PART 1

Galaxies

If galaxies did not exist we would have no difficulty in explaining the fact. WILLIAM SASLAW

Galaxies are fundamental constituents of the Universe. They are groups of approximately 10^5–10^{13} stars[1] that are gravitationally bound and take part in the general expansion of the Universe. Galaxies have diameters ranging from 10,000 to 200,000 light-years[2] and they possess widely varying gas and interstellar dust contents. The distances between galaxies are typically 100–1000 times their diameters. They represent 10^8 overdensities above the mean stellar density of the local Universe. In total, galaxy masses range from 10^6 to 10^{14} solar mass ($M_\odot$).

Their component stars vary from $\sim$0.1 $M_\odot$ brown dwarfs that do not undergo thermonuclear fusion, to rapidly evolving stars of at least $\sim$50 $M_\odot$ and possibly as massive as 100 $M_\odot$. The stars' evolutionary state ranges from protostars undergoing contraction to begin thermonuclear reactions, to main-sequence dwarf stars that fuse hydrogen to helium in their cores, through to red giant stars with expansive gaseous atmospheres. The stellar end-products are white dwarfs, neutron stars and black holes. The specific evolutionary path of a star is governed by its mass. The most massive stars evolve over millions of years, whilst the lowest mass stars can evolve for billions of years.

At least 300,000 years after the Big Bang start of the Universe, structures that would become galaxies began to condense out of primordial hydrogen and helium. Current observational and theoretical studies of the formation and evolution of large-scale structure (groups, clusters and superclusters of galaxies) suggest that cold dark matter (CDM) is the predominant matter in the universe. Observations of individual galaxies suggest that CDM is the dominant matter in galaxies (see Section 2.5 for more information), making up more than 50% of a galaxy's mass. CDM, a theoretical massive, slow-moving particle (or particles), has not yet been detected. However, a CDM dominated universe would suggest that galaxies were built from the aggregation of smaller structures, in a sort of "bottom-up" construction approach. In fact the closer galaxies are detected to the time of the Big Bang, the stronger this argument becomes.

From about 300,000 years after the Big Bang, the attractive force of gravity was in control and dictated that the first galaxies formed within 1 billion years (Gyr). Gravity increased gas densities and temperatures until physical conditions allowed the first stars to form. Elements heavier in atomic weight than hydrogen and helium were then made by thermonuclear fusion inside the first (massive) stars, and expelled into the interstellar medium (ISM) by subsequent supernovae explosions. These explosions propagated shock waves through nearby interstellar gas causing gas densities to increase and new star formation to be initiated. Numerous cycles of star formation–supernovae explosions–star formation continued, utilizing the increasingly heavy element enriched ISM.

Enough time, about 14 Gyr, has now elapsed since the beginning of our Universe, to allow a stable system of planets rich in heavy elements to exist around a very average G dwarf star called the Sun. Our Sun is in the

Figure 1.1 (opposite)

Optical image of the barred spiral galaxy NGC 1365 in the Fornax cluster of galaxies.

Credit: SSRO/PROMPT and NOAO/AURA/NSF.

1 The exponent above 10 represents the number of zeros after 1; e.g. 10^9 is 1000,000,000 or 1 billion. If the exponent is negative, e.g. 10^{-2} then it is 1 divided by 10^2 or 1/100 = 0.01.

2 A light-year is the distance that light travels, at 2.9×10^5 kms^{-1}, in a year. It is approximately 9.46×10^{12} km.

outer suburbs of a dense disk of stars that has spiral arms of gas and dust[3] where stars preferentially form. A lower density, large spheroidal halo of predominantly older stars surrounds the Galaxy.[4] Our Galaxy contains at least 100 billion stars, and it is regarded as an average sized spiral. From our vantage point our Galaxy and a vast variety of other galaxies are observed.

The appearance of galaxies varies due to their intrinsic properties and the differing lines of sight (with differing gas and dust contents) through our Galaxy along which they are observed. These three-dimensional objects are also viewed projected on a two-dimensional sky surface or celestial sphere. Hence their angle of inclination to our line of sight greatly influences how an observer perceives them.

Galaxies can be broadly grouped into elliptical, spiral, lenticular and irregular classes. Ellipticals range from circular shaped to highly elongated or oval-like congregations of predominantly old, evolved stars. Spirals are Catherine wheel-like, with "fireworks" of young stars, dust and gas illuminating majestic spiral arms that can wrap around their nuclei many times. Stellar bars (elongated distributions of usually old stars) can be found in the centers of some spirals giving a spindle-like appearance (see the barred spiral NGC 1365 in Figure 1.1). The lenticulars (or S0 types) can be regarded as a visual link between ellipticals and spirals. They are disk- (like spirals) or lens-like though composed of predominantly old stellar populations lacking in dust and gas (like ellipticals). The irregulars, as their name suggests, lack coherent spiral or elliptical shapes. They contain regions rich in dust and gas and have active star-formation sites, yet are structurally quite amorphous.

