# Introduction to Astronomy

AA1051

Available as a *University Certificate*
and a module for *CertHE*, *DipHE* and *BSc in Astronomy*.

## Sample Notes

These sample pages from the Course Notes for the module *Introduction to Astronomy* have been selected to give an indication of the level and approach of the course. They are not designed to be read as a whole, but are intended to give you a flavour of the syllabus, style, diagrams, images, equations, mathematical content and presentation. They are a subset of the colour, navigable on-line version of the learning materials.

All enrolled students will be sent a CDRom with all the Course Notes and learning materials, in addition to having access to them via the course website.

- All sections of notes will be available in modest colour and basic navigation in pdf format suitable for downloading and printing at home. It is anticipated that most students will prefer to use the notes in the colour pdf files on the CDRom.

- B/w paper copies will be sent out to anyone who has notified us that they have special educational needs.

July 2008

Section 1

# The Celestial Sphere

*Historical documents show that many cultures have traditionally developed an (imaginary) Celestial Sphere surrounding the Earth, populated with constellations depicting mythical figures and objects. Modern day astronomers have retained the idea of a celestial sphere and use it as the framework for quantitative measurements of the positions of celestial objects.*

## Introduction - An Observational Science

ICON KEY

- Valuable information
- Test yourself
- Worked example
- Kaufmann[1]
- ≈ Important Equation

Astronomy is the study of the physical Universe, the entire Cosmos around us, and as such is a fabulous and fascinating challenge. Unlike other physical sciences where the investigator can design an experiment to measure a particular quantity, astronomy is largely an observational science. Astronomers cannot set up control experiments or make adjustments to the universe to isolate the one aspect of it that they are trying to investigate. Instead they are constrained to making observations of the universe as it actually is. Therefore astronomy depends upon the acquisition of observational data, followed by its careful analysis and interpretation to infer the properties of remote celestial objects.

Over the last century, advances in technology have done much to enhance our view of the universe. In this first section, we will describe the measurement of the fundamental observational quantities - position and time - as commonly used by astronomers. Later in the course, we will show how various observational quantities are used to determine physical properties of stars, nebulae and galaxies.

---

[1] Whenever you see a book icon in the margin, you will find a reference to the recommended text *Universe* by Kaufmann. Publisher's details of this can be found in the Astronomy Workbook. Specific references to page numbers or diagrams will assume Kaufmann 6th edition, but general references to chapters are valid for 5th or 6th editions.

See Footnote 1 on Page 1-1.

If you have a copy of the recommended text (*Universe* by Kaufmann) you should read Chapters 1 and 2.

### Fundamental Observational Quantities

It is not necessary to make detailed observations of the night sky to discover some of its fundamental properties. Even with the unaided eye we can see point sources of light scattered randomly over the celestial sphere. Our ancestors were able to identify groups of stars, or constellations that can still be seen today. Hence we know that the vast majority of stars appear to maintain the same relative position for long periods of time. It is also obvious that stars have a range of brightness and many people can discern stars of different colours. In the opening sections of this course we will look in detail at each of these topics, starting here with the positions of the stars.

## Positional Astronomy

When defining the positions of astronomical objects it is convenient to consider them as lying on the surface of the celestial sphere, which is a large, imaginary sphere centred on the Earth. Because all stars are at a much greater distance than the dimensions of the Earth itself, this effectively defines the stars' directions in space. As the Earth rotates about its axis each day, the celestial sphere appears to turn overhead, (see Figure 2-11 in Chapter 2 of Kaufmann) leading to the phenomenon of the stars rising in the east and setting in the west on a daily basis, just like the Sun and Moon.

Astronomers use a celestial co-ordinate scheme that is based on the celestial sphere and is analogous to the geographical system of latitude and longitude used for positions on Earth. This is shown in Figure 1.1.

