Curtis Struck

GALAXY COLLISIONS

Forging New Worlds from Cosmic Crashes

Springer

PRAXIS

Galaxy Collisions

Forging New Worlds from Cosmic Crashes

Curtis Struck

Galaxy Collisions

Forging New Worlds from Cosmic Crashes

Springer

Published in association with
Praxis Publishing
Chichester, UK

PRAXIS

Professor Curtis Struck
Iowa State University
Ames
Iowa
USA

SPRINGER–PRAXIS BOOKS IN POPULAR ASTRONOMY
SUBJECT *ADVISORY EDITOR*: John Mason, M.B.E., B.Sc., M.Sc., Ph.D.

ISBN 978-0-387-85370-3 e-ISBN 978-0-387-85371-0
DOI 10.1007/978-0-387-85371-0
Springer New York Dordrecht Heidelberg London

Library of Congress Control Number: 2011921115

Cover design: Jim Wilkie
Project copy editor: Dr John Mason
Typesetting: BookEns, Royston, Herts., UK

Printed on acid-free paper

Springer is a part of Springer Science+Business Media (springer.com)

Contents

Preface

Sparks fly as an ancient blacksmith hammers a piece of glowing metal on his anvil. Similarly, interstellar gases are flung off the outer disk of a galaxy as a consequence of tidal forces following a close encounter with another. The gases gather in a vast plume, compressed in some regions, where gravitational forces squeeze out new star clusters, the galactic "sparks." The smith returns his metal to the fire to be reheated. As hundreds of millions of years pass, gas in the great tidal plume falls back onto the galaxy. Some of it finds its way into the core, and fuels the hot fires of a galactic starburst, whose "coals" are hundreds of millions of newly formed stars. The smith works his metal repeatedly, tempering and strengthening it. The collision induces compression waves, which propagate through the galaxy disk, inducing more star formation, and ultimately producing a mature disk, with relatively little leftover gas.

For thousands of years the blacksmith was the master of a metal-based technology. He was as powerful and magical to his contemporaries as a modern day "rocket scientist." His power was in his knowledge not in his ability to muster political or military resources. He was an important part of the process that led to more complex civilizations possessing much more sophisticated technologies. Galaxy collisions also play a key role in the great story of the evolution of galaxies, and the development of structure in the universe. Both stories involve the ancient "element" of fire in some sense, and both involve the refinement of metals from seemingly unpromising raw materials. In metallurgy it is the chemical refinement of raw ores. In evolving galaxies, it is the nuclear production of the chemical elements beyond helium, which astronomers call "metals." Color images of disturbed galaxies with knots of bright young star clusters suggest an extension of the metaphor to fine jewelry. Nonetheless, despite this rather stretched metaphor, the fact remains that the world of galaxies is very different to ours.

Galaxies appear ghostly, especially when seen with the naked eye through the lenses of a small telescope. However, this is far from the truth. Galaxies are the heftiest structures in the universe, except for clusters and superclusters of galaxies. The metals produced by the generations of stars that define their evolution allowed the formation of solar systems, planets, and life forms like us. Although they appear barely visible and ephemeral on the night sky, the story of their evolution underlies the story of ours.

At first sight, galaxies appear to be very isolated entities. At least this is the way it looked to many of the astronomers who first cataloged them in the last century. It took some time to realize that galaxies can in fact fall together and collide. The buildup of galaxies through collisions is very vigorous, even unremittingly violent, in the early ages of the universe. Only recently have we discovered that a continuing rain of small galaxies onto larger ones like our own Milky Way continues to the present time. The story of single-celled life is the continual division and propagation of daughter cells. To a large degree, the life story of galaxies is the exact opposite; continual buildup, especially in the early days.

The great story of the buildup of the largest structures in the universe is studied in two general ways. At the present time, the primary way is via large-scale studies of the statistical averages (and characteristic deviations from these averages) of many individual cases, using both observations and sophisticated computer models. We can learn much about the properties and kinds of galaxies through the ages of the universe in this way. We can learn more about the details, such as the buildup of successive populations of stars (and perhaps planets), in the second way, which is the detailed study of how specific types of collisions and mergers change galaxies. The first way is the shortest route to understanding the big picture of galaxy evolution, though the statistical details can sometimes be rather dry. The second way carries the risk of what scientists sometimes call butterfly collecting or botany – collecting many pretty examples, but not seeing the whole picture. On the other hand, there are paths to big picture truths through the study of many interesting galaxy family sagas. We will try to explore both paths, without losing our way, in the following chapters.

Galaxy collisions are a slippery topic on several levels. Firstly, it is rather hard to envision such a collision. Like continental drift, the objects and the process are just too big. Also like continental drift, the process takes a very long time. However, our minds can get around those difficulties in the same way that they get around many others, by ignoring them! In this book, I will talk about the vast galaxies with the same easy familiarity that I talk about my car, and I will describe their collision processes as though they occurred over a timescale similar to that of a typical television drama. This approach takes out a lot of the awe, but it is a practical necessity.

The second reason that the subject of this book is a bit slippery is that it involves some complex dynamical processes. One my greatest challenges has been to explain these clearly, while ruthlessly striving not to get sucked into the whirlpool of complications. We have really learned an enormous amount about these distant phenomena, using a variety of powerful physical and mathematical tools. However, most readers of this book will be more interested in the big picture (appropriately for this topic!) than the fine print. I have worked hard on this, but no doubt I have fallen short in some places.

A third slippery aspect of galaxy collisions is that it is not so much a self-contained subject as a nexus or meeting place of many other topics in astronomy and astrophysics. A little knowledge of a lot of these topics is very helpful, and again I have wrestled with providing the minimum amount of background that is necessary, and to avoid sidetracks, even if many of them are actually beautiful byways. There is another side to this coin. Because of the nature of the field, many of the contributions have been made by researchers in related fields pursuing a sidetrack that leads in, and often relatively quickly out, of the field of galaxy collisions.

