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Galaxies: an overview

1.1 Introduction

The Sun is located towards the outskirts of the **Milky Way**, a gravitationally-bound collection of stars, or **galaxy**, similar to countless other such systems.¹ These systems, in turn, are arranged into bound clusters and still larger structures, but it is the galaxies themselves that are usually considered to be the fundamental building blocks of the Universe. Part of the reason that galaxies occupy this pride of place is historic: until well into the twentieth century, it was by no means clear that any objects existed beyond the confines of the Milky Way, and so no larger structures could be studied. The huge contrast in brightness between galaxies and their surroundings also picks them out as basic constituents of the Universe, but it should be borne in mind that this distinction also represents a human bias: if our eyes were tuned to the X-ray part of the spectrum rather than optical light, then clusters of galaxies would stand out as the most impressive individual structures. Perhaps the best explanation for the enduring appeal of galaxies to astronomers is even more strongly anthropocentric: with their rich variety of

¹ The Milky Way is often referred to simply as “the Galaxy.” We therefore use the adjective “Galactic” to mean “belonging to the Milky Way,” whereas “galactic” refers to galaxies in general.

shapes and intricate spiral patterns, they provide the most visually stunning phenomena in the night sky.

Our goal in this book is to present the fullest description possible of these beautiful objects. To this end, we will discuss the current understanding of the individual elements, such as stars and gas, that make up galaxies, and the way in which these elements are arranged to form complete systems. Generally speaking, small-scale phenomena are best observed within our own galaxy, the Milky Way, where they are sufficiently nearby to be seen clearly. Large-scale galactic structures, on the other hand, are often best observed in external galaxies where we have a clear perspective on the whole system; when we try to study the large-scale properties of the Milky Way, we have considerable difficulty in seeing the wood for the trees. Analyses of the properties of the Milky Way and external systems are thus complementary in our quest for a complete description of the properties of galaxies, and so in this text we draw together these disparate strands and attempt to weave a coherent picture from them.

As will become clear through the course of the book, our picture of galaxies and their structure is still far from complete. By its very nature, astronomy is an observational science: we cannot tune the physical parameters of a galaxy to see how they alter its appearance; nor can we change our vantage point to get a better idea of its three-dimensional shape. Instead, we must synthesize all the fragmentary data that are observationally accessible in order to make the best sense that we can of our limited information. One key tool in this synthesis is the **cosmological principle**, which expresses our belief that the laws of physics are the same throughout the Universe. By applying the laws of physics as we know them locally to objects on the scales of galaxies, we seek to make sense of the observed properties of these systems.

The remainder of this chapter is devoted to a brief description of the historical development of galactic astronomy. It is not intended to provide a comprehensive history of the subject, but rather it seeks to show how the various ideas that make up our understanding of galactic astronomy developed, and to place the material in subsequent chapters into some sort of context.

1.2 A brief history of galactic astronomy

On a moon-less summer night away from city lights, a swathe of light can be seen stretching across the sky from horizon to horizon. This dramatic sight has intrigued people since ancient times, and has been the subject of many myths and legends. Its appearance as a stream of diffuse white light led the ancient Greeks to describe it as a river of milk flowing from the breast of Hera, wife of Zeus – the very word “galaxy” comes from the Greek word for milk. The Romans, too, saw this path across the sky as a *Via Lactea*, or

Milky Way. It was only in 1610 when Galileo first turned his telescope on the Milky Way that it was discovered that this band is not made up from a luminous “celestial fluid,” but rather consists of huge numbers of faint stars which could not be resolved with the naked eye. Thus, the Milky Way was discovered to be primarily a stellar system.

The next major development in the scientific study of the Milky Way came in the mid-eighteenth century, when Immanuel Kant published his treatise, *General Natural History and Theory of the Heavens*. In it, he demonstrated how the planar structure of the Solar System arose naturally from the attractive force of gravity from the Sun which bound the system, and the ordered rotation of the planets which prevented its collapse. Drawing on the earlier work of Thomas Wright, Kant went on to point out that the apparent structure of the Milky Way could arise if this stellar system were similar in arrangement to the Solar System, but on a huge scale. He reasoned that the force of gravity acts between stars just as it does between Sun and planets, and so the stellar system should take on a disk-like structure if it possesses a systematic rotational motion to balance the inward gravitational pull. The central plane of this distribution is usually referred to as the **Galactic plane** or the **plane** for short. From our location within it, a disk-shaped stellar distribution would be seen as a band of stars stretching across the sky in a great circle, just as the Milky Way appears to us. On account of the huge scale of the structure, the period of its rotation would be so long that the motions of stars on the sky would be immeasurably small. Drawing an analogy with comets in the solar system, Kant also pointed out that the small number of stars found a long way from the band of the Milky Way cannot share the ordered motion of the major component of the system, but must lie on more randomly distributed orbits. Finally, Kant suggested that the Milky Way might not be the only such stellar system, and that some of the **nebulae** – faint, fuzzy, approximately elliptical patches of light seen in the sky – might be complete **island universes**, similar in structure to the Milky Way but viewed from large distances and at a variety of angles to the line of sight. Given the small amount of observational evidence which lay behind it, the remarkable prescience of this whole line of argument is a tribute to Kant’s powers of reasoning.

Towards the end of the eighteenth century, increasingly powerful telescopes led to more systematic studies of nebulae. The comet hunter Charles Messier compiled a catalog of 109 of the brightest nebulae in the northern sky, primarily so that he could distinguish between these permanent diffuse patches of light and the transient comets that he was seeking. This list contains the most dramatic of the nebulae that are visible from the northern hemisphere, and prominent celestial objects are still frequently described by their number in Messier’s catalog. The Great Nebula in Andromeda, for example, is referred to as Messier 31, usually abbreviated to M31.

In a far more extensive survey, William Herschel, his sister Caroline and his son John made a study of the entire sky as visible from both the northern



Figure 1.1 Lord Rosse's sketch of the Whirlpool Nebula, M51, c. 1850. [Reproduced from Berry (1898)]

and southern hemispheres. In the course of these observations the Herschels compiled a catalog of nearly 5000 nebulae. Their telescopes were also able to resolve the light from some of the closest nebulae – now known to be star clusters associated with the Milky Way – into individual stars. This discovery convinced William that many of the still-unresolved nebulae were Kant's island universes which, given sufficiently good observations, would be shown to be made up from individual stars. However, he was also struck by the appearance of **planetary nebulae**, some of which consist of a continuous ring of glowing material surrounding what appears to be a single normal star. These systems, Herschel argued, were fundamentally different from the island universes, and thus the distinction between the truly gaseous nebulae and unresolved stellar systems was recognized. However, it was only in the late nineteenth century that pioneering studies of the spectra of nebulae by William Huggins allowed the distinction between stellar and gaseous systems to be quantified unambiguously. The Herschels' original list of both gaseous and stellar nebulae was steadily added to over the course of the nineteenth century, until Dreyer (1888) produced a compilation of 7840 objects in his *New General Catalogue*. Subsequently, he supplemented this list with a further 5086 objects forming the *Index Catalogue* (Dreyer 1895, Dreyer 1908). To this day, most reasonably bright non-stellar objects are identified by their numbers in these catalogs, abbreviated as the **NGC** or the **IC**, respectively.