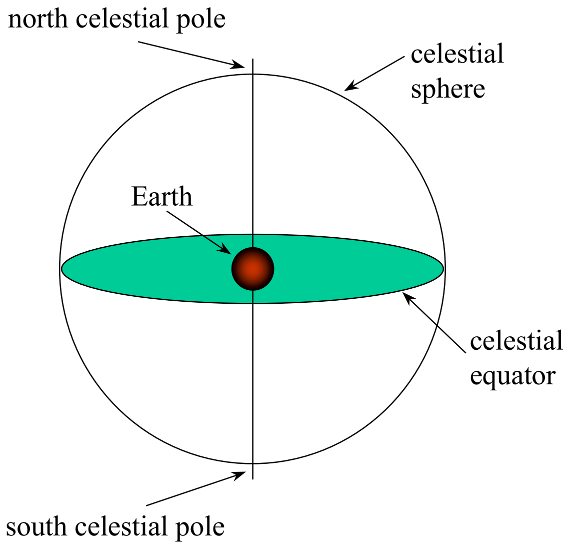



**Figure 1.1**
The Celestial Sphere. The vertical line through the Earth's poles is the rotation axis.

## Stellar Magnitudes

At the beginning of this section we saw that the Greek astronomer Hipparchus classified the brightness of naked eye stars according to a system of stellar magnitudes. The smaller the numerical value of the magnitude of a star, then the brighter the star. The system of magnitudes in use today is in line with this historical definition, and has been extended to include negative and non-integer values. If a star is brighter than magnitude 0.0 then its magnitude is expressed as a negative number. For example the magnitude of Sirius (Alpha Canis Majoris) is –1.4. The magnitude of objects as they appear on the sky is known as the apparent magnitude. The full range of apparent magnitudes on the modern scale is shown in Kaufmann Figure 19-6, running from –26 for the Sun through the traditional naked-eye range of 1 to 6 magnitudes, and up (in magnitude) to the very faintest stars that can be detected with the largest telescopes and most sensitive detectors, currently approaching 30$^{th}$ magnitude. Table 2.4 gives the apparent magnitudes of a number of familiar astronomical objects. Most of the stars that define the brightest constellations are first magnitude stars. Norton's 2000 Star Atlas provides approximate magnitudes of the bright stars.

**Table 2.4**
Apparent magnitudes of common objects. Note that magnitudes for planets are approximate and variable as their brightness depend upon their distance from Earth.
See also the *Astronomy Workbook* for a list of examples.

| Object | Apparent magnitude (m) |
|---|---|
| **Venus** | –4 |
| **Jupiter** | –2.5 |
| **Sirius** | –1.4 |
| **Saturn** | –0.4 |
| **Vega ($\alpha$ Lyrae)** | 0.0 |
| **Polaris** | 2.1 |
| **Megrez (Plough)** | 3.3 |
| **R Lyrae (near Vega)** | +4.5 |
| **Neptune** | 7.62 |

The magnitude scale was put on a sound quantitative basis in the 1850s by the British Astronomer, N. R. Pogson, who proposed that for two objects a

> magnitude difference of 5 magnitudes corresponded to a factor of exactly 100 in brightness.

This is clearly a logarithmic scale, where a magnitude difference represents a multiplicative factor, reflecting the manner in which the human eye operates. Note however that it is *not* quite the same logarithmic scale as we discussed when plotting graphs above, where two orders of magnitude were equivalent to a factor of a 100.

For example, for stellar magnitudes, a star of first magnitude is 100 times as bright as a star of 6th magnitude. Pogson's magnitude system also requires that a difference of just one magnitude corresponds to a constant ratio of brightness. In the Magnitudes Exercise in the *Astronomy Workbook*, Table 2.1 shows that a difference of one magnitude corresponds to a constant ratio of brightness equal to 2.512. It then follows that five magnitudes correspond to a ratio of $2.512^5$ which equals 100, in agreement with Pogson's statement above.

## Flux

Astronomers usually use the term flux to describe the brightness of a star. This can be defined as:

> Flux ($F$): Total flow of light energy perpendicularly crossing unit area per unit time. It has units of J $s^{-1}$ $m^{-2}$ or equivalently W $m^{-2}$.