1.1 Prehistory of galaxies

The term "galaxy" has its origin in the Greek *kiklos Galaxias* meaning milky circle, which is a reference to the diffuse, cloudy appearance of the Milky Way.

The discovery of galaxies as individual stellar systems scattered throughout the Universe took a long and arduous path. The Andromeda Galaxy, M 31, and the Large Magellanic Cloud had been recorded by Al-Sufi in his publications in the tenth century and were known to people of the Middle East. From the voyage of Ferdinand Magellan in 1519–1522 that took him to southern latitudes, the Large and Small Magellanic Clouds (Figure 1.2) became better known in Europe,[5] however they were not regularly known by these names until the nineteenth century.

In 1612 Simon Marius observed M 31 with a telescope and described its nebulous appearance as "the flame of a candle is seen through [a] transparent horn". In 1774 Charles Messier included the Andromeda Galaxy as the thirty-first entry (Messier 31) in his first catalogue (Messier 1784) of "nebulae" that also included other galaxies such as the satellite of M 31, the smaller M 32 and M 33 in Triangulum.

By the mid-eighteenth century the Englishman Thomas Wright proposed that the Sun was positioned away from the center of a slightly flattened, yet predominantly spherical system of stars. His ideas were published in his *An Original Theory or New Hypothesis of the Universe* (Wright 1750). Wright was one of the first to begin to understand the appearance of the Milky Way by discussing the role of an observer looking at a three-dimensional stellar system (their "universe").

The philosopher Immanuel Kant read about Wright's work but did not see the original diagrams. It was this omission that strangely helped Kant to hypothesize a disk of stars, which would naturally explain the appearance of the Milky Way in the sky. He then took the next step, amazing at the time, of proposing that similar "disks" of stars were scattered throughout the Universe as he was aware of observations of many "nebulous objects" detected around the sky. He published *The Universal Natural History and Theory of Heavens* (Kant 1755) though it was not distributed widely.

3 Interstellar dust grains make up about 1% of the ISM and are formed in the envelopes of late-evolved stars like red giants or carbon stars. They are much smaller than the dust on Earth, ranging from a few molecules to a diameter of 0.1 mm. They begin as carbon or silicate grains, and then accumulate additional atoms (e.g. H, O, C, N) to form icy mantles of water ice, methane, carbon monoxide and ammonia. All of this is encased in a sticky outer layer of molecules and simple organic compounds created through the interaction of the mantle with ultraviolet (UV) radiation. The grains are about the same size as the wavelength of blue light, meaning that they absorb and scatter UV and blue light much more efficiently than red light.

4 Throughout the atlas, the Milky Way, our Galaxy, will be denoted by an upper case G.

5 Amerigo Vespucci possibly mentioned the existence of the two Clouds and the dark Coalsack Nebula in a letter during his third voyage of 1503–1504 that took him to the south-east coast of South America. Andrea Corsali, an Italian serving on a Portuguese expedition, in a letter written in 1515 to Giuliano de Medici sketched both the Southern Cross and the two Clouds.

