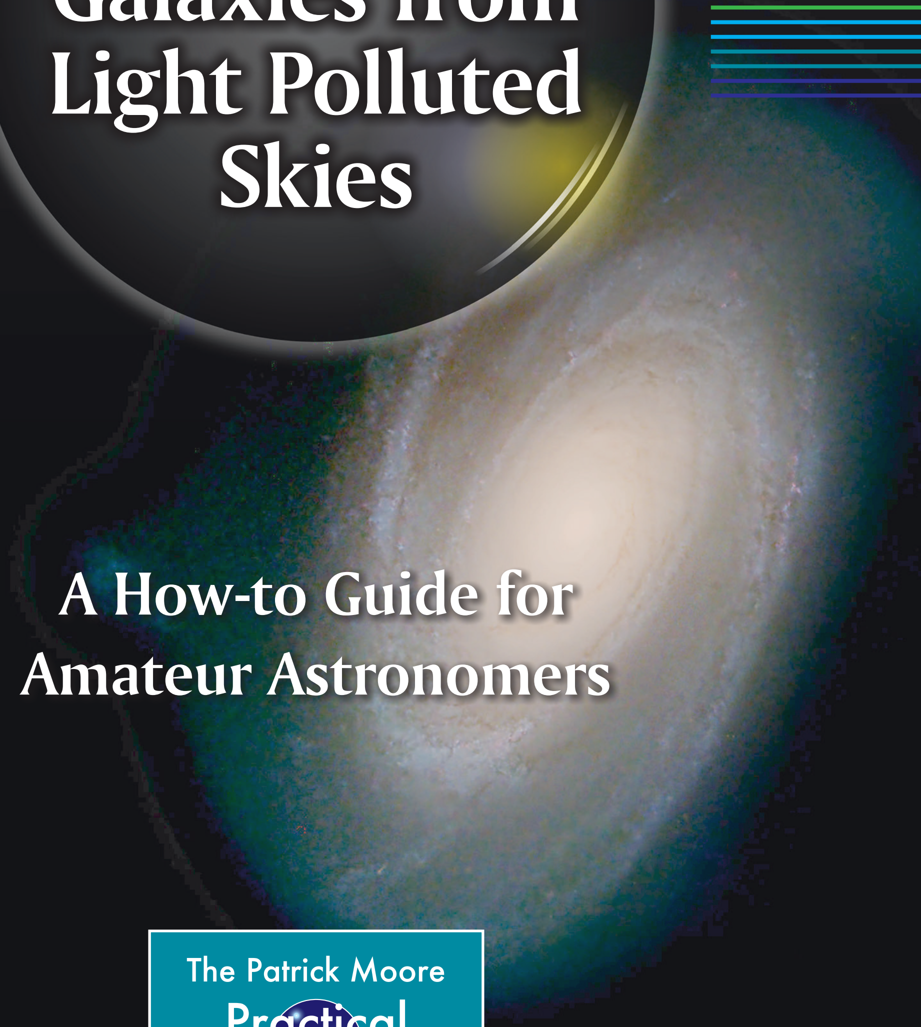
Jane Clark

Photographing Galaxies from Light Polluted Skies

A How-to Guide for Amateur Astronomers



The Patrick Moore Practical Astronomy Series

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The Patrick Moore Practical Astronomy Series is a treasure trove of how-to guides for the amateur astronomer. The books in this series are written for hobbyists at all levels, from the enthusiastic newcomer to the veteran observer. They thus go far beyond more general, popular-level books in both scope and depth, exploring in detail the latest trends, techniques, and equipment being used by amateur astronomers around the world.

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Overall, this series bridges the gap between the many introductory books available and more specialized technical publications, providing digestible, hands-on guides for those wishing to expand their knowledge of the night skies.

Jane Clark

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A How-to Guide for Amateur Astronomers

Springer

Jane Clark
Risca, UK

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To two people who died tragically young
while this book was in production:
My sister Susan Gregory, aged 56
My astronomer friend Gregory
Titley, aged 36

Preface

I have set this book out using the case study method. That is, I think I can best show you how to photograph galaxies in a suburban environment by discussing actual galaxies that I imaged from my back yard.

I think you are likely to trip over many of the same problems as me: stray reflections caused by neighbors who shine lights where they have no business to, humid air which reflects back the ever-increasing amount of light people send up into the sky, the switch from orange street lights to while-light LEDs, and so on.

Even if you lived in a desert hundreds of miles from the nearest town, you would still have to figure out how to focus and collimate, how to capture and store images and all the other things astrophotographers do. These issues are common to all of us, and I will discuss them.

Before getting into galaxies, I was a solar system astronomer. I always knew I wanted to move on from the Solar System. I did not do this in a rational, thought-out way. I just started, and became hooked. My first results weren't great. They weren't even good. I used the wrong hardware, the wrong software and used them both in the wrong way. The day job did not help one tiny bit with spending long night hours in the observatory. Eventually, two years ago, I reached retirement age and was no longer constrained to be wide awake during the day.

I still wasn't so committed to galaxy photography. I thought I was going to make a mathematical model of colliding galaxies, and began a program of reading to figure out how to do this. But, like the lead character Buck in Jack London's *Call of the Wild*, I was drawn away from the comfort of my desk to the discomfort of my unheated observatory.

With the persistence that would allegedly get a determined monkey to type out great literature, I tried this and that. In among the Facebook "likes" I received some occasionally blunt feedback from people who knew what they were doing. It occasionally stung, but the critics were rarely wrong, and they were far more useful to me than people who will "like" anything you load onto Facebook.

Eventually, fifteen months ago, it all came together and I could reproducibly make halfway decent images of galaxies. This was the time to write up, while I still remember the learning curve. I now had to get a set of images ready for the submission date I agreed with Springer. This hitherto informal project became much more formal and focused. My haphazard learning style would no longer do. The result is that I am better now than I was fifteen months ago. I have done things I would never have believed possible.

The cases I have chosen are not the images that were straightforward to produce. I have a good collection of those. I had fun producing them, but I didn't really learn much about photography from them. No, the ones that initially flummoxed me are the ones I have written about, so that you can glean knowledge of ways out of difficulty.

Some external factors helped. The rise of CMOS astrophotography cameras is as big a leap forward as the rise of CCD cameras was from film astrophotography. I gradually traded my way up to a really good camera.

Another step forward was the rise of artificial intelligence (AI) for image processing. AI may yet break our civilization. I'm not blind to that risk. But it has moved image processing software on a lot. In our highly automated smartphone cameras, we are not aware of the AI. But astrophotography is much less automated. Astrophotographers still have to do a lot of the image processing manually. The day may come when it's as automatic as photographing your kids or cats in cute poses. It may arrive quicker than we realize. But it's not here yet.

The telescopes and mounts have got better. We are seeing better optical and mechanical quality than ten or fifteen years ago.

I think in a way the Covid pandemic helped too. Astronomy was a great lockdown activity. Some great software was written by hobbyists. Online communities grew a lot stronger. The various social media may also destroy our civilization one day, but they have their uses.

We therefore now live in a golden era for amateur astronomy. I have expensive hardware and software now. There is cheaper kit and free software around that will work. Stuff for a quarter the price of my equipment is better than a quarter as good. You pay more and more for marginal improvements.