There is a core of researchers who have spent most of their careers in this field (even if it does sometimes feel more like a nomadic camp rather than a settled community), in contrast to more self-contained areas of science. Altogether, thousands of both the nomads and settled farmers of research have contributed to this field. One of the unhappiest parts of writing a book like this is accepting that even major contributions will get only a brief mention, and many significant ones none at all. Not to mention the fact that what is major is still somewhat in the eyes of the beholder in this very active field.

A consolation for these woes is the possibility of inciting an interest, or at least some curiosity, in readers new to the field. I hope this tourist brochure of the world of galaxies and their interactions will be useful as a starting point for deeper explorations. That is the primary goal of this book.

As we will see, galaxy collisions occur throughout the world of galaxies, so the study of collisions is inevitably an exploration of the galaxy world. It is very natural to pursue that exploration on a path that is parallel to the evolution of a typical collision and merger. Before beginning on that path, Chapter 1 provides some general background on the history of the discovery of galaxies, some of their systematic properties, and how they have been discovered. In this chapter, I also define some basic terminology that is used throughout the book, including Hubble's galaxy types. In Chapters 2 and 3 we begin the journey in earnest, by exploring the early stages of galaxy collisions. Many of the most beautiful forms in the world of galaxies are found in this area, and we will study a number of these individual systems.

Galaxy collisions build up galaxies, because most collisions end in the merger of the collision partners. We explore this process and its consequences in Chapters 4 and 5. The former chapter treats mergers between near equals; the latter treats the capture of smaller objects by bigger ones. One of the most spectacular consequences of galaxy collisions is the increase in the rate of star formation induced through the merger process. We consider the statistics and the physical processes behind this in Chapter 6. We will also consider the role of mergers and induced star formation in creating the phenomenon of active galactic nuclei in that chapter.

Armed with a basic understanding of galaxies and their evolution in collisions, we return to our own Local Group of galaxies in Chapter 7 in search of evidence of collisions in its history. While we find that the Local Group has been a fairly quiet village in the world of galaxies, it appears that future development is inevitable.

Finally, in Chapter 8 we take a broad look across many scales in the galaxy world. In so doing we get a better view of the environments of galaxy collisions, their cosmological context, and how the collision process is repeated on the larger scale of galaxy groups and clusters.

I have attempted to avoid unnecessary jargon and abbreviations in this book where possible. When it is cumbersome not to, I have tried to confine the technical terms to the chapter or section where they are most relevant and used in context. However, a number of these technical terms are collected and defined in the Glossary for easy reference.

There are relatively few general reading sources on galaxy collisions; this is part of the reason that this book was written, but a number of such sources have been listed in the Resources section at the end of the book. These are sources that are relevant to every chapter in the book, while some more specific references will be given at the end of each chapter. It is hoped that all of these resources will provide a starting point for readers interested in digging deeper.

Acknowledgments

This book is a small and humble distillate from a huge range of inputs and experiences of the author over several decades. I am afraid that these inputs are too many to remember, let alone properly acknowledge individually. I apologize to many for that, and also for any errors or inadequacies in my treatment of the rich materials that have been given to me.

However, a few collective nods of appreciation are due. First, to the researchers, research organizations, and publishers who have given me permission to use images and other material. This field is graced by hauntingly beautiful images, which provide constant inspiration. Many of these resources would not be available were it not for the professional and general outreach work of the NASA Extragalactic Database, the arXiv preprint server, the Space Telescope Science Institute, the JPL Infrared Processing and Analysis Center, and others cited in the text and figures below.

Next, I would like to give my warmest thanks to my research collaborators, Iowa State colleagues, and students, who are a huge source of continuing inspiration and education. How many of my blind spots have been illuminated in our conversations over the years! How much have you challenged me and kept me on track!

Similarly, I am very grateful to Dr John Mason, Clive Horwood, and the editorial staff at Springer-Praxis for all their help. Though it is a cliché, I found this project much more difficult than I expected, and I found the professional and personal interruptions much more numerous than planned. John and Clive, thanks for your tolerance of my delays, mistakes of inexperience and gentle management overall.

Finally, I am very mindful of the personal support provided by friends and family not only during this project, but also for my work that, over the years, provided a basis for it. Certainly, my immediate family endured neglect and occasional grumpiness as I struggled with the chapters below. But a much wider circle provided support, even with simple encouragement along the lines of, "I'd like to read it when you finish," which held out the possibility that I might actually finish. I hope you all find a little something of interest and inspiration in the world of colliding galaxies.

Curtis Struck
October 2010

Illustrations

1 Exploring the World of Galaxies

In this book, we are going to explore the world of the galaxies and, in particular, study their interactions. For most people this is a very unfamiliar world. I mentioned in the Preface that galaxies have a ghostly or ephemeral appearance in small telescopes. Their appearance in our culture is also somewhat insubstantial. Most of us learned in school that the faint fuzzy band of light that can be seen stretching across the sky on summer evenings is a manifestation of the millions of distant stars contained within our own Milky Way galaxy. Some of us are old enough to remember cars or televisions with names like "Galaxie" or "Quasar." (As far as I know, no company has yet named their product "super-massive black hole," though I have known some that might be appropriately described that way.) A perusal of the astronomy coffee table books at the local bookstore will reveal many beautiful space telescope images of galaxies and galaxy collisions, including some that I have had the pleasure to work with. Similar images abound in science fiction movies and TV shows.

These images can inspire, but no single image can convey the activity that spans huge ranges of spatial and temporal scales in galaxy collisions. Moreover, all of these scales are remote. In terms of size and mass and characteristic times, galaxies (at about 10^{22} meters across with masses of about 10^{42} kg) are even more remote from human scales than atoms (at about 10^{-10} m and 10^{-26} kg). However, great or tiny size is not necessarily a barrier to our understanding of the importance of a phenomenon in our universe. Submicroscopic germs and global climates are very much on our minds these days. Yet knowledge of the role of galaxies in our cosmic evolution, and the possibility of their continuing influence on our planet, has only been obtained within the past couple of decades, and is still somewhat tentative. Thus, it may be a bit early to expect to see teenagers sporting t-shirt slogans like "Love your galaxy" or "No fear of galaxy collisions."

