Cosmic dust grains are solid particles similar to soot or smoke particles, and represent agglomerations that are more appropriately thought of as macroscopic solids than as molecules. The existence of dust was first inferred from its attenuation of visible light from background light sources, via absorption and scattering of photons. This dimming of light is referred to as “extinction” and is commonly quantified in astronomical magnitudes with the symbol $A$ and a subscript representing the wavelength or bandpass; the most common fiducial value is $A_V$ where $V$ represents the visible bandpass centered at 5500 Å.

Astronomical magnitudes are a logarithmic system for describing the relative fluxes for sources of different measured brightness. In the most general case, the magnitudes $m_1$ and $m_2$ for sources with fluxes $f_1$ and $f_2$ obey the relationship

$$m_1 - m_2 = -2.5 \log \frac{f_1}{f_2}. \quad (1)$$

A single source will likewise follow the relationship

$$m - M = -2.5 \log \frac{f(d)}{f(10\text{pc})} = +5 \log \left( \frac{d}{10\text{pc}} \right). \quad (2)$$

where $d$ is the distance of the source and

$m =$ apparent magnitude – what the source looks like

$M =$ absolute magnitude – what it looks like at a distance of 10 pc

$= a \ way \ of \ describing \ intrinsic \ brightness, \ i.e. \ the \ luminosity$

$f(d) =$ flux measured when the source is at a distance $d$

$f(10\text{pc}) =$ flux measured if the source were at a distance of 10 pc

Note that magnitudes are usually measured in some specified bandpass, i.e. an interval of wavelengths or frequencies. Measurements with real telescopes, filters, and detectors, are not simply a full summation of the source spectrum across a bandpass, but have wavelength-dependent sensitivity or response. Instrumental photometric systems are thus
described by a central or effective wavelength $\lambda_{\text{eff}}$ and a bandpass width, usually expressed as the Full Width at Half Maximum (FWHM) of the response function. The FWHM represents the separation in wavelength between the points where the response function falls to 50% of its peak value. The most common bandpasses, specified by a letter, are the Johnson-Cousins UBVRI system in the optical region, where the letters stand for ultraviolet-blue-visible-red-(near) infrared; and its extension designated by JHK in the infrared. The characteristics of these bandpasses are summarized in Table 1.

Inspection of eq. (1) shows that magnitudes are always relative indicators of flux or luminosity, and to convert from magnitudes to normal physical units we have to define a “zero point” that fixes the absolute flux scale. This is normally done by specifying a flux corresponding to 0 magnitude, and the flux measured from the bright star Vega is commonly adopted for this purpose. Zero point fluxes are typically tabulated as the flux density $f_\lambda$ or $f_\nu$ at the central wavelength of the bandpass, rather than as the flux integrated over the bandpass, although the magnitude is in fact integrated over the bandpass.

If we have a star that has an apparent magnitude $m$, and introduce a cloud between the star and us, part of the light from the star is removed by the dust and the apparent magnitude becomes $m' = m + A$, which is a larger number than $m$ and hence fainter. Note that $A$ is closely related to optical depth $\tau$ which we have previously used as a measure of how much light interacts with an absorbing or scattering medium, and it is straightforward to show that $A \approx \tau$.

A very important aspect of extinction in the interstellar medium is that it is a function of wavelength: $A$ is larger at shorter wavelengths, which means that blue light undergoes more extinction than red light. When light shines through a cloud containing dust, the preferential removal of short wavelength photons makes the spectral energy distribution
become increasingly weighted to long wavelength photons, i.e. the spectrum is reddened (as in a sunset).

The dependence of extinction on wavelength \( A(\lambda) \) can be measured by studying stars for which we know their intrinsic spectrum, based on studies of nearby, unabsorbed stars of the same spectral type and metallicity. Roughly, \( A \propto \frac{1}{\lambda} \) in the visible spectrum (Figure 1). There is a prominent feature at \( \approx 2200 \, \text{Å} \) (the “2200-Å bump”) which is believed to be due to graphite-like carbon in the dust grains.