Another development which is rapidly advancing is the use of remote observatories. I dedicate my final chapter to my adventures with a remote observatory company to enable me to explore the galaxies in the Southern Hemisphere I can't see, using telescopes of which I can only dream. Did you ever think you would process images taken with a 24-inch telescope? Observatory ownership may not be the way forward for everyone. There are ways to have the fun without incurring crippling costs.

I have focused on the best software for astro image processing, PixInsight. It isn't free. You pay a one-off fee, which entitles you to updates. You can go quite a long way with Siril for free if you really can't afford PixInsight, but I have no regrets about investing the money or the time to master PixInsight. It is still developing rapidly. It may have changed by the time you read this.

In Chap. 1 I show how the ideas we now have about galaxies emerged as we began to realize that we live in one. Then I jump in with both feet to discuss how we use telescopes, and how we begin to process images. Once we have that background information, I move on to my case studies. The bulk of the book consists of those case studies.

Chapters 4 and 5 are much more pedagogical than the chapters that follow them. By the time you get to Chap. 6, I figured that there would be much less value to repeating every step every time. There is also some repetition. I thought that this was a sin, but a lesser sin than interrupting the narrative while you find cross-referenced pages would be. I hope I'm right.

My aim is to give you some tools and techniques so that you can explore the night skies for yourself, and to save you from spending years floundering like I did. I welcome any feedback at jane.clark@finerandd.com.

In the interest of full disclosure, I should state that I have only commented on equipment I own. In the case of Telescope Live, I pay a full subscription. No-one has sponsored me, and none of the suppliers knew I was writing the book until two weeks ago when I double-checked with Telescope Live that they were OK with me publishing the images. Therefore, I have no financial interest in plugging any equipment or service.

Risca, Wales, UK Jane Clark
May 2024

Acknowledgments

My first thanks go to my astronomer friends from whom I learned a lot about astrophotography. I often picked up ideas from people I barely knew, but I would particularly mention Lee Pullen, Chris Lee, Ryan Parle, Dave Bennett, Andy Smith, Bob Stuart and Rob Davies, and the late Mike West, all of whom have asked questions or made comments that made me think. Many other astronomers have encouraged me such as Alison Camacho, Mel Rigby, Fiona Lambert, Stephen Price, Richard Mansfield, Pete Quin, Andrew Grasemann, Edward and Theresa Cooper, Greg Titley, Aaron Cuthbertson, Tiffany Kew, Phill Wallace, Mike Bradley, Ray Dent, Tony Cook, Sue Walker, Bob Bowen, and Carolyn Alexander. If I have offended someone by omission, I apologize.

I would also like to thank my daughter and son-in-law for their encouragement, and my dear friend Pauline Thomas for encouragement and support of my strange hobby.

I gratefully acknowledge Alar and Juri Toomre, Min Yun, Kathryn Kreckel, Wendy Freedman, and the late Greg Titley for permission to use their images.

Finally, I would like to thank my editors: Michael Maimone for encouraging this project when it was little more than a mad idea, Hisako Niko, and Nivetha Moorthi on the production side.

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About the Author

Jane Clark is a British amateur astronomer who earned her living as an engineering physicist before retiring in 2022. She has a PhD in Physics and an MBA from Warwick University. She completed 2 years of postdoctoral training at Case Western Reserve University in Ohio before returning to England to begin an industrial career. She became interested in both astronomy and photography as a teenager in the 1970s, photography much more seriously, although as her career progressed and family commitments increased, both interests lapsed. She acquired a telescope in 2006, shortly after completing her MBA, and quickly became hooked on observing. This experience made her realize that astronomy is a lot more fun than business administration. In 2017 she achieved her ambition of having an observatory in her back yard. She is a member of Bristol, Cardiff and Newtown Astronomical Societies, and was a founder member of West Norfolk Astronomy Society. Jane gives talks to astronomy clubs, and other societies as diverse as the cub scouts, the University of the Third Age, and church wives' groups.

Chapter 1
How We Became Aware of Galaxies

Telescopes became good enough to detect what we know to be galaxies around the time of Messier, though of course some people claim to be able to see the nucleus of the Andromeda galaxy without a telescope. Charles Messier first published his catalogue of nebulae in 1774, with 45 objects; and eventually built it up to 102 objects. More have since been added: there are now 110.

He lived a long life, during which he discovered 13 comets, a good haul for anyone. He worked as an astronomer for the French Navy; and was honored in his lifetime by several foreign scientific societies.

Messier's motive was that his catalogue was his list of "I'm not going to be fooled by that one again" objects. There does not appear to have been much knowledge of what they were. Of the 110, we now know 40 to be galaxies.

So how did we get there?

Hubble's discovery that the Andromeda Nebula M31 is outside our galaxy is the stuff of legend. It took me a while to realize that in order to know that, he had to have a concept that our own galaxy exists, and of what our galaxy is. This took a while.

The first piece of progress was to realize that the Sun is a star. It is alleged that certain Greek scholars had this idea, though their cosmology was radically different from the ideas of modern science according to J.L.E. Dreyer, an astronomer and historian whom we will meet again [1]. I therefore treat these claims with some skepticism. Aristarchus of Samos was said by later writers to have "placed the Sun among the Stars" [1], a rather vague statement which could mean anything.

A more plausible claim goes to a philosopher & monk named Giordano Bruno (1548–1600) whose ideas about many things were unorthodox. He believed that the stars were other suns, and thought it likely that intelligent life could exist on some of them. This was unlikely to be popular with a Catholic Church which was losing ground to the Reformation and therefore feeling threatened and retreating into extreme conservatism. Bruno was executed in a particularly barbaric way, more probably for his exotic theological views than for his radical cosmology.

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Christiaan Huygens, a contemporary of Isaac Newton, made the assumption that the star Sirius would have the same brightness as the Sun. On the basis of its brightness, he estimated its distance. Looked at the Sun through ever-smaller pinholes until he thought that the Sun was as bright as he remembered Sirus to be [2]. Scottish astronomer James Gregory tried the same idea, but comparing Sirius to a planet during the night [3]. Hughens estimated 30,000 AU to Sirius; Gregory estimated 83,000 AU. Neither realized that Sirius is much brighter than the Sun, and that it is in fact over half a million AU away. But it was a start. Buth the idea existed that stars were well outside the Solar System; and that the Sun was a star.

In 1750, English astronomer Thomas Wright published *An original theory or new hypothesis of the Universe* [4]. In this book he asserts that the Milky Way is planar. He also suggests that some nebulae may be similar star systems, which we may perhaps never have telescopes good enough to see.

This idea inspired the philosopher Immanuel Kant, who had studied Newton's Principia and was numerate enough to follow it. He was a good enough scientist to deduce the idea that the Moon's orbit could slow the Earth's rotation. In his book "The Universal Natural History and Theory of Heaven" in 1755. He writes (and I have used Google Translate here) [5]

> Because it is more natural and understandable that they are not individual stars that are so large, but systems of many, the distance of which is represented in such a narrow space that the light, which is imperceptible from each of them individually, forms into one given their immeasurable number pale glow. The analogy with the star system in which we find ourselves, its shape, which is exactly as it should be according to our teaching concept, the weakness of the light, which requires an assumed infinite distance: everything agrees perfectly, these elliptical figures such world orders and, so to speak, Milky Ways, the constitution of which we have just developed; and if conjectures in which analogy and observation completely agree to support one another have the same worth as formal proofs, then the certainty of these systems will have to be taken for granted.

For a long time afterwards, investigators were unable to move beyond the idea of stars of equal brightness. There's no hiding from the fact that the idea of so-called "island universes" was around in the 1750s.

