5. Astronomy Through the Atmosphere

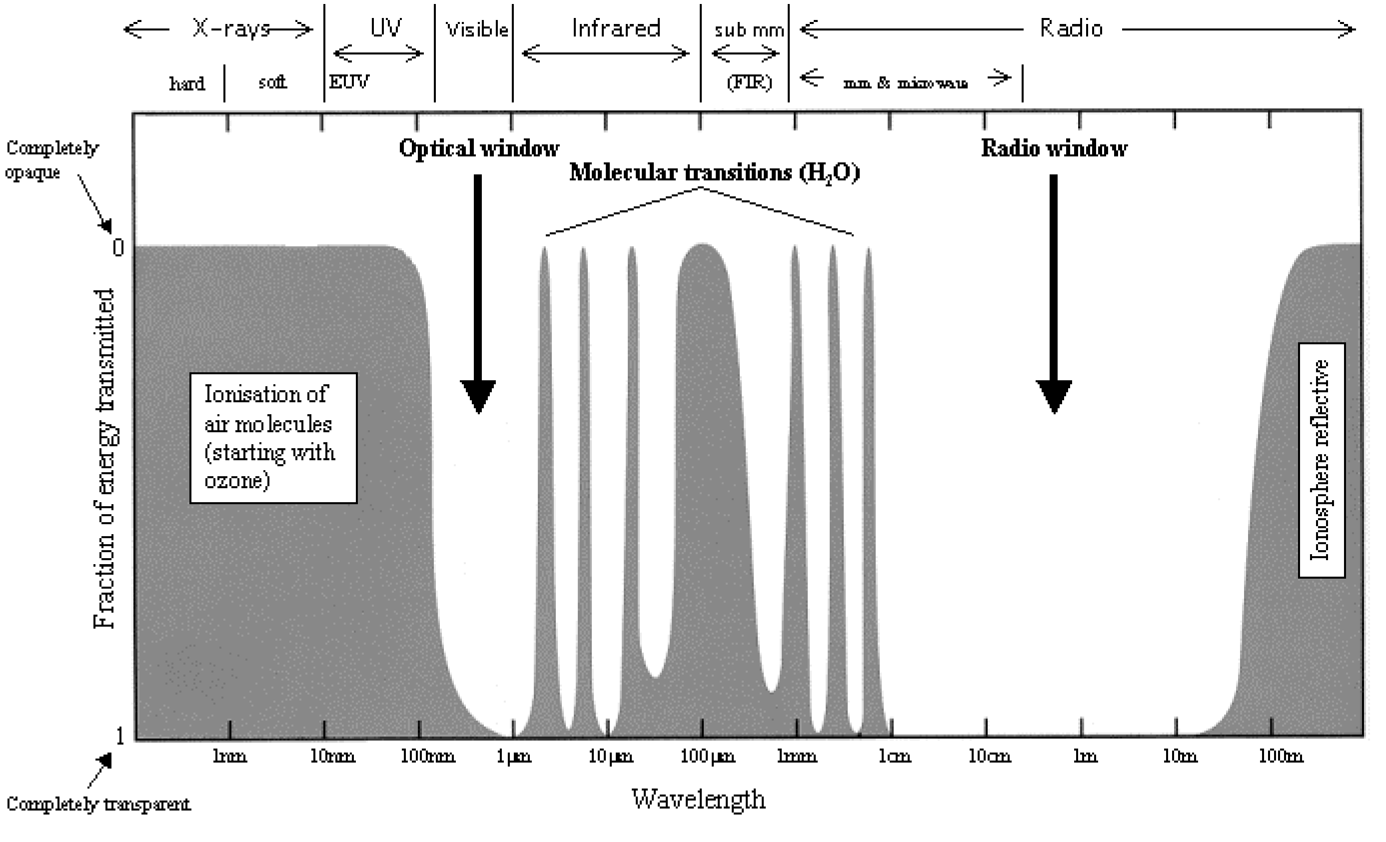
Ground based observations are affected by:

- Absorption
- Refraction
- Scattering
- Scintillation

In this section we will briefly consider some of the effects of these four phenomena.

