MARTIN BEECH

The Pillars of CREATION

Giant Molecular Clouds, Star Formation, and Cosmic Recycling

Springer

PRAXIS

The Pillars of Creation

Giant Molecular Clouds, Star Formation, and Cosmic Recycling

Martin Beech

The Pillars of Creation

Giant Molecular Clouds, Star Formation, and Cosmic Recycling

Springer

Published in association with
Praxis Publishing
Chichester, UK

Martin Beech
Campion College
At The University of Regina
Regina, SK, Canada

SPRINGER-PRAXIS BOOKS IN SPACE EXPLORATION

Springer Praxis Books
ISBN 978-3-319-48774-8 ISBN 978-3-319-48775-5 (eBook)
DOI 10.1007/978-3-319-48775-5

Library of Congress Control Number: 2016962718

Cover design: Jim Wilkie

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The human spirit is the lamp of God,
Searching all the innermost parts.

—Proverbs 20:27

Human knowledge grows and science works by casting its proverbial gaze ever forward, searching out those dark recesses, holding the lamp of understanding as high as possible, and casting its light as far as it will go, looking for the new and novel. It is at those quicksilver moments of new illumination that we arrive at the very hinge of discovery—caught in the ever-moving now, sandwiched between the weight of the past and the untouched future—we push our way forward, edging toward the previously unseen.

By casting our gaze toward the deepest shadows, the shadows that lurk within the realm of the unknown, we also illuminate, just a little more, the trail of history. The context of the past becomes ever more clear each time we move forward, and the discovery of the new behooves us to look back and ask pointed questions, such as how did we get here? Sometimes our new view of the past reveals that a crooked, roundabout, road to discovery has been taken, and sometimes it illuminates a better path—an alternative highway not shown on the map we originally had in hand—a road, as it were, drawn in invisible ink, requiring just the right illumination and viewing conditions for it to be seen. Sometimes, by casting light upon the unknown, we illuminate a cul-de-sac (a literal Tolkienian *bag end*), and it is realized that a wrong turn has been made and we can go no further. At these moments, there is no choice but to start again, retrace our steps, and start over, the trail starting out in a different direction. The new road may take us further than before; it may not.

This is how science works: ask questions, collect data, and take mental journeys of mathematical and cognitive adventure. Some questions of the world around us are easy to formulate and profound in their depth but incredibly difficult to answer. We will likely never know, for certain, how the universe came into existence, but we can assuredly ask detailed questions and expect reasonably detailed answers, of the phenomenon and objects that we presently see within the fold of the cosmos. In the story to follow, we take it as fact that the universe had a moment of specific creation, bringing into existence, about 13.7 billion years ago, a vast reservoir of raw materials. We ask not how this material came into existence but, rather, what has happened to all of that primordial material since it was first created. In short, we are asking, what is the history of star formation?

To answer this seemingly straightforward question, we will need to take a number of long journeys, both in time and space. The narrative to be developed will require the bringing together of material from many notebooks, diaries, textbooks, and journals—the tactile repositories of scientific journeys of exploration. Most of all, however, our narrative will be built upon the derived knowledge of the stars, the interstellar medium, and giant molecular clouds. The primordial nucleosynthesis that followed the first moments of creation may well have produced the basic building materials, but it is the circumstance of star formation that has allowed the universe to shine and sparkle with possibility. Stars, as we shall see, are the great sub-creators. They make chemistry possible, and it is them that have enabled the conditions for planets and life to come about. They are the veritable engines of creation. Although the Big Bang provided the fecund spark of initiation, the primordial universe that it sired was born hopelessly sterile, and it is only by the continued recycling of the interstellar medium, through star formation and stellar evolution, that the universe has been animated beyond a chaotic mess of elementary atomic particles, radiation, dark matter, dark energy, and expanding spacetime.

Physical measure and human ingenuity have, over the eons, separated out the stars from the planets, but throughout most of human history, cradled within a spherical shell encircling the Sun just beyond the sphere of Saturn, the stars were close and familiar. It is hardly surprising that our distant ancestors believed that the stars could influence the very ebb and flow of life. Indeed, by modern standards, the stars, for them, were almost touchable. The wonderfully complete picture of the classic medieval universe has now long been discarded. It no longer fits the facts as revealed by numbers and data, the indisputable truth of measure having overruled human sensibility, suspicion, and delusion. The stars are distant, the stars are remote, and they care not for humanity. What we see in the heavens today is the very same matter that was seen by our distant ancestors, but now, we see deeper and we know much more about what it is that we observe. In a sense of reverse astrology, the stars no longer dictate our future, but it is us that know and tell of the full cycle of their lives. How mightily the times have changed.

Figure P.1 shows one of the most remarkable astronomical images ever taken. It is the Hubble Deep Field. Almost alarmingly, given the rapid pace of modern scientific research, this image, which was released by NASA on January 15, 1996, is old hat. There are now the Hubble Ultra-Deep Field and Hubble eXtreme Deep Field[1] images. The Hubble Deep Field image, however, was the pioneer. It was the first image to catch the collective public imagination, literally forcing the viewer to contemplate their infinite smallness in contradistinction to the incredible vastness of the observable universe. Humanity is humbled by

[1] Although the images and data evolve rapidly, it is almost comforting to note that NASA and research scientists in general continue to mutilate the English language and generate spellings and acronyms through the seemingly random sampling of words and letters.