We can begin the process of familiarization with the galaxy world by using a number of metaphors to more familiar ideas and things in our world. For example, we can compare the scientific exploration of it in the past few centuries to other famous explorations. One aspect of this exploration is similar to the European discovery of the North American continent, and of the first travels of humans out of Africa. That is, an impression of vast emptiness. The average distance between galaxies is about ten times their physical extent, and a much larger multiple of the size of their visible stellar components.

Another aspect of galaxy interactions is like Jane Goodall's famous exploration of the social and technological world of chimpanzees. Most likely, humans

C. Struck, *Galaxy Collisions: Forging New Worlds from Cosmic Crashes*, Springer Praxis Books, DOI 10.1007/978-0-387-85371-0_1, © Springer Science+Business Media, LLC 2011

have known about chimpanzees since the time of their own origin, but who bothered to look at how they behaved in detail? Similarly, humans have always had the Milky Way to look at, but the scientific study of it was long neglected, though in fairness it took a long time to develop the tools which were necessary to pursue that study in any detail. As we will see below, even when galaxies began to be investigated in detail, the notion of collisions and interactions was initially dismissed.

The study of the world of galaxies can sometimes seem like Alice's exploration of Wonderland – very confusing! For example, galaxies and components of galaxies move in a three-dimensional world without the constraints of ground or air resistance. These motions are governed by laws of gravity that are formally the same as on the surface of the Earth, but the practical consequences of these laws are very different.

Still another aspect of the strangeness of the galaxy world comes from the fact that galaxies are composite objects with a great deal of nearly empty space between the stars, gas clouds and particles of dark matter that populate them. Despite their isolation, these objects are all bound together by the galaxy's gravity, and generally move on similar orbits. Comparisons with flying flocks of birds or traveling schools of fish come to mind.

In many subfields of astronomy, the composite nature of galaxies is overlooked. For example, in studies of specific constituents, like stars or star clusters, the galaxy may be viewed as essentially a vessel holding the object of study. This is like studies of an individual fish caught from a school. For cosmological studies, the global properties of galaxies may be viewed only as signposts providing information on the overall structure and history of the universe. This is like the fisherman searching for schools of fish, interested only in their size, location and other bulk properties, not in the schooling behavior of the fish. We will learn a bit more about the constituents of galaxies on one hand, and their distribution across the space-time universe, on the other. However, most of our attention will be focused on the schools and their interactions.

There is another point of comparison between the ocean world and the galaxy world. The great galaxy explorer Edwin Hubble put it as follows in his book *The Realm of the Nebulae*. "Toward the end of the nineteenth century, however, the accumulation of observational data brought into prominence the problem of the status of the nebulae and, with it, the theory of island universes as a possible solution." We will talk more about Hubble, nebulae and island universes shortly.

I am afraid that a few parts of the exploration of galaxies and their evolution may seem as difficult as many early explorations on Earth. A full understanding of some aspects of galaxy interactions is technically difficult. Fortunately, most of the world of galaxies is truly a paradise to behold, with many exemplary individuals who have much to teach us. As a guide to this world, I will do my best to show you some of the great sights.

Yet, a goal of this book is to get beyond the beautiful images to some of the new knowledge of what galaxies are, how they came to be, and how processes on the galactic scale can affect beings on small planets orbiting relatively ordinary stars within them. When we take stock of an individual human life, we mainly remember a handful of pivotal events or accomplishments, rather than the slowly changing day-to-day rituals of that life. It is not entirely obvious that the sum of the latter are much less important than any one of the former events, but it cannot be denied that the single pivotal events are important. The lives of galaxies have both kinds of events. Major collisions are certainly pivotal. Small micro-collisions are more routine events. As with humans, the cumulative effects of many small events, or what are called "secular" changes in dynamics, may be as important as the pivotal ones. However, that doesn't diminish the importance of the big changes. The focus of this book will be on explaining the big changes in the lives of galaxies induced by collisions.

1.1 Finding the galaxies

Our knowledge of galaxies has been hard won. Indeed, the history of the discovery of the nature of the Milky Way and other galaxies might more accurately be described as a comedy of errors rather than as the steady progress of science. It is still a great intellectual achievement, and we shouldn't expect the resolution of great mysteries of nature to be easy. For a long time the primary reason for this comedy was that astronomers did not have sufficient sensitivity and resolution in their instruments to see very many galaxies, or details within galaxies. More recently we have learned that the bulk of the mass in galaxies may be invisible dark matter. That is, it doesn't emit light or any other electromagnetic radiation, so that we can only detect its presence indirectly. Galaxies are still very hard to see!

If galaxies are so big, and contain so much stuff, why is this so? To answer this question it is worth looking back briefly at the history of the discoverers, and the technologies they had to work with. From the beginning of humankind, four galaxies have been visible to naked eye observers. Two of them, the Magellanic Clouds are seen from the southern hemisphere, and so not easily observable to most of the early civilizations in the northern hemisphere. The Milky Way is visible from all parts of the Earth, but the true nature of this broad fuzzy band was very hard to discern, at least before the invention of the telescope.

Recorded speculations on the nature of the Milky Way date back to classical Greek times. With even a small crude telescope, Galileo was able to resolve the milkiness into numerous stars about 400 years ago. Then the immediate question was – do we see this dense band of stars because it is a dense band of stars, or because it is the only region of the sky where an infinite distribution of stars is not obscured by some intervening material. Given our current knowledge of galaxies and galaxy disks, the latter idea seems a bit crazy. Without that knowledge, or even a basic understanding of Newton's universal law of gravity, it was very reasonable to begin with the idea that stars were distributed uniformly and that this distribution extended out to infinity, or at least to some great distance. In ancient scenarios the Earth was at the center of that distribution.

