Lecture 4

1 Metal Abundances

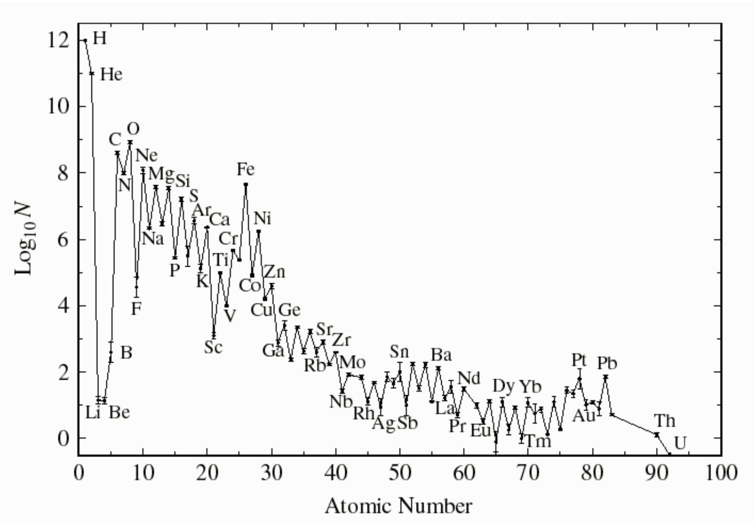

Figure 1: Solar abundances on a log scale.

Theory of abundances must explain some general features e.g.

- Dominance of H and He
- Decrease of abundance with increasing Z
- Odd even effect
- Peak around Fe

Two main reasons for odd-even effect: even Z elements have more isotopes and because all nucleons can be paired with another of opposite spin. Nuclei with odd Z have an unpaired proton. Combination of BBN and stellar nucleosynthesis required.

We will often refer to chemical 'abundances'. These are usually given in 'bracket' notation:

$$[X/H] = logN(X) - logN(H) - log(X/H)_{\odot}. \tag{1}$$

N(X) is the column density measured in atoms cm^{-2}. This notation tells us the abundance of an element relative to solar on a logarithmic scale. E.g. [X/H]=-2 means 1/100 the solar value. The convention for solar abundances is to allocate the logarithmic abundance of H a value of 12. Tabulated log $(X/H)_{\odot}$ values usually therefore need to have 12 subtracted. E.g. tabulated log $(O/H)_{\odot}$ +12 abundance is 8.83, so $8.83 - 12 = -3.17$, i.e. oxygen is about 1000 times less abundant than H in the Sun. Oxygen has had its solar abundance revised many times in the last few years, e.g. due to Ni blends. Current problem is that new O/H messes up helio-seismology.

Example: If N(O) = 10^{16} and N(H)= 10^{21} [O/H] $= 16 - 21 + 3.17 = -1.83 \sim 1/68\ Z_{\odot}$.

Most elements have solar abundances determined both through photospheric methods and measurements from meteorites. In general, the 2 agree very well. Nonetheless, abundances relative to solar usually take the meteoritic value for ISM work and photospheric values for stellar abundances.

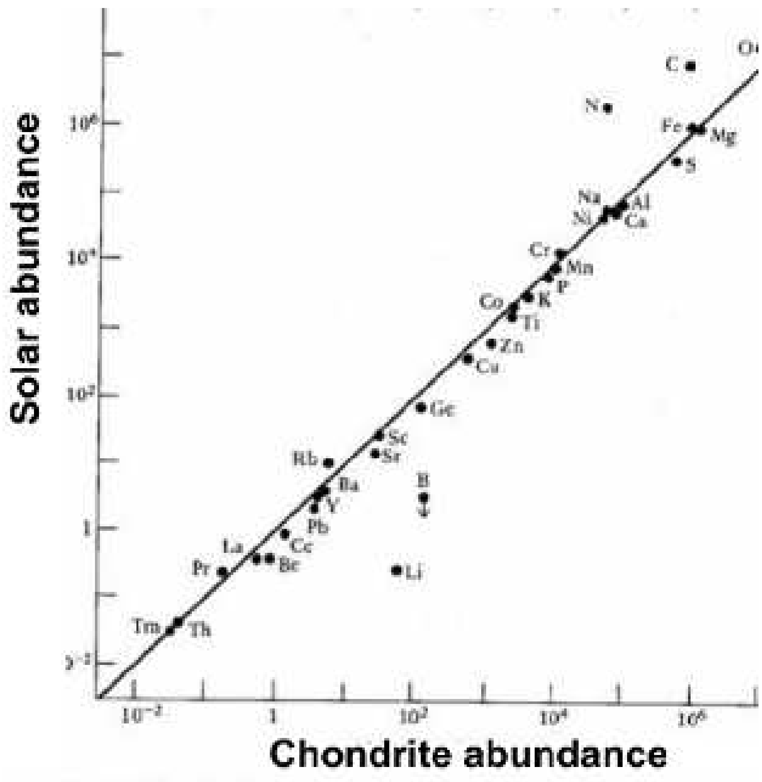

Figure 2: Photospheric and meteoritic abundances.