The nineteenth century saw continued improvements in observations resulting from advances in telescope technology. In 1845, William Parsons, Third Earl of Rosse, finished construction of a telescope with the then-enormous diameter of 72 inches (a size not surpassed until the completion

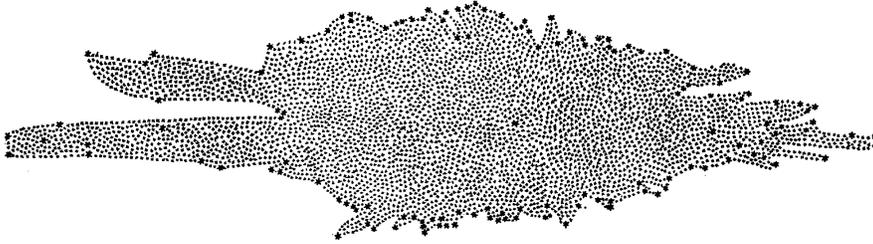


Figure 1.2 Map of the Milky Way derived from William Herschel's "star gauging." The bright star near the middle marks the location of the Sun. [Reproduced from Herschel (1785)]

of the 100-inch Mount Wilson telescope in 1917). With this unprecedented light collecting area, Lord Rosse was able to observe the faint nebulae in much greater detail than had previously been possible. His examination of the nebulae cataloged by the Herschels revealed that many of the objects fell into two distinct categories: some appeared as completely featureless, very regular elliptical distributions of light; while others were less symmetric, displaying a distinctive spiral structure (see Figure 1.1). The very appearance of the whirlpool-like shapes in these latter **spiral nebulae** added weight to Kant's suggestion that these systems rotate about an axis perpendicular to their planes. Furthermore, Lord Rosse was able to use his powerful telescope to resolve individual point sources within the spiral nebulae. Although these objects were probably giant gaseous emitting regions rather than individual stars, the fact that at least some of the emission from nebulae could be resolved into individual objects supported Kant's conjecture that the nebulae were actually island universes made up of many distinct sources.

At the end of the nineteenth century, the application of photography to astronomy revolutionized the subject. By exposing photographic plates for long periods, it became possible to observe much fainter objects than were accessible to visual observations. Moreover, photographs could record images of hundreds of thousands of objects on a single plate, and the brightnesses of the individual images could be measured much more accurately from a photograph than was possible through the eyepiece of a telescope. Thus, a new age of quantitative astronomy was born.

1.2.1 Photometric models of the Milky Way

In the early years of the twentieth century, the detailed structure of the Milky Way provided an obvious target for study using photographic techniques. Previously, only crude studies of the shape of the Milky Way had been possible: Herschel (1785) had attempted to determine the shape of the system using a technique he termed **star gauging** in which he laboriously counted the number of stars that he could observe to successive limits of apparent brightness in 683 different regions of the sky. He then assumed that

all the stars have approximately the same intrinsic brightness; that they are arranged approximately uniformly through the body of the Milky Way; and that he could see the stars all the way to the edge of the system. On the basis of these assumptions, he was able to map out the distribution of stars in the Milky Way: he concluded that the Sun lies close to the middle of stellar distribution, and that the distribution is flattened such that it extends approximately five times further in the plane of the Milky Way than in the direction perpendicular to the plane (see Figure 1.2). Since Herschel had no measure of the intrinsic luminosities of the stars that he observed, he was unable to put an absolute scale on the size of this system.

In order to refine such studies by making use of the large amounts of information that could be obtained from photographic plates, Jacobus Kapteyn decided to study in great detail 200 **selected areas** distributed across the sky. He coordinated a large collaboration of astronomers from all over the world to obtain the necessary photographs, and to analyze them by measuring the number of stars of different brightnesses and their small shifts in apparent position (**proper motions**) from year to year. He also used photographic plates to record the spectra of the stars in order to determine their types and their line-of-sight velocities (from the Doppler shifts in characteristic lines in the spectra). From an analysis of the proper-motion data, Kapteyn was able to estimate average distances for stars at various apparent brightness levels, and, from an analysis of the star-count data, he inferred the complete three-dimensional distribution of stars in space.

The final picture which emerged from this immense undertaking (Kapteyn & van Rhijn 1920, Kapteyn 1922) is usually referred to as the **Kapteyn Universe**. In agreement with Herschel's work, Kapteyn found that we are located close to the center of an approximately oblate spheroidal distribution of stars which extends about five times as far in the plane as perpendicular to it. He also demonstrated that the density of stars drops uniformly with distance from the center of the Milky Way. Moreover, Kapteyn was able to use the proper motion data to provide the first estimate of the absolute scale for the size of the Milky Way: he concluded that the density of stars dropped to half its maximum value at a radius of 800 parsecs² in the plane of the galaxy (and thus, from the measured flattening, the density dropped to half its maximum value at a distance $800/5 \sim 150$ pc from the center perpendicular to the plane). In the plane, the density dropped to 10% of its central value at a radius of 2800 pc and 1% of its central value at a radius of 8500 pc.

Kapteyn's analysis also indicated that the Sun was located slightly out of the plane of the Milky Way at a distance of just 650 pc from the center. This proximity to the center provides an uncomfortably heliocentric feature

² A **parsec**, usually abbreviated to **pc**, is 3.26 light years or 3.1×10^{16} m. It is roughly the distance from the Sun to its nearest neighbor star. Astronomers usually use kiloparsecs (kpc) and megaparsecs (Mpc) to measure larger distances.

in the Kapteyn Universe. Less than 10 percent of all the stars in this model lie within 700 pc of the center of the Milky Way; since presumably we could have evolved on a planet orbiting any of our galaxy's stars, it is statistically rather unlikely that we should find ourselves so close to the center. Kapteyn himself was well aware that there was an alternative explanation for the data: if there was an absorbing **interstellar medium** between the stars, then the light from distant stars would be dimmed by the absorbing medium. If this dimming were incorrectly interpreted as a distance effect, then the stars would be erroneously placed at excessive distances, leading to a spurious systematic falloff in stellar density in all directions. If this effect were strong, then we would appear to lie close to the center of the distribution whatever the true arrangement of stars.

There was plenty of evidence that some regions are, indeed, obscured: a dark rift along the central plane of the Milky Way is plainly visible to the naked eye, and numerous other dark patches where there are no stars show up clearly on photographs. If these regions were simply local voids in the distribution of stars, we should at least be able to see fainter, more distant stars beyond them. Stellar voids could account for the total absence of stars in some directions, but only if we were located at the end of a system of long, straight tunnels through the Milky Way, which are entirely empty of stars. It seemed far more likely that the absence of stars results from a nearby cloud of obscuring material which blocks the light from all the more distant objects. Kapteyn therefore expended considerable effort in trying to determine whether these dark clouds were isolated phenomena, or whether a more general absorbing medium pervades the Milky Way.