If two stars of apparent magnitudes $m$ and $n$ have measured fluxes $F_m$ and $F_n$ respectively, then we can use the idea of a constant ratio per magnitude to obtain a general formula for the ratio of the fluxes.

$$\frac{F_m}{F_n} = 2.512^{(n-m)} \qquad \text{Equation 2.1}$$

Note that the star with the greater magnitude will have the smaller flux.

Example 1

If one star has a magnitude of six (6th magnitude) and another star has a magnitude of one (1st magnitude) what is the ratio of fluxes from these stars?

Solution Let us suppose that the fainter star has magnitude $n = 6$, and the brighter star has magnitude $m = 1$. Then the magnitude difference $(n - m) = 6 - 1 = 5$. In Equation 2.1, $F_m$ will represent the flux of the 1st magnitude star, and $F_n$ will represent the flux of the 6th magnitude star. The ratio of the fluxes that we are required to find is then the quantity on the left hand side of Equation 2.1. Let us now substitute in the values.

$$\frac{F_m}{F_n} = \frac{F_{m=1}}{F_{n=6}} = 2.512^{(n-m)}$$
$$= 2.512^5 = 100$$

In performing this last step it is necessary to use a calculator or other means to raise the number 2.512 to the power 5. The result obtained for the ratio of the fluxes of the two stars is exactly 100, confirming that Equation 2.1 is a mathematical version of Pogson's statement in the shaded box that a magnitude difference of five magnitudes corresponds to a factor of 100 in brightness, here expressed in terms of the flux.

Mathematical formulation of the magnitude scale.

Equation 2.1 above can be rearranged to find the magnitude difference between two objects expressed in terms of the logarithm of the flux ratio. This form, known as Pogson's relation, is what we will use most frequently for many calculations in this course.

$$m - n = -2.5 \times \log \frac{F_m}{F_n} \qquad \text{Equation 2.2}$$

where 'log' means the logarithm to base 10 of a number.

This expression tells us that the *difference* in magnitudes of two stars is equal to -2.5 times the logarithm of the flux *ratio* of those same two stars. It is clear from this equation that Pogson's magnitude scale is really logarithmic rather than linear, reproducing the logarithmic response of the human eye on which Hipparchus' system was based. The factor of –2.5 is present in Equation 2.2 to ensure that a factor of 100 leads to *five* astronomical magnitudes, whereas without it, a factor of 100 would correspond to just *two* orders of magnitude. The minus sign is there to ensure that fainter stars have more positive magnitudes. Note that the decibel scale in sound measurement has a very similar defining equation, except that its numerical factor is different (with +10.0 rather than –2.5).

Let us now use the same example as above to demonstrate that Equation 2.2 is also exactly equivalent to Pogson's original formulation of magnitude scale as given in the shaded box.

Worked Example 2

If one star has an apparent magnitude of six (6th magnitude) and another star has an apparent magnitude of one (1st magnitude) what is the ratio of fluxes from these stars?

Solution Use Equation 2.2 with $m$ = 1, $n$ =6 and $F_m/F_n$ the required flux ratio

$$m - n = -2.5 \log \frac{F_m}{F_n}$$

$$1 - 6 = -5 = -2.5 \log \frac{F_m}{F_n}$$

The LHS of equation above gives –5 and we divide both sides by –2.5 to get:

$$2 = \log \frac{F_m}{F_n}$$

Taking the antilog of both sides gives the required answer:

$$\text{antilog}(2) = 10^2 = 100 = \frac{F_m}{F_n} = \text{ratio of fluxes}$$

*i.e.* the 1st mag star is 100 times as bright as the 6th mag star, just as expected.

### Gaps in the HR diagram

Other zones in the HR diagram are unstable areas in which stars either do not exist, or spend only small fractions of their lives as their internal structures change from one zone of stability to another.

Good examples of these are the variable stars that are found in the triangular zone between the upper left hand portion of the main sequence and the red giant branch. Variable stars such as Cepheid and RR-Lyrae variables occupy this zone and represent stars either moving towards the red giant phase from the main sequence, or stars moving up the red giant branch as their core burning phases change prior to becoming supernovae. We will discuss this in more detail when we cover stellar evolution later in the course.

