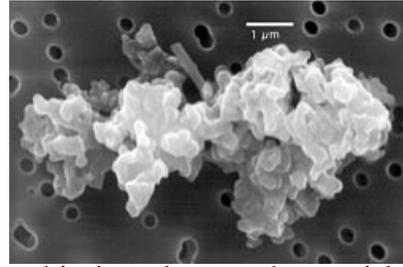


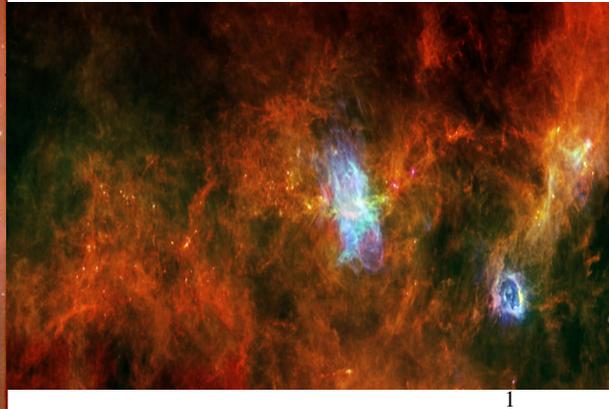
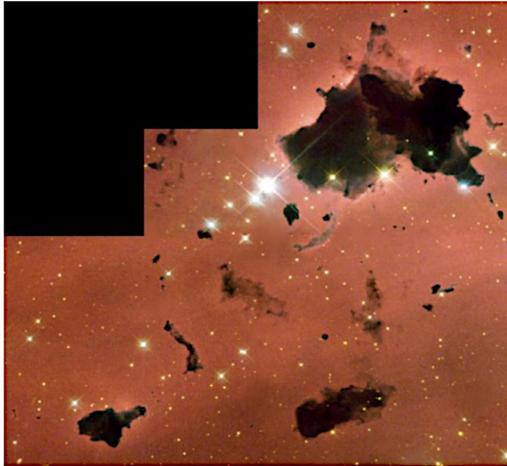
# Dust

The four letter word in astrophysics  
MBW sec 10.3.7 and S&G in MANY  
places also Carroll and Ostlie ch 12.1



Porous chondrite interplanetary dust particle.

## Interstellar extinction      Interstellar Emission



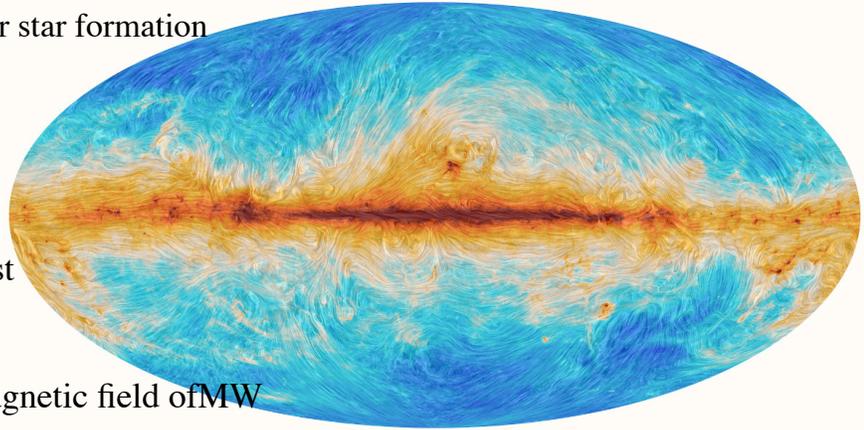
## References to Dust in S&G

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see <http://w.astro.berkeley.edu/~ay216/08/NOTES/> for the UCB  
class on the ISM

## Why Study Dust?? (Draine 2003)

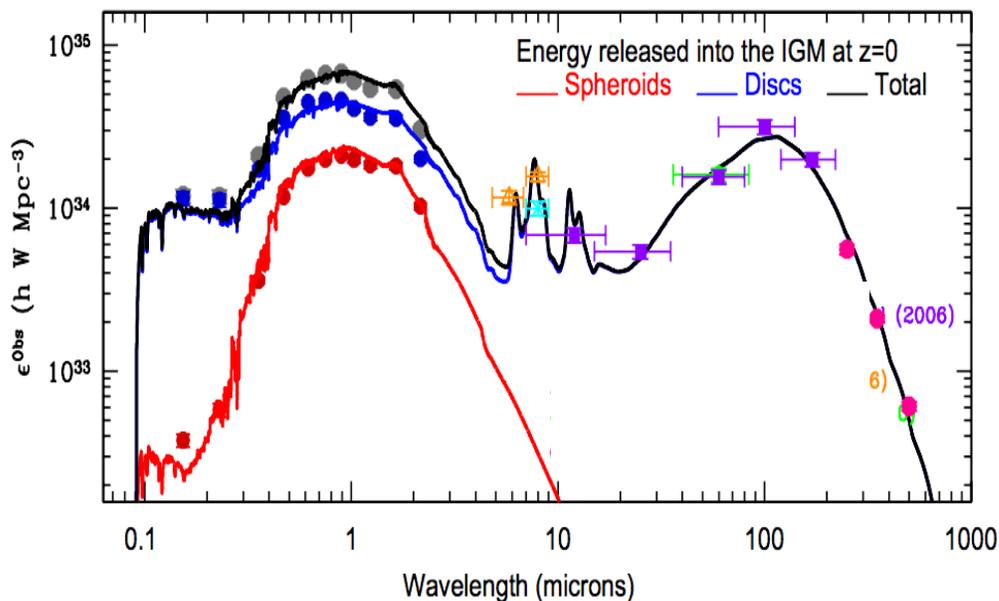
- Dust grains play a central role in the astrophysics of the interstellar medium, from the thermodynamics and chemistry of the gas to the dynamics of star formation.
- *Dust shapes the spectra of galaxies* Radiation at short wavelengths is attenuated, and energy is radiated in the infrared.
  - Half of the energy emitted by stars in the MW (and many other spirals) 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- mapping magnetic field of 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**

