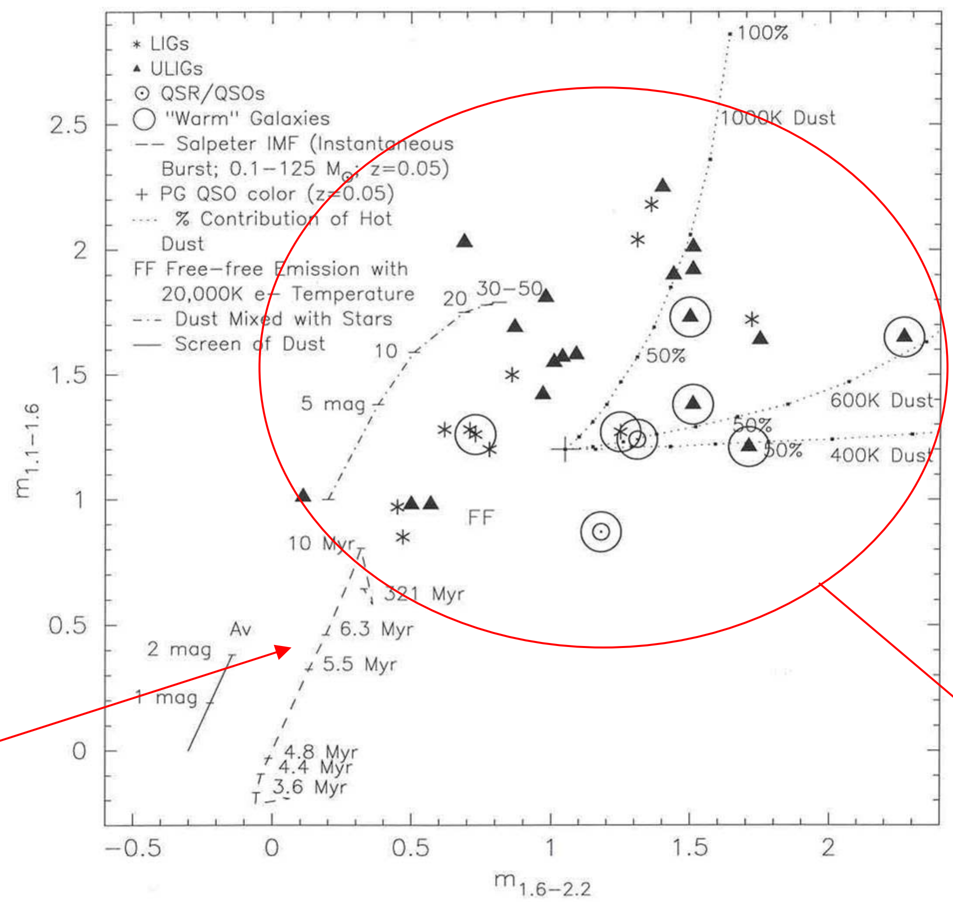
Population Synthesis Models: Color-Color Diagram



Models

Data

Components of Galaxies – Dust

Where does Dust come from?

- Mass Loss From Evolving Low Mass Stars
- Supernovae

Evidence for Dust

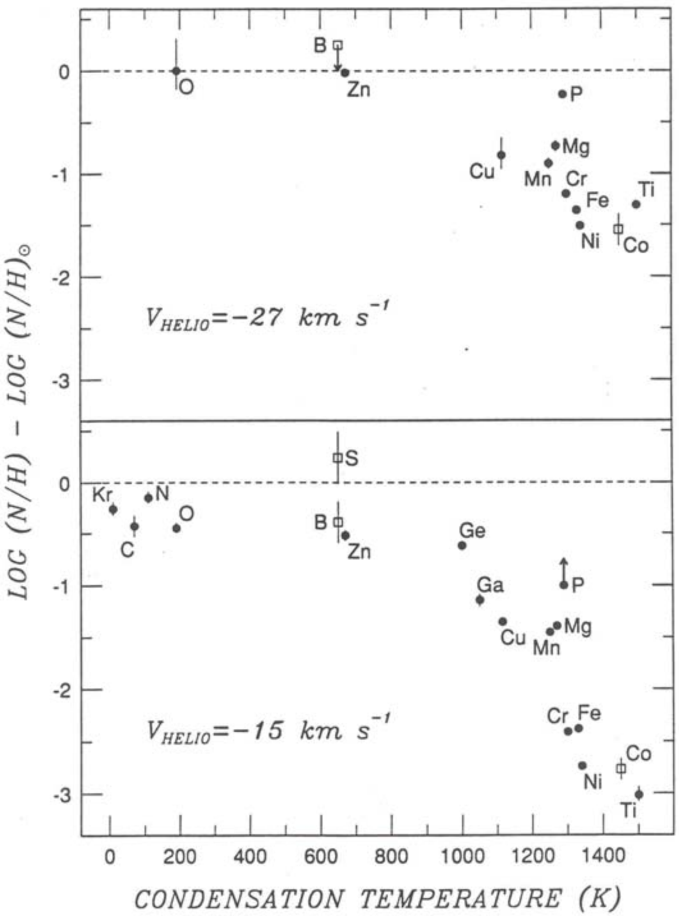


Figure 4.1. Interstellar elemental abundances relative to hydrogen compared with those in the Sun, for two clouds on the line of sight towards ζ Oph. The two clouds are distinguished by their velocity shifts relative to the Sun. The data are displayed as a function of the condensation temperature of the appropriate material. The underabundance of elements relative to the Sun, i.e. the depletion, can be large. In the cloud at -15 km s^{-1} titanium is depleted by three orders of magnitude. (From Federman S R *et al* 1993 *Astrophysical Journal* **413** L51.)