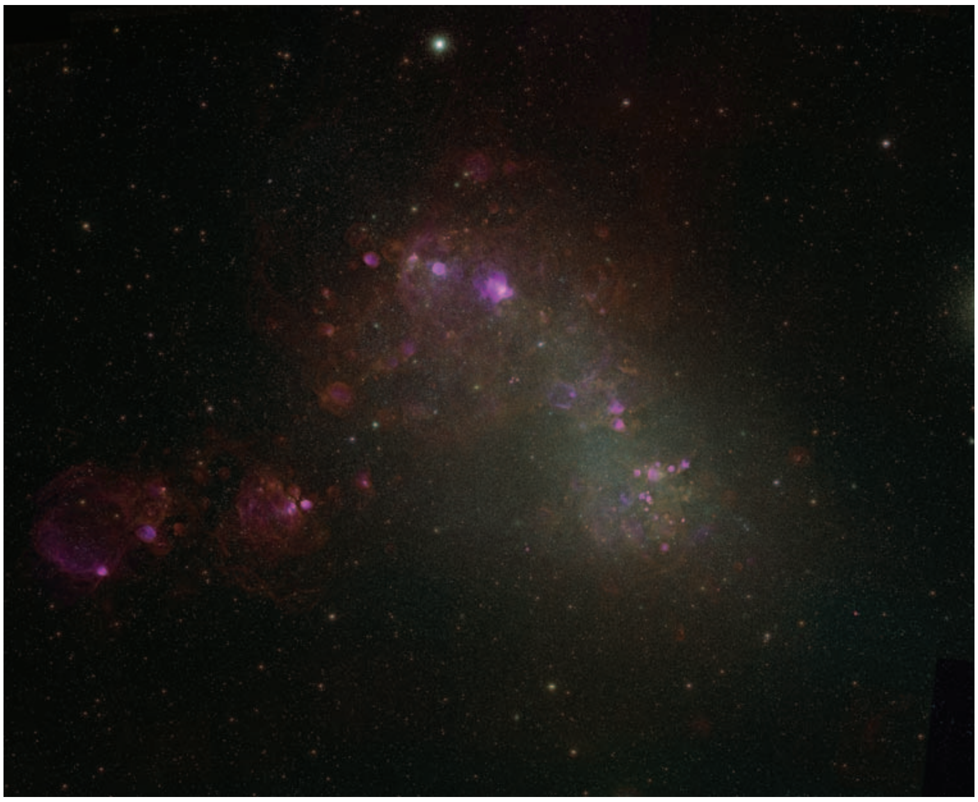

Figure 1.2

Optical image of the Small Magellanic Cloud. The image was constructed from more than 500 separate images, using green and red continuum, and narrowband [O III] (blue), [S II] (green), Hα (red) filters. Star light (green and red continuum) is suppresed to enhance the interstellar medium as indicated by the gaseous emission lines [O III], [S II] and Hα that occur in or near star-forming regions.

Credit: F. Winkler/Middlebury College, the MCELS Team and NOAO/AURA/NSF.

By 1761 Johann Heinrich Lambert, in a collection of essays, had independently suggested the same ideas, though history tends to concentrate more on the contribution of Kant. Kant and Lambert had, on the shoulders of Wright, launched the idea of "island universes" as separate entities. Wright, Kant and Lambert had many details wrong, yet they had together provided the starting points of the modern day view of the Galaxy, and the large-scale structure of the Universe.

Whilst a somewhat simplified theoretical basis had been laid, the observational efforts were hampered until large reflecting telescopes became available to try to resolve the structure of these "nebulous objects". In the last two decades of the eighteenth century, William Herschel, inspired by Charles Messier's catalogue of nebulae, tried to resolve these objects. Indeed for a time, he believed all such nebulae were star clusters. Interestingly, Messier had in fact observed the Virgo Cluster of galaxies, and Herschel had similarly seen the Coma Cluster. Determining the exact nature of "nebulae" was daunting as they contained objects as varied as globular clusters, supernova remnants, planetary nebulae, as well as galaxies.

The son of William, John Herschel, began to catalogue nebulae beginning in the 1840s (Herschel 1864) preceding Dreyer's New General Catalogue (Dreyer 1888) and two Index Catalogues of 1895 and 1908 (Dreyer 1895, 1908). John Herschel and William Parsons, Third Earl of Rosse, who built the 72 inch "Leviathan of Parsonstown" telescope, began a protracted debate about the stellar nature of the nebulae. Parson's sketches of spiral structure (e.g. the Whirlpool Galaxy, Messier 51, Parsons (1850), Figure 1.3) that cemented the term "spiral nebulae", are still widely recognized today.

Whilst the Leviathan of Parsonstown aided some observations, Parsons, erroneously, claimed to resolve the Orion Nebula into stars. Meanwhile, John Herschel began some of the first statistical studies of the all-sky distribution of the nebulae, and confirmed the Virgo Cluster and surrounding environs, as well as discovering the Pisces Supercluster:

> The general conclusion which may be drawn from this survey, however, is that the nebulous system is distinct from the sidereal, though involving, and perhaps, to a certain extent, intermixed with the latter.
>
> JOHN HERSCHEL

Despite Herschel's somewhat vague conclusion, the scientific chase was quickening. Astronomers adopted the term "galaxy" relatively quickly. In 1837, Duncan