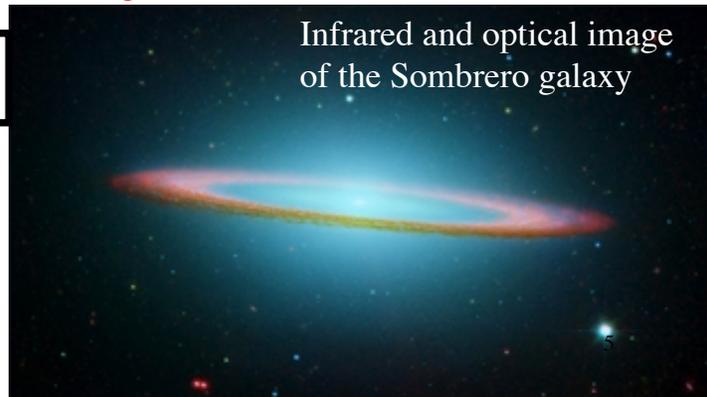


# Why Dust

- Dust *attenuates* and *scatters* UV/optical/NIR  
Amount of attenuation and spectral shape of absorption/emission depends on dust properties (grain size/type)
- Dust geometry + optical thickness crucial- **many stars are embedded in the dust** – dust has ~100% covering for  $N(H) > 3 \times 10^{21} \text{atms/cm}^2$
- Attenuation  $\sim 1/\lambda$  (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**

**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](http://www.astro.virginia.edu/class/whittle/astr553/Topic09/Lecture_9.pdf)



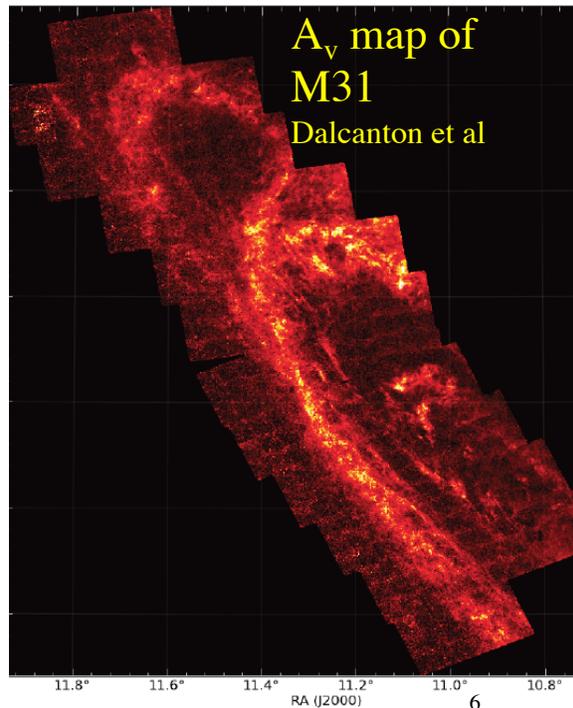
## Where is the Dust

- 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 visible, indicating calibration issues with the WFC3/IR chip (Sections 4.1 & 5.3).

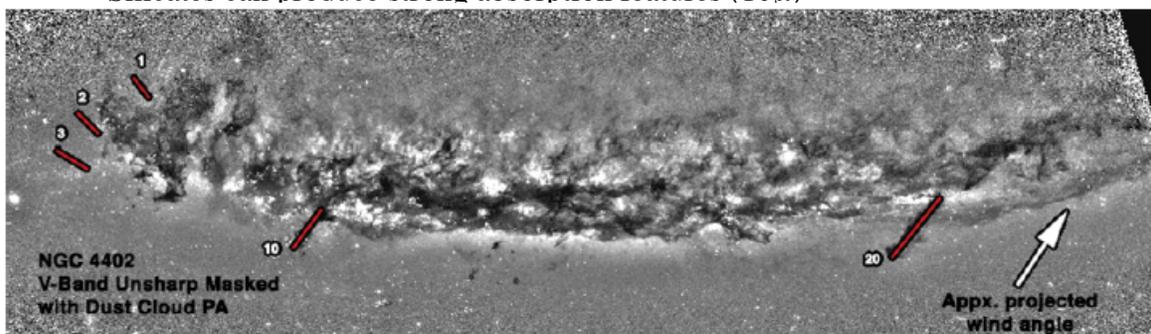
## Dusty Facts

- **Dust grains come in wide range of sizes** (power law distribution of size (a))
  - $dn/da \sim a^{-3.5}$  with  $a_{\max} \sim 0.3 \mu\text{m}$  over factor of  $10^3$  in size
- **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  $\sim 0.7\text{-}1\%$  ( by mass) of the interstellar medium in a MW like galaxy.
- **Dust explains: the  $\lambda^{-1}$  form of the UV/optical extinction curve** (large scattering efficiency ( $\sim 60\%$ ) and scattering angle)
  - Dust grains scatter and absorb radiation efficiently at wavelengths less than their own dimensions.
- **Dust is destroyed at  $T > 1300\text{K}$**  (sublimation)
- Dust heated by diffuse stellar radiation has  $T \sim 10\text{-}20\text{K}$  and peak of emission spectrum is at  $\sim 200 \mu\text{m}$ ;- dust near bright stars is hotter.
- **The ISM is exceedingly dirty**
  - If the ISM had the density of the earths atmosphere number density ( $3 \times 10^{19} \text{cm}^{-3}$ ) it would be a thick smog with  $\sim 1$  mag/meter extinction

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## Even More Dusty Facts

- Dust is formed from SN/stellar ejecta and/or in ISM (molecular clouds)
- Grains provide surface for complex astrochemistry (and  $\text{H}_2$  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 ( $10 \mu$ )