The observational evidence backing this up was at this point rather thin. People had an idea that the Milky way encircles the Earth, and that there are more stars along this circle than elsewhere in the sky. And the existence of nebulas was known. I wonder if people focus on these ideas of the 1750s using the lens of hindsight. Crazy theories were no doubt as common then as now. We have just forgotten about those of old.

So now we will follow the slow accumulation of data capable of supporting, or not supporting, the "island universes" idea.

The next great advances were made by William Herschel, who did so much more than discover the planet Uranus. I was told during a recent visit to the Herschel Museum in Bath, England that he was an obsessive telescope mirror grinder, so much so that his sister spoon-fed him while he worked. He made the best telescopes of his day, and put them to good use. This sister, Caroline, was in fact his co-worker for much of his observation, and is credited with the discovery of eight comets, a very respectable total.

One of the things Herschel did was to study binary stars in great detail, on which subject he published papers over several years [6, 7, 8]. He was therefore well aware that pairs of stars varied in brightness.

Yet he did not break away from the assumption that all stars are equally bright. He assumed that first magnitude stars were at a certain distance, second magnitude stars were at double that distance, and so on, doubling the distance for every drop in magnitude [9]. Considering that he was writing 53 years before the first successful parallax measurement of the distance to a star [10], it is hard to criticize him for making this assumption.

People often make assumptions they know not to be the whole truth in order to make scientific progress. For example, Isaac Newton knew full well that his law of gravity implied that the stars get pulled together, but he suspended enough disbelief to work out the details of the Solar System. He had no way to investigate the mutual gravitational attraction of stars, even though he knew that there was an issue there.

As is well-known, Herschel started life as musician and composer. His music is by no means unpleasant. There's a YouTube playlist at https://youtube.com/playlist?list=OLAK5uy_kM2hNgNOJ3JPOm3rrbQ_gLn3_Ufuj79IU&si=zn0D2gIHoFmVgsm2. I was also impressed to note when reading one of his papers that he must have read Newton's Principia. He was a very bright guy.

After considering various scenarios, dominated by the mutual gravitational attraction of stars, Hershel goes on to state that from his observations of the distribution across the sky, and brightnesses (his proxy for distance),

> I shall now proceed to shew that the stupendous sideral system we inhabit, this extensive stratum, and its secondary branch, consisting of many millions of stars, is, in all probability a *detached nebula* [9].

The italics are Herschel's. This is the first claim, backed up with evidence, that we live in a region of space that is unusually highly populated with stars, outside which there aren't so many stars. Nowadays we would call that isolated region of stars a galaxy.

He goes on to describe the number of stars he saw [9]:

> In order to go upon grounds that seem to me to be capable of great certainty, they being no less than an actual survey of the bounds of our sidereal system, which I have plainly perceived, as far as I have yet gone round it, every where terminated, and in most places very narrowly too, it will be proper to shew the strength of my sounding line, if I may so call it, that it may appear whether it was sufficiently long for the purpose.
>
> In the most crowded part of the milky way I have had fields of view that contained no less than 588 stars, and these were continued for many minutes, so that in a quarter of an hour's time there passed no less than 116000 stars through the field of view of my telescope.

He is clearly not tracking the apparent motion of the sky, but, rather, letting stars pass through the view of a static telescope. Because he had the best telescopes of his day, funded by his patron King George III,[1] his audience would not have been famil-

[1] King George III of Great Britain, who was also the monarch of Hershel's native land Hannover, gets a bad press, particularly in the USA. The fact that he funded the top astronomer in his domains

iar with the sheer numbers of stars he could see. It was a very different world, in which nobody got to see the results of the great spaceborne observatories almost as soon as they were released. There wasn't even photography. Herschel's son John would go on to devise the process of 'fixing' a photographic image with sodium thiosulphate, a process which lasted until the rise of digital photography in the late twentieth century. We will hear more of him in due course.

As a result of all this, and of dividing the sky into regions to search, his map of the star-containing region is shown in Fig. 1.1. There is one bold black dot in the center. This is his position of the Sun. So his universe is heliocentric.

A final point about Herschel is that he found and catalogued far more nebulae than Messier. It is curious that history has forgotten this, and remembered Messier as the great cataloguer.

In 1833 his son John Herschel published a massive 156-page paper entitled *Observations of Nebulae and Clusters of Stars, Made at Slough, with a Twenty-Feet Reflector, between the Years 1825 and 1833* [11]. The twenty feet refers to the focal length, not the aperture. The drawings in this document are a wonder to behold.

Just as comparison, Fig. 1.2 shows his drawings of globular clusters M13 & M5. The high quality of his draftsmanship and observational ability are unmistakable.

Of M64, Fig. 1.3, top right, he remarks that his father, William Herschel, noticed the feature we now call the 'black eye".

M51 is the only one we would not nowadays immediately recognize. He was also puzzled by this one, and wrote:

> M51 – This very singular object is thus described by Messier: *Cloudy without stars…One cannot see it but with difficulty with an ordinary 3½-foot telescope…It is double, each part having a bright center, the one separated from the other by 4' 35". The two atmospheres touch each other.*[2] By this description it is evident that the peculiar phenomena of the nebulous ring which encircles the central nucleus had escaped his observation, as might have been expected from the inferior light of his telescopes. My Father describes it in his observations of MESSIER'S nebulae (which are not included in his catalogues,) as a bright round nebula, surrounded by a halo or glory at a distance from it, and accompanied with a

Fig. 1.1 Herschel's map of the Milky Way. The bold black dot in the middle is the position of the Sun. (Image from Reference [9], copyright expired)

shows that he can't have been all bad.

[2] I have translated the words in the italics from the French in which Herschel quotes Messier.

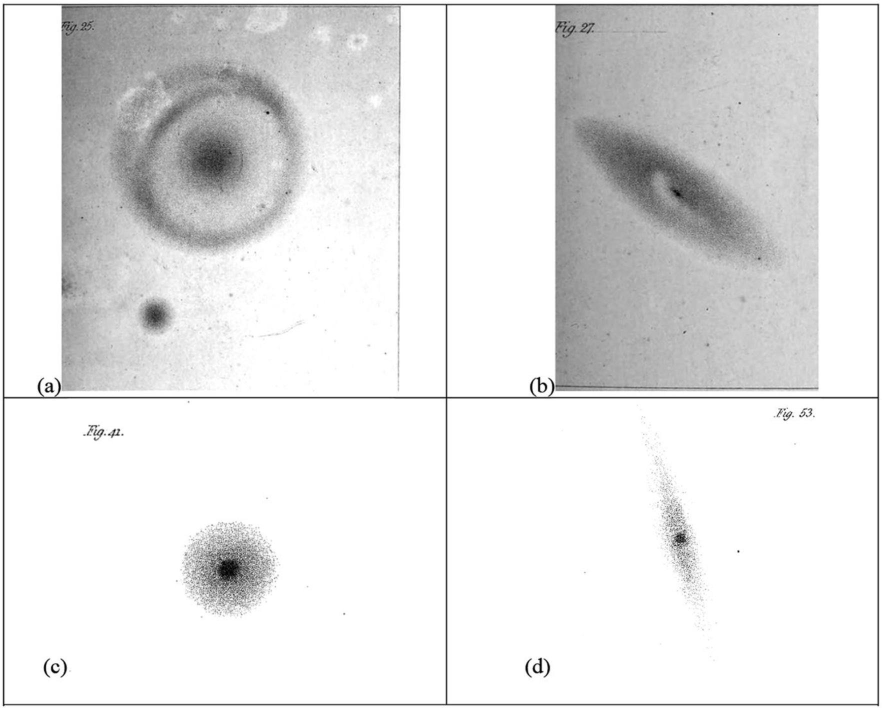

Fig. 1.2 John Herschel's drawings of galaxies. (a) M51, (b) M64, (c) M94 & (d) M65. (Images from Reference [11], copyright expired)