In order to assess the significance of absorption, Kapteyn sought to understand the physical processes that might be responsible for the obscuration. At the time, it was already well known that gas atoms can deflect light rays by the Rayleigh scattering process. If interstellar space were filled with gas, then light traveling to us from a distant star would have a high probability of being scattered in a random direction out of our line of sight, greatly diminishing the star's brightness. Thus, Rayleigh scattering provided a sensible mechanism which might produce apparent absorption in the Milky Way. To test this hypothesis, Kapteyn noted that the Rayleigh scattering process is much more efficient for blue light than for red light. We would therefore expect the light from stars to be more efficiently dimmed in the blue part of the spectrum than in the red, and so more distant stars should appear systematically redder – an effect known as **reddening**. Kapteyn (1909) looked for this effect by comparing the apparent brightnesses of stars as recorded by photographic plates to those estimated visually. Since photographic plates are more sensitive to blue light than the human eye, reddening of distant stars should have produced systematically greater brightnesses for the visual estimates than for the photographic data. Kapteyn found only small amounts of reddening in his data, and concluded that obscuration was unimportant.

In fact, we now know that the dominant source of obscuration is absorption by interstellar dust rather than Rayleigh scattering. The wavelength dependence of dust absorption is much smaller than that of Rayleigh scattering, and so absorption by dust reddens stars much less strongly than does Rayleigh scattering. With this more uniform absorption across the spectrum, the small amount of reddening detected by Kapteyn corresponds to a much larger total amount of obscuration.

The true degree to which dust obscures our view of the Milky Way was only recognized when Trumpler (1930) studied a sample of **open clusters** – loose concentrations of typically a few hundred stars found close to the plane of the Milky Way. He estimated the distances to these clusters by measuring their angular extents and assuming that they all are intrinsically the same size. He was then able to show that stars in remote clusters are systematically far fainter than would be predicted from their estimated distances. He thus demonstrated the existence of a strongly-absorbing interstellar medium which is responsible for this excess dimming. In fact, the amount of absorption implied by Trumpler’s analysis is sufficient to invalidate Kapteyn’s analysis of star counts entirely, and so we now know that his heliocentric picture of the Milky Way is erroneous.

Even at the time of Kapteyn’s analysis, evidence was mounting which suggested that his model of the Universe was incorrect. In a classic series of papers (Shapley 1918b, Shapley 1918a, Shapley 1919c, Shapley 1919b, Shapley 1919a), Harlow Shapley presented a radically different picture of the Milky Way. Shapley had undertaken a detailed study of **globular clusters**. These approximately spherical systems, originally classified as nebulae, were readily resolved with telescopes into aggregates of between 10^4 and 10^6 stars. Unlike the stars of the Milky Way, globular clusters are not restricted to a narrow band in the sky, but are distributed throughout the sky. However, Shapley demonstrated that this distribution is not uniform: although there are roughly equal numbers of clusters on either side of the plane, they are not distributed uniformly in longitude along the plane; instead, they show a marked concentration toward the great star clouds in Sagittarius, which also define the brightest section of the Milky Way. Shapley argued that the massive globular clusters must be a major structural element of the Milky Way, and one would expect such a major element to be distributed symmetrically around the center of the system. The large asymmetry in the distribution of globular clusters implied that we are not near the center of the Milky Way, in contradiction to Kapteyn’s analysis. Shapley went on to estimate the distances to the globular clusters using the apparent brightnesses of variable stars (with known intrinsic luminosities) and the apparent size and brightness of each cluster as a whole (assuming they are all intrinsically of comparable sizes and luminosities). On the basis of these measurements, he concluded that the Sun was some 15 kpc from the center of the globular cluster distribution, and hence, presumably, from the center of the Milky Way. Thus Shapley’s picture of the Milky Way differed radically from the

Figure 1.3 Schematic diagram showing Kapteyn's and Shapley's differing views of the size and structure of the Milky Way. Kapteyn placed the Sun (\odot) close to the center of the stellar system (represented as a grayscale), whereas Shapley used the distribution of globular clusters to conclude that we lay far from the true center of the Milky Way, but possibly in a local stellar density enhancement.

Kapteyn Universe. Shapley further estimated that the whole globular cluster system was close to 100 kpc across, almost ten times larger than the Kapteyn model.

As Figure 1.3 illustrates, there was clearly a major inconsistency between Shapley's view of the Milky Way and Kapteyn's Universe. In retrospect, we know that these models can only be reconciled if we allow for the effects of interstellar absorption. The absorbing dust in the Milky Way is strongly concentrated to the plane, and so the apparent stellar brightnesses are strongly dimmed leading to the illusion that we lie close to the center of a relatively small stellar distribution. With the approximately spherical distribution of globular clusters, on the other hand, only the small fraction of the systems that lie close to the plane of the Milky Way will appear dimmed by dust absorption, so the overall derived distribution will not be significantly distorted. In this context, it is interesting to note that Shapley himself pointed out that no globular clusters are visible within about a kiloparsec of the plane of the Milky Way. Since he was unaware of the large amount of dimming which afflicts objects close to the plane, Shapley argued that the absence of detected globular clusters in this part of the sky arose because strong gravitational forces close to the plane of the Milky Way would have disrupted any clusters originally in this region.

In order to try to reconcile his picture of the Milky Way with the more

heliocentric Kapteyn Universe, Shapley also suggested that the stellar analysis had picked out a local concentration of stars which was, indeed, centered close to the Sun, but that the global center of the distribution was at the same distance as the center of the globular cluster distribution, some 15 kpc away. There is certainly a small element of truth in this argument, since the Sun does lie close to the center of a local loose cluster of stars referred to as **Gould's Belt**. However, the ultimate reconciliation between the disparate views of the Milky Way had to await the recognition that the apparent stellar distribution is dominated by the effects of absorption. In fact, it was only much more recently, with the development of computer programs capable of numerically evaluating the effects of extinction on stellar number counts [such as that written by Bahcall & Soneira (1980)], that quantitative sense could be made of such data.

1.2.2 The nature of the spiral nebulae

Shapley's radical model of a large Milky Way must have played a key role in the development of his ideas regarding the nature of spiral nebulae. To him, the suggestion that the nebulae were independent island universes similar to the Milky Way was quite implausible. The extent of his new Milky Way model expanded the scale of the known Universe so far that it was hard to believe that yet more remote objects could exist. Further, the spiral nebulae have quite small angular sizes; if they were comparable in size to Shapley's enlarged Milky Way, then they would have to lie at what were then inconceivably large distances.

Shapley's ideas were by no means universally accepted, and many still adhered to Kapteyn's smaller model of the Milky Way and concluded that spiral nebulae were other similar systems. This split in the astronomical community led George Ellery Hale (director of the Mount Wilson Observatory) to suggest that the issues might be debated at the National Academy of Science in Washington as part of a lecture series in memory of his father, William Ellery Hale. Shapley himself was the obvious choice of advocate for the new ideas, and the role of his opponent fell to Heber Curtis, who had studied spiral nebulae in great detail and was convinced of their extragalactic nature. Their public confrontation took place at the National Academy in April 1920, and has since become known as the **Great Debate**.