When seventeenth century observations like Galileo's seemed to contradict that idea, the door was opened to attempts to patch the torn theory, or develop new ones.

The most significant developments came in the mid-eighteenth century. Among the most well known are the speculative theories of Thomas Wright, an English teacher, astronomer, artist, architect and amateur theologian, who published his ideas in a book called *An Original Theory or New Hypothesis of the Universe* in 1750. His basic picture of cosmological structure was that the universe of stars was formed in a relatively thin spherical shell of enormous radius. Since our Solar System lies within the shell, when we look in a direction nearly tangential to the shell, and thus, through it, we see many more stars than when we look perpendicular to the shell along a radius. The former case corresponds to the Milky Way, while the latter case corresponds to what we would now call looking toward the galactic poles. Wright did also discuss the fact that a distribution of planar rings could account for the observed stellar distribution of stars on the night sky. While this conception brought him close to the modern view of the Milky Way, it was a secondary theory for Wright. Remarkably, Wright also expanded his notion of a universe as a shell to include the possibility of many other universes. These could exist on larger or smaller shells concentric to our universe, or as completely independent spheres. The modern idea of a multiverse comprising many universes has some common features, though based on completely different philosophical underpinnings.

The great philosopher Immanuel Kant began his career with work in the physical sciences, including what we would now call cosmology, among others. He acquired a summary description of Wright's book, though without the artistic and descriptive illustrations. Perhaps because of this, he thought Wright's primary model for the universe (and the Milky Way) was disk-like. He adopted this model and sought to elaborate it. In particular, he argued for the idea that the so-called nebulous stars, which would soon be called nebulae, are other comparable star systems. Many of these had a roughly elliptical form, and Kant realized that this could be explained as the result of seeing disks of stars from many different points of view. In essence, Kant argued that the nebulous stars were what would much later be called island universes or galaxies.

Scientists and historians of later times have dismissed Wright's and Kant's work as too philosophical or speculative. Like Kepler's, or even Newton's work before him, Wright's work did have a strong basis in theological considerations. It is certainly true that neither Wright nor Kant pursued a lifetime of astronomical observation in an attempt to test their theories. They were the general theorists. Anyone with even modest familiarity with the literature of modern theoretical physics knows the key role of symmetry principles there. Like the theological arguments of earlier centuries, symmetry arguments do not rest on much more than their intrinsic simplicity, beauty, and order. At least that is true initially; later their predictions can be tested against observation.

Eventually, the questions of what is the Milky Way, and what are the nebulae or galaxies, also had to be answered by observation, and by people who would devote their lives to those observations. Such people included William and Caroline Herschel, who also began their work in the eighteenth century. The Herschels and others pursued two lines of study that were crucial to answering the questions above. The first direction has been called the natural history of galaxies (or nebulae). That is, the Herschels and Charles Messier in France undertook to describe and catalog all the nebulae visible through their telescopes (and the Herschels made some of the best telescopes of the time). Interestingly, their primary goals were not to do natural history or answer the questions above, but to identify fuzzy objects in the sky that could be easily mistaken for comets. Comet hunting and comet studies were then cutting edge science, and would continue to be so for some time.

The second direction that was very important for William Herschel was estimating the distances of the stars, or at least their relative distances. Like the nature of the Milky Way this had been a long unsolved problem. It would be a great focus of nineteenth century astronomy, and ultimately the answer to the question of the nature of the nebulae would be answered by determinations of their distances in the twentieth century. The Herschels could only make a start on this long scientific crusade, but their methodology and determination made for a very good beginning.

In the late eighteenth century, the Herschels had no model tools for determining stellar distances. It would be more than a half a century before stellar parallaxes were finally measured, allowing distances to a small number of nearby stars to be determined accurately. This method, which is essentially the same as trigonometric surveying, would provide the first step for calibrating other distance estimators, which could be extended to still greater distances. The Herschels had none of these techniques. All they had to work with were assumptions and star counts. Among the former they adopted the notions that the stellar system was finite, that they could see to the end of it, and that stars were relatively smoothly distributed within it. With these assumptions star counts were proportional to the distance to the edge of the stellar system in any given direction. Based on this methodology, they derived a model for the Milky Way shown in Figure 1.1. By modern standards it looks more like an amoeba than a galaxy. It is incorrect in several fundamental ways, including the fact that the Sun is near the center of the system, rather than toward the edge of the stellar disk, which we now know to be the case. The artistry of the figure is also much less than that of Thomas Wright. However, the diagram is based on data, and that fact alone makes it a great advance on the theological speculations of Wright.

In this brief historical overview, I will not say much about the nineteenth century. It was a time for the beginnings of important technological developments, including larger telescopes, the use of photography to record observations and the use of spectroscopy to learn about what the stars were made of. The first two developments were very important for the study of the intrinsically faint galaxies; bigger telescopes collect more light, and photographic plates could collect it for much longer time spans than the eye. In this century, astronomy

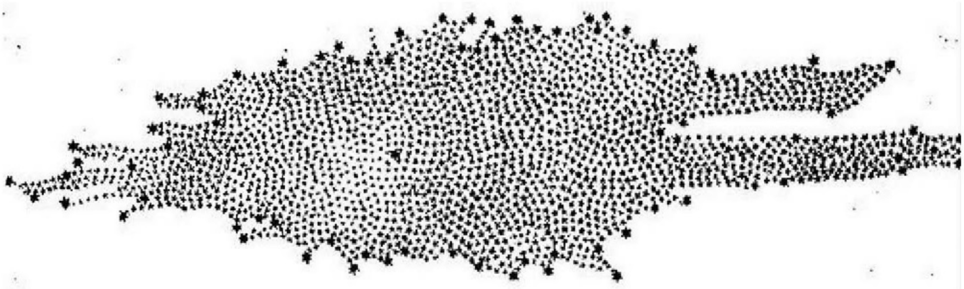

Figure 1.1 William Herschel's map of the Milky Way, based on star counts (from Wikipedia Commons, originally published in the *Philosophical Transactions of the Royal Society*, 1785).

moved from the study of the Solar System to the stars. By the end of the nineteenth century, large catalogs of stars and their characteristics were being assembled. Studies of stellar parallaxes to determine distances and of the orbits of binary star systems were the norm.