Absorption

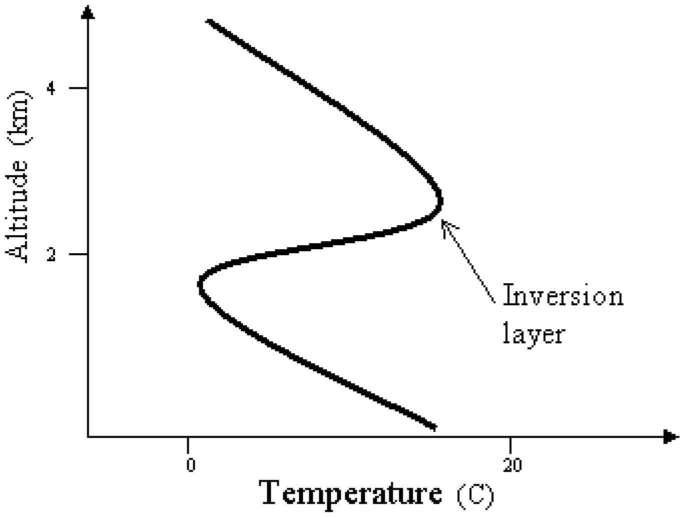
The Earth's atmosphere is opaque to E-M radiation, apart from two windows: in the **optical** and **radio** regions of the E-M spectrum.



Absorption

Between the optical and radio windows (i.e. in the infra-red) there are numerous absorption bands due to **molecular transitions** (mainly of water)

It is possible to get *above* the clouds containing this water vapour because of the **temperature structure** of the atmosphere. Above about 2km there is a thin **inversion layer**, where the temperature *increases* with height. Clouds form at the *base* of the inversion layer, leaving generally clear, dry air above.



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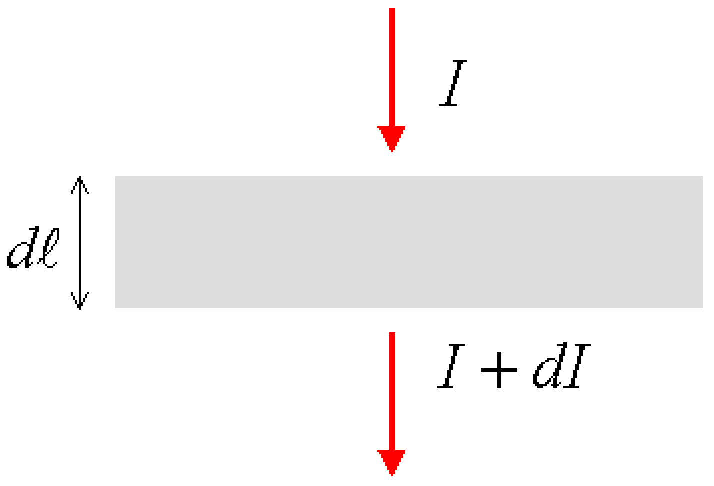
The world's best observatories (e.g. La Palma, Hawaii, La Silla, Paranal) are all at altitudes which place them above inversion layers.

How does absorption in the atmosphere affect the apparent brightness of objects?

We model the atmosphere as a series of plane-parallel slabs.

Consider a thin slab of thickness $d\ell$ and radiation of intensity I incident perpendicular to the slab



We model the absorption in the slab as:

$$dI = -I\,\kappa\,d\ell \qquad (5.1)$$

Absorption coefficient, which is not in general constant, but depends on depth ℓ in the atmosphere

Re-arranging, and integrating from the source (at distance D, emitting radiation of intensity I_0) to the Earth's surface

$$\int_{I_0}^{I_{obs}} \frac{dI}{I} = -\int_0^D \kappa\, d\ell \qquad (5.2)$$

Although we are thinking mainly about atmospheric absorption in this section, the same formula can describe e.g. **interstellar absorption** along line of sight

We define the right hand integral as the **optical depth**, denoted by τ.

Thus

$$\ln\left(\frac{I_{obs}}{I_0}\right) = -\tau \qquad (5.3)$$

or

$$I_{obs} = I_0\, e^{-\tau} \qquad (5.4)$$

- If $\tau = 0$ we describe the atmosphere as **"transparent"** and $I_{obs} = I_0$
- If $\tau << 1$ we describe the atmosphere as **"optically thin"** and $I_{obs} \approx I_0$
- If $\tau \geq 1$ we describe the atmosphere as **"optically thick"** and $I_{obs} << I_0$

