Chapter 3: Radiation Mechanisms of Electromagnetic Emissions

3.1 Introduction of Radiation Mechanisms of Electromagnetic Emissions:

Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules.
Electromagnetic radiation is produced by either thermal mechanisms or non-thermal mechanisms.
Examples of thermal radiation include
• Continuous spectrum emissions related to the temperature of the object or material.
• Specific frequency emissions from neutral hydrogen and other atoms and molecules.
Examples of non-thermal mechanisms include
• Emissions due to synchrotron radiation.
• Amplified emissions due to astrophysical masers.
In what follows we briefly describe five continuum emission mechanisms:
• Thermal (Black Body) Radiation
• Bremsstrahlung (free-free emission)
• Recombination (free-bound emission)
• Two-Photon emission
• Synchrotron emission

3.2 Thermal Radiation Mechanisms

Thermal radiation, process by which energy, in the form of electromagnetic radiation, is emitted by a heated surface in all directions and travels directly to its point of absorption at the speed of light; thermal radiation does not require an intervening medium to carry it.
Thermal radiation ranges in wavelength from the longest infrared rays through the visible-light spectrum to the shortest ultraviolet rays. The intensity and distribution of radiant energy within this range is governed by the temperature of the emitting surface. The total radiant heat energy emitted by a surface is proportional to the fourth power of its absolute temperature (the Stefan–Boltzmann law).

Properties of Thermal Radiation

Thermal radiation emitted by a body at any temperature consists of a wide range of frequencies. The frequency distribution is given by Planck's law of black-body radiation .

The dominant frequency (or color) range of the emitted radiation shifts to higher frequencies as the temperature of the emitter increases. For example, a *red hot* object radiates. This is determined by Wien's displacement law.

The total amount of radiation of all frequencies increases steeply as the temperature rises; it grows as T^4, as expressed by the Stefan–Boltzmann law.

Note // Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules.

3.2.1 Blackbody Radiation

A *blackbody* is defined as an object that does not reflect or scatter radiation shining upon it, but absorbs and reemits the radiation completely. A blackbody is a kind of an ideal radiator.

The radiation of a blackbody depends only on its temperature, being perfectly independent of its shape, material and internal constitution. The wavelength distribution of the radiation follows *Planck's law*, which is a function of temperature only. The intensity at a frequency ν of a blackbody at temperature T is:

$$B_\nu(T) = B(\nu; T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/(kT)} - 1}, \qquad \text{………………..(3.3)}$$

where

h = the Planck constant = 6.63×10^{-34} J s ,

c = the speed of light ≈ 3×108 m s^{-1} ,

k = the Boltzmann constant = 1.38×10^{-23} J K^{-1}.

Since radiation energy is constantly transformed into thermal energy of the atoms of the walls and back to radiation, the blackbody radiation is also called *thermal radiation*. The spectrum of a blackbody given by Planck's law (eq. 3.3) is continuous.

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/(\lambda kT)} - 1} \qquad \text{…………(3.4)}$$

Properties of the Planck Law

a—$h\nu \ll kT$: The Rayleigh–Jeans Law. In this case the exponential can be expanded

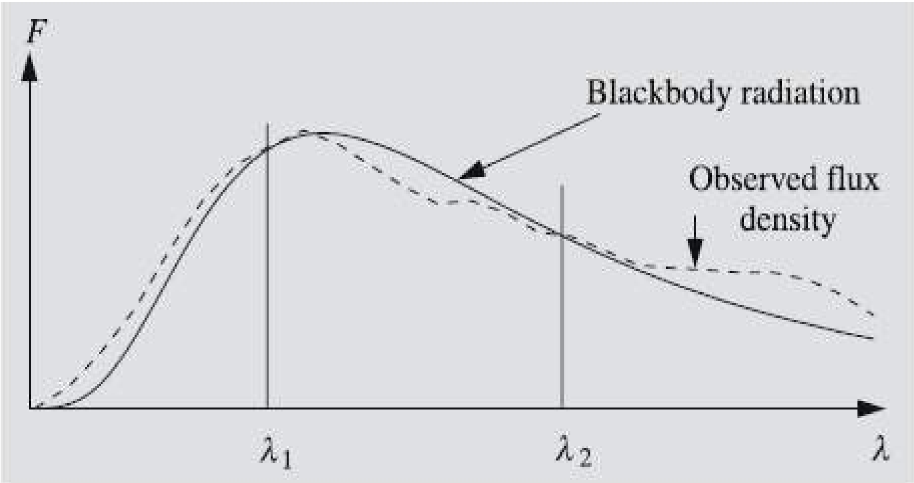
$$\exp\left(\frac{h\nu}{kT}\right) - 1 = \frac{h\nu}{kT} + \cdots$$

so that for $h\nu \ll kT$, we have the *Rayleigh–Jeans law*:

$$I_\nu^{RJ}(T) = \frac{2\nu^2}{c^2} kT.$$

b—$h\nu \gg kT$: Wien Law. In this limit the term unity in the denominator can be dropped in comparison with $\exp(h\nu/kT)$, so we have the *Wien law*:

$$I_\nu^W(T) = \frac{2h\nu^3}{c^2} \exp\left(\frac{-h\nu}{kT}\right).$$



Blackbody Properties:

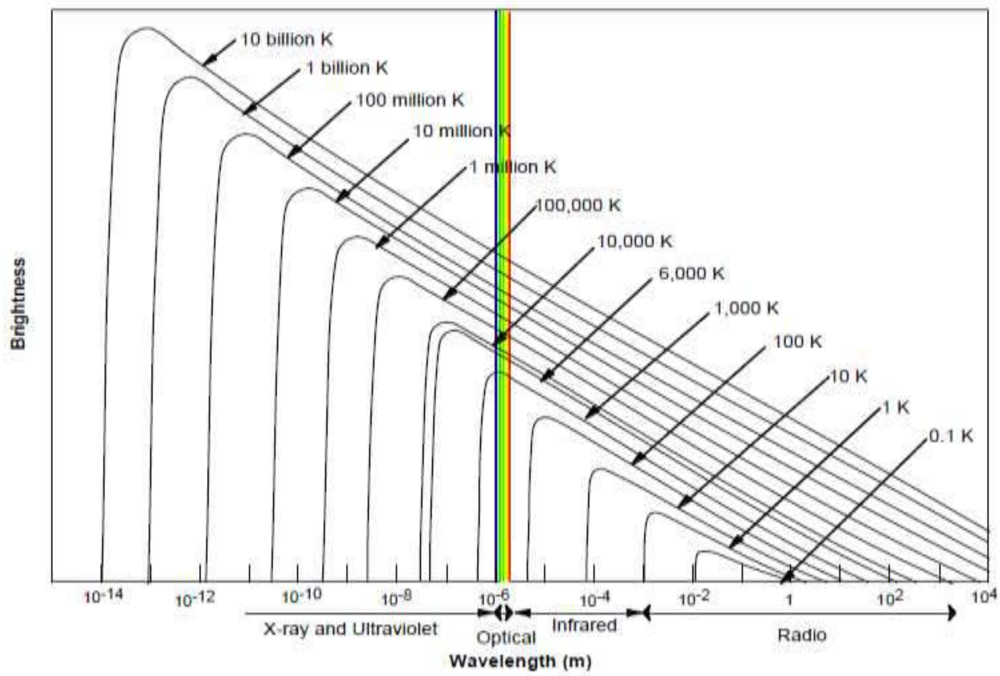
Blackbodies thus have three characteristics:

1. A blackbody with a temperature higher than absolute zero emits some energy at all wavelengths.
2. A blackbody at higher temperature emits more energy at all wavelengths than does a cooler one.
3. The higher the temperature, the shorter the wavelength at which the maximum energy is emitted.

For radiation produced by thermal mechanisms, the following table gives samples of wavelength ranges, the temperatures of the matter emitting in that range, and some example sources of such thermal radiation.

Type of Radiation	Wavelength Range (nanometers $[10^{-9}$ m])	Radiated by Objects at this Temperature	Typical Sources
Gamma rays	Less than 0.01	More than 10^8 K	Few astronomical sources this hot; some gamma rays produced in nuclear reactions
X-rays	0.01 - 20	10^6 - 10^8 K	Gas in clusters of galaxies; supernova remnants, solar corona
Ultraviolet	20 - 400	10^5 - 10^6 K	Supernova remnants, very hot stars
Visible	400 - 700	10^3 - 10^5 K	Exterior of stars
Infrared	10^3 - 10^6	10 - 10^3 K	Cool clouds of dust and gas; planets, satellites
Radio	More than 10^6	Less than 10 K	Dark dust clouds

Brightness of Electromagnetic Radiation at Different Wavelengths for Blackbody Objects at Various Temperatures



Two important laws of radiation had already been discovered:

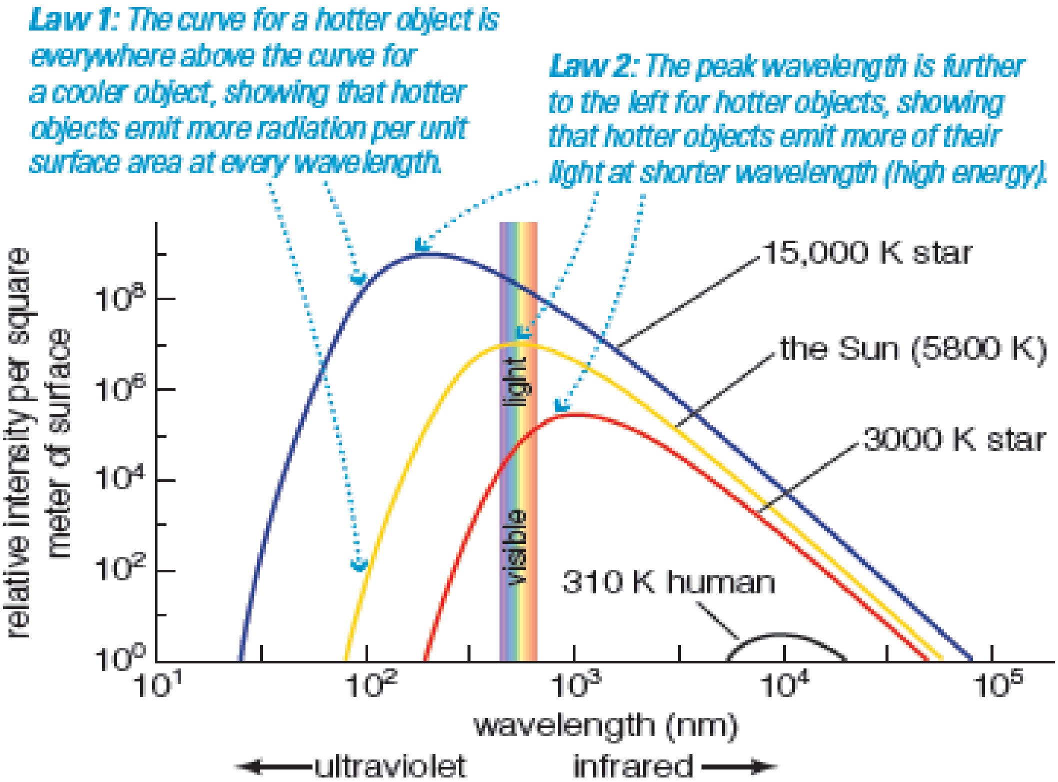
Law 1 (*Stefan-Boltzmann law*):

emitted power (per square meter of surface) $= \sigma T^4$

where σ (Greek letter *sigma*) is a constant with a measured value of $\sigma = 5.7 \times 10^{-8}$ watt/(m$^2 \times$ K^4) and T is on the Kelvin scale (K).

$$\text{Law 2 (Wien's law): } \lambda_{max} \approx \frac{2{,}900{,}000}{T \text{ (Kelvin scale)}} \text{ nm}$$

where λ_{max} (read as "lambda-max") is the wavelength (in nanometers) of maximum intensity, which is the peak of a thermal radiation spectrum.



Continuum Emissions from Ionized Gas

Thermal blackbody radiation is also emitted by gases. Plasmas are ionized gases and are considered to be a fourth state of matter, after the solid, liquid, and gaseous states. As a matter of fact, plasmas are the most common form of matter in the known universe (constituting up to 99% of it!) since they occur inside stars and in the interstellar gas. An atom in a gas becomes ionized when another atom bombards it with sufficient energy to knock out an electron, thus leaving a positively charged ion and a negatively charged electron.

Thermal Radiation of Giant planets

Two sources of radiation:

- Directly reflected Sun light
- Absorbed Solar radiation, reradiated as a cool blackbody

e.g. Jupiter: $L_{sun} = 3.86 \times 10^{33}$ erg s^{-1}

$a_J = 7.8 \times 10^{13}$ cm Jupiter orbital radius

$R_J = 7.1 \times 10^{9}$ cm Jupiter radius

Solar radiation incident on the planet is:

$$L_J = \frac{\pi R_J^2}{4\pi a_J^2} \times L_{sun} \approx 2 \times 10^{-9} L_{sun}$$

Suppose planet directly reflects 10% - in the optical Jupiter is ~10^{10} times fainter than the Sun as seen from another star - about 25 magnitudes.

3.2.2 Bremsstrahlung (Free-free Radio) Emissions

Free-free Radio Emission from an HII Region

Thermal bremsstrahlung from an ionized hydrogen cloud (HII region) is often called ***free-free*** emission because it is produced by free electrons scattering off ions without being captured—the electrons are free before the interaction and remain free afterwards. We will assume that the energy lost by an electron when it interacts with an ion is much smaller than the initial electron energy. We will ignore radiation from electron-electron collisions and from ions.

Radio photons are produced by weak interactions, meaning the change ΔEe of electron kinetic energy is much smaller than the intial kinetic energy E . The reason is that the energy (E_γ = hν) of a radio photon is much smaller than the average kinetic energy of an electron in an HII region. This numerical comparison is an example of how astrophysical "intuition" simplifies the electron-ion scattering problem.

The mean electron energy in a plasma of temperature T is:

$$E_e = \frac{3kT}{2} \quad \text{……(3.13)}$$

For an HII region with T ≈10^4K, this is

$$E_e \approx \frac{3 \times 1.38 \times 10^{-16}\ \text{erg K}^{-1} \times 10^4\ \text{K}}{2} \approx 2 \times 10^{-12}\ \text{erg} \approx 1\ \text{eV}$$

[This is another useful conversion factor to remember: 1 eV is the typical energy associated with the temperature T $\approx 10^4$K.] The energy of a photon is $E_\gamma = h\nu$ ·. For example, a radio photon of frequency ν= 10 GHz has energy

$$E_\gamma \approx 6.63 \times 10^{-27} \text{ erg s } \times 10^{10} \text{ Hz } \approx 6.63 \times 10^{-17} \text{ erg } \approx 4 \times 10^{-5} \text{ eV}.$$

The great inequality $E_\gamma << E_e$ means that most radio photons are produced by weak interactions that cause the trajectory of the electron to deflect by only a small angle (<< 1 radian). We may make the approximation that *the electron path is nearly straight as it interacts with an ion to produce radio radiation*.

MATHEMATICAL INSIGHT The Doppler Shift

We can calculate an object's radial (toward or away from us) velocity from its Doppler shift. For speeds that are small compared to the speed of light (less than a few percent of *c*), the formula is

$$\frac{v_{rad}}{c} = \frac{\lambda_{shift} - \lambda_{rest}}{\lambda_{rest}}$$

where v_{rad} is the radial velocity of the object, λ_{rest} is the rest wavelength of a particular spectral line, and λ_{shift} is the shifted wavelength of the same line. A positive answer means the object is redshifted and moving away from us; a negative answer means it is blueshifted and moving toward us.

EXAMPLE: One of the visible lines of hydrogen has a rest wavelength of 656.285 nm, but it appears in the spectrum of the star Vega at 656.255 nm. How is Vega moving relative to us?

SOLUTION:

Step 1 Understand: We can calculate the radial velocity from the given formula. Note that the line's wavelength in Vega's spectrum is slightly *shorter* than its rest wavelength, which means it is blueshifted and Vega's radial motion is *toward* us.

Step 2 Solve: We plug in the rest wavelength ($\lambda_{rest} = 656.285$ nm) and the wavelength in Vega's spectrum ($\lambda_{shift} = 656.255$ nm):

$$\frac{v_{rad}}{c} = \frac{\lambda_{shift} - \lambda_{rest}}{\lambda_{rest}} = \frac{656.255 \text{ nm} - 656.285 \text{ nm}}{656.285 \text{ nm}} = -4.5712 \times 10^{-5}$$

Step 3 Explain: We have found Vega's radial velocity as a fraction of the speed of light; it is negative because Vega is moving toward us. To convert to a velocity in km/s, we multiply by the speed of light:

$$v_{rad} = -4.5712 \times 10^{-5} \times c = -4.5712 \times 10^{-5} \times (3 \times 10^5 \text{ km/s}) = -13.7 \text{ km/s}$$

Vega is moving *toward* us at 13.7 km/s. This speed is typical of stars in our neighborhood of the galaxy.

