Galaxies in Turmoil

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The Active and Starburst Galaxies and the Black Holes That Drive Them

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For Christine

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Preface

Active galaxies involve some of the most extreme conditions and some of the most intriguing phenomena found anywhere in the universe and their study is amongst the hottest areas of research interest, yet there is currently no book that makes the topic available at a non-mathematical and not too technical a level. The purpose of this book is to try and fill this gap.

The book is aimed at readers who already have an interest in and some knowledge of astronomy, who wish to get to grips with the confusing plethora of types of active galaxies – perhaps in order to go on to study some aspect of the topic in greater detail, perhaps so that they can extend their observational program, perhaps simply because active galaxies are fascinating in their own right. The study of active galaxies dates back to the beginning of the twentieth century, but serious work on them has been undertaken only in the last five decades or so. New types of active galaxies and new aspects to existing known types have been found every time a new part of the spectrum – radio, infrared, ultraviolet, x-ray or gamma ray – has been opened up to observers. This has resulted in innumerable apparently different varieties of objects out there in extragalactic space and this can confuse and perhaps put off a student new to the subject. I hope that this book will go far towards reducing the muddle, and to this end Appendix 2 lists all the types of active galaxy names that I have been able to discover in current use, together with a brief note about each of them. I would recommend that the reader has frequent recourse to this appendix, at least until he or she has become familiar with the main classes of active galaxies.

Observers with small or moderate sized telescopes have probably been put off from trying to look at active galaxies since most of the images that they will have encountered will have come from the largest of professional telescopes. This impression though is false – some active galaxies can even be found using binoculars. Many more are accessible through the commonly available 0.15–0.3 m telescopes, and hundreds may be imaged if a CCD camera is also to hand. To try and encourage the observation and study of active galaxies by as wide a range of astronomers as possible, the final chapter of the book lists, among other things, the observing details of the brighter active galaxies.

Since the book is intended to provide a readable broad account of active galaxies, the use of equations has been (almost) completely avoided. Although active galaxies is a highly complex field of study, some of the very fine details have been omitted so that the reader can obtain an understanding of the whole subject without becoming too bogged down in the technicalities. Also the more specialist or secondary topics have been separated from the main text into boxes and these can be looked at by the reader or not as the need arises.

While the book is not intended to provide the basis for specialist or research level studies of active galaxies, it is possible that it may be useful as background material for anyone with such interests. In particular, since all aspects of all types of active galaxies are included, research workers may find it useful as a quick reference to the properties of and phenomena within those types of active galaxies that are outside their specialisms.

The ambiguous numbers "billion" and "trillion" are used here to mean 1,000,000,000 and 1,000,000,000,000 respectively. When it is needed, for example in converting redshifts to distances, the value of 71 km/s per megaparsec (21.5 km/s per million light years) has been employed. Finally I have used two terms throughout the book that may not be familiar to all readers. The first is the old-fashioned time period of an aeon. This equals 1,000,000,000 years and so is ideally suited to the discussion of the lives of galaxies. The second word is the megasun. This is a term that I have coined for a mass of a million solar masses and which is valuable during discussions of massive black holes and related topics.

I hope that you, the reader, will be as fascinated by active galaxies as I have been, and that some of the mystery and confusion that surrounds the topic will be reduced by this book. I hope also that some readers may be encouraged to go out with their binoculars and telescopes and see what's really happening out there for themselves.

Chris Kitchin, April 2006

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Classical Galaxies

Summary

- How galaxies came to be recognized as large, independent and distant systems of stars, gas and dust outside the Milky Way Galaxy.
- The classification of galaxies based upon their visible shapes.
- How galaxies may have formed.
- The Milky Way Galaxy and its properties.
- How the expansion of the universe came to be discovered and the implications of that expansion.
- The age of the universe.

- Boxes
  Spectroscopy
  Doppler shifts
  The Big Bang
  Look-back time.

Readers already possessing a good background knowledge of astronomy may wish to proceed directly to Chap. 2; however unless they also have a good knowledge of spectroscopy, they are advised to read Boxes 1.1 and 1.2 before doing so.

1.1 The Great Debate

1.1.1 How It All Started

Many modern astronomers learn with some astonishment that people now in their early eighties were born before it was known that galaxies lay outside and far away from our own Milky Way and were themselves vast collections of stars and gas clouds. It is a measure of the stunning speed with which we have learnt about the universe that today's telescopes routinely study objects so far away that light has been traveling through space to reach us for nearly three times longer than the Earth has been in existence, whilst well under a century ago the best astronomers using the largest telescopes struggled to reach out a mere 2 million light years (0.6 Mpc). Of course, nebulae themselves could be observed further away than 2 Mly, but individual stars were another matter. Thus it was not until 1924 that Edwin Hubble obtained the first observational proof that one spiral nebula at least lay considerably beyond the limits of the Milky Way.

