3. Radiation

Nearly all our information about events beyond the Solar system is brought to us by electromagnetic radiation—radio, submillimeter, infrared, visual, ultraviolet, *X*-rays, γ-rays. The particles associated with the electromagnetic field which carry the energy of the electromagnetic radiation are called *photons*.

3.1 Photons

Empirical facts:

- photons are bosons with zero rest mass
- Each carries a linear momentum **p**
- $\mathbf{p} = \hbar\mathbf{k}$ defines the wave vector **k**
- the photon energy $E = cp = h\nu$ so $p = h\nu/c$
- ν is the frequency, $h = 6.63 \times 10^{-27}$ ergs sec is Planck's constant
  $\hbar = \frac{h}{2\pi} = 1.0545 \text{ x } 10^{-27}$ ergs sec
- the photon wavelength $\lambda = c/\nu$
- photons travel in straight lines - call them rays.

3.2 The specific intensity

The *monochromatic specific intensity*, I_ν , is used to characterize the strength of the radiation field at any point **r** in space, so $I_\nu = I_\nu(\mathbf{r})$. Choose an infinitesimal area *dA* at the position **r** and measure the energy $d\varepsilon$ of the photon rays that cross *dA* normal to *dA* in a time *dt* contained in a solid angle $d\Omega$ about a specified direction.

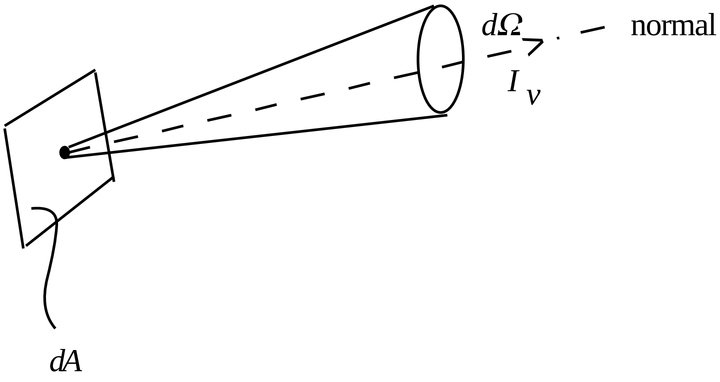


Fig. 3-1

The energy $d\varepsilon$ is written

$$d\varepsilon = I_\nu \, d\nu \, dA \, dt \, d\Omega \tag{3.1}$$

and the units of I_ν are

energy per Hz per unit area per second per ster.

(One Hz = 1 cycle per second.)

Photons travel in straight lines so along any photon direction (ray) I_ν is constant (unless the photon interacts with matter).

Proof. Consider two small areas dA_1 and dA_2, a distance R apart. A set of rays passes through both dA_1 and dA_2. If I_1 and I_2 are the specific intensities, energy passing through A_1 in a time dt is

$$I_1 dA_1 dt d\Omega_1 d\nu$$

and through A_2 is

$$I_2 dA_2 dt d\Omega_2 d\nu \quad .$$

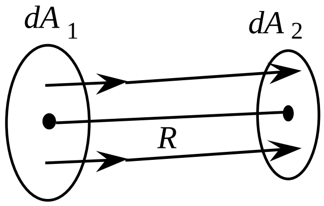


Fig. 3-2

But $d\Omega_1 = \frac{dA_2}{R^2}$, $d\Omega_2 = \frac{dA_1}{R^2}$.

Hence $I_1 = I_2$.

Thus along a ray $\frac{dI_\nu}{ds} = 0$ where s is measured along the ray.

A *mean intensity* may be obtained by averaging over the solid angle

$$J_\nu = \frac{1}{4\pi}\int I_\nu d\Omega . \qquad (3.2)$$

3.2.1 Flux

We discussed the flux from a point source in §2. To relate the flux F_ν to the specific intensity I_ν place a surface dA at any point and calculate the photon energy crossing dA in unit time carried by photons with rays contained within the solid angle $d\Omega$

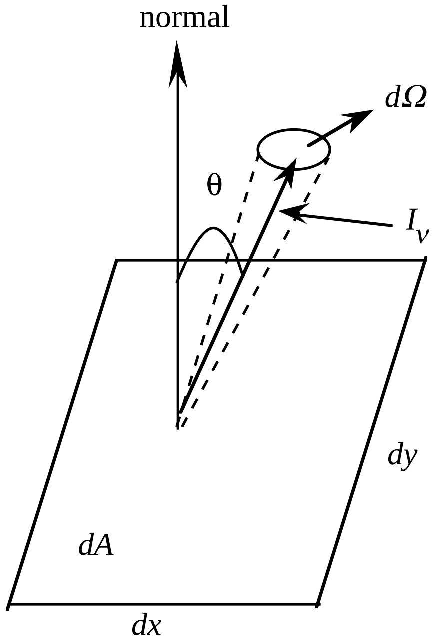


Fig. 3.3

It is

$$dF_\nu = I_\nu \cos\theta\, d\Omega \text{ ergs cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}\text{ Hz}^{-1} \ . \tag{3.3}$$

Integrating over all directions $d\Omega$ gives the flux, the energy crossing unit area per unit time per unit frequency,

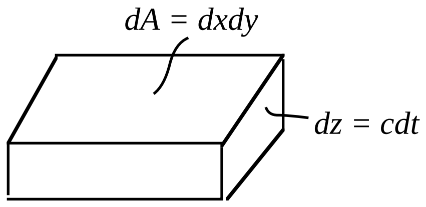
$$F_\nu = \int I_\nu \cos\theta\, d\Omega \text{ ergs cm}^{-2}\text{ s}^{-1}\text{ Hz}^{-1} . \tag{3.4}$$

For an isotropic radiation field I_ν , $F_\nu = I_\nu \int \cos\theta\, d\Omega = 0$ —there are as many photons crossing the surface from left to right as there are from right to left, so net flux is zero.

3.3 Energy Density

Instead of total flux or intensity, we can use energy density as a measure of the strength of the radiation field. Energy density is the photon energy per unit volume.

Consider a slab of surface area $dA = dxdy$ and thickness dz. In a time $dt = dz/c$, the photons will fill a volume $cdAdt$.



The photon energy per unit solid angle per Hz is

$$d\varepsilon = u_\nu(\Omega)d\nu\, d\,\Omega\, dxdydz = u_\nu(\Omega)d\gamma\, d\,\Omega\, dA\, cdt \tag{3.5}$$

But also by definition of I_ν

$$d\varepsilon = I_\nu(\Omega)d\nu\, d\,\Omega\, dA\, dt\,. \tag{3.6}$$

Hence energy density per unit solid angle is

$$u_\nu(\Omega) = \frac{I_\nu(\Omega)}{c} \tag{3.7}$$

and the energy density

$$u_\nu = \int u_\nu(\Omega)d\,\Omega = \frac{1}{c}\int I_\nu d\,\Omega = \frac{4\pi}{c} J_\nu\,. \tag{3.8}$$

J_ν is the mean intensity(see (3.2)).

