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

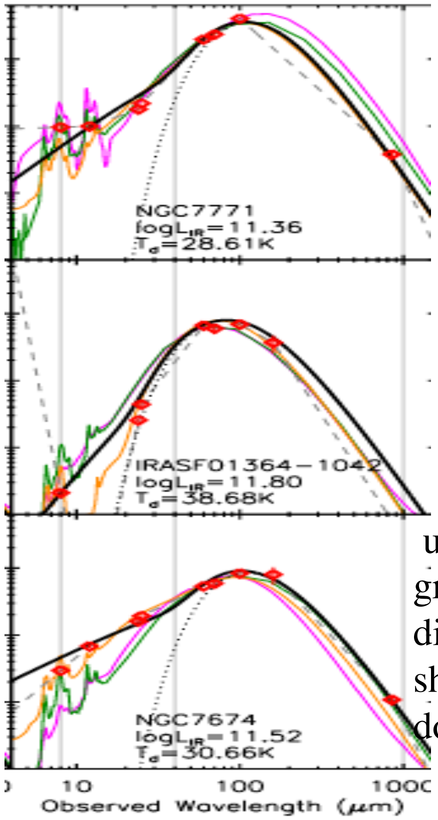
The peak of Black body is at $\lambda=2900\mu m/T(K)$ in $F(\lambda)$

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

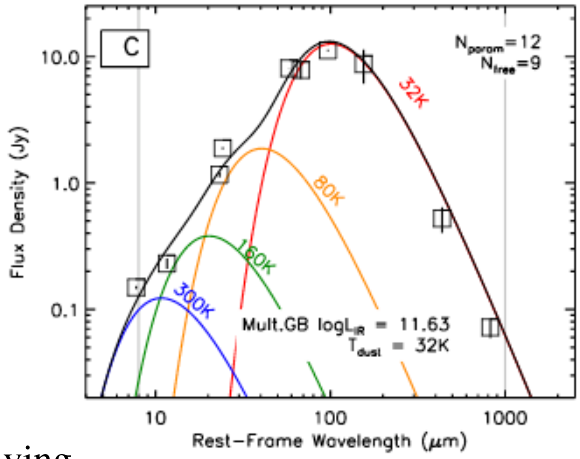
Grey body fits most spectra very well (!?)

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



Fit to Data



underlying greybody distribution shown as a dotted black line

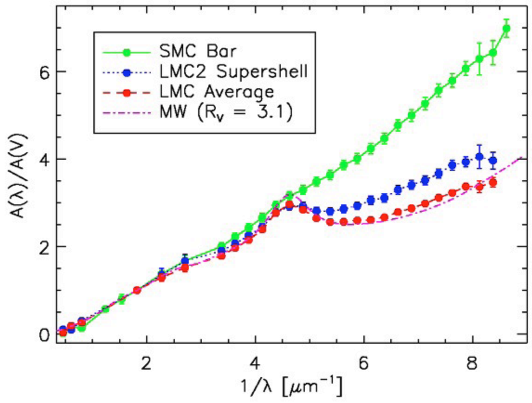
- Casey, Caitlin M. MNRAS. 425 (2012) - Fit to broad band IR spectra with 4 'grey bodies'

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

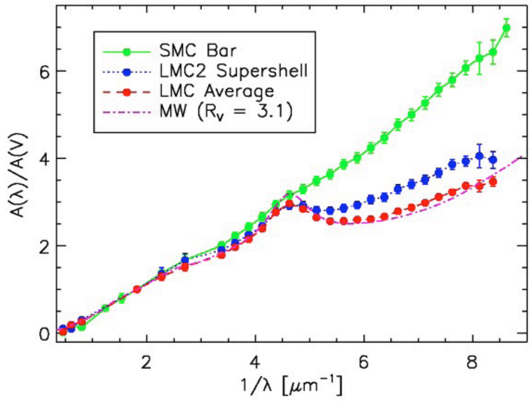
and $R_V=A_V /E(B-V$

•$m-M=5\log d-5+A_v$

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



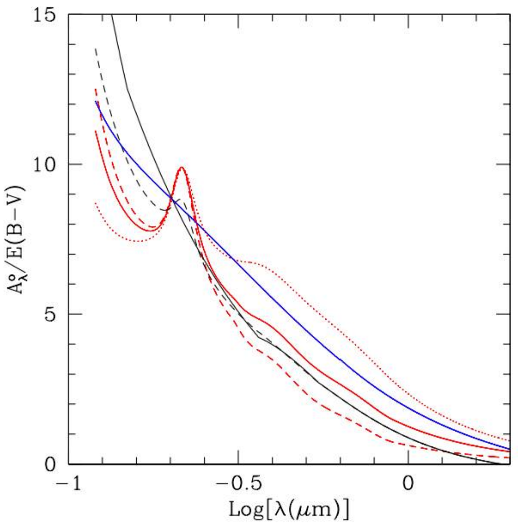
Reddening/Extinction MBW pg 479

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

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

Examples of extinction curves in local galaxies.

