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Spiral Structure in Galaxies

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For my wife, Colleen,

and my boys, David and Andrew

Contents

Preface

A spiral galaxy is a type of galaxy originally described by Edwin Hubble in his 1936 work *The Realm of Nebulae* and, as such, forms part of the Hubble sequence. Spiral galaxies consist of a flat, rotating disk containing stars, gas and dust, and a central concentration of stars known as the bulge. These are surrounded by a much fainter halo of stars, many of which reside in globular clusters.

Spiral galaxies are named for the spiral structures that extend from the center into the galactic disk. The spiral arms are sites of ongoing star formation and are brighter than the surrounding disk because of the young, hot OB stars that inhabit them. Roughly two-thirds of all spirals are observed to have an additional component in the form of a bar-like structure, extending from the central bulge, at the ends of which the spiral arms begin. The proportion of barred spirals relative to their barless cousins has changed over the history of the Universe, with only about 10% containing bars about 8 billion years ago, to roughly a quarter 2.5 billion years ago, until the present, where over two-thirds of the galaxies in the visible Universe have bars.

This book focuses on why these disk-shaped (or spiral) galaxies have spiral arms. Why do these structures exist? Why are they so stable? And what is the connection between the spiral arms and the star formation that is seen within them? In this book you will find the answers to these questions and more.

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Author Biography

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Marc S Seigar is a Professor of Astrophysics and Associate Dean of the Swenson College of Science and Engineering at the University of Minnesota Duluth (UMD). He is also the current director of the Marshall W Alworth Planetarium at UMD. Prior to his arrival at UMD, he worked as a Professor of Astrophysics at the University of Arkansas at Little Rock, a Project Scientist at the University of California, Irvine, and a Staff Astronomer at the United Kingdom Infrared Telescope. Professor Seigar has published numerous papers and conference proceedings articles in the field of galaxy dynamics, spiral structure, and dark matter.

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Chapter 1

The discovery of spiral galaxies

William Parsons, 3rd Earl of Rosse (a photograph of whom can be seen in figure 1.1) was an Anglo-Irish astronomer who had several telescopes built. His 72 inch telescope, built in 1845 (also shown in figure 1.1) and colloquially known as the 'Leviathan of Parsonstown', was the world's largest telescope, in terms of aperture size, until the early 20th century.

During the 1840s, Rosse had the Leviathan of Parsonstown built, a 72 inch (6 feet/1.83 m) telescope at Birr Castle, Parsonstown, County Offaly, Ireland. The 72 inch (1.8 m) telescope replaced a 36 inch (910 mm) telescope that he had built previously. He had to invent many of the techniques he used for constructing the Leviathan, both because its size was without precedent and because earlier telescope builders had guarded their secrets or had simply failed to publish their methods. Details of the metal, casting, grinding and polishing of the 3 ton 'speculum' were presented in 1844 at the Belfast Natural History Society. Rosse's telescope was considered a marvelous technical and architectural achievement, and images of it were circulated widely within the British Commonwealth. Building of the Leviathan began in 1842 and it was first used in 1845; regular use waited another two years, due to the Great Irish Famine. Using this telescope, Rosse saw and cataloged a large number of nebulae (including a number that would later be recognized as galaxies).

Lord Rosse performed astronomical studies and discovered the spiral nature of some nebulae, today known to be spiral galaxies. Rosse's telescope Leviathan was the first to reveal the spiral structure of M51, a Galaxy nicknamed later as the 'Whirlpool Galaxy', and his drawings of it (see figure 1.2) closely resemble modern photographs.

At the time of Rosse's observations of M51 (in 1845), it was referred to as a spiral nebula. It was the first of many spiral nebulae that he observed with his Leviathan. In 1845, there was no method for determining the distances to spiral nebulae, and so it was believed that they were part of the Milky Way Galaxy. It would take an

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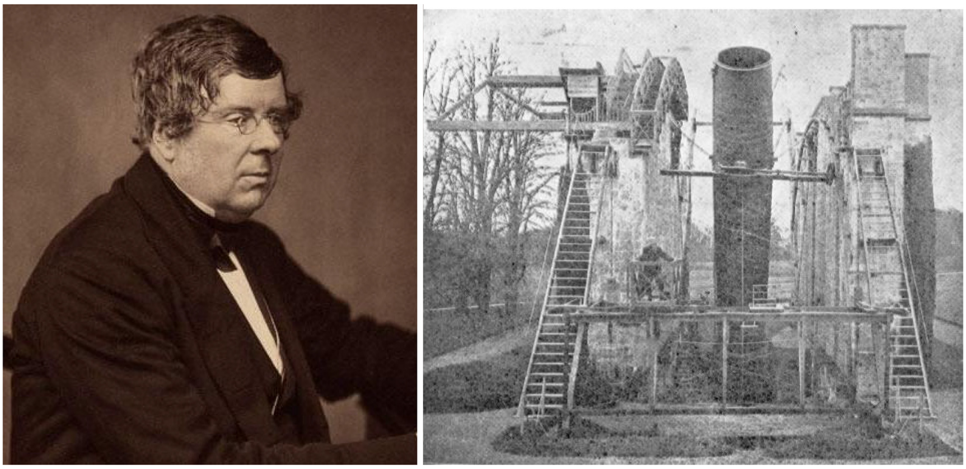