Hubble was trying to study individual stars within M 31, the great spiral nebula in Andromeda. Even with the largest telescope in the world, the 2.5-m (100-inch) Hooker telescope at Mount Wilson, Hubble could only detect the brightest single stars in M 31 (Fig. 1.1). He was hunting for the exploding stars called novae and in late 1923 thought that he had found one. A search through the Mount Wilson plate archive showed that the star had been imaged several times previously, going as far back as 1909. Armed with these observations, Hubble soon decided that he had found a Cepheid variable star and not a nova. To check this he observed again early in 1924. Sure enough, it was a Cepheid whose period was just over 31 days. This was an exciting result because a dozen years earlier Henrietta Leavitt, working at Harvard college observatory, had established that Cepheids' periods and absolute magnitudes[1] were related to each other. Thus Hubble was able to calculate his Cepheid's absolute magnitude to be about −3 and since its apparent magnitude averaged about 18.5, its distance must be some 700,000 ly (200 kpc). Now at that time there was some argument over the size of the Milky Way, but even the largest estimate was for a diameter of just 300,000 ly (100 kpc). M 31 must thus be at least 500,000 ly (150 kpc) beyond the Milky Way's most distant outskirts.

Hubble's results were published in 1925 and decisively ended the dispute about whether spiral nebulae were a part of the Milky Way or outside it, which had divided astronomers for decades. In fact we now

[1]Astronomers use the magnitude scale as a measure of the brightnesses of stars and other objects. Apparent magnitude is the brightness as the object actually appears in the sky, while absolute magnitude is the apparent magnitude that the object would have if its distance were 33 ly (10 pc). Differences between absolute magnitudes thus reflect real differences between the brightnesses of objects; differences between apparent magnitudes may be due to different distances to the objects involved and/or to differing actual brightnesses. A difference of one magnitude corresponds to a factor of $\times 2.512$ ($= 10^{0.4}$) between the brightnesses of two objects, a difference of two magnitudes is a factor of $\times 2.512^2$ ($= \times 6.3$), three magnitudes a factor of 2.512^3 ($= \times 15.9$), etc. The scale is an inverse one, i.e. the brighter the object the lower the numerical value of the magnitude and the zero point is fixed so that stars of magnitude 6^m are just visible to the unaided eye from a good dark observing site. The apparent magnitudes of some sample objects are: Sun (-26.7^m), Sirius A (-1.5^m), Polaris ($+2.3^m$), Sirius B ($+8.7^m$), while the currently faintest detectable objects are about $+27^m$. The Sun's absolute magnitude for comparison is $+4.7^m$, while that of Sirius is $+1.4^m$.

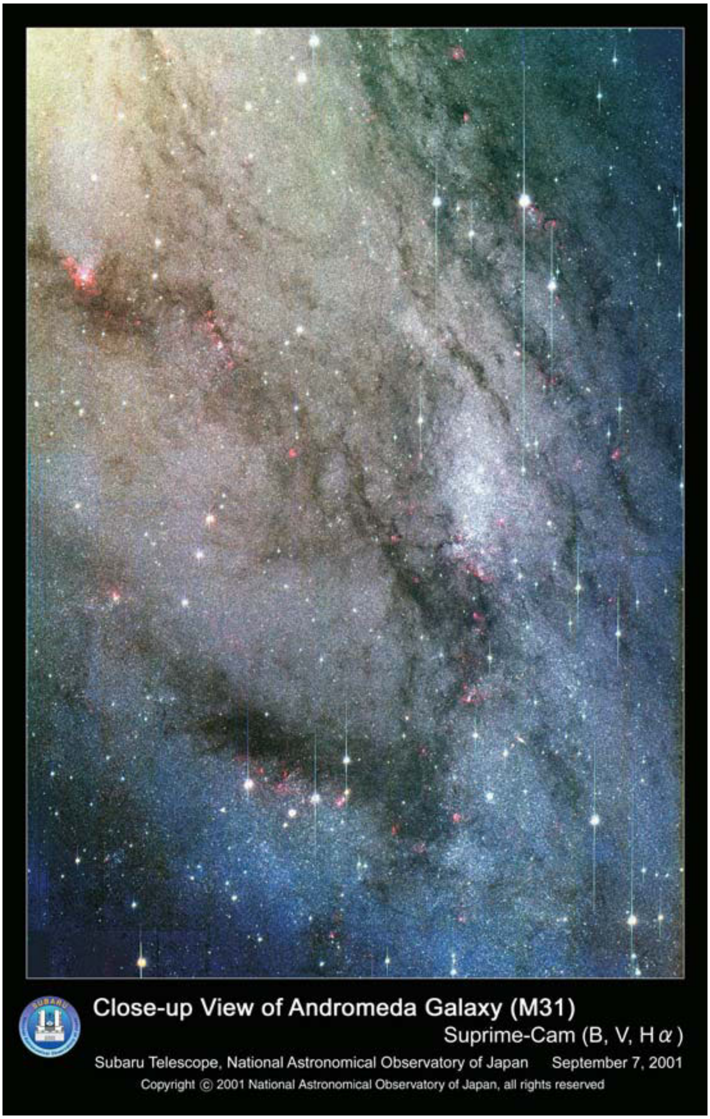

Figure 1.1 Individual stars within the Andromeda galaxy, M 31. Color image obtained using the Suprime-Cam on the 8-m (315-inch) Subaru telescope in 2001. (Copyright © Subaru Telescope, National Astronomical Observatory of Japan.)