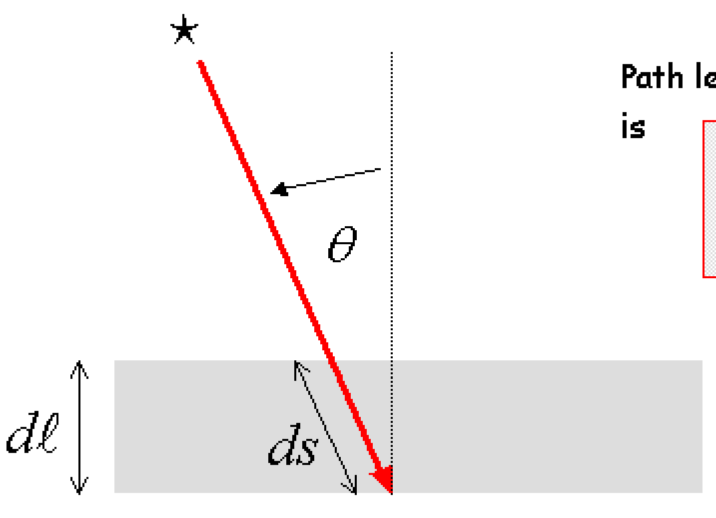
Expressing in terms of apparent magnitude

We can write $\log_{10} x = \ln x \log_{10} e$ (5.5)

So
$$\log_{10}\left(\frac{I_{obs}}{I_0}\right) = -\tau \log_{10} e = -0.4\left(m_{obs} - m_0\right) \quad (5.6)$$

or
$$\Delta m = \left(m_{obs} - m_0\right) = 2.5\,\tau \log_{10} e \approx 1.09\,\tau \quad (5.7)$$

Suppose we observe a star at zenith angle θ



Path length through slab of thickness $d\ell$ is

$$ds = \frac{d\ell}{\cos\theta} = d\ell \sec\theta \quad (5.8)$$

So this introduces an extra factor of $\sec\theta$ in eqs. 5.1 - 5.3.

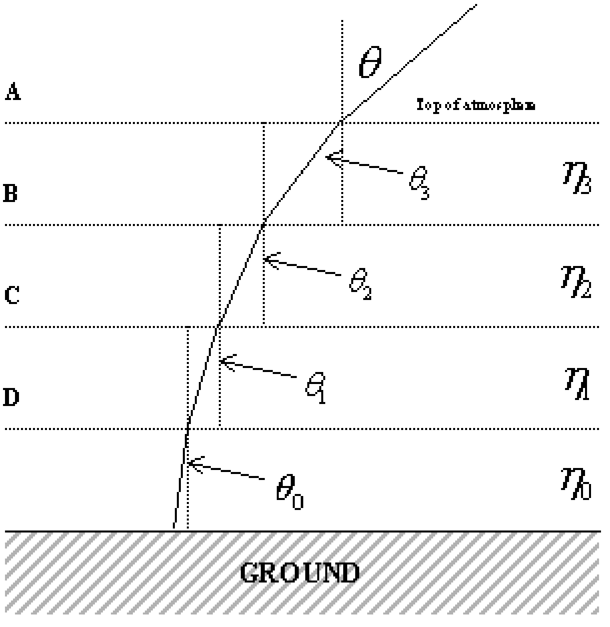
Hence
$$\Delta m_\theta \approx 1.09\,\tau \sec\theta = \Delta m \sec\theta \quad (5.9)$$

Zenith extinction

This treatment is only an approximation, as the light ray is also **refracted** by the atmosphere, thus changing θ along its path.

Refraction

We model the atmosphere as plane-parallel and consider a light ray incident at zenith angle θ on the **top** of the atmosphere.



Suppose we break the atmosphere into four parallel slabs, each with uniform refractive index: $\eta_0 \cdots \eta_3$

Applying Snell's Law,

at level A: $\sin\theta = \eta_3 \sin\theta_3$

at level B: $\eta_3 \sin\theta_3 = \eta_2 \sin\theta_2$

at level C: $\eta_2 \sin\theta_2 = \eta_1 \sin\theta_1$

Finally, at level D: $\eta_1 \sin\theta_1 = \eta_0 \sin\theta_0$

Putting these together:

$$\sin\theta = \eta_0 \sin\theta_0 \quad (5.10)$$

Extends to an arbitrary number of slabs: to correct the observed zenith angle for refraction, we need only to know η_0 at ground level

Plane-parallel treatment valid for $\theta_0 \leq 60^\circ$. At larger zenith angles a more exact treatment that includes the **curvature** of the Earth is needed.

Scattering

Air molecules, dust and water vapour all scatter light. However, their different **sizes** cause different effects on light.

3 regimes:-

1. Particle size, $a >> \lambda_{opt}$ particles scatter all wavelengths equally

Examples: water droplets

This is why clouds and mist appear ***white***

2. Particle size, $a \sim \lambda_{opt}$ scattering power $\propto 1/\lambda$

Examples: fine dust, cigarette smoke

This is why e.g. smoke rings have a bluish tinge: blue light is scattered by the smoke particles more than red light.