These investigations, especially the developing methodologies of distance determination, were prerequisites to gaining an understanding of the nature of the nebulae. Moreover, although they were improving, the observational tools were not yet up to the task of understanding galaxies. There were exceptions to this generalization. One of the most oft cited is the Third Earl of Rosse (William Parsons) with his huge 72-inch "Leviathan" telescope at Birr Castle in Ireland. He discovered the spiral arms of the object Messier 51, now known as the Whirlpool galaxy (Figure 1.2). Later he discovered spirals in other nebulae, so that the "spiral nebulae" became a class. Incidentally, when Rosse observed a small companion galaxy at the end of one of the spiral arms in M51 he made the first telescopic discovery of colliding galaxies. (Prehistoric naked eye observers of the Magellanic Clouds were the first to discover colliding galaxies, but they had much less understanding of what they were seeing than Rosse.) On the other hand, comparison of Figures 1.2 and 1.8 (below) show that his observations only gave an impression, rather than an accurate map of the interaction.

The twentieth century dawned and astronomers like Jacobus Kapteyn were applying statistical tools to determine the structure of the Milky Way from extensive observations of stars. However, the nature of Rosse's spiral nebulae was still far from clear. The confusion of the time is evident in University of Chicago Professor F. R. Moulton's encyclopedic text *An Introduction to Astronomy*, published in 1916. Some quotes from the section on the spiral nebulae:

> ... they seem to be vast swarms of incandescent solid or liquid particles, perhaps many with larger masses, surrounded by gaseous materials. There is difficulty in explaining their luminosity, though Lockyer attempted to account for the light of all nebulae by ascribing it to heat generated by the collisions of meteorites of which he supposed they are largely composed. ... The suggestion has been

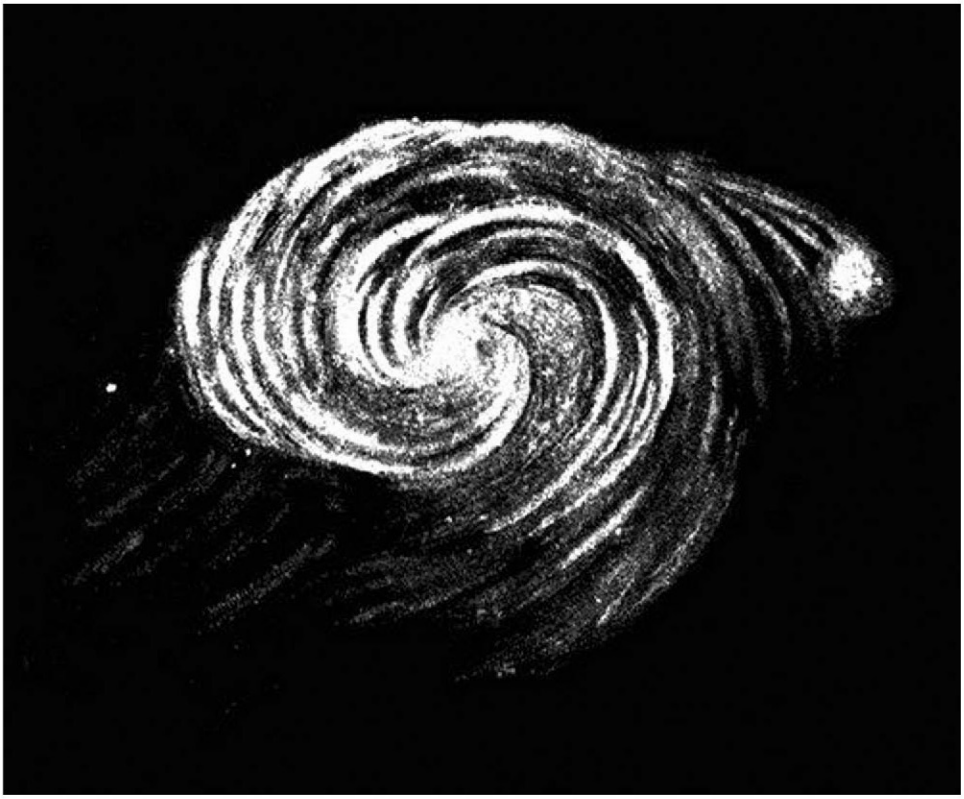

Figure 1.2 Lord Rosse's sketch of the Whirlpool galaxy (M51), as seen with his 72-inch "Leviathan" telescope (from Wikipedia Commons, original from 1845).

> made that a spiral nebula may develop when a star is visited closely by another star, or when a group of stars passes near another group of stars.

In these quotes the good professor paints a picture of the spirals as a galactic phenomenon, existing on roughly a stellar scale. Indeed his description sounds rather close to a modern one describing a forming star or proto-star cluster. But he isn't quite sure in the end. He writes:

> There is one fact, which is opposed to the suggested explanation of spiral nebulae, and that is, as Slipher first found, their radial velocities average very great. For example, the Great Andromeda Nebula is approaching the Solar System at the rate of 200 miles per second...

These quotes show a stunning ignorance of galaxies, less than a century ago, compared with our present knowledge. However, in the last quote one can smell the first smoke of the coming revolution.