MATHEMATICAL INSIGHT — Calculating Stellar Radii

Although we can rarely measure stellar radii directly, we can calculate radii using the laws of thermal radiation. As given in Mathematical Insight 5.2, the amount (power) of thermal radiation emitted by a star of surface temperature T (on the Kelvin scale) is

$$\text{emitted power (per square meter of surface)} = \sigma T^4$$

where the constant $\sigma = 5.7 \times 10^{-8}\ \text{watt}/(\text{m}^2 \times \text{K}^4)$.

The luminosity L of a star is its power per unit area multiplied by its total surface area, and a star of radius r has surface area $4\pi r^2$. That is,

$$L = 4\pi r^2 \times \sigma T^4$$

With a bit of algebra, we can solve this formula for the star's radius r:

$$r = \sqrt{\frac{L}{4\pi\sigma T^4}}$$

EXAMPLE: The red supergiant star Betelgeuse has a luminosity of $120{,}000 L_{Sun}$ and a surface temperature of about 3650 K. What is its radius?

SOLUTION:

Step 1 Understand: We are given Betelgeuse's luminosity L and surface temperature T, so we can use the above formula to find its radius. To make the units consistent with the units given for σ, we must convert the luminosity to watts.

Step 2 Solve: Remembering that $L_{Sun} = 3.8 \times 10^{26}$ watts, we find

$$L_{Bet} = 120{,}000 \times L_{Sun} = 120{,}000 \times 3.8 \times 10^{26}\ \text{watts} = 4.6 \times 10^{31}\ \text{watts}$$

Now we can use our formula to calculate radius:

$$r = \sqrt{\frac{L}{4\pi\sigma T^4}} = \sqrt{\frac{4.6 \times 10^{31}\ \text{watts}}{4\pi \times \left(5.7 \times 10^{-8} \frac{\text{watt}}{\text{m}^2 \times \text{K}^4}\right) \times (3650\ \text{K})^4}} = \sqrt{\frac{4.6 \times 10^{31}\ \text{watts}}{1.3 \times 10^{8} \frac{\text{watts}}{\text{m}^2}}} = 5.9 \times 10^{11}\ \text{m}$$

Step 3 Explain: Betelgeuse has a radius of about 590 billion meters, or 590 million kilometers. This is almost four times the Earth-Sun distance (1 AU ≈ 150 million km), which means that the orbits of all the inner planets of our solar system could fit easily inside Betelgeuse.

MATHEMATICAL INSIGHT — Temperature and Wavelength of Background Radiation

Figure 22.8 shows that the cosmic microwave background has a nearly perfect thermal radiation spectrum for an object at a temperature of 2.73 K. Wien's law (see Mathematical Insight 5.2) therefore tells us that the wavelength of photons at the peak of the spectrum is

$$\lambda_{max} \approx \frac{2{,}900{,}000}{T\ (\text{Kelvin})}\ \text{nm} = \frac{2{,}900{,}000}{2.73}\ \text{nm} = 1.1 \times 10^6\ \text{nm}$$

Because 10^6 nm = 1 mm, this peak wavelength is equivalent to 1.1 millimeters. But what was the wavelength of the cosmic microwave photons in the past?

From Mathematical Insight 20.5, the universe has grown in size by a factor of $1 + z$ since the time light left objects that we observe to have a redshift z. Therefore, we find the peak wavelength of cosmic microwave photons at that time by dividing the current peak wavelength by $1 + z$:

$$\lambda_{max}\ (\text{at redshift } z) \approx \frac{1.1\ \text{mm}}{1 + z}$$

Combining this result with Wien's law and a little algebra, we find a simple formula for the temperature of the universe at any earlier time at which we see objects with redshift z:

$$T_{universe}\ (\text{at redshift } z) \approx 2.73\ \text{K} \times (1 + z)$$

EXAMPLE 1: Photons first moved freely when the universe had cooled to a temperature of about 3000 K. What was the peak wavelength of the photons at that time?

SOLUTION:

Step 1 Understand: We can simply use Wien's law relating peak wavelength to temperature.

Step 2 Solve: We use the temperature of 3000 K in Wien's law:

$$\lambda_{max} \approx \frac{2{,}900{,}000}{T\ (\text{Kelvin})}\ \text{nm} = \frac{2{,}900{,}000}{3000}\ \text{nm} = 970\ \text{nm}$$

Step 3 Explain: The peak wavelength of the photons when they first began to travel freely was about 970 nanometers, which is in the infrared portion of the electromagnetic spectrum fairly close to the wavelength of red visible light (see Figure 5.7).

EXAMPLE 2: How much has the expansion of the universe stretched the wavelengths of the background radiation since it began to travel freely through the universe?

SOLUTION:

Step 1 Understand: We can use the formula that relates the temperature of the background radiation to the cosmological redshift z. We are given the 3000 K temperature, so we need to find the stretching factor $(1 + z)$.

Step 2 Solve: We divide both sides of the earlier equation by the current temperature of the universe, 2.73 K, to find

$$1 + z = \frac{T_{universe}\ (\text{at redshift } z)}{2.73\ \text{K}}$$

In this case, we are looking for the stretching factor corresponding to the time when the universe had a temperature of 3000 K. Plugging this value into the formula, we find

$$1 + z = \frac{3000\ \text{K}}{2.73\ \text{K}} \approx 1100$$

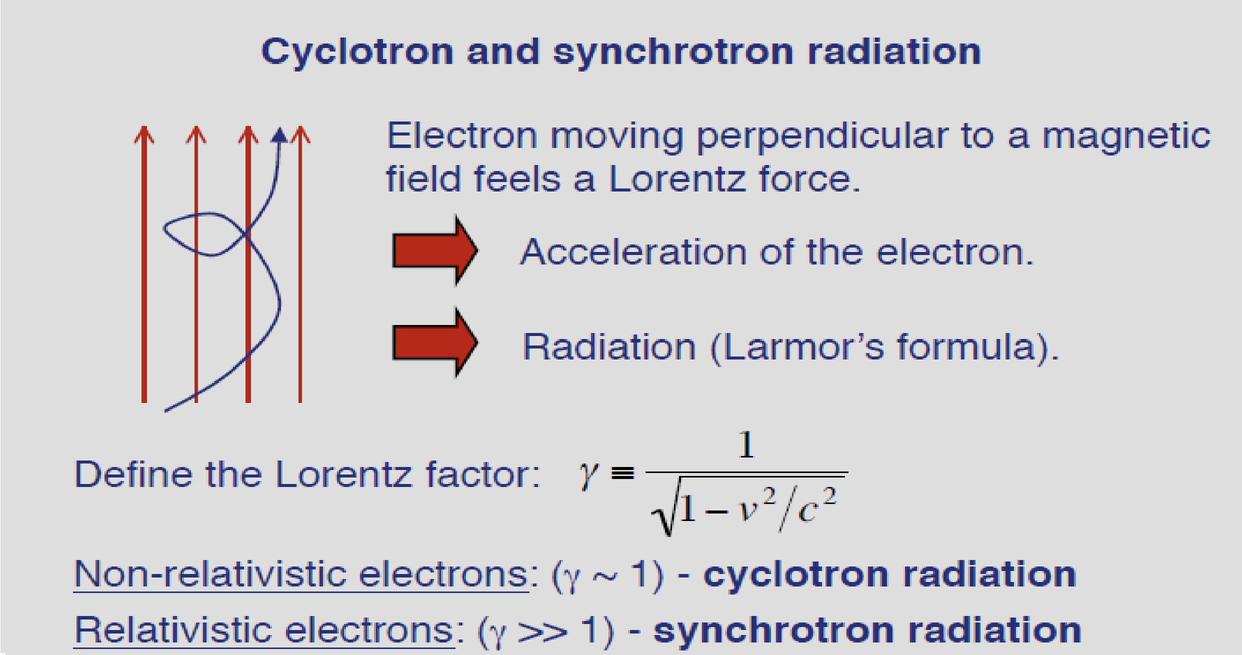
Step 3 Explain: The expansion of the universe has stretched photons by a factor of about 1100 since the time they first began to travel freely across the universe, when the universe was about 380,000 years old. (The answer has no units because it is the *ratio* of the size of the universe now to the size of the universe then.)

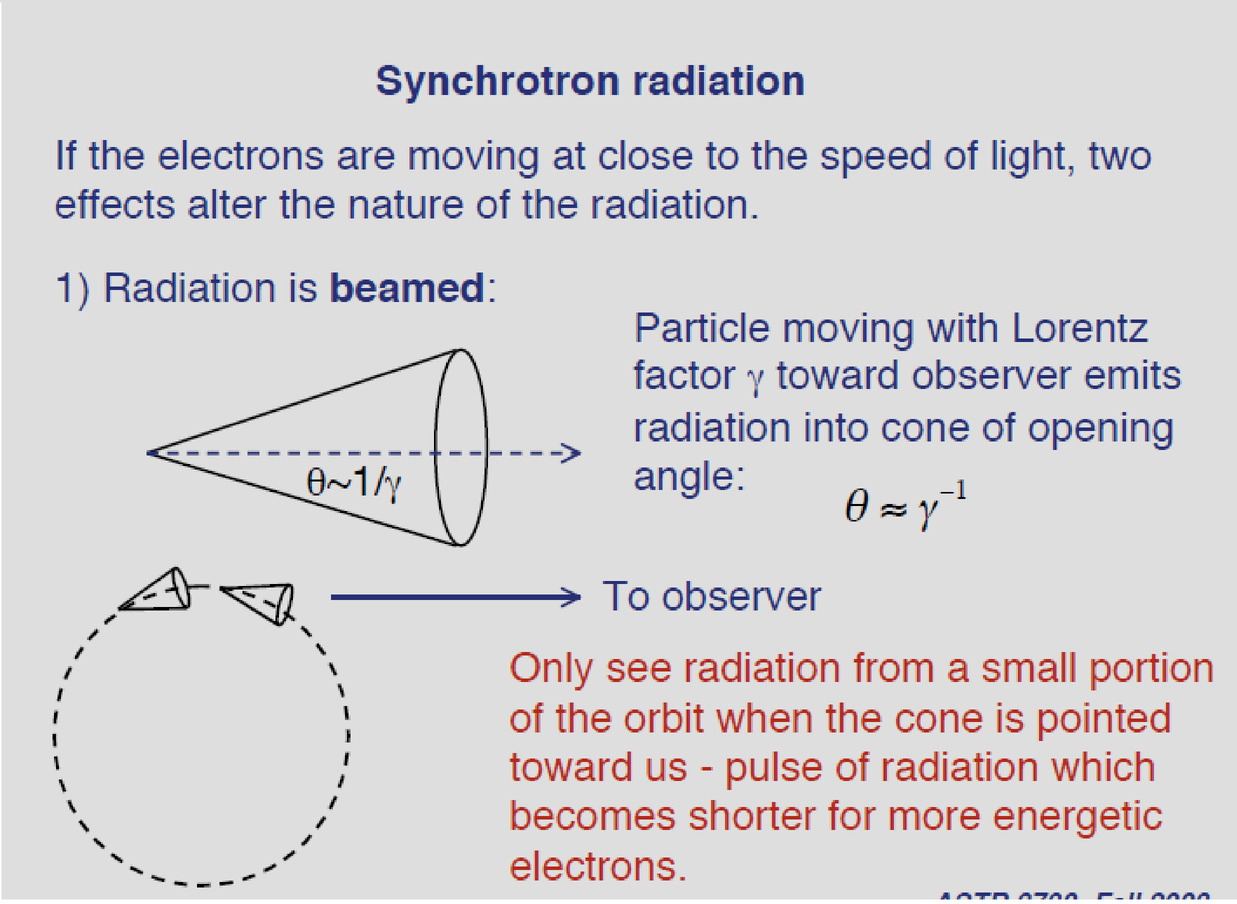
3.3 Non-thermal Mechanisms

Radiation is also produced by mechanisms unrelated to the temperature of object (that is, thermal radiation). Here we discuss some examples of non-thermal radiation.

3.3.1 Synchrotron Radiation

The synchrotron radiation of ultra-relativistic electrons dominates much of high energy astrophysics.





However, when the speed of the particle reaches nearly the speed of light, it emits a much stronger form of cyclotron radiation called *synchrotron radiation* (see fig. a).
Quasars are one source of synchrotron radiation not only at radio wavelengths, but also at visible and x-ray wavelengths.
Note // An important difference in radiation from thermal versus non-thermal mechanisms is that while the intensity (energy) of thermal radiation *increases* with frequency, the intensity of non-thermal radiation usually *decreases* with frequency.

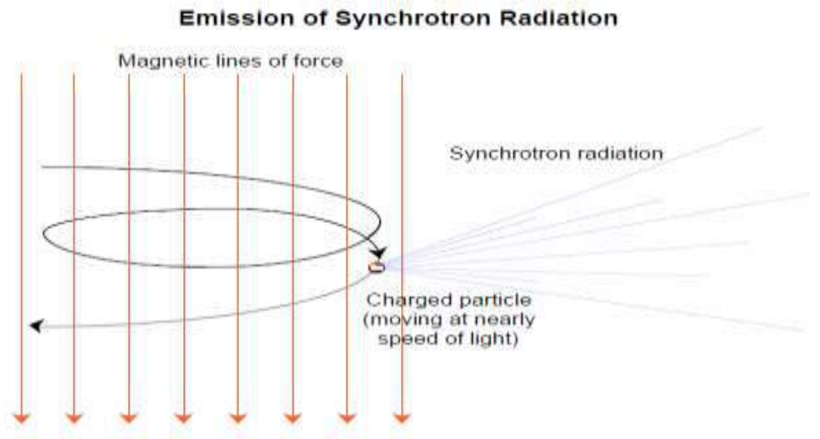
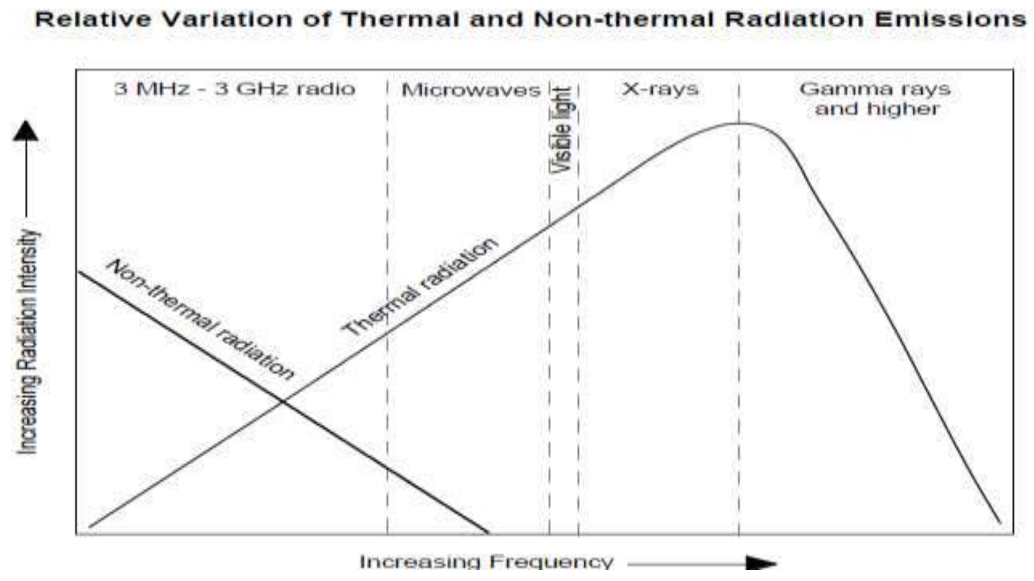


Fig. a: **Synchrotron Radiation**



Astrophysical Sources of Non-thermal Radiation (synchrotron radiation)

- Planetary magnetospheres

- Solar Corona

- Supernova remnants

- Pulsars

- Active galactic nuclei and jets.

Spectral Properties of Synchrotron Radiation.

The main properties of the synchrotron radiation are the following:

1. High intensity;
2. Very broad and continuous spectral range from infrared up to the hard x-ray region;
3. Natural narrow angular collimation;
4. High degree of polarization;
5. Pulsed time structure;
6. High brightness of the source due to small cross section of the electron beam and high degree of collimation of the radiation;
7. Ultra-high vacuum environment and high beam stability;
8. All properties quantitatively evaluable.

The **Lorentz force** is the combination of electric and magnetic force on a point charge due to electromagnetic fields. A particle of charge *q* moving with velocity **v** in the presence of an electric field **E** and a magnetic field **B** experiences a force: **F= qE x qv x B**

Useful formulae for synchrotron radiation

For a **single particle**, spectrum extends up to a peak frequency roughly given by:

$$\nu \sim \gamma^2 \underset{\uparrow}{\nu_c} \sim \frac{\gamma^2 qB}{2\pi mc}$$

cyclotron frequency

Can produce very high frequency radiation, with a continuous spectrum (no lines).