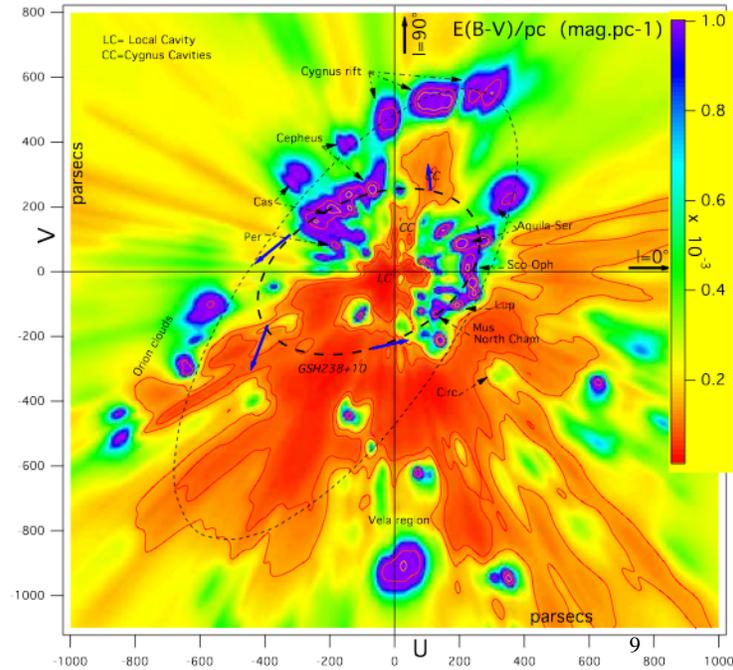


# Dust is Highly Patchy

- 3-D map of the local extinction-  $r < 1 \text{ kpc}$

(Lallement 2014)

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

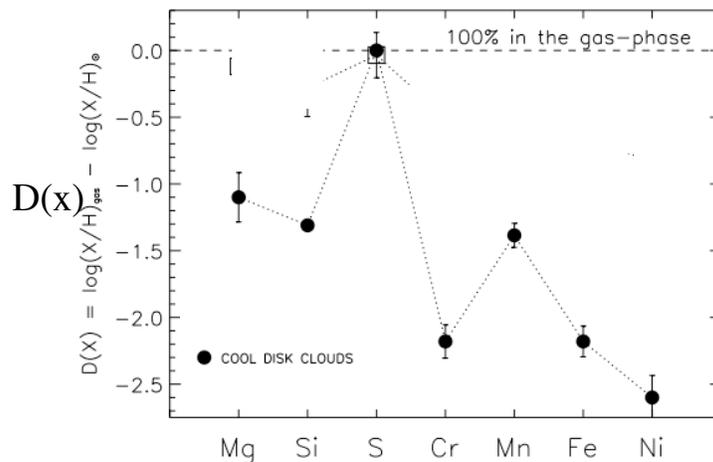


## Effects of Dust on Chemical Composition of ISM

- 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.

