Aim: Introduce the interactions between radiation and matter, why these processes are important in gaseous astrophysical systems, and how these give rise to the observed spectra of astronomical objects.

Reference Books:

- Radiative Processes in Astrophysics, Rybicki and Lightman
- Astrophysics of Gaseous nebulae and AGNs, Osterbrock & Ferland
- Introduction to Stellar Astrophysics: Stellar Atmospheres, Bohm-Vitense
  Recommended additional library reading:
- Interpreting Astronomical Spectra, Emerson
- High Energy Astrophysics, Longair
Nearly all information from distant objects is conveyed by electromagnetic radiation.

Exceptions: cosmic rays, meteorites, neutrinos, gravitational waves.

Example: Spectrum of distant quasar: absorption by neutral hydrogen probes distribution of gas in high-redshift Universe.

Shapes of absorption features tell us about physical conditions in the absorbing gas.
Lyman $\alpha$ forest

Lyman $\alpha$ is the $n = 2$ to 1 electron transition in hydrogen at a wavelength of 122nm.

Distant quasar emits Ly-$\alpha$ line at a high redshift. Intervening neutral hydrogen clouds can absorb radiation at the Ly-$\alpha$ wavelength. The intervening clouds are at a lower redshift than the distant quasar, so the absorption features appear at shorter (bluer) wavelengths than the Ly-$\alpha$ emission line from the quasar.

Figure from E. Wright, UCLA
Example: Regions of massive-star formation in the Milky Way and other galaxies.

These spectra are generated (largely) via forbidden-line emission. Collisions excite atoms and ions into long-lived metastable states. When they finally decay, photons carry away energy, allowing nebular material to cool.
Heart Nebula – Hα, [N II], [O III]
Outline:

• Basics: radiative transfer equation, black body radiation, the diffusion approximation

• Atomic and molecular processes: bound-bound, bound-free and free-free transitions, electron scattering, Boltzmann and Saha laws, 21cm emission

• The Einstein relations, line opacities and emissivities

• Atomic and molecular line transitions and line broadening mechanisms,

• Application of these ideas to a variety of astronomical situations, including
  – the interstellar medium (why does the ISM have several distinct temperature regimes?)
  – star formation (where molecules and dust are important)
Radiative transfer basics

For scales $L \gg$ wavelength $\lambda$ of radiation, radiation travels in straight lines (rays) in free space (ignore diffraction).

First goal: derive the **transfer equation** for radiation in this limit.

**Energy flux $F$:**

Imagine radiation passing through an area $dA$ for a time $dt$. Amount of energy passing through the surface is given by:

$$F \ dA \ dt$$

Energy flux $F$ has units $W \ m^{-2}$

$F$ depends on orientation of surface to radiation source.

**Isotropic source**

An **isotropic** source of radiation emits energy equally in all directions. e.g. an isolated spherical star. Conservation of energy gives the *inverse square law*:

$$F \propto 1/r^2$$
Solid angle

Defined as \((\text{surface area})/r^2\)

Unit is steradian

Area of unit sphere = \(4\pi\) steradian

Consider a sphere of radius \(r\).

Area of a surface element \(dS\) is:

\[ dS = r \, d\theta \times r \sin \theta \, d\phi = r^2 \, d\Omega \]

where \(d\Omega\) is the solid angle subtended by \(dS\) at the centre of the sphere. Area of sphere is then,

\[ S = r^2 \int d\Omega = r^2 \int_0^{2\pi} d\phi \int_0^\pi \sin \theta d\theta \]
Specific Intensity

Construct an area $dA$ normal to a ray. Consider all rays passing through $dA$ whose directions lie within a solid angle $d\Omega$:

Energy through $dA$ in time $dt$ in frequency range $d\nu$ is:

$$dE = I_\nu dA \, d\Omega \, d\nu \, dt$$

Defines the specific intensity or brightness $I_\nu$

$I_\nu$ has units $W \, m^{-2} \, Hz^{-1} \, steradian^{-1}$

$I_\nu$ depends upon location, direction, and frequency.
Specific intensity is constant along a ray in free space

- Consider areas $dA_1$ and $dA_2$ normal to a ray. Energy $dE$ is carried through both areas by those rays that pass through them both.

$$dE = I_{v1} \, dA_1 \, d\Omega_1 \, d\nu_1 \, dt = I_{v2} \, dA_2 \, d\Omega_2 \, d\nu_2 \, dt$$

where $d\Omega_1$ is the solid angle subtended by $dA_2$ at $dA_1$

Using $d\Omega_1 = dA_2 / R^2$, $d\Omega_2 = dA_1 / R^2$, and $d\nu_1 = d\nu_2$, we have

$$I_{v1} = I_{v2}$$

i.e. the specific intensity is constant along a ray in free space.

In terms of distance $s$ along a ray, write:

$$d \, I_v / ds = 0$$

where $ds$ is a differential element of length along the ray.

(Soon we’ll include emission and absorption along the ray path.)
Net flux

Flux through an element at angle $\theta$ is reduced because the foreshortened area is smaller:

$$dF_\nu = I_\nu \cos \theta d\Omega$$

$$F_\nu (n) = \int I_\nu \cos \theta d\Omega$$

$F_\nu (n)$ is the **net flux** in the direction of $n$.

For an isotropic radiation field $F_\nu (n) = 0$.
Momentum flux

The momentum of a photon is $E/c$

Momentum flux $p_\nu$ in the direction of $\mathbf{n} =$

(photon flux times momentum per photon):

$$p_\nu(n) = \frac{1}{c} \int I_\nu \cos^2 \theta d\Omega.$$ 

One factor of $\cos \theta$ comes from foreshortening

Only the normal component of the momentum acts on the surface, hence the second factor of $\cos \theta$

$F_\nu$ and $p_\nu$ are described as *moments* of the intensity
Lecture 1 revision quiz

• What is the solid angle subtended by a star of radius $R$, seen from
  – the surface of the star?
  – a location a distance $a$ from the star’s centre?
• Write down the expression defining the specific intensity $I_\nu$ in terms of energy per unit area per unit time per unit frequency per unit solid angle. What are the units of $I_\nu$?
• Why is there a $\cos \theta$ term in the corresponding definition of monochromatic flux $F_\nu$?
• Contrast the solar flux received on Mars when the Sun is overhead with that received in St Andrews at midday in midwinter