- Abundance of Interstellar gas measured along the line of sight to near stars – not typical of Sun
- Metals missing from interstellar gas are capable of forming solids which are heat stable & resistant

Creation of Dust

- Evidence - Missing metals in interstellar gas
- Gas moves farther away from stars, cools, & condenses out of gas
- Examples:

  1) Si & O → Mg + Fe → Silicates
  2) Fe → Fe particles
  3) Si + C → Silicon carbide, graphite, metal oxides

Effect on Radiation

- Scattering (e.g. Nebulae have same spectrum as central star)

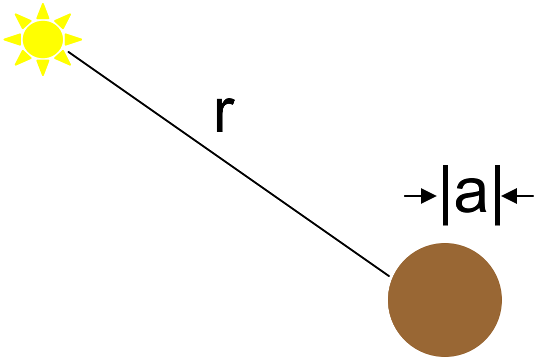
- Absorption (of UV light from Stars/AGN)

  → Generation of far-infrared photons

  → Typical Dust temperatures T = 10 – 60 K

Absorption of Radiation from a Star by Dust

Consider a dust grain of diameter *a* = 0.1 μm at a distance *r* from a star of luminosity L_*



The flux received by the grain is

$$\left(\frac{L_*}{4\pi r^2}\right)\pi a^2 Q_{\mathrm{in}},$$

where Q_{in} is the absorption efficiency. The dust grains will radiate away

$$4\pi a^2(\sigma T_{\mathrm{dust}}^4)Q_{\mathrm{out}},$$

where Q_{out} is the emission efficiency.

Thus,

$$T_{\rm dust} = \left(\left[\frac{L_*}{16\pi r^2 \sigma} \right] \frac{Q_{\rm in}}{Q_{\rm out}} \right)^{1/4}$$

So, if L_* = 2x10^{28} W = 100 L_{solar} and r = 10^{14} m = 700 AU, then,

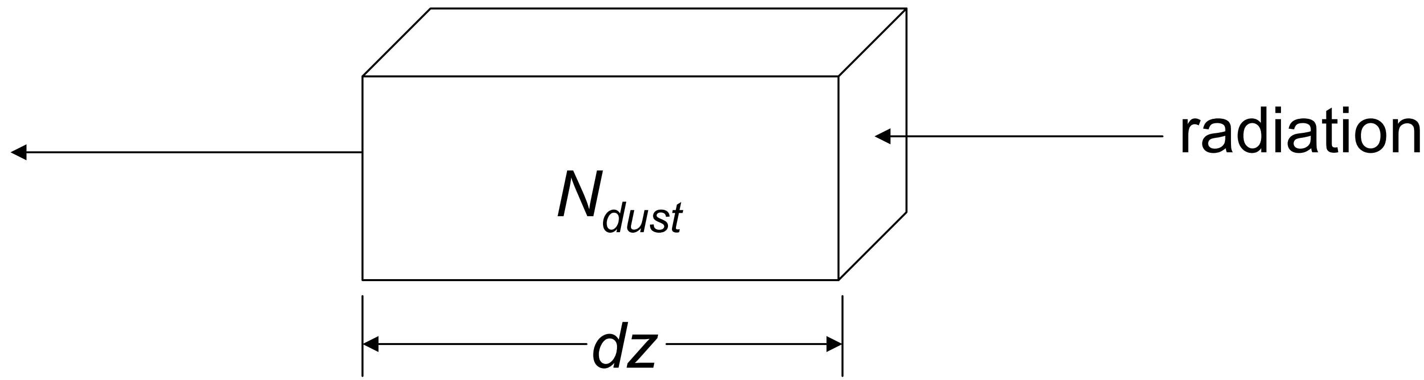
$$T_{\rm dust} = 30\ {\rm K} \left(\frac{Q_{\rm in}}{Q_{\rm out}} \right)^{1/4}.$$

where σ = 5.7x10^{-8} W m^{-2} K^{-4}. From Wien's Law, a dust grain emitting thermal radiation at this temperature emits the peak of it flux at a λ of

$$\lambda_{\rm peak} = \frac{0.3\ {\rm cm\ K^{-1}}}{T({\rm K})} = \frac{0.3\ {\rm cm\ K^{-1}}}{30\ {\rm K}} \sim 100\mu{\rm m}.$$

Opacity

A beam of radiation with intensity *I* traverses a slab of dust of thickness *dz*.