Are solar system abundances representative? Probably not! The Sun seems quite enriched in heavy elements (interesting trend that planet bearing stars may be more enriched). Also abundance gradients in the galaxy. Also, LZ relation amongst galaxies. But the solar value is still a convenient reference.

2 Dust and Metals

The presence of dust in a galaxy has numerous effects on light: it scatters, absorbs, polarizes, re-emits radiation. It regulates heating and cooling. It is important for formation of molecules and therefore star formation. See Annual Reviews by Mathis (1990) and Draine (2003).

The more metals are present, the more raw materials for dust. Depletion takes metals out of gas phase.

$$D(X) = log(N_X/N_H)_{ISM} - log(N_X/N_H)_{\odot} \tag{2}$$

and fractional depletion is

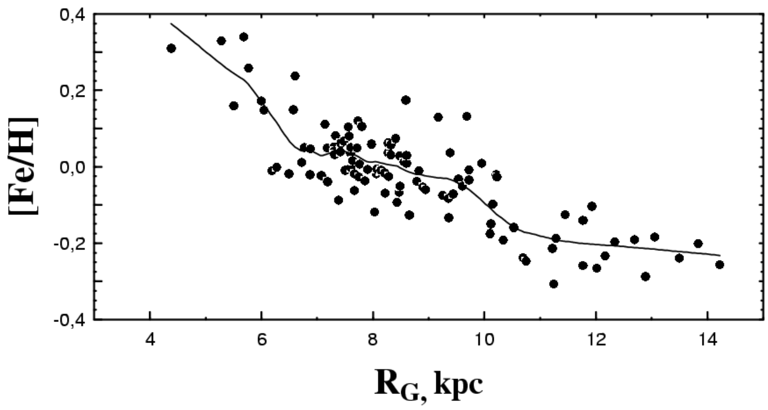

Figure 3: Abundance gradient in the Galaxy.

$$\delta(X) = 1 - 10^{D(X)} \tag{3}$$

In practice, we can determine D(X) by comparing 2 elements with fundamentally similar absolute abundances, but different depletion properties, e.g. Zn and Cr.

$$\delta(X) = 1 - 10^{[Cr/Zn]} \tag{4}$$

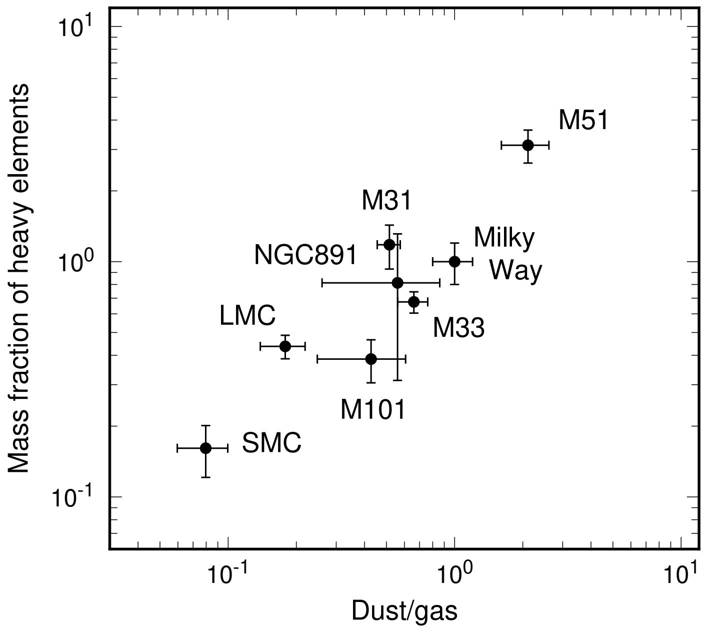

Figure 4: As the metallicity of a galaxy increases, so does its dust fraction (data from Issa et al 1990 and Alton et al 2000).

E.g. if [Cr/Zn] $= -1.0$ (10 times less Cr than Zn relative to solar) $\delta(X) = 0.9$ i.e 90% of metals are in dust AKA the dust:metals ratio. Observed depletions correlate with condensation temperature (T_C is temperature at which 50% of atoms condense into solid phase), expected if grains form around cool stars. Some 60% of the ISM is in dust, but depends on environment, both density and velocity.

