ISM. VII: Dust and the Two-Phase Model

A. ISM Abundances: Oxygen

- Most abundant metal
- Solar abundances (aside)
  - Mainly derived from meteoritic abundances
  - e.g. Anders & Grevesse
  - Table (logarithmic scale $\epsilon_X$ with H=12)

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- Observing Oxygen in the ISM
  - OI\(\lambda 1355\)
  - Semi-forbidden line with $f_{1355} = 1.25 \times 10^{-6}$
  - Why such an ‘unusual’ transition?
    - Consider OI\(\lambda 1302\) with $f_{1302} = 0.049$
    - Approximate column density

\[
\log N_O = \log N_H - 12 + \epsilon_O \quad (1)
\]
\[
\approx 21 - 12 + 8.74 \quad (2)
\]
\[
= 17.7 \quad (3)
\]
\[ \tau_0 = \frac{1.497 \times 10^{-2}}{b} N_j \lambda f_{jk} \]

\[ \approx 9745 \]  

\[ \tau_{1355} \approx 0.2 \]

- Meyer et al. (1998): GHRS observations of Oxygen
  - High resolution
  - High SNR
  - Fig

![HST GHRS spectra of the interstellar O i λ1355.598 absorption line toward γ Cas, δ Ori, ε Per, τ CMa, and γ Ara at a velocity resolution of 3.5 km s\(^{-1}\) and toward λ Ori and ζ Per at a resolution of 16 km s\(^{-1}\). The spectra are displayed from top to bottom in order of increasing total hydrogen column density in the observed sight lines. The mea-]
Ol

Table

<table>
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<tr>
<th>Star</th>
<th>N(H) / (cm^-2)</th>
<th>log n_H / (cm^-3)</th>
<th>log f(H_2) / (cm^-2)</th>
<th>W(1356) / (mÅ)</th>
<th>N(O_II) / (cm^-2)</th>
<th>10^6 O/H / (cm^-2)</th>
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<td>1.5 (0.2) × 10^{10}</td>
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- N(H) = 2N(H_2) + N(H_i) is the total hydrogen column density (±1 σ) in the observed sight lines. These values reflect the H_2 column densities measured by Savage et al. 1977 and the weighted means of the Bohlin, Savage, & Drake 1978 and Diplas & Savage 1994 N(H_i) data.
- f(H_2) = 2N(H_2)/N(H) is the fractional abundance of hydrogen nuclei in H_2 in the observed sight lines.
- Measured equivalent widths (±1 σ) of the O i 1355.598 Å absorption line.
- Derived O i column densities (±1 σ) in the observed sight lines. The ζ Per and ζ Oph values are taken from the analyses of Cardelli et al. 1991 and Savage, Cardelli, & Soffia 1992. The ζ Per, ζ Ori, and γ Ara values are corrected for a slight amount of saturation using respective Gaussian b-values (±1 σ) of 2.0 × 10^{-2}, 5.0 × 10^{-2}, and 3.0 × 10^{-2} km s^{-1}. The other sight lines are assumed to be optically thin in the O i 1356 transition.
- Abundance of interstellar gas-phase oxygen (±1 σ) per 10^6 H atoms in the observed sight lines. The uncertainties reflect the propagated N(H) and N(O_i) errors.

- N(H) is evaluated from 21cm emission and H_2 data
- < n(H) >= N_H / d with d measured from parallax
- Results

- Oxygen is uniformly distributed throughout the ISM
  - i.e. the ISM is well mixed
  - Presumably, the same is true for all elements
Complete Ionization Potentials for the First 10 Elements (eV)

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First 5 Ionization Potentials (eV) only, for other "A" group elements

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Fuel for future star formation
- Modest offset between the ISM and the Sun
- Error in the Solar determination? (it has dropped by 2 × in the past decade)
- Dust depletion?

