AY 20 Fall 2010

Stellar Atmospheres: Radiation & Optical Depth

Reading: Carroll & Ostlie, Chapter 9.1, 9.2

Stellar properties from observables

Direct measurements

- Distances (parallax)
- Luminosities (U,B,V etc)
- Masses (binaries)
- Radii (eclipsing binaries, interferometeric measures)

Rayleigh Criterion
Distance Modulus
Planck Function
Stefan-Boltzmann Law
Kirchkoff's Laws
Maxwell-Boltzmann Distribution
Boltzmann Equation
Saha Equation

Using stellar spectra:

- Spectral type $\equiv T_{eff}$
- Luminosity classes $\equiv$ gravity, pressure, density
- Radial velocities, z

Position on HR Diagram:

- Stellar radii
- Distances (spectroscopic parallax)
- main-sequence masses (approx)
- Ages of stars (later)

Spectra also provide info on:

- Rotational velocities
- Chemical abundances
- Magnetic fields
- Mass inflow-outflow

Stellar Atmospheres

Gaseous layers overlying opaque interior of stars

Photons from these layers → observables

Stellar spectra depend on atmosphere's properties

- Temperature
- Density
- Composition

Spectral lines direct result of interaction of emerging photons with atmosphere

How does radiation propagate through atmosphere?

Concepts:

- specific intensity (intensity)
- mean intensity
- specific energy density
- radiative flux (flux)
- radiation pressure