Normally, the electrons which produce synchrotron radiation have a (wide) range of energies. If number of particles with energy between E and E+dE can be written as:

$$N(E)dE = CE^{-p}dE$$

i.e. as a power-law in energy, then it turns out that the spectrum of the resulting synchrotron radiation is *also* a power-law, but with a different index:

$$P(\nu) \propto \nu^{-s} \propto \nu^{-(p-1)/2}$$

Measure the spectral index of the radiation (s), this then gives an indication of the distribution of particle energies (p)!

$$s = \frac{p-1}{2}$$

3.3.2 Inverse Compton Scattering

Inverse Compton scattering involves the scattering of low energy photons to high energies by ultra-relativistic electrons so that the photons gain and the electrons lose energy. The process is called inverse because the electrons lose energy rather than the photons, the opposite of the standard Compton effect.

Inverse Compton Radiation

The general result that the frequency of the scattered photons is $\nu \approx \gamma^2 \nu_0$ is of profound importance in high energy astrophysics. We know that there are electrons with Lorentz factors $\gamma \sim 100 - 1000$ in various types of astronomical source and consequently they scatter any low energy photons to very much higher energies. Consider the scattering of radio, infrared and optical photons scattered by electrons with $\gamma = 1000$.

Waveband	Frequency (Hz) ν_0	Scattered Frequency (Hz) and Waveband
Radio	10^9	$10^{15} = \text{UV}$
Far-infrared	3×10^{12}	$3 \times 10^{18} = \text{X-rays}$
Optical	4×10^{14}	$4 \times 10^{21} \equiv 1.6\text{MeV} = \gamma\text{-rays}$

Thus, inverse Compton scattering is a means of creating very high energy photons indeed. It also becomes an inevitable drain of energy for high energy electrons whenever they pass through a region in which there is a large energy density of photons.

3.3.3 Masers

Astronomical *masers* are another source of non-thermal radiation. "**Maser**" is short for ***microwave-amplified stimulated emission of radiation***. Masers are very compact sites within molecular clouds where emission from certain molecular lines can be enormously amplified. The interstellar medium contains only a smattering of molecular species such as water (H_2O), hydroxyl radicals (OH), silicon monoxide (SiO), and methanol (CH_3OH).

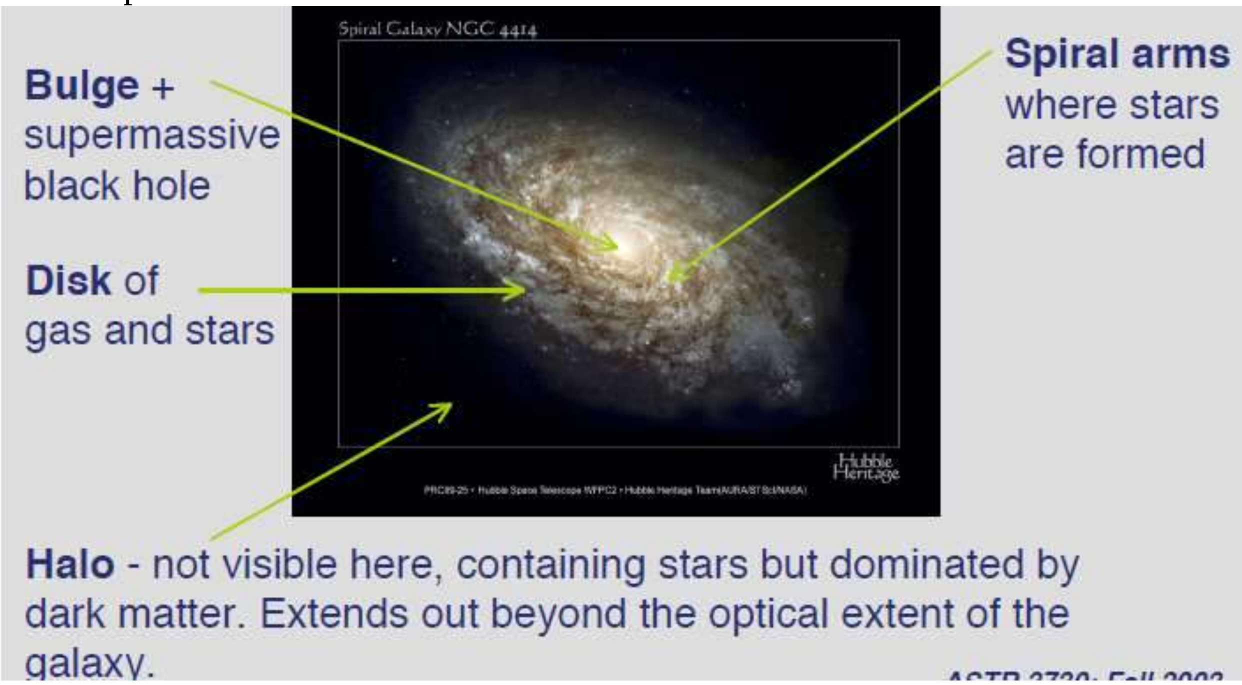
Chapter 4: The Radiation Properties of galaxies

4.1. The Radiation of our Galaxy (Milky Way)

There are some 10^{11} stars in our Galaxy, most of them in the disc, and they dominate the visible light emitted from it, so this view is quite understandable. However, while stars are luminous and hence easily seen, they are only the visible tips of our Galactic iceberg. There is more to the Galaxy, vastly more, than meets the eye.

Components of the Milky Way

Sun and Solar System lie in a spiral galaxy - most common type in relatively isolated parts of the Universe.



Gas and dust

Most of the Milky Way's gas and dust lies in the disc, and is found within a vertical distance of 150 pc of the Galactic plane: it does not extend nearly so far from the mid-plane of the Galaxy as do the stars. The gas is roughly 70% hydrogen and 28% helium (by mass). The remaining 2% is made up of the other elements - these are collectively referred to (by astronomers) as metals. The hydrogen can exist in various forms depending on the density, temperature, and flux of ultraviolet (UV) radiation in each locality.

From our vantage - out in the disk, easiest to see the structure in the Milky Way in the infra-red.

Map in Galactic co-ordinates. Infra-red radiation is not strongly absorbed by dust, so looking here at cool stars throughout the Milky Way

■ What are the shapes and approximate masses of each of the four main structural components of the Galaxy?

❑ The dark-matter halo and the stellar halo are both slightly flattened (oblate) spheroids. The disc has the flattened circular form its name implies, and the central bulge is elongated into a bar. Very roughly, the stellar halo has a mass of $10^9 M_\odot$, the bulge mass is $10^{10} M_\odot$, the mass of the disc is $10^{11} M_\odot$ and the dark-matter halo has a mass of $10^{12} M_\odot$, although this last value is particularly uncertain.

■ If the radius of the Galactic disc is 15 kpc, then its diameter is 30 kpc. How many light-years is 30 kpc?

❑ 1 pc = 3.26 ly, so 30 kpc = 30×10^3 pc $\times$ 3.26 ly pc^{-1} = 9.8×10^4 ly $\approx$ 100 000 ly.

■ What is the total mass of gas in the Galaxy, in solar masses?

❑ The mass of gas is 10% of the stellar mass of the Galaxy, and the latter is about $10^{11} M_\odot$, so the mass of gas is

$$10\% \times 10^{11} M_\odot = (10/100) \times 10^{11} M_\odot = 10^{-1} \times 10^{11} M_\odot = 10^{10} M_\odot$$

■ What is the total mass of dust in the Galaxy, in solar masses?

❑ The mass of dust is 0.1% of the stellar mass of the Galaxy, and the latter is $10^{11} M_\odot$, so the mass of dust is

$$0.1\% \times 10^{11} M_\odot = (0.1/100) \times 10^{11} M_\odot = 10^{-3} \times 10^{11} M_\odot = 10^8 M_\odot$$

QUESTION 1.1

If the Sun is 8.5 kpc from the Galactic centre and moving in a circular orbit at 220 km s^{-1}, how long will it take to travel once around the Galaxy? Express your answer in both SI units (seconds) and years.

(Recall that the relationship between a body's speed, v, the distance travelled, d, and the time taken, t, is $v = d/t$, and that the circumference of a circle of radius R is $d = 2\pi R$.)

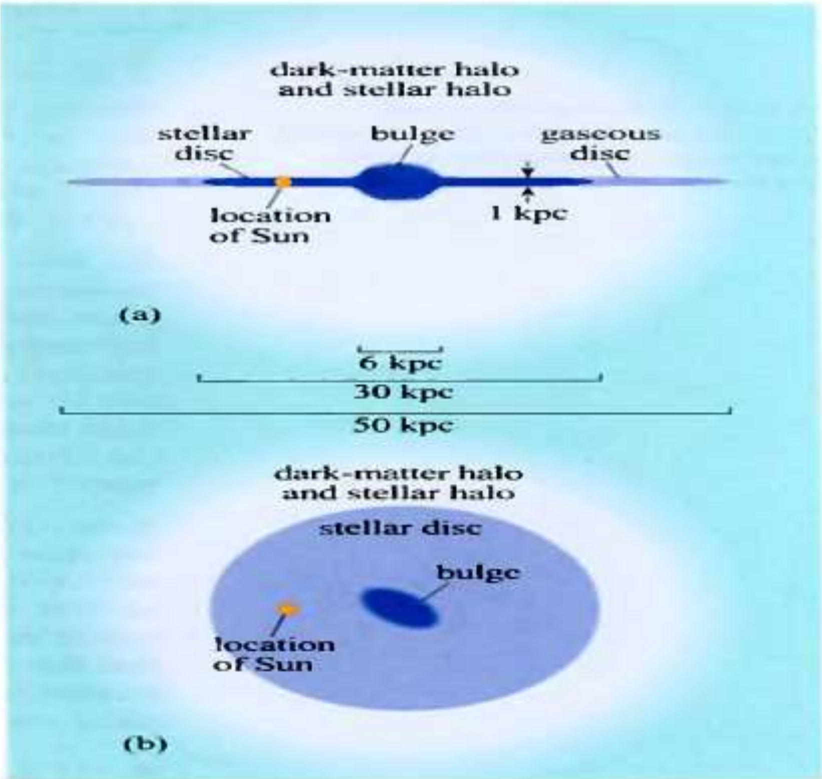


Figure 1.5 (a) Edge-on and (b) face-on schematic views of the four major structural components of the Milky Way: the dark-matter halo, the disc, the stellar halo and the bulge. The sizes indicated in this figure are expressed in kiloparsec (kpc), where 1 kpc ≈ 3260 ly.

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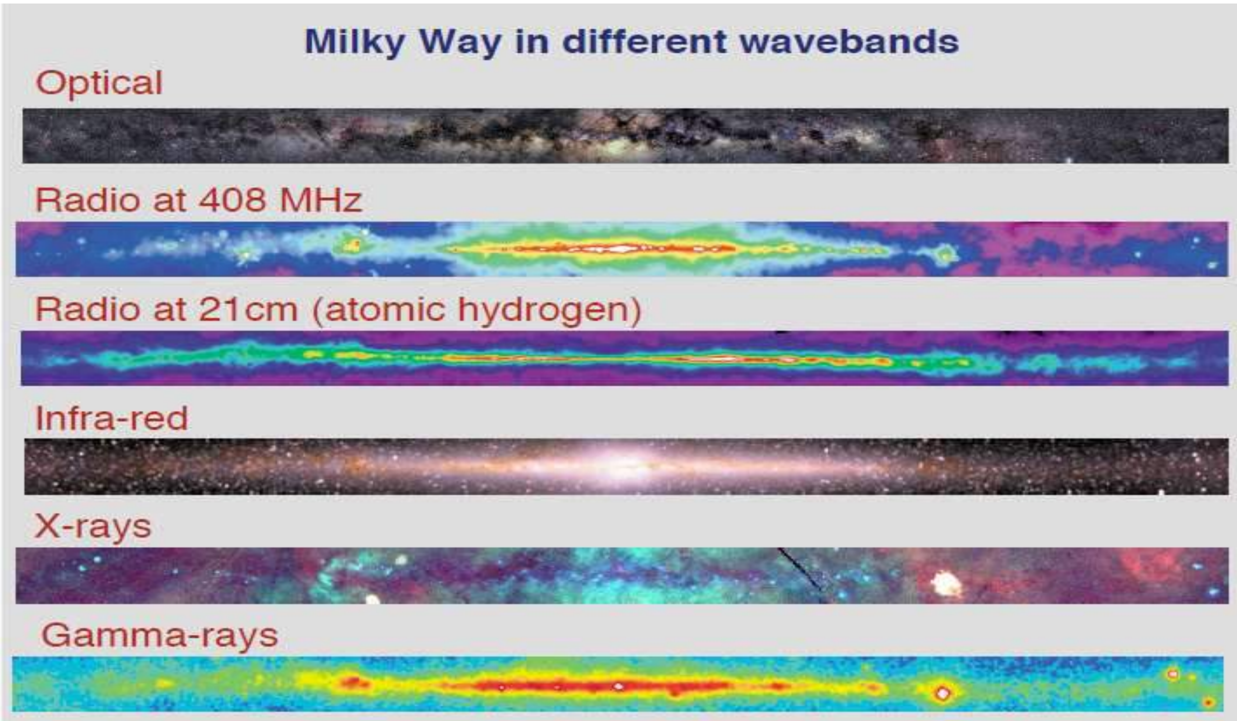

Gas in the Milky Way exists in different phases:

- **Molecular gas** (T = 10 - 100 K)
- **Atomic hydrogen** (neutral gas, called H I)
- **Ionized gas** (called H II)

Most of the gas is in atomic form, but stars form out of the molecular material:

- **Giant molecular cloud** forms a whole cluster of stars, may have mass of 10^6 M_{sun}, size ~10 pc = 3 x 10^{19} cm
- **Molecular cloud core** of a few Solar masses, perhaps 0.1 pc in size, forms one or (normally) a few stars.

Post-main-sequence evolution

Once hydrogen burning has finished, evolution speeds up because further nuclear reactions yield much less energy:

- H -> He: yields 6 x 10^{18} erg / g (of pure hydrogen)
- He -> C: yields 6 x 10^{17} erg / g (of pure helium)

Complicated evolution gives:

Low-mass stars	Intermediate-mass	High-mass
↓	↓	↓
Red giants	Giant phases	
↓	↓	↓
Planetary nebulae	Type II supernovae	
↓	↓	↓
White dwarfs	Neutron stars	Black holes

The gaseous content of the disc

BOX 1.3 THE 21 CENTIMETRE EMISSION LINE OF ATOMIC HYDROGEN

A major indicator of the distribution and line-of-sight velocity of neutral (atomic) hydrogen (HI) gas, not just in the Milky Way but other galaxies as well, is its emission line in the radio region of the spectrum at a wavelength of 21 cm. The origin of this **21 centimetre radiation** involves the relative *spins* of the electron and proton that constitute the hydrogen atom. These spins are illustrated in a classical (i.e. non-quantum) sense in Figure 1.17, where the proton and the electron are pictured as small spheres spinning at a fixed rate around axes through their centres. The quantum physics of the hydrogen atom ensures that the electron spin is always either parallel to that of the proton, as in Figure 1.17a, or anti-parallel (i.e. opposed to it), as in Figure 1.17b. There is a small energy difference between the states shown in Figure 1.17, and it is the transition from the higher energy state (a) to the lower energy state (b) that gives rise to the 21 cm emission line.

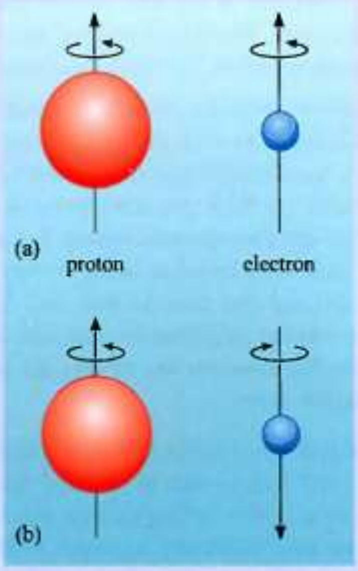

Figure 1.17 A classical view of the hydrogen atom, in which the proton and electron spins are (a) parallel or (b) anti-parallel.

- What is the energy difference between these two states, in SI units (joules) and electronvolts?

- The energy difference between the states is just the energy of the emitted photon. This is given by

$$\varepsilon = hf = hc/\lambda \quad (1.6)$$

Thus the energy difference between the two states associated with the 21 cm line is

$$\begin{aligned}\varepsilon &= hc/\lambda \\ &= 6.63 \times 10^{-34}\,\mathrm{J\,s} \times 3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}/0.21\,\mathrm{m} \\ &= 9.5 \times 10^{-25}\,\mathrm{J}\end{aligned}$$

Since $1\,\mathrm{eV} = 1.60 \times 10^{-19}\,\mathrm{J}$, the energy difference can also be expressed as

$$\begin{aligned}\varepsilon &= 9.5 \times 10^{-25}\,\mathrm{J}/1.60 \times 10^{-19}\,\mathrm{J\,eV^{-1}} \\ &= 5.9 \times 10^{-6}\,\mathrm{eV}\end{aligned}$$

For us to observe this emission line, the hydrogen atoms must be in an environment where they can readily gain the energy required to raise them into the upper energy level at a reasonable rate compared with the rate at which they are reverting to the lower energy level by emitting radiation. One energy source is provided by collisions between hydrogen atoms as a result of their random thermal motion – this is an example of **collisional excitation**. For a reasonable proportion of such collisions to be sufficiently energetic, the average translational kinetic energy of an atom, e_k, must exceed the energy difference between levels, ε, such that $e_k \geq \varepsilon$. For thermal motion, the average translational kinetic energy is related to the temperature T of the gas particles via the equation $e_k = 3kT/2$, where k is the Boltzmann constant. Thus, by requiring $e_k \geq \varepsilon$, we get $3kT/2 \geq \varepsilon$ and hence $T \geq 2\varepsilon/3k$.