B. ISM Abundances: Other metals
- Dominant ions in an HI region
  - Consider the radiation field
    ▶ Very high opacity to radiation with \( h\nu > 1\text{Ryd} \)
    ▶ Optically thin to radiation with \( h\nu < 1\text{Ryd} \)
- Ionization potential
  ▶ \( \text{IP(HI)} = 13.6 \text{eV} \)
  ▶ Majority of abundant elements have \( \text{IP} < 1\text{Ryd} \) for the first ionization state
  ▶ Majority of abundant elements have \( \text{IP} > 1\text{Ryd} \) for the second ionization state
  ▶ OI, NI, ArI are obvious exceptions
  ▶ Table

Low-ion: Dominant species of an element in an HI region
- e.g. FeII, CII, SII, HI, OI
- High-ions: SiIV, CIV
- Observations
  - Majority of resonance lines have \( \lambda < 3000\text{Å} \)
UV spectroscopy is required ⇒ Space observatory
HST: FOS, GHRS, STIS (COS?)

- Example: μCol (Howk et al. 1999)

Absorption lines are significantly offset from the stellar velocity → ISM

Analysis
- Apparent optical depth method
A Line profile fitting

• Column densities

A Table

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<th>Comp 2 (20 km s$^{-1}$)</th>
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<td>Ti ii</td>
<td>11.94 ± 0.008</td>
<td>11.94 ± 0.008</td>
<td>11.94 ± 0.008</td>
<td>11.94 ± 0.008</td>
<td>11.94 ± 0.008</td>
</tr>
<tr>
<td>Cr ii</td>
<td>12.62 ± 0.005</td>
<td>12.62 ± 0.005</td>
<td>12.62 ± 0.005</td>
<td>12.62 ± 0.005</td>
<td>12.62 ± 0.005</td>
</tr>
<tr>
<td>Mn i</td>
<td>12.55 ± 0.002</td>
<td>12.55 ± 0.002</td>
<td>12.55 ± 0.002</td>
<td>12.55 ± 0.002</td>
<td>12.55 ± 0.002</td>
</tr>
<tr>
<td>Fe i</td>
<td>14.33 ± 0.004</td>
<td>14.33 ± 0.004</td>
<td>14.33 ± 0.004</td>
<td>14.33 ± 0.004</td>
<td>14.33 ± 0.004</td>
</tr>
<tr>
<td>Fe ii</td>
<td>13.97 ± 0.007</td>
<td>13.97 ± 0.007</td>
<td>13.97 ± 0.007</td>
<td>13.97 ± 0.007</td>
<td>13.97 ± 0.007</td>
</tr>
<tr>
<td>Ni ii</td>
<td>14.33 ± 0.004</td>
<td>14.33 ± 0.004</td>
<td>14.33 ± 0.004</td>
<td>14.33 ± 0.004</td>
<td>14.33 ± 0.004</td>
</tr>
<tr>
<td>Cu ii</td>
<td>&lt;11.5</td>
<td>12.55 ± 0.008</td>
<td>11.16 ± 0.008</td>
<td>11.16 ± 0.008</td>
<td>11.16 ± 0.008</td>
</tr>
</tbody>
</table>

* Total sightline column densities derived from integrations of $N(v)$ profiles; unless otherwise noted.
+ Adopted column densities for the components considered here with ± 1σ errors, given in atoms cm$^{-2}$
+ Column densities for components 2-5 are derived from our component fitting analysis. Values for component 1 were derived through integrations of $N(v)$ profiles, unless otherwise noted.
+ Derived using the continuum reconstruction method (see Appendix A).
+ A 2σ upper limit derived from the 1351.6 Å line.
+ Based on the Mg i 1250 Å line.
+ Based on the Na i 589 Å line.
+ The Ca ii data given here are from the profile-fitting results of Smith, York, & Witt (1977) (see their Table 1).
+ The Ti ii data given here are from the profile-fitting results of Walsh et al. 1997 (see their Table 3).
+ They have estimated the errors in the column density values to be ±10%–20%. The errors we have adopted in this table are slightly higher than this estimate.
+ We have excluded the Fe i 2344 Å line and those lines with $\lambda$ < 0.9 Å in deriving this value because of possible oscillator strength uncertainties.
+ The adopted column density given is derived from our component fitting measurements (see text).