Note that reddening is actually very important because it allows us to deduce the total attenuation – the two are proportional to each other. If the absorption were totally “grey” and hence independent of wavelength, the shape of the spectrum of a source sitting behind a dust cloud would be unaffected, and we would have difficulty inferring how much extinction the source is subject to. The fact that extinction is wavelength-dependent also means that we can see through dusty clouds by making measurements at long wavelengths (infrared, radio) where little attenuation takes place.

Quantifying Reddening

A standard way of quantifying reddening is via the “color excess” defined as \( E(B - V) \equiv A_B - A_V \). The color of a star is given by a difference between magnitudes measured in two bandpasses. If we are talking about a color based on apparent magnitudes, the dependence on distance in eq. (2) cancels out when we take the difference between two such magnitudes. Consider then a star that has absolute magnitudes \( M_B \) and \( M_V \), such that its intrinsic color is \( M_B - M_V \). When we observe the star in the presence of dust, the color we measure is

\[
(m_B - m_V)' = (m_B + A_B) - (m_V + A_V) = (m_B - m_V) + (A_B - A_V)
\]

\[
= (m_B - m_V) + E(B - V) = (M_B - M_V) + E(B - V). \quad (3)
\]
In practice then if we measure a color for a star of \((m_B - m_V)\)', and look up \((M_B - M_V)\) for an unreddened star of the same spectral type (calibrated from nearby stars with no extinction), then the difference gives us the color excess \(E(B - V)\).

If we know the reddening, which is the *differential attenuation*, how much attenuation does this correspond to at a particular wavelength \(\lambda\) ? In other words, what is \(A_\lambda\)? To answer this question we must know the functional relationship between \(A\) and \(\lambda\). It turns out that empirically, in the Milky Way the reddening law follows a family of curves with similar shape that differ only in slope (see Figure 1), and the slope is parametrized based on the \(B\) and \(V\) bandpasses via the quantity

\[
R \equiv \frac{A_V}{E(B - V)},
\]

or equivalently \(A_V = R \cdot E(B - V)\). The value of \(R\) varies somewhat between different sightlines, but an overall average value adopted in the absence of other information is \(R = 3.1\). The “reddening law” \(A(\lambda)\) is tabulated in Table 2, normalized to \(A_V = 1\). In general the values in Table 2 can be scaled by the actual \(A_V\) to determine the extinction \(A_\lambda\) for the wavelength of interest.

If we have independent information on the spectral type of a star – for example, based on a spectrum since the stellar absorption features are unaffected by interstellar extinction – a comparison between the measured color and the intrinsic color for its spectral type can be used to determine \(E(B - V)\) and hence \(A_V\). Intrinsic colors and absolute magnitudes for stars that are useful for this purpose are listed in Table 3.

Another way of going from a reddening estimate to an estimate of the extinction \(A_V\) that is applicable to emission-line nebulae is to use measurements of line flux ratios with intrinsic ratios that are well known from atomic physics. The best examples are the hydrogen Balmer lines: these lines form in fixed ratios due to the physics of recombination, and their ratios will change if the spectrum is reddened.
Dust and Gas

Dust does not exist in isolation in the interstellar medium, but will be mixed with gas in either atomic, molecular, or ionized form. Along a given sightline, the quantity of dust will thus scale on average in proportion to the quantity of gas, such that the extinction is greater for larger gas column densities. In the local interstellar medium this relationship can be expressed quantitatively as

\[ A_V = (5.36 \times 10^{-22} \text{ cm}^2) N_H, \]  

(5)

where \( N_H = N(H) + 2N(H_2) + N(H^+) \).