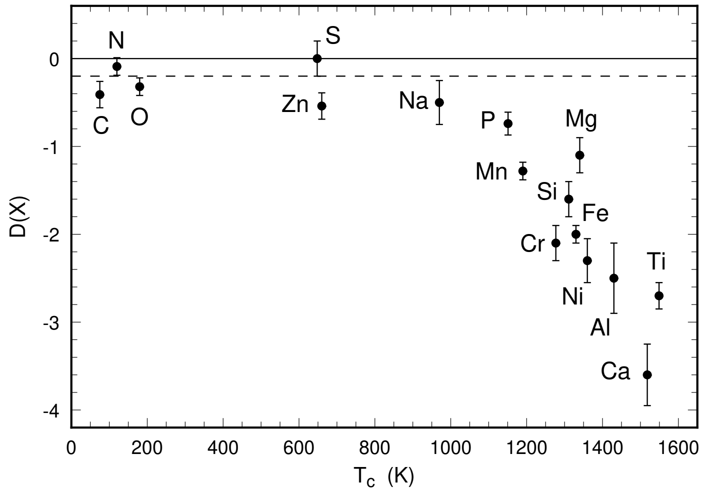

Figure 5: Depletion fraction as a function of concensation temperature.

$$D(X) = D_0(X) + mlog(n/n_0) \tag{5}$$

$D_0(X)$ is the depletion at some reference density n_0, and m is just the slope of the relation. Depletion also depends on cloud velocity. Higher velocity clouds have lower depletions because they have been accelerated by shocks - the Routley-Spitzer effect.

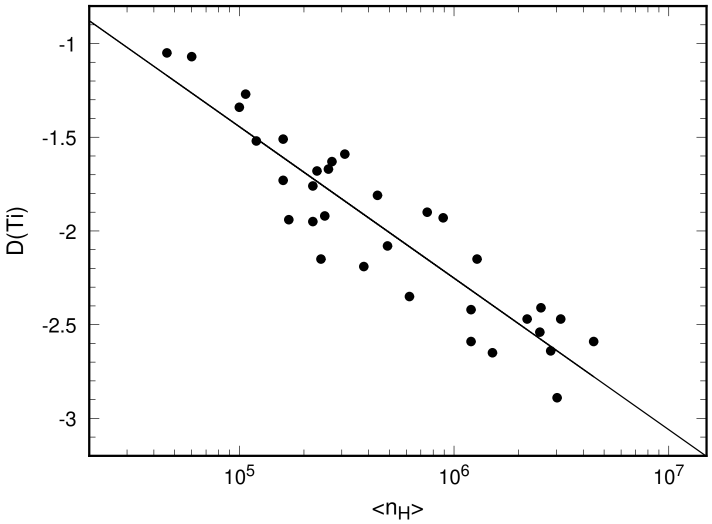

Figure 6: Depletion increases at higher densities.

3 Extinction

Dust can form by direct condensation when T is low enough e.g.

- Winds around cool giant stars (GB or AGB)
- Massive stars under-going mass-loss e.g. η Carina
- Nova envelopes
- SN ejecta

3.1 Theory

Extinction has contributions from scattering and absorption. Scattering is most efficient when particle size is same order as wavelength. Intensity of light, $I(\lambda)$ at distance r from particle depends on angular scattering function, $f(\theta, \phi)$ (θ is angle from incident radiation, ϕ is azimuthal angle)

$$I(\lambda) = I_0(\lambda)e^{-\tau} = I_0(\lambda)\frac{f(\theta,\phi)}{4\pi}\frac{\lambda^2}{\pi r^2} \tag{6}$$

Scattering cross section is integral of $f(\theta, \phi)$ over all solid angles

$$C_{sca} = \frac{\lambda^2}{4\pi^2}\int f(\theta,\phi)d\Omega \tag{7}$$

The scattering efficiency is the ratio between scattering and geometric cross sections of dust grain with radius a

$$Q_{sca} = \frac{C_{sca}}{\pi a^2} \tag{8}$$

In a similar way we can define the extinction efficiency as

$$Q_{ext} = Q_{abs} + Q_{sca} \tag{9}$$

$$\tau = N_d C_{ext} = Q_{ext} N_d \pi a^2 \qquad \text{analagous to} \quad \tau = \sigma N \quad \text{in absorption} \tag{10}$$

where C_{ext} is the extinction cross section and N_d is the column density of dust grains. Expressing the loss of flux as a magnitude

$$A_\lambda = -2.5log(I/I_0) = 1.086 N_d \pi a^2 Q_{ext} = 1.086 N_d C_{ext} = 1.086\tau \tag{11}$$