• Relative abundances
Define: \[ [X/H] = \log \frac{N(X)}{N(H)} - (\epsilon_X - 12) \]

Tab

<table>
<thead>
<tr>
<th>Element</th>
<th>( [X/H]^a )</th>
<th>Comp 1 ( (3 \text{ km s}^{-1}) )</th>
<th>Comp 2 ( (20 \text{ km s}^{-1}) )</th>
<th>Comp 3 ( (35 \text{ km s}^{-1}) )</th>
<th>Comp 4 ( (41 \text{ km s}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>8.56</td>
<td>8.50 ± 0.04</td>
<td>8.55 ± 0.03</td>
<td>8.57 ± 0.03</td>
<td>8.59 ± 0.03</td>
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<tr>
<td>N</td>
<td>7.97</td>
<td>7.99 ± 0.04</td>
<td>7.98 ± 0.03</td>
<td>7.99 ± 0.03</td>
<td>7.98 ± 0.03</td>
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<td>O</td>
<td>8.07</td>
<td>8.07 ± 0.04</td>
<td>8.05 ± 0.03</td>
<td>8.05 ± 0.03</td>
<td>8.05 ± 0.03</td>
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<tr>
<td>Mg</td>
<td>7.56</td>
<td>7.52 ± 0.04</td>
<td>7.54 ± 0.03</td>
<td>7.54 ± 0.03</td>
<td>7.54 ± 0.03</td>
</tr>
<tr>
<td>Al</td>
<td>6.56</td>
<td>6.59 ± 0.04</td>
<td>6.58 ± 0.03</td>
<td>6.58 ± 0.03</td>
<td>6.58 ± 0.03</td>
</tr>
<tr>
<td>Si</td>
<td>7.54</td>
<td>7.57 ± 0.04</td>
<td>7.55 ± 0.03</td>
<td>7.56 ± 0.03</td>
<td>7.56 ± 0.03</td>
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<tr>
<td>P</td>
<td>5.87</td>
<td>5.87 ± 0.04</td>
<td>5.87 ± 0.03</td>
<td>5.87 ± 0.03</td>
<td>5.87 ± 0.03</td>
</tr>
<tr>
<td>S</td>
<td>7.27</td>
<td>7.27 ± 0.04</td>
<td>7.26 ± 0.03</td>
<td>7.26 ± 0.03</td>
<td>7.26 ± 0.03</td>
</tr>
<tr>
<td>Ti</td>
<td>4.99</td>
<td>4.99 ± 0.04</td>
<td>4.98 ± 0.03</td>
<td>4.98 ± 0.03</td>
<td>4.98 ± 0.03</td>
</tr>
<tr>
<td>Cr</td>
<td>5.68</td>
<td>5.69 ± 0.04</td>
<td>5.68 ± 0.03</td>
<td>5.68 ± 0.03</td>
<td>5.68 ± 0.03</td>
</tr>
<tr>
<td>Mn</td>
<td>5.53</td>
<td>5.53 ± 0.04</td>
<td>5.53 ± 0.03</td>
<td>5.53 ± 0.03</td>
<td>5.53 ± 0.03</td>
</tr>
<tr>
<td>Fe</td>
<td>7.17</td>
<td>7.19 ± 0.04</td>
<td>7.18 ± 0.03</td>
<td>7.18 ± 0.03</td>
<td>7.18 ± 0.03</td>
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<tr>
<td>Ni</td>
<td>6.28</td>
<td>6.30 ± 0.04</td>
<td>6.29 ± 0.03</td>
<td>6.29 ± 0.03</td>
<td>6.29 ± 0.03</td>
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<tr>
<td>Zn</td>
<td>4.65</td>
<td>4.67 ± 0.04</td>
<td>4.67 ± 0.03</td>
<td>4.67 ± 0.03</td>
<td>4.67 ± 0.03</td>
</tr>
</tbody>
</table>

\( a \) The logarithmic "solar" abundances of the elements, \( [X/H]_{\odot} \), are used in deriving the normalized gas phase abundances. We have adopted the solar system meteoritic abundance from Anders & Grevesse 1993 except for C, N, and O, which are photospheric values from Grevesse & Noels 1993.