Therefore we see that the HR diagram can tell us much about a star. It is extremely important and will also figure highly in any further study of astronomy or astrophysics. As the course progresses we will discuss the detailed physics of stars, and learn how they behave and why they are so stable for such lengthy periods.

## Fundamental stellar parameters

### Masses of main-sequence stars

Although the mass of a star is extremely difficult to determine (it is not possible to just go and weigh one!) you will see (in Section 7) that there are ways to determine this for some stars. It turns out that stars have masses in the relatively narrow range of about 0.1 $M_\odot$ to about 50 $M_\odot$. On the main-sequence, the mass decreases steadily from the most massive objects located in the top left of the HR diagram, as shown in Figure 4.3.

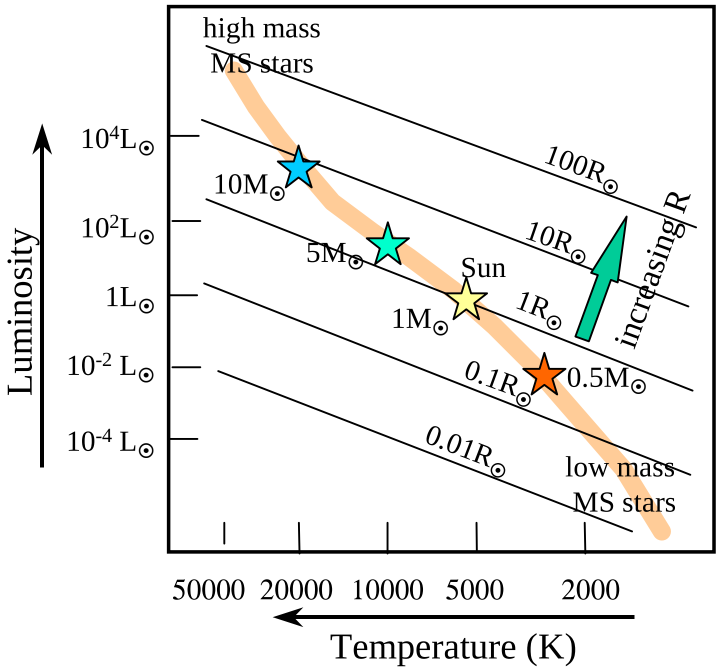



**Figure 4.3**
Theoretical HR diagram showing masses of main sequence stars and lines of constant radius.

## Atomic Hydrogen Spectrum

We can now use the energy level diagram for hydrogen to deduce what the hydrogen spectrum will be like. Let us assume that we need to derive the absorption line spectrum for atomic hydrogen. The absorption process removes a photon from the radiation field and increases the energy of the electron. Only certain photons will be absorbed: those which have energy equal to the gaps between any two energy levels in the energy level diagram.

The energy level diagram Figure 5.10 shows some of the different transitions possible. Notice there are different groups of absorption lines: those that start in the ground state ($n$ = 1); then those that start from $n$ = 2 and so on. Each of the groups is called a series. The most famous group in astronomical spectra is the Balmer series from $n$ = 2 to a higher level. This series is well known because it is lies in the visible portion of the spectrum. The Lyman series is in the ultraviolet region of the spectrum. All the other series will be toward longer (redder) wavelengths.

Astronomers denote the Balmer lines in sequence from the principal line ($n$ = 2 to 3) with the notation Hα, Hβ, Hγ, Hδ etc. (Sometimes the Greek symbols appear as subscripts.) The wavelength λ and frequency ν can be calculated using the Planck relation

$$\Delta E = E_n - E_m = h\nu = \frac{hc}{\lambda} \qquad \text{Equation 5.6}$$

and we can use the energies of the different energy levels (go back to Table 5.1) that we calculated using the Bohr Equation (5.3) and $R_H$(=13.6 eV) the ionisation potential of hydrogen.

Worked Example

Calculate the wavelength of the Hβ line.