Putting in the value of ε, we get the requirement $T \geq 2 \times 9.5 \times 10^{-25}\,\mathrm{J}/(3 \times 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}) = 0.046\,\mathrm{K}$. This condition is met everywhere in the ISM, so the 21 cm line is readily emitted wherever atomic hydrogen exists.

The radial velocity of a cloud of atomic hydrogen can be measured from the Doppler shift of the 21 cm emission line. In general, the radial velocity (i.e. the component of velocity along the line of sight) of an object that emits (or absorbs) radiation at a wavelength λ_{em} is given by

$$v_r = c(\lambda_{obs} - \lambda_{em})/\lambda_{em} \quad (1.7)$$

where λ_{obs} is the wavelength at which the radiation is observed and c is the speed of light. This relationship is valid provided that the radial velocity is much smaller than the speed of light, v_r must be less than about $0.1c$. Note also that the convention used in Equation 1.7, and throughout this book, is that an object moving *away* from the observer has a *positive* radial velocity.

- Gas clouds cooler than about 100 K generally do not emit the 21 cm line; why not?
- At $T < 100$ K, hydrogen forms into H_2 molecules, so no atomic hydrogen remains.

- Why are hot HII regions often found in association with cool, dense clouds?
- New stars form within cool, dense clouds. Only very hot (and therefore massive) stars, particularly the short lived but highly luminous main sequence stars of spectral classes O and B, can ionize hydrogen in their vicinity and thus produce HII regions. As massive stars are short lived, they can be observed still in close association with the original dense clouds. Hence HII regions are found near the cool, dense clouds from which the O and B stars formed.

The vertical distribution of stars provides an example of exponential decay. More specifically, the **number density** of stars (i.e. the number of stars per unit volume), n, decreases with distance from the mid-plane, according to the equation:

$$n(z) = n_0 \, e^{-|z|/h} \qquad (1.8)$$

Here, the positive quantity $|z|$ represents the distance above or below the mid-plane; h is an important distance parameter called the **scale height** of the disc that characterizes the 'thickness' of the disc; n_0 is the number density of stars in the mid-plane; and $n(z)$ is the number density of stars at a displacement z from the mid-plane, with $z > 0$ for points above the mid-plane and $z < 0$ for points below the mid-plane. The symbol $|z|$ is often read as 'the absolute value of z' or 'the modulus of z', since the modulus sign, $|\;|$, indicates that only the magnitude (as opposed to the sign) of the enclosed quantity should be considered. That is, $|z|$ is always a positive quantity, irrespective of the value of z.

- What is the ratio of the number density of stars at a distance h from the mid-plane, to the mid-plane number density?
- When $z = h$, Equation 1.8 becomes $n(h) = n_0 e^{-|h|/h} = n_0 e^{-1}$

  You can evaluate e^{-1} using a calculator, or you can note that $e^{-1} = 1/e \approx 1/2.718$. Hence $n(h) \approx n_0 \times 1/2.718 \approx 0.37 n_0$, and hence $n(h)/n_0 \approx 0.37$.

Overview of the Milky Way

- The Milky Way – our Galaxy – is a barred spiral galaxy with four major structural components: a dark-matter halo which is only detected gravitationally, a disc, a stellar halo and a central bulge. The total mass is $\sim 10^{12} M_\odot$.
- The nature of the dark matter is unclear, but it may account for 90% of the total mass.
- The directly detectable matter consists mainly of stars (~90% by mass), gas (~10%) and dust (~0.1%).
- The disc is about 30 kpc in diameter and 1 kpc thick. The stellar halo is roughly spherical; its diameter is difficult to determine but estimates of more than 40 kpc are common. The nuclear bulge is a triaxial bar extending out to about 3 kpc from the centre.
- The stars of the Milky Way may be divided into a number of populations, each of which predominates in a particular region of the Galaxy. The very youngest stars are found mainly in the spiral arms. Population I stars reside in the disc. The oldest known stars, of Population II, are found mainly as individual stars of the stellar halo, and less commonly but more recognizably in globular clusters.
- The disc is in a state of differential rotation, with stars in the vicinity of the Sun taking about 2×10^8 yr to make a complete orbit of the Galactic centre.

The mass of the Milky Way

- The rotation curve that describes movement about the Galactic centre constrains the total mass of the Galaxy. Interior to the Sun's orbit, the mass is approximately $10^{11} M_\odot$. It is difficult to determine how much material resides beyond the Sun's orbit, and estimates for the total mass range from $4 \times 10^{11} M_\odot$ to $6 \times 10^{12} M_\odot$.

The disc

- There are about 10^{11} stars in all, with a total mass $\sim 10^{11} M_\odot$.
- Most stars and gas are approximately 70% hydrogen, 28% helium, and 2% heavier elements (metals) by mass.
- Hydrogen occurs in the form of molecules (H_2), atoms (HI) or ions (HII), according to local conditions. Molecular hydrogen is difficult to detect, however, so carbon monoxide (CO) is used as a tracer of H_2.
- Dust consists of μm-sized solid compounds, especially graphite and silicates with icy mantles, and accounts for about 1% of the ISM by mass.
- The (number) density of the disc's visible constituents, stars, gas and dust, falls off with distance from the mid-plane. In each case this is described by a scale height.
- The Sun is one of the Pop. I stars, located about 8.5 kpc from the centre of the Galaxy, close to the mid-plane of the disc. It is part of the thin-disc subpopulation that has a scale height of about 300 pc. There is also a thick disc subpopulation with a scale height of about 1000–1300 pc.
- The spiral arms are sites of active star formation. Attempts to trace the arms make use of young, short-lived objects in the disc such as bright HII regions, young open clusters, OB associations, dense clouds and clouds of neutral hydrogen gas.

MATHEMATICAL INSIGHT 23.1 Mass-to-Light Ratio

An object's mass-to-light ratio (M/L) is its total mass in units of *solar masses* divided by its total *visible* luminosity in units of *solar luminosities*. For example, the mass-to-light ratio of the Sun is

$$\frac{M}{L} \text{ for Sun} = \frac{1M_{Sun}}{1L_{Sun}} = 1\frac{M_{Sun}}{L_{Sun}}$$

We read this answer with its units as "1 solar mass per solar luminosity." The following examples clarify the idea of the mass-to-light ratio and explain what it can tell us about the existence of dark matter.

EXAMPLE 1: What is the mass-to-light ratio of a $1M_{Sun}$ red giant with a luminosity of $100L_{Sun}$?

SOLUTION:

Step 1 Understand: Finding a mass-to-light ratio simply requires knowing an object's total mass in solar masses and its total luminosity in solar luminosities. We have been given both.

Step 2 Solve: We divide to find the mass-to-light ratio:

$$\frac{M}{L} = \frac{1M_{Sun}}{100L_{Sun}} = 0.01\frac{M_{Sun}}{L_{Sun}}$$

Step 3 Explain: The red giant has a mass-to-light ratio of 0.01 solar mass per solar luminosity. Note that the ratio is *less* than 1 because a red giant puts out *more* light per unit mass than the Sun. More generally, stars *more luminous* than the Sun have mass-to-light ratios *less* than 1 and stars *less luminous* than the Sun have mass-to-light ratios *greater* than 1.

EXAMPLE 2: The Milky Way Galaxy contains about 90 billion (9×10^{10}) solar masses of material within the Sun's orbit, and the total luminosity of stars within that same region is about 15 billion (1.5×10^{10}) solar luminosities. What is the mass-to-light ratio of the matter in our galaxy within the Sun's orbit?

SOLUTION:

Step 1 Understand: Again, we simply divide the mass of this region by its luminosity, both in solar units.

Step 2 Solve: The mass-to-light ratio within the Sun's orbit is

$$\frac{M}{L} = \frac{9 \times 10^{10} M_{Sun}}{1.5 \times 10^{10} L_{Sun}} = 6\frac{M_{Sun}}{L_{Sun}}$$

Step 3 Explain: The mass-to-light ratio of the matter within the Sun's orbit is about 6 solar masses per solar luminosity. This is *greater* than the Sun's ratio of 1 solar mass per solar luminosity, telling us that most matter in this region is *dimmer* per unit mass than our Sun. This is not surprising, because most stars are smaller and dimmer than our Sun.

EXAMPLE 3: Observations of orbital speeds in a spiral galaxy indicate that its total mass is $5 \times 10^{11} M_{Sun}$; its luminosity is $1.5 \times 10^{10} L_{Sun}$. What is its mass-to-light ratio?

SOLUTION:

Step 1 Understand: This problem is essentially the same as the others, but with different implications.

Step 2 Solve: We divide the galaxy's mass by its luminosity:

$$\frac{M}{L} = \frac{5 \times 10^{11} M_{Sun}}{1.5 \times 10^{10} L_{Sun}} = 33\frac{M_{Sun}}{L_{Sun}}$$

Step 3 Explain: The galaxy has a mass-to-light ratio of 33 solar masses per solar luminosity, which is more than five times the mass-to-light ratio for the matter in the Milky Way Galaxy within the Sun's orbit. We conclude that, on average, the mass in this galaxy is *much less* luminous than the mass found in the inner regions of the Milky Way, suggesting that the galaxy must contain a lot of mass that emits little or no light.

4.2 The Radiation of Normal Galaxies

The classification of galaxies (The Hubble classification):

A classification scheme for galaxies was first introduced by Hubble, in 1926. A modified version of this **Hubble classification scheme** is given in Figure 2.2. Though alternative schemes are sometimes used, Hubble's scheme still provides the most common basis for the morphological classification of galaxies. As you can see, the scheme recognizes four major **Hubble classes** of galaxy: **elliptical**, **lenticular**, **spiral** and **irregular**, with both the lenticular and spiral classes being subdivided into **barred** and **unbarred** varieties. In addition, the various classes and subclasses are divided into a number of **Hubble types**, each of which is denoted by a combination of letters and numbers.

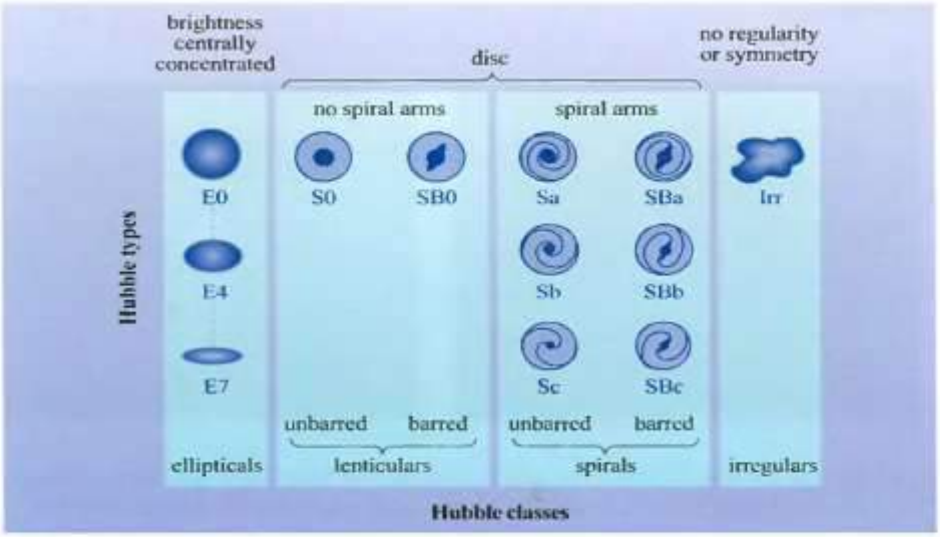

Figure 2.2 The Hubble classification scheme for galaxies.

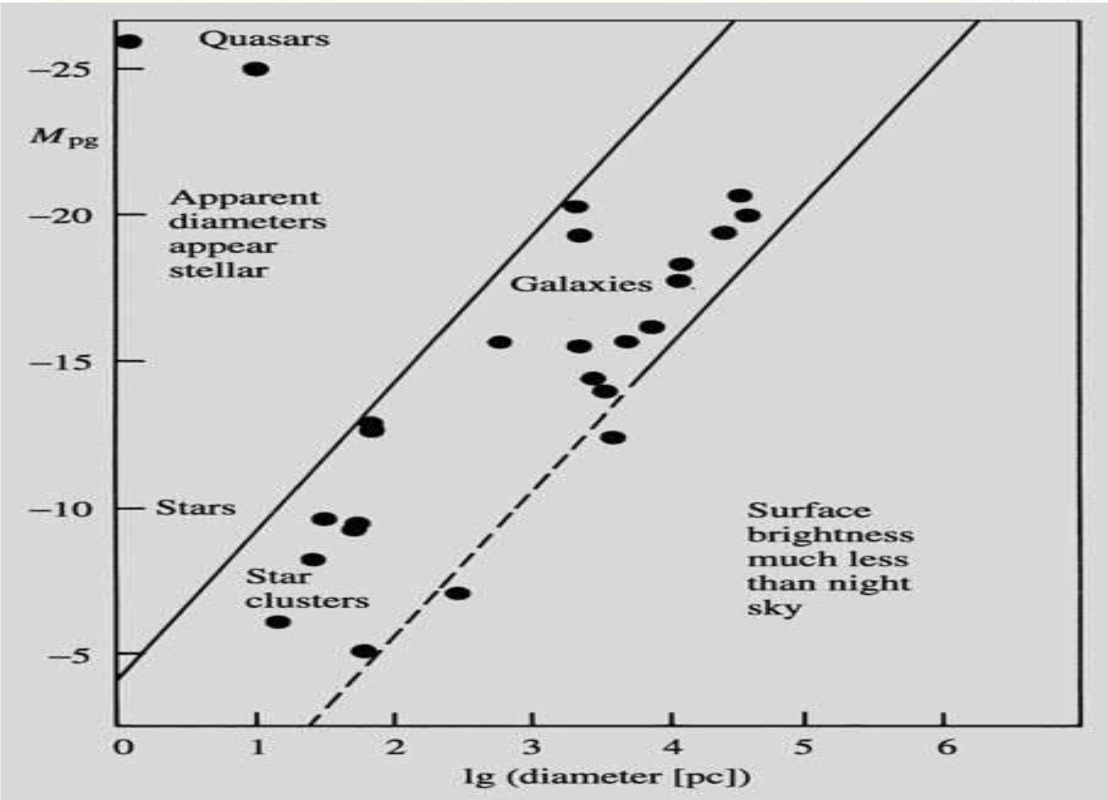

Fig. Magnitudes and diameters of observable extragalactic objects. Objects to the upper left look like stars. The quasars in this region have been discovered on the basis of their spectra.

The radiation laws of elliptical galaxies:

The elliptical galaxies appear in the sky as elliptical concentrations of stars, in which the density falls off in a regular fashion as one goes outwards. Usually there are no signs of interstellar matter (dark bands of dust, bright young stars). The ellipticals differ from each other only in shape and on this basis they are classified as E0, E1, . . . , E7. If the major and minor axes of an elliptical galaxy are *a* and *b*, its type is defined to be E*n*, where:

$$n = 10\left(1 - \frac{b}{a}\right).$$

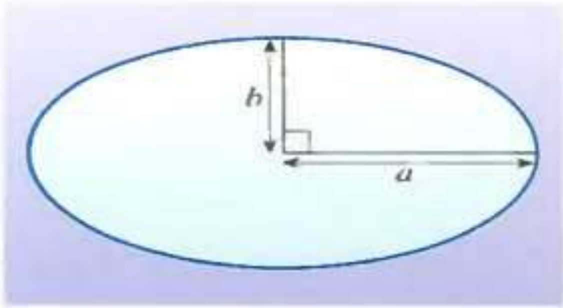

Figure: The semimajor axis, a, and the semiminor axis, b, of an ellipse.

We can use photometry to study the brightness distribution in ellipticals. Since we see the galaxy projected as a two-dimensional object on the sky, it is convenient to speak of the luminosity per unit surface area $L(r)$, where r is the projected distance from the center of the elliptical. Studies show that the light from most ellipticals can be described well by a simple relationship (known as de Vaucouleur's law):

$$L(r) = L(0)e^{-(r/r_0)^{1/4}}$$

In this expression $L(0)$ and $r0$ are constants. The values of $L(0)$ are found not to vary very much, with a typical value of about 2 x10^5 $L_\odot/pc^2$.

The radiation laws of Spiral galaxies

The luminosity of the disk falls off sharply with r, the distance from the center. We can approximately fit the observed falloff with an exponential expression. That is, if L_0 is the luminosity at the center, the $L(r)$, the luminosity at radius r, is given by:

$$L(r) = L_0\, e^{(-r/D)}$$

In this expression, D is called the *luminosity scale length* and gives a measure of the characteristic radius of the galaxy as seen in visible light. Typical values of D are about 5 kpc. This means that the luminosity of the disk of a spiral falls to 1/e of its peak value at r = 5 kpc.