\( b \) We present the sightline integrated values of \( [X/H] \) in this column. Thus \( [X/H] = \log \frac{N(X)}{N(H)} - \log \frac{N(H)}{N_{\odot}} \).

\( c \) Here we have used the value of \( N_{\odot} = 13.68 \pm 0.05 \) (see Appendix in Savage 1993). This treatment has neglected contributions from He. However, our photosynthesis model (see i) implies the corrections are relatively small (\( -0.04 \) to \( -0.05 \) due to the counted values).

\( d \) For the components 1 and 2 we have referenced the gas phase abundances to solar by comparing the column densities to that of silicon. Thus \( [X/H] = \log \frac{N(X)/N_{\odot}}{N(Si)/N_{\odot}} \).

\( e \) For components 3 and 4 we have referenced the gas phase abundances to solar by comparing the column densities to that of silicon. Thus \( [X/H] = \log \frac{N(X)/N_{\odot}}{N(Si)/N_{\odot}} \).

Fig

S/H, Zn/H, P/H have roughly solar values
Why are Fe, Ni, Si, and Mn sub-solar?
Does the ISM have a different nucleosynthetic pattern than the Sun?

C. Dust Depletion

- In the Galactic ISM, the majority of Fe, Si, Ni, Cr, and Ti are ‘locked up’ in dust grains
  - We observe gas-phase abundances
Therefore, $[\text{Fe}/\text{H}]_{\text{gas}} < 0$

Consider a cloud with $[\text{Fe}/\text{H}]_{\text{gas}} = -1$

\[ f_{\text{gas}} = \frac{M_{\text{gas}}}{M_{\text{tot}}} = 10^{[\text{Fe}/\text{H}]_{s}} = 0.1 \]  \hfill (7)

- How do we know it is dust?
  - Reddening is observed
  - Obscuration is observed

- Condensation Temperature
  - G. Field: Observed winds for Red Giants
    - Observed Silicate absorption features
    - Concluded → Material contains dust grains
    - Grain forms as winds push gas off the Red Giant
    - This is the dominant mechanism for forming dust cores
  - $T_C$: Temperature at which 50% of the gas condenses into the solid phase
  - Expect smaller $f_{\text{gas}}$ for higher $T_C$ because it will have had a longer time to form dust
  - Plot $[X/\text{H}]$ vs. $T_C$

- Strong evidence that the observed gas-phase pattern of the ISM is due to dust, not nucleosynthesis
• Depletion/density relation
  ◦ Jenkins (1986, 2003): Noted a correlation between $n_H$ and depletion
  ◦ Measure $n_H$
    ▲ Observe 21cm emission
    ▲ Determine the distance to the star
    ▲ $< n_H > = \frac{N_{HI}}{d}$ (ignoring $H_2$)
  ◦ Examine the correlations

Figure 1: Observed element depletions as a function of the generalized line-of-sight depletion multiplier $F_*$
declined in [5]. In each case, the dashed line represents the best linear fit to Eq. 1 which ultimately defined
the constants $A_X$ (slopes) and $A_{0X}$ (intercepts) listed by Jenkins (2003). Cases excluded in the best-fit

◊ $F_* \propto n_H$, the volume density
◊ Correlation indicates the environment (volume density) also influences grain formation
  ▲ Dense clouds ⇒ More two body interactions
  ▲ Less dense clouds ⇒ More susceptible to SN shocks which destroys grains
  ▲ Environment affects the dust ‘mantle’ as append to the core
D. Dust Properties

- General
  - Dust scatters and absorbs light in the ISM
  - Remits light at much longer wavelengths (IR)