If I_ν is isotropic

$$u_\nu = \frac{4\pi}{c} I_\nu \text{ ergs cm}^{-3}\text{ Hz}^{-1} \tag{3.9}$$

$$u = \int u_\nu d\nu = \frac{4\pi}{c} \int I_\nu d\nu \quad \text{ergs cm}^{-3} \quad . \tag{3.10}$$

To obtain photon density n_ν and $n = \int n_\nu d\nu$, divide u_ν by $h\nu$. Thus

$$n_\nu = \frac{u_\nu}{h\nu} \text{ , } n = \int \frac{u_\nu}{h\nu} d\nu \text{ cm}^{-3} \text{ .} \tag{3.11}$$

3.4 Radiation Pressure

Pressure is force per unit area or momentum transfer per unit area per unit time. Because each photon has a momentum, $p = \frac{E}{c}$, a collection of photons exerts pressure. Consider photons bouncing back and forth between two plates of area A and separation L.

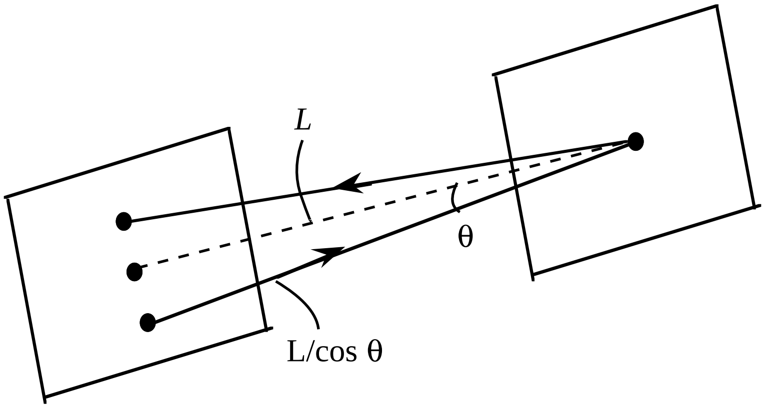


Fig. 3-4

Pressure is force per unit area and force is the rate of change of momentum. Each reflected photon transfers momentum $2p\ \cos\theta$ in a time Δt and $\Delta t = \frac{1}{c}\ \frac{2L}{\cos\theta}$. Hence

$$\Delta P = \frac{2p\ cos\theta}{A\Delta t} = \frac{pc}{AL}\ \cos^2\theta. \tag{3.12}$$

AL is the volume and pc is the photon erergy so pc/AL is the energy density Δu. Thus

$$\Delta P = \Delta u\ \cos^2\theta. \tag{3.13}$$

For an isotropic distribution, averaging over θ (equivalent to adding all the photons)

$$P = \frac{1}{3}\ u\ . \tag{3.14}$$

The same argument applies to particles except that $E = \frac{1}{2}p\mathrm{v}$ so $P = \frac{2}{3}u$.

3.5 Flux from a sphere of uniform brightness

A sphere of uniform brightness B is a sphere on the surface of which the specific intensity is everywhere equal to a constant B.

At a point P, the specific intensity or brightness along any ray through P is B if the ray intersects the sphere, and zero if it doesn't. We calculate the flux F

received at a point *P*, a distance *r*=*OP* from the center of the sphere

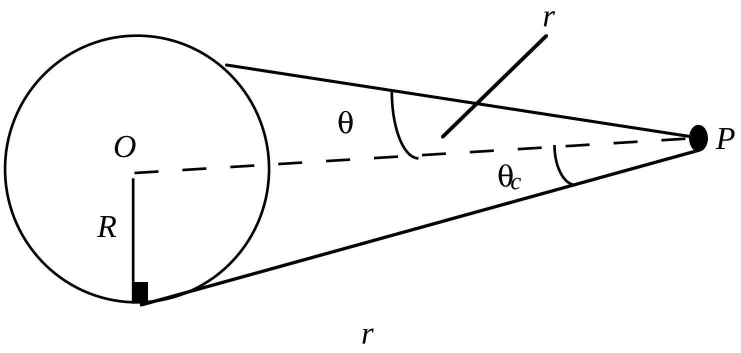


Fig. 3-5

$$F = \int I \cos\theta \, d\Omega$$

$$= B \int_0^{2\pi} d\phi \int_0^{\theta_c} \sin\theta \cos\theta \; d\theta$$

$$= \pi B(1\text{-}\cos^2 \theta_c) = \pi B \sin^2 \theta_c \qquad (3.15)$$

where $\sin\theta_c = R/r$ is the ray which is tangent to the sphere. Hence

$$F = \pi B(R/r)^2 \; . \qquad (3.16)$$

The specific intensity I=B is constant and the solid angle subtended by the source diminishes so that the $1/r^2$ law is satisfied.

Note that if

$$r = R,\ F \equiv F_s = \pi B. \tag{3.17}$$

i.e., the flux at a surface of uniform brightness B is πB.

The luminosity L is obtained from

$$L = 4\pi\ r^2 F \tag{3.18}$$

where F is the flux at any r.

Hence at r=R,

$$L = 4\pi R^2 F_s = 4\pi R^2 (\pi B)\ . \tag{3.19}$$

If we know L and F_s, we can obtain R, the stellar radius.

3.5.1 Thermal Radiation

Systems in thermal equilibrium may be characterized by a temperature T. The radiation I_ν from a blackbody—an enclosure that absorbs all the photons incident on its interior surface—comes into equilibrium between photons absorbed and photons emitted and I_ν is a function only of ν that depends only on T and is independent of angle (isotropic)

$$I_\nu = B_\nu(T). \tag{3.20}$$

The *Planck function* is (see *Radiative Processes in Astrophysics*, Rybicki and Lightman, Wiley 1979)

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(h\nu/kT\right) - 1} \ \mathrm{erg\ cm^{-2}\,Hz^{-1}\ s^{-1}\,sr^{-1}} \tag{3.21}$$

where k is Boltzmann's constant $k = 1.38 \times 10^{-16}$ ergs K^{-1} .

In terms of wavelength

$$I_\nu(T)\, d\nu = I_\lambda(T)\, d\lambda \tag{3.22}$$

so

$$I_\lambda = \frac{I_\nu d\nu}{d\lambda} = \frac{I_\nu c}{\lambda^2} \tag{3.23}$$

$$B_\lambda(T) = \frac{c}{\lambda^2}\, B_\lambda(T) = \frac{2hc}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}. \tag{3.24}$$

in ergs $\mathrm{cm}^{-2}\ \lambda^{-1}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$.

If λ is in cm, $\frac{hc}{kT\lambda} = 1.441/\lambda T$.

If λ is in nm, $\frac{hc}{kT\lambda} = \frac{1.441 \times 10^7}{\lambda T}$.

3.5.2 High and low ν limits

For $h\nu >> kT$,

$$B_\nu(T) \sim \frac{2h\nu^3}{c^2} e^{-h\nu/kT} \tag{3.25}$$

decreases exponentially (called the Wien tail).

For $h\nu << kT$.

$$\exp(h\nu/kT) \sim 1 + h\nu/kT + \ldots$$

so

$$B_\nu(T) \sim \frac{2\nu^2}{c^2} kT \tag{3.26}$$

(in radio astronomy, intensity is often given simply as a brightness temperature T.)