know that the Milky Way galaxy (hereinafter called the Galaxy with an upper case G to distinguish it from all other galaxies) and the Andromeda galaxy are separated by almost 2 Mly (0.6 Mpc) and that the Galaxy is "only" about 100,000 ly (30 kpc) in diameter. Lord Rosse had first noticed spiral nebulae in 1845 whilst making visual observations using his 1.8-m (72-inch) reflector in Eire. The advent of photography enabled many more spiral nebulae to be found. The images also revealed other nebulae, some of which were irregular in shape while others had smooth, symmetrical, circular or elliptical shapes. These latter nebulae, even though bereft of any spiral structure, also became classed with the "spirals". By the end of the nineteenth century astronomers estimated the number of detectable spiral nebulae of both types to be in excess of 100,000.

Meanwhile, spectroscopy of nebulae undertaken both visually and photographically by William Huggins and others showed that in general they divided into two types; nebulae with bright emission lines like those that may be seen coming from hot gases in the laboratory, and nebulae with absorption lines like the spectra of stars (see Box 1.1). Generally the irregular nebulae had emission-line spectra, whilst the spirals had the absorption lines. Despite this evidence hinting that spiral nebulae were composed of stars, many astronomers, including Huggins, thought that the spiral nebulae were gaseous, perhaps even being planetary systems in the process of formation. Others scientists plumped for the "island universe" theory – the idea that spiral nebulae were composed of stars, maybe even millions of stars, but were so distant that they just appeared as blurs.

Box 1.1 Spectroscopy

The light that enables us to see things is just a small part of the complete electromagnetic (e-m) spectrum, which ranges from the longest radio waves to the shortest gamma waves. Confusingly e-m radiation sometimes behaves like a wave while at other times it behaves as though composed of particles. With wave-type behavior, we discuss e-m radiation in terms of its wavelength and frequency, while when it acts as though formed of particles; we talk about photons (or quanta) and their energies. The reasons for this apparently contradictory behavior lie deep within quantum theory and are beyond the scope of this book – the reader is simply asked to accept "that it is so" if not acquainted with that theory.

The dual nature of e-m radiation leads to wavelength and frequency tending to be used when discussing radiation in the ultraviolet, visual, infrared, microwave and radio regions, since interactions involving those types of e-m radiation tend to be dominated by wave-type behavior. While photon energies are apt to be invoked for x-rays and gamma rays since then the e-m radiation tends to have a particle-type behavior. To add to the confusion, a non-SI unit, the electron-volt (eV), is usually used as a measure for the energies of photons because the numbers then involved are more convenient. The electron-volt is defined as the energy gained by an electron when it is accelerated by one volt. Its value is $1\,\text{eV} = 1.6022 \times 10^{-19}\,\text{J}$. The divisions between regions of the e-m spectrum are arbitrary since its essential nature does not vary, but they are convenient and they are shown in Fig. 1.2 together with the generally accepted ranges of wavelength, frequency and photon energy. Additional sub-divisions are sometimes encountered such as soft and hard x-rays for the long wave and short wave x-rays respectively, extreme ultraviolet (EUV) for the shortest wave ultraviolet region, near, mid and far infrared (NIR, MIR, FIR), plus sub-millimeter waves for the region between the infrared and microwaves.

The complete e-m spectrum is infinite in extent, but it is customary to refer to a plot or image of a short segment of it that shows how intensity varies with wavelength, as a spectrum as well. Thus we have the rainbow where e-m radiation of different wavelengths within the visual part of the spectrum has been separated out by the effect of its passage through raindrops – although, strictly, this is not a pure spectrum since some wavelengths overlap each other. Purer visual spectra are obtained using instruments called spectroscopes. These employ diffraction gratings, interference filters, prisms, etc. to separate the various wavelengths (colors) so that they may then be imaged by a charge-coupled device (CCD) or photographic emulsion