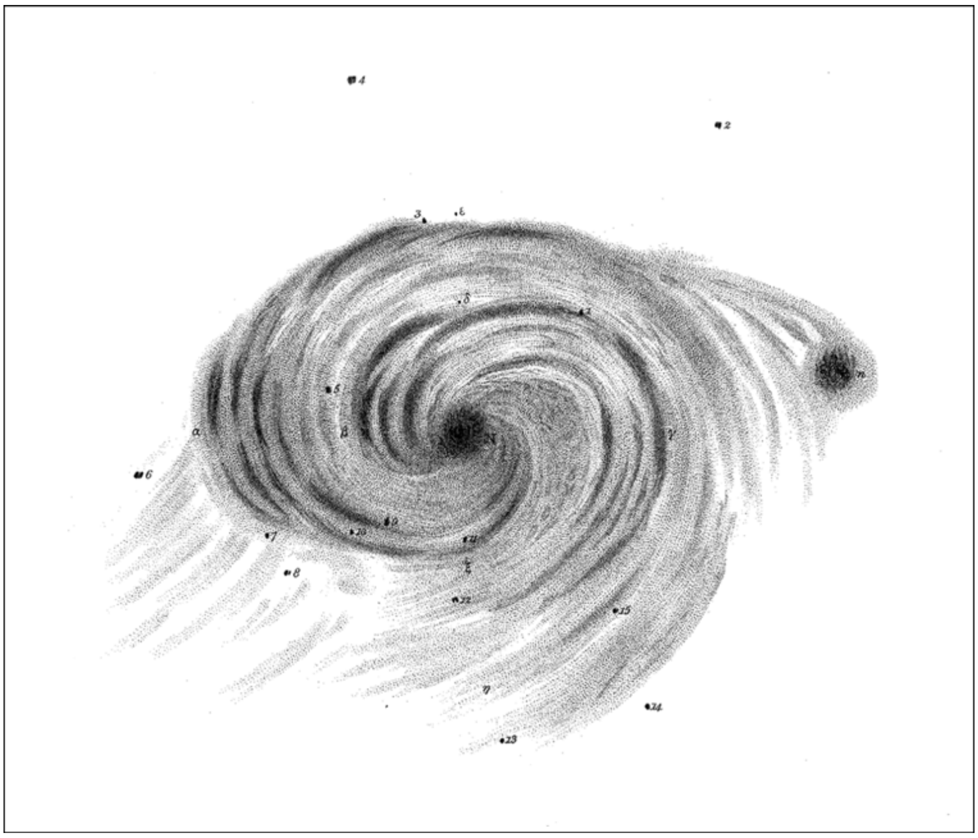

Figure 1.3

Sketch of Messier 51 by William Parsons, Earl of Rosse. North is 90° clockwise (CW) from up.

Credit: From Parsons (1850).

Bradford published a popular account of astronomy that used the word "galaxy" for the Milky Way. By 1870 it seemed to have been generally accepted into the literature as various derivations of the term were being vigorously debated. In that same year the journal *Nature* (Evans 1870) stated:

> Mr. John Jeremiah states that "Heol y Gwynt" is the only proper Welsh name for the Milky Way. Such is far from being the case. I am acquainted with no less than nine other names, equally proper for that luminous appearance, such as y llwybr llaethog, y ffordd laeth, llwybr y gwynt, galaeth, eirianrod, crygeidwen, caer Gwydion, llwybr Olwen, and llwybr y mab afradlawn. Of these names, y llwybr llaethog and y ffordd laeth answer precisely to Milky Way; llwybr y gwynt (common enough in Carmarthenshire) is synonymous with heol y gwynt; galaeth (from llaeth, milk) corresponds with galaxy; eirianrod signifies a bright circle; and crygeidwen a white cluster.
>
> D. SILVAN EVANS

Whilst the Welsh had clearly cornered the market on Milky Way nomenclature and the residents of Carmarthenshire could readily describe their night sky, the physical nature of the nebulae had still not been determined. In the mid-1860s William Huggins used the new technique of spectroscopy to identify emission lines that showed many nebulae were gaseous. His initial observations of M 31 (Figure 1.4) and its nearby satellite galaxy M 32 showed no bright lines like those in the gaseous nebulae. They had continuous "star-like" spectra.

These became known as "white nebulae". About the same time Abbe (1867) studied John Herschel's 1864 catalogue and determined that Huggins, gaseous nebulae were distributed across the sky like star clusters and were thus part of the Milky Way whilst the other "white" nebulae were not. This essentially correct spatial separation was (unfortunately) not supported by many other astronomers of the time.

In 1885 a stellar transient was detected in M 31. Assuming a nearby distance for M 31 the event was regarded as a normal stellar event, a nova, and named Nova 1885. It is now realized that what occurred was the much more explosive supernova event, denoted S Andromedae, with its greater intrinsic brightness consistent with the modern cosmological distance of M 31.

Figure 1.4

Messier 31 in the ultraviolet: Galaxy Evolution Explorer's far-ultraviolet 135–175 nanometers (blue) and near-ultraviolet 175–280 nanometers (green). Infrared: Spitzer Space Telescope 24 µm (red).

Credit: NASA/JPL-Caltech/K. Gordon (University of Arizona), GALEX Science.

In the meantime, new clusters and even superclusters of nebulae were being noted by Stratonoff (Perseus–Pisces following on from Herschel), Easton and Reynolds. Notable clues were being collected. Spectroscopy had shown the stellar-like nature of the spiral or white nebulae, but were they nearby inside a single stellar system (our Galaxy) or outside at much larger distances? Spectroscopy also began to provide measurements of their velocities. Vesto Slipher at Lowell Observatory, beginning in 1912, detected large radial velocities in the nebulae from Doppler shifts[6] of various spectral lines. Within five years he had detected an average velocity of $\sim$570 km s^{-1} for about 30 nebulae compared to $\sim$20 km s^{-1} for stars (Slipher 1917). These velocities were far larger than could be explained if the nebulae were part of our Galaxy. The interpretation of the detected Doppler shifts and the subsequent inferred velocities was debated. Slipher had also improved upon Huggin's earlier spectra of M 31 and again noted a stellar spectrum by 1912. More discoveries of "novae" by Curtis and Ritchey in nebulae seemed to favor an extragalactic origin, though some were novae and others were supernovae.

There was still no great breakthrough but the foundations of discovery had been laid. In 1920 a topical "debate" between Harlow Shapley and Heber Curtis covered the nature of spiral nebulae. Curtis correctly argued that the nebulae were extragalactic but failed to convince the audience, whilst Shapley elegantly argued their local nature based on wrong conclusions. The answer, however, had already been found.