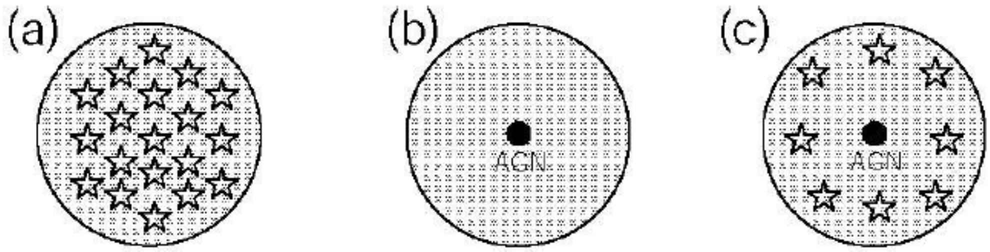
- Milky-Way extinction law for **three different values of R_V,** 3.1 (continuous red line), 5.0 (dashed red line), and 2. (dotted red line)
- the Large Magellanic Cloud's 30 Doradus region (dashed black line) and of the Small Magellanic Cloud's bar (continuous black line) have R_V=2.7
- **The starburst 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



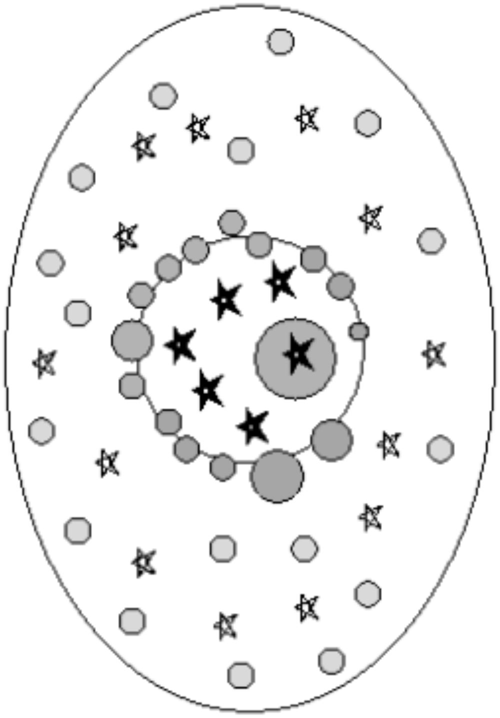
Dust and Geometry

- 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



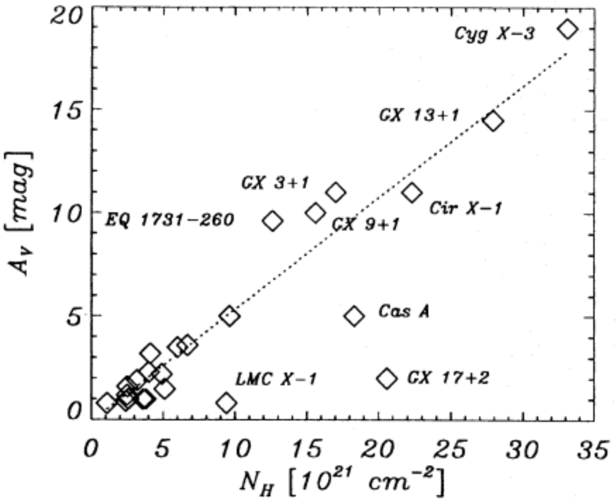
- The starburst region (center of figure) has a newly formed stellar population, (dark starred symbols), some still embedded in the parental clouds.
- dust and gas (dark-gray circles) from the previous generation of stars to the edges of the region is further out.
- The galaxy' s diffuse ISM (light-gray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