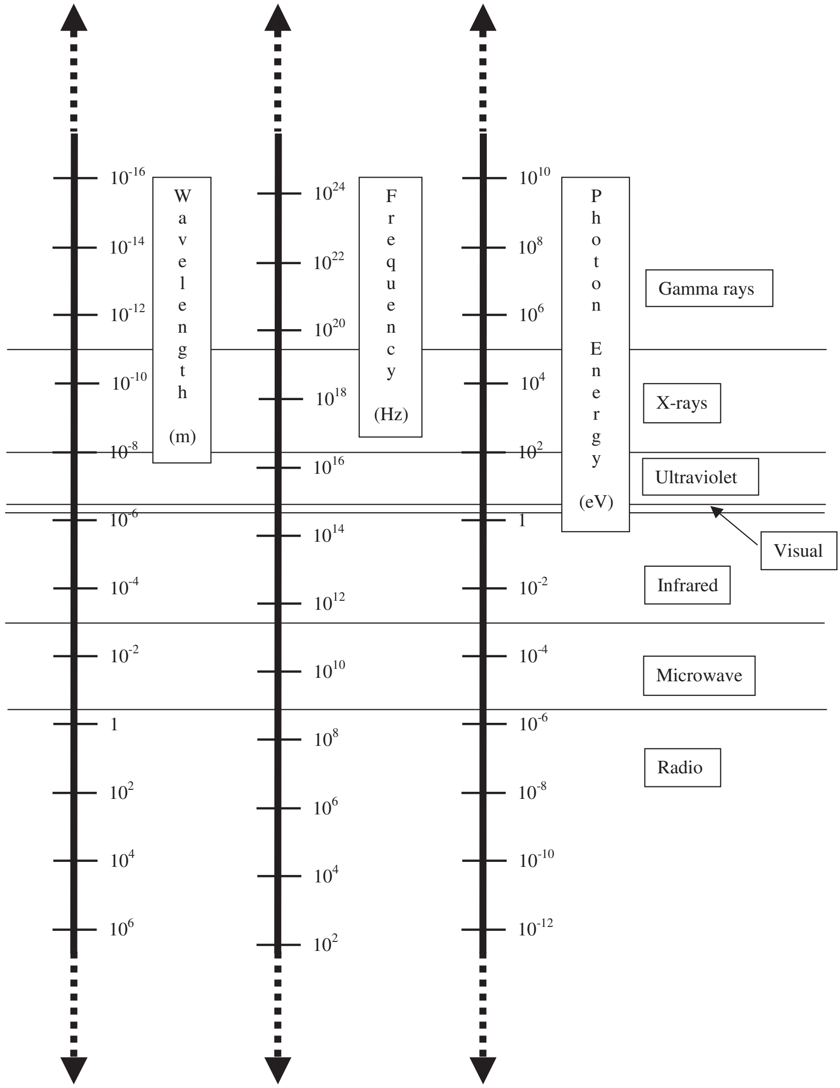

Figure 1.2 The e-m spectrum showing how its generally accepted subdivisions relate to wavelength, frequency and photon energy.

or seen directly by the eye, etc.[2] For other parts of the e-m spectrum, individual spectra may be produced using detectors that are intrinsically sensitive to different wavelengths, or which may be tuned to scan across a range of wavelengths. Other than for the visual region, spectra are usually shown as a plot of intensity versus wavelength, frequency or photon energy, and are then often called spectral energy distributions (SEDs), especially when the range covered is large.

Astronomers rely upon the spectra of the objects that they observe to provide a vast amount of information – probably more astronomical knowledge comes from spectroscopy than from all the other techniques used to study the universe put together. While not essential to acquiring an understanding of galaxies in general and active galaxies in particular, some further appreciation of what is involved with spectroscopy will help the reader considerably, especially in seeing *how* knowledge has been gained. Spectroscopy started in the visual region and since it is probably the most familiar part of the e-m spectrum to most people, we may use visual spectra to illustrate the concepts, nomenclatures and processes involved in studying galaxies spectroscopically, though identical or similar ideas are used whatever the wavelength involved.

Figure 1.3 illustrates the main types of spectra that will be encountered. At the top, resembling a rainbow, is the spectrum that would be observed from a hot solid, liquid or very dense gas and which is known as a continuous spectrum. Now, when they are in a gaseous form, the various chemical elements emit and absorb radiation at specific wavelengths in patterns unique to each element. Since light enters most spectroscopes through a slit and the spectrum is composed of images of the slit at each wavelength, the wavelengths

[2]There is not space here to go into further details of diffraction gratings, spectroscopes, etc. The interested reader may obtain further information from (amongst other sources) the author's book *Astrophysical Techniques*, 4 th edn, published by IoP Publishing, 2003.