Table: Properties of spirals and ellipticals.

Property	Spirals	Ellipticals
Gas	yes	some
Dust	yes	some
Young stars	yes	none
Shape	flat	round
Stellar motions	circular rotation	random
Color	blue	red

Table A comparison of Hubble classes. ***Properties of three of the main classes of galaxy.***

Property	Ellipticals	Spirals	Irregulars
approximate proportion of all galaxies	$\gtrsim 60\%$	$\lesssim 30\%$	$\lesssim 15\%$
mass of molecular and atomic gas as % of mass of stars		5–15%	
stellar populations			Populations I and II
approximate mass range			
approximate luminosity range	a few times $10^5 L_\odot$ to $\sim 10^{11} L_\odot$	$\sim 10^9 L_\odot$ to a few times $10^{11} L_\odot$	$\sim 10^7 L_\odot$ to $10^{10} L_\odot$
approximate diameter range[a]	$(0.01\text{–}5)\, d_{MW}$	$(0.02\text{–}1.5)\, d_{MW}$	$(0.05\text{–}0.25)\, d_{MW}$
angular momentum per unit mass			low

[a] d_{MW}, diameter of Milky Way.

Dark matter in galaxies

When we look at a galaxy in visible light we obviously see the most luminous objects. However, some of the mass may not be luminous. It could be there but hard to detect. The only sure way to trace out the total mass, whether it is bright or dark, is to study its gravitational effects. In a galaxy, the easiest way to study the gravitational forces is to measure the rotation curve.

Rotation curves can be determined from the measurement of Doppler shifts in spectral lines. This can be done with optical lines, such as H_α.

We can use the rotation curve to give us the mass distribution in the halo. If $M(r)$ is the mass interior to radius r, then $v(r)$ is related to it by the fact that the acceleration of gravity must provide the acceleration for a circular orbit (v^2/r), so

$$\frac{GM(r)}{r^2} = \frac{v^2(r)}{r}$$

Solving for $M(r)$ gives

$$M(r) = \frac{rv^2(r)}{G} \tag{17.3}$$

We can relate $M(r)$ to the density distribution $\rho(r)$ by the equation of mass continuity (equation 9.33), which was one of the equations of stellar structure:

$$\mathrm{d}M/\mathrm{d}r = 4\pi r^2 \rho(r) \tag{17.4}$$

Solving for $\rho(r)$ gives

$$\rho(r) = \left(\frac{1}{4\pi r^2}\right)\left(\frac{\mathrm{d}M(r)}{\mathrm{d}r}\right) \tag{17.5}$$

If we take $v(r) = v_0$, a constant, then differentiating equation (17.3) with respect to r gives

$$\frac{\mathrm{d}M(r)}{\mathrm{d}r} = \frac{v_0^2}{G} \tag{17.6}$$

Finally, substituting equation (17.6) into equation (17.5) gives

$$\rho(r) = \frac{v_0^2}{4\pi G r^2} \tag{17.7}$$

The density in the halo therefore falls off as $1/r^2$. It is not nearly as fast as the exponential falloff in the light of the disk.

The determination of the distances of galaxies

More distant galaxies have more uncertain distances, as a rule. In general, the distances to galaxies are determined by comparing objects in near galaxies with similar objects in more distant ones. For the most nearby galaxies, direct measurements of Cepheid variables yield good distances. Further out, the size of the largest HII region, or the average brightness of a globular cluster can be used. The Tully-Fisher relation is used to 100 million parsecs. This relation is a correlation between the luminosity of a galaxy and the breadth of the 21 cm line. Beyond this, the size of galaxies as measured on the sky and the brightest galaxy in a cluster are used to determine the distance.

Table . Each distance-determination method is useful only for a certain range of distances

Method	Distances to which the method is useful
Cepheid variables	10 million parsecs
Size of largest HII region, average brightness of globular cluster	25 million parsecs
Type I supernovae; Tully-Fisher relation (relates luminosity with breadth of 21 cm line)	100 million parsecs
Size of galaxies	100s of millions of parsecs
Brightest galaxy in a cluster	1,000 million parsecs

I. Methods based on geometry

The basic idea behind the geometrical methods used to determine the distances to other galaxies is very simple: within an external galaxy, identify a feature of known linear diameter *l*, measure the angular diameter, θ, of that feature, then work out the feature's distance, d, by using the formula:

$$d = l/(\theta\ /\text{radians})$$

II. Methods involving a 'standard candle'

Once a standard candle has been identified, its distance is found by comparing the flux density, F, that it provides to observers on Earth, with its (known) luminosity L.

$$d = \sqrt{\frac{L}{4\pi F}} \tag{2.3}$$

Techniques that use this approach to measure distance are generically referred to as **standard candle methods.**

III. Supernova methods

<u>Type II supernova methods</u>

Type II supernovae provide another means of determining galactic distances. The technique is based on the relationship between the radius R, temperature T and luminosity L of a spherical black body.

$$L = 4\pi R^2 \sigma T^4 \tag{2.4}$$

Here, $\sigma = 5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$ is the Stefan–Boltzmann constant, one of the fundamental constants of radiation physics. In simple terms, the main idea in this approach is to treat the exploding supernova as a spherical black body and, at some particular time, to determine both its temperature and its radius from directly observable quantities. Equation 2.4 can then be used to determine the luminosity at that time, enabling the Type II supernova to play the role of a standard candle.

$$\frac{F_1}{F_0} = \frac{R_1^2 T_1^4}{R_0^2 T_0^4} \tag{2.5}$$

This can be rearranged to give

$$\frac{R_1}{R_0} = \left(\frac{F_1}{F_0}\right)^{1/2} \left(\frac{T_0}{T_1}\right)^2 \tag{2.6}$$

However the supernova is expanding, and Doppler shifts in spectral lines can be used to measure the speed (v) of its outer layers. Given a time interval Δt between the observations, and assuming a uniform rate of expansion, the radius of the supernova at the later time is related to the radius at the earlier time by

$$R_1 = R_0 + v\Delta t$$

- Substitute the expression for R_1 into Equation 2.6. Of the quantities in the resulting equation, how many are measured, and how many are unknown?
- The resulting equation is

$$\frac{R_0 + v\Delta t}{R_0} = \left(\frac{F_1}{F_0}\right)^{1/2} \left(\frac{T_0}{T_1}\right)^2 \tag{2.7}$$

Of the quantities in this expression, F_0, T_0, F_1, T_1, v and Δt have been measured, and only R_0 is unknown.

Equation 2.7 can be rearranged to provide an expression for the unknown quantity R_0 in terms of quantities that can be measured.

$$R_0 = \frac{v\Delta t}{\left[\left(\frac{F_1}{F_0}\right)^{1/2} \left(\frac{T_0}{T_1}\right)^2 - 1\right]} \tag{2.8}$$

The spectra of distant galaxies

The spectra of distant galaxies exhibit red-shifts. As you will see later, these red-shifts are not simply the result of the Doppler effect, though they do arise from a change with time of the separation between us and the galaxies. A red-shift corresponds to an increasing separation. A schematic example of a red-shifted galactic spectrum is shown in Figure 2.29.

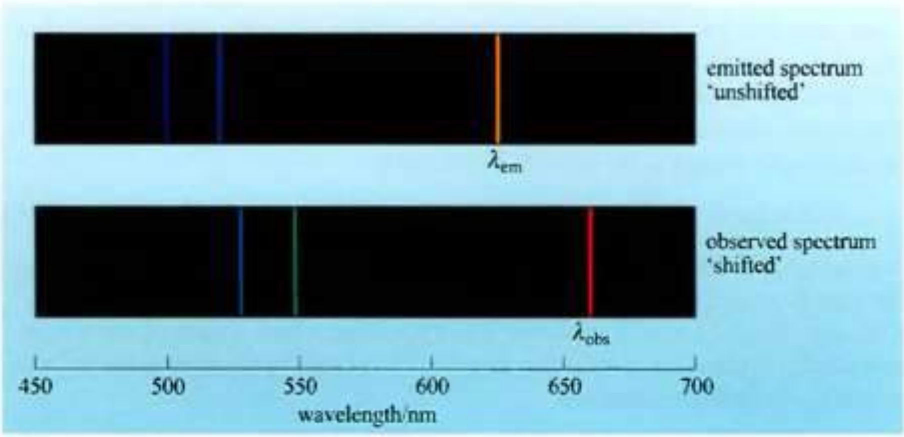

Figure 2.29 As a result of red-shift, a spectral line emitted at a wavelength λ_{em} is seen by observers at a wavelength λ_{obs}.

To evaluate the redshift z in a specific case, all that is needed is a value for the observed wavelength (λ_{obs}) of a spectral line that has a known wavelength (λ_{em}) at the point of emission. The value of z can then be obtained from the definition

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} = \frac{\lambda_{obs}}{\lambda_{em}} - 1 \qquad (2.11)$$

Generally speaking, all the spectral lines originating in a distant galaxy will be red-shifted to the same extent, so the redshift of any particular line in that galaxy's spectrum will also be the redshift of the galaxy itself. In the few cases where the spectrum of a galaxy shows a blue-shift rather than a red-shift, Equation 2.11 will give a negative value for z. Throughout this chapter we speak exclusively of redshifts, with the tacit understanding that a blue-shifted spectrum is characterized by a negative redshift.

■ Oxygen emits a spectral line at an 'unshifted' wavelength of 500.9 nm. Suppose that this line is observed in the spectrum of a galaxy at a wavelength of 596.1 nm. What is the redshift of the galaxy from which the line was emitted?

❑ $z = \frac{(596.1 - 500.9)\,\text{nm}}{500.9\,\text{nm}} = 0.190$

Hubbies law

$$z = \frac{H_0}{c} d \qquad (2.12)$$

where c is the speed of light (3.00×10^8 m s^{-1}) and H_0 is a constant of proportionality known as the **Hubble constant.**

$$v = H_0 d \qquad (2.13)$$

QUESTION 2.11

If it is assumed that galaxies have random velocities of typically 300 km s^{-1}:

(a) Calculate the typical redshift that would be expected for nearby galaxies (i.e. galaxies that are so close that the systematic redshifts predicted by Hubble's law can be ignored). Would this redshift necessarily be positive?

(b) At what distance does the redshift predicted by Hubble's law dominate over the spread in redshift calculated in part (a)? Assume that Hubble's law dominates when the Hubble redshift is a factor of ten greater than the typical redshift due to the random motion of galaxies, and that $H_0 = 72$ km s^{-1} Mpc^{-1}.

The spectra emission of Normal galaxies

The spectrum of a *star* normally consists of a continuous thermal spectrum with absorption lines cut into it (Figure 3.1). As you probably know, it is possible to learn a lot about the star from a study of these absorption lines.

- The strengths and widths of the absorption lines contain information about the star's chemical composition, surface temperature and luminosity. By looking for Doppler shifts in the lines you can measure radial velocity and, if the Doppler shifts are periodic in time, you can detect the binary nature of a star.

The gas in a galaxy is partly visible in the form of hot clouds known as HII regions. Such regions are usually only seen where there is ongoing star formation, and so are prominent in spiral and irregular galaxies. The optical spectrum of an HII region consists of just a few emission lines, as can be seen in Figure 3.2. HII regions can make a substantial contribution to the spectra of galaxies because they are very bright. The only other gaseous objects in a normal galaxy to emit at optical wavelengths are supernova remnants and planetary nebulae, and these are faint compared with HII regions.

Broadband spectrum

The spectra of stars and HII regions extend far beyond the optical region. The Sun, for example, radiates throughout the ultraviolet. X-ray, infrared and radio regions the electromagnetic spectrum. The majority of the Sun's radiation is concentrated into the optical part of its spectrum but, as you will shortly see, this is not the case for active galaxies, for which it is necessary to consider all the observed wavelength ranges.

We shall call this the ***broadband spectrum*** to distinguish it from the narrower optical spectrum.

Note// The optical spectrum is just one part of the broadband spectrum albeit an important part. The spectrum of a normal galaxy is the composite spectrum of the stars and gas that make up the galaxy.

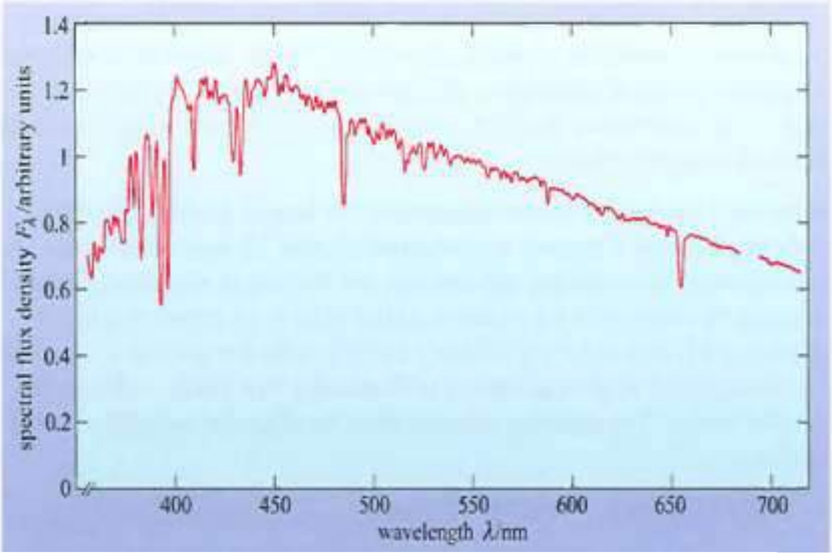

Figure 3.1 The optical spectrum of a star – in this case of spectral type F5 – shown as the spectral flux density, F_λ, plotted against wavelength. (From data described in Silva and Cornell, 1992)

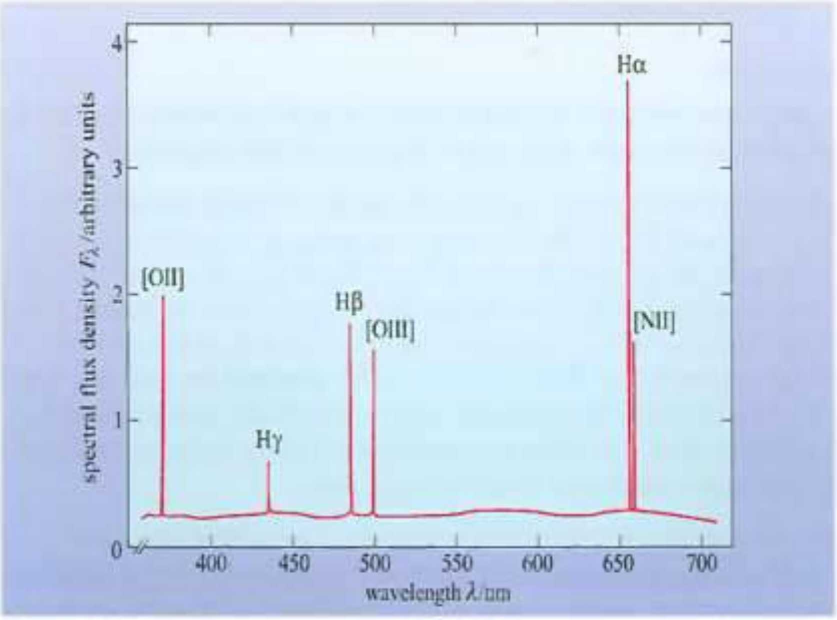

Figure 3.2 The schematic spectrum of a typical HII region, showing emission lines. HII denotes a singly ionized hydrogen atom, NII represents a singly ionized nitrogen atom, and OII and OIII denote singly and doubly ionized oxygen atoms. [NII], [OIII] and [OII] denote particular electronic transitions in these ions – the meaning of the square brackets is explained in Section 3.2.1. Hα, Hβ and Hγ are the first three Balmer lines of hydrogen.

Optical spectra of Normal galaxies

Normal galaxies are made up of stars and (in the case of spiral and irregular galaxies) gas and dust. Their spectra consist of the sum of the spectra of these components. The optical spectra of normal stars are continuous spectra overlaid by absorption lines (Figure 3.1). There are two factors to consider when adding up the spectra of a number of stars to produce the spectrum of a galaxy.

The optical spectrum of an HII region consists mainly of emission lines, as in Figure 3.2. When the spectra of the HII regions and the stars of a galaxy are added together, the emission lines from the HII regions tend to remain as prominent features in the spectrum unless a line coincides with a stellar absorption line.

BOX 3.1 DOPPLER BROADENING

The Doppler effect causes wavelengths to be lengthened when the source is moving away from the observer (*red-shifted*) and shortened when the source is moving towards the observer (*blue-shifted*).

Light from an astrophysical source is the sum of many photons emitted by individual atoms. Each of these atoms is in motion and so their photons will be seen as blue- or red-shifted according to the relative speeds of the atom and the observer. For example, even though all hydrogen atoms emit Hα photons of precisely the same wavelength, an observer will see the photons arrive with a spread of wavelengths: the effect is to broaden the Hα spectral line – called **Doppler broadening**.

In general, if the emitting atoms are in motion with a range of speeds Δv along the line of sight to the observer (the *velocity dispersion*) then the Doppler broadening is given by

$$\Delta\lambda/\lambda \approx \Delta v/c \qquad (3.1)$$

where c is the speed of light, and λ is the central wavelength of the spectral line.