1.2 "It is worthy of notice"

Our present detailed knowledge of galaxies has been compiled over a relatively short time. It was not until the mid-1920s that spiral nebulae were proven beyond doubt to be separate galaxies in their own right. One astronomer made the breakthrough, and it began with photographic surveys of the Magellanic Clouds. Based on this data Henrietta Leavitt of Harvard College Observatory detected Cepheid[7] variable stars in the Magellanic Clouds (Figure 1.2). Beginning this work in 1905, with photographic plates taken by the Bruce telescope in Peru, the discovery can be traced to Leavitt (1908) who noticed a strange relationship in the properties of Cepheids in the Small Magellanic Cloud:

> It is worthy of notice that in table VI the brighter variables have the longer periods. H.S. LEAVITT

Leavitt had discovered that the star's period of variability (the time after a cyclical brightness change is repeated) was related to its mean brightness. By assuming that the width of the Small Magellanic Cloud was negligible compared to its distance away from us, which is essentially true, the apparent brightness of such stars would be related to their intrinsic brightnesses or luminosities. Hence the observed periods would directly correlate with the luminosity of the stars, allowing a distance to be calculated if the luminosity of Cepheids could be calculated.

6 The Doppler effect is the change in wavelength of radiation when the radiation source and observer are moving away or toward each other.

7 Cepheid variables are named after their prototype, δ Cephei.

If distances to local, nearby Cepheid variables with known periods could be determined, the period–luminosity relationship of Magellanic Cloud Cepheids could be calibrated and distances to the Clouds obtained. Leavitt had discovered the first useful cosmic yardstick! However, nature conspired to make such measurements very difficult. From 1913 to 1924 journal publications associated with Cepheid variables seemed to invariably attract the word "problem" in their titles and had piqued the interest of noted astronomers such as Stebbins, Duncan, Shapley, Hertzsprung, Cannon, Eddington, Adams, Jeans, van Maanen, Vogt, Luyten, Humason, Kapteyn and van Rhijn. This did not deter one of them, for as early as 1913 Ejnar Hertzsprung produced a first calibration of the period–luminosity relationship of Galactic Cepheids and derived an extremely large (at the time) distance of 10 kiloparsecs[8] for the Small Magellanic Cloud (SMC). Shapley, however, continued to argue that the Clouds were subsystems within our Galaxy. For comparison, the modern day distance to the SMC is 60 kpc.

Eventually a more accurate Cepheid period–luminosity calibration was derived and the apparent magnitudes[9] of Magellanic Cloud Cepheids were converted into absolute magnitudes, allowing a more accurate distance to the Clouds to be derived. This would definitively place them well outside the limits of our Galaxy.

In the meantime, other galaxies were being observed. From the early 1920s onwards John C. Duncan, Edwin Hubble and others did this and detected Cepheids in, amongst other Local Group galaxies, M 33 (Duncan 1922), M 31, IC 1613 and NGC 6822. At the same time, a theoretical treatment using the observed rotation of M 31 by Ernst Öpik (Öpik 1922) derived a large distance of 450 kpc. In the end it would be observations that comprehensively decided the matter.

A joint meeting of the American Astronomical Society and the American Association for the Advancement of Science was held in Washington, D.C. On New Year's Day, 1925, a paper by Hubble (who strangely did not attend, but read in his absence), announced his discovery of Cepheids in spiral galaxies. The paper (Hubble 1925) derived a distance of 285 kpc for both M 31 and M 33, whilst modern day estimates are 780 kpc and 860 kpc, respectively. It was correctly announced at the time that spiral nebulae were extragalactic and were not components of our Galaxy. The true "Kantian" nature of the universe had been proven with the help of a special variable star.

Figure 1.5 (opposite)

Messier 51, NGC 5194, the Whirlpool Galaxy in X-rays (purple), ultraviolet (blue), optical (green) and infrared (red). The companion galaxy NGC 5195 is also shown to the north.

Credit: X-ray: NASA/CXC/Wesleyan U./R. Kilgard et al.*; UV: NASA/JPL-Caltech; Optical: NASA/ESA/S. Beckwith, Hubble Heritage Team (STScI/AURA); IR: NASA/JPL-Caltech/University of Arizona/R. Kennicutt.*

1.3 Multiwavelength laboratories in space

Galaxies can be regarded as laboratories in space that provide information on widely differing phenomena such as star formation, the cold ($T < 25$ K),[10] warm ($25 \text{ K} < T < 20{,}000$ K) and hot ($T > 20{,}000$ K) interstellar medium (ISM), stellar populations, high-velocity particles, non-thermal (non-stellar) activity and dark matter (more on dark matter in Section 2.5).

While observations of our own Galaxy allow the highest angular resolution inspection of nearby phenomena in a relatively normal spiral galaxy, our viewpoint is naturally restricted when observing other galaxies.

Galaxies vary in morphology, luminosity, mass (both luminous and dark), age, non-thermal activity, kinematics and star-formation properties. They also exist in widely varying environments that range from low-density regions to medium-density regions of groups of galaxies (with 3–50 members) to the crowded centers of rich clusters (numbering well over 1000 total members) with central densities of $\sim$100 galaxies per Mpc^2.