As the temperature increases in the optical, the color changes from red (600 nm) through yellow (560 nm) to green (500 nm) to blue (450 nm). The color temperature is the temperature that describes the shape of the blackbody curve—it can be defined as the temperature that reproduces the ratio of $I_\nu(T)$ at two different wavelengths. So instead of color, we can use a physical property, the temperature.

The frequency at which $B_\nu(T)$ peaks is given by

$$\frac{d}{d\nu} B_\nu(T) = 0.$$

If $x = h\nu/kT$,

$$\frac{d}{dx}\left(\frac{x^3}{e^x - 1}\right) = \frac{3x^2\left(e^x - 1\right) - x^3 e^x}{\left(e^x - 1\right)^2} \tag{3.27}$$

which equals zero when

$$x = 3(1 - e^{-x}) \tag{3.28}$$

with solution $x = 2.82$.

Thus

$$h\nu_{\max} = 2.82\, kT\ .$$

$$\nu_{\max} = 5.88 \text{ x } 10^{10}\, T \text{ Hz.} \tag{3.29}$$

In wavelengths,

$$B_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/kT\lambda} - 1} \tag{3.30}$$

If $y = hc/kT\lambda$,

$$\frac{d}{dy} \frac{y^5}{e^y - 1} = 0 \tag{3.31}$$

which works out to be $y = 5(1 - e^{-y})$ with solution $y = 4.97$.

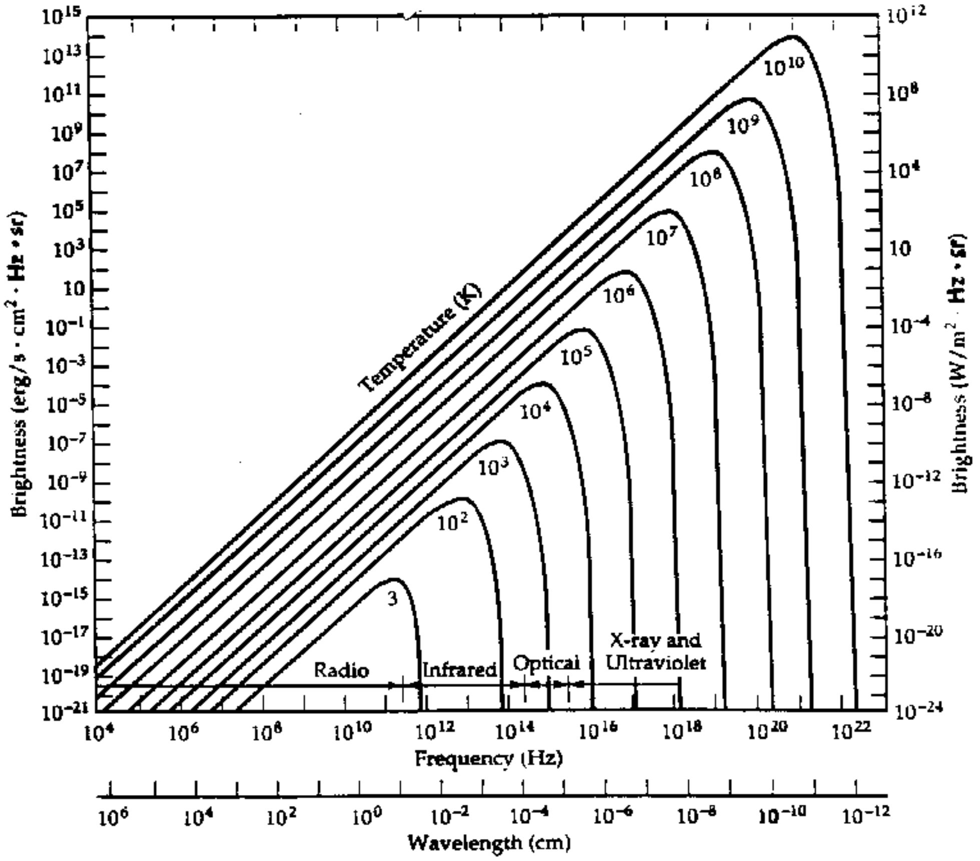
$B_\lambda(T)$ peaks at λ_{max} where

$$\lambda_{max} = \frac{0.2898}{T} \text{ cm} \tag{3.32}$$

—note $\lambda_{\max} \neq c/\nu_{\max}$.

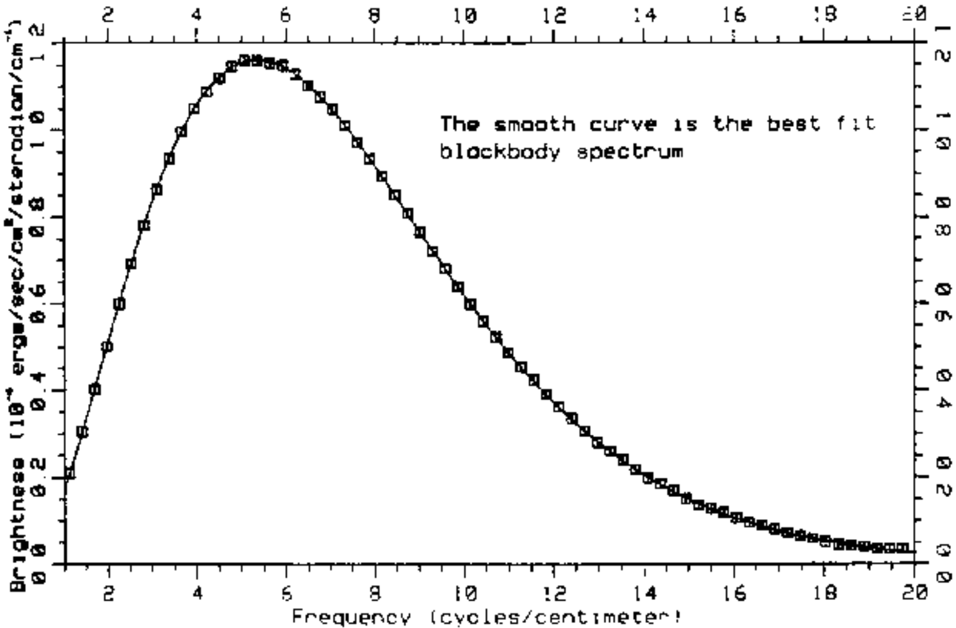
The location of the peak of Bn(T) at any given temperature is called Wien's displacement law. The Sun peaks at 500 nm hence

$$T = 5796\text{K}.$$



Blackbody radiation emission. A log–log plot of the Planck curves for a wide range of temperatures. Note that the wavelengths run from longer to shorter in units of centimeters.

Fig. 3-6



Preliminary spectrum of the cosmic microwave background from the FIRAS instrument at the north Galactic pole, compared to a blackbody. Boxes are measured points and show size of assumed 1% error band. The units for the vertical axis are 10^{-4} ergs s^{-1} cm^{-2} sr^{-1} cm.