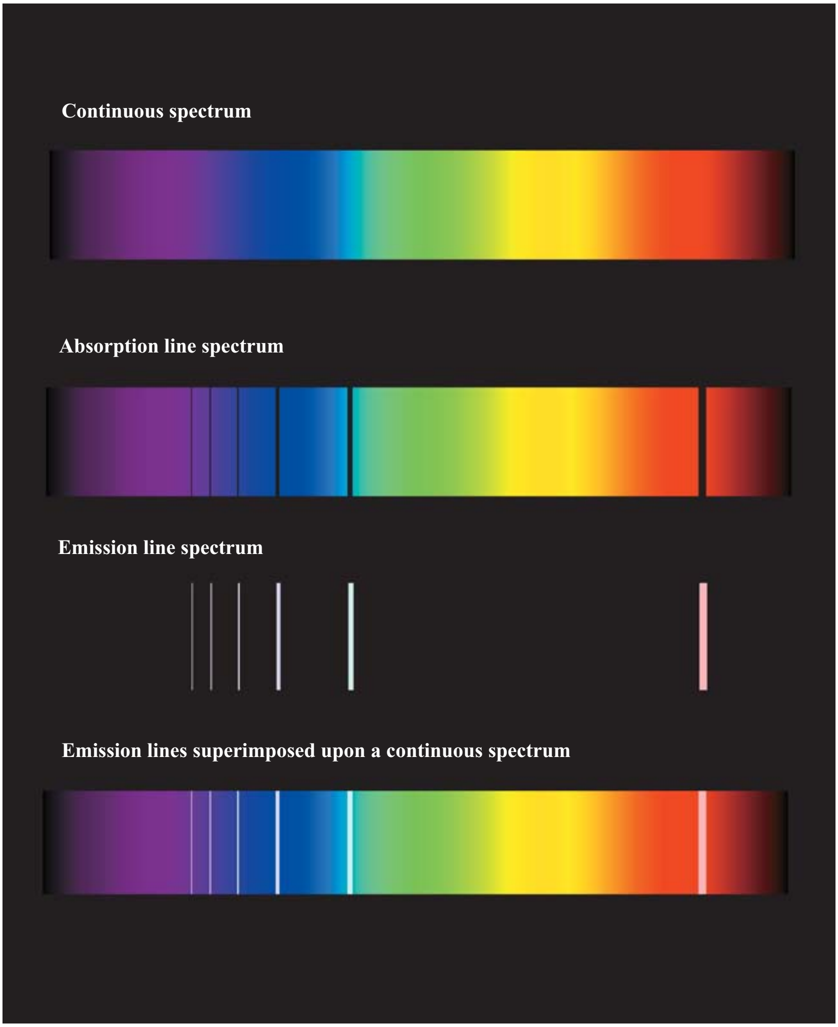

Figure 1.3 Types of visual spectra.

absorbed or emitted by an element appear as dark or bright lines running across the spectrum. These dark or bright regions are thus called the element's spectrum lines. At visible wavelengths, for example, hydrogen will normally have lines at wavelengths of 656.3 nm (red), 486.1 nm (blue–green), 434.0 nm (blue), and 410.2 nm (blue). If the density of the hydrogen gas is low then the series of lines may continue further towards the violet. Note that it is still quite common practice amongst some astronomers to use ångstroms as the unit for wavelength. Since 1 nm = 10 Å, the above wavelengths would become 6563 Å, 4861 Å, etc. and the reader should watch out for this if consulting other sources.

Pointing a telescope equipped with a spectroscope at stars and (most) galaxies will reveal spectra like the second one down in Fig. 1.3 and which is called an absorption-line spectrum. It is produced, to a first approximation, when the hot dense gas forming the inner layers of a star emits a continuous spectrum. That continuous emission then passes through the less dense outer layers of the star and the elements in those layers absorb at their characteristic wavelengths leaving the dark regions (absorption lines) in the final spectrum emitted from the star. Galaxies are seen by the light emitted by their millions of constituent stars, and so their spectra are composites of all the individual stellar spectra. The exceptions to this latter statement form the bulk of the material covered by the rest of this book and so will be left until later.

Hot gaseous nebulae such as H II regions (Box 2.2), planetary nebulae and supernova remnants produce spectra similar to the third example down in Fig 1.3. Here the thin gas forming the nebula is simply emitting at its characteristic wavelengths and so producing a pattern of bright lines against a dark background. Such a spectrum is called an emission-line spectrum (there may be a faint underlying continuous spectrum as well in many cases).

Finally the fourth spectrum in Fig. 1.3 is of the type to be found from many of the galaxies discussed later in this book and also from a few rare types of individual stars. It is an emission-line spectrum superimposed onto a continuous spectrum. It is also, somewhat confusingly, called an emission-line spectrum, although the context usually makes it clear whether it is the third or fourth type of spectrum shown in Fig. 1.3 that is intended. The latter type of emission-line spectra may well contain some absorption lines in addition to its emission lines.