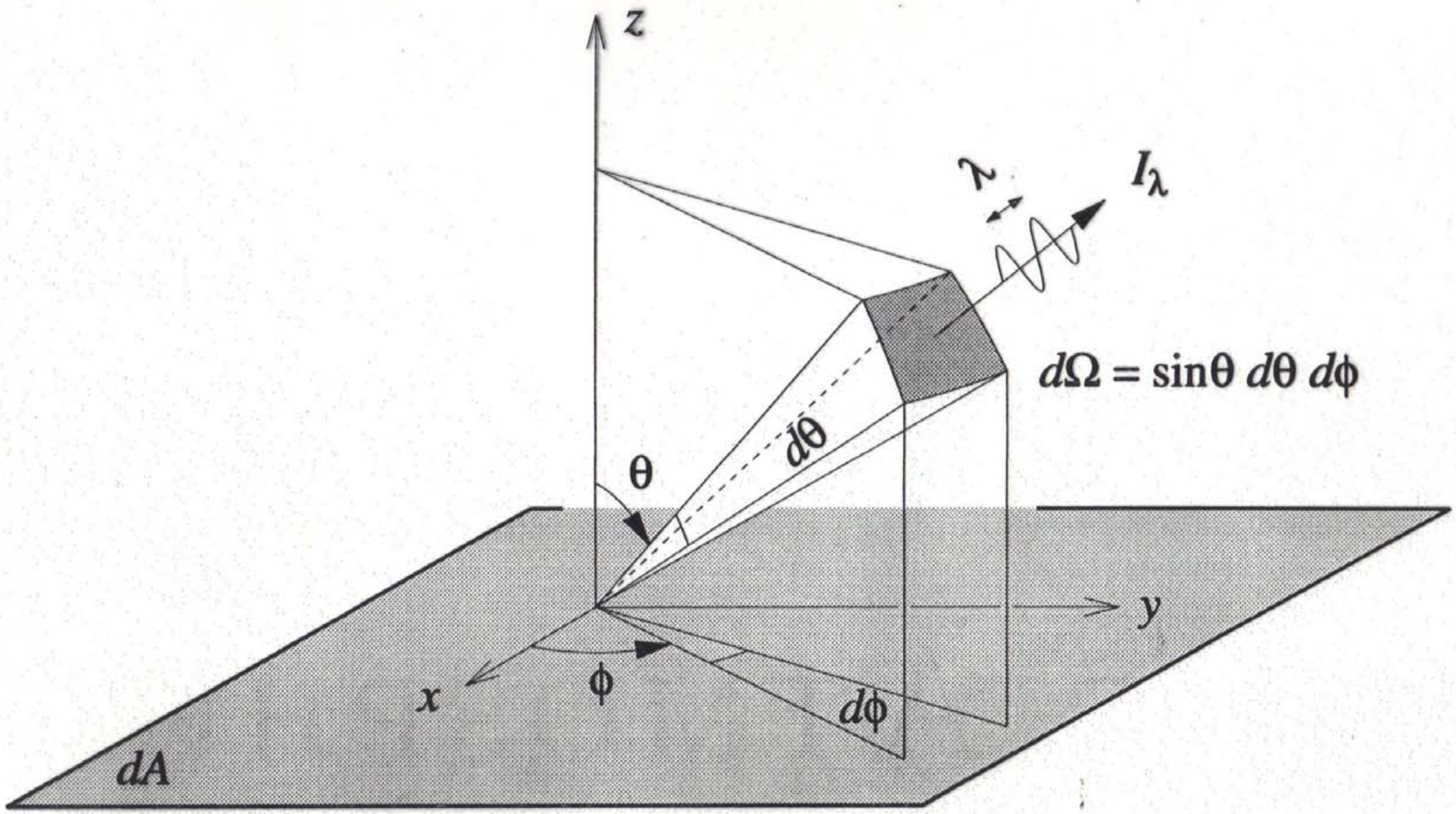


Figure 9.1 Intensity I_λ.

Light with wavelength between λ and $\lambda + d\lambda$ passing through surface dA at angle θ into cone of solid angle $d\Omega$

Specific Intensity, Mean Intensity derivations in class, C & O (9.1)

Specific intensity (intensity) I_λ is related to $E_\lambda d\lambda$

(energy at wavelengths between λ and $\lambda+d\lambda$ passing through surface A into solid angle $d\Omega$, which is at angle θ to z-direction) through:

$$E_\lambda d\lambda = I_\lambda d\lambda dt dA \cos\theta \sin\theta d\theta d\varphi$$ (I_λ units: ergs/sec/cm^3/str)

Mean intensity $\equiv \langle I_\lambda \rangle$

$$\langle I_\lambda \rangle = \frac{1}{4\pi}\int I_\lambda d\Omega = \frac{1}{4\pi}\int_0^\pi \sin\theta d\theta \int_0^{2\pi} d\varphi$$

For pure B-B radiation (isotropic):

$I_\lambda = \langle I_\lambda \rangle = B_\lambda$ = Planck function

Specific Radiative Flux, Specific Energy Density, Radiation Pressure: derivations in class, C & O (9.1)

Specific Flux (flux) , $F_\lambda d\lambda$

= net energy between λ and $\lambda+d\lambda$ passing per unit time through unit area in direction of z=axis (ergs/sec/cm^2)

$$F_\lambda = L_\lambda / 4\pi d^2$$

$$L = dE_\lambda / dt$$

$$\therefore F_\lambda = 1/4\pi d^2 \times \int I_\lambda d\lambda dA \cos\theta d\Omega$$

$$F_\lambda = \int I_\lambda d\lambda \cos\theta d\Omega$$

flux cancels for oppositely directed rays, due to $\cos\theta$ term

Radiation Pressure, P_{rad}

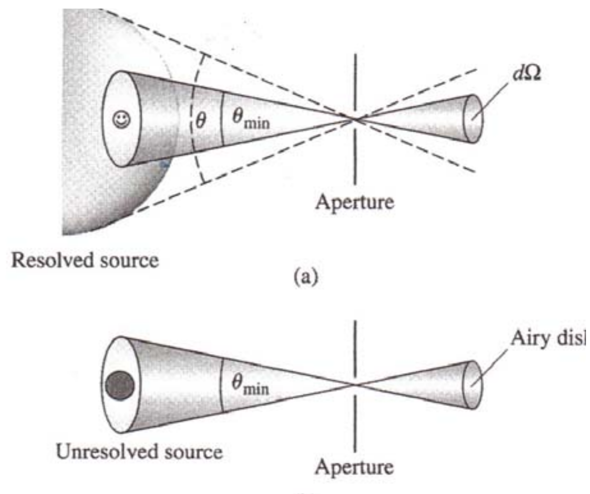
Isotropic radiation: $P_{rad\lambda} d\lambda = 4\pi/3c \times I_\lambda d\lambda$

Non-isotropic radiation: $P_{rad} = 4\pi/3c \times \sigma/\pi \times T^4{}_{eff}$

$= 1/3aT^4 = 1/3U$,

U =specific energy density

Measured quantity depends on resolution



a) Resolved source (assume uniform over whole surface), $\theta > \theta_{min}$
Measure specific intensity (energy/sec through aperture area into $d\Omega$, defined by θ_{min})