Fig. 3.7

The cosmic background spectrum in Fig. 3-8 peaks at 5.43 cm^{-1}. Multiple by c to get 1.60×10^{11} Hz. Wien's law gives $T = \dfrac{1.60 \times 10^{11}}{5.88 \times 10^{10}} = 2.73\text{K}$.

3.6 Stefan-Boltzmann Law

The total energy density in an isotropic radiation blackbody field at temperature T

$$
\begin{aligned}
u &= \frac{1}{c} \int I_\nu d\nu d\Omega = \frac{4\pi}{c} \int I_\nu d\nu \\
&= \frac{4\pi}{c} \int \frac{2h\nu^3 \, d\nu}{c^2 \left(e^{h\nu/kT} - 1\right)} \qquad (3.33) \\
&= \frac{4\pi}{c} \frac{2h}{c^2} \left(\frac{kT}{h}\right)^4 \int_0^\infty \frac{x^3 dx}{e^x - 1}
\end{aligned}
$$

where $x = h\nu/ kT$. The integral is a definite integral and it is a number $\pi^4/15$. So energy density u is

$$u = \frac{8\pi^5}{15} \frac{k^4}{h^3 c^3} T^4 \equiv aT^4 \qquad (3.34)$$

where

$$a = 7.56464 \text{ x } 10^{-15} \text{ ergs cm}^{-3} K^{-4} \ . \qquad (3.35)$$

The emergent flux from the surface of a blackbody F_S is given by (it is isotropic)

$$F_s = \pi B = \pi \int I_\nu d\nu = \frac{c}{4} u \qquad (3.36)$$

So at the surface

.

$$F_s = \frac{ac}{4} T^4 = \sigma T^4 \tag{3.37}$$

σ is the Stefan-Boltzmann constant with the value

$$\sigma = 5.66956\text{x}10^{-5} \text{ ergs cm}^{-2} \text{ s}^{-1} K^{-4}. \tag{3.38}$$

Thus, for example, a sphere of radius $R = 7.0\text{x}10^{10}$ cm with a temperature of 5770°K has a luminosity (~ the Sun)

$$L = 4\pi R^2 F_\text{s} = 4\pi R^2 \sigma T^4 \tag{3.39}$$

$$= 3.9\text{x}10^{33} \text{ ergs s}^{-1} \tag{3.40}$$

Various temperatures may be defined.

An effective temperature T_{eff} is such that the measured flux

$$F_s = \sigma T_{eff}^4 . \tag{3.41}$$

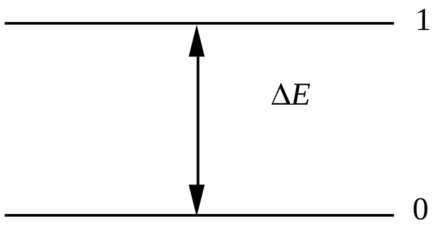
A brightness temperature T_B at frequency ν is such that $I_\nu = B_\nu(T_B)$. A color temperature T_c is used such that

$$\frac{I_{\nu_1}}{I_{\nu_2}} = \frac{B_{\nu_1}(T_c)}{B_{\nu_2}(T_c)}. \tag{3.42}$$

3.6.1 Einstein A and B coefficients (optional)

Atoms and molecules have discrete states and photons can be emitted and absorbed in transitions between them. The rates at which they do can be related by the following argument.

Consider an atom with two levels 0 and 1, sitting in a radiation field,



separated in energy by ΔE. In a transition from state 1 to state 0, a photon of energy $\Delta E = h\upsilon_{10}$ is emitted. In a transition from 0 to 1, a photon of energy ΔE is absorbed. The absorption results from the presence of a radiation energy density

$$\rho(\nu_{10}) = \frac{4\pi}{c} B_\nu(T) \tag{3.43}$$

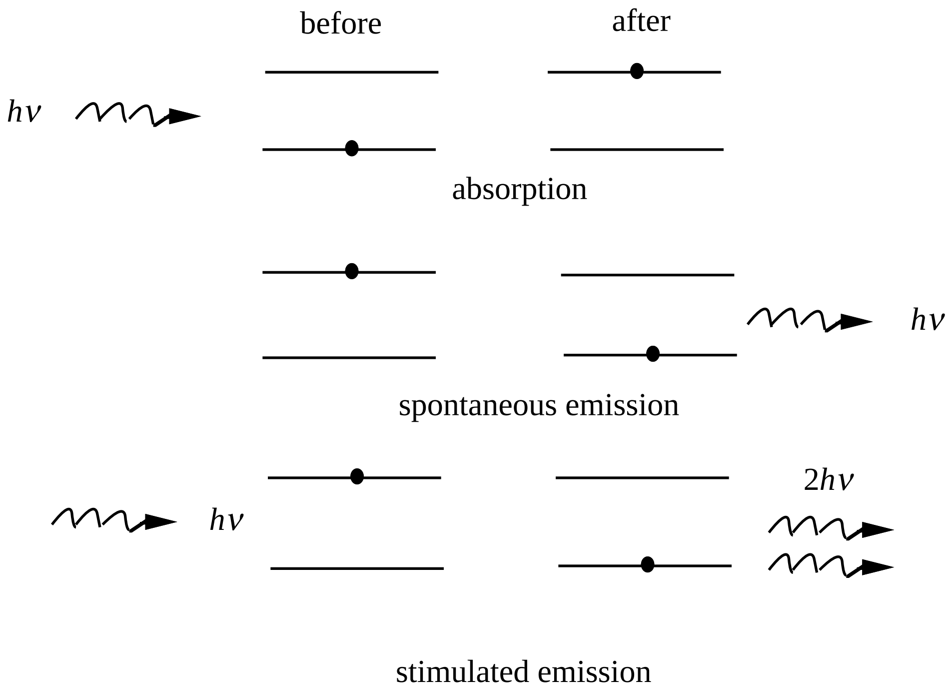
and occurs at a rate

$$n_o \rho(\nu_{10}) B_{01} \tag{3.44}$$

where n_0 is the density of atoms in state 0 and B_{01} is an atomic parameter. Emission occurs in two ways. By stimulated emission at a rate

$$n_1\rho\ (\nu_{\backslash 0})B_{10}\ , \tag{3.45}$$

where n_1 is the density of state 1, and by spontaneous emission at a rate n_1A_{10},



In equilibrium

$$n_o\rho(\nu_{10})\ B_{01} = n_1\ \{\rho\ (\nu_{10})\ B_{10} + A_{10}\} \tag{3.46}$$

But also in equilibrium

$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\ exp\ \left(-h\nu_{10}/kT\right)\ . \qquad (3.47)$$

The g's are statistical weights and are equal to the number of levels having the same energy and angular momentum. From these two equations satisfied at all T and all ν, and written in the form

$$\frac{A_{10}}{\rho} = \frac{n_0}{n_1} B_{01} - B_{10} \qquad (3.48)$$

we conclude that

$$g_0 B_{01} = g_1 \mathrm{B}_{10} \qquad (3.49)$$

and

$$A_{10} = \frac{8\pi h\nu_{10}^3}{c^3}\ \frac{\mathrm{g}_0}{\mathrm{g}_1} B_{01} = \frac{8\pi h\nu_{10}^3}{c^3}\ B_{10} \qquad (3.50)\ .$$

Apart from statistical weights, the rate coefficients for absorption and stimulated emission are equal. The radiative lifetime of state 1 is $1/A_{10}$.