Figure 1.1. Left panel: William Parsons, 3rd Earl of Rosse, image courtesy Wikipedia. Right panel: The 72 inch refracting telescope at Birr Castle, the largest telescope of its time, colloquially known as the Leviathan of Parsonstown'.

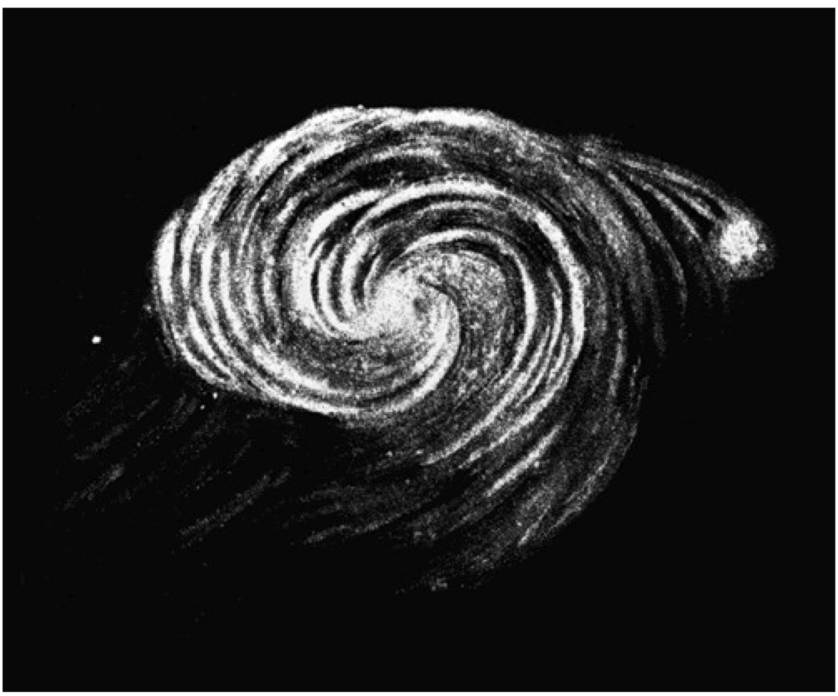

Figure 1.2. Lord Rosse's drawing of M51, the 'Whirlpool Galaxy', as observed through the Leviathan of Parsonstown.

analysis of a certain type of star, known as Cepheid Variables, to provide the first technique to measure the distances to these nebulae.

On 10 September, 1784, Edward Pigott detected the variability of Eta Aquilae, the first known representative of the class of classical Cepheid variables. However, the archetypal star for classical Cepheids is Delta Cephei, discovered to be variable by John Goodricke a few months later. Little was it known at the time that Cepheid variables would hold a key to dramatically changing our view of the Universe in the early part of the 20th century. Fundamental to this would be a discovery by one of the unsung heroes of 20th century astronomy.

Henrietta Swan Leavitt (pictured in figure 1.3) was an American astronomer. A graduate of Radcliffe College, Leavitt started working at the Harvard College Observatory as a 'computer' in 1893, examining photographic plates in order to measure and catalog the brightness of the stars. The term 'computer', in use from the early 17th century meant 'one who computes': a person performing mathematical calculations, before electronic computers became commercially available. Teams of people were frequently used to undertake long and often tedious calculations; the work was divided so that this could be done in parallel. Harvard College Observatory employed a team of women to perform these calculations, and Henrietta Swan Leavitt was one of them. She was hired at the observatory by Edward Charles Pickering and was assigned the task of cataloging stars (in the early 1900s, women were not allowed to operate telescopes). Paid at a rate of just 30 cents per hour, she was reportedly hardworking, serious-minded, and devoted to her family, her church, and her career.

Pickering assigned Leavitt to study 'variable stars', whose luminosity varies over time. According to science writer Jeremy Bernstein, 'variable stars had been of interest for years, but when she was studying those plates, I doubt Pickering

Figure 1.3. Henrietta Swan Leavitt, unknown source.

thought she would make a significant discovery—one that would eventually change astronomy'. Leavitt noted thousands of variable stars in images of the Magellanic Clouds. In 1908, she published her results in the Annals of the Astronomical Observatory of Harvard College, noting that a few of the variables showed a pattern: brighter ones appeared to have longer periods. After further study, she confirmed in 1912 that the Cepheid variables[1] with greater intrinsic luminosity did have longer periods, and that the relationship was quite close and predictable.