For a range of sizes with n(a)da grains per unit volume

$$A_\lambda = 1.086\pi \int a^2 Q_{ext}(a) n(a) da \tag{12}$$

For a given grain model we therefore need to know Q_{ext} which has components from absorption and scattering, $Q_{ext} = Q_{abs} + Q_{sca}$. Scattering efficiencies are calculated through Mie theory. When $a << \lambda$ a useful approximation is

$$Q_{sca} \simeq \frac{8}{3}(\frac{2\pi a}{\lambda})^4 \mid \frac{m^2-1}{m^2+2} \mid^2 \tag{13}$$

$$Q_{abs} \simeq \frac{8\pi a}{\lambda} Im(\frac{m^2-1}{m^2+2}) \tag{14}$$

$$m = n - ik \quad \text{the complex refractive index} \tag{15}$$

For pure dielectrics (poor conductors but efficient supporters of electrostatic fields) $k = 0$; ices and silicates behave this way. In this case there is zero absorption and efficiency reduces to Raylaigh scattering: $Q_{sca} \propto \lambda^{-4}$ and $Q_{abs} = 0$. More generally $(m^2-1)/(m^2+2)$ is only weakly dependent on wavelength and $Q_{abs} \propto \lambda^{-1}$ is a good approximation. Absorption will therefore dominate over scattering at longer wavelengths.

3.2 Practice

How to determine extinction in a particular direction? Use pairs of stars of identical spectral type but different reddening.

$$m_{1,2}(\lambda) = M_{1,2}(\lambda) + 5logd_{1,2} + A_{1,2}(\lambda) \tag{16}$$

Where subscripts 1 and 2 denote reddened and comparison stars. Assuming $M_1(\lambda) = M_2(\lambda)$ and $A_\lambda = A_1(\lambda) >> A_2(\lambda)$

$$\Delta m(\lambda) = 5log(d_1/d_2) + A_\lambda \tag{17}$$

In order to get rid of constant term, often use normalized extinction

$$E_{norm} = \frac{\Delta m(\lambda) - \Delta m(\lambda_2)}{\Delta m(\lambda_1) - \Delta m(\lambda_2)} = \frac{A(\lambda) - A(\lambda_2)}{A(\lambda_1) - A(\lambda_2)} = \frac{E(\lambda - \lambda_2)}{E(\lambda 1 - \lambda_2)} \tag{18}$$

$E(\lambda_1 - \lambda_2)$ is the colour excess, or selective extinction. Often normalise extinction curves relative to $E(B-V)$. NED offers dial-up Galactic extinctions based on maps of Schlegel, Finkbeiner & Davis (1998) so that spectra can be corrected for Galactic extinction. Also define a total-to-selective extinction

$$R_V = \frac{A_V}{E(B-V)} \tag{19}$$

and the absolute extinction

$$\xi(\lambda) = \frac{A_\lambda}{A_V} \tag{20}$$

Sometimes this is written $\xi(\lambda) = \frac{A_\lambda}{A_B}$, so be careful! $\xi_V = 1.33\xi_B$. These quantities are also related by

$$\frac{E(\lambda - V)}{E(B-V)} = R_V(\xi(\lambda) - 1) \tag{21}$$

Often, the absolute extinction, $\xi(\lambda)$, is deduced by measuring a normalized extinction and assuming a value of R_v. This number tends to be low in low density environments where dust grains are smaller. $R_v \simeq 3.1$ in MW.

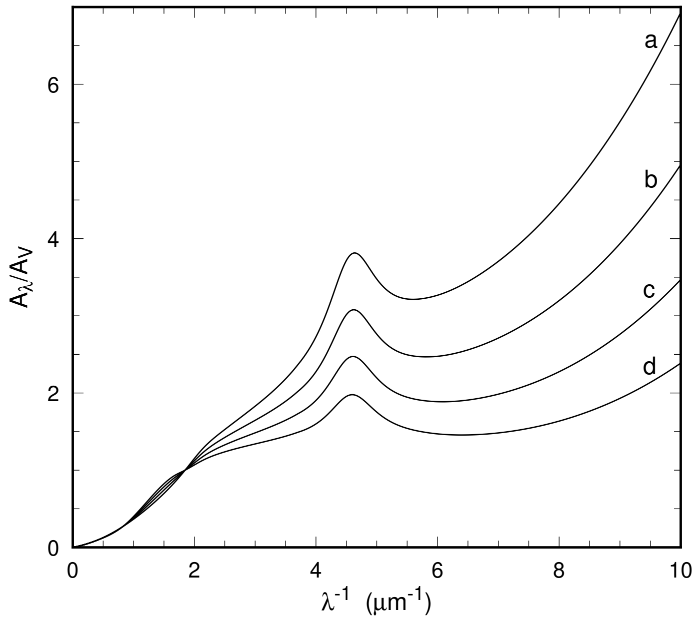

Figure 7: Theoretical extinction curves with R_V=2.5, 3.1, 4.0, 5.5 (top to bottom).