Therefore in order to accurately understand the physical properties of galaxies it is necessary to study a large variety of them. These varied properties should be studied in regions other than the traditional optical region of the electromagnetic spectrum[11] to achieve a complete multiwavelength picture (e.g. Figure 1.5 and compare to Figure 1.3):

8 1 parsec(pc) = 3.26 light-years. A table of useful astronomical constants is given in Appendix F, page 237.

9 The brightness of astronomical objects is measured in magnitudes. On the magnitude scale small numbers indicate bright objects. The scale is logarithmic and defined by a difference of 5 magnitudes corresponding to a brightness difference of 100. Apparent magnitudes are those observed, whilst absolute magnitudes are a measure of the intrinsic luminosity of an object, defined as their apparent magnitude at a distance of 10 pc.

10 K stands for kelvin, a unit of temperature. One kelvin equals one degree of Celsius, and 0 K, absolute zero, corresponds to −273 °C.

11 The complete range of electromagnetic radiation (energy that propagates through a vacuum at the speed of light, c) ranging from gamma rays (shortest wavelengths, highest frequencies, highest energies) to radio waves (longest wavelengths, smallest frequencies, lowest energies).

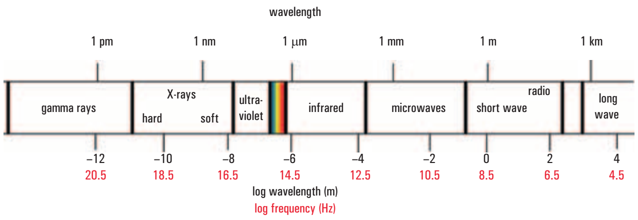

Figure 1.6

The electromagnetic spectrum. Prefixes are p – pico, 10^{-12}; n – nano, 10^{-9}; µ – micro, 10^{-6}; m – milli, 10^{-3}; and k – kilo, 10^{3}.

Credit: B. Lynds.

> They [galaxies] are to astronomy what atoms are to physics. ALLAN SANDAGE

Since the 1930s astronomers have been able to accurately detect radiation from galaxies in non-optical regions of the electromagnetic spectrum (Figure 1.6). To be precise, the first non-optical astronomical detection occurred much earlier than the 1930s. In 1800 William Herschel detected infrared radiation from the Sun. Now, more than 200 years later, all major regions of the electromagnetic spectrum – gamma ray, X-ray, ultraviolet, optical, infrared, submillimeter and radio – are being used to study galaxies (Figure 1.7):

> Trying to understand the universe through visible light alone is like listening to a Beethoven symphony and hearing only the cellos. JAMES B. KALER

This expansion into new regions of the electromagnetic spectrum has provided important discoveries about physical processes in galaxies, and greatly improved our understanding of previously known processes. In many cases the sensitivity and angular resolution of these multiwavelength observations can provide excellent images that allow detailed studies on relatively small spatial scales (e.g. 50–100 pc) in nearby galaxies (Figure 1.8). To put this spatial scale into perspective, many giant molecular clouds in nearby spiral galaxies that are stellar nurseries span ∼100 pc. Imaging with this level of spatial resolution allows substructure such as nuclei, spiral arms, jets, tidal tails and rings of nearby galaxies to be investigated.