Leavitt used the simplifying assumption that all of the Cepheids within each Magellanic Cloud were at approximately the same distances from Earth, so that their intrinsic brightness could be deduced from their apparent brightness (as measured from the photographic plates) and from the distance to each of the clouds. She noted that 'since the variables are probably at nearly the same distance from the Earth, their periods are apparently associated with their actual emission of light, as determined by their mass, density, and surface brightness'.

Her discovery, which she produced from studying some 1777 variable stars recorded on Harvard's photographic plates, is known as the 'period–luminosity relationship' for Cepheid variables: the logarithm of the period is linearly related to the logarithm of the star's average intrinsic optical luminosity. The period–luminosity relationship for Cepheids made them the first 'standard candle' in astronomy, allowing scientists to compute the distances to objects that are too distant for stellar parallax observations. Leavitt was not recognized for her work until after her death.

Edwin Powell Hubble (pictured in figure 1.4) was an American astronomer. He played a crucial role in establishing the fields of extragalactic astronomy and observational cosmology and is regarded as one of the most important astronomers of all time. Hubble's arrival at Mount Wilson Observatory, California in 1919, coincided roughly with the completion of the 100 inch (2.5 m) Hooker Telescope, then the world's largest telescope. At that time, the prevailing view of the cosmos was that the Universe consisted entirely of the Milky Way Galaxy. Using the Hooker Telescope at Mount Wilson, Hubble identified Cepheid variables in several spiral nebulae, including the Andromeda nebula and the Triangulum nebula. His observations, made in 1922–23, proved conclusively that these nebulae were much too distant to be part of the Milky Way and were, in fact, entire galaxies outside our own, suspected by researchers at least as early as 1755 when Immanuel Kant's *General History of Nature and Theory of the Heavens* appeared. This idea had been opposed by many in the astronomy establishment of the time, in particular by the Harvard University-based Harlow Shapley. Despite the opposition, Hubble, then a 35-year-old scientist, had his findings first published in *The New York Times* on 23 November, 1924, and then more formally presented in the form of a paper at the 1 January, 1925 meeting of the American Astronomical Society.

[1] https://en.wikipedia.org/wiki/Cepheid_variable

Figure 1.4. Edwin Hubble observing at the 100 inch telescope at Mount Wilson Observatory, California. Photograph by Margaret Bourke-White, 1937.

Hubble's findings fundamentally changed the scientific view of the Universe. Supporters state that Hubble's discovery of nebulae, outside of our Galaxy, helped pave the way for future astronomers. Although some of his more renowned colleagues simply scoffed at his results, Hubble ended up publishing his findings on nebulae. The so-called nebulae, are, of course, now referred to as galaxies. Hubble's published work earned him an award titled the American Association Prize and five hundred dollars from Burton E Livingston of the Committee on Awards. At the time, the Nobel Prize in Physics did not recognize work done in astronomy, otherwise Hubble would have surely won it. Hubble spent much of the later part of his career attempting to have astronomy considered an area of physics, instead of being its own science. He did this largely so that astronomers—including himself—could be recognized by the Nobel Prize Committee for their valuable contributions to astrophysics. This campaign was unsuccessful in Hubble's lifetime, but shortly after his death, the Nobel Prize Committee decided that astronomical work would be eligible for the physics prize.

This story brings us to the point where we now understand that spiral galaxies exist outside of our own Milky Way. But why are they disk shaped? Any why do they have spiral arms? Why are the arms sustainable for billions of years? These are the questions that will be addressed by this book, starting with how galaxies in the Universe are classified.

Suggested further reading

Hubble E 1926 Extragalactic nebulae *Astrophys. J.* **64** 321–69

Johnson G 2005 *Miss Leavitt's Stars : The Untold Story of the Woman Who Discovered How To Measure the Universe* 1st edn (New York: Norton)

Knight C (ed) 1867 *William Parsons, 3rd Earl of Rosse. Biography: Or Third Division of 'The English Cyclopedia'* vol 5 (London: Bradbury: Evans, & Co.) pp 166–7

Lamb G M 2005 Before computers there were these humans… *Christian Science Monitor* July 5, 2005

Leavitt, Henrietta Swan, Pickering and Edward C Harvard College Observatory Circular **173** 1–3

Lord Rosse's Telescope, The Practical Mechanic and Engineer's Magazine, Feb 1844, p 185

Parsons M 6th Earl of Rosse 1968 William Parsons, third Earl of Rosse *Hermathena* **107** 5–13