- Extinction
  - Ignore remission by dust
  - Radiative transfer
    \[ I_{\nu} = I_{\nu}(0)e^{-\tau_{\nu}} \]  
    (8)
  - Define extinction (in magnitudes)
    \[ A_{\lambda} = 1.086\tau_{\lambda} = 1.086N_{d}Q_{e}(\lambda)\sigma_{d} \]  
    (9)
    ▲ \( N_{d} \) = Column density of dust
    ▲ \( \sigma_{d} \) = Mean physical grain cross-section
    ▲ \( Q_{e} \) = Efficiency coefficient for extinction
  - In this case
    \[ A_{\lambda} = -2.5\log\frac{F_{\nu}}{F_{\nu}(0)} \]  
    (10)
    \[ m_{\lambda} - M_{\lambda} = -5 + 5\log d_{pc} + A_{\lambda} \]  
    (11)
  - Extinction efficiency factor
    \[ Q_{e} \equiv \frac{s_{\nu}}{\sigma_{d}} \]  
    (12)
    ▲ \( s_{\nu} \) = The optical cross-section

- Mie theory
  - See Bohrem & Huffman (1983)
  - Consider a spherical dust grain with radius \( a \) and an incident wave with wavelength \( \lambda \)
  - Fig
Wave will be scattered and diffracted

Define \( x \equiv \frac{2\pi a}{\lambda} \)

Index of refraction

\[ m = n - ik \quad (13) \]

Imaginary part is for absorption

For small \( x \) \((a \gg \lambda)\)

\[
Q_a = \frac{\sigma_{abs}(x)}{\pi a^2} = -4xIm\left(\frac{m^2 - 1}{m^2 + 2}\right) \quad (14)
\]

\[
Q_s = \frac{\sigma_{scatt}(x)}{\pi a^2} = \frac{8}{3}x^4\text{Real}\left[\frac{m^2 - 1}{m^2 + 2}\right] \quad (15)
\]

\[
Q_e = Q_a + Q_s \quad (16)
\]

Wavelength dependence

\[ \Delta Q_a \propto \lambda^{-1} \] which is as observed

\[ \Delta Q_s \propto \lambda^{-4}, \text{i.e. the Rayleigh scattering expression} \]

Fig (Spitzer 7.1)

---

Note: \( Q_e \rightarrow 2 \) as \( x \rightarrow \infty \)

\[ \Delta \text{The particle absorbs an area } \pi a^2 \]

\[ \Delta \text{The particle diffracts an equal amount!} \]

Integral over \( Q_e \): Kramers-Kronig

\[
\int_0^\infty Q_e d\lambda = 4\pi a^2 \left(\frac{\epsilon_0 - 1}{\epsilon_0 + 2}\right) \equiv 4\pi a^2 F_K \quad (17)
\]

\[ \Delta \epsilon_0 \text{ is the dielectric constant of the grain in the low frequency limit } \epsilon_0 = m^2 \]

\[ \Delta F_K \text{ is as defined} \]
• Grain temperature

  ◦ Heating
    ▲ Absorption of starlight (dominant)
    ▲ Collisions with gas particles
    ▲ Exothermic chemical reactions on the grain surface

  \[
  H_{\text{rad}} = \int Q_a(\lambda) \frac{1}{4} u_{\lambda} c 4\pi a^2 d\lambda
  \]  

  (18)

  ◦ Cooling
    ▲ Emission of IR radiation
    ▲ In thermal equilibrium

  \[
  \kappa_{\lambda} = \frac{\lambda^2}{2\pi^2} \frac{\lambda^2}{2\pi^2} \frac{\lambda^2}{2\pi^2} = j_{\lambda}
  \]  

  (19)

  \[
  n_d Q_a \pi a^2 B_{\lambda} = n_d \frac{\varepsilon_{\lambda}}{4\pi}
  \]  

  (20)

  \[
  \varepsilon_{\lambda} = Q_a \pi a^2 \cdot \pi B_{\lambda}
  \]  

  (21)

  ▲ Radiative losses

  \[
  L_{\text{rad}} = \int Q_a(\lambda) \pi B_{\lambda}(T_d) 4\pi a^2 d\lambda
  \]  