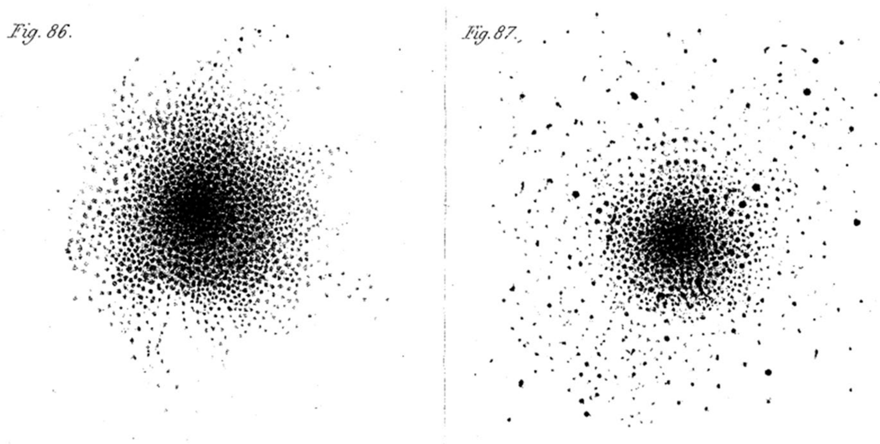

Fig. 1.3 John Herschel's drawings of globular clusters. Left: M13. Right: M5. (Images from Reference [11], copyright expired)

> companion; but I do not find that the partial subdivision of the ring into two branches throughout its south following limb was noticed by him. This is, however, one of its most remarkable and interesting features. Supposing it to consist of stars, the appearance it would present to a spectator placed on a planet attendant on one of them ex-centrically situated towards the north preceding quarter of the central mass, would be exactly similar to that of our Milky Way, traversing in a manner precisely analogous the firmament of large stars, into which the central cluster would be seen projected, and (owing to its greater distance) appearing, like it, to consist of stars much smaller than those in other parts of the heavens. Can it be, then, that we have here a brother-system bearing a real physical resemblance to our own?

So we have the remarkable insight for the year 1833 that we could very plausibly call a hint of the idea of a galaxy separate from the Milky Way. Given his difficulty seeing the object, this is an especially clever idea.

Progress was slow on the question of galaxies for the next century or so.

Interstellar Distance Measurement

During the nineteenth century, progress was slowly made on developing ways to measure distances to stars.

Geheiman-Rath & Bessel measured the parallax to the star 61 Cygni, publishing their result in late 1838: they found this star to be 10.28 light years or 657,700 AU away. The modern value reported by the planetarium software *Cartes du Ciel* is 11.4 light years, the value found by the Hipparcos space probe. This was the first reasonably accurate value of a stellar distance to be published. The principle of parallax is shown in Fig. 1.4.

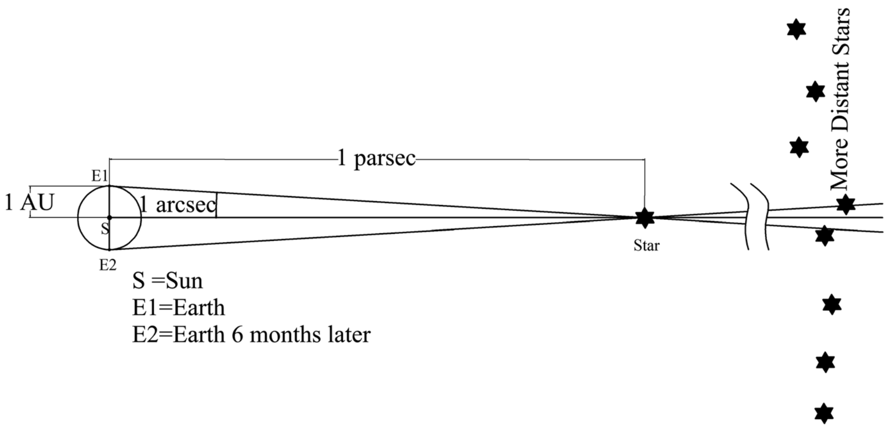

Fig. 1.4 The principle of parallax. The position of a star against the much more distant background is noted at times six months apart. If the angle is 1 arcsecond, the distance is defined as 1 parsec or 1 pc. If the angle were 0.1 arcseconds, the distance would be 10 pc. 1 pc = 3.26 light years. (Image by the Author)

At about the same time, John Herschel spent time from 1834–8 in what is now South Africa mapping the skies of the Southern Hemisphere.

Nineteenth century technology did not allow the parallax measurement of many stellar distances. The progress made with these difficult measures is shown in Table 1.1.

In order to map out a galaxy, it is necessary to measure the distances to many, many stars: we now know that there are of the order of 100 billion stars in the Milky Way.

Therefore a method other than parallax was required to determine stellar distances: there just weren't enough parallax measurements to do the job.

Henrietta Swan Leavitt of Harvard University, was given the job of analyzing large numbers of variable stars in photographs of the Magellanic Clouds. Each cloud could be taken to be at a fixed distance from the Earth. In the Small Magellanic Cloud, she identified 25 Cepheid variables [13], a type of star that pulsates regularly, and noticed a simple relationship between the time it took them to go through once cycle of pulsation and their brightness (Fig. 1.5). This at last gave a "standard candle": a way to measure distances by comparing the periods and brightnesses of any Cepheid variables that can be observed. Thus, there was a distance measurement that did not depend on parallaxes. For this, Miss Leavitt was nominated for a Nobel Prize. Unfortunately, she had died prematurely of cancer, and so was ineligible to win the prize.

A decade later, Harlow Shapley reported the distance of the Large Magellanic Cloud as 34.5 kpc, and that of the Small Magellanic Cloud as 31.6 kpc [14].

At about the same time as Leavitt's law was published, a way was found to relate the brightness of stars to their spectra, in particular to their temperatures deduced from their spectra. A history of the origins of this diagram, with references, is given by Nielsen in 1964 [15]: it is now known after its two independent discoverers as a Hertzsprung-Russell diagram, or HR diagram. These two astronomers were working independently on different continents, but were in correspondence with one another, and seem to have enjoyed friendly relations.

Hertzsprung plotted the diagram for the well-known open clusters the Pleiades (M45) and the Hyades (C41) and Russell plotted bright nearby stars for which the parallaxes were known in 1911.

They both discovered what we now call the main sequence, which contains the vast majority of stars, and the giant branch, which is nowadays subdivided. The branch for white dwarfs was discovered later.