The amount of radiation removed from the beam is

$$dI = -I\kappa dz = -IN_{\rm dust}(z)\sigma dz = -Id\tau,$$

where κ is the absorption coefficient, N_{dust} is the density of dust grains, σ is the absorption cross section, and τ is the opacity

$$dI = -I\kappa dz = -IN_{\text{dust}}(z)\sigma dz = -Id\tau,$$

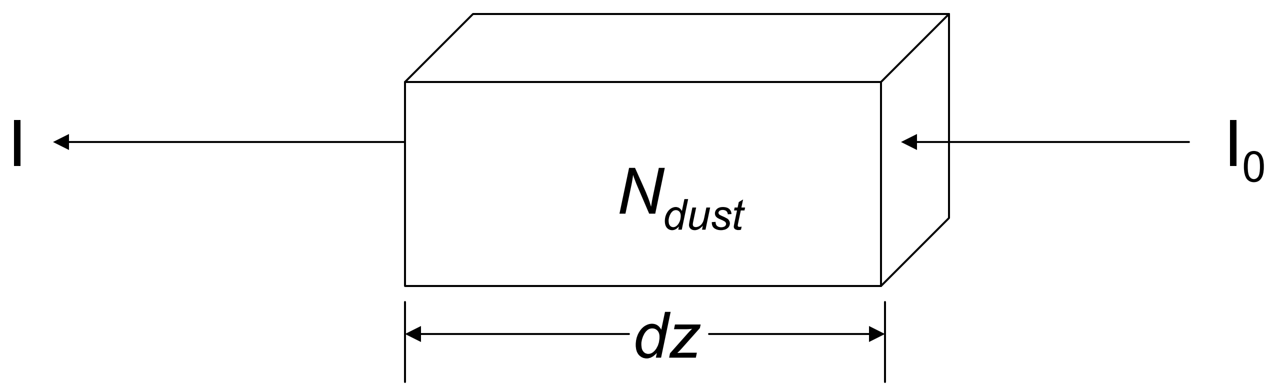
At $\tau = 1$, a photon has traveled one mean free path, ℓ

$$\ell = (N_{dust}\ \sigma)^{-1}$$

Integrating $dI = -I\ d\tau$ & solving for intensity yields,

$$I = I_0 e^{-\tau},$$

where I_0 is the intensity prior to crossing the dust slab.



In terms of opacity,

$$\tau = -2.3026 \log \frac{I}{I_0}.$$

Extinction

In terms of magnitudes of extinction at some wavelength *X*, A_X,

$$A_X = [m(X) - m_0(X)] = -2.5\log\frac{I(X)}{I_0(X)} = 1.086\tau.$$

where m_0 is the magnitude in the absence of extinction, *m* is the extinguished magnitude.

If the spectral type & luminosity of a star is known, as well as the distance *d* to the star, then the extinction can be determined

$$m_X - M_X = A_X + 5\log(d) - 5,$$

where m_X is the observed extinguished magnitude & M_X is the absolute magnitude of the star.

Color Excess

In terms of color excess as measured between wavelengths *X* & *Y*, *E(X – Y),*

$$E(X - Y) = [m(X) - m(Y)] - [m_0(X) - m_0(Y)] = A_X - A_Y.$$

I.e., color excess is the extinction between two wavelengths.