Not only does each element have a unique pattern of spectrum lines, which enables the composition of even the most distant stars, nebulae and galaxies to be determined, but also if the atoms of an element lose an electron (become ionized) then another, different unique pattern of lines emerges. Losing second, third, fourth, etc. electrons (becoming doubly, triply, quadruply, etc. ionized) results in yet further different and unique patterns of lines. Rather more rarely an atom can gain an electron (become negatively ionized) and not surprisingly that also leads to a different pattern of lines. Since the level of ionization mostly depends upon the temperature of the gas, recognizing the patterns of ions' lines in spectra provides an estimate of the temperature of the region producing those lines. A common form of notation to indicate whether an element is present as neutral atoms or ions is the chemical symbol of the element followed by a Roman numeral whose value is one more than the number of missing electrons. Thus neutral iron is symbolized as Fe I, singly ionized iron as Fe II, doubly ionized iron as Fe III and so on. The rare negative ions are indicated with a negative sign as a trailing superscript, H^-, for negatively ionized hydrogen for example. Individual spectrum lines can now be labeled by their wavelength and state of ionization of the element. Thus the red line of hydrogen (Fig. 1.12, below) is H I 656.3.

Finally, in dealing with active galaxies later in this book we shall encounter "allowed" and "forbidden" spectrum lines (see also Box 3.1). All the lines so far mentioned have been "allowed". "Forbidden" lines are not actually forbidden – it is just that the probability of their occurrence is much lower under normal conditions than that for the allowed lines. Under normal conditions, such as may be found in most stars, forbidden lines are either undetectable or are very much weaker than the allowed lines of the same element. When the density of the gas is very low however, such as within gaseous nebulae and the interstellar medium, forbidden emission lines can become the strongest lines in the spectrum. Thus H II regions (Box 2.2) have emission-line spectra dominated by forbidden lines from ionized oxygen and nitrogen, while Seyfert galaxies' (Sect. 3.2.2) spectra contain strong emission lines from sulphur and neon in addition to those of oxygen and nitrogen. The nomenclature for allowed and forbidden lines is via the use of square brackets around the ion symbol. Both brackets are used when the line is strongly forbidden, but just a single bracket for lines whose probability of occurrence is somewhat stronger, but not as high as that of an allowed line. Thus [O III] 495.9 and [Ne III] 396.7 are forbidden lines, C II] 232.7 and Si III] 189.2 (both in the ultraviolet) are "semi"-forbidden lines, while He I 587.6 and H I 486.1 are allowed lines.

In April 1920 the leading proponents of the two theories, Harlow Shapley and Heber D. Curtis, delivered talks to the US National Academy of Sciences. The battle was called the "Great Debate" with Shapley putting the case for spiral nebulae being local and Curtis the case for their being distant galaxies. Their relatively brief lectures were followed by much fuller written presentations of their cases. However, despite the publicity that resulted from this clash, neither idea prevailed. So it was not until Hubble's discovery of Cepheids in M 31 four years later that the great debate was finally settled. Our modern view of the universe with our Milky Way Galaxy being just one out of millions of similar structures distributed over billions of light years, thus essentially dates from the publication of Hubble's 1925 paper.

1.1.2 Galaxies Today

Our present view of galaxies is that they are large collections of stars, brown dwarfs and planets, etc., together with varying proportions of

1.2 Galaxies to the Forefront

1.2.1 Sorting Out the Galaxies

Hubble's work meant that the known volume of the universe increased at least 10-fold overnight. Indeed, taking the modern values for the size of the Galaxy and the distance to M 31, the increase in volume was actually by a factor of 8,000, and Hubble soon went on to observe galaxies much further out than M 31. Today, the volume of the visible universe is known to be some 2,000 trillion times that of the Milky Way Galaxy, and around a trillion other galaxies are to be found within that region.

Hubble's access to the Hooker telescope meant that few other astronomers could compete with him when it came to studying galaxies. He made the most of his opportunities and the year following the publication of his M 31 Cepheids paper, he had accumulated sufficient observations to start sorting out a classification system for galaxies. Classification does not sound all that exciting, yet it is one of the most powerful of scientific tools. It is almost always one of the first courses of action for researchers whenever a new field of study opens up in science. Classification serves to highlight and identify those objects that are normal and representative and to pick out the ones that are atypical. As the field of study matures and the regular objects begin to be understood, it is then the atypical ones that become the most interesting and informative. Several more sophisticated galaxy classification schemes have been developed since Hubble's work, but his original, relatively simple, system is still the most widely used and unless very specialized work is being undertaken, it is the most useful.