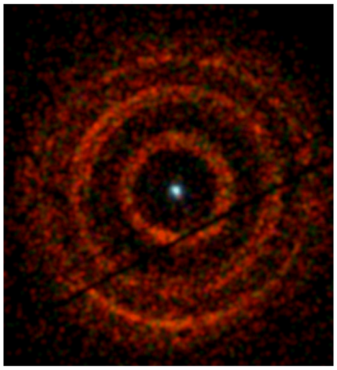
Dust to Gas Ratio

- 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

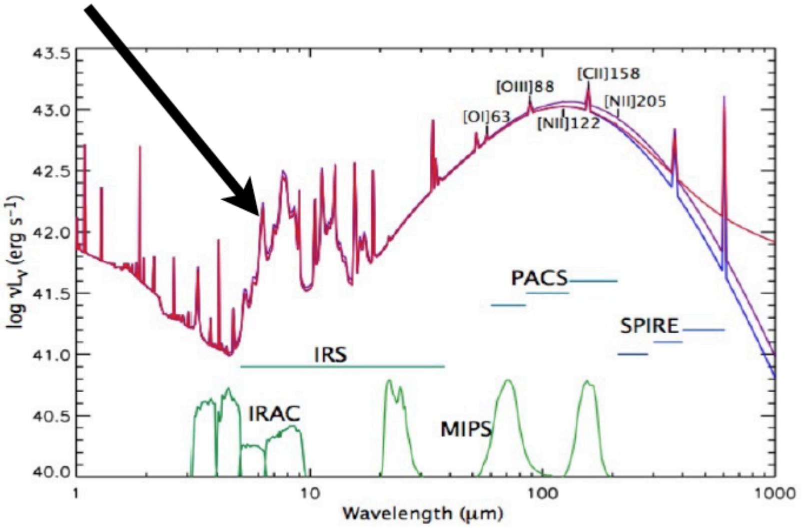
- Most Si and Fe, and 50% of C and 20% of O get locked up in dense dust grain cores
- interstellar chemistry is carbon-dominated
- Dust grain surfaces: shield molecules from UV radiation field, produce H_2 through catalysis: $H+H+grain \to H_2+grain$

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

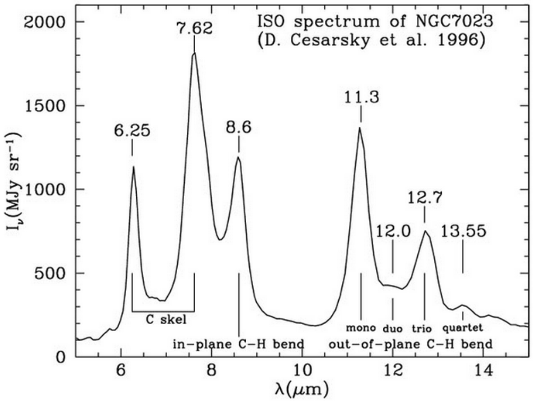
PAH's: Polycyclic Aromatic Hydrocarbons

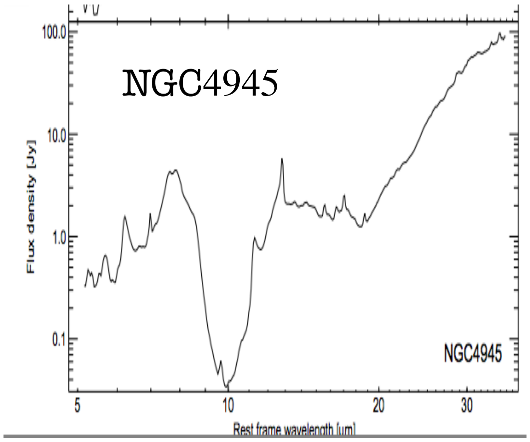


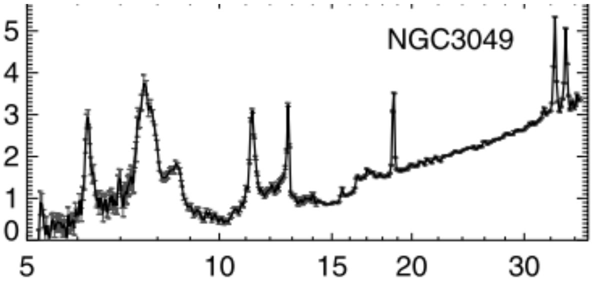
Green are the bands in the 2 IR
instruments which were flown on Spitzer and Herschel

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







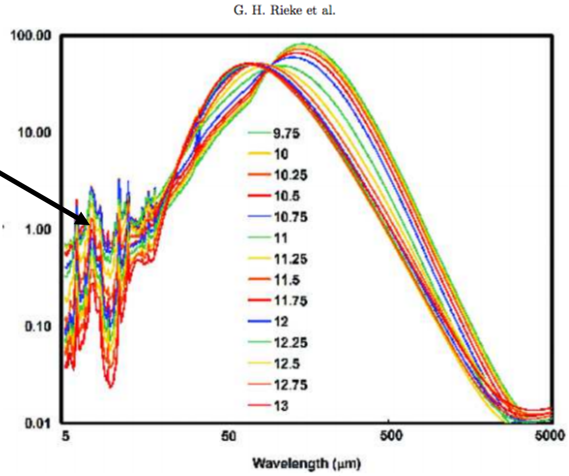
λ (μ)