Extinction Curve in Terms of *E(B-V)* vs. λ^{-1}

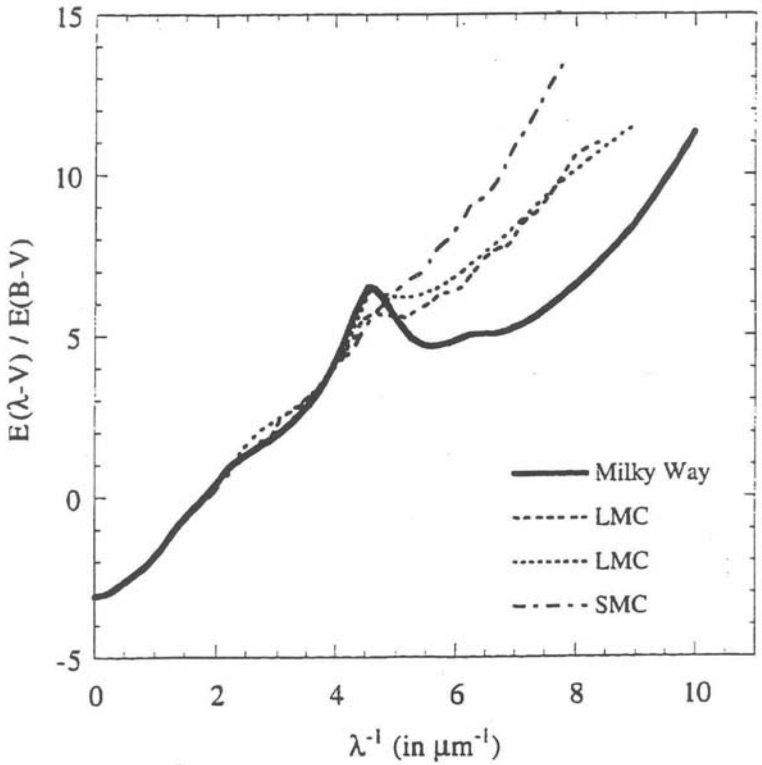


Fig. B.1.— Extinction Curves for the Milky Way Galaxy, the LMC, and the SMC

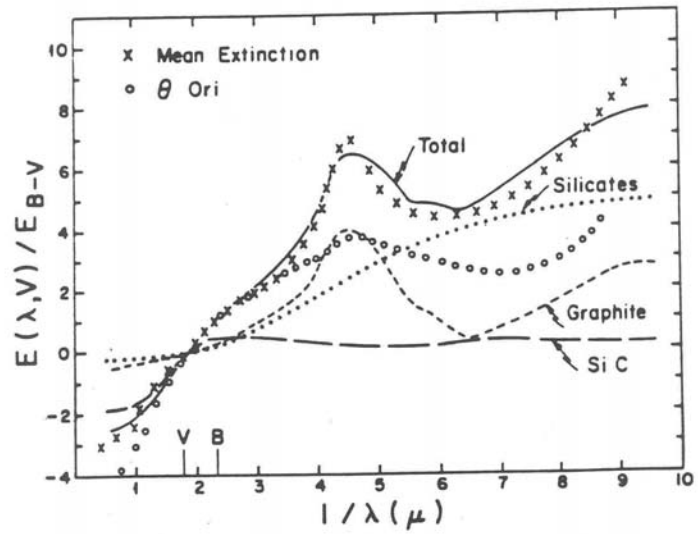
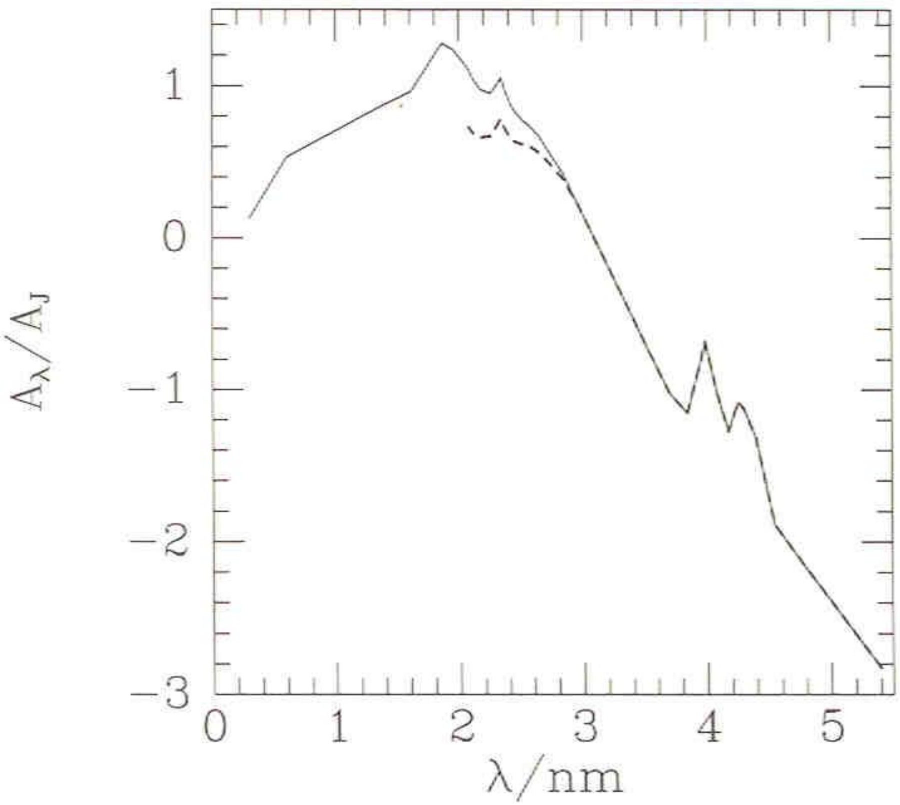


Figure 7.2 Dependence of selective extinction on wavelength. The ratio of $E(\lambda, V)$ to E_{B-V} is plotted against the reciprocal wavelength in microns. The crosses give the mean observed extinction for normal stars [2]; in the ultraviolet these are based on 14 observed stars, excluding 3 abnormal ones; the circles give observed values for $\theta^1 + \theta^2$ Ori, showing abnormal extinction. The other curves are computed theoretically [16] for grains of three different types (see text), with the sum of the three shown by the solid line.

- Note that the extinction law for the Galaxy differs from that of the LMC & SMC
- Typically, the extinction is given in terms of all 3 extinction laws.