The relationship

$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\ exp\ \left(-h\nu_{10}/kT_{\mathrm{exc}}\right) \qquad (3.51)$$

is often expressed by an excitation temperature T_{exc} whether or not thermal equilibrium prevails, the equation defining T_{exc}. In many astrophysical environments T_{exc} is negative—there is an overpopulation of the excited state—leading to the possibility of maser or laser action.

3.7 Radiation balance

The Earth is heated by the radiation from the Sun and it loses by radiation the same average power it receives. The Sun illuminates $\pi R_{\oplus}^{2}$ of the projected Earth area, the Earth radiates from its actual surface area of $4\pi R_{\oplus}^{2}$ so the average *insolation* is 1/4 the solar constant 1370 W/m^2. Recall from p.1-22 that the solar constant is the solar flux arriving at Earth. The insolation is

$$F_{ins} = 1/4 \text{ x } 1370\ W/m^2 = 3.42 \times 10^5 \text{ erg s}^{-1} \text{ cm}^{-2} \ .$$

The outgoing flux is σT^4 so (1W = 10^7 ergs s^{-1})

$$(5.67 \text{ x } 10^{-5} \text{ ergs cm}^{-2} \text{ s}^{-1})\ T^4 = 3.42 \text{ x } 10^5 \text{ ergs s}^{-1} \text{ cm}^{-2} \qquad T \text{ in } K$$

$$\therefore\ T = 280K = 7°C = 45°F.$$

Actual value is modified by the greenhouse effect—infrared radiation emitted by the surface is absorbed by CO_2 and H_2O in the atmosphere—half the absorbed radiation is then lost to space and the other half retained—heating the atmosphere. If the greenhouse were without windows and totally absorbing, T would be increased to the value

$$\tfrac{1}{2}(5.67 \text{ x } 10^{-5}\, T^4) = (F_{ins} = \ 3.42 \times 10^5)$$

$$T = 333\ K\ = 60°\ C = 140°\ F$$

—not comfortable. The actual situation is complicated by reflection from clouds and the oceans. The absorbed radiation is about 61% of the total insolation. The ratio of reflected energy to incident energy is called the *albedo*. There is also a minor source of heat flowing from the hot interior of the Earth.

3.7.1 Temperatures of the planetary surfaces

The effective equilibrium blackbody temperatures of the planets are given in Table 3-1.

Table 3-1

Planet	***T*(*K*)**	**Planet**	***T*(*K*)**
Mercury	445	Jupiter	122
Venus	325	Saturn	90
Earth	277	Uranus	63
Mars	235	Neptune	50
		Pluto	44

On Venus, with its dense atmosphere of CO_2 the actual surface temperature is $700K = 427°C = 801° F$.

3.8 Spectral Sequence of Stars

Historically, stars were classified by color. Color as a property is independent of distance, though a correction may be required for the interstellar reddening of starlight through extinction by interstellar dust(more in Chapter 7). Each color range is specified as a spectral class labelled O, B, A, F, G, K, M in proceeding from the blue violet color to red. You may remember it more easily as *Oh, be a fine girl (guy), kiss me* or *Only Bungling Astronomers Forget Generally Known Mnemonics*. Each class is divided numerically into finer steps. The Sun is a typical G2 star. The colors can be characterized by a *color temperature*. Table 3-2 summarizes the classification. Remember $B\text{-}V \equiv M_B\text{-}M_V = m_B\text{-}m_V$.

Table 3-2

The Spectral Sequence			
Spectral Class	**Color**	**B-V**	**Temperature**
O	blue-violet	-0.35	28,000-50,000
B	blue-white	-0.16	10,000-28,000
A	white	+0.13	7,500-10,000
F	yellow-white	+0.42	6,000-7,000
G	yellow	+0.70	5,000-6,000
K	orange	+1.2	3,000-5,000
M	red-orange	+1.2	2,500-3,500

The classification has been extended into the infrared, adding classes RNS, and still more recently *L* and *T*.

Once distances could be determined, the absolute magnitudes or luminosities could be calculated. The diagram showing the luminosities as a function of spectral type is the Hertzsprung-Russell or H-R diagram. Here it is:

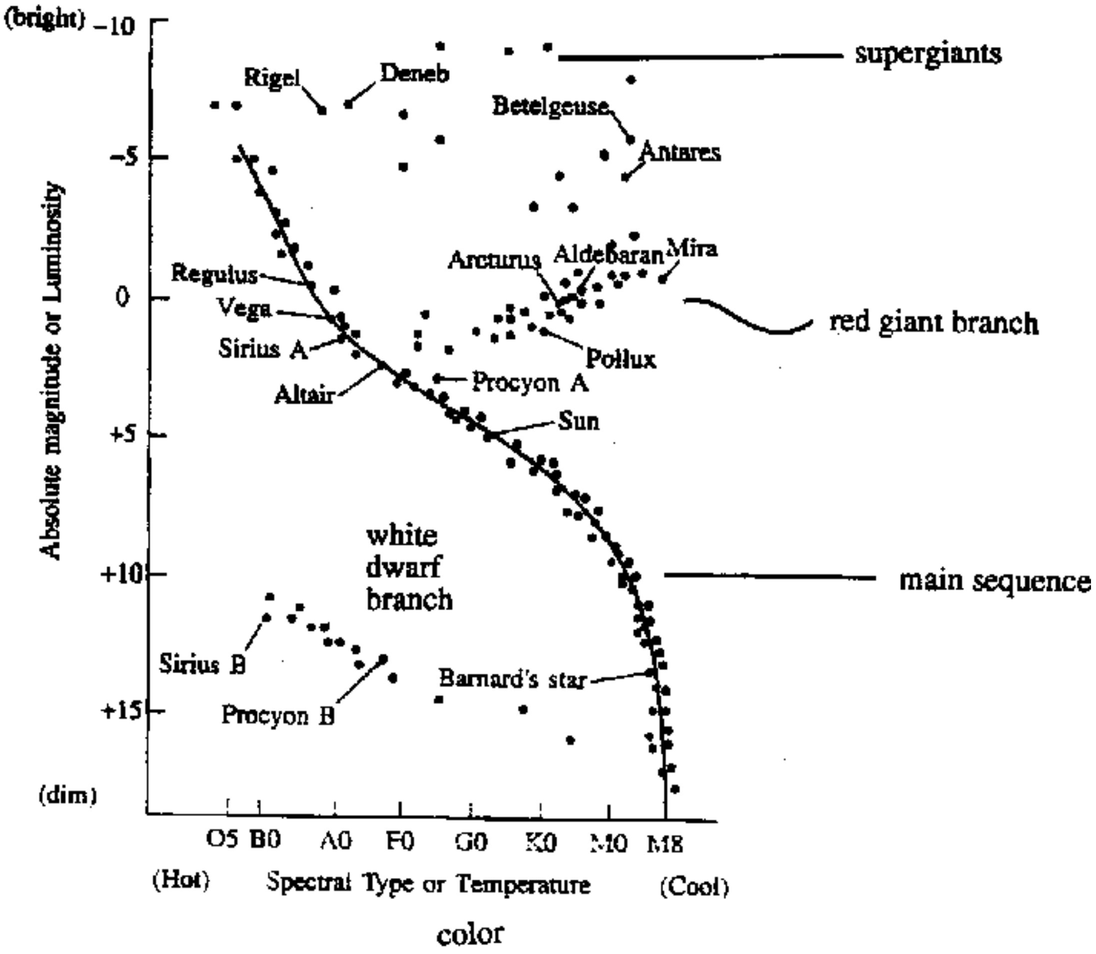


Fig. 3-8

The radii of stars can be estimated from $L = 4\pi R^2 F_s = 4\pi R^2 \sigma T^4$

