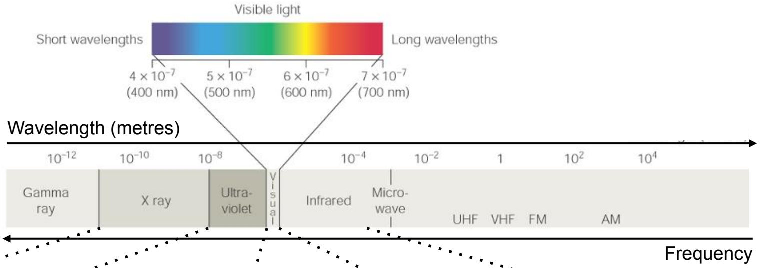
The Earth's Atmosphere and Astronomical Observations

The Electromagnetic Spectrum



M81 – "grand design" spiral galaxy

X-ray: Black hole accretion disks

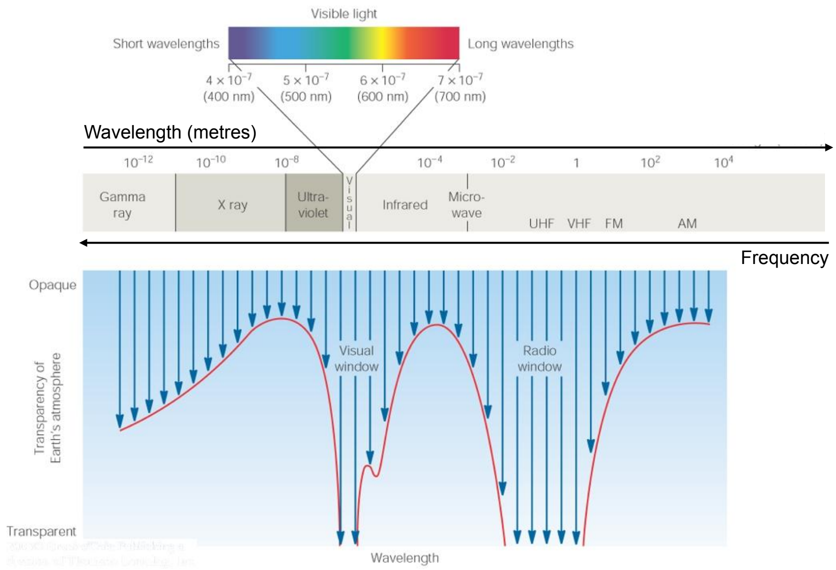
Ultraviolet: 10^6-10^8yr-old stars

Optical: >10^9yr-old stars

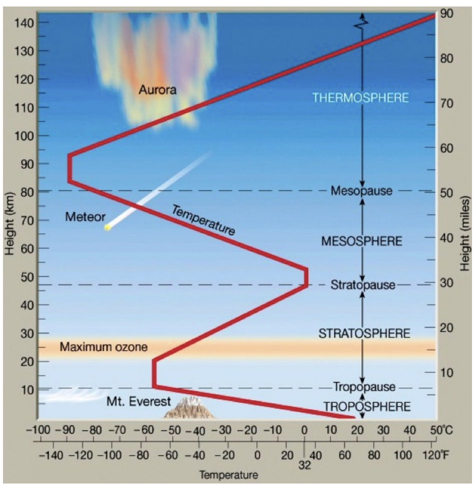
Infrared: Cold dust T<10^3K

Radio: Magnetically accelerated electrons

The Electromagnetic Spectrum



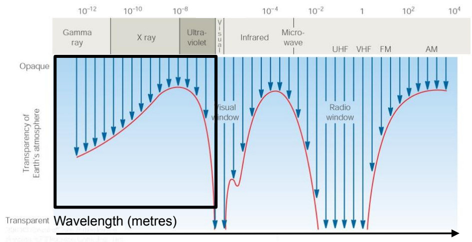
Structure of the Atmosphere



- Space observatories at H>200km
  - E.g. Hubble, Chandra
- Ionosphere (H>~70km):
  - Reflects radio waves at λ>10m
- Thermosphere:
  - Atomic oxygen and nitrogen absorb UV and X-ray photons
- Stratosphere:
  - Contains Ozone which causes temperature to increase
  - Clouds form at inversion layer ($dT/dH>0$)
- Troposphere:
  - Contains 75% of atmospheric gases
  - O_2 and CO_2 molecules absorb infrared photons
- Highest ground-based observatories at H~4km
  - E.g. Mauna Kea