American magician Harry Garrison

3. Particle size, $a << \lambda_{opt}$ scattering power $\propto 1/\lambda^4$ **Rayleigh scattering**

Examples: air molecules

Explains why the daytime sky is blue, and why the sun appears red at sunset (blue light scattered out of line of sight)

Ring of Brodgar, Orkney Mainland

Rayleigh scattering is **anisotropic** $\Rightarrow$ sky light is **polarised**

We can analyse the loss of intensity due to scattering in the same way as for absorption.

$$dI = -I \, \kappa \, d\ell \quad \Rightarrow \quad \tau = \int_0^D \kappa(\ell) \, d\ell$$

is larger for **blue** light

Scattering coefficient, $\kappa \propto \lambda^{-4}$ for Rayleigh scattering by air molecules

$\Rightarrow$ Stars appear **reddened**

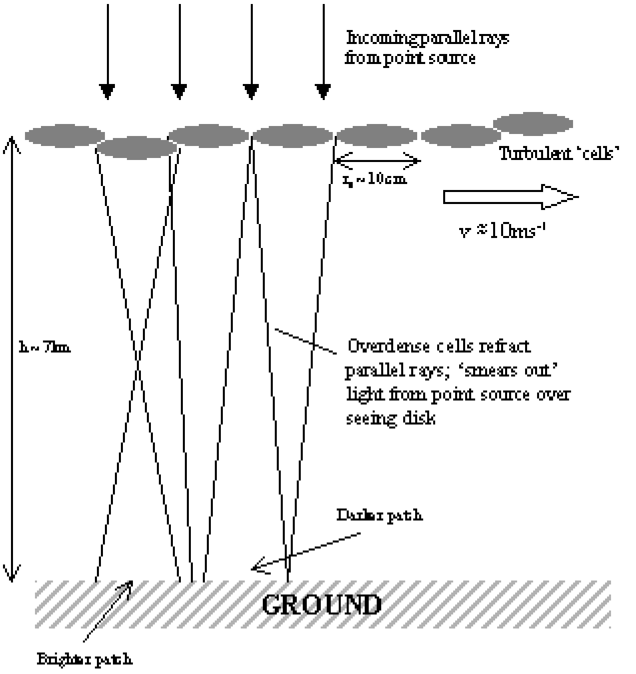
At visible wavelengths, the scattering of sunlight makes the sky so bright that we must observe at night.

In the **Far Infra-Red** (and beyond) on the other hand, scattering makes a small enough contribution that we *can* observe during the day too.

(As we saw in previous sections, however, the **thermal** emission from the sky may be a problem at FIR wavelengths).

Scintillation

Scintillation, or 'twinkling' of starlight is caused by **turbulence** in the atmosphere. Air 'cells' of varying density - and hence refractive index - are continually passing across the line of sight to a star, and changing the pattern of illumination from the star which reaches ground level.



Typical scale length for the cells is r_0 ~ 10cm, at a height of ~ 7km. Hence, illumination from the star at any instant will not be uniform, but will consist of brighter and darker patches, typically also ~ 10cm across. Cells 'smear out' the light from a point source over 'seeing disk':

$$\text{Angular radius of seeing disk} \sim \frac{10\ \text{cm}}{7\ \text{km}} = 3\ \text{arcsec.}$$

The cells are continually moving across the line of sight, with a transverse speed of about 10m/s.

$$\text{Scintillation timescale of variations} \sim \frac{10\ \text{cm}}{10\ \text{m/s}} = 0.01\ \text{sec.}$$

If the telescope aperture, $D \sim r_0$

We see rapid variations in position and brightness of the image as individual cells cross the line of sight.

If the telescope aperature, $D \gg r_0$

We see an image formed from many cells added together

⇒ Average brightness of the image is ~ constant, but there are rapid variations in the position, size and shape of the seeing disk

Can be corrected using Adaptive Optics (see Honours Astronomy)

Radio observations are also affected by scintillation – this time not from the Earth's atmosphere, but from turbulence in the **interstellar** and **interplanetary medium**.

The typical size of turbulent 'cells' is much larger (as is the wavelength of the radiation).

(Some astronomers have suggested that this might have consequences for SETI searches)

Example

At 700nm the zenith extinction (Δm_{700}) is 0.08 magnitudes. Estimate the extinction (Δm_{400}) at 400nm.

After correction for the atmosphere, a star is found to have a true colour index $(B-V)_0$ = -0.13. At a particular observatory, the zenith extinction (Δm) for the B band is 0.29 and for the V band is 0.17.

At what zenith distance would the star have the same apparent magnitude in the two bands?