Temperature also effects the excitation of the atoms and molecules in the stellar atmosphere and the different spectral classes differ in the details of the spectra. In the outer atmosphere of the star, the density is low and the atoms of the atmosphere absorb radiation emitted from the interior. Absorption lines appear that are characteristic of the atoms present which in turn depend on the temperature. In the Sun, the absorption features are called Fraunhofer absorption lines.

If the atmosphere is hot enough, the atoms can lose electrons and become ions, which have their own unique absorption (and emission) lines.

O stars show the presence of ionized atoms, especially He^+.

B stars—neutral He, some Hydrogen

A stars—strong hydrogen, ionized metals. (it is easier to ionize a metal than He or H)

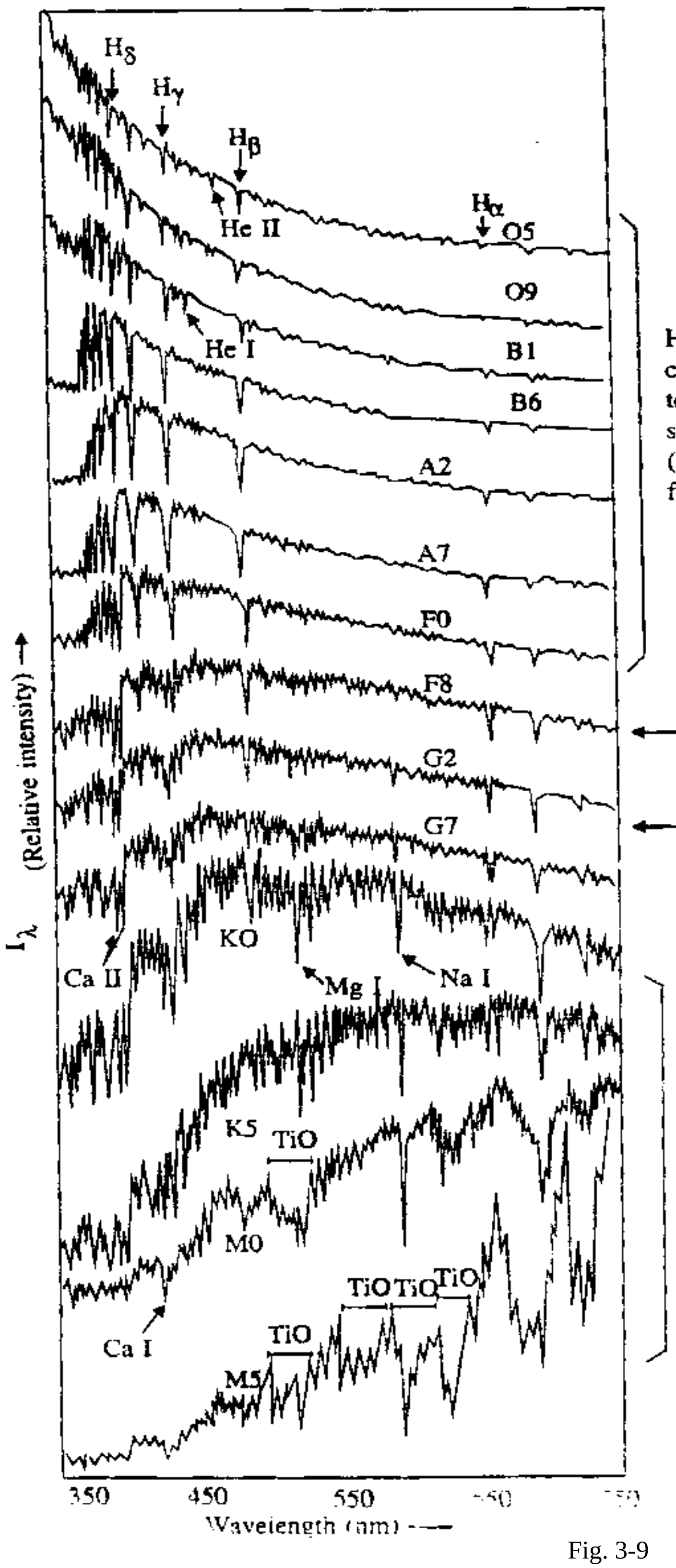
F stars - hydrogen, ionized Ca^+, Fe^+

G stars - Ca^+, ionized and neutral metals

K stars - neutral metals

M stars - molecules like TiO, VO and neutral Ca.

Here is a picture of the spectra of several stars.



$$B_\nu(T) \sim \frac{2\nu^2}{c^2}kT$$

Here we are seeing the Rayleigh-Jean's continua, flux proportional to temperature, with relatively small and few absorption features. (Compare shape of curves in the figure in Section 3.5.2.)

here we clearly see the peak of the Planck function, around 4500 Å

the Sun fits here (G2)