**Solution** The Hβ line results from a transition between level 2 and level 4. We can therefore use Equation 5.3 with $n$ = 4 and $m$ =2.

$$\Delta E = (-0.85) - (-3.40)\text{eV}$$

Equation 5.6 can then be used to calculate the wavelength.

$$\lambda = \frac{hc}{\Delta E} = \frac{6.63\times10^{-34}\times3\times10^{8}}{2.55\times1.6\times10^{-19}}\times10^{9}$$
$$= 487.5 \text{ nm}$$

Notice how the transitions on the energy level diagram produce the famous Balmer line spectrum shown in Figure 5.10. The spectral lines are well spaced towards the red, but towards the blue become closer as the lines approach the series limit.

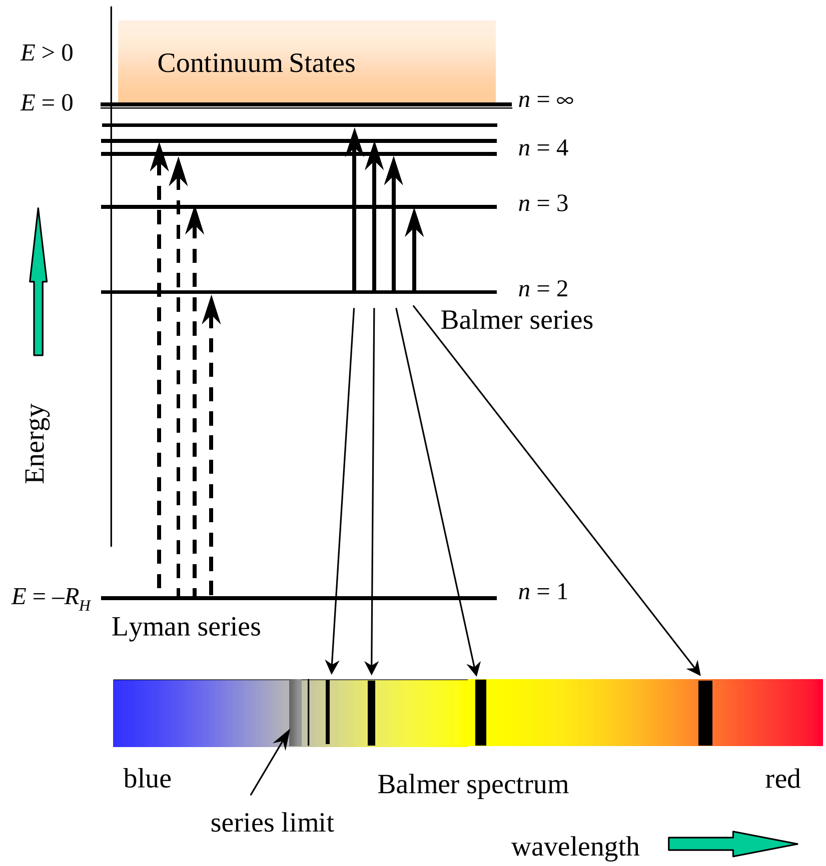



**Figure 5.10**
Formation of absorption lines due to hydrogen atom

Like hydrogen, all atoms have energy levels between which their electrons can move. However, these are usually much more complex for heavier elements than for hydrogen and helium. In each case there is more than one electron in the system, so there are different ionisation states. Each atom and ion has its own unique energy level diagram which provides each ion with a unique pattern of lines in its spectrum. These unique patterns are the signatures of the elements and allow astronomers to detect the presence and calculate the abundance of elements in astronomical bodies such as stars and nebulae.

## Origins of Stellar Spectroscopy

Astronomers at Harvard noticed that spectra could show great differences in their general appearances: the majority show absorption lines, only a few show emission lines. Early catalogues of spectra were classified by Annie Cannon and included around 200,000 stars brighter than ninth magnitude in a total of 9 volumes. The volumes are known as the Henry Draper Catalogue since the work was funded by a large donation from his estate. Stars were arranged in sequence based on the presence and strengths of certain lines. The pioneering work of Kirchhoff and Bunsen showed that the absorption lines are caused by absorbing gas in the cool outer layers of stars. If the process is the same in all stars (Kirchhoff's rules) why do spectra look so different from the sun? (*eg* stars show a great variation in the strength of the H lines.) Astronomers first thought that the absence of absorption lines implied the absence of that chemical. But this is not necessarily true because

3. **Chromatic aberration** is due to dispersion in the lens resulting in light rays of different wavelength (colour) being brought to a focus at different points along the optical axis (*Universe* Figure 6-7).

