AS4011: STARS & NEBULAE I

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**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.

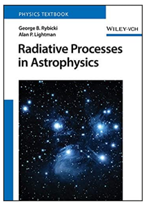
Reference Books:

- *Radiative Processes in Astrophysics*, Rybicki and Lightman
- *Physics of the Interstellar & Intergalactic Medium*, Bruce Draine
- *Astrophysics of Gaseous nebulae and AGNs*, Osterbrock & Ferland

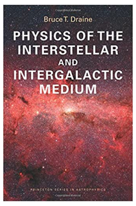
Recommended additional library reading:

- *Introduction to Stellar Astrophysics: Stellar Atmospheres*, Bohm-Vitense
- *Interpreting Astronomical Spectra*, Emerson
- *High Energy Astrophysics*, Longair

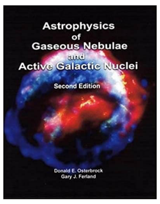
*Radiative processes in astrophysics*
Rybicki & Lightman, e-book




*Physics of the interstellar & intergalactic medium*
Bruce Draine, e-book



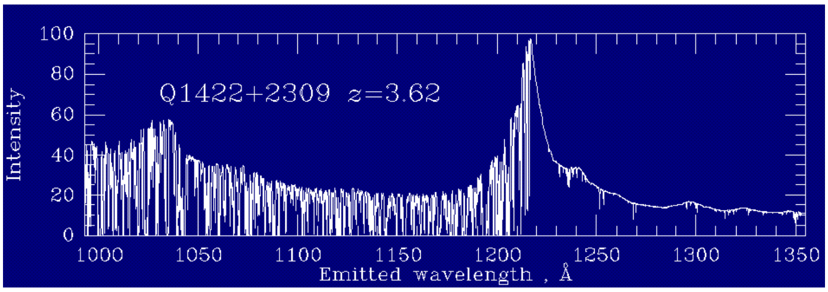

*Astrophysics of gaseous nebulae and active galactic nuclei (AGN$^2$)*
Osterbrock & Ferland



## 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 α forest

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

Distant quasar emits Ly-α line at a high redshift. Intervening neutral hydrogen clouds can absorb radiation at the Ly-α 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-α emission line from the quasar.

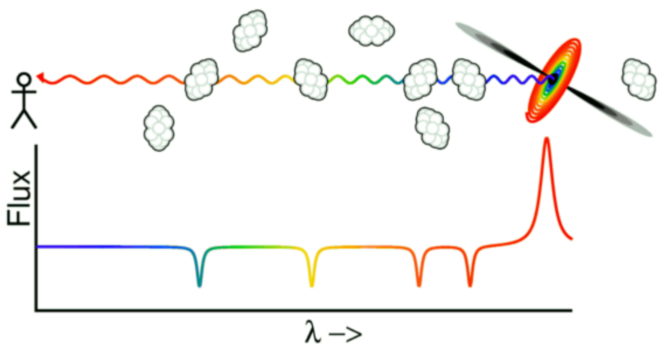



Figure from E. Wright, UCLA

Example: Regions of massive-star formation in the Milky Way and other galaxies.

818 *A. Campbell* et al.

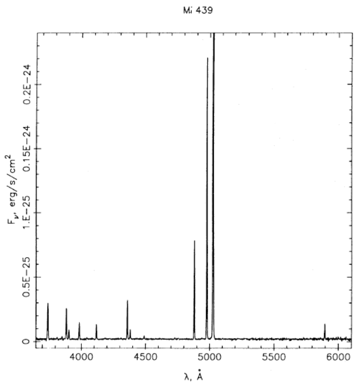



**Figure 1.** The spectrum of a typical H II galaxy, Mich 439. This object has an electron temperature of ≃13 800 K and an oxygen abundance of ≃$1\times10^{-4}$.

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]

# Radiation hydrodynamics simulations…

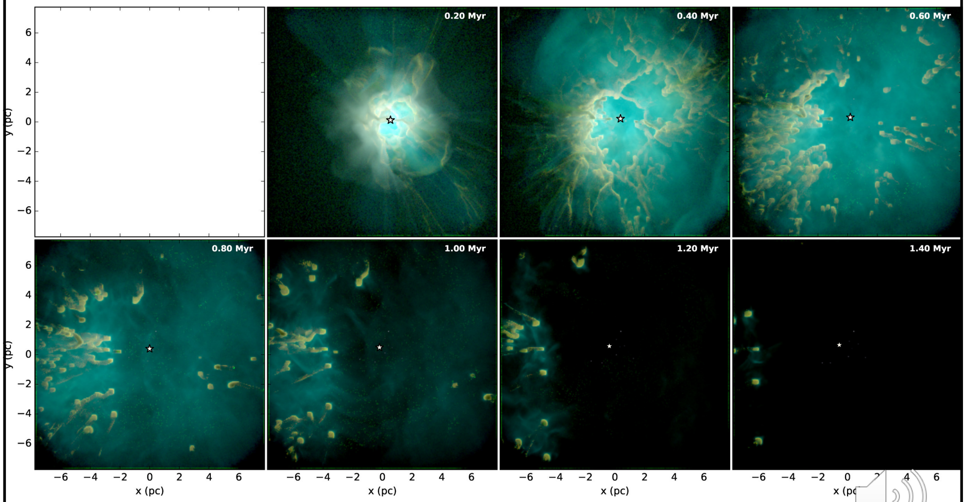



Image from Tim Harries (Exeter)