Absorption at High Photon Energies

The opacity introduced by neutral hydrogen makes it difficult to empirically determine dust absorption properties in the far-ultraviolet region (i.e. beyond the hydrogen ionization threshold at \( \lambda < 912 \, \text{Å} \) or \( h\nu > 13.6 \, \text{eV} \)). Dust extinction in this spectral region can be estimated theoretically based on our understanding of grain composition (see below). One such prediction is shown in Figure 2, expressed as an equivalent cross section per hydrogen atom. Note that this corresponds to the coefficient in equation (5) since \( A_\lambda/N_H \approx \tau_\lambda/N_H = \sigma_\lambda(\text{dust})/(\text{H atom}) \).

An essential point to note in Figure 2 is that \( A_\lambda \) rises with increasing photon energy until achieving a maximum at \( h\nu \approx 30 \, \text{eV} \), thereafter decreasing at higher energy. While the precise location of the peak is somewhat model dependent, the general prediction of a turnover is robust, since fundamental optical relations place a bound on the opacity integrated over all wavelengths, set by the total the amount of matter in grains. At energies beyond 200 eV, dust extinction shown in Figure 2 displays a series of abrupt, sawtooth-like resulting from inner-shell ionization of atoms within the grains.
What are dust grains made of? We can infer some information directly from features such as the 2200-Å bump observed in absorption, or from other solid-state features that appear as broad infrared emission features. But the most detailed information about grain composition comes from an indirect method: if we know the overall composition of the interstellar medium, but find that the gas-phase abundances are reduced from this level, the difference presumably represents what is bound up in grains.

In applying this strategy, we usually adopt “cosmic abundances,” which are usually solar values, as being representative of the local ISM. How do we then measure the gas-phase abundances in a cloud with dust? Absorption lines measured in the spectrum of a background star are the most accurate means. Such abundance estimates are generally more accurate than abundances measured from H II regions, and the grains in H II may also undergo modification such that they are not typical of the ISM.

In the cool phases of the ISM, most atoms are in the ground state and the spectral lines of interest for study in absorption are those that trace transitions with the ground state as the lower level; such lines are called resonance lines. Due to the way that nature has put together atoms, most resonance lines for the abundant elements are found in the ultraviolet part of the electromagnetic spectrum. A few prominent examples are also found in the optical part of the spectrum, notably the Ca II H and K lines at 3968 and 3934 Å and the Na I D lines at ∼ 5890 Å. (The H, K, and D notation goes back to the labels created by Fraunhofer for the solar spectrum – see Carroll & Ostlie pp. 127 – 128 for more details.) The spectral absorption lines that we commonly see in optical spectra of stars typically result from transitions between excited states. Measurement of most resonance lines and detailed studies of the ISM in absorption thus require measurements from space. The most important satellites to date with UV spectroscopy capability have been Copernicus, the
International Ultraviolet Explorer, the Hubble Space Telescope, and the Far Ultraviolet Spectroscopic Explorer.

The amount of absorption occurring in a given spectral line is expressed in terms of the **equivalent width**, and the quantitative relation between equivalent width and the number of absorbing atoms along the line of sight is called the **curve of growth**. Details in the context of absorption lines in stars are described in Carroll & Ostlie Sec. 9.4; the physics is much the same for interstellar absorption lines, although pressure broadening is usually irrelevant there.

Absorption line studies are a very powerful tool for probing the composition and kinematics (gas motions) for interstellar matter more generally. An additional example where these methods have been highly valuable is through measurement of spectra for distant quasars, where absorption lines are produced by intervening clouds of material along the line of sight. Absorption of Lyα by intergalactic hydrogen produces a “forest” of lines at wavelengths less than the measured Lyα feature in the quasar, with absorption wavelengths reflecting the cosmological redshifts of the absorbing clouds. The distribution and properties of Lyα absorbers contains important information on the aggregation of matter into galaxies over cosmic time. Large galaxy-like objects with large gas column densities can also be identified from their characteristic **damped** absorption profiles with broad wings. The deuterium abundance from such measurements is used to estimate the primordial abundance of deuterium, an important consistency test for Big Bang nucleosynthesis models.