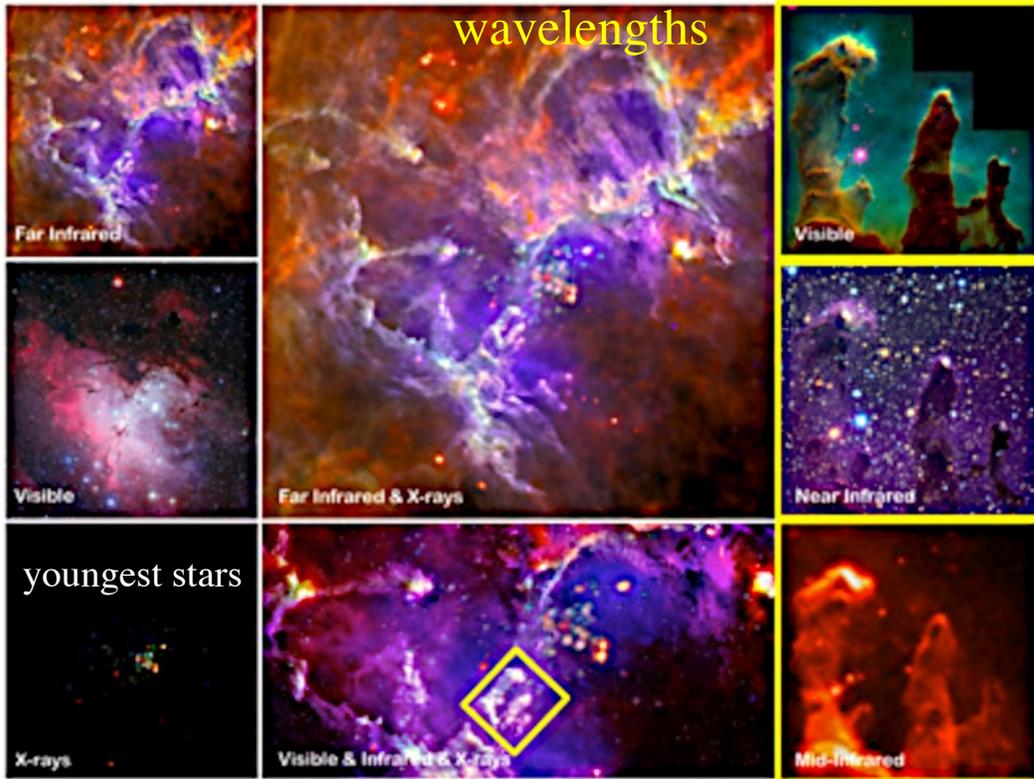


$D(x)$  = 'depletion'- the reduction in the metallicity compared to solar

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

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

# Emission and Absorption- Same place different



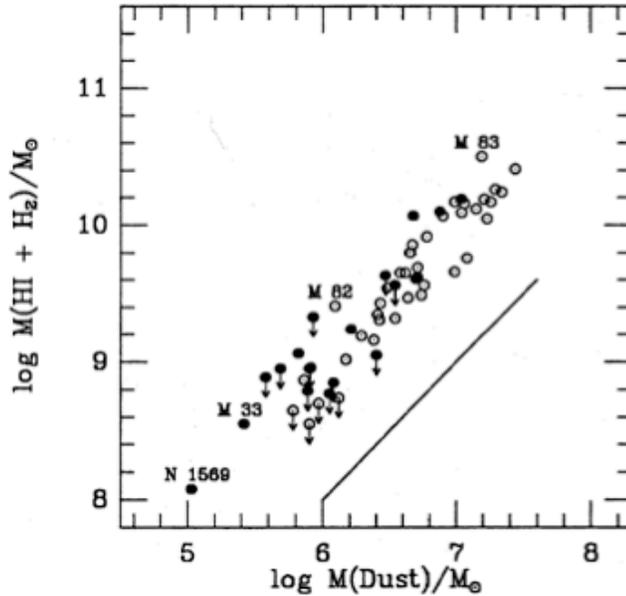
11



12

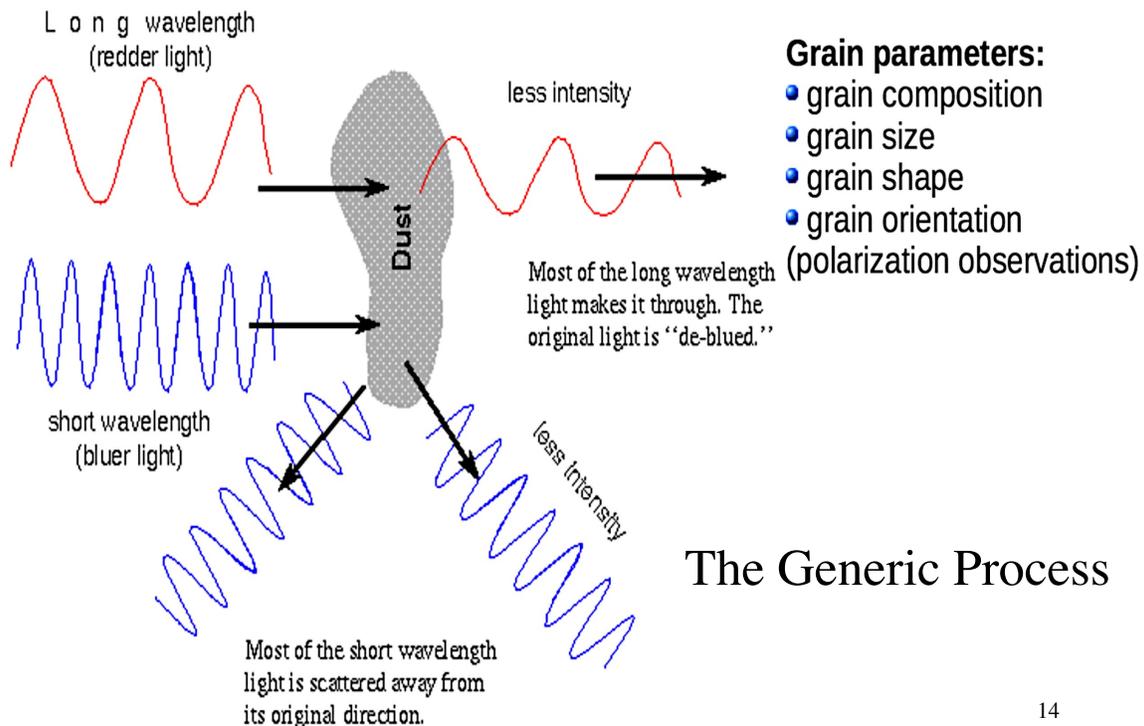
## Strong correlation of Gas and Dust

- 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.
- Warm dust ( $T \sim 20\text{-}100\text{k}$ ) 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

### Reddening and Extinction



### The Generic Process

## 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 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  $Q_\lambda$  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  $\lambda = 2900 \mu\text{m} / T(\text{K})$  in  $F(\lambda)$**   
 (units) ergs/cm<sup>2</sup>/sec/Å)

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,  $\sim 60 - 200 \mu\text{m}$
- the majority of dust has  $T_d \sim 10 - 50\text{K}$

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## Reddening and Extinction

- **Dust effects the transfer of radiation through a galaxy**
- In general the extinction due to dust can be parameterized by
  - $I_\lambda = I_0 e^{-\tau(\lambda)}$
  - $dI_\lambda / dx = -k(\lambda) I_\lambda$ ;  $k(\lambda) \sim \lambda^{-1}$
 (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)
- **$E(B-V) = (B-V) - (B-V)_0$**

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## Reddening and Extinction

**Extinction and reddening are linked**

$A_V = R \cdot E(B-V)$ ; pg 33+34

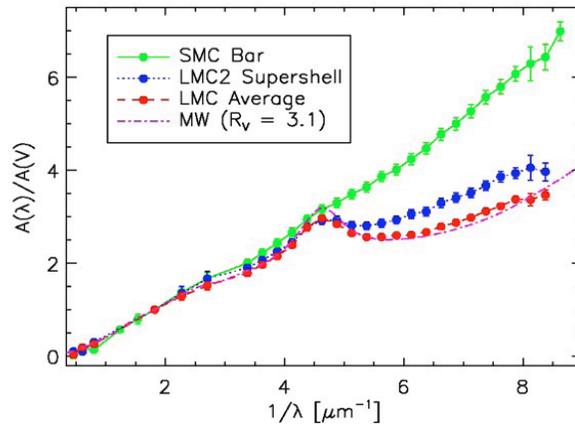
$A_\lambda$  is called the extinction at wavelength  $\lambda$ .

$R \sim 3.1$  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  $\lambda$  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

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## 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  $E_{\lambda-V} = A_\lambda - A_V$
- $E_{\lambda-V}$  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  $A \sim 30$  mags in the optical

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

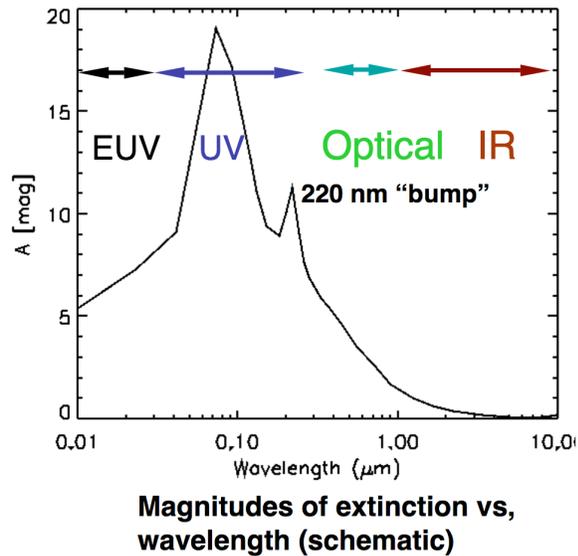
18

# Extinction

- $I(\lambda) = I_0(\lambda) \exp[\tau_\lambda^{\text{ext}}]$

$$A_\lambda = -2.5 \log_{10}[I(\lambda)/I_0(\lambda)] = 2.5 \log_{10}(e) \tau_\lambda^{\text{ext}}$$