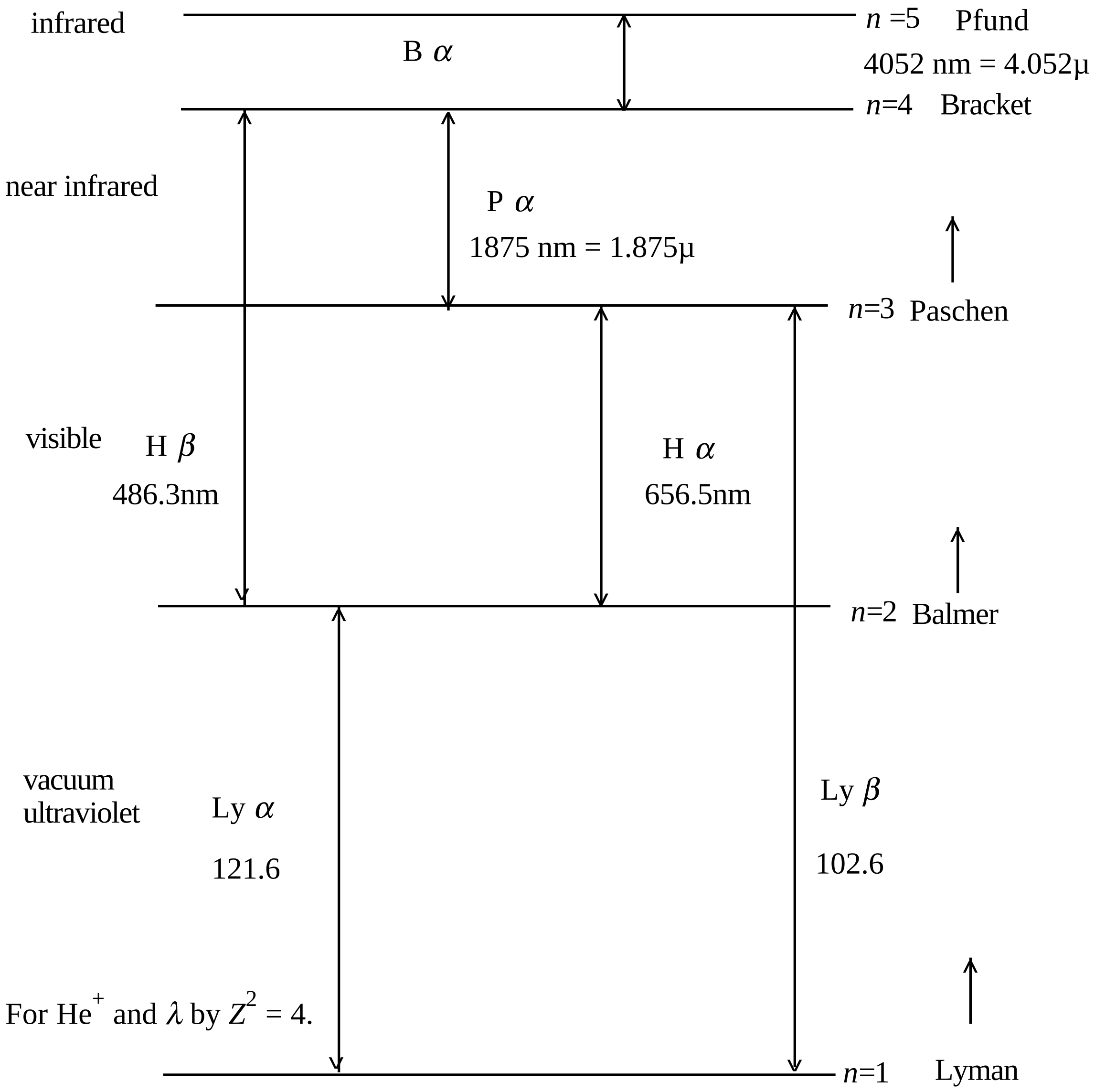
$$B_\nu \sim \frac{2h\nu^3}{c^2} e^{-h\nu/kT}$$

Here we are on the Wien tail, with lots of messy absorption lines and molecular bands.

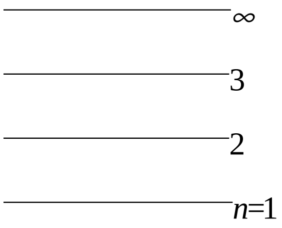
Fig. 3-9

Table 1-1 is the level diagram for atomic hydrogen.

Table 1-1



I will explain the notation. The hydrogen atom has discrete energy levels labeled by a principal quantum number *n* and transitions take place between energy levels.



A change in *n* of 1 is an alpha line, 2 beta, 3 gamma... The Lyman series is a transition to or from n=1 and the lines are denoted as Lyα, Lyβ... The transitions into or out of n=2 are Balmer lines denoted Hα, Hβ ...etc. Thus Hα is $n = 3 \rightarrow 2$. Hβ is $4 \rightarrow 2$. The label I means a neutral atom, II a singly charged ion and so on. So CaII = Ca^+, calcium having lost an electron and TiO is the molecule titanium oxide, VO is vanadium oxide.

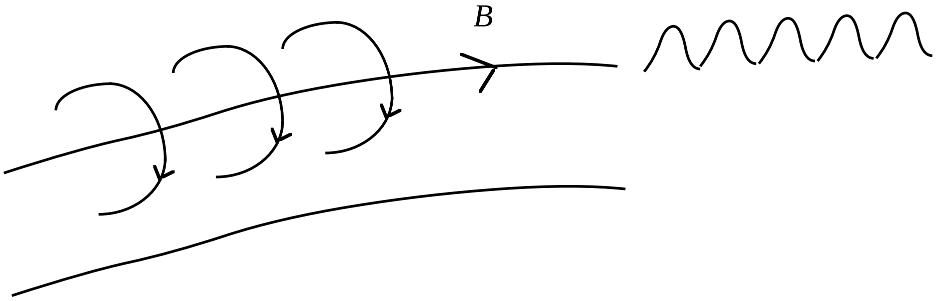
Figure 3-9 shows a series of approximate blackbody curves interrupted by absorption features whose wavelengths identify the absorbing atoms and whose strengths provide a measure of their abundances.

3.9 Other Radiation Mechanisms

Here we look briefly at microscopic processes other than atomic and molecular emissions that lead to radiation. Radiation is created by the acceleration of charged particles.

3.9.1 Synchrotron radiation

Synchrotron radiation is produced spontaneously by relativistic electrons accelerated by magnetic fields—the electrons move in helical patterns spiralling around field lines.



Radiation is called *cyclotron* radiation for non-relativistic electrons—frequency is simply the frequency of gyration around the magnetic field. Synchrotron radiation is highly polarized continuum emission with the radiation occurring in the direction of the electron's motion. Its variation with frequency depends on the electron energy distribution but is often $\nu^{-\alpha}$ where α is between 0 and -2, quite different from thermal. It is called non-thermal emission.

3.9.2 Bremsstrahlung

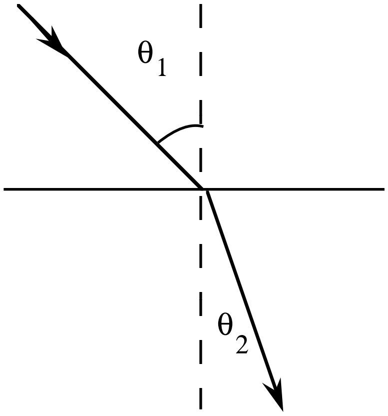
Electrons scatter of charged particles and the Coulomb interactions cause the electrons to accelerate and radiate. Radiation is a nearly unpolarized continuum. It has a flat spectrum in the radio and is Planck-like in the X-ray region.

A similar but weaker process occurs in the scattering of electrons by atoms. It is usually called *free-free emission*. The inverse can occur—free-free absorption—it is responsible for absorption in the Sun's atmosphere in the far infrared.

3.10 Telescopes

Two types - *refracting* and *reflecting*

Snell's law of refraction

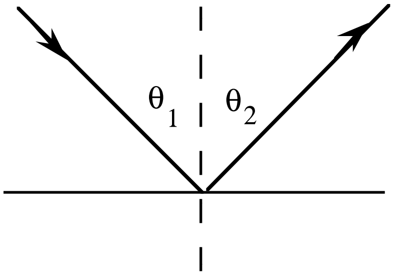


$$n_1(\lambda)\sin\theta_1 = n_2(\lambda)\sin\theta_2$$

Fig 3-10

$n(\lambda)$ is the refractive index at wavelength λ. It is a property of the medium and is a function of wavelength.