A_λ vs. λ



- Note that $A_\lambda \approx \lambda^{-1}$ at long wavelengths

Table 3.21 The standard interstellar extinction law

Band X	$\frac{E(X-V)}{E(B-V)}$	$\frac{A_X}{A_V}$
U	1.64	1.531
B	1.00	1.324
V	0.00	1.000
R	−0.78	0.748
I	−1.60	0.482
J	−2.22	0.282
H	−2.55	0.175
K	−2.74	0.112
L	−2.91	0.058
M	−3.02	0.023
N	−2.93	0.052

SOURCE: From data published in Rieke & Lebofsky (1985)

N(H) vs. E(B – V)

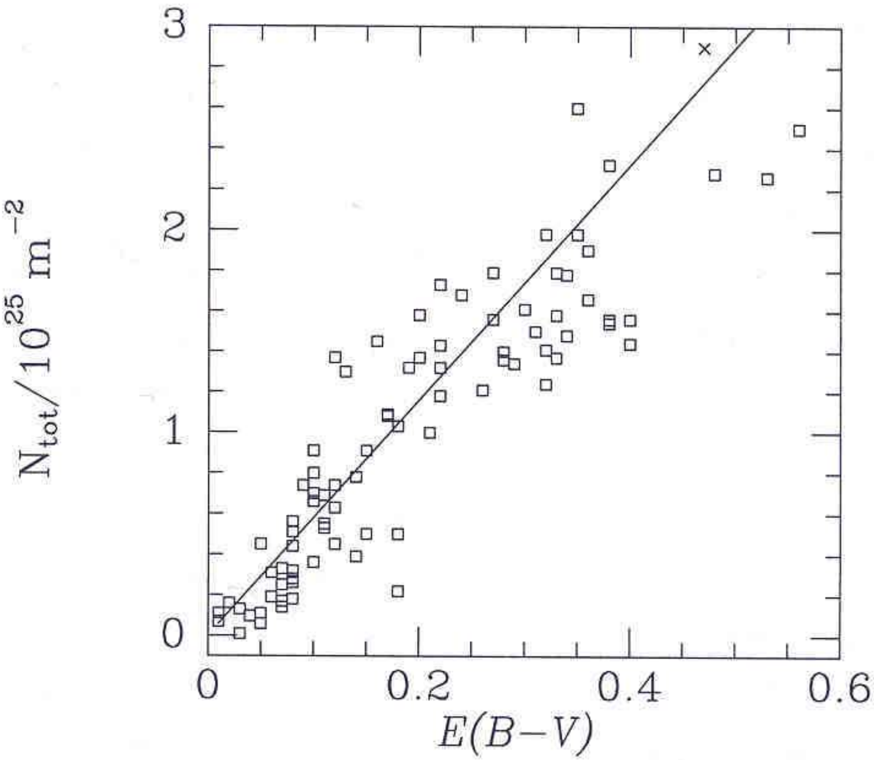


Figure 8.14 The reddening $E(B-V)$ down various lines of sight is approximately proportional to the column density of hydrogen, $N(\mathrm{H_{tot}})$, along that line of sight. The straight line is given by equation (8.49). [From data published in Bohlin *et al.* (1978)]

$$E(B-V) = \frac{N_H}{5.8 \times 10^{25}\mathrm{m}^{-2}},$$

where N_H is the number density of hydrogen gas in molecular & atomic form.

Example 1

A star in a cluster located 25 pc from the Earth is observed. The spectral type of the star is known to be O8 (i.e., M_V = -4.9)

- If the apparent *V* magnitude is measured to be m_V = 5, what is the optical extinction to this star.

$$A_V = m_V - M_V - 5\log 25 + 5 = 7.9 \text{ mags of extinction at } V.$$

- What is the extinction at *K*?

From Table 3.21,

$$\frac{A_K}{A_V} = 0.112.$$

- What is the opacity at *V* & *K*?

We know that $A_X = 1.086\ \tau_X$. Thus,

$$\tau_V = \frac{A_V}{1.086} = 7.27.$$

$$\tau_K = \frac{A_K}{1.086} = 0.81.$$

- Note that
  1) starlight traverses a path that is optically thick at *V*
  2) and optically thin at *K*

- Thus the infrared wavelength range is important because stars form in molecular clouds.

- In terms of the measured intensity vs. the intensity in the absence of dust, how much has the intensity been been extinguished by at V & K?

$$\left(\frac{I}{I_0}\right)_V = e^{-\tau_V} = 7 \times 10^{-4}.$$

$$\left(\frac{I}{I_0}\right)_K = e^{-\tau_K} = 0.44.$$

- What is the extinction as measured at 60 μm?

Table 3.21 doesn't list the extinction at 60 μm. But we know that $A_X \sim \lambda_X^{-1}$ at long wavelengths.

$$A_{60\mu\mathrm{m}} = A_K \left(\frac{\lambda_K}{\lambda_{60\mu\mathrm{m}}}\right) = 0.88 \left(\frac{2.2}{60}\right) = 0.0323.$$

The corresponding values of $\tau_{60\mu m}$ & $(I/I_0)_{60\mu m}$ are 0.030 & 0.97.

• What is the color excess *E(B – V)* ?