Form of the extinction  
as a function of wavelength



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

## Alternatively

- $I_\lambda = I_\lambda(0) e^{-\tau_\lambda}$ , where  $I_\lambda$  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  $\lambda$  due to extinction,
- $E(B-V) \equiv A_B - A_V$  is the color excess measured between the  $B$  and  $V$  bands, and  $R_V \equiv A_V / E(B-V)$  The
- “normalized extinction”  $1/R_V$  measures the the slope of the extinction curve in the 4500Å - 5500Å region (e.g  $B$  and  $V$ )
- $R_V = A(V) / [A(B) - A(V)] = A(V) / E(B-V) = (A_B / A_V) - 1$   
 $R_V = A_V / E_{B-V} \sim 3.1$  for the standard extinction law.
- bigger values of  $R_V$  mean shallower slope and less UV extinction for a given  $A_V$ .
- $R_V$  differs from place to place

# 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

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

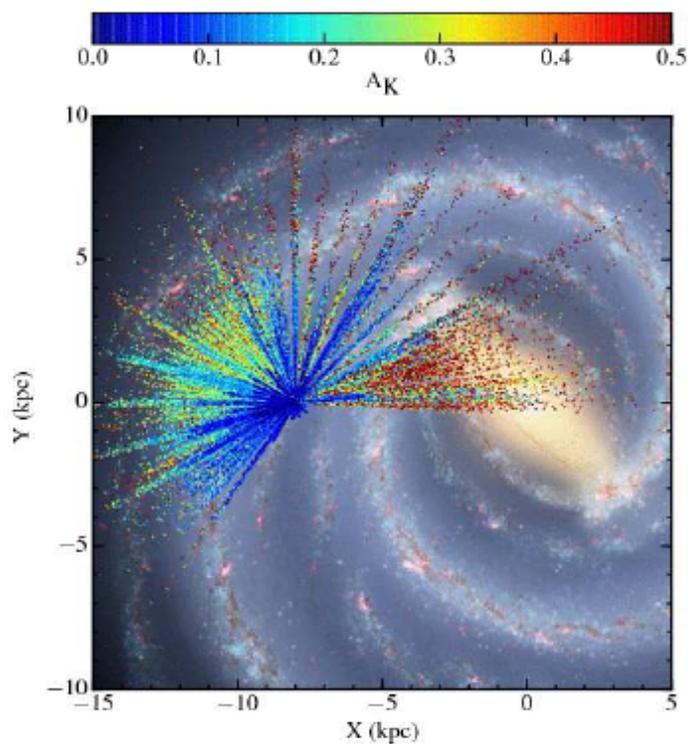
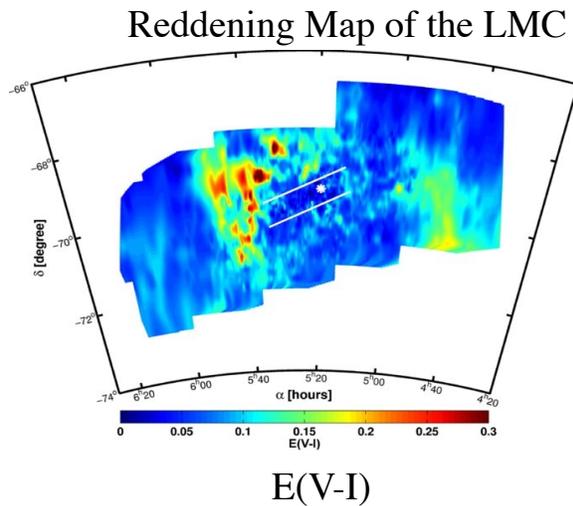


FIG. 31.— Distribution of extinction across the Galactic plane

## 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)



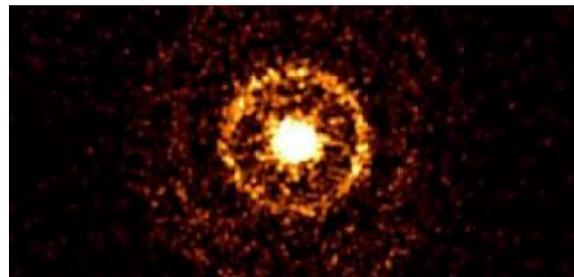
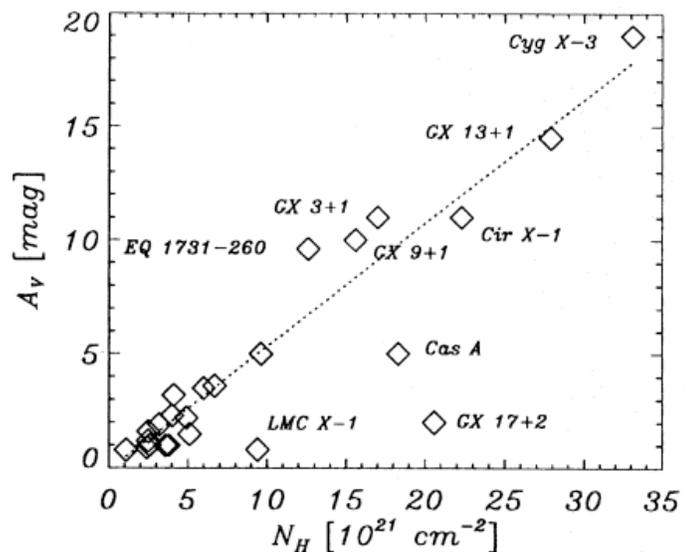
It depends on how the stars and the dust are intermixed