Table 1.1 Progress in measuring stellar parallaxes 1840–1912

Year	Number of reliable stellar parallaxes measured
1840	3
1880	20
1912	163

Source: Reference [12]

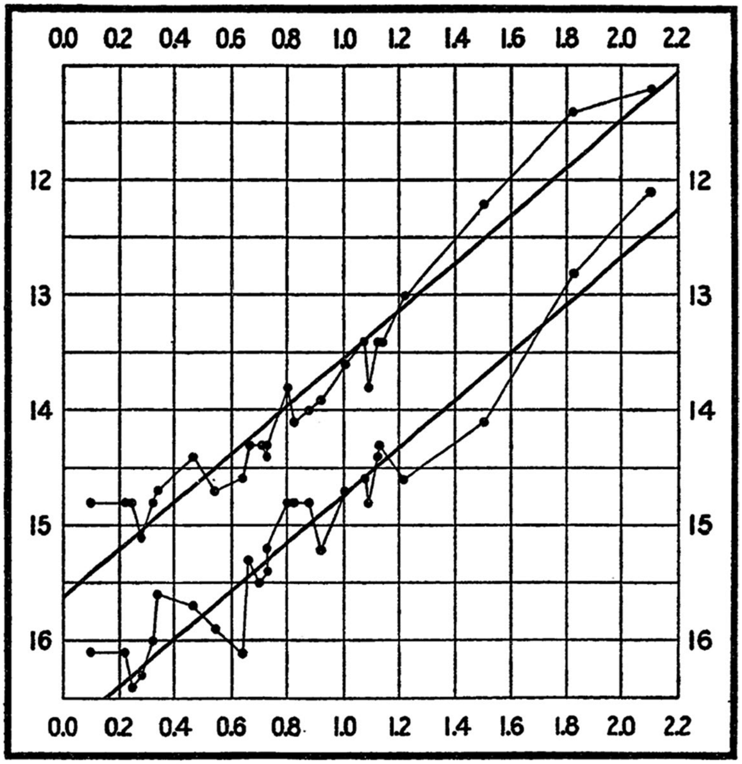

Fig. 1.5 Leavitt's Law for Cepheid variable stars in the Small Magellanic Cloud. The vertical axis is brightness expressed as magnitude, and the horizontal axis is the logarithm of the pulsation period. The upper line is the maximum brightness; the lower line is the minimum brightness. (Image: E. C. Pickering & H. C. Leavitt. ©American Astronomical Society. Source: Reference [13])

There are two key points for our story. First, stars cannot occupy just any position on the HR diagram. Figure 1.6 shows this. This has important implications for the theory of stellar evolution, which is outside the scope of this book. Second, a new way to estimate distances to stars now appeared: from the spectrum, or a proxy measure such as the difference between blue and visible magnitudes,[3] the absolute magnitude can be estimated, and the distance obtained. This distance determination method is called spectral parallax. It has a much longer range than geometric parallax, and can even be used to estimate the distances to stars in other galaxies, via a method called the tip-of-the-red-giant-branch method.

[3] These are measured using the so-called Bessell filters, B for Blue and V for Visible, which peaks in the green. Such filters are sold by Baader Planetarium, see e.g. https://www.baader-planetarium.com/en/baader-ubvri-bessel-filter-set-%E2%80%93-photometric.html. This website shows the transmission curves for these filters.

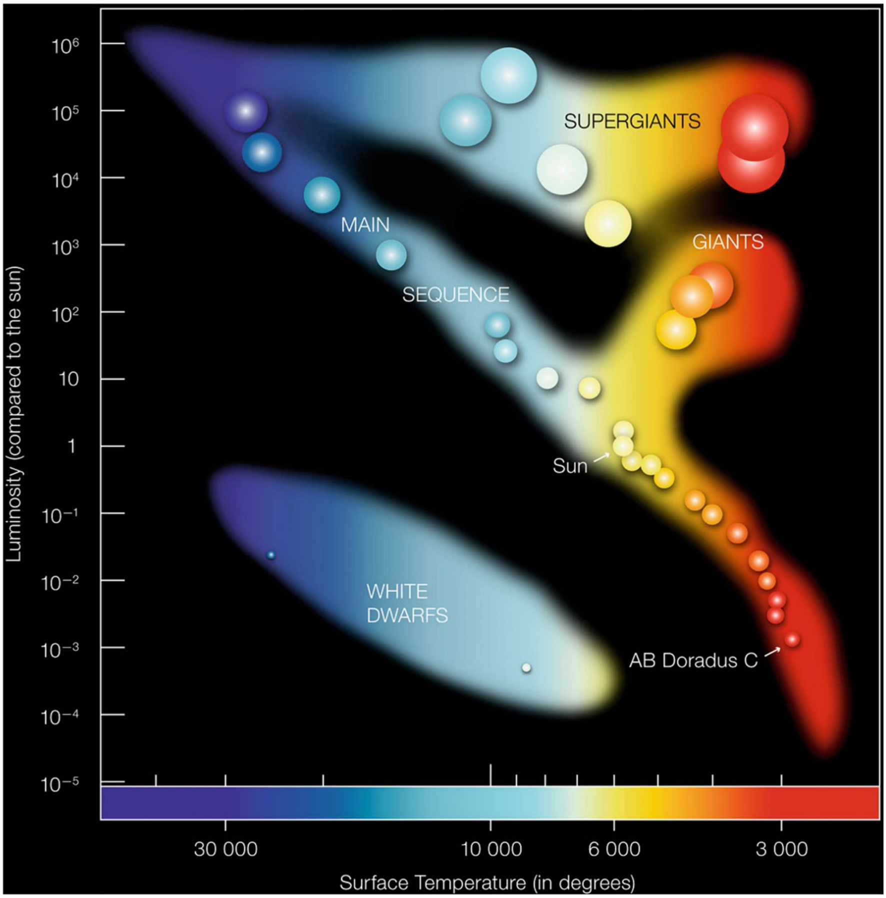

Fig. 1.6 An example of a Hertzsprung-Russell diagram plotted for 23,000 stars. The vertical axis, the luminosity, is given as a multiple of the luminosity of the Sun. The Horizontal axis is given as temperature in Kelvin. (Image Credit: ESO, source https://www.eso.org/public/images/eso0728c)

So now we have moved from the rather vague ad-hoc estimates of distance by Seeliger and Kapteyn to a much more precise method. The HR diagram acquired an underlying scientific basis once the theory of stellar evolution was developed.

Another method of distance method was developed that works only for clusters of stars if they move though space together as a unit & don't rotate. This method is useful because, first, it gave astronomers a way to cross-check their geometric parallax distance measurements. Since the geometric parallaxes are tiny and notoriously easy to get wrong because of atmospheric effects, this was useful. The second useful thing was that it gave a way to obtain absolute magnitudes for the HR diagrams for clusters of stars. This was especially important for the Hyades, which was the first open cluster to be close enough for geometric parallax methods, for the unsurprising reason that it is the nearest.

The method was first devised to work out the direction and speed of travel of the Sun through the field of nearby stars, which is towards the constellation of Hercules. The idea first came from a geometer named Bravais[16], who is best known for his work on the geometry of crystal lattices. He was ahead of his time in both fields. The first person to be able to measure the sun's travel was Kapteyn [17], whom we have already mentioned.

The method of Bravais & Kapteyn seems to have been first used by Lewis Boss in 1908 [18]. The principle of the method is shown in Figs. 1.7 and 1.8.

In the same way that parallel, straight railroad lines on flat plane appear to converge to a point, so do the proper motions of the stars in a co-moving cluster in a three-dimensional space also appear to converge to a point. The cunning trick is that we also know these stars are moving either towards or away from us because the Doppler effect can be seen in their spectral lines.