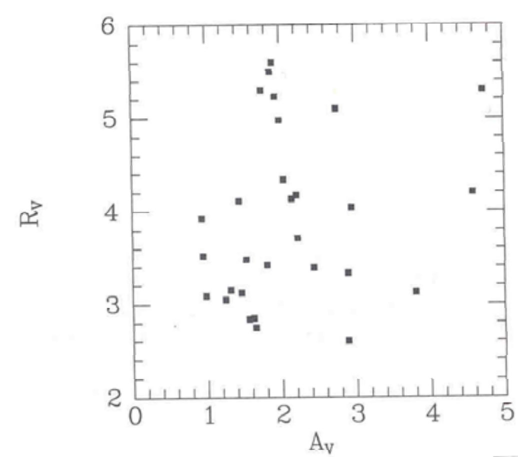
$$E(B-V) = A_B - A_V = (1.324A_V) - A_V = 0.324A_V = 2.6,$$

where the relation A_B = 1.324 A_V is taken from Table 3.21.

• Note that

1) the factor 0.324 is often referred to as *1/R*, where *R* is the slope of the extinction curve near *E(B – V).*
2) *R* has a lot of scatter, but *R* ≈ 3.1 is still commonly used.

• Given the above *E(B – V)* = 2.6, what is the column density of hydrogen along the line of sight to the star?



$$N(H_{\rm tot}) = 5.8 \times 10^{25} E(B-V)\ {\rm m}^{-2} = 1.5 \times 10^{26}\ {\rm m}^{-2}.$$

Example 2 – How Extreme can Extinction get?

- Recent X-ray observations of the luminous infrared galaxy NGC 6240 were used to calculate a column density of *N(H)* = $2\text{x}10^{28}$ m^{-2}.

- What is the color excess *E(B – V)* & the optical extinction along the line of sight to the X-ray emitting source?

$$E(B-V) \sim N(H)/5.8 \times 10^{25}\ \text{m}^{-2} = 345\ \text{mags},$$

and

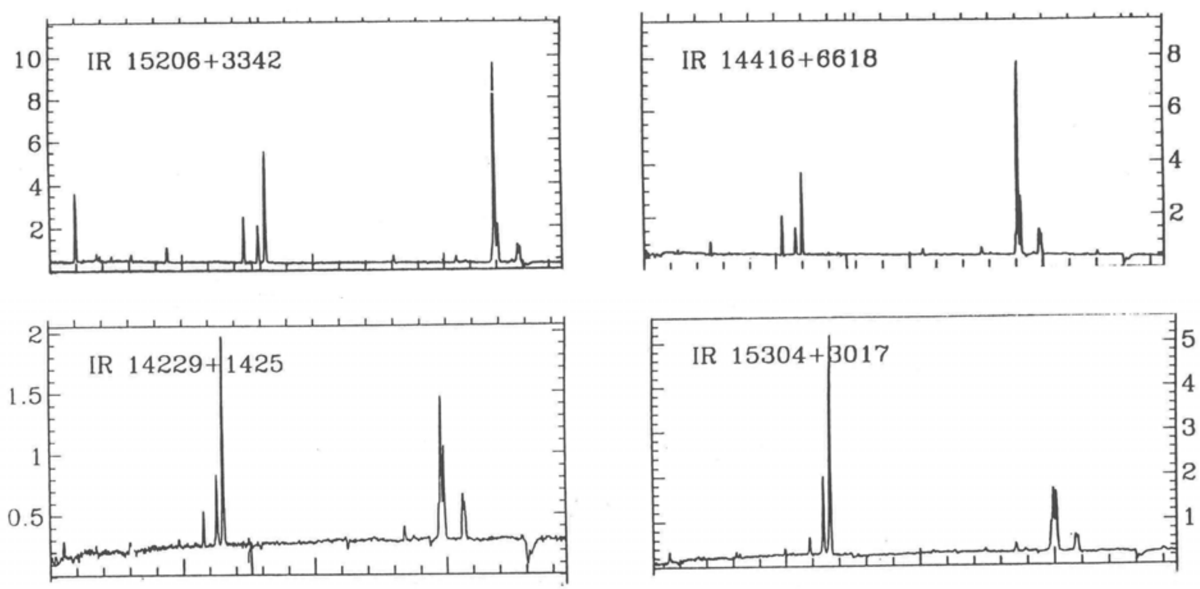
$$A_V \sim 3.1E(B-V) = 1070\ \text{mags of optical extinction!}$$

- What is the extinction at 60 μm?

$$A_{60\mu\text{m}} \sim A_V \left(\frac{0.55\mu\text{m}}{60\mu\text{m}}\right) = 9.8\ \text{mags of extinction at } 60\mu\text{m}.$$