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.**

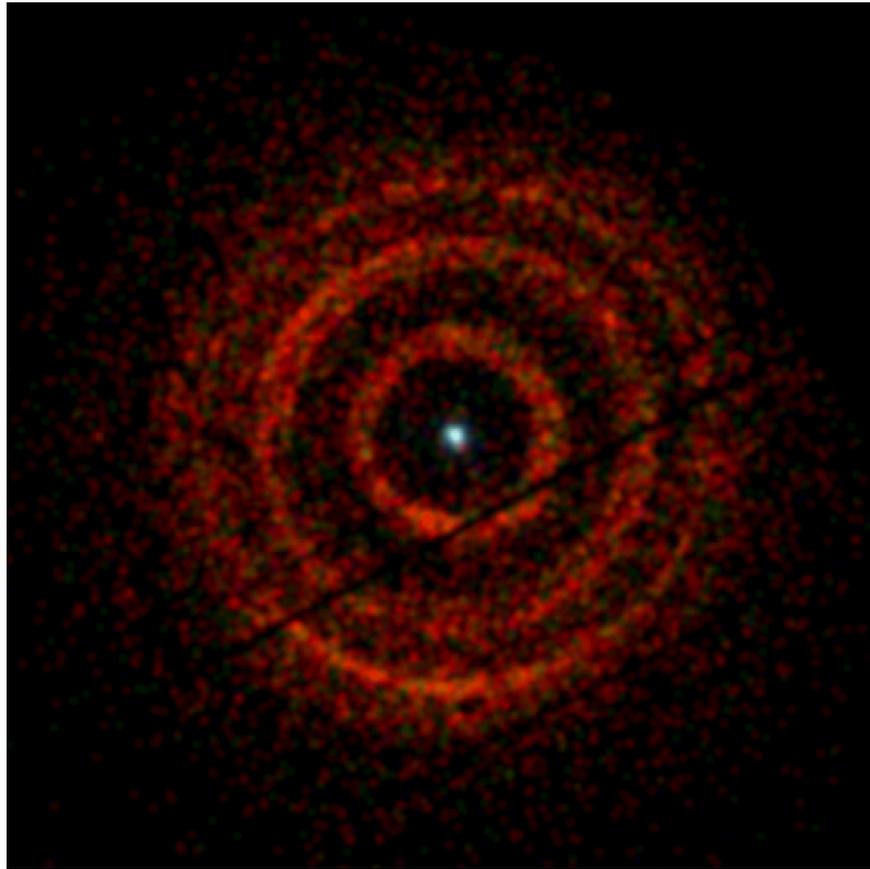
23

## 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
- $E(B-V)/N_H \sim 1.45 \times 10^{-22} \text{ mag cm}^2/\text{atoms}$   
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

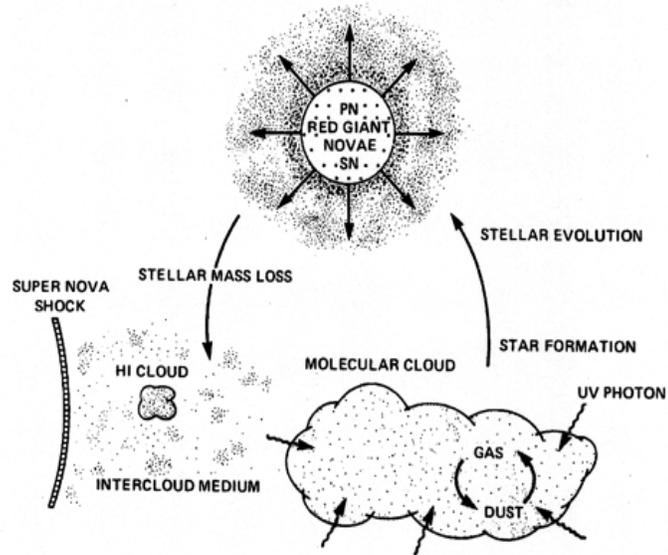
- Most Si and Fe, and 50% of C and 20% of O get locked up in dust grains cores
  - Dust grain surfaces: shield molecules from UV radiation field, produce  $H_2$  through catalysis:  $H+H+grain \rightarrow H_2+grain$  drives much of gas-phase chemistry

'Stuff' sticks to dust grains, provides sites for chemistry to occur- add UV light to get complex molecules- **stuff of life**

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

## Dust Formation

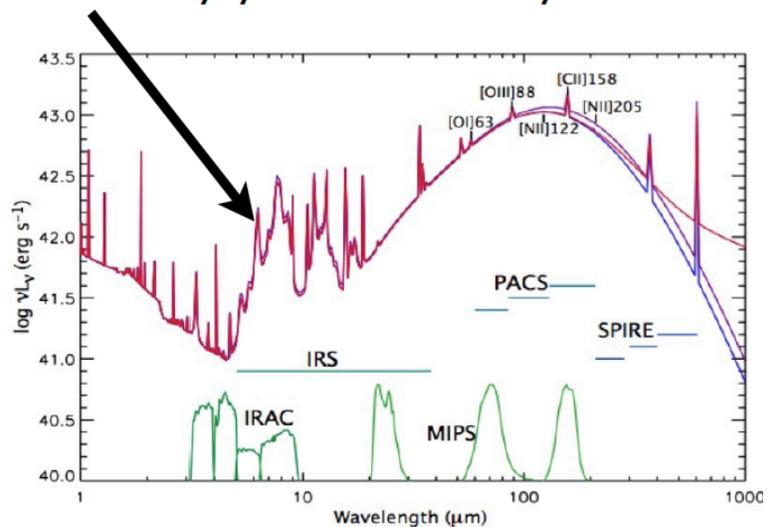


**Figure 8.1.** Schematic representation of the lifecycle of cosmic dust. Grains of 'stardust' originating in the atmospheres and outflows of evolved stars (red giants, planetary nebulae, novae and supernovae) are ejected into low-density phases of the interstellar medium, where they are exposed to ultraviolet 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