The Doppler effect is illustrated in Fig. 1.9. Red light has a longer wavelength than blue light. Movement away from us makes light appear redder, while movement towards us makes light appear bluer. (The same thing happens if space is expanding, making the distance to the star increase. In that case, the effect is called the cosmological redshift.)

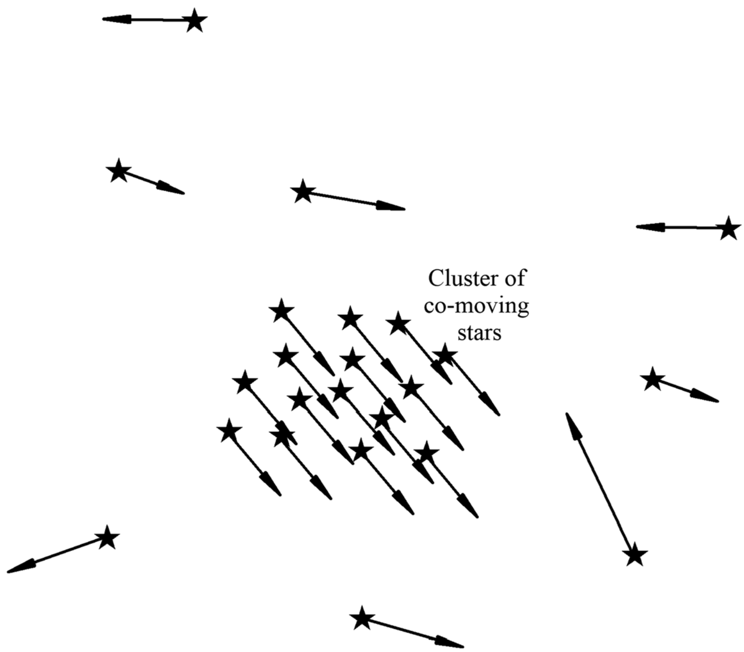

Fig. 1.7 In two dimensions, a cluster of co-moving stars would have parallel proper motions. (Figure by the Author)

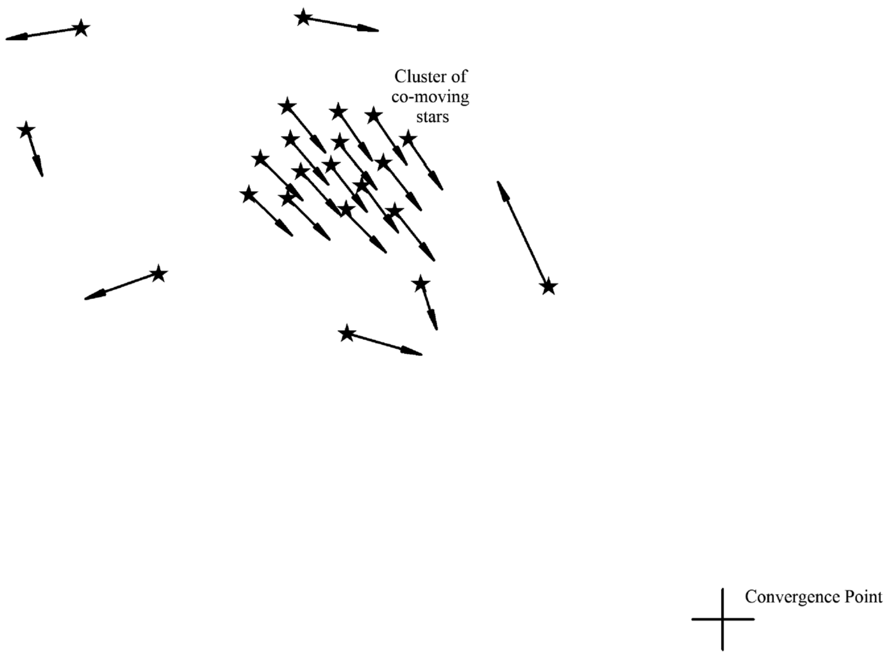

Fig. 1.8 In three dimensions, the apparent motions of a cluster of co-moving stars are not parallel. Instead they appear to converge to a point. (Figure by the Author)

By mathematical rearrangement, the distance to the cluster can be calculated from the above information. The distance thus obtained is known as the moving cluster parallax. There was a time when this method was thought to be of historic interest only, but unfortunately data from a space probe called the Hipparcos satellite showed a very different distance to the Pleiades from that obtained by other methods. This embarrassment gave a new lease of life to the moving cluster method, because it was one of the ways people showed that the reported distance was wrong [19].

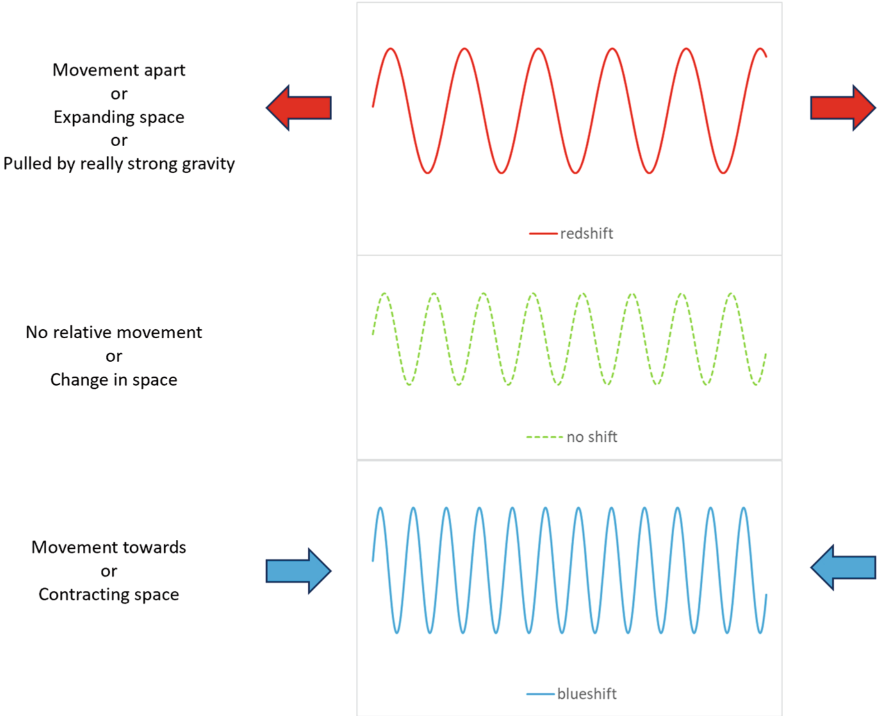

Fig. 1.9 In the doppler effect, the light from a star moving away appears to be redder if the star is moving away (top) and bluer if it is moving towards the observer (bottom). Red light has a longer wavelength than blue light. (Image by the Author)

Models of the Universe by 1922

J. C. Kapteyn, 1922

Kapteyn's modus operandi was to form strong relationships with observers who worked in climates with clearer skies than the Netherlands, and to analyze their data. He had a small team of people doing this in his university in Groningen. This was not only forced on him by the need for clear skies, but also by the fact that his university could not afford a top-class observatory.

He produced an approximate model in 1922 [20], the year he died, probably of cancer [21]. His model was not intended to be exact; but with the computational power then available, it was meant to be tractable. The contours of star density are shown in Fig. 1.10. For the first time, the Sun is shown offset from the center of the universe, by a distance of almost 2 kiloparsecs (kpc). Seeliger had earlier produced a not dissimilar model, with the Sun at the center [22].