Atmospheric Attenuation

- Ultraviolet, X-ray, Gamma-ray photons are absorbed very efficiently by atomic oxygen and nitrogen
  - Photo-ionization (photoelectric effect) at: ~4eV < E < ~0.511MeV
  - Compton scattering dominates at: ~0.511MeV < E < ~5MeV
  - Pair production starts at: E > 1.022MeV



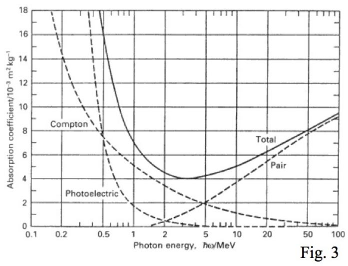
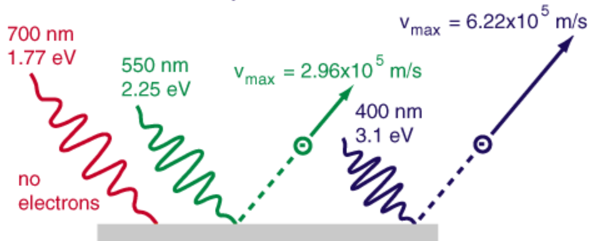


Fig. 3

Photoelectric effect

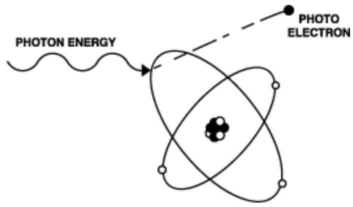
- Light can make metals emit electrons
- Not all photons can do it – need minimum energy
- But higher-energy light does not produce more electrons
- Instead, they produce faster electrons

$$E_{photon} = h\nu$$



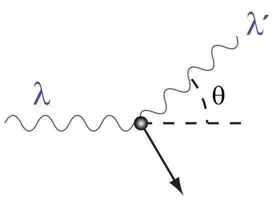
Photoelectric effect

- Einstein's explanation:
  - Assume light is a stream of photons, each with energy $h\nu$
  - Assume electrons are bound with some energy ϕ (work function)
  - No electrons emitted if $h\nu < h\nu_0 = \phi$
- A light packet with energy $h\nu$ will
  - spend ϕ in releasing the electron and
  - the rest of the energy will go into KE
  - i.e. $h\nu = KE + \phi$
- Cut-off frequency is that which "ejects" an electron with KE=0:
  - $\nu_0 = \phi / h$



Compton Scattering

- Photons of energy comparable to the rest mass energy of the electron (0.511MeV) scatter off electrons bound to the atoms, causing electrons to recoil, but not be removed from the atom

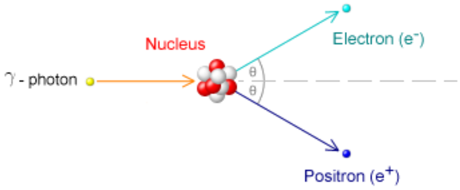


$\lambda' - \lambda = (h/m_e c)(1 - \cos\vartheta)$

h is Planck's constant
m_e is electron mass
c is speed of light

Pair Production

- Photons of energy exceeding twice the rest mass energy of the electron (E>1.022MeV) can interact with atomic nuclei and produce an electron-positron pair
- To conserve energy and momentum pair production can only take place via interaction of the photon with a nucleus (or other suitable particle)



Atmospheric Attenuation

- Infrared/millimetre photons (10^{-6}m < λ < 10^{-3}m):
  - Have insufficient energy to ionize atomic Nitrogen and Oxygen
  - Quantum energies that match the energies separating quantum states of molecular vibrations (infrared) and rotations (millimetre)
- Main species responsible for IR attenuation are H_20 and CO_2

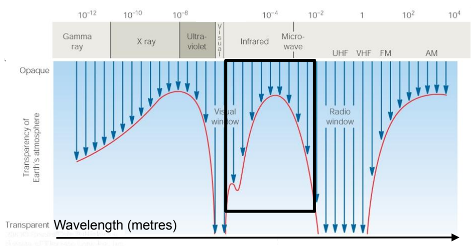


Figure 2.1 from Glass

Vibrations of simple molecules

Fundamental or normal modes

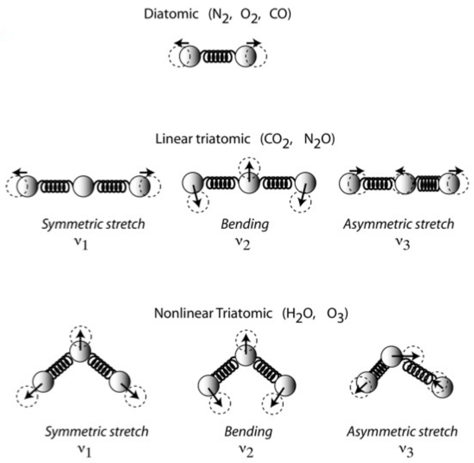
ν_1 Symmetric stretch

ν_2 Bend (Scissoring)