If source is 2 x more distant, energy reduced by $\frac{1}{4}$

but area contributing to energy is larger by factor of 4

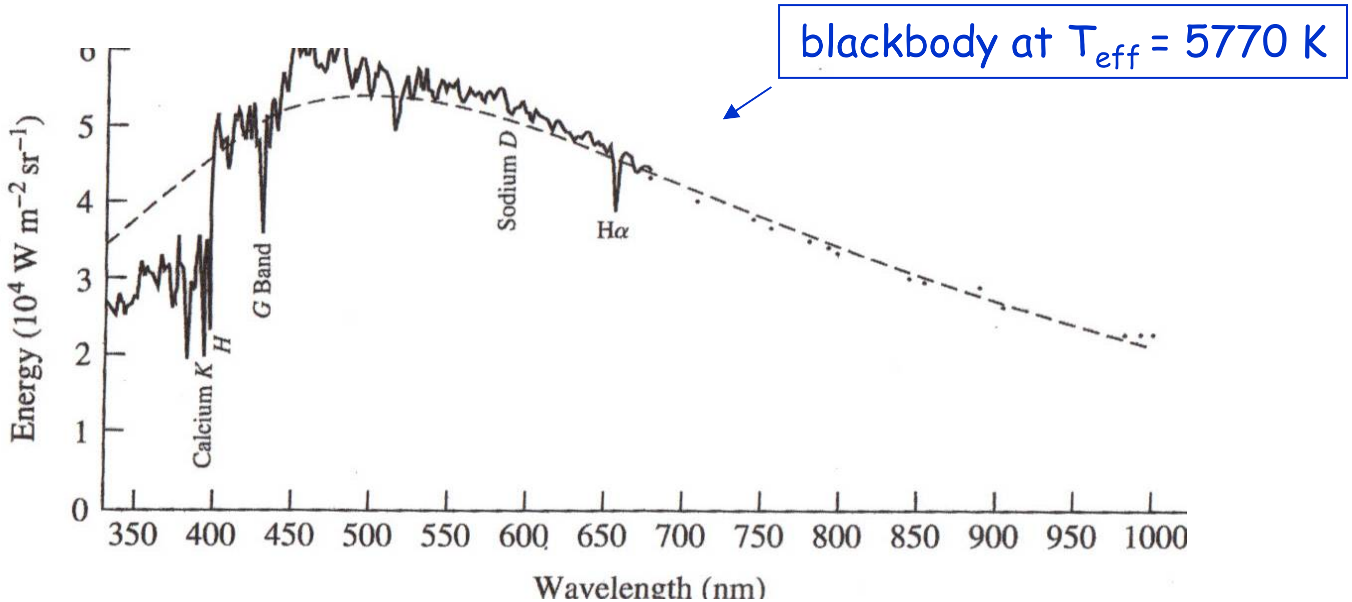
specific intensity constant

b) Unresolved source, $\theta < \theta_{min}$: measure radiative flux

Energy leaves source at all angles, $\therefore$ integrate over all directions, dispersed through diffraction pattern (most in Airy disk)

As distance increases flux decreases as $1/d^2$

Stars are not blackbodies



- Sun is clearly not a blackbody
- Spectral lines impact continuous spectrum of emission
- Line blanketing by dense pattern of metal absorption lines
    - (emission lines in UV or X-ray bands possible)
- Absorption effects ≡ "opacity"

Stellar temperature scales

Effective temperature T_{eff}

from $F = \sigma T_e^4$ works only for a specific level of a star

Excitation temperature T_{ex}

As in Boltzmann equation: $N_b/N_a = g_b/g_a e^{-(E_b-E_a)/kT_{ex}}$

Temperature needed to effect excitation

Ionization temperature T_i

As in Saha equation:

$$\frac{N_{i+1}}{N_i} = \frac{2Z_{i+1}}{n_e Z_i}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-\chi_i/kT}$$

Kinetic temperature T_k

Applies for Maxwell Boltzmann distribution function, $n_v dv$

Color temperature T_c

From fit to Planck curve

Thermodynamic equilibrium

T_{exc} T_i T_k T_c apply anywhere within atmosphere (not T_{eff})

Consider an ideal box:

- no net flow of energy in/out, nor between matter and radiation
  - every process and its inverse occur at same rate (e.g. photons emitted and absorbed at same rate)
    - T_{exc} T_i T_k T_c are equal

≡ thermodynamic equilibrium

BUT stars are not in thermodynamic equilibrium

Conditions in atmosphere → many particle speeds, photon energies, different temperatures

Concept of Local Thermodynamic Equilibrium (LTE)

- Define a "box" over which temperature remains "constant"
  - i.e. distance over which T changes >> mean free path of particles/photons