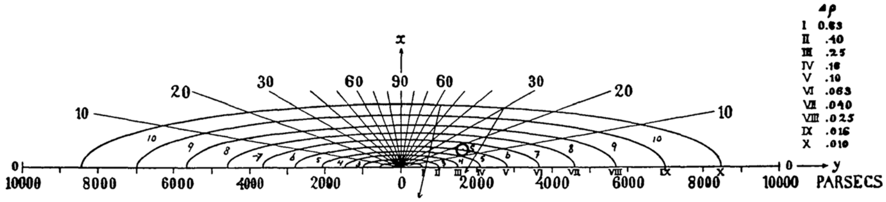

Fig. 1.10 Kapteyn's Universe. Source: Reference [20]. He shows the universe to be made of shells, each with an average star density listed in Table 1.2. For the first time, the Sun is not at the centre of the system. It is close to the centre, at the point shown to the right of centre where Shells 5 & 6 meet. (Image: J. C. Kapteyn, Reference [20] © American Astronomical Society)

Table 1.2 Average number of stars per cubic parsec in the shells shown in Fig. 1.10

Shell	Average density of stars per cubic parsec
1	0.0358
2	0.0226
3	0.0143
4	0.00900
5	0.00568
6	0.00358
7	0.00226
8	0.00143
9	0.000900
10	0.000568

Source: Reference [20], © American Astronomical Society

For Kapteyn, his demise came at a particularly unfortunate time, as he did not live to see the great leaps forward made in the later 1920s.

Eddington [23] and Seeliger [24] produced similar models of the universe, though Seeliger's was heliocentric.

H. Shapley

Shapley discovered a much bigger universe than did Kapteyn. His method was to use variable stars, mainly Cepheid variables, to measure the distances to globular clusters during the late 1910s. After an immense amount of work, he found that the globular clusters were much further away than the size of Kapteyn's universe; and that they appear in the sky at points around the constellation Sagittarius. They are not at all evenly distributed.

Globular clusters are distinct entities with a characteristic appearance (Fig. 1.11). They contain hundreds of thousands of stars. Cepheid variables and RR Lyrae variables are common.

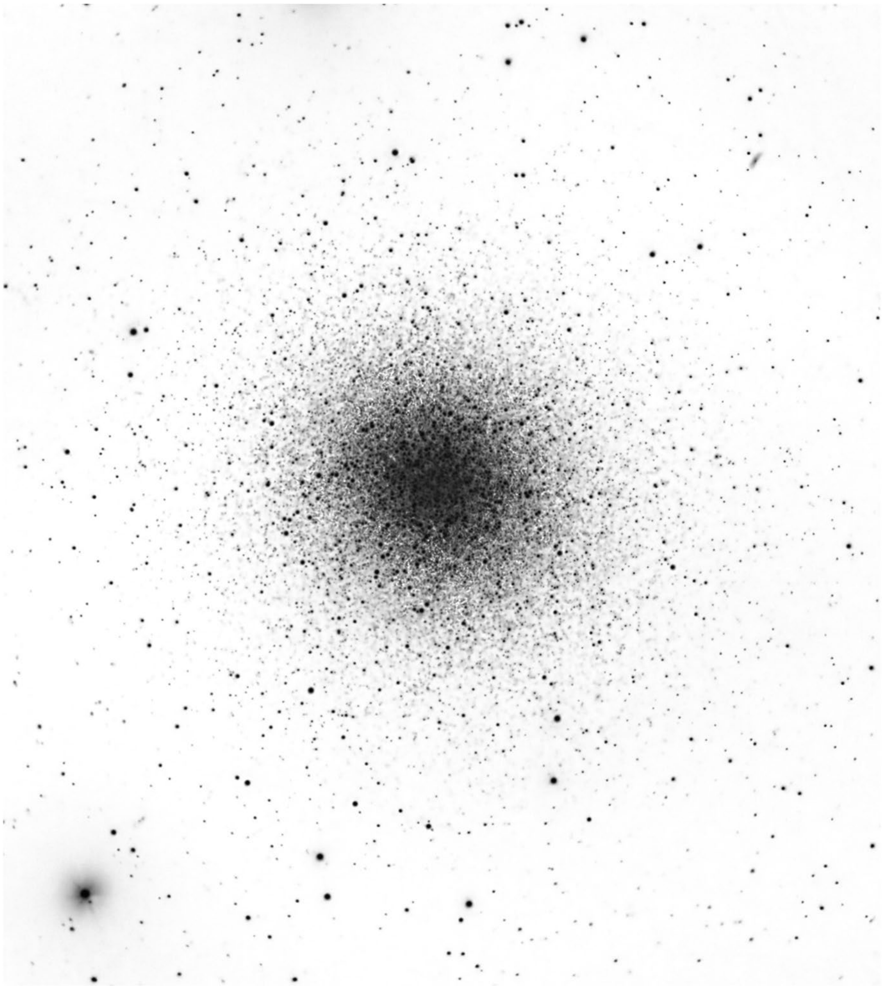

Fig. 1.11 A globular cluster, M13. Celestron C11 at f/6.3, 83×60s. (Image by the author)

By this time, astronomers were well aware that the Milky Way has a bulge in Sagittarius. It is not visible from the United Kingdom, but I got a clear enough view of it during a trip to Australia. You can't miss it.

Shapley proposed that the globular clusters orbit around this bulge, and put it at their center [25]. This required quite a leap of the imagination, especially since the distance to the central bulge was not then known. For this to be true, and for the Sun to be part of the Milky Way, Shapley proposed a galaxy rather like the one shown in Fig. 1.12. Shapley put the size of the Milky way at about 300,000 light years, or roughly 100 kpc.

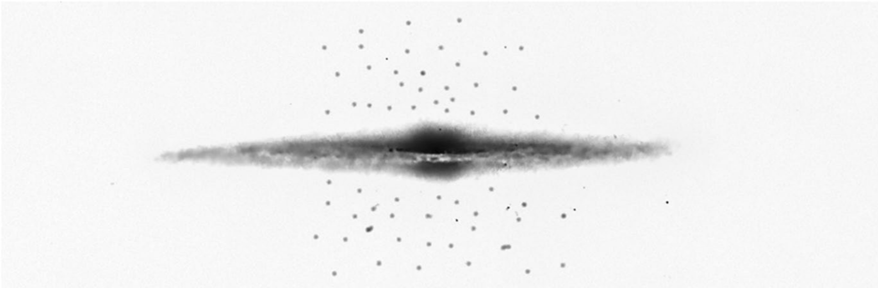

Fig. 1.12 Shapley's view of the universe, with globular clusters orbiting the center. (Image by the Author. (I cheated slightly, and used a photo of the needle Galaxy, NG4565, and drew in the globular clusters using the image processing software Gimp))

I have shown the galaxy edge-on on purpose. The details of the plane were not then known. Shapley believed that the stars were not evenly distributed, but he did not know enough to fill in the details; and wisely kept his counsel.

Hubble: The Andromeda Nebula M31 Is Outside the Milky Way

Not long afterwards, in about 1924, Edwin Hubble, by then a staffer at the Mount Wilson Observatory, with its newly commissioned 100-inch telescope, discovered a Cepheid variable, the celebrated V1, while looking for novae in M31. This showed that M31 was ten times as far away as the Small Magellanic Cloud, where Leavitt had discovered her law. He went on to confirm this result with over forty such variables, and published his results in a 1929 review paper [26]. In Fig. 1.13, I have plotted Hubble's 1929 data on Cepheid Variables, and compared them with Leavitt's data from Fig. 1.5.