Various parameterizations of the Galactic extinction law exist. Two useful references are Pei, 1992, ApJ, 395, 130 and Cardelli, Clayton & Mathis, 1989, ApJ, 345, 245. Needs combination of several laws (at least 7 parameters) usually with Drude profile for 2175 Å feature. Between $0.9 < \lambda < 5.0\mu$m the extinction curve approximates to a power law

$$A(\lambda) \propto \lambda^{-1.7} \tag{22}$$

The 3 best studied extinction curves are for the MW, SMC and LMC. The most prominent feature is at 2175 Å, thought to be associated with graphite grains. Weak in LMC (but stronger in star forming regions) and usually absent in SMC. Often considered a 'diffuse interstellar band' (DIB), see lecture by G. Walker.

If the metallicity of a 'cloud' is lower, we expect the ratio of dust to gas to be lower. There is therefore an intrinsic relation between the amount of neutral gas and extinction . Can therefore determine A_λ as a function of a column density.

MW: N(HI) $\sim 5.9 \times 10^{21} \times E(B-V)$
LMC: N(HI) $\sim 2.4 \times 10^{22} \times E(B-V)$
SMC: N(HI) $\sim 0.5 - 4.4 \times 10^{22} \times E(B-V)$

Interesting that the dust to metals ratio appears approximately constant; $Z_{MW} : Z_{LMC} : Z_{SMC} \sim 1 : 1/3 : 1/8$.

Often want to correct spectra of external galaxies for their intrinsic extinction.

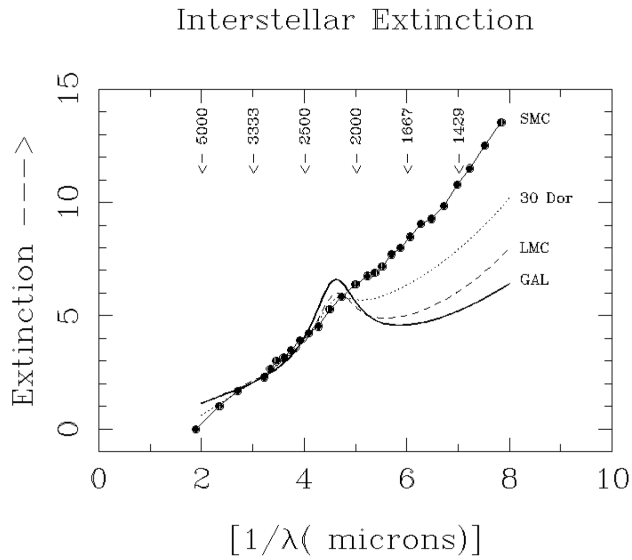

Figure 8: $\frac{E(\lambda-V)}{E(B-V)}$ as a function of inverse wavelength.

$$A_\lambda = -2.5log(F_i/F_o) \longrightarrow F_i/F_o = 10^{0.4A_\lambda} \tag{23}$$

Define

$$k(\lambda) = \xi(\lambda)R_V \longrightarrow E(B-V) = \frac{A_\lambda}{k(\lambda)} \tag{24}$$

Taking the ratio of intrinsic and observed fluxes for Hα and Hβ and compare to theoretical (case B) value ($F_i(H\alpha)/F_i(H\beta) = 2.85$) gives $E(B-V)$:

$$\frac{F_i(H\alpha)/F_o(H\alpha)}{F_i(H\beta)/F_o(H\beta)} = \frac{10^{0.4k(H\alpha)E(B-V)}}{10^{0.4k(H\beta)E(B-V)}} \tag{25}$$

$$E(B-V) = \frac{log(\frac{2.85}{F_o(H\alpha)/F_o(H\beta)})}{0.4[k(H\alpha) - k(H\beta)]} \tag{26}$$

Values of k(λ) given by extinction curve. E.g. using CCM89 with R_V=3.1, k(Hβ) = 3.609 and k(Hα) = 2.535. Correct the observed fluxes using

$$F_i = F_o \times 10^{0.4k(\lambda)E(B-V)} \tag{27}$$