At about the time of Moulton's text, the major breakthrough for understanding the nature of galaxies was coming from studies of a rare class of stars, the Cepheid variables. In the first decade of the twentieth century, Henrietta Leavitt, working at Harvard College Observatory, made her seminal discovery that the pulsation period of Cepheid variables correlated very well with their intrinsic luminosities. With this correlation, Cepheids became the most important of what astronomers call "standard candles," i.e., objects whose intrinsic total brightness or luminosity can be determined by some independent means. Thus, like candles all factory made to a set standard, we know their brightness, once it has been determined for some subset.

Ejnar Hertzsprung, using stars in the Milky Way, whose distances could be determined by other means, calibrated Leavitt's correlation between Cepheid periods and luminosities. Hertzsprung then used the correlation to estimate the distance to the Magellanic Clouds. His estimate was poor by modern standards, but good enough to show that the Clouds were too far away to be considered star clusters within the Milky Way.

New distance determinations showed that the globular star clusters were also much more distant than previously thought. Yet the globular cluster system seemed to be centered on the Milky Way. Were they part of the Milky Way system or separate? And thus, was the Milky Way much larger than formerly believed? If so, how could the spiral nebulae be like the Milky Way unless they were also much bigger, and as a result, much more distant than previously envisaged? This was a time of great confusion and controversy about these interwoven questions. The details make for a very interesting historical story. For our purposes, it suffices to know that Edwin Hubble broke the logjam in 1924.

He did this by discovering Cepheids in the nearby spiral galaxies M31 (the Andromeda galaxy) and M33 (called the Pinwheel, in the constellation of Triangulum), and using the period-luminosity relation to estimate the distances. The distances he derived were large, and showed that these galaxies were indeed island universes comparable with the Milky Way. An interesting aside is that Hubble's distances to these and other galaxies were underestimated by about a factor of two. Walter Baade resolved this discrepancy in the 1940s when he discovered that there were two classes of Cepheid with slightly different period-luminosity relations. One class had been used to calibrate the relation, while those found in the external galaxies belonged to the other class. The details of Cepheid calibration continue to be worked on to this day, though that work is now about details and smaller corrections. In any case, although the debates continued for a few more years, with this discovery Hubble resolved the nature of the spiral nebulae and showed that the Milky Way was not alone, but rather a member of a huge population, spread across a vast volume of space.

Almost any scientist would be happy with one such momentous discovery in their career, but Hubble's work had not reached its peak. He went on to consider not only the sizes and distances of galaxies, but how they moved relative to the Milky Way. Because of their great distance the motion of galaxies across the sky is nearly impossible to observe. Only recently have we been able to measure it for a few of the closest galaxies; such observations were far beyond the capability of

Hubble's instruments. However, he (actually Vesto Slipher and others) could measure the motion of galaxies toward or away from us. This was achieved by use of the Doppler shift phenomenon.

The Doppler shift is the slight change of the wavelength of a spectral line for objects moving toward or away from the observer. Ordinarily this wavelength shift is very small; only if the relative velocity between source and observer is close to the speed of light is it large. However, this relative velocity can be measured quite accurately in astronomical spectra. The relative velocity compared to the speed of light is proportional to the relative wavelength shift. Both the velocity and the wavelength shift are often called the redshift. It is actually only red if the source and observer are moving away from each other. If they are moving toward each other the spectral line is shifted to a shorter wavelength, giving a blue shift. *A priori*, Hubble seems to have expected that the galaxies would be moving randomly through the universe, and so he expected about equal numbers of red and blue shifts to be observed. Yet, with few exceptions, the measured shifts were red. That result was strange enough, but when Hubble plotted redshift against distance for a small sample of galaxies (first in 1929, then with more data in the 1930s), he discovered something even more significant – the redshifts (or recession velocities) increased linearly with distance. The relation can be written, $v = Hd$, now called the Hubble Law, where v is the recession velocity, d is the distance, and H is the so-called Hubble constant (with units of inverse time or frequency).

The Hubble Law says that the farther away a galaxy is, the faster it is moving away from us (Figure 1.3). This was pretty mysterious... unless you were Einstein. Actually, it was not so much Einstein as other scientists applying his equations of General Relativity to cosmology, who realized that this is the signature of universal expansion. The other galaxies were not all traveling away from the Milky Way, they are just participating in the overall expansion, or space-time stretching of our universe. Hubble was rather lucky to make this discovery. If the Milky Way resided within a giant cluster of galaxies, like about half of all galaxies do, the observations might have realized the simple expectation of just as many galaxies coming toward us as moving away. This is because the enormous self-gravity of such a cluster overcomes the universal expansion, and most member galaxies are moving randomly (and at high speeds) relative to each other. With such a small sample of nearby galaxies, Hubble wasn't really sampling on a large enough scale to give a proper measure of the cosmological expansion, but he did get lucky (Figure 1.3). In the late twentieth century one of the primary scientific goals of the Hubble Space Telescope was to detect Cepheids and measure galaxy distances out as far as the Virgo cluster of galaxies (the nearest great cluster), in order to get a better measure of the rate of cosmological expansion. These studies are very much in the tradition of the master by his telescopic namesake.