Calculating Extinction Using Hydrogen Recombination Lines

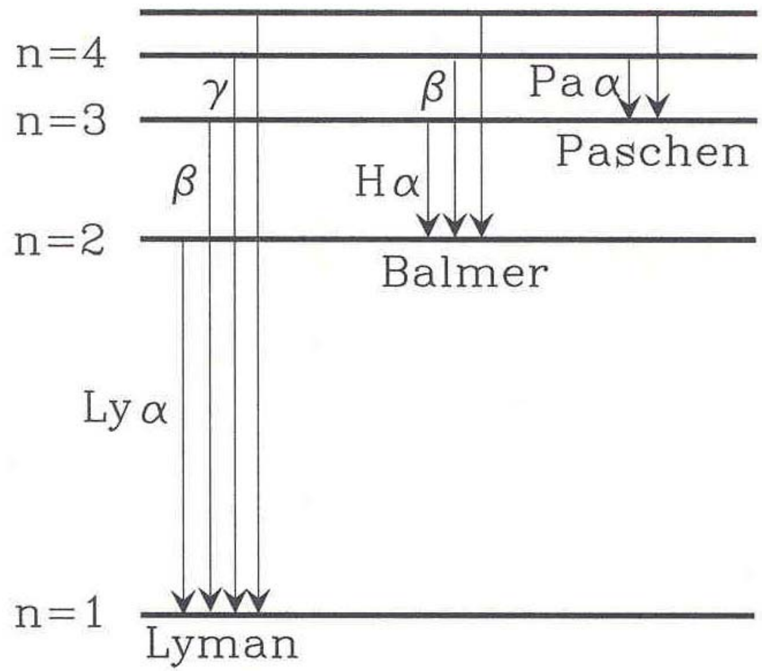
- Extinction via stellar type has little use for distant objects
- Solution: Hydrogen recombination lines – intrinsic line ratios are known
- This technique can only be done for galaxies with strong emission lines