Why would the atoms be in motion? An obvious reason is that they are 'hot'. Atoms in a hot gas, for example, will be moving randomly with a range of speeds related to the temperature of the gas. For a gas of atoms of mass m at a temperature T, the velocity dispersion is given by

$$\Delta v \approx \left(\frac{2kT}{m}\right)^{1/2} \qquad (3.2)$$

where k is the Boltzmann constant ($1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$).

QUESTION 3.1

Calculate the velocity dispersion for hydrogen atoms in the solar photosphere (temperature ~6×10^3 K). Then work out the width in nanometres of the Hα line (656.3 nm) due to thermal Doppler broadening.

It is very common for Doppler broadening to be expressed as a speed rather than $\Delta\lambda$ or even $\Delta\lambda/\lambda$. So astronomers would say that the width of the solar Hα line is about $10\,\mathrm{km\,s^{-1}}$.

You can also see that thermal Doppler broadening depends on the mass of the atom so, for the same temperature, hydrogen lines will be wider than iron lines.

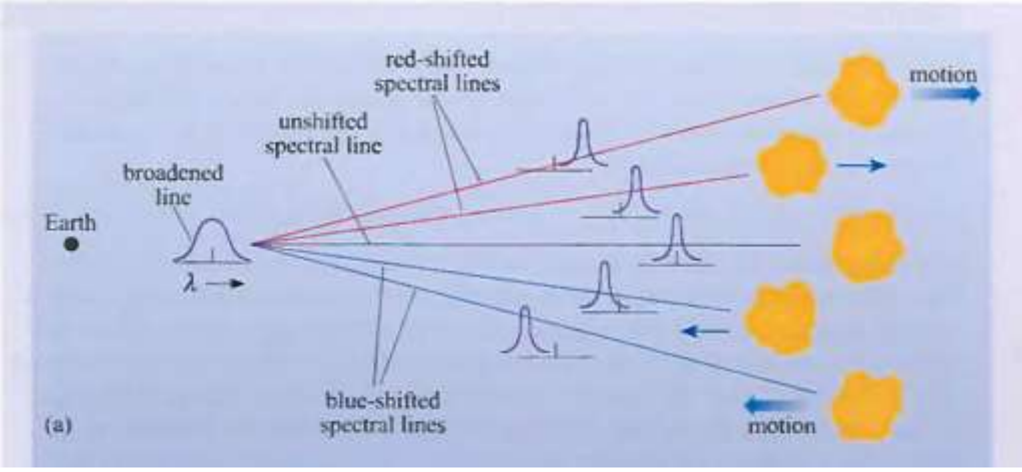

Figure 3.3 Doppler broadening arises when the source of a spectral line contains atoms moving at different speeds along the line of sight (a).

The optical spectrum of a spiral galaxy consists of the continuous spectrum from starlight with a few shallow absorption lines from stars, plus a few rather weak emission lines from the HII regions. Figure 3.4 shows an example. Note that the Hα line in this spectrum is a result of both absorption from stars and emission from HII regions.

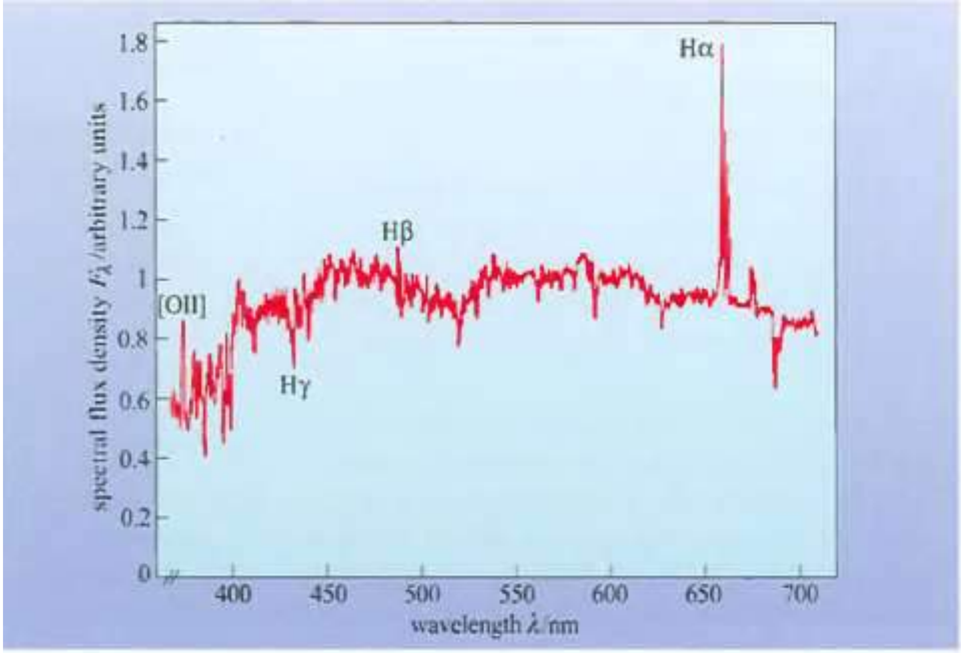

Figure 3.4 The optical spectrum of the normal spiral galaxy NGC 4750. It shows absorption lines and some emission lines. (Note that because of the Doppler shift caused by the motion of the galaxy, a particular spectral line is not necessarily at the same wavelength in all the figures in which it appears.

Physical properties of morphological classes

- Elliptical galaxies are essentially ellipsoidal distributions of old (Population II) stars, almost devoid of cold gas and dust. Their three-dimensional shape is difficult to determine, but some at least appear to be triaxial ellipsoids with very little rotation. Some of the smaller ellipticals may be oblate spheroids.
- Lenticular galaxies appear to be an intermediate class between the most flattened of elliptical galaxies and the most tightly wound spirals. They show clear signs of a disc and a central bulge, but they have no spiral arms and little cold interstellar gas.
- Spiral galaxies have a disc, a central bulge and often a central bar. Within this class, spiral arms may be more or less tightly wound and the bulge may be more or less prominent in relation to the disc. (The Milky Way is a spiral galaxy and was traditionally described as being of Hubble type Sb or Sc, but it is now known to have a bar and is probably best described as type SBbc.)
- The largest normal galaxies are the cD galaxies – giant ellipticals which may have been formed in mergers and which are often found close to the centres of clusters of galaxies.

The measurement of the physical properties of galaxies

- The surface brightness of galaxies varies from point to point. Continuous lines passing through points of equal surface brightness are called isophotes. As it is often difficult to determine the edge of a galaxy, observations of galaxies are often confined to the region within some specified isophote.
- Empirical relations obtained from observations of nearby galaxies are used to estimate quantities such as the luminosity and angular size of a distant galaxy, on the basis of its flux density within a given isophote.
- Galactic masses are generally hard to measure. However, the methods that may be used to determine them include the use of rotation curves for spirals, velocity dispersions and X-ray halos for ellipticals, and velocity dispersions for clusters of galaxies.
- The masses of clusters of galaxies are of the order of ten times greater than the estimated masses of the matter that has been detected via electromagnetic radiation, indicating that they contain substantial amounts of dark matter.
- The stellar content of galaxies can be estimated through the process of population synthesis. Direct observations at various wavelengths can be used to establish the importance of gas and dust in a galaxy.

4.2 The radiation properties of Active Galaxies (AGN)

An active galaxy is a galaxy with a nucleus that produces an exceptionally large amount of energy, up to 10^{15} solar luminosities. This is about 10,000 times the amount of energy produced by the entire Milky Way Galaxy. The spectrum of an active galaxy is quite flat compared with the spectrum of a star, and in many cases contains both broad and narrow emission lines. The luminosity in the radio waves through far-infrared is dominated by synchrotron radiation—radiation produced by electrons spiraling around a magnetic field line. The luminosity in the ultraviolet is dominated by the ‘‘blue bump’’ produced by hot (10,000 K), dense gas. And the near-infrared radiation is dominated by emission from cool dust (see Fig.)..

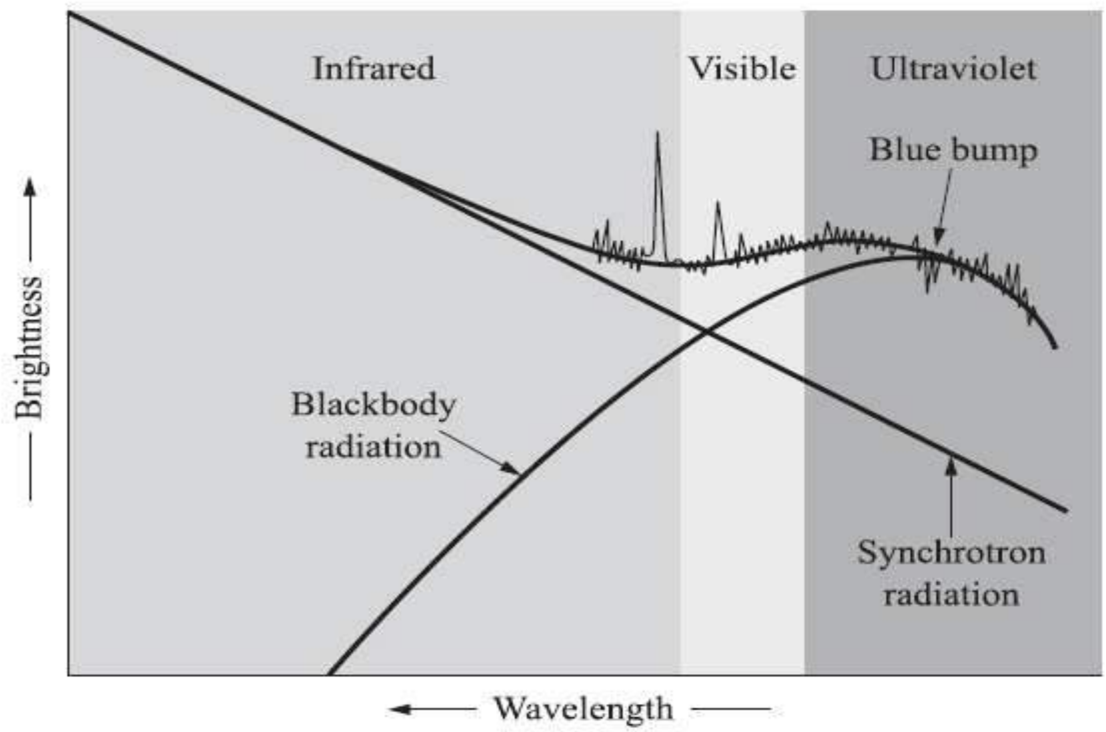

Fig. The spectrum of an active galaxy.

The luminosity of Active Galaxies

The staggering luminosities of these objects may be explained by the presence of a supermassive black hole in the center. As stars, gas, and dust fall in towards the black hole, conservation of angular momentum forces them into an accretion disk, where they spiral around the black hole. As they turn, they emit ultraviolet and X-ray radiation, which is subsequently absorbed by the surrounding dust and gas, heating it, so that the radiation is re-emitted as continuum radiation at lower temperatures.

The radiation produced by the infalling material pushes outward on the outer rim of the accretion disk. For a given mass, the luminosity has an upper limit, beyond which all the outer matter would be swept away by the radiation. This is called the Eddington Luminosity, L_{Edd}, and is given by:

$$L_{\text{Edd}} = 30{,}000 \frac{M}{M_{\text{Sun}}} L_{\text{Sun}}$$

where M is the mass of the black hole, M_{Sun} is the mass of the Sun, and L_{Sun} is the luminosity of the Sun. This equation can be turned around to give the lowest possible mass that a central black hole could have to produce the luminosity of an active galaxy. The mass could be higher, but not lower than this value, and still produce this luminosity..

Q1// What is the Eddington Luminosity of a quasar with a black hole mass of 500,000,000 M_{Sun}?

Q2// What is the smallest possible mass of a quasar with luminosity 10^{15} L_{Sun}?

Types of active galaxy

- All active galaxies have a compact, energetic nucleus – an AGN.
- Seyfert galaxies are spiral galaxies with bright, point-like nuclei which vary in brightness. They show excesses at far infrared and other wavelengths, and have strong, broad emission lines.
- Quasars resemble very distant Seyfert galaxies with very luminous nuclei. They are variable. About 10% are strong radio sources thought to be powered by jets of material moving at speeds close to the speed of light.

- Radio galaxies are distinguished by having giant radio lobes fed by one or two jets. They have a compact nucleus like Seyfert galaxies. The compact nucleus is variable, and its emission lines may be broad or narrow.
- Blazars exhibit a continuous spectrum across a wide range of wavelengths and emission lines, when present, are broad and weak. They are variable on very rapid timescales.

The central engine

- An object that fluctuates in brightness on a timescale Δt can have a radius no greater than $R \sim c\Delta t$.
- The point-like nature of AGNs and their rapid variability imply that the emitting region is smaller than the size of the Solar System.
- The central engine of a typical AGN is believed to contain a supermassive black hole of mass $\sim 10^8 M_\odot$ and Schwarzschild radius $\sim 3 \times 10^{11}$ m (2 AU).
- Infalling material is thought to form an accretion disc around the black hole, converting gravitational energy into thermal energy and radiation. A typical AGN luminosity of 10^{38} W can be accounted for by an accretion rate of $0.2 M_\odot$ per year.
- The maximum luminosity of an accreting black hole is given by the Eddington limit, at which the gravitational force on the infalling material is balanced by the radiation pressure of the emitted radiation.
- Jets are thought to be ejected perpendicular to the accretion disc.

The spectra of galaxies

- The spectrum of a galaxy is the composite spectrum of the objects of which it is composed.
- The optical spectrum of a normal galaxy contains contributions from stars and HII regions. An elliptical galaxy has no HII regions and has an optical spectrum that looks somewhat like a stellar spectrum but with rather fainter absorption lines. A spiral galaxy has both stars and star-forming regions, and its optical spectrum is the composite of its stars and its HII regions (which show rather weak emission lines).
- The widths of spectral lines from a galaxy may be affected by Doppler broadening due either to thermal motion or to bulk motion of the emitting material.
- An active galaxy has an optical spectrum that is the composite of the spectrum of a normal galaxy and powerful additional radiation characterized by strong emission lines. The broadening comes from bulk motion of the emitting gas.
- A broadband spectrum comprises radiation from a galaxy over all wavelength ranges. To judge a broadband spectrum fairly, it is necessary to use a λF_λ plot on logarithmic axes which is called a spectral energy distribution (SED).
- The SEDs of normal galaxies peak at optical wavelengths while the SEDs of active galaxies show emission of substantial amounts of energy across a wide range of wavelengths that cannot be attributed to emission from stars alone.

The spectra emission of Active galaxies

Figure 3.6 (overleaf) shows a schematic optical spectrum of an active galaxy. It is immediately apparent that the emission lines are stronger and broader than in the spectrum of a normal galaxy shown in Figure 3.4.

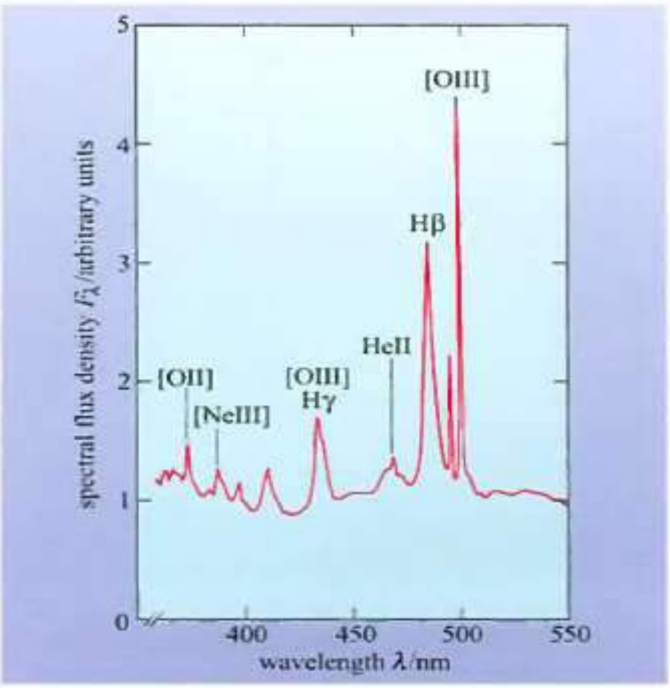

Figure 3.6 The schematic optical spectrum of an active galaxy. Note the strong and broad emission lines, especially the two hydrogen lines Hβ and Hγ. The forbidden lines remain narrow ([OIII] at $\lambda = 436$ nm is almost coincident with Hγ).

- From what you have learned so far, what might be the nature of this component?
- The strong emission lines suggest that the galaxy contains hot gas similar to an HII region. The broad lines imply that the gas must be either extremely hot or in rapid motion.

Broadband spectra of Active galaxies

The broadband spectrum is the spectrum over all the observed wavelength ranges. To plot the broadband spectrum of any object it is necessary to choose logarithmic axes.

- Why is it necessary to use logarithmic axes?
- Because both the spectral flux density, F_λ, and the wavelength vary by many powers of 10.