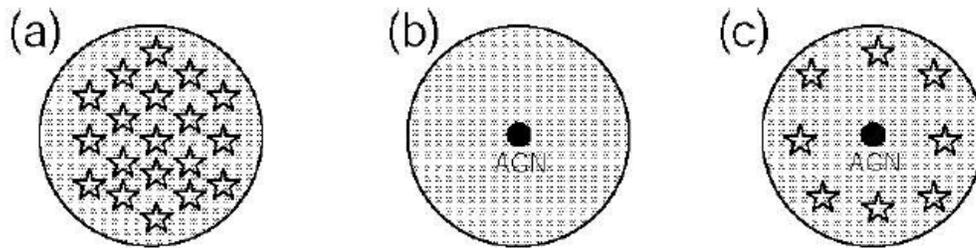


Green are the bands in the 2 most sensitive IR instruments Spitzer and Herschel

## 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

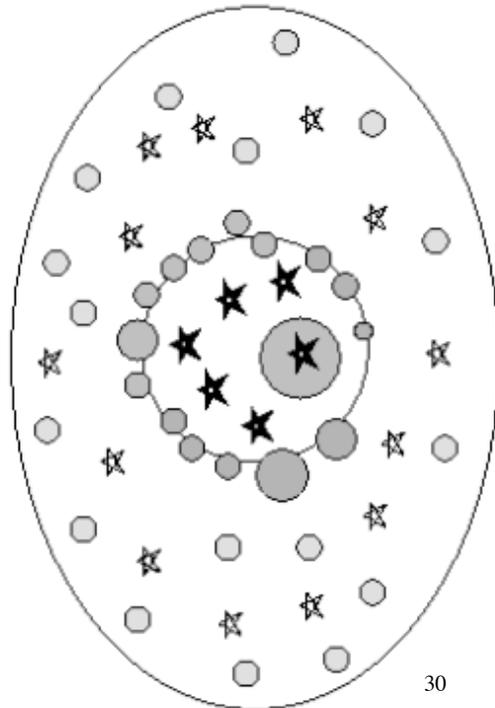
**So it ain't simple**



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## 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

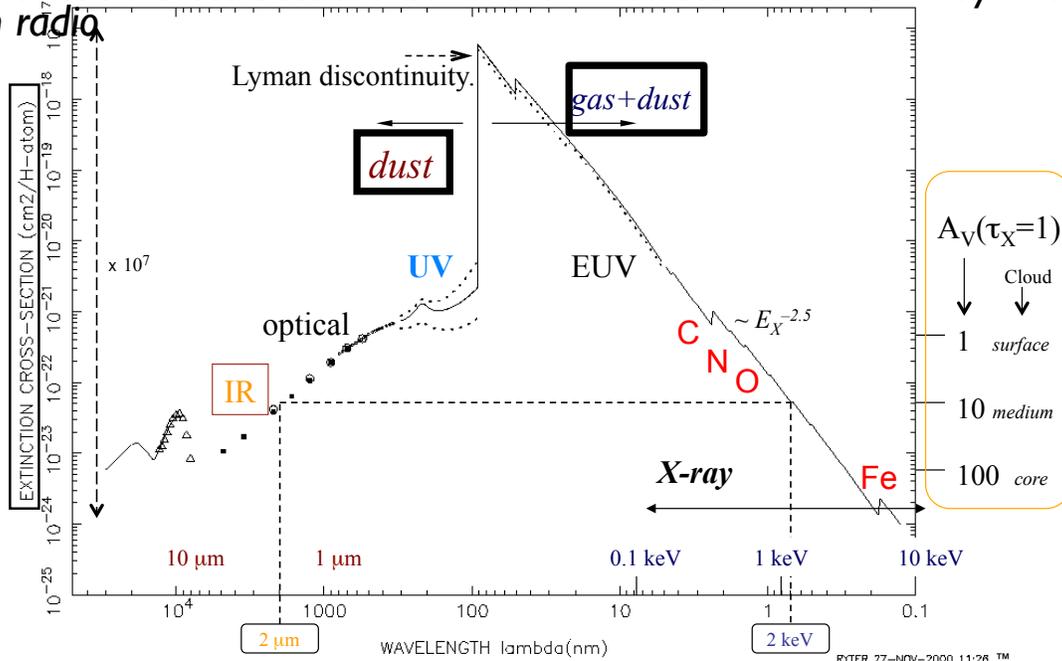


Taken from Calzetti 2000

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## Extinction - the Big Picture

Extinction Cross Section Peaks in UV- Lowest in IR and X-ray- None in radio

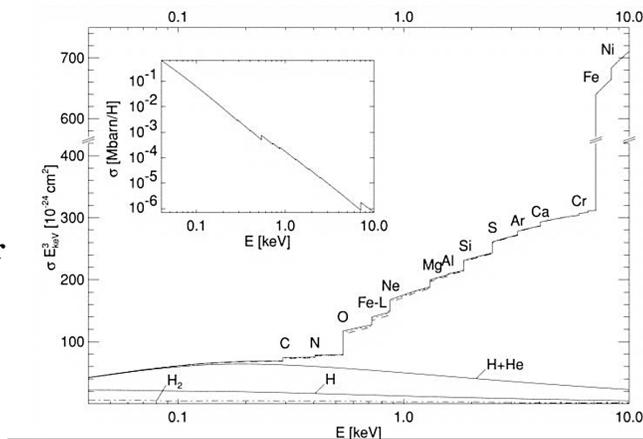


T. Montmerle

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## 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 .
- $I(E) = \exp(-\sigma_{\text{ism}}(E)N_{\text{H}})I_{\text{source}}(E)$



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

Wilms et al 2000

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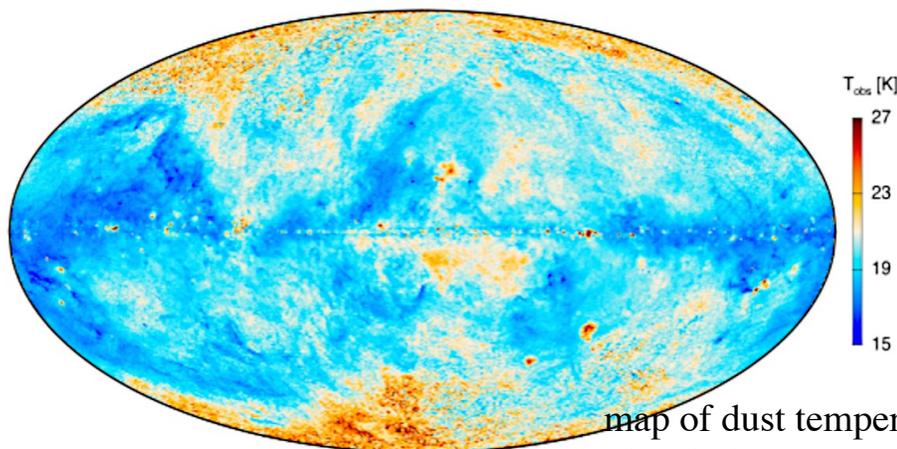
## Connection Between Reddening and Extinction

- 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.