ν_3 Asymmetric stretch

A normal mode is IR-active if the dipole moment changes during mode motion.

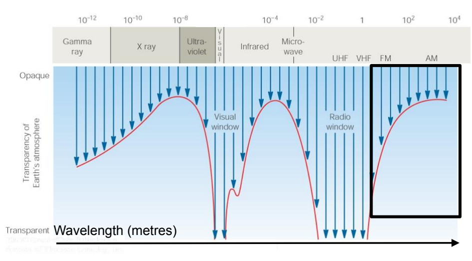
Overtones, combinations and differences of fundamental vibrations are also possible (e.g., $2v_1$, v_1+v_3 etc.)

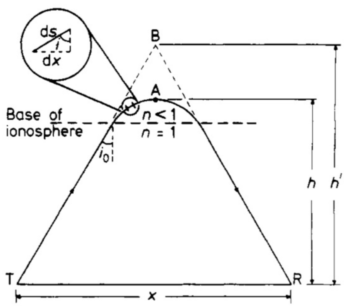


A non-linear molecule of N atoms has 3N-6 normal modes of vibration; a linear molecule has 3N-5.

Atmospheric Attenuation

- Radio waves (10^{-6}m < λ < 10^{-3}m):
  - Transparent window: 3MHz – 0.3THz; 10^2m – 10^{-3}m
  - Upper frequency limit imposed by H_20 and CO_2 in atmosphere
  - Lower frequency limit imposed by plasma frequency of the ionosphere
  - At lower frequencies the radio waves are reflected by ionosphere





Physics of the Ionosphere

- UV radiation from the Sun dissociates and ionizes nitrogen and oxygen in the upper atmosphere, generating the ionosphere
- The ionosphere extends from ~60km to 300km above the earth's surface: 1 in 10^3 particles is ionized in this region
- Free electrons in the ionosphere refract radio waves and can cause them to be reflected
- Ionospheric reflection of radio waves is responsible for the the atmosphere being opaque to low frequency radio waves
- This is helpful for global radio communication and frustrating for radio astronomers!

Physics of the Ionosphere

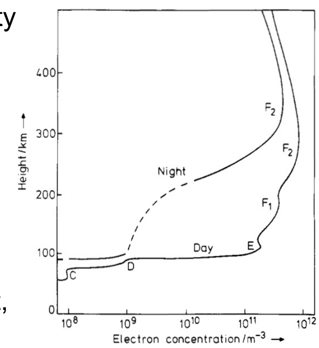
- Consider an electromagnetic wave of frequency f traveling through an ionized medium
- The electric field vector of the wave varies with time as follows:
  $E = E_0 \sin(2 \pi f t)$
- If this field is in (say) the x-direction then an electron will experience a force –eE and its equation of motion will be:
  $m_e\, d^2x/dt^2 = -eE = -eE_0 \sin(2 \pi f t)$
- Integrate to give:
  $x = [eE_0 \sin(2 \pi f t)] / [4 \pi^2 f^2 m_e]$
- Which then gives:
  $d^2x/dt^2 = -(4 \pi^2 f^2)\, x$
- The free electrons therefore vibrate with simple harmonic motion

Physics of the Ionosphere

- The oscillation of the electrons can be thought of as inducing a net polarization of the ionosphere
- The induced polarization oscillates in anti-phase with the electric field, and can be written as:
  $P = – N e x$
  N is the number density of electrons
  P is the dipole moment per unit volume
- Then: $P = – (N e^2 E) / (4 \pi^2 f^2 m_e)$
- From dielectric theory we know that: $P = \varepsilon_0 (\varepsilon_r – 1) E$
  ε_0 is the permittivity of free space
  ε_r is the relative permittivity of the dielectric (i.e. the ionosphere)