Starburst: OB stars

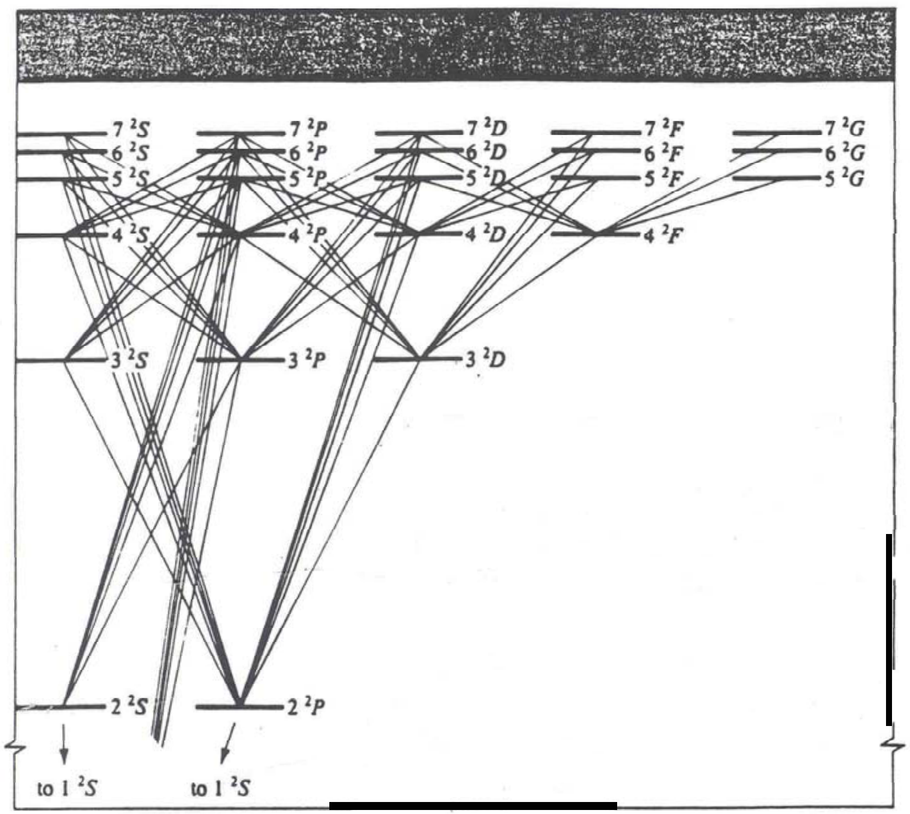
AGN: accretion disks

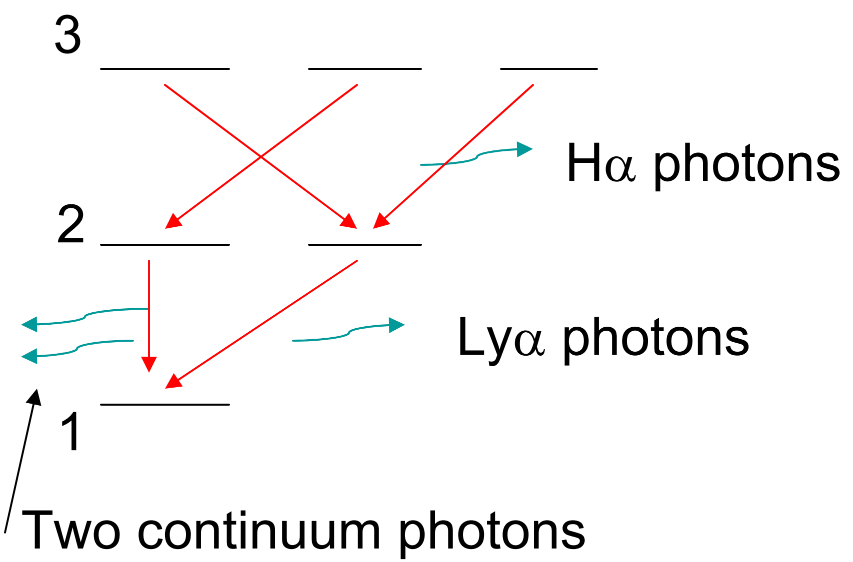
Energy Level Diagram – Useful Lines



- Lyα at 0.1216 μm (n = 2 $\rightarrow$ 1)
- Hβ at 0.4861 μm (n = 4 $\rightarrow$ 2)
- Hα at 0.6563 μm (n = 3 $\rightarrow$ 2)

Energy Level Diagram – Relative Transition Rates





l.d.l. → ⅔ Lyα + ⅓ • 2(continuum γ)

h.d.l. → 1 Lyα + 0 (continuum γ)

- For high density limit (h.d.l.), $N_{e-} > 10^{11}$ cm $^{-3}$. Collisions are important.

The intrinsic line ratios can be determined if the relative transition rates are known. For example, if we consider Lyα & Hα,

$$\frac{I_{\mathrm{Ly}\alpha}}{I_{\mathrm{H}\alpha}} = K \frac{\alpha_B h\nu_{\mathrm{Ly}\alpha}}{\alpha_{\mathrm{H}\alpha} h\nu_{\mathrm{H}\alpha}}.$$

where

K = number of Lyα photons produced per Hα photon

α_B = recombination rate summed over all levels above ground level ($cm^3\ s^{-1}$)

$\alpha_{H\alpha}$ = effective recombination coefficient for Hα

Intrinsic ratios typically used are,

$$\frac{\mathrm{Ly}\alpha}{\mathrm{H}\alpha} \sim 8.1 \text{ (Starburst) or } \sim 16 \text{ (AGN)},$$

$$\frac{\mathrm{H}\alpha}{\mathrm{H}\beta} \sim 2.85 \text{ (Starburst) or } \sim 3.1 \text{ (AGN)}$$

Color Excess Calculations using Recombination Lines

To calculate the color excess *E(B – V),* the intensities of two recombination lines must be measured, then an extinction curve must be adopted.

From the definition of magnitude & color excess,

$$E(\lambda_2 - \lambda_1) = 2.5 \left[\log \left(\frac{I_2}{I_1} \right)_{\text{intrinsic}} - \log \left(\frac{I_2}{I_1} \right)_{\text{measured}} \right]$$

From the extinction curve, we can solve for the quantity,

$$\frac{E(\lambda_2 - \lambda_1)}{E(B-V)} = \frac{E(\lambda_2 - V)}{E(B-V)} - \frac{E(\lambda_2 - V)}{E(B-V)}.$$

Example 3

Lyα & Hα are measured from a redshift *z* ~ 2.2 radio galaxy TX 0200+015. The ratio of these lines are determined to be Lyα / Hα ~ 1.7

- What is the color excess *E(B – V)* along the line of sight to the line-emitting gas?

From the extinction curve for the galaxy, we can determine that

$$\frac{E(\mathrm{Ly}\alpha - V)}{E(B-V)} = \frac{E(0.1216\mu\mathrm{m} - V)}{E(B-V)} = 6.95 \quad \text{and} \quad \frac{E(\mathrm{H}\alpha - V)}{E(B-V)} = \frac{E(0.6563\mu\mathrm{m} - V)}{E(B-V)} = -0.83.$$

Thus,

$$\frac{E(\mathrm{Ly}\alpha - \mathrm{H}\alpha)}{E(B-V)} = \frac{E(0.1216\mu\mathrm{m} - V)}{E(B-V)} - \frac{E(0.6563\mu\mathrm{m} - V)}{E(B-V)} = 7.78 \text{ (Milky Way)}.$$

E(Lyα – Hα) / *E(B – V)* ~ 11.22 (LMC & SMC extinction curves)

Example 3, cont.

Now,

$$E(\mathrm{Ly}\alpha - \mathrm{H}\alpha) = 2.5\left[\log\left(\frac{I_{\mathrm{Ly}\alpha}}{I_{\mathrm{H}\alpha}}\right)_{\mathrm{intrinsic}} - \log\left(\frac{I_{\mathrm{Ly}\alpha}}{I_{\mathrm{H}\alpha}}\right)_{\mathrm{measured}}\right].$$

Thus,

$$E(\mathrm{Ly}\alpha - \mathrm{H}\alpha) = 2.5[\log(16) - \log(1.7)] = 2.43.$$

Taking the two expressions for E(Lya – Ha) & setting them equal to each other, & solving for E(B – V), we get,

$$E(B - V) = 0.31 \quad (\mathrm{MW}), \quad \sim 0.21 \quad (\mathrm{LMC}), \quad \text{and} \quad \sim 0.14 \quad (\mathrm{SMC}).$$