The classification scheme proposed by Hubble divides the galaxies into three main morphological types – spiral, elliptical and irregular. It then goes on to sub-divide these main groupings. The spiral galaxies, which had originally inspired the Great Debate, are first separated into "normal" and "barred" forms. A barred spiral galaxy has its spiral arms arising, not directly from the galaxy's nucleus, but from the ends of a rectangular "bar" that projects outwards from opposite sides of the nucleus (Figs. 1.4 and 1.5), while for a normal spiral galaxy the arms arise directly from the nucleus (Figs. 1.4 and 1.5). The normal and barred types are then further divided into three on the basis of the relatives sizes of their nuclei and the openness of the spiral winding of the arms. Sa and SBa (the "B" is for "barred") types thus have tightly wound arms and large nuclei, while Sc and SBc have much less tightly wound arms with a clumpy appearance due to the presence of many H

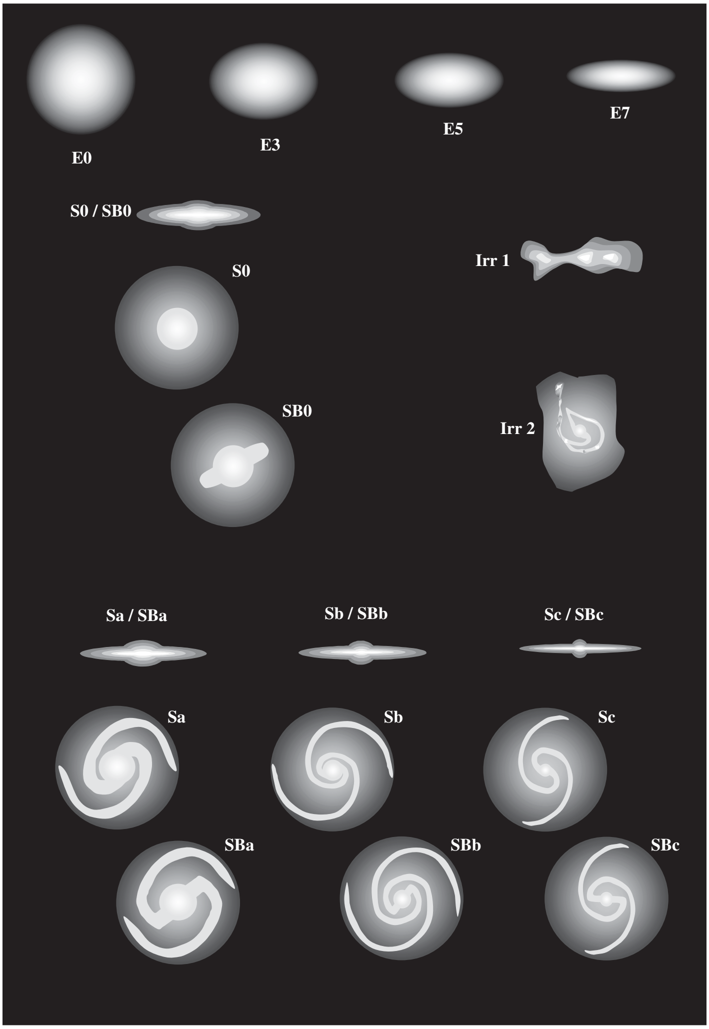

Figure 1.4 The Hubble system of galaxy classification. The galaxies are shown with their longest dimensions to the same scale, but in practice galaxies of all types may be found over a range of sizes (Table 1.1). Irregular galaxies are often small whilst giant ellipticals make the largest known galaxies. The spiral galaxies are shown with just two arms, but there may be more, and with the flocculent spiral galaxies there are many short segments of arms.

II regions (Box 2.2) together with relatively small nuclei. Sb and SBb types occupy the intermediate position. About half of the spiral galaxies clearly have a central bar, though weaker and hidden bars may well be present in most "normal" spiral galaxies.

Figure 1.5 Hubble classes of spiral galaxies:
(i) M 63, the Sunflower galaxy, an Sb type galaxy. A combination of two 5-minute exposures with a 0.4-m Schmidt–Cassegrain telescope, imaged using a STL1301E CCD camera. Log-stretching is used to display the image to its best advantage in print form. (Image courtesy of Bob Forrest and the University of Hertfordshire Observatory.)
(ii) An HST image of NGC 3370, an Sc type galaxy. (Image courtesy of STScI.)

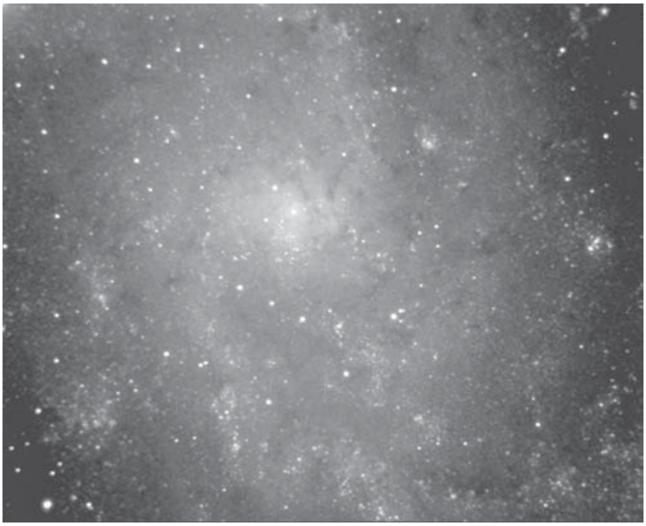

Figure 1.5 *Continued*
(iii) M 33, an Scd type galaxy. A combination of two 5-minute exposures with a 0.4-m Schmidt–Cassegrain telescope, imaged using a STL1301E CCD camera. Log-stretching is used to display the image to its best advantage in print form. (Image courtesy of Bob Forrest and the University of Hertfordshire Observatory.)
(iv) An HST image of NGC 1300, an SBb type galaxy. (Image courtesy of NASA, ESA and the Hubble heritage team (STScI/AURA).)

