on
  - geometry
  - heating

- 'Backwards' evolution of IR spectrum with redshift allows 'easy' observation of high redshift universe

Next Time

- Onto the Milky Way
- **Read S+G Chapter 2**