In fact, this title is something of a misnomer since the meeting did not take the form of a debate, but rather consisted of two short lectures in which each party presented his case [Hoskins (1976) gives a detailed account of the meeting]. Shapley's contribution concentrated primarily on his model of the Milky Way, and seems to have made only passing mention of its implications for the nature of spiral nebulae. Curtis, on the other hand, used much of his allotted time to discuss the evidence for and against the island universe hypothesis, unsurprisingly concluding that the hypothesis appears valid. Since

each talk lasted only about half an hour and concentrated on different aspects of the issue, there was no real winner in this “debate,” although the consensus seems to have been that Curtis was the better speaker and gave a clearer exposition of his ideas.

More important than the debate itself were the expanded accounts of their addresses, which Shapley and Curtis published the following year (Shapley 1921; Curtis 1921). These papers went into greater technical detail than had been possible in their face-to-face encounter, and provided the opportunity for each to rebut the other’s arguments. Curtis’ paper cast doubt on the very difficult measurements that Shapley had used to calculate the distances to nearby stars. In particular, he was unconvinced by the large values of the distances that Shapley attributed to the Cepheid variable stars which were used to calibrate the distances to similar stars in globular clusters. Curtis also presented an analysis in which he incorrectly assumed that the brightest stars seen in globular clusters were comparable to the most luminous nearby stars; in fact, the brightest globular cluster members are giant stars with much higher intrinsic luminosities, and so Curtis radically underestimated their distances.

On the issue of the nature of spiral nebulae, Curtis advanced a wide range of arguments in support of his thesis that they were external to the Milky Way. In particular, he pointed out that spiral nebulae have angular sizes ranging from more than two degrees for the Great Andromeda Nebula, M31, down to a few arcseconds for the smallest nebulae which had been photographed at that time. If these objects are of comparable intrinsic size, then their distances must differ by more than a factor of a thousand. Even if the Andromeda Nebula were within the Milky Way, other apparently smaller nebulae would have to lie at huge distances well beyond the bounds of even Shapley’s extended Milky Way.

He also noted that quite a number of novae – bright stellar sources which appear briefly before fading back to obscurity – had been detected in the direction of M31. The large number of novae in this small region of sky implied that they must be physically associated with M31. Moreover, the novae in the direction of M31 were very much fainter than those seen from elsewhere in the Milky Way, implying that they were located much further away. Invoking the inverse-square law for the variation in apparent brightness with distance, Curtis calculated that M31 was at a distance of around 100 kpc. At this distance, the angular size of M31 implied that its linear size was around 3 kpc, comparable in size to Kapteyn’s model of the Milky Way. With hindsight, we know that Curtis made two mistakes in his analysis which conveniently canceled out: by confusing Galactic novae with much brighter supernovae in M31, he underestimated the distance to the nebula by about a factor of five; however, the Kapteyn model of the Milky Way is also too small by a similar factor. He thus correctly (if fortuitously) concluded that M31 and the Milky Way are comparable systems of similar linear extent.



Figure 1.4 Optical image of the edge-on galaxy, NGC 891, originally discovered by Caroline Herschel. Note the prominent dust lane in the plane of the galaxy, and the presence of both extensive disk and central spheroidal stellar components. [DSS image from the Palomar/National Geographic Society Sky Survey, reproduced by permission]

The dispersion of the light from spiral nebulae into spectra provided two further pieces of evidence in favor of the idea that they were distinct stellar systems. First, the characteristic absorption lines in the spectra of many nebulae are the same as those seen in normal stars, and the total spectra resemble closely the spectrum that would be obtained from the integrated starlight of the Milky Way, which suggests that they are similar systems. Second, the lines in the spectra of both stars and galaxies are shifted relative to their rest wavelengths. These shifts can be understood if they arise from the Doppler shift due to the line-of-sight motions of the emitting body. However, the inferred velocities for the nebulae are many times larger than those of the stars in the Milky Way, suggesting that the nebulae and stars do not form a single dynamical entity. Moreover, although the nebulae have large line-of-sight velocities, their positions on the sky have not changed detectably with time. Unless the nebulae all happen to be moving exactly away from us, which seems most unlikely, the lack of any apparent motions transverse to the line of sight implies that they must be at very large distances. However, no explanation was offered as to why the vast majority of spiral nebulae have Doppler shifts which imply that they are receding from the Milky Way. This systematic effect could easily be interpreted as suggesting that the Milky Way is repelling the nebulae, implying that they must be physically associated with each other. The true significance of this phenomenon, the expansion of the Universe initiated by the Big Bang, would only be uncovered almost a decade later.

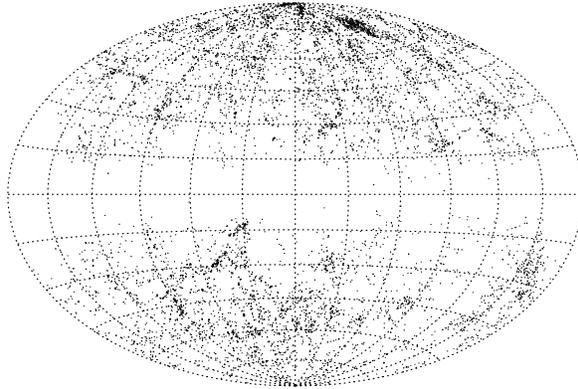


Figure 1.5 Map showing the distribution of New General Catalogue (NGC) and Index Catalogue (IC) objects which have been identified as spiral or elliptical nebulae. In this Aitoff projection, the plane of the Milky Way runs horizontally through the center of the map. Note the dearth of objects in the “zone of avoidance” within fifteen degrees of the plane.

One last particularly elegant piece of reasoning presented by Curtis came from the observation that edge-on spiral nebulae often contain dark bands through their centers (see Figure 1.4). Curtis interpreted this band as a ring of absorbing material surrounding the systems. He further pointed out that the **zone of avoidance** – a region close to the plane of the Milky Way where no spiral nebulae are observed (see Figure 1.5) – could be explained naturally if the Milky Way were encircled by a similar absorbing ring, and the spiral nebulae all lay beyond this ring. He thus neatly brought together the ideas that the Milky Way would look similar to a spiral nebula if viewed from the outside, and that the nebulae must lie beyond the fringes of the Milky Way. The only slight flaw in this reasoning was the assumption that the absorbing material lies in a single ring at large radii; as we now know, absorption arises from dust which is distributed throughout the plane of the Milky Way. Curtis was forced to assume that the absorbing material lay only at large distances since he adhered to Kapteyn’s analysis of the stellar distribution in the Milky Way which relied on their being no absorption of stellar light within the system.