Later workers, especially Gérard de Vaucouleurs, have added to Hubble's scheme, most notably by identifying classes Sd and SBd that have even greater degrees of openness and by adding a luminosity classification. De Vaucouleurs also labeled normal galaxies as types SA to match the SB of the barred galaxies, so that the reader may come across classes such as SAc that are identical to Hubble's class Sc. Here, since we are concerned mostly with galaxies that are not of a standard form, Hubble's original scheme will suffice.

Spiral galaxies may be divided independently from Hubble's system into "Grand Design" and "Flocculent" types on the basis of the appearance of their spiral arms. Grand design spirals, such as NGC 1300 (Fig. 1.5), have well-defined symmetrical and lengthy arms. Usually there are just two arms, but three or four are also possible. Flocculent galaxies have a spiral appearance, but when examined more closely this arises from numerous short segments of "arms" distributed chaotically. The differences reflect the different mechanisms underlying the formation of the spiral patterns. A grand design galaxy's arms are thought to develop as the result of a density wave propagating through its disk. The wave increases the density of the disk material, leading to increased rates of star formation. The arms then become visible through the high luminosities of massive young stars. Since such stars have short lives, the arms fade away at the trailing edge of the density wave as the massive stars die while new young stars are added at the leading edge. In fact, many less massive, longer-lived stars will be left behind as the arm moves on, so that the spiral appearance is deceptive. With the flocculent spiral galaxies, their short spiral segments are star-forming regions that have been dragged into their shapes during their orbital motion around the galaxy. Objects' spatial velocities within the disk of a galaxy do not fall off with distance in the Keplerian fashion of the solar system's planets, but are more or less constant. Nonetheless, material further from the nucleus has a greater distance to travel to complete its orbit, and so the angular velocity decreases outwards through the disk. Thus the outer parts of star-forming regions will gradually fall behind the inner parts, elongat-

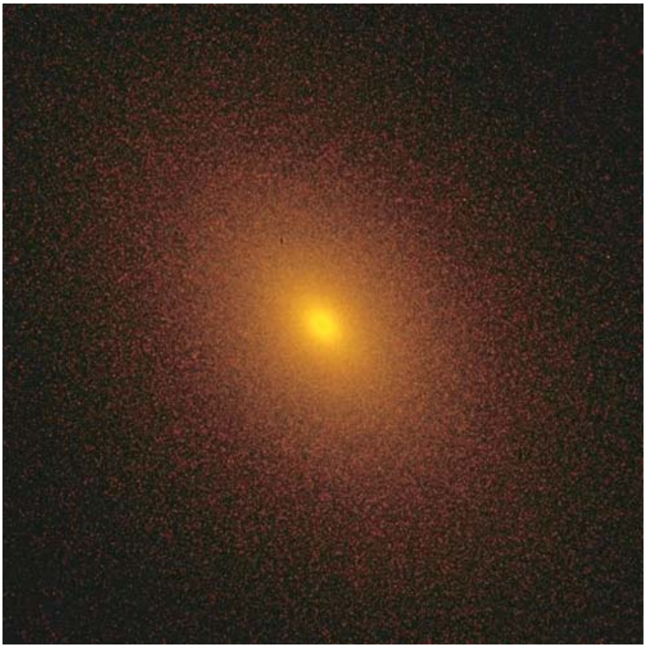

Figure 1.6 NGC 221 (M 32), an E2 type galaxy that is also sometimes classified as a peculiar galaxy. (Image courtesy of Tod Lauer.)

ing the regions and so leading to the spiral appearances of flocculent galaxies.

Elliptical galaxies have no obviously visible internal structure; they are simply elliptical in shape with a sharp drop in brightness from their centers to their edges. Hubble therefore just divided them up on the basis of their degree of ellipticity. He identified eight classes from E0 to E7. The number for the class is related to the ellipticity – E0 galaxies appear circular, while E 7 galaxies have an aspect ratio[3] of 3.3 (Figs 1.4 and 1.6). Hubble's classification however is of the apparent shapes of the galaxies, i.e. as they are seen projected against the sky and does not

[3]The aspect ratio is the length of an object divided by its width – the larger the aspect ratio, the longer and thinner is the object. The number (N) for Hubble's elliptical galaxy classification is related to the galaxy's length (L) and width (W) by $N = \frac{10(L-W)}{L}$.