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## 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

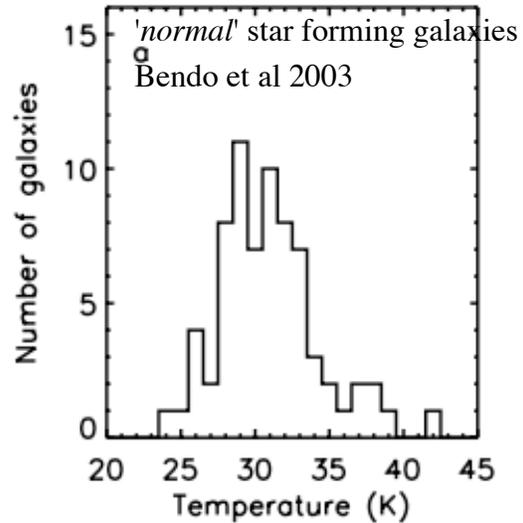
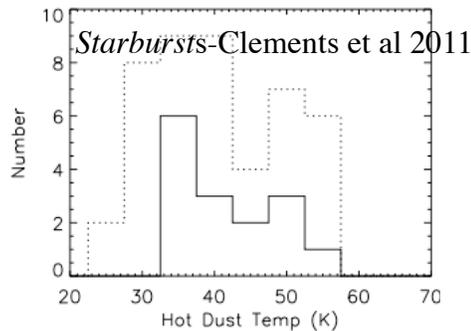


map of dust temperature of MW  
Planck data

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## Dust Temperatures

- In 'normal' star forming galaxies average dust temperatures are  $\sim 30\text{k}$
- In rapid star forming galaxies (starburst galaxies) the dust is hotter, the peak of the SED shifts from  $100\text{-}200\ \mu\text{m}$  to  $60\text{-}100\ \mu\text{m}$
- Remember  $L \sim A\sigma T^4$  so need a lot of area to get high luminosity at low temperatures-factor of 2 in  $T \rightarrow 16$  in  $L$



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

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## Reminder Black Bodies

$\lambda_{\text{peak}} \sim 29\mu / T_{100}$  ;  $\lambda_{\text{peak}}$  in units of microns and  $T$  in units of 100k

$T \sim \lambda^{-1}$  but  $L \sim AT^4$  so to get a lot of luminosity at long wavelengths needs a large emitting area,  $A$

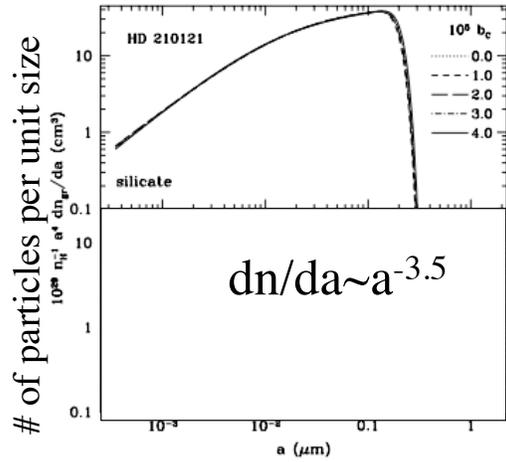
Temperature is set primarily by equilibrium; energy absorbed=energy emitted and physics of dust grains (grains cool very fast).

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# 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).

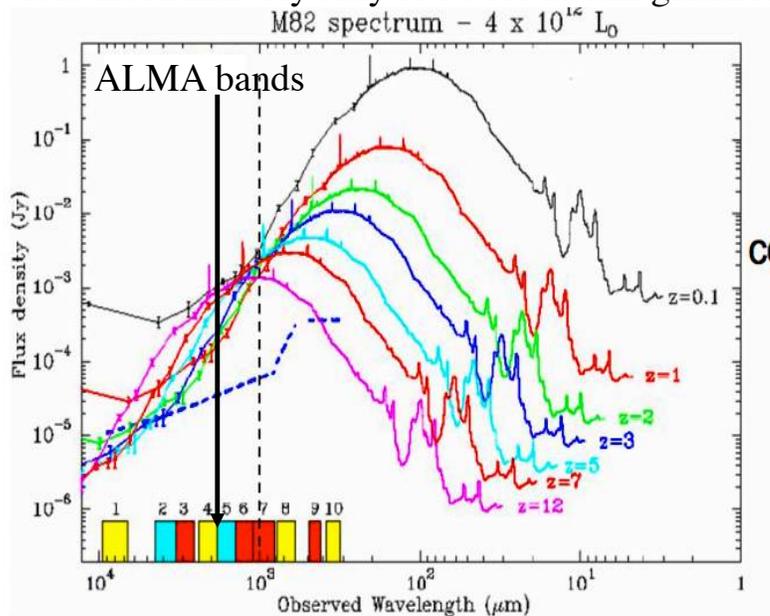


size of particles microns  
Weingartner and Draine 2001

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## 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<sup>2</sup>  
cosmological dimming

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## 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
- The shape of the interstellar extinction curve contains information about the size and composition of interstellar dust grains.
- The relatively smooth variation of the extinction with wavelength from 0.1 to 3  $\mu\text{m}$  indicates that a wide distribution of grain sizes are present.
  - A substantial fraction of the heavy elements are bound up in dust.

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## Next Time

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