For his part, Shapley produced several strong points in favor of the hypothesis that spiral nebulae are intrinsically different from the Milky Way. Foremost amongst these arguments was his belief that the Milky Way was a very large system, which would imply that the relatively small spiral nebulae would have to be at tremendous distances to be comparable systems. However, he also pointed to a number of analyses which imply that the Milky Way has other properties that distinguish it from the spiral nebulae. The Milky Way has a lower surface brightness (i.e. luminosity per unit area) than

any of the spiral nebulae, and many spiral nebulae were observed to be significantly bluer than stars in the Milky Way. These distinctions implied that the nebulae and the Milky Way could not be intrinsically similar systems. With hindsight, we can put the differences down to the effects of the absorption of which both Shapley and Curtis were unaware: since we see the Milky Way edge-on, stars on the far side of the Galaxy are viewed through much absorbing material, and so the surface brightness of the system is greatly reduced when compared to observations of more face-on systems; similarly, light from the bright blue stars which populate the spiral arms in the Milky Way is strongly attenuated, and so we preferentially see the more-plentiful nearby faint red stars, which makes the system appear redder than external galaxies.

Perhaps the most telling argument reported by Shapley was the result of a set of measurements by Adriaan van Maanen, which compared images of several spiral nebulae taken over a number of years. The comparisons implied that the spiral structure in these systems rotates at a perceptible rate, with a rotational period of only around 10^5 years. If the nebulae had radii in excess of around 5 kpc, then their outer parts would have to be rotating at velocities in excess of the speed of light in order to maintain this apparent rotation rate! The absurdity of this conclusion implied that the spiral nebulae must be very much smaller than 5 kpc, and so could not be comparable in size to the Milky Way. The reasoning here was impeccable, and Curtis conceded that if the observations were confirmed then the whole island universe hypothesis would have to be abandoned. Van Maanen was a well-respected observer, and so his results carried a great deal of weight at the time. It was only several years later, when Lundmark re-measured van Maanen's photographic plates, that it was conclusively demonstrated that the detection of rotational motion was spurious. We will probably never know where van Maanen went wrong in this set of measurements.

It is clear that both Shapley and Curtis had grasped important aspects of the truth as we now perceive it. In her review of their encounter, Trimble (1995) makes the insightful point that each party made best use of data that they had collected themselves: Shapley's analysis of his globular cluster observations produced the fundamental change in ideas about the location of the Sun and the size of the Milky Way, and Curtis' understanding of the true nature of the spiral nebulae came from his long study of these systems. Most of the confusion arose when other peoples' analyses, such as Kapteyn's model of the Milky Way and van Maanen's rotation measurements, were added to the debate.

Within five years, Edwin Hubble had resolved the controversy as to the nature of spiral nebulae once and for all. Using the superior optics of the recently-completed 100-inch telescope at Mount Wilson, he was able to resolve the outer parts of two nearby spiral nebulae into swarms of very faint objects indistinguishable from stars. If these objects were assumed to be comparable to the brightest stars in the Milky Way, then the nebulae must

be at large distances. The clinching observation came in late 1923 when Hubble established that the brightnesses of a few of these myriad stellar images in the Andromeda Nebula, M31, varied in the characteristic periodic manner of **Cepheid variable stars**. It had already been established that the intrinsic luminosities of these particular stars can be determined directly from their periods of variability, and so by measuring the periods of the Cepheids in M31, Hubble was able to estimate their luminosities. Measuring their apparent brightnesses then yielded a direct estimate for their distances. Using this method, Hubble (1922) obtained a value for the distance to M31 of some 300 kpc. Although more recent calibrations of the luminosities of Cepheids imply that this estimate is more than a factor of two too small, it nonetheless firmly demonstrated that the Andromeda Nebula is not an element within the Milky Way, but is a comparable stellar system in its own right. Thus, it was finally established that the Milky Way is but one galaxy amongst its peers. The spiral nebulae are thus actually **spiral galaxies**, while the more featureless elliptical nebulae are mostly **elliptical galaxies**.

1.2.3 Kinematic models of the Milky Way

At about the same time that Hubble was demonstrating that spiral nebulae are indeed separate galaxies, Bertil Lindblad was producing new insights into the properties of the Milky Way using an entirely different approach. He calculated the total mass of Kapteyn's model by adding up the contributions from all the stars. He then used the Doppler shifts in the lines seen in spectra of globular clusters to show that these objects move with velocities as high as 250 km s^{-1} . Such speeds are significantly higher than the escape velocity from Kapteyn's Universe; the relatively small total mass of this system results in a gravitational field that is too weak to retain the globular clusters as gravitationally bound members of the system. The fact that a large number of globular clusters are associated with the Milky Way implies either that the true gravitational forces are stronger than those predicted by the Kapteyn model, thus permanently binding the clusters to the Milky Way, or that globular clusters continuously form at a sufficient rate to replace their escaping kin. Since globular clusters each contain up to a million stars, there is not enough mass in the Kapteyn Universe to provide the raw materials required to replenish the continually-escaping globular clusters. These dynamical arguments provided perhaps the last nail in the coffin of the Kapteyn Universe, and suggested that Shapley's model for the Milky Way with its larger mass (and correspondingly greater escape velocity) was closer to the truth.

Lindblad (1927) went on to develop a more detailed kinematic model of our galaxy, which sought to explain its apparent structure in terms of the motions of its constituents under their mutual gravitational attraction. He proposed that the Milky Way might be divided into a number of subsystems, each of which was symmetric about the central axis of the whole

system (which, in agreement with Shapley, he placed a considerable distance from the Sun). Each component was further assumed to rotate about this symmetry axis with some characteristic speed. Echoing the ideas of Kant two centuries earlier, Lindblad noted that the degree to which each subsystem is flattened would depend on whether its motions were dominated by rotational or random motions: the most slowly rotating subsystems would be made up of objects on largely random orbits and hence would display little in the way of flattening.

Since Shapley's analysis had shown that the distribution of globular clusters in the Milky Way is approximately spherical, Lindblad proposed that these objects constitute a subsystem with almost no rotational motion. Furthermore, since almost all the stars in the solar neighborhood possess very little velocity relative to the Sun, the random component of these stars' motions must be small, and so Lindblad concluded that they must follow well-ordered circular orbits and thus produce the highly-flattened disk of the Milky Way. By measuring the velocity of the Sun and its neighboring stars relative to the mean velocity of the non-rotating globular cluster population, Lindblad was able to demonstrate that the nearby disk stars rotate around the Milky Way with a velocity of between 200 and 300 km s⁻¹.