λ (μ)

What Photons Does the Dust Emit (see MBW figure 10.8)

- 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

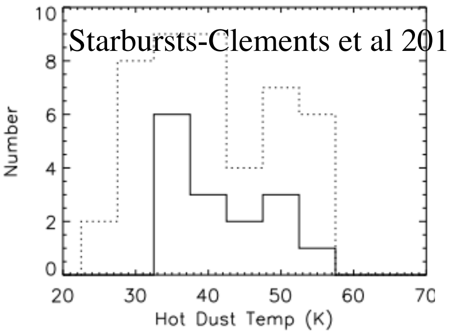
(Kennicutt and Evans 2012)

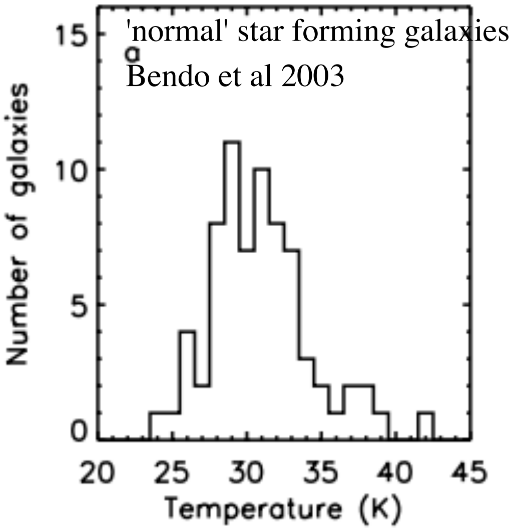


IR spectra of rapidly star forming galaxies over range of $10^{3.25}$ in luminosity Rieke et al 2008
Peak varies from ~40-200μ
If use BB formula T varies by 5 (λ_{max} ~ 1/T)

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


Starbursts-Clements et al 2011


'normal' star forming galaxies
Bendo et al 2003

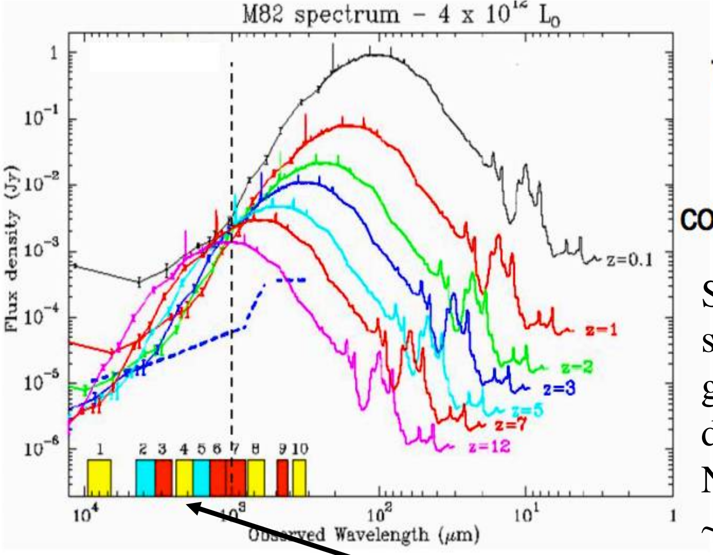
But spectra often not well described by single temperature (sum over many emission regions)

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 !**

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

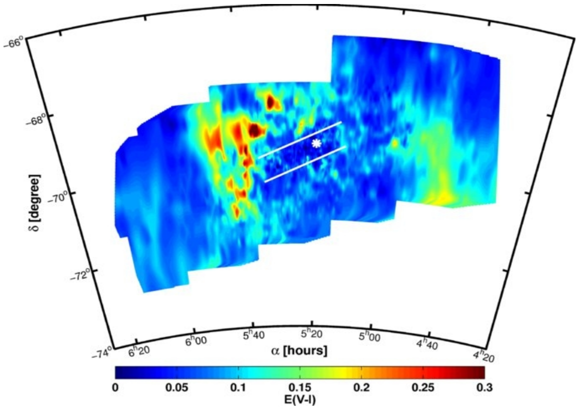
ALMA bands

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)