  (22)

  ◦ Evaluate the temperature

  \[
  \pi a^2 c \int Q_a(\lambda) u_{\lambda} d\lambda = 4\pi a^2 \int Q_a(\lambda) \pi B_{\lambda}(T_d) d\lambda
  \]  

  (23)

  ▲ Let \( u_{\lambda} = \) optical and near-UV energy density \((\approx 7 \times 10^{-13} \text{ erg/cm}^{-3})\)

  ▲ Assume (first), that \( Q_a(\lambda) \approx 1 \)

  ▲ Blackbody

  \[
  B = \int B_{\lambda} d\lambda = \frac{\sigma T_d^4}{\pi}
  \]  

  (24)

  ▲ Reduce..

  \[
  cu = \pi B(T_d)
  \]  

  (25)

  \[
  T_d = \left( \frac{cu}{4\sigma} \right)^{1/4} = 3.1 \text{ K}
  \]  

  (26)

  ▲ But, the IR excess from the Galactic plane implies \( T_d = 20 \text{ K} !! \)

  ◦ Recall that Mie theory indicates \( Q_a \propto \lambda^{-1} \)

  ▲ Therefore \( Q_a(\text{UV}) > Q_a(\text{IR}) \)

  ▲ Approximate the ISM diffuse starlight as a dilute blackbody with \( T_R = 10^4 \text{ K} \)

  ▲ Express

  \[
  u_{\nu} = \frac{\nu^3}{e^{\hbar \nu/kT_R} - 1}
  \]  

  (27)
Our equilibrium equation becomes

\[ u_0 \int_0^\infty \frac{\nu^3 Q_\alpha(\nu)}{e^{h\nu/kT} - 1} d\nu = \int_0^\infty \frac{\nu^3 Q_\alpha(\nu)}{e^{h\nu/kT_d} - 1} d\nu \quad (28) \]

Let \( x \equiv h\nu/kT \)

Evaluate

\[ u_0 T_R^5 I_4 = T_d^5 I_4 \quad (29) \]

\[ I_4 = \int_0^\infty \frac{xdx}{e^x - 1} \quad (30) \]

Therefore

\[ T_d = \tilde{u}^{1/5} T_R \quad (31) \]

\( \tilde{u} \) is related to the geometric dilution of starlight

\( \tilde{u} \approx 10^{-14} \)

Therefore, \( T_d \approx 16K \)

Grains are also somewhat hotter than this because they are less efficient at emitting at UV and optical wavelengths

E. Interstellar Dust: Observations

- First evidence for dust:
  Robert Trumpler (1930), Lick Obs. Bull. 14, 154
  - Trumpler examined open clusters in the Galactic plane
  - Chose a subset with similar richness and assumed they had similar physical origin
  - Observed
    ▲ Apparent magnitude \( m \) of B and A stars
    ▲ Angular size \( \theta \) of the cluster
  - Determined
    ▲ Distance by adopting the absolute magnitude \( M \) for these stars according to their spectral type
      \[ 5 \log d'_{pc} = m - M + 5 \quad (32) \]
    ▲ Physical size
      \[ \delta' = \theta d' \quad (33) \]
  - Plotted the two quantities
Observed a rising $\delta'$ with increasing $d'$.

But the assumptions was that all of these clusters had the same $\delta'$!

Introduced dust:

$$5 \log d = m + M + 5 - ad$$  \hspace{1cm} (34)

- $a$ is an extinction (photographic magnitudes/kpc)
- Trumpler adjusted $a$ until $\delta'$ was constant
- Determined $a = 0.8$ photomag/kpc  \hspace{1cm} (35)

- Other evidence for dust:
  (a) dark clouds with a relative absence of stars
  (b) reflection nebula (Rayleigh scattering)
  (c) reddening of starlight and extinction
  (d) polarization of starlight by aligned, non-spherical dust grains
  (e) IR continuum emission
  (f) diffuse galactic light – scattered from stars
  (g) depletion of Fe, Si, Ca, etc. from the gas phase
  (h) existence of large masses of $H_2$ – formed on grains
(i) X-ray halos around point sources behind dust