These ideas were developed into a complete theory of Galactic stellar kinematics by Jan Oort (Oort 1927, Oort 1928). Amongst the phenomena explained by this theory were the so-called **high-velocity stars**. These stars make up an asymmetric tail in the distribution of stellar velocities, traveling at velocities such that they lag behind the rotational motion of the Sun. Thus, although these stars have high velocities relative to the Sun, they are somewhat misnamed since they are actually moving at very low speeds, with their high relative velocities arising almost entirely from the motion of the Sun around the Milky Way. Oort pointed out that such a population would arise if there were a stellar component of our galaxy with little net rotation. The members of this population would, while in the solar neighborhood, have insufficient tangential velocities to maintain them on circular orbits against the gravitational pull of the Milky Way, and thus their orbits should carry them radially inward toward the center of the system. Since this population of stars has little net rotation, we should expect them to form an approximately spherical concentration toward the center of the Milky Way. Oort's analysis of the remaining stars in the solar neighborhood showed that their kinematics were exactly what would be expected if they were following approximately circular orbits in a differentially rotating disk (i.e., one in which stars nearer the center have a faster angular rotation rate than those at larger radii) with the Sun located far from the disk's center. Images of edge-on spiral galaxies (see Figure 1.4) reveal the presence of both relatively unflattened spheroidal distributions of stars at their centers and highly-flattened disks that extend to larger radii. Thus, Oort's stellar kinematic analysis confirmed the idea that the Milky Way is indistinguishable in structure from these external galaxies.

A great advance in dynamical studies of the Milky Way and other galaxies came from the discovery that the gas in these systems emits at radio wavelengths. Karl Jansky established in 1932 that the Milky Way emits a broad spectrum of radio waves, but the major breakthrough came from the discovery that it also emits strongly in a spectral line at 21 cm. The existence of this emission line, arising from a hyperfine transition in atomic hydrogen, was predicted by H.C. van de Hulst in 1944, but it was not until 1951 that this prediction was observationally confirmed by Ewan and Purcell at Harvard, Christiansen in Australia, and Muller and Oort in the Netherlands. This radio emission provided the ideal tool for studying the large-scale kinematics of the Milky Way: the distinctive line enabled astronomers to measure line-of-sight motions of atomic hydrogen via Doppler shifts in the line's detected wavelength. Further, radiation at such long wavelengths is entirely unaffected by dust, and so the absorption which limits our ability to study the stellar structure of the Milky Way at optical wavelengths ceases to be a problem. Observations of 21 cm emission revealed that atomic hydrogen is a major component of the Milky Way, permeating its disk out to distances beyond twice the solar radius; it therefore provides us with a tracer of the properties of the disk of the Milky Way over a wide range of radii.

By combining 21 cm observations obtained from both the northern and southern hemispheres, Oort, Kerr & Westerhout (1958) were able to produce the first complete map of the distribution of atomic hydrogen throughout much of the Galaxy (see Figure 1.6). These and subsequent observations showed that the gas is strongly concentrated toward the plane, that it is distributed fairly uniformly in azimuth, and that it travels on approximately circular orbits about the Galactic center (as would be expected for such a highly flattened component).

More detailed examination of the gas distribution revealed that such a simple axisymmetric model is an oversimplification. Even on the largest scales, the atomic hydrogen in the Milky Way is not arranged uniformly in azimuth: more gas lies on one side of the system than on the other. The gas disk is not flat, either, but warps away from the plane of the Milky Way at large radii. As Figure 1.6 shows, there are also long, narrow regions in which the density of gas is significantly enhanced, and Oort, Kerr & Westerhout (1958) were quick to identify these features with the spiral structure found in other galaxies (see Figure 1.1). Since the arms are associated with density enhancements in the disk, it is not surprising that these asymmetric perturbations in the gravitational potential produce non-circular motions in the orbiting gas. The map presented in Figure 1.6 was constructed by assuming that the gas follows circular orbits, and the presence of non-circular motions distorts its appearance. It is this phenomenon which is responsible for the spurious manner in which the arm features appear to converge on the Sun. Thus, although mapping out the Galaxy through its 21 cm emission represented a major advance in our study of the structure of the Milky Way,

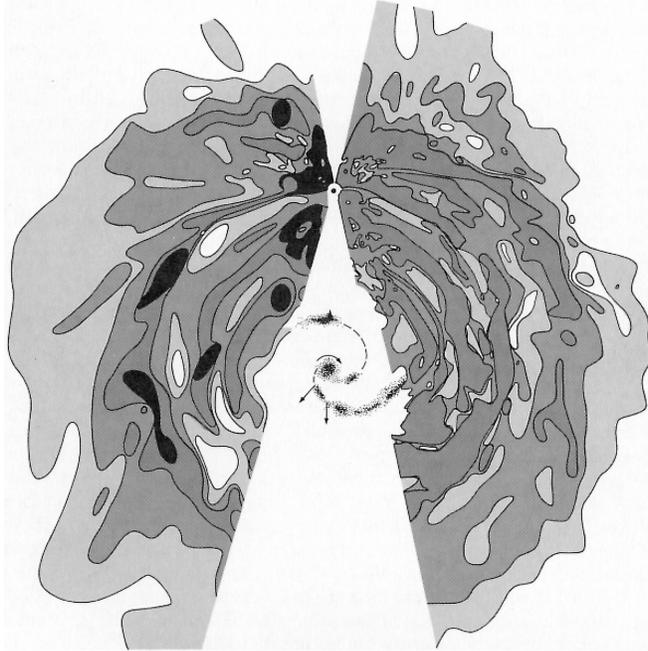


Figure 1.6 The distribution of atomic hydrogen in the plane of the Milky Way as inferred from early 21 cm observations. The Sun is located at the point marked “ \odot .” The empty cone toward the Galactic Center and anti-center cannot be mapped out using the kinematic technique employed here. [Reproduced from Oort, Kerr & Westerhout (1958), by permission]

the complexity of interpreting non-circular motions meant that the picture was still ambiguous.

The strongest signs of non-circular gas orbits in the Milky Way come from close to the Galactic center, where 21 cm emission has been observed to be Doppler shifted from its expected circular velocity by hundreds of kilometers per second. These anomalous velocities were originally interpreted as implying that the gas is being flung from the center of our galaxy, but it was subsequently realized that they could equally be interpreted as resulting from non-circular orbits in a strongly non-axisymmetric gravitational potential (Peters 1975). Since at least one third of external spiral galaxies are observed to contain a bar-like asymmetric structure at their centers (see Figure 1.7), we might reasonably conclude that the non-circular motions in the Milky Way are induced by a similar **galactic bar**.

The early radio observations used single dish antennae, which gave a spatial resolution of only a degree or so, and this limitation made it difficult to study even the large-scale distribution of hydrogen in external galaxies. Far greater resolution was achieved with the construction of **interferom-**



Figure 1.7 Optical image of the galaxy, NGC 3992. Note the prominent bar in this system in addition to the spheroidal and disk stellar components. [DSS image from the Palomar/National Geographic Society Sky Survey, reproduced by permission]

eters, which consist of a set of moderate-sized radio dishes arrayed over several kilometers. The angular resolution of such an instrument is equivalent to that of a single dish the size of the whole array. Data obtained from these interferometers, such as the Westerbork Synthesis Radio Telescope in the Netherlands and the Very Large Array in New Mexico, revealed that other spiral galaxies also have hydrogen disks in which the gas follows approximately circular orbits, but with the same complications due to warping and non-circular streaming as the Milky Way. These disks could be traced to large radii, well beyond the observed optical edges of the galaxies.