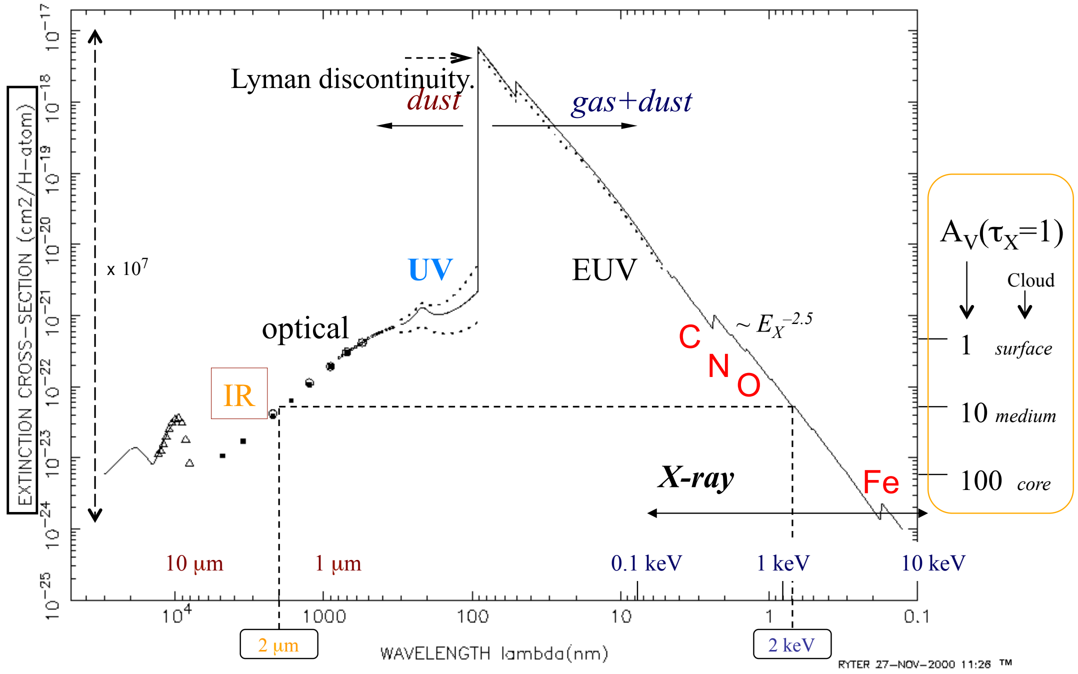
$R_V = A_V/E_{B-V}$ ~3.1 for the standard extinction law.

$1/R_V = (A_B-A_V)/A_V = (A_B/A_V) - 1$

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.

Extinction - the Big Picture



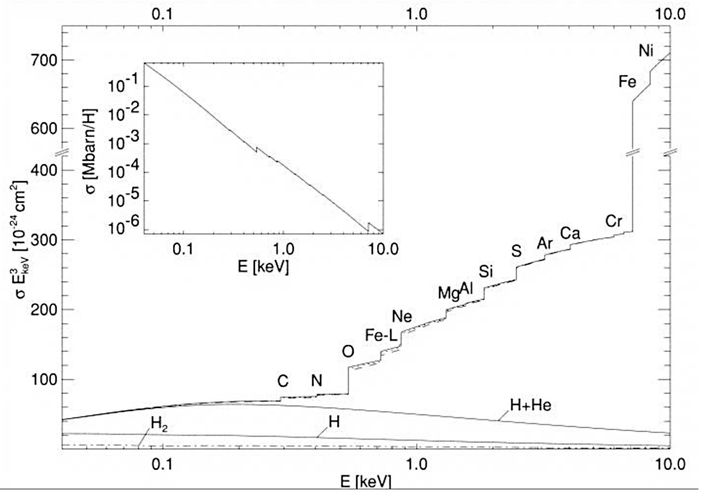
T. Montmerle

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



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

Wilms et al 2000

Even More Stars/Galaxies

- **The 2018 STScI Spring Symposium The 21st Century H-R Diagram:**
- **The Power of Precision Photometry**
- The Hertzsprung-Russell Diagram has revolutionized stellar physics over the past century. It remains an essential tool in the 21st century for studying stellar properties and behavior. New observing capabilities have improved precision and accuracy, which in turn have uncovered new populations of stars and revealed limits in our physical understanding of their structure and evolution. Now is the time to prepare for the next generation of facilities that will bring forward a new wave of diagnostics to analyze the Hertzsprung-Russell Diagram.
- Please join us in Baltimore for the 2018 Spring Symposium. Discussions will include:
- • Simple stellar and multiple populations in the Milky Way and nearby galaxies.
- • Stellar models and synthetic H-R diagrams.
- • Stellar populations in distant galaxies.
- • Young stellar objects and evolution to the main sequence.
- • Variability, transients, and the H-R diagram.
- • Preparing for future missions and observatories.