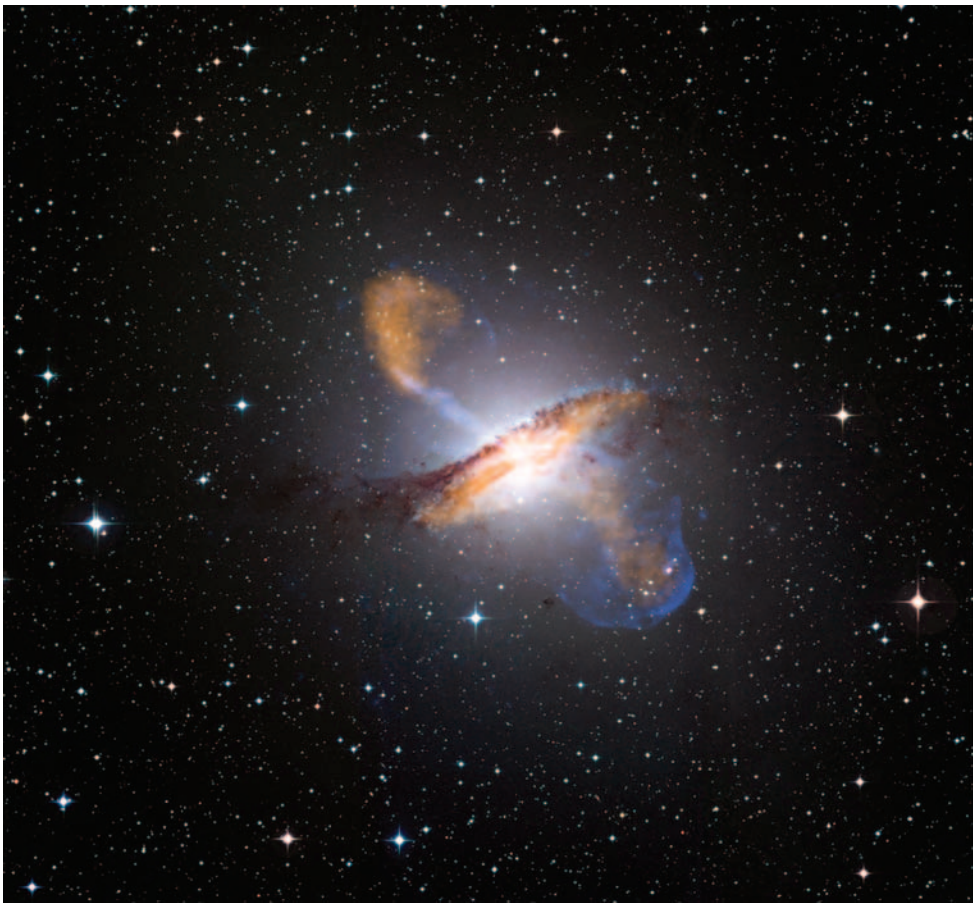

Figure 1.7

The radio galaxy NGC 5128/Centaurus A. Emission in X-rays is shown in blue, submillimeter in orange, and optical in white, brown.

Credit: X-ray: NASA/CXC/CfA/R. Kraft et al.*; Submillimeter: MPIfR/ESO/APEX/A. Weiss* et al.*; Optical: ESO/WFI.*

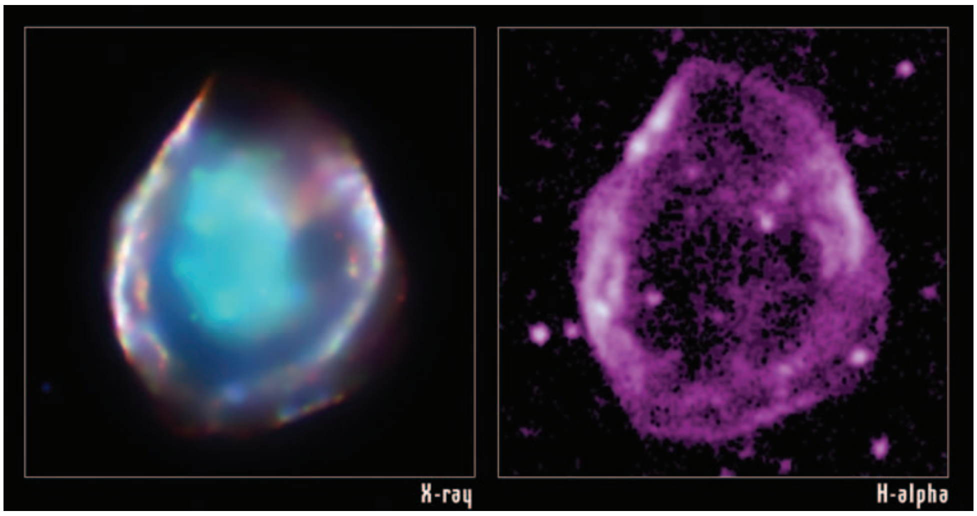

Figure 1.8

X-ray and optical (Hα) images of the supernova remnant DEM L71 in the Large Magellanic Cloud. The side of the image is ~50 pc at the distance of the LMC.

Credit: X-ray: NASA/CXC/Rutgers/ J. Hughes et al.; *Optical: Rutgers Fabry-Perot.*

1.4 The atlas galaxy sample

The choice of galaxies to include in this atlas was influenced by several factors. Firstly, the images had to be readily available from astronomers or from data archives. Secondly, such an atlas should aim to present images of galaxies that have good signal-to-noise and subtend large regions of the sky. Hence, many nearby galaxies (with distances less than 20 Mpc) that have been the target of extensive multiwavelength observations are included. Of the Local Group (the group of more than 35 galaxies within ~1 Mpc of the Galaxy), the Andromeda Galaxy NGC 224/M 31, the Small Magellanic Cloud (SMC), NGC 598/M 33 (Figure 1.9), the Large Magellanic Cloud (LMC), NGC 6822 and of course the Galaxy are included.

When galaxies display interesting multiwavelength properties suggestive of unique astrophysical processes, or are representative of a certain class of galaxies, endeavors have been made to include them. This means including galaxies at distances greater than 20 Mpc even though they may have less extensive multiwavelength coverage or their images may have lower signal-to-noise.

1.5 Atlas galaxy categories

Our atlas galaxies are grouped into several, not necessarily mutually exclusive, categories. These are normal (N), interacting (I), merging (M), starburst (S) and active (A). The reasons for inclusion of a galaxy into a specific category is explained in the individual galaxy summaries in Part 4. Active galaxies typically have strong emission over a large portion of the electromagnetic spectrum making them prime targets for multiwavelength observations and thus they make up a large fraction of our sample.