The distances to galaxies are great; millions of light years for some of the nearest, billions of light years for the most distant. We know that because in the time since Hubble's work a number of other standard candles have been found and calibrated. Some of these (especially supernova explosions) can be used out

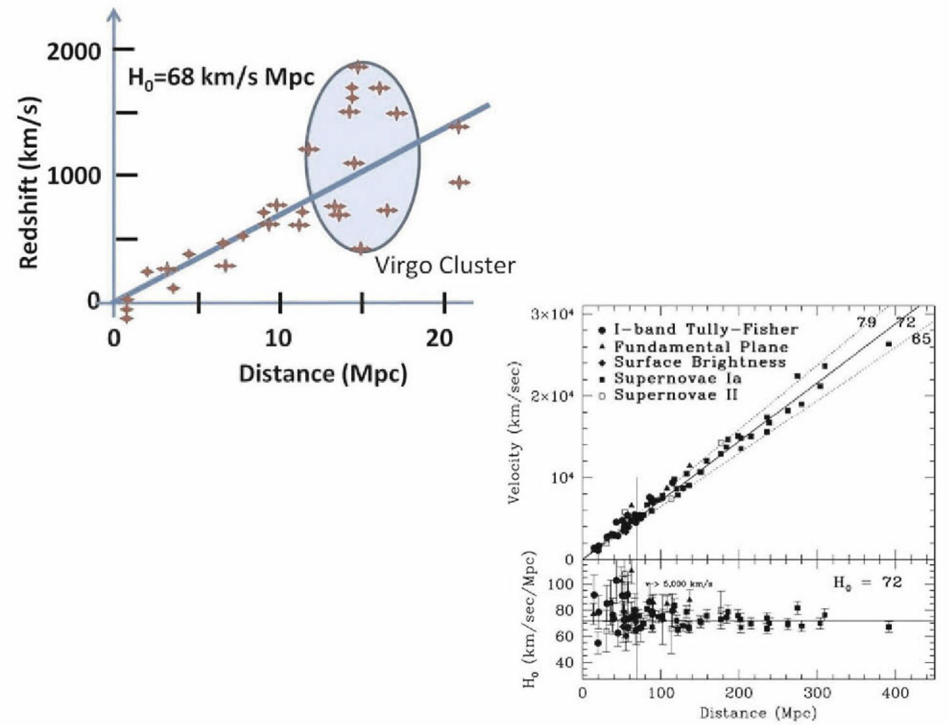

Figure 1.3 The Hubble Diagram, depicting the linear Hubble Law relation between galaxy distance and redshift. The diagram to the upper left is a version of Hubble's original. It fits within the range of the two points closest to the origin in the diagram on the lower right. The labels on the latter refer to different techniques used to estimate galaxy distances. This latter diagram is the result of extensive observations with the Hubble Space Telescope (from Wikipedia Commons/W.C. Keel (upper left) and W.L. Freedman, *et al.*, *Astrophys. J.*, Vol. 553 (lower right)).

to far greater distances than the Cepheids. Once calibrated, Hubble's Law can itself be used for distance determination – measure the recession velocity of a distant galaxy, calibrate the Hubble constant from relatively nearby galaxies, and solve the equation for the distance to the distant galaxy. Cosmologists are not fond of this procedure because they would like to use independent distance estimates to look for deviations from the Hubble Law, which can tell us interesting things about the nature and evolution of the cosmic expansion. However, the procedure is a handy tool for quickly estimating galaxy distances.

The travel time for light to reach us from distant galaxies depends directly on the distance between us, which depends on the recession velocity. Therefore, the redshift is also a measure of how long ago the light left a distant galaxy. Roughly speaking a redshift (e.g., relative wavelength shift) of 1 means the light left the distant galaxy when the universe was about half its present age of around 13.6

Gyr.[1] We observe a very few galaxies out to redshifts of about 6, whose light left those galaxies when the universe was less than a Gyr old. Since we can now observe galaxies with such long light travel times, we can do galaxy archaeology. That is, the typical structures of those distant galaxies can be viewed as artifacts from the history of galaxy evolution. That is not the topic of this book. However, the subject of galaxy collisions is intimately tied up with that of galaxy evolution, so the latter topic will reappear many times below.

For now, let us return to the mid-twentieth century to note that Hubble spent much of his later career studying the structure of galaxies at very low redshifts by modern standards. He was looking for a rational classification scheme for galaxy structure. He did not live to complete and publish this work. His student, Alan Sandage, and many others continued it in the second half of the twentieth century.

1.2 Galaxies properties: classification and evolving views

The work of Baade, Hubble, Shapley, and soon many others in the mid-twentieth century, on galaxy structure, distances, groupings and the different populations of stars within them provided a strong foundation for the emerging field of extragalactic astronomy. As a result the developments from, say, the 1950s become more numerous and rapid. Many of those developments are not part of the main story of this short book, so we must limit ourselves to a brief consideration of the most relevant highlights of galaxy studies from that time to the present.

A good place to start that discussion is with the classification scheme of galaxies that Hubble developed. This scheme is shown in Figure 1.4, which is taken from Hubble's book *The Realm of the Nebulae*. Hubble spent thousands of days (and nights) obtaining and studying photographic plate images of galaxies. Many of these images contain an enormous amount of detail. The intellectual discipline required to boil that vast amount of information down to such a simple tuning fork diagram is stunning. To a first approximation the diagram can be viewed as a one-dimensional sequence from quite round (or spherical in three-dimensions) galaxies on the far left to very flat galaxies on the right. The diagram doesn't look like that description, because the disk galaxies along the two tines of the fork are sketched in face-on views to show the nature of their spiral arms, rather than in thin edge-on views. However, flatness is not the most fundamental characteristic of galaxies, and the tuning fork contains much more information, some of it implicit.

First, the galaxies in the handle of the fork are the so-called ellipticals. That is, elliptical in projection on the sky, but probably ellipsoidal in three dimensions.