The first two of these aberrations are produced by many optical systems (including mirrors and your eye) but the third is due solely to variations of the refractive index of the lens material, as a function of wavelength.

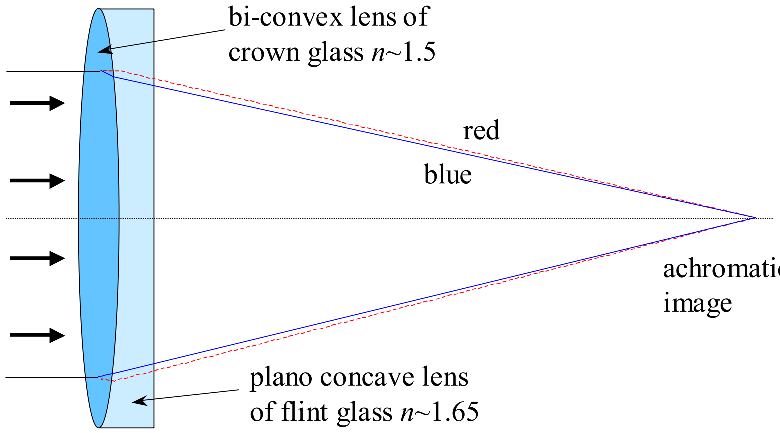



**Figure 6.7**
An achromatic doublet lens constructed from two separate lenses made of crown and flint glass.

Chromatic aberration can be greatly improved by using a **compound lens** (see Figure 6.7) for the objective (primary) lens. This can be made of two separate lenses, each of a different type of glass (crown and flint) that have different refractive indices. The crown lens is convex (or positive) and the flint lens is plano-concave (or negative). The compound lens is designed so that the chromatic aberrations in each of the two lenses cancel out for two specific wavelengths. However the correction is only approximately right for light of other colours. See also the historical discussion later in this section.

## Telescope Designs

Today's telescopes fall into three general classes of design: **refractors**, **reflectors** and **catadioptric systems**. The very first astronomical systems, dating back to 1605, were simple refracting telescopes. Modern amateur (and smaller professional) systems are usually compact catadioptric designs.

### Refractors

Most early telescopes used refraction in a glass lens to form an image of visible light. An astronomical telescope can be used visually by viewing with the naked eye or to produce an image on a detector.

Rays of light arriving from a very distant star or planet are, for practical purposes, parallel to each other. In astronomical use we can say that the object is effectively at an infinite distance. The rays are bent slightly at each surface of the lens and with careful design all the rays that pass through the lens will pass through a single point called the focus. This is true for the two arrangements shown in Figure 6.8.

## Carbon - Nitrogen - Oxygen Cycle

The CNO cycle starts by a proton fusing with carbon ($C^{12}$) to form an unstable isotope of nitrogen $N^{13}$. This decays by means of beta decay producing $C^{13}$ together with a positron and a neutrino.

$$\begin{aligned}
&C^{12} + H^{1} \rightarrow N^{13} + \gamma \\
&N^{13} \rightarrow C^{13} + e^{+} + \nu \\
&C^{13} + H^{1} \rightarrow N^{14} + \gamma \\
&N^{14} + H^{1} \rightarrow O^{15} + \gamma \\
&O^{15} \rightarrow N^{15} + e^{+} + \nu \\
&N^{15} + H^{1} \rightarrow C^{12} + He^{4}
\end{aligned} \qquad \text{Equation 9.17}$$

The following steps involve similar reactions, until the final reaction produces $He^4$ and releases $C^{12}$. Notice that the C required for the reaction to take place only appears as a catalyst in this reaction. The carbon which is used up at the first stage of the reaction is regenerated in the last stage, resulting in no net use of carbon.