Law of reflection



$$\theta_1 = \theta_2 \text{ at all wavelengths} \tag{3.52}$$

Fig. 3-11

Refracting telescopes make use of a shaped lens to bring parallel light rays to a common point, the *focus*

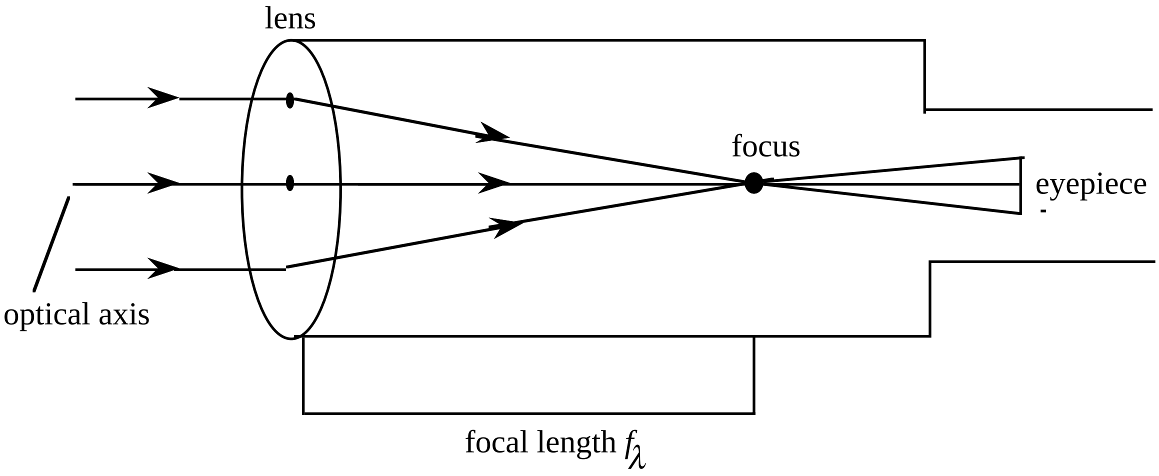


Fig. 3-12

f_λ is the *focal length*. The plane containing the focus, perpendicular to the optical axis is the *focal plane*.

Aberration is any distortion of the image. Aberration will occur if the optical axis is not exactly parallel to the incoming light rays. For a refracting telescope (but not a reflecting telescope) aberration occurs because the refractive index depends on wavelength. Spherical aberration occurs if not all elements of the lens or mirror have the same focal point.

Reflecting telescopes use shaped mirrors

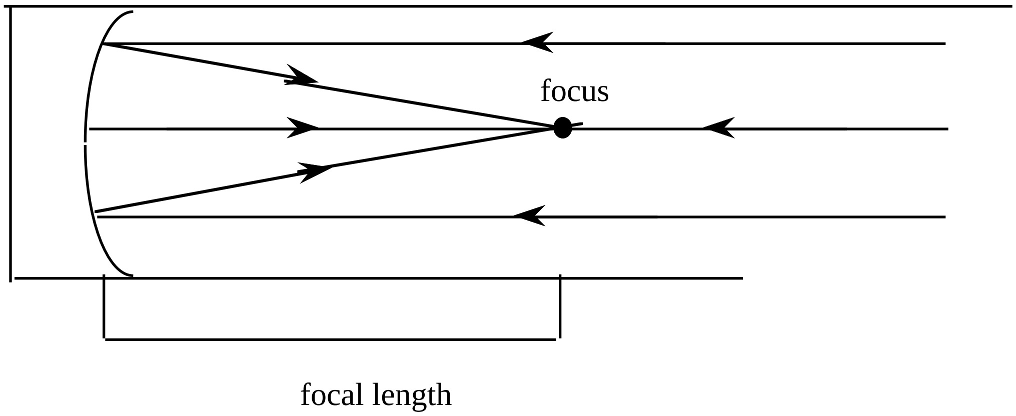


Fig. 3-13

The diagram illustrates a Prime focus optical system. The Newtonian system has in addition a secondary mirror to redirect the light through a hole in the side to a new focus

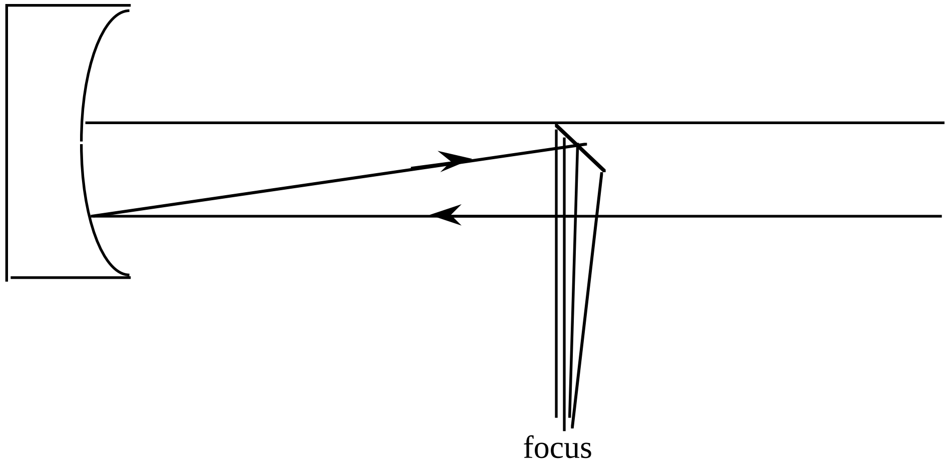


Fig. 3-14

In the Cassegrain optical system, there is a hole in the primary mirror and the secondary mirror reflects light into a new focus.

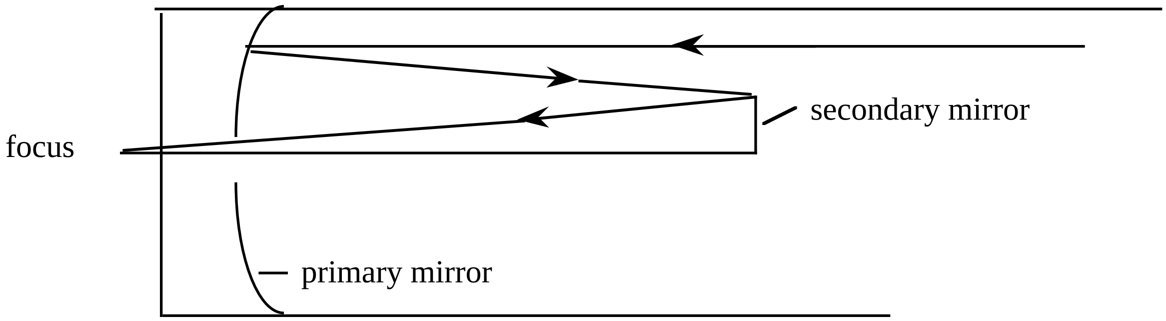


Fig. 3-15

Another version is the Coudé, which uses a third mirror between the primary and secondary.

See Ostlie and Carroll, Chapter 6, for an extensive discussion of particular telescopes.