Figure 3.7 shows the broadband spectrum of the Sun: it has a strong peak at optical wavelengths with very small contributions at X-ray and radio wavelengths.

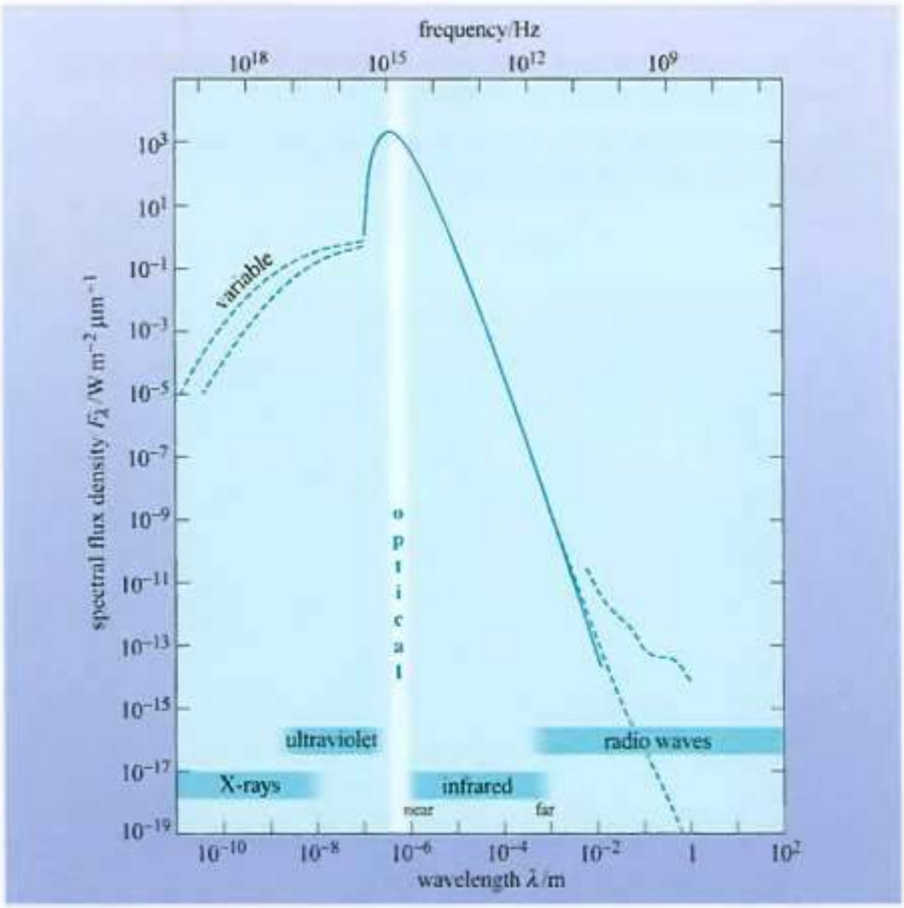

Figure 3.7 The broadband spectrum of the Sun. The dashed lines indicate the maximum and minimum in regions where the flux density varies. (Adapted from Nicolson, 1982)

Broadband spectra of Normal galaxies

Figure 3.8 shows schematically the broadband spectrum of a normal spiral galaxy. It resembles that of the Sun, although the peak occurs at a slightly longer wavelength and there are relatively greater spectral flux densities at X-ray, infrared and radio wavelengths.

■ List the objects in a normal galaxy that emit at (a) X-ray, (b) infrared and (c) radio wavelengths.

❑ (a) X-rays are emitted by X-ray binary stars, supernova remnants and the hot interstellar medium.

(b) Infrared radiation comes predominantly from cool stars, dust clouds, and dust surrounding HII regions.

(c) Radio waves are emitted by supernova remnants, atomic hydrogen and molecules such as CO.

From Figure 3.8 you would conclude that the spectrum peaks in the optical, but there is a subtlety in the definition of F_λ which needs to be addressed.

■ Look again at the broadband spectrum in Figure 3.8. Is this galaxy brighter in X-rays or in the far-infrared ($\lambda \sim 100\,\mu m$)?

❑ The F_λ curve is higher in the X-ray region, so the galaxy appears to be brighter in X-rays than in the far-infrared (far-IR).

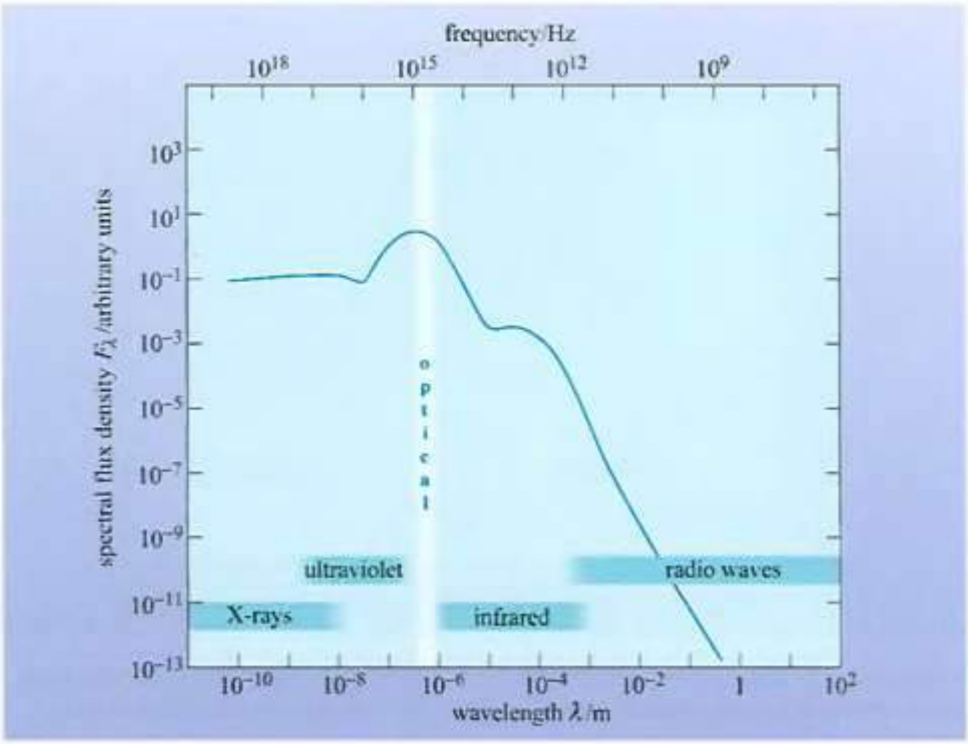

Figure 3.8 Schematic broadband spectrum of a normal spiral galaxy.

Spectral energy distribution (or SED) of galaxies

To correct this bias in F_λ spectra, astronomers often plot the quantity λF_λ instead. λF_λ, pronounced 'lambda eff lambda', (with units of W m^{-2}) is a useful quantity when we are comparing widely separated parts of a broadband spectrum. If the

A broadband spectrum plotted in this way is known as a ***spectral energy distribution (or SED)*** because the height of the curve is a measure of the energy emitted at each point in the spectrum.

(SED) of Normal galaxies:

In Figure 3.9, λF_λ has been plotted against λ for the normal galaxy spectrum of Figure 3.8, and it can be clearly seen that this curve has a peak at optical wavelengths, confirming what was suspected. But it also shows that more energy is being radiated at far-IR wavelengths than in X-rays, the opposite of the impression given by Figure 3.8. From now on in this chapter broadband spectra will be plotted as SEDs with λF_λ against λ on logarithmic axes.

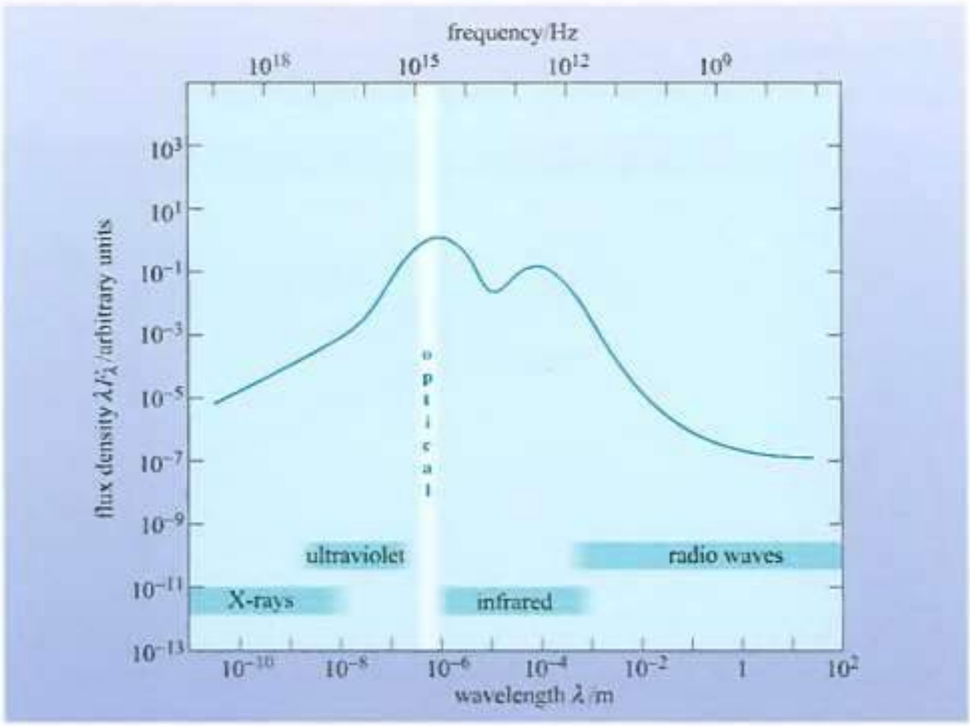

Figure 3.9 The spectral energy distribution (SED) of the galaxy in Figure 3.8. The vertical axis is now λF_λ instead of F_λ.

(SED) of Active galaxies:

Figure 3.10 shows the spectral energy distribution of an active galaxy.

For the active galaxy (known from its catalogue number as 3C 273) the peak emission is in the X-ray and ultraviolet regions. Many other active galaxies are bright in this region and the feature is known as the "big blue bump".

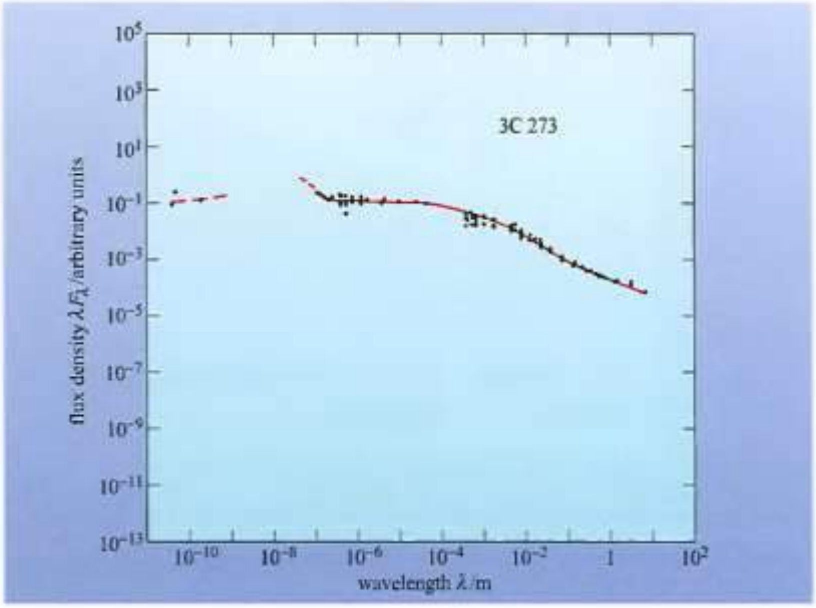

Figure 3.10 The spectral energy distribution of an active galaxy, the quasar 3C 273. The filled circles are measurements and the red curve shows the spectrum as determined from the data. (Data provided by NASA/IPAC Extragalactic Database)

- In broad terms, what is the major difference between the SED of the normal galaxy in Figure 3.9 and the SED of the active galaxy in Figure 3.10?
- Compared with the (unquantified) peak emission, the SED of the active galaxy is much flatter than that of the normal spiral galaxy. This indicates that there is relatively much more emission (by several orders of magnitude) at X-ray wavelengths and at radio wavelengths.

Spectral optical of Active galaxies

I. Spectral optical for Seyfert galaxies

Spectra of the bright nuclei reveal that Seyferts can be classified into two types by the relative widths of their emission lines.

Type 1 Seyferts have two sets of emission lines (Figure 3.13a).

Type 2 Seyferts only show prominent narrow lines (Figure 3.13b). The broad lines are either absent or very weak in the optical spectra of type 2 Seyferts.

An analysis of which lines are present allows the densities of the gas in the broad- and narrow-line regions to be determined.

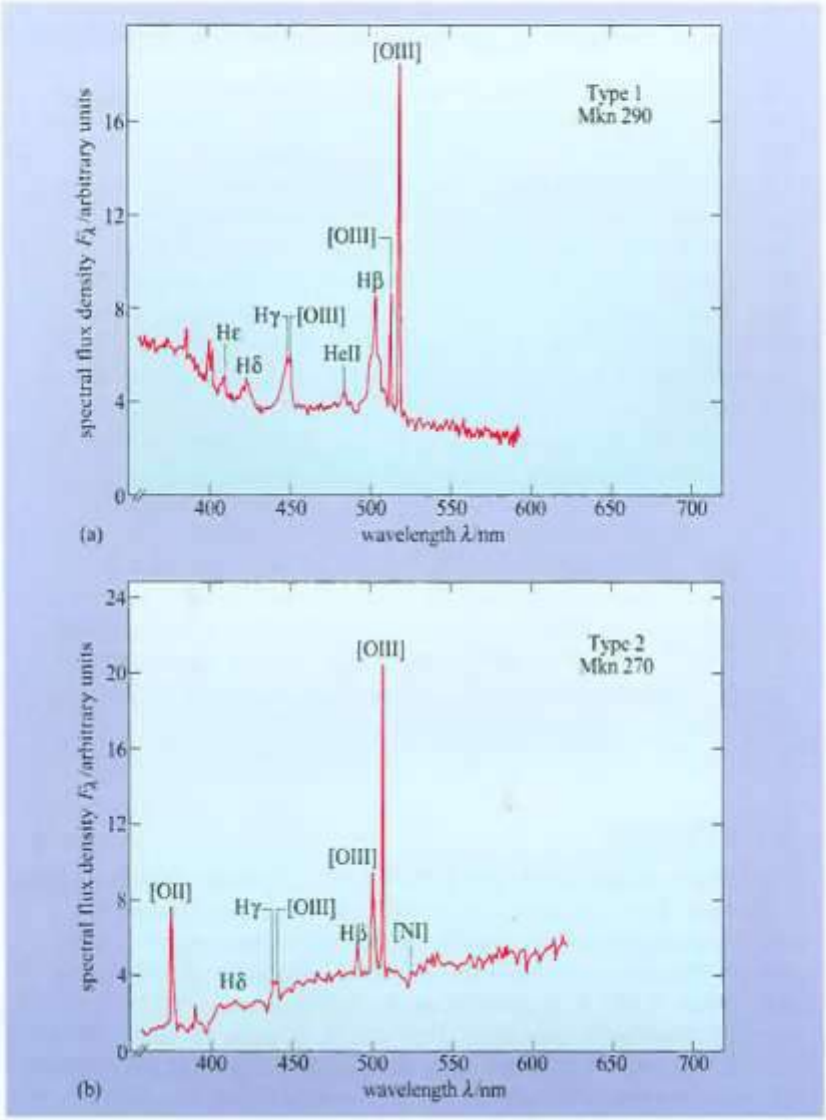

Figure 3.13 The optical spectra of two Seyfert galaxies.
(a) Markarian 290, a type 1 Seyfert.
(b) Markarian 270, a type 2 Seyfert.
Note that the broad hydrogen lines (especially Hβ) visible in (a) appear narrower in (b). (Netzer, 1990)

II. Spectral optical for Quasars

Figure 3.15 shows the optical spectrum of 3C 273, which was the first quasar to be discovered (you have already seen its broadband spectrum in Figure 3.10).

All quasars must therefore be highly luminous to be seen by us at all.

The optical spectra of quasars are similar to those of Seyfert 1 galaxies, with prominent broad lines but rather weaker narrow lines.

Quasars show spectral excesses in the infrared and at other wavelengths. About 10% of quasars are strong radio sources and are said to be radio loud. Some astronomers prefer to retain the older term **QSO (quasi-stellar object) for radio-quiet quasars** that are not strong sources of radio waves.