This bombshell result was a game-changer. People could now think in terms, not so much of using our galaxy to understand the spiral nebulae, as to use the spiral nebulae to understand our galaxy.

Although people had proposed a spiral structure for the Milky Way, such as Cornelius Easton in 1900 [27], this structure was not confirmed until after World War II, when radio astronomers were able to detect the spiral structure [28].

Sometimes the Milky Way is referred to as 'the Galaxy' with a capital G, whereas lower-case galaxy is any galaxy.

The bar in the Milky Way was postulated as early as 1964, but unambiguously observed in 1991 [29]. The size of the Galactic bar was found in 2005 to be larger than thought [30].

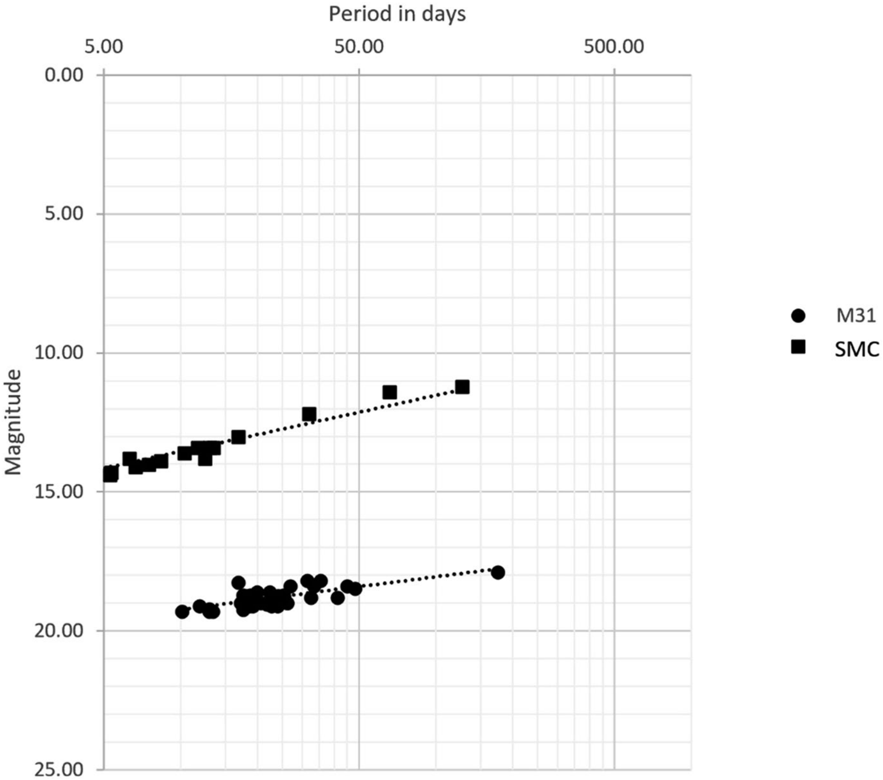

Fig. 1.13 Hubble's and Leavitt's data for Cepheid variables in the Small Magellanic Cloud (SMC) and M31, showing that the variables in M31 are roughly five magnitudes dimmer than those in the SMC, corresponding to a factor of 10 difference in distance. (Image by the Author, data from References [13, 26])

Hubble's Classification System & the Expanding Universe

In 1927 Hubble published his classification of galaxies [31], which was subsequently turned into the 'tuning fork' diagram (Fig. 1.14). You will still see people talk about galaxies to the left of this diagram as "early type" galaxies, and those to the right as "late type" galaxies, even though no-one now seriously believes that such an evolutionary path exists. I suppose it's a bit like the way metallurgy is still full of alchemists' jargon: jargon seems to outlive its usefulness. Hubble examined something like 400 galaxies to derive this classification.

Hubble was one of a few people who noticed that the spectra of galaxies are redshifted. He worked out that the redshift is roughly proportional to distance, and thereby discovered the expansion of the universe, as shown in Fig. 1.15. His work was published in 1929 [33]. He had an incredibly busy and productive decade in the 1920s.

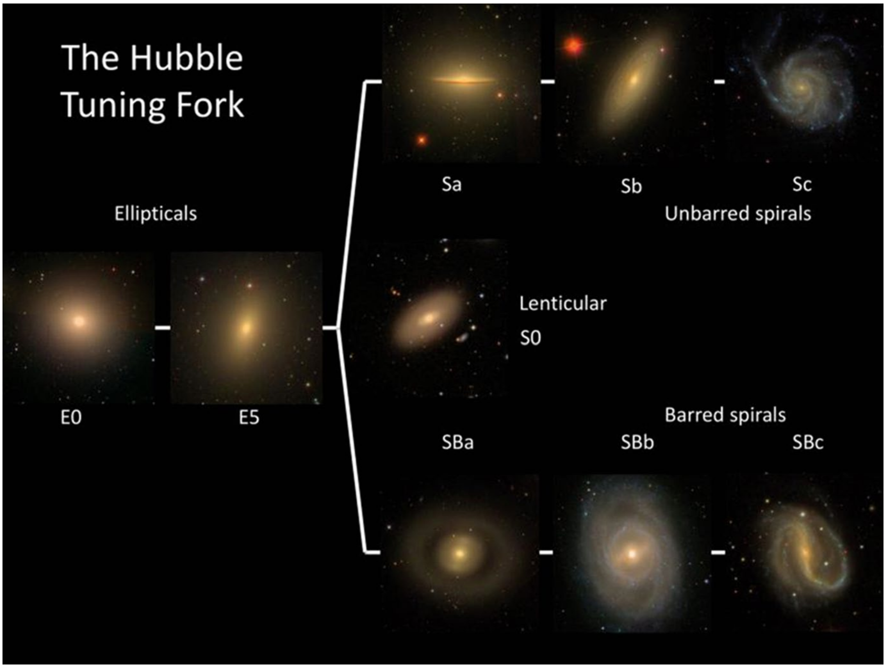

Fig. 1.14 A modern version of the 'tuning fork' diagram, which Hubble never actually used in his original paper, to illustrate his classification of the Galaxies [31]. (Source: Reference [32], made available under a CC by 4.0 license from https://ras.ac.uk/news-and-press/research-highlights/citizen-scientists-re-tune-hubbles-galaxy-classification)

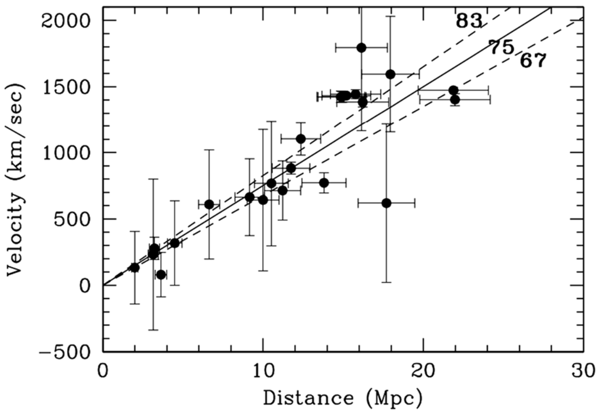

Fig. 1.15 A modern version of the redshift of the local universe as found by Hubble. (Source: Freedman et al. [34], used with permission. Numbers in the top right show different values of the Hubble constant for different curves fitted through the data, in units of km s^{-1} Mpc^{-1})