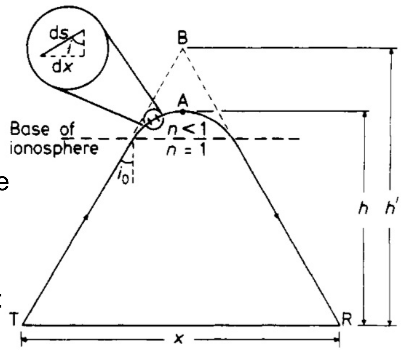
Physics of the Ionosphere

- We can therefore write: $\varepsilon_r – 1 = – (N e^2) / (4 \pi^2 f^2 m_e \varepsilon_0)$
- In vacuo the speed of light is: $c = (\varepsilon_0 \mu_0)^{-0.5}$
  μ_0 is the free space permeability
- In an isotropic medium of relative permeability μ_r the speed of light becomes:
  $(\mu_0 \mu_r \varepsilon_0 \varepsilon_r)^{-0.5} = c / (\mu_r \varepsilon_r)^{0.5} = c / n$
  n is the refractive index of the medium
- Taking μ_r=1 for the ionosphere, the refractive index of the ionosphere is:
  $n = (\varepsilon_r)^{0.5} = [1 – (N e^2) / (4 \pi^2 f^2 m_e \varepsilon_0)]^{0.5}$
- N, the electron density, increases with height, so n, refractive index, decreases with height



Physics of the Ionosphere

- A pulse of radio waves strikes the ionosphere at an angle i_0
- The decreasing refractive index bends the path and at point “A” the angle of refraction becomes 90°
- Adopting $i_0=0$ and applying Snell’s law gives: $\sin(i_0) = n_A = 0$
- The pulse of radio waves is therefore reflected if: $(N e^2) / (4 \pi^2 f^2 m_e \varepsilon_0) = 1$
- Which implies a critical frequency of: $f = [(N e^2) / (4 \pi^2 m_e \varepsilon_0)]^{0.5}$



- Typically $N \sim 6 \times 10^{10} m^{-3}$ which renders the atmosphere opaque at frequencies of f < ~2.2MHz

Optical Extinction

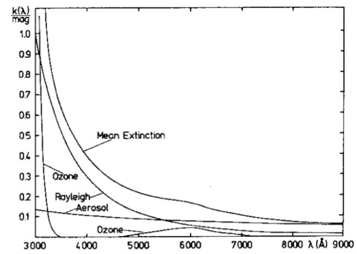
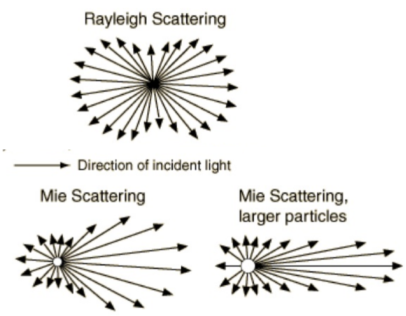


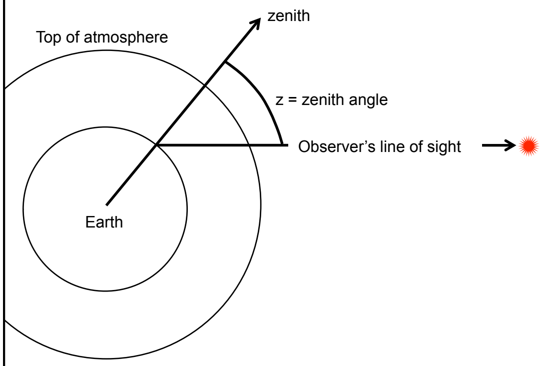
Fig. 1. Mean vertical extinction at Flagstaff, Arizona, in May-June 1976. The assumed ozone and Rayleigh contributions are shown separately

- The atmosphere is not 100% transparent to optical radiation
- Rayleigh scattering off small molecules:
  - Wavelength small compared to size of molecule, λ<~0.1r
  - Air molecules, e.g. O_2, CO_2, H_2O, …
  - Scattered intensity is strongly wavelength dependent: I propto λ^{-4}
- Mie scattering off larger molecules:
  - Wavelength comparable with size of molecule, λ>~0.1r
  - Aerosols, e.g. volcanic dust, car exhaust fumes, cigarette smoke
  - Scattered intensity is almost wavelength independent



Airmass

- Extinction depends on the position on the sky that is being observed



Define X to be the path length through the atmosphere

Define X=1 at z=0 (i.e. at zenith)