Since it is the gravitational pull of a galaxy that provides the force which retains the gas on its approximately circular orbits, it is straightforward to translate the observed orbital velocities in a gas disk into an estimate of the distribution of mass in the galaxy. We can compare the mass derived in this way to the sum of the masses of the individual components such as the stars in the disk and spheroid, and the hydrogen gas itself. The surprising result of such comparisons in the 1970s was that the total mass inferred dynamically exceeds the sum of all the known components, and that the discrepancy becomes greater as we look to larger radii in a galaxy. From these observations it was inferred that galaxies are embedded in huge **dark halos**, which contain considerably more mass than the visible galaxies themselves. This unexpected discovery was originally dubbed the “missing mass problem”, but this title is somewhat confusing, since we know from the kinematics that there is an excess of mass rather than a deficit. The real problem is that we do not know what form the excess mass takes, since it evidently is not made up of directly-visible material. Our inability to identify

the nature of the material which dominates the mass of many systems is therefore now usually referred to as the “dark matter problem.” Its resolution remains one of the major goals of galactic astronomy.

1.2.4 Stellar populations

The recognition by Lindblad and Oort that spiral galaxies could be broken down kinematically into separate spheroidal and disk components ties in closely with the key notion of distinctive **stellar populations**. Taking advantage of the wartime blackout in Los Angeles, Baade (1944) used the 100-inch Mount Wilson telescope to resolve individual stars in the inner regions of several nearby spiral galaxies, where the spheroidal component dominates. He also obtained resolved stellar images in a couple of nearby elliptical galaxies. By analyzing the colors and brightnesses of the stellar images, Baade realized that the brightest stars in both elliptical galaxies and the spheroidal components of spiral galaxies are **red giants**; these stars are quite different in appearance from the **blue supergiants** which dominate the spiral arms in the disks of galaxies. These observations suggested to Baade the existence of two characteristic stellar populations: **population I**, which contains luminous blue stars, accompanied by dust and gas; and **population II**, which is dominated by luminous red stars in an essentially gas- and dust-free environment. Open clusters and stellar disks comprise population I material, while globular clusters, galactic spheroids and elliptical galaxies are made up of population II stars.

Detailed studies of the colors and brightnesses of stars in the different types of star cluster confirmed the clear distinction between the two stellar populations. In the early part of the twentieth century, Ejnar Hertzsprung and Henry Norris Russell independently discovered that, in a plot of color versus luminosity, stars are not randomly scattered, but rather are concentrated within tightly defined bands. Such a plot was termed an **HR diagram** after its inventors, although in its modern form it is more usually described as a **color–magnitude**, or **CM diagram**. When CM diagrams were constructed for stellar clusters, the bands which are populated by the stars of open clusters were found to differ from those which are populated by globular-cluster stars. From this discovery it followed that the stellar populations of these two types of cluster contain very different types of stars.

The location of a star in a CM diagram depends on the rate at which it is generating energy by nuclear fusion in its core, and on the structure of the star itself. The two decades up to about 1965 saw advances in understanding of the energy generation processes and the development of computers capable of calculating detailed models of stellar structure. It thus became possible to predict where a star should appear on the CM diagram, and how its location changes with time as the star’s structure evolves. From these calculations, it has become clear that the difference between open and globular clusters arises from their ages: younger stars occupy the regions of CM diagrams populated

by open-cluster stars, whereas globular-cluster stars fall only in regions of the CM diagram that are occupied by old stars. Thus, the distinction between populations I and II is also one of age, with population I stars having formed more recently than those of population II.

Confirmation of this distinction has come from detailed spectral analysis of stars from the two populations. These studies allow one to determine the chemical compositions of stars from the strengths of characteristic spectral absorption features. Population II stars are found to be very deficient in all elements heavier than helium (or **metals** as they are somewhat confusingly termed by astronomers), whereas population I stars have rather higher metal abundances, comparable to the solar fraction of heavy elements (which is not very surprising since the Sun is itself a population I star). Some of the heavy elements found in stars are only produced in the supernova explosions which end many stars' lives. Hence, the presence of these elements in a star indicates that the star must contain material synthesized by supernovae in a previous stellar generation. The difference between the metal abundances in the two stellar populations thus once again points to a difference in ages. A star that formed late in the history of a galaxy will be made from material that has had time to be processed through several earlier generations of stars, and will thus generally have high metal abundances; the star will therefore be classified as a population I object. A star that formed much earlier will have been produced from material whose chemical abundances lie much closer to the primordial composition of the Universe with only very small amounts of metals, and so the star will be a population II object.

It therefore seems highly probable that the globular clusters and spheroid of the Milky Way, being made up of population II stars, are the parts of the Milky Way that formed first, with the population I stars in the disk forming later. This evolutionary sequence is confirmed by the fact that stars are observed to form in the disk even today, whereas no star-forming regions can be seen away from the Galactic plane. It is notable that even the most metal-poor stars that have been observed in the Galaxy contain trace amounts of heavy elements, which they could not have synthesized themselves. The idea has therefore been mooted that there might have been a still-earlier generation of **population III** stars which produced these elements, but the existence of such objects lacks any direct observational confirmation.

1.2.5 More recent developments

As should be apparent from the above discussion, much of the history of astronomy has been dictated by the technology available to astronomers. We have, for example, been able to form images of progressively fainter objects as larger and larger telescopes have been built. Similarly, the quantitative analysis of astronomical images only became practicable with the invention of photographic detectors which could be used to obtain a permanent record of the data.

Technological advances continue to play a key role in the development of the subject. For example, the rapid developments of computer technology in the latter part of the twentieth century have allowed astronomers to handle large quantities of data and to automate much of the analysis of these data. With these techniques, it has been possible to undertake enormous surveys which automatically monitor the light from literally millions of stars on a nightly basis. The purpose of these experiments is to look for the magnification of light from a distant star that will occur if a massive object forms a temporary gravitational lens as it passes through our line of sight to the star. If the dark halo of the Milky Way is made up of compact massive objects, then their presence could be detected by this phenomenon. The probability of a single star being magnified in this way is very small, and so it is only by using computers to monitor automatically very large numbers of stars that we stand a good chance of detecting the effects and thus determining the content of the Milky Way's dark halo.

Observational techniques have also continued to benefit from advances in technology. The introduction of very efficient **charge coupled devices (CCDs)** to replace photographic plates as light detectors has revolutionized optical astronomy. These detectors are similar to those found in camcorders, except that they are cooled with liquid nitrogen to reduce the level of thermal noise. Since CCDs are some ten times more efficient than photographs at detecting light, they have enabled astronomers to study very faint phenomena such as the outermost parts of galaxies for the first time. Developments in detector technology have also expanded the region of the spectrum over which observations can be made. Of particular importance has been the development in the 1980s of infrared detector arrays analogous to the optical CCDs. These efficient digital devices have made it possible to study galaxies in the near infrared, where the absorbing effects of dust are small, providing a clearer picture of the underlying stellar light distribution.