- Differential extinction
  - Observe two stars with identical spectral type

\[
\Delta m(\lambda) \equiv m_2(\lambda) - m_1(\lambda) = 5 \log d_2 - 5 \log d_1 + M_2 - M_1 + A_2(\lambda) - A_1(\lambda)
\]  

\[
\Delta (A(\lambda_a) - A(\lambda_b)) = \Delta E(\lambda_a - \lambda_b)
\]

**OB stars are best as they vary less with T**

- Also, they are very bright
- Observe the stars at two wavelengths

\[
\Delta m(\lambda_a) - \Delta m(\lambda_b) = [A_2(\lambda_a) - A_1(\lambda_a)] - [A_2(\lambda_b) - A_1(\lambda_b)]
\]

\[
= \Delta (A(\lambda_a) - A(\lambda_b))
\]

\[
\equiv E(\lambda_a - \lambda_b)
\]

**E(\lambda_a - \lambda_b) is referred to as the color excess**

- Generally, one defines the color excess in the B and V bands

\[
E_{B-V} = A(\lambda_B) - A(\lambda_V) = A_B - A_V
\]

\[
\lambda_B \approx 4350\,\text{Å} \\
\lambda_V \approx 5550\,\text{Å}
\]

- Extinction curves
  - Define the selective extinction by normalizing relative to \(E_{B-V}\)

\[
e(\lambda) = \frac{E_{\lambda-V}}{E_{B-V}} = \frac{A_\lambda - A_V}{A_B - A_V}
\]

- Define the ratio of total to selective extinction

\[
R_V \equiv \frac{A_V}{E_{B-V}}
\]

**\(R_V \approx 3.1 - 3.3\) in the Milky Way**

**\(R_V = 3.1\) is generally assumed but not well measured**

**Larger \(R_V\) implies larger dust grains**

- Milky Way extinction curve
  - Empirically measured
  - Fitted by Cardelli et al. (1989)
  - Fig (assumes \(R_V = 3.1\))
Other extinction curves
- Empirically measured for LMC, SMC
- Synthesis curve for starbursts (Calzetti)
• Dust density
  ◦ Recall
  \[ A_V = 1.086 \tau_V = 1.086 n_d \ell Q_e(V) \pi a_d^2 \]  (46)
  ◦ Adopt \( A_V = 2, \ell = 1, Q_e = 2 \)
  \[ n_d \approx 1.0 \times 10^{-12} \left( \frac{a_d}{10^{-5}\text{cm}} \right)^2 \text{cm}^{-3} \]  (47)
  ◦ Mass density
  \[ m_d n_d = \frac{4}{3} \pi a_d^3 \rho_d n_d = 4.3 \times 10^{-27} \rho_d \left( \frac{a_d}{10^{-5}\text{cm}} \right) \text{g/cm}^3 \]  (48)

▲ For ice grains
  \[ \rho_D \sim 1 \text{g/cm}^3 \]  (49)
  \[ a_D \sim 0.3\mu \]  (50)

▲ Therefore
  \[ m_d n_d = 10^{-26} \text{g/cm}^3 \]  (51)

▲ Comparing against the gas density (\( \bar{n} \sim 1 \text{cm}^{-3} \))
  \[ \frac{\rho_d}{\rho_g} = \frac{10^{-26}\text{g/cm}^3}{(1\text{cm}^{-3})2 \times 10^{-24}\text{g}} \approx 10^{-2} \]  (52)

▲ Compare this against the value you get by assuming 100% of the Fe, Si, and Mg is in dust and also 2/3 of the C

• Some useful relations (Milky Way)
  \[ A_V = 2\text{mag/kpc} \quad (R_V = 3.1) \]  (53)
  \[ E_{B-V} = 0.61\text{mag/kpc} \]  (54)
  \[ N_H = 5.9 \times 10^{21} E_{B-V} = 2 \times 10^{21} A_V \quad \text{cm}^{-2} \]  (55)