The CNO cycle dominates at very high temperatures and so is the main energy generation process in hot, massive stars at the upper end of the main-sequence.

However it is obvious that the presence of carbon is essential for the CNO cycle to operate. In Chapter 10, we shall see that all heavy elements including carbon are believed to have been formed in the interiors of stars over many generations of stellar birth and death. The very earliest stars would not have had sufficient carbon to support the CNO cycle, so they could only have generated energy via the pp cycle, whatever their mass.

## Summary of Main Points

- The Sun is about 5 billion years old. So using its luminosity, we can estimate the total energy it must have generated in the past.
- Thermal, gravitational and chemical energy reserves of the Sun all fall short of the energy required to fuel its main-sequence lifetime by several orders of magnitude.
- Only nuclear energy is sufficient to fuel the Sun's main-sequence life.
- Energy generation on the main-sequence is via fusion of hydrogen to helium.
- Main-sequence stars less massive than the Sun are fuelled by the pp chain, whereas massive stars on the main-sequence are fuelled by the CNO cycle.

.

### Distribution of galaxies in space

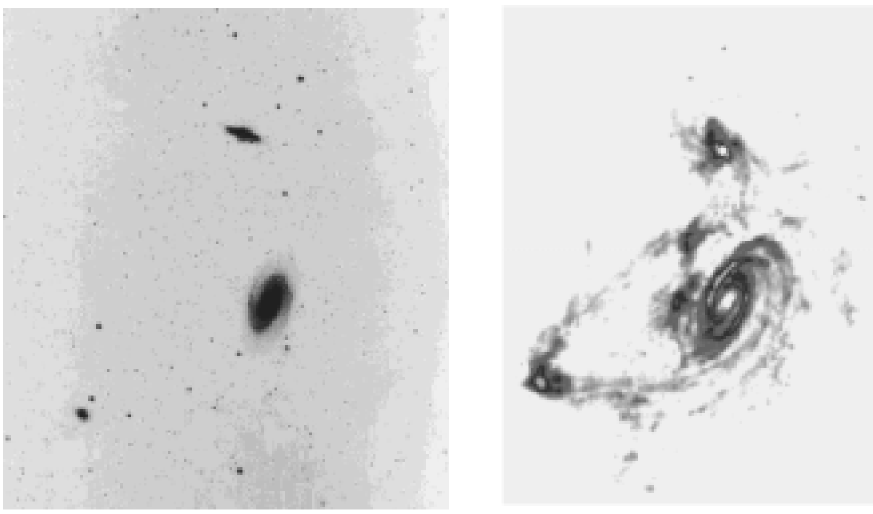
Again, like stars, galaxies are rarely found isolated in space. They occur in groups, clusters and superclusters. The latter leads into cosmology, and we will address this later. The scale of galaxies themselves and the separations between them in loose associations such as the Local Group (containing the Galaxy, M31 and M33 and other smaller galaxies) are such that they can be quite well described as “cities of stars” (as in the title of this chapter). Kaufmann gives a good description of the Local Group and clustering of galaxies in Section 26-6.

### Extended halos of galaxies

You will note that in our table of galaxy parameters, the diameter of the galaxy was referred to as the *optical* diameter. This is an important point and begs the question of “what determines the edge of a galaxy?”. Clearly this must be an observational effect, because as the density of stars on the sky (*i.e.* the number of stars per square parsec as seen from outside the galaxy) decreases towards its edge, their luminosity contribution will decrease and at some point they will be no longer observable above the background of our night sky (which is not perfectly black) or the limit of the sensitivity of a detector sent into space. A more sensitive detector might suggest a bigger galaxy as it can detect fainter emission (*i.e.* a smaller number of stars per square parsec). This is, in fact the case. In practice, one measures an isophotal diameter, usually defined as the diameter at which the brightness falls to the equivalent of one 25$^{th}$ magnitude star per square arcsecond of the galaxy image.