---

1 Gyr, for gigayear, is equal to 1,000 million years, or 10^9 years.

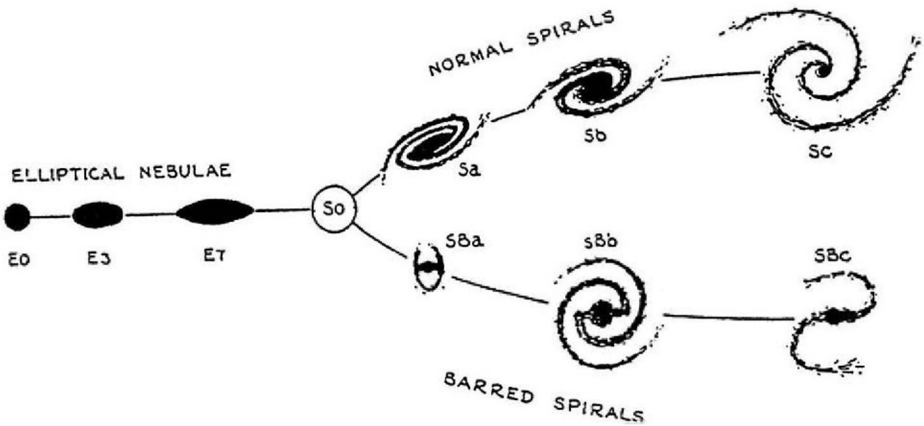

Figure 1.4 Hubble's sketch of his "tuning fork" scheme for classifying galaxies, from his 1958 book *The Realm of the Nebulae*. The handle of the fork consists of elliptical galaxies with varying degrees of flatness, as projected on the sky. Each tine of the fork consists of spiral galaxies, with the openness of the spiral arms increasing to the right. The lower tine consists of spirals that also contain a bar component.

The visible parts of these galaxies consist mostly of very old stars, with few to no younger stars and interstellar gas clouds. For this reason the ellipticals are red in color. They are like extremely large star clusters, which vary in their degree of flattening. The (apparent) flattening of an elliptical can be characterized by the ratio of the longest to the shortest axis in the image, and that ratio ranges from 1 (the E0 class) to about 0.3 (the E7 class). The latter value is somewhat arbitrary; it recognizes the practical fact that any flatter elliptical would probably be taken for an edge-on disk galaxy. It was originally thought that the flattest ellipticals must be rotating relatively rapidly like the disk galaxies. Spectral observations became sensitive enough in the 1970s to disprove this; almost all ellipticals rotate relatively slowly. That is, not rapidly enough for centrifugal forces to hold them up against their own self-gravity, again in contrast to the disk galaxies. In many ways, the ellipticals are the simplest galaxies.

The disk galaxies are more complex in several ways. Firstly, they often have two strong spiral arms, as shown in Figures 1.4 and 1.5. Because of this they are called spiral galaxies as often as disk galaxies. In Hubble's scheme these galaxies are classified according to how tightly the spiral arms are wrapped. The most tightly wound are class Sa and the least tightly bound are class Sc. In addition to the disk component most spiral galaxies also have a central bulge component. For our purposes the bulge can be roughly viewed as a little elliptical galaxy in the center of the disk. This is not quite true; there are some moderate differences between ellipticals and bulges on average (and a subclass of bulges that are quite different). For example, bulges tend to be more round on average, and to rotate somewhat more rapidly than ellipticals. However, like ellipticals, bulges tend to be made up of old stars, with few young stars or gas clouds. On the other hand,

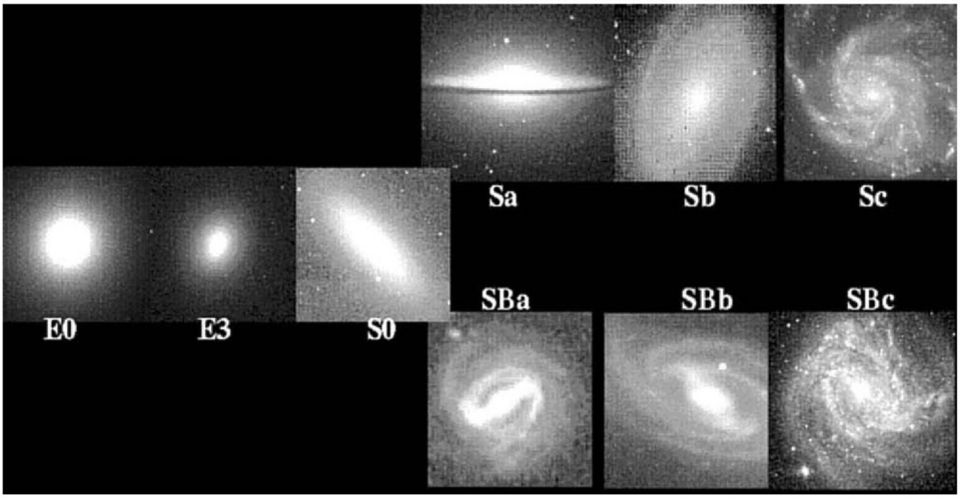

Figure 1.5 A montage of images of galaxies representing the Hubble classes shown in the previous figure (montage from the website of William Keel, with images by Keel and his colleagues from the Digital Sky Survey. The DSS was produced by the Space Telescope Science Institute, under a grant from NASA).

spiral arms tend to host young stars or young star clusters, often making the disk galaxy blue, on average.

The size of the bulge correlates with the spiral arm structure in the sense that tightly wound Sa types have large bulges, while loosely wound Sc types have small bulges. Hubble used both features as classification criteria, and if the two did not correlate so well the upper tine of the fork would not be a one-dimensional line. Our modern understanding of the dependence of spiral wave structure on how the net gravitational attraction varies with radius in the disk, and the fact that the bulge contributes to this net gravity, helps us understand the correlation.

The lower tine of the tuning fork represents a second class of disk galaxies, which are distinguished by having another major component besides disk and bulge, i.e., a bar. The bar component is a three-dimensional ellipsoid, which is much more elongated than a bulge, like an elliptical galaxy of type E3-E7. The lower tine parallels the upper with types SBa through SBc, where the capital B stands for barred. Bars are believed to consist mostly of stars on orbits that keep them within the bar most of the time. Observations of barred galaxies at different tilts or inclinations relative to the plane of the sky show that bars generally lie in the plane of the disk. In fact, their formation and evolution are thought to be intimately related to the disk, though that is not a story for this book. What distinguishes the bar from the disk is that the orbits of the stars are different in each, and like a great stirring bar, the bar moves through the disk. Actually, since the bar moves relatively slowly it is more accurate to say that disk stars orbit through the bar. As do gas clouds.