Telescopes: Lord Rosse's Reflectors http://amazingspace.org/resources/explorations//groundup/lesson/scopes/rosse/index.php

1912: Henrietta Leavitt Discovers the Distance Key *Everyday Cosmology* N.p., n.d. Web. 20 Oct.2014

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Chapter 2

The classification of galaxies

After Edwin Hubble discovered that galaxies outside of the Milky Way existed, he spent some time classifying galaxies based upon their shapes. He came up with a system known as the Hubble sequence or Hubble Tuning Fork Diagram (see figure 2.1). The Hubble sequence is simply a morphological classification scheme for galaxies. The sequence is broken down into two broad categories of galaxies, elliptical galaxies on the left and spiral galaxies on the right. Spirals are further broken down into normal spiral galaxies on the top and barred spirals on the bottom. Lenticular galaxies (or S0 galaxies) are located at the junction between ellipticals and spirals. About 20 percent of galaxies in the Universe do not fall into this scheme, and these are referred to as irregular galaxies.

2.1 Elliptical galaxies

Elliptical galaxies, some examples of which are shown in figure 2.2, are found on the left side of the Hubble sequence. They are classified from E0, which are perfectly circular, to E7, which are highly elongated. They are classified by the letter E followed by a number n. The value of n is an integer determined by the ratio of the semi-minor axis, b, and the semi-major axis, a, of the galaxy using the following equation:

$$n = 10 \times \left(1 - \frac{b}{a}\right) \tag{2.1}$$

Unlike spiral galaxies, elliptical galaxies are not supported by rotation. The orbits of the constituent stars are random and often very elongated, leading to a shape for the galaxy determined by the speed of the stars in each direction. Faster moving stars can travel further before they are turned back by gravity, resulting in the creation of the long axis[1] of the elliptical galaxy in the direction these stars are moving.

[1] http://astronomy.swin.edu.au/cosmos/A/Axis

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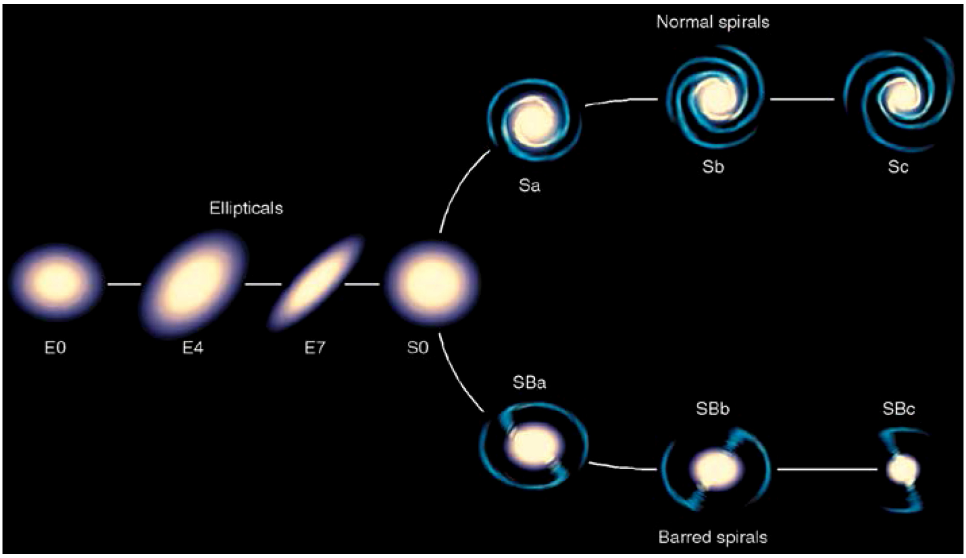

Figure 2.1. The Hubble Tuning Fork Diagram, which classifies galaxies into two categories, elliptical galaxies on the left and spiral galaxies on the right. Spiral galaxies are further subdivided into two categories, normal spirals on the top and barred spirals on the bottom. A third class of galaxy, S0s or lenticular galaxies is placed at the junction between ellipticals and spirals.

Figure 2.2. Left panel: NGC 5128 (or Centaurus A) is a type EO peculiar elliptical galaxy. Image courtesy of NOAO/AURA/NSF. Right panel: the giant elliptical galaxy ESO 325-G004. Image courtesy of NASA, ESA, and the Hubble Heritage Team.

Elliptical galaxies are the most common type of galaxy in the Universe. They also span the widest range in mass, from dwarf elliptical galaxies containing about 10^7 solar masses in stars to giant elliptical galaxies containing about 10^{13} solar masses in stars. In general, they are red in color, which signifies that they are no longer forming stars. Astronomers therefore refer to them as ‘red and dead’.