## Outline:

- Basics: radiative transfer equation, sources and sinks of radiation, black body radiation
- 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 $L$ » 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 emits energy equally into all solid angles (uniformly cover the surface of a sphere), e.g., an isolated spherical star. Energy conservation gives the *inverse square law*:

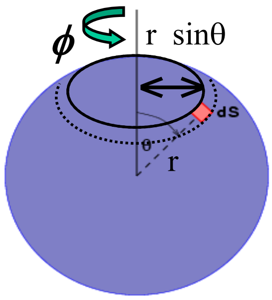
$$F \propto 1/r^2$$

## Solid angle

Defined as (projected 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:

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

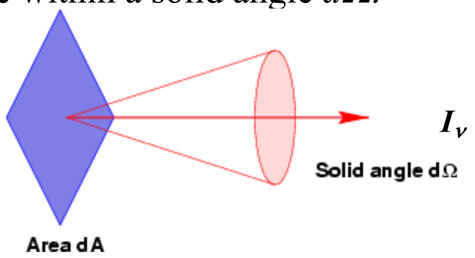
where $d\Omega$ is the *solid angle* subtended by $dS$ at the centre of the sphere. Area of sphere is then,

$$S = r^2 \int d\Omega = r^2 \int_0^{2\pi} d\phi \int_0^{\pi} \sin\theta\, d\theta = 4\,\pi\, r^2$$

## 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:

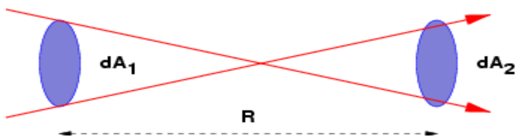
$$dE_\nu = I_\nu \, dA \, d\Omega \, d\nu \, dt$$

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 $dE_\nu$ is carried through both areas by those rays that pass through them both.

$$dE_\nu = I_{\nu 1} \, dA_1 \, d\Omega_1 \, d\nu_1 \, dt = I_{\nu 2} \, dA_2 \, d\Omega_2 \, d\nu_2 \, dt$$

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

$$I_{\nu 1} = I_{\nu 2}$$

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

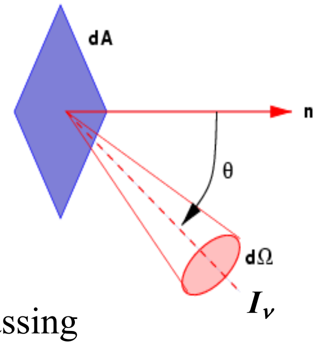
In terms of distance $s$ along a ray, write:

$$d\, I_\nu / ds = 0$$

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

Soon we'll include emission and absorption along the ray path

## Flux – a vector quantity




Flux in the direction **n** from radiation passing through dA at angle **θ** is reduced because the foreshortened area is smaller:

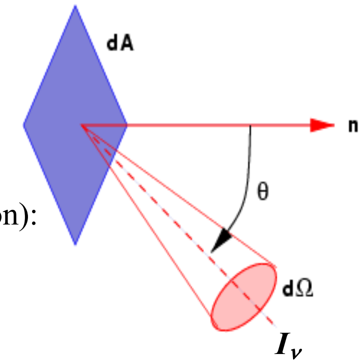
$$dF_\nu = I_\nu \cos\theta\, d\Omega$$

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

$F_\nu(\mathbf{n})$ is the **net flux** in the direction of **n**

For an isotropic radiation field $F_\nu(\mathbf{n}) = 0$

## Momentum flux




The momentum of a photon is *E/c*

Momentum flux $p_\nu$ in the direction of **n** = (photon flux times momentum per photon):

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

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: *n*-th moment is $\int I_\nu \cos^n\theta\, d\Omega$

## 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?
- How will the solid angle of a circular wall clock change as you view it from different distances and directions?
- 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

## Lecture 1 revision quiz

- In the optical image of the Heart Nebula, look up the wavelengths of the emission lines from H, N, and O. From what ionisation stage of these elements do the lines originate? What are the physical mechanisms that produce the emission lines?
- With a classmate(s), discuss and be able to explain the concept of "collisionally excited line cooling"
- When a star starts emitting ionising radiation it creates a region of ionised gas. Why does the ionised gas expand into the surrounding neutral gas?

## Lecture 1 revision quiz

- Specific intensity is defined for a ray passing normal to a surface dA. How will the formula change if the ray passes through dA at an angle $\theta$ with respect to the normal?
- Show that the net flux is zero for an isotropic radiation field.
- Using the relativistic mass-energy-momentum relation, show that the momentum of a photon is $p = E/c$.
- Check the units of flux and momentum flux are correct.