In addition to the improvements in light-gathering potential provided by the new detector technologies, advances have also been made through the construction of ever bigger telescopes. A number of telescopes with diameters of around eight meters are currently at various stages of planning or construction. However, an even larger telescope is already in operation: the Keck Telescope on Mauna Kea in Hawaii consists of 36 hexagonal mirror segments each 1.8 meters across, mounted together in a honeycomb pattern. The exact alignment of all the mirror segments is maintained by computer, allowing the system to act as a single telescope with a light-collecting power that is equivalent to that of a single mirror 10 meters in diameter. A duplicate of this amazing piece of technology is being built adjacent to the original, so that these two huge telescopes will be able to operate in concert.

Significant advances have also been made in the quality of the images recorded. Motions in the earth's atmosphere distort the light from astronomical objects, causing the familiar twinkling of stars. These distortions blur out any structure in objects which have angular scales of less than about

an arcsecond. This degradation can be ameliorated by furnishing telescopes with moving mirrors that compensate for the motions of the atmosphere in order to reduce its distorting influence. Such **active optics** can decrease the amount of blurring by more than a factor of two, but still greater gains can be made by getting above the earth's atmosphere entirely. The Hubble Space Telescope (HST) is a satellite telescope with a 2.4 m mirror, which was designed to produce images that can resolve structure down to a scale of 0.1 arcseconds. Initially, a flaw in the shape of the mirror prevented this goal from being achieved, but the introduction of new optics to correct its myopia has enabled the HST to exploit fully its location above the earth's atmosphere. In addition to studying small-scale structures such as the very cores of galaxies in unprecedented detail, the improved image quality and lower background light level in space have allowed the HST to image very faint objects; such studies have, for example, demonstrated that the dark matter halo of the Milky Way cannot be made up from intrinsically faint low-mass stars.

Observations from space have proved important in several other areas of the study of galactic structure. The Hipparcos Satellite, for example, contained a small (29 cm diameter) optical telescope dedicated to measuring accurate stellar positions (a field of study known as **astrometry**). Over its four year lifetime, this satellite measured the positions of more than 100 000 stars to an accuracy of ~ 0.002 arcseconds. In addition to the absolute positions of the target stars on the sky, the satellite also measured the small periodic shift in apparent location of the stars that arises from the changing position of the earth as it orbits around the Sun. The magnitude of this effect, known as **parallax**, depends on the distance to the star, and so the Hipparcos observations provide a measure of the distances to all the target stars out to distances of several hundred parsecs (at which point the parallax becomes too small to measure). Thus, Hipparcos measured the full three-dimensional spatial coordinates for a large sample of relatively nearby stars. The satellite also recorded the shifts in the location of the stars due to their own orbital motions; combining these observations with the line-of-sight velocities inferred from Doppler shifts in spectra obtained from the ground, we can reconstruct the full three-dimensional velocities of the target stars. Thus, Hipparcos has provided us with a wealth of information on the spatial and kinematic properties of the Milky Way which has yet to be fully exploited.

The development of astronomical satellites has also opened up parts of the electromagnetic spectrum that are unobservable from the ground due to their absorption by the earth's atmosphere. The whole field of X-ray astronomy, for example, only became possible with the advent of space flight. Solar observations were made from rockets as early as the 1940s, and these experiments were followed by rocket observations of the moon and other bright X-ray sources in the 1960s. However, X-ray astronomy only really came of age with the development of satellite technology, and particularly the launch

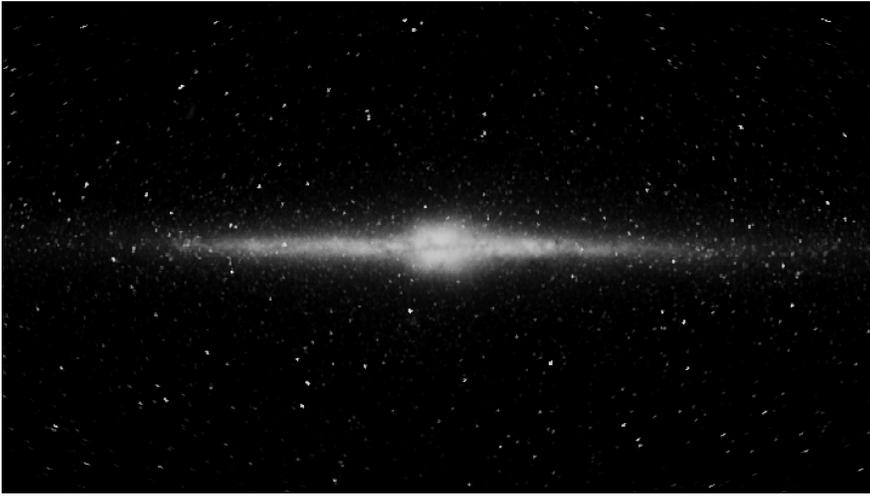


Figure 1.8 Infrared image of the Milky Way obtained by the COBE satellite. [Reproduced courtesy of NASA Goddard Space Flight Center and the COBE Science Working Group]

of the Einstein Observatory in 1978. This mission and its successors have produced images of some of the most energetic phenomena in the Universe, including the ultra-luminous **active galactic nuclei**, believed to be powered by super-massive black holes, which lurk at the centers of some galaxies. X-ray observations have also revealed an entire new component of galaxies: a halo of gas which is so hot that it emits at these short wavelengths. The discovery of this component in elliptical galaxies was particularly surprising since, as we have discussed above, it had long been supposed that these systems were essentially gas-free.

One last example of space-based observations of importance to the study of galaxies comes from the infrared part of the spectrum. At the longer infrared wavelengths, the earth's atmosphere is opaque and so little could be learned from the ground. The Infrared Astronomical Satellite (IRAS), launched in 1983, provided the first comprehensive survey at these wavelengths. Cool dust in galaxies re-radiates the light that it absorbs at these long infrared wavelengths, and so this survey gave us the first comprehensive map of the distribution of dust in the Milky Way. These observations revealed that the far infrared emission from dust is strongly concentrated toward the plane of the Galaxy, which ties in with the large amount of optical extinction in this region. However, it also turned up the unexpected discovery of diffuse patches of emission – termed **cirrus** by analogy with the terrestrial thin clouds – far from the plane of the Milky Way. Dust is clearly more pervasive in the Galaxy than had been expected.

A more recent study of the Milky Way at infrared wavelengths has been made by the Cosmic Background Explorer (COBE) satellite. Although pri-

marily intended to test cosmological theories, the telescopes on this satellite also recorded the strong flux from both stars (at near infrared wavelengths) and dust (at far infrared wavelengths) in the Milky Way. At the near infrared wavelengths, little light is absorbed by dust, and so the all-sky image produced by COBE at these wavelengths provides us with a uniquely clear picture of the large-scale stellar distribution in the Milky Way. The COBE image of the plane of the Milky Way is presented in Figure 1.8. Comparing this image to the picture of NGC 891 in Figure 1.4, it is strikingly apparent that – once the confusing effects of dust obscuration have been removed – the Milky Way is indistinguishable from the multitude of other galaxies which make up the cosmos.