Isophotal diameters are a convenient standard, but are not necessarily telling us the whole story. For example, it has been known for some years that observations of neutral hydrogen gas reveal that the galaxies are in fact much bigger than we deduce by observing starlight alone. An example of this is shown in Figure 11.11. Why this is the case, and how large these extended halos really are, is still a matter of debate.

**Figure 11.11**
M81 M82 NGC3077 Cluster
a) Image in optical light and b) High resolution image[7] showing neutral hydrogen gas (HI) connecting the cluster (Yun et al, 1994) See also http://www.aoc.nao.edu/~myun.



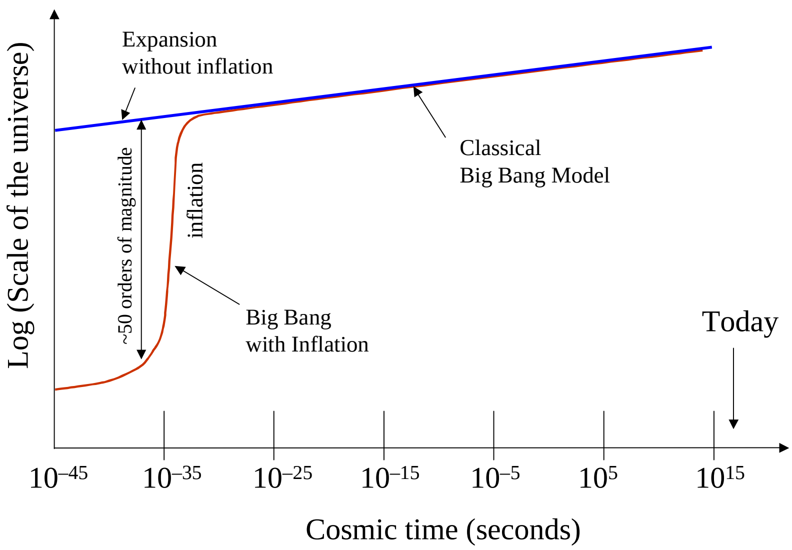
a) b)

[7] Reprinted by permission from Nature (http://www.nature.com) Vol 372, p530, copyright 1994 Macmillan Magazines Ltd.

## Inflation

The CBR is remarkably isotropic: deviations from isotropy are no more than about 1 part in $10^5$. This is strong evidence in support of the assumption of isotropy. This isotropy is actually one of the problems for the big bang model. For directions separated by more than about 3° the regions of the universe emitting the CBR towards us could never, in the big bang model, have been in causal contact. This means that no agent could have passed between them to equalise the temperature of the CBR. So, why is the CBR so isotropic? This is called the horizon problem. Clearly the solution to this problem must lie in whatever model of the universe takes effect in the tiny interval of time before the big bang model takes effect. The solution to this problem might lie in inflation. In this model, a region of the initial universe that was in causal contact is inflated by a huge factor (perhaps $10^{50}$) when the universe was at an age of about $10^{-34}$ seconds, as shown in Figure 12.4. This inflated region would now form the entire observable universe (and universe beyond what is observable). Since the region was initially in causal contact the temperature would have been equalised and the CBR today would appear isotropic.

**Figure 12.4**
The effect of inflation on the scale factor of the universe as a function of cosmic time.




You might like to find out more about inflation in other reading. Inflation is also supposed to solve the flatness problem. The density parameter $\Omega_o$ is observed to be quite close to 1. In the big bang model a value of 1 is not very likely - it requires an implausible degree of fine-tuning. However, inflation predicts that $\Omega_o$ will be exactly 1.0. Thus inflation solves the flatness problem too. This would be wonderful except that after a period in which observations gave values of $\Omega_o$ that appeared consistent with 1, the latest measurements are suggesting strongly that $\Omega \approx 0.2 - 0.3$. Inflation might not be the complete answer.

## Dark matter

There is evidence that much of the matter in the universe is in an unknown form, which is revealed only by its gravitational effects. The existence of this dark matter is most convincingly demonstrated in the haloes of spiral galaxies, at radii beyond the starlight. Measurements of the rotation of hydrogen gas in the haloes show that