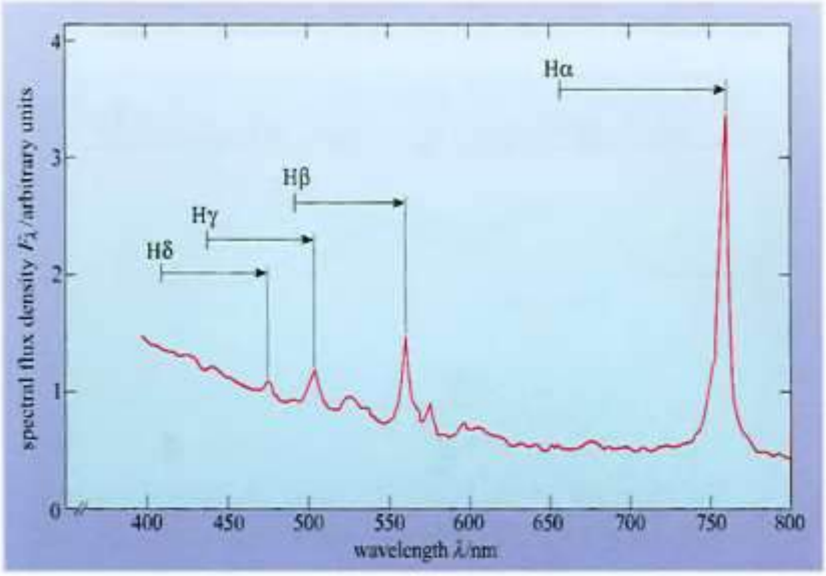

Figure 3.15 The optical spectrum of 3C 273, the first quasar to be discovered. The arrows show how the prominent hydrogen emission lines have been greatly red-shifted from their normal wavelengths. (Kaufmann, 1979)

III. Spectral optical for Radio galaxies

Radio galaxies dominate the sky at radio wavelengths. They show enormous regions of radio emission outside the visible extent of the host galaxy - usually these radio lobes occur in pairs.

The optical spectrum of the nucleus of a radio galaxy looks very much like that of any other AGN. Like Seyferts radio galaxies can be classified into two types depending on whether broad lines are present (broad-line radio galaxies) or only narrow lines (narrow-line radio galaxies). Figure 3.22 shows an example of a spectrum of a broad-line radio galaxy.

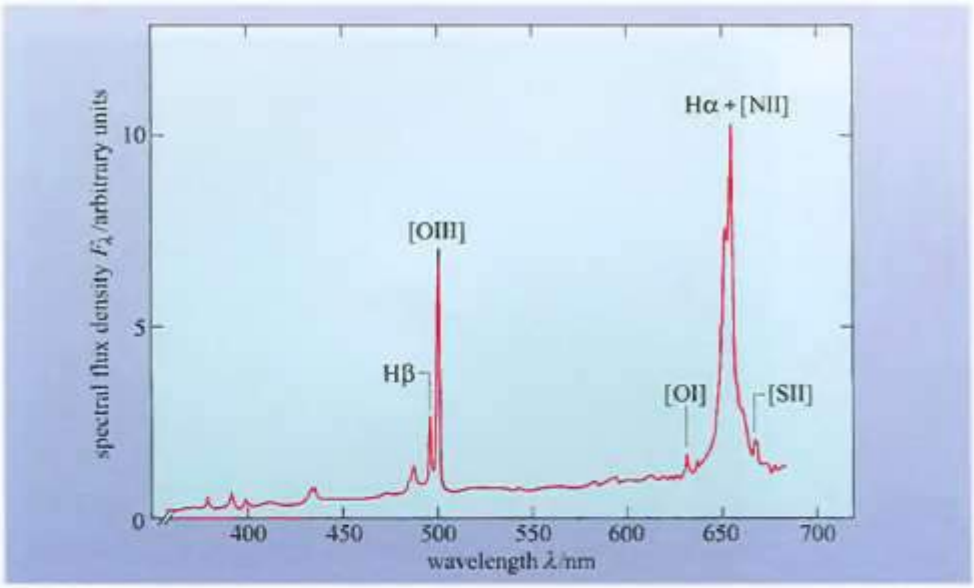

Figure 3.22 The optical spectrum of the nucleus of the radio galaxy 3C 445 (adjusted to zero redshift). (Osterbrock *et al.*, 1976)

Dust sublimation radius for an AGN:

If the engine has a luminosity, L, then the flux density at a radius r from the engine will be $L/4\pi r^2$. A dust grain of radius a will intercept the radiation over an area πa^2 (Figure 3.33) and, if no energy is reflected, the power absorbed will be

$$\text{power absorbed} = \pi a^2 \times \frac{L}{4\pi r^2} = \frac{La^2}{4r^2}$$

Figure 3.33 A spherical dust grain of radius a will intercept radiation over an area πa^2.

The temperature of the dust grain will rise until the power emitted by thermal radiation is equal to the power absorbed. If the grain behaves as a black body we can write

$$\text{power emitted} = 4\pi a^2 \sigma T^4$$

where σ is the Stefan–Boltzmann constant ($\sigma = 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$).

Here we assume that the temperature of the grain is the same over its whole surface, which would be appropriate if, for instance, the grain were rotating. Next, we make the power absorbed equal to the power radiated

$$\frac{La^2}{4r^2} = 4\pi a^2 \sigma T^4$$

Finally, if we divide both sides by a^2, the radius a is cancelled out (as it should – the size of the dust grain should not come into it) and we can rearrange for r to get:

$$r = \left(\frac{L}{16\pi\sigma T^4}\right)^{1/2} \tag{3.7}$$

This distance is called the **sublimation radius** for the dust.

QUESTION 3.12

Calculate the dust sublimation radius, in metres and parsecs, for an AGN of luminosity 10^{38} W. (Assume that dust cannot exist above a temperature of 2000 K.)

Glossary

1. **Absolute magnitude:** A measure of an object's luminosity; defined to be the apparent magnitude the object would have if it were
 located exactly 10 parsecs away.
2. **arcminute** (or **minute of arc**) 1/60 of 1°.. **arcsecond** (or **second of arc**) 1/60 of an arcminute, or 1/3600 of 1°.
3. **Accretion disk** A rapidly rotating disk of material that gradually falls inward as it orbits a starlike object (e.g., white dwarf, neutron star, or black hole).
4. **Active galactic nuclei :**The unusually luminous centers of some galaxies, thought to be powered by accretion onto supermassive black holes. Quasars are the brightest type of active galactic nuclei; radio galaxies also contain active galactic nuclei.
5. **Active galaxy** A term sometimes used to describe a galaxy that contains an *active galactic nucleus*.
6. **Apparent magnitude:** A measure of the apparent brightness of an object in the sky, based on the ancient system developed by Hipparchus.
7. **Barred spiral galaxies:** Spiral galaxies that have a straight bar of stars cutting across their centers.
8. **BL Lac objects:** A class of active galactic nuclei that probably represent the centers of radio galaxies whose jets happen to be pointed directly at us.
9. **Bulge** (of a spiral galaxy) :The central portion of a spiral galaxy that is roughly spherical (or football shaped) and bulges above and below the plane of the galactic disk.
10. **Continuous spectrum:** A spectrum (of light) that spans a broad range of wavelengths without interruption by emission or absorption lines.
11. **Dark matter:** Matter that we infer to exist from its gravitational effects but from which we have not detected any light; dark matter apparently dominates the total mass of the universe.
12. **Dark energy**: Name sometimes given to energy that could be causing the expansion of the universe to accelerate. See cosmological constant.
13. **Electromagnetic radiation:** Another name for light of all types, from radio waves through gamma rays.
14. **Electromagnetic spectrum:** The complete spectrum of light, including radio waves, infrared light, visible light, ultraviolet light, X rays, and gamma rays.
15. **Disk** (of a galaxy): The portion of a spiral galaxy that looks like a disk and contains an interstellar medium with cool gas and dust; stars of many ages are found in the disk.
16. **Doppler effect** (shift) : The effect that shifts the wavelengths of spectral features in objects that are moving toward or away from the observer.
17. **Emission** (of light): The process by which matter emits energy in the form of light.
18. **Emission line :** A bright band (a "line") of single color, superimposed on a fainter or completely absent rainbow of light, occurring when light viewed through a diffraction element such as a prism shows an excess of photons at or near a specific wavelength.
19. **Gravitational constant** The experimentally measured constant *G* that appears in the law of universal gravitation: $G = 6.67 * 10^{-11}\ m^3 / kg\ .\ s^2$
20. **Gamma rays:** Light with very short wavelengths (and hence high frequencies)— shorter than those of X rays.
21. **Halo** (of a galaxy): The spherical region surrounding the disk of a spiral galaxy.
22. **Halo component:** (of a galaxy) The portion of any galaxy that is spherical (or football-like) in shape and contains very little cool gas; it generally contains only very old stars.
23. **High-mass stars:** Stars born with masses above about 8*M*Sun; these stars will end their lives by exploding as supernovae.
24. **Hubble's law:** Mathematical expression of the idea that more distant galaxies move away from us faster: $v = H0 * d$, where *v* is a galaxy's speed away from us, *d* is its distance, and *H*0 is Hubble's constant.

25. **Hubble's constant:** A number that expresses the current rate of expansion of the universe; designated *H*0, it is usually stated in units of km/s/Mpc. The reciprocal of Hubble's constant is the age the universe would have *if* the expansion rate had never changed.
26. **Infrared light:** Light with wavelengths that fall in the portion of the electromagnetic spectrum between radio waves and visible light.
27. **Interstellar medium:** The gas and dust that fills the space between stars in a galaxy.
28. **Inverse square law for light:** The law stating that an object's apparent brightness depends on its actual luminosity and the inverse square of its distance from the observer:

$$\text{Apparent brightness} = \text{luminosity} / 4\pi * (\text{distance})^2$$

29. **Ionization:** The process of stripping one or more electrons from an atom. **ionization nebula :** A colorful, wispy cloud of gas that glows because neighboring hot stars irradiate it with ultraviolet photons that can ionize hydrogen atoms; also called an *emission nebula* or *H II region*.
30. **Local Group:** The group of about 40 galaxies to which the Milky Way Galaxy belongs.
31. **Luminosity:** The total power output of an object, usually measured in watts or in units of solar luminosities ($L_{Sun} = 3.8 * 10^{26}$ watts).
32. **Luminosity class:** A category describing the region of the H-R diagram in which a star falls. Luminosity class I represents supergiants, III represents giants, and V represents main-sequence stars; luminosity classes II and IV are intermediate to the others.
33. **Mass-to-light ratio:** The mass of an object divided by its luminosity, usually stated in units of solar masses per solar luminosity. Objects with high mass-to-light ratios must contain substantial quantities of dark matter.
34. **Microwaves:** Light with wavelengths in the range of micrometers to millimeters. Microwaves are generally considered to be a subset of the radio wave portion of the electromagnetic spectrum.
35. **Nebula:** A cloud of gas in space, usually one that is glowing.
36. **Nuclear fission:** The process in which a larger nucleus splits into two (or more) smaller particles.
37. **Nuclear fusion:** The process in which two (or more) smaller nuclei slam together and make one larger nucleus.
38. **Planetary nebula:** The glowing cloud of gas ejected from a low-mass star at the end of its life.
39. **Plasma:** A gas consisting of ions and electrons.
40. **Radial motion:** The component of an object's motion directed toward or away from us.
41. **Radial velocity:** The portion of any object's total velocity that is directed toward or away from us. This part of the velocity is the only part that we can measure with the Doppler effect.
42. **Radiation pressure:** Pressure exerted by photons of light.
43. **Radiation zone** (of a star): A region of the interior in which energy is transported primarily by radiative diffusion.
44. **Radiative diffusion:** The process by which photons gradually migrate from a hot region (such as the solar core) to a cooler region (such as the solar surface).
45. **Radiative energy:** Energy carried by light; the energy of a photon is Planck's constant times its frequency, or $h * f$.
46. **Radioactive decay:** The spontaneous change of an atom into a different element, in which its nucleus breaks apart or a proton turns into an electron. This decay releases heat in a planet's interior.
47. **Radio galaxy:** A galaxy that emits unusually large quantities of radio waves; thought to contain an active galactic nucleus powered by a supermassive black hole.

48. **Radio waves:** Light with very long wavelengths (and hence low frequencies)—longer than those of infrared light.
49. **Rotation curve:** A graph that plots rotational (or orbital) velocity against distance from the center for any object or set of objects.
50. **Redshift** (Doppler): A Doppler shift in which spectral features are shifted to longer wavelengths, observed when an object is moving away from the observer.
51. **Quasar:** The brightest type of active galactic nucleus.
52. **Solar wind:** A stream of charged particles ejected from the Sun.
53. **Spiral galaxies:** Galaxies that look like flat white disks with yellowish bulges at their centers. The disks are filled with cool gas and dust, interspersed with hotter ionized gas, and usually displays beautiful spiral arms.
54. **Standard candle:** An object for which we have some means of knowing its true luminosity, so that we can use its apparent brightness to determine its distance with the luminosity–distance formula.
55. **Spectroscopy** (in astronomical research): The process of obtaining spectra from astronomical objects.
56. **Starburst galaxy:** A galaxy in which stars are forming at an unusually high rate.
57. **Stefan–Boltzmann constant:** A constant that appears in the laws of thermal radiation, with value $\sigma = 5.7 \times 10^{-8} \dfrac{\text{watt}}{\text{m}^2 \times \text{K}^4}$:
58. **Supernova:** The explosion of a star.
59. **Supernova remnant:** A glowing, expanding cloud of debris from a supernova explosion.
60. **Synchrotron radiation:** A type of radio emission that occurs when electrons moving at nearly the speed of light spiral around magnetic field lines.
61. **Temperature:** A measure of the average kinetic energy of particles in a substance.
62. **Thermal energy:** The collective kinetic energy, as measured by temperature, of the many individual particles moving within a substance.
63. **Thermal radiation:** The spectrum of radiation produced by an opaque object that depends only on the object's temperature; sometimes called *blackbody radiation*.
64. **Transmission** (of light): The process in which light passes through matter without being absorbed.
65. **21-cm line:** A spectral line from atomic hydrogen with wavelength 21 cm (in the radio portion of the spectrum).
66. **Ultraviolet light (UV):** Light with wavelengths that fall in the portion of the electromagnetic spectrum between visible light and X rays.
67. **Universal law of gravitation:** The law expressing the force of gravity (*Fg*) between two objects, given by the formula:

$$F_g = G\,\frac{M_1 M_2}{d^2}$$

$$\left(\text{where } G = 6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right)$$

68. **Universe:** The sum total of all matter and energy.
69. **Visible light:** The light our eyes can see, ranging in wavelength from about 400 to 700 nm.
70. **Visual binary:** A binary star system in which both stars can be resolved through a telescope.
71. **Wavelength:** The distance between adjacent peaks (or troughs) of a wave.
72. **White dwarfs:** The hot, compact corpses of low-mass stars, typically with a mass similar to that of the Sun compressed to a volume the size of Earth.

73. **X rays:** Light with wavelengths that fall in the portion of the electromagnetic spectrum between ultraviolet light and gamma rays.
74. **X-ray binary:** A binary star system that emits substantial amounts of X rays, thought to be from an accretion disk around a neutron star or black hole.
75. **X-ray burster:** An object that emits a burst of X rays every few hours to every few days; each burst lasts a few seconds and is thought to be caused by helium fusion on the surface of an accreting neutron star in a binary system.
76. **X-ray bursts:** Bursts of X- rays coming from sudden ignition of fusion on the surface of an accreting neutron star in an X-ray binary system.

Problems:

Q1// The surface of a star is radiating as a black body with a temperature of 6000 K. If the temperature were to increase by 250 K, by what fraction would the energy liberated per unit area increase?

Q2// The constant in Wien's displacement law is $2{\cdot}90 \times 10^{-3}$ m K. What is the wavelength corresponding to the maximum radiation output of a star whose surface temperature is 5000 K?

Q3// The wavelength associated with the hydrogen spectrum may be expressed in the form: $\lambda_{mn} = R(1/n^2 - 1/m^2)$

For the lines in the visible part of the spectrum (Balmer series), $n = 2$ and the first line of the series, Hα is at 6562 A°. Show why observations of the lines of the Lyman series $(n = 1)$ may only be made from rockets or satellites.

Q4// A spectrometer is just able to detect a wavelength shift of 0·01 A°. What would be the minimum strength of magnetic field that might be detected in a star if the spectral region around 4500 A° were to be used?

Q5// From the spectrum taken of a star, the Hβ line (4861 A°) exhibits a blue wavelength displacement of 0·69 A° . What is the relative velocity of approach of the star?

Q6//a. ______________________ ____________________ is a non-thermal mechanism producing electromagnetic radiation by accelerating charged particles in a magnetic field to nearly the
speed of light.

b. The intensity of non-thermal radiation often __________________ with frequency.

c. In the interstellar medium, areas within clouds of molecules that greatly amplify the radiation passing through them are called astrophysical __________.

Q7// a) Find the fraction of radiation that a blackbody emits in the range [λ1, λ2], where λ1 and $\lambda_2 >> \lambda_{\max}$. b) How much energy does a 100W incandescent light bulb radiate in the radio wavelengths, $\lambda \geq 1$ cm? Assume the temperature is 2500 K.

Q8// Flux densities at the wavelengths 440 nm and 550 nm are 1.30 and 1.00Wm^{-2} m^{-1}, respectively. Find the colour temperature.

Q9// Show that in the Wien approximation the relative error of B_λ is:

$$\frac{\Delta B_\lambda}{B_\lambda} = -e^{-hc/(\lambda kT)} .$$