1.5.1 Normal galaxies

Normal galaxies include galaxies that appear morphologically normal, do not possess unusual star-formation rates, and have continuum[12] spectra with a thermal (stellar) form characterized by one or more temperatures. However, upon close examination, few galaxies are completely "normal". For example, galaxies are seldom isolated from other galaxies and will often display some morphological signature of a dynamical disturbance. As well, many nearby galaxies that appear to be morphologically normal on the large scale are increasingly found to contain some type of low-luminosity active nucleus (e.g. the Galaxy, page 55; NGC 3031/M 81, page 177).

1.5.2 Interacting galaxies

Interacting galaxies display morphological signatures of a gravitational interaction with another nearby galaxy or are influenced by the passage through a dense medium that can "strip out" constituent gas. Such "ram pressure" stripping occurs frequently in cluster galaxies that are moving through a hot intracluster medium (ICM).

12 The general continuous shape of an object's spectrum, not including discrete lines.

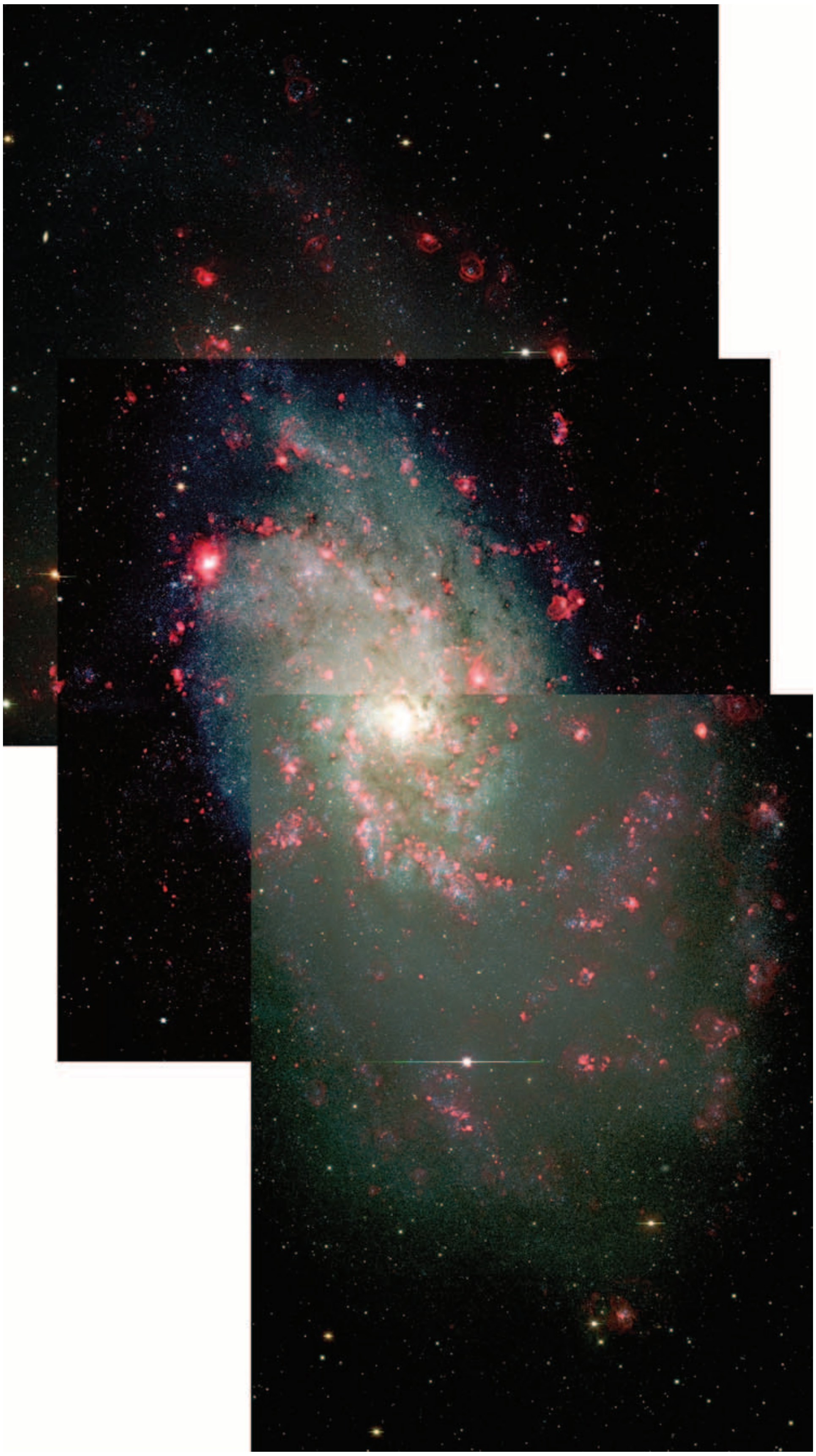

Figure 1.9

NGC 598/M 33. An optical image made from three filters. Blue light is radiation through a B filter (∼450 nm), green light through a V filter (∼550 nm) and red light is from the hydrogen emission line Hα at 656 nm. The galaxy was observed with the KPNO 4 m and Mosaicl camera by Phil Massey (Lowell Observatory) and Shadrian Holmes (University of Texas).

Credit: P. Massey and the Local Group Survey Team.