At z>0: cos z = 1 / X

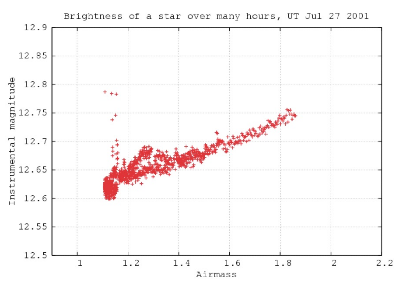
i.e.: X = sec z

Assumes plane parallel atmosphere; a good approximation for X<=2

If optical depth depends only on path length, then:
$\tau(X) = \tau_0 X$
$F_{observed} = F_{top} \exp(-\tau_0 X)$

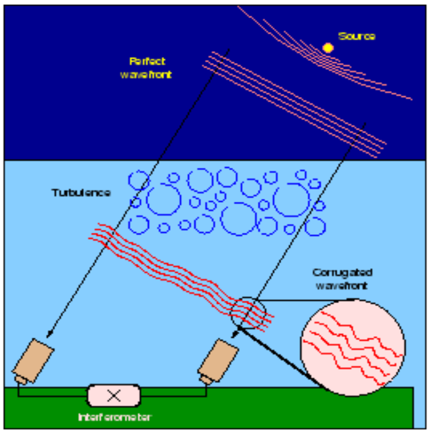
Extinction Coefficients

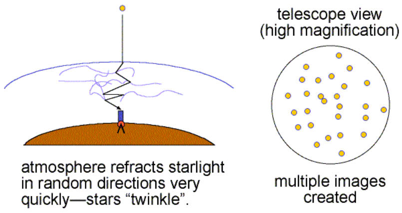
- Re-writing the previous expression in terms of magnitudes gives observed magnitudes in terms of the exoatmospheric magnitude (m_0), airmass, and the optical depth at zenith:
- $m = -2.5\log_{10}(F_{top} \exp(-\tau_0 X)) = m_0 + 1.086\tau_0 X$
- Extinction makes objects fainter, so their magnitude increases
- Extinction coefficient is then defined as: $k = 1.086\ \tau_0$
- m_0 and κ can be measured by fitting a straight line to m as a function of X

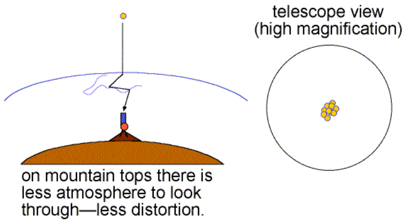


Atmospheric Turbulence

- Turbulence causes the refractive index of the atmosphere to change randomly and rapidly – this blurs our view of stars and galaxies

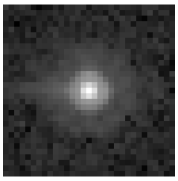


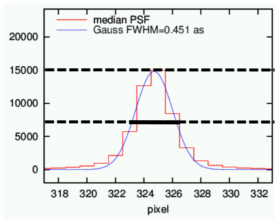




"Seeing"

- In practice seeing blurs our view of stars and galaxies
- A star is blurred from a point to a smooth light distribution
- Astronomers measure seeing by fitting (e.g.) a Gaussian to the measured light distribution
- Seeing is defined as the full width at half maximum
- Typically FWHM = 1arcsec at 550nm

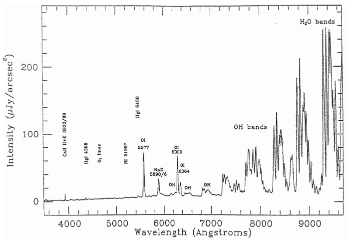




- It can be shown from Kolmogorov theory of turbulence that seeing has a gentle wavelength dependence: FWHM propto $\lambda^{-0.2}$

Atmospheric Emission

- The atmosphere also emits radiation at optical wavelengths:
  - Rayleigh scattered moonlight and starlight
  - Emission from excited atoms and molecules in upper atmosphere (airglow)
- Airglow:
  - dominated by the hydroxyl radical OH^-
  - Increases rapidly in strength beyond 700nm
- The sky brightness is a strong function of wavelength:



Filter	λ(um)	mag/arcsec^2	photons/cm^2/s/um/arcsec^2
U	0.36	21.6	1.74x10e-2
B	0.44	22.3	1.76x10e-2
V	0.55	21.1	3.62x10e-2
R	0.64	20.3	5.50x10e-2
I	0.79	19.2	1.02x10e-1
J	1.23	14.8	2.49
H	1.66	13.4	4.20
K	2.22	12.6	3.98