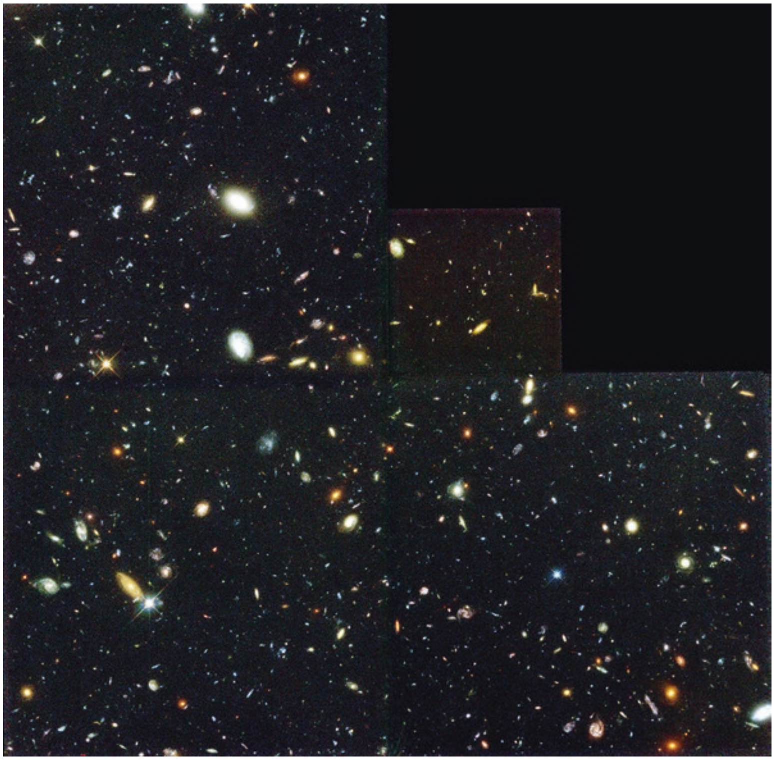

Fig. P.1 The Hubble Deep Field. This image was assembled from 342 separate exposures taken over 10 consecutive days starting December 18, 1995. The field of view covers an area of about 7 square arc minutes on the sky and corresponds to about one 24-millionth of the entire backdrop of the heavens. (Image courtesy of NASA/ESA/HST)

images such as the Hubble Deep Field, although our collective id happily survives the implications.

Taking the incredible image that the Deep Field is and converting it into the equally beautiful dataset of numbers that it contains, it is revealed [1] that there are less than 20 individual stars in the image but some 3000 images of galaxies. The most distant galaxies are located over 12 billion light-years away, and a detailed analysis of galactic distances and light emission reveals that star formation was much more rampant in the distant past, attaining a peak some about 8–10 billion years ago. By the time the Sun was formed, some 4.5 billion years ago, star formation in the universe was on the wane, which is not to say that star formation is going to end any time soon, as we shall see later on.

Coming back to the raw numbers, the Hubble Deep Field enables us to make an estimate of the number of protons and electrons that exist in the observable universe [2]. This is an incredible result, since these particles are the basic building blocks of all matter, and they constitute the matter that we, as human beings, can physically experience, whether by feel or sight. Remarkably, the number of protons and electrons in the observable universe can be estimated in a space no larger than the back of an envelope (or, for the more modern readers, a space the size of a cell phone screen). The calculation is actually quite straightforward (the very hard bit is actually getting the observational data). The area covered by the Deep Field is about 1.9×10^{-3} square degrees on the sky (which is about the same area as that covered by the following wingdings square □ seen at a distance of 4 m [3]), and the mathematicians tell us that there is 41,253 square degrees over the entire surface of a sphere. Taking the Deep Field to be a typical view of the observable universe, this suggests that the number of galaxies N_{gal} in the observable universe is $N_{gal} = (41{,}253/1.9 \times 10^{-3}) \times 3000 = 6.5 \times 10^{10}$, with the 3000 coming from the actual galaxy count in the Deep Field. This number tells us that our Milky Way galaxy is just one of at least 65 billion galaxies in the observable universe.

Let us suppose, and these numbers will be justified later, that each galaxy contains 100 billion stars ($N^* = 10^{11}$) and that the typical mass of a star is half that of the Sun ($M^* = 10^{30}$ kg). The physicists tell us that the mass of the proton is $m_p = 1.7 \times 10^{-27}$ kg, so a typical star (assumed to be made entirely of hydrogen) will contain of order $N_P = M^*/m_p = 6 \times 10^{56}$ protons. We can now determine the approximate number of raw matter building blocks—protons and electrons—that there are in the universe: $N_{pe} = 2 \times N_{gal} \times N^* \times N_P = 8 \times 10^{78}$; the 2 in the calculation accounts for the fact that there is an equal number of electrons and protons;—the universe has no net electrical charge.

As one would expect, the number of protons and electrons is staggeringly large, but equally as staggering is the fact that we can estimate their number (to within a factor of about 10). For our story, however, it is the long-term fate of these 8×10^{78} protons and electrons that is of interest [4]. These myriad miniscule bodies are the building blocks of the stars, and the question to be explored in the following chapters is how such groupings of 10^{57} protons and electrons are formed, transformed, and recycled.

The dome of the celestial sphere is never more exhilarating than on a clear winter's night. The stars are bright and crisp on the sky, and it would seem that their number is uncountable. Dominant among the wintertime constellations is Orion, with his three star-studded belt, long legs, and outstretched arms. We have all seen Orion and marveled. And, indeed, when we look at this gangly limbed constellation, we are catching the light from stars in the making, and lurking in the background, hidden to the gaze of our eye, is a massive molecular cloud that covers the entire vista.

As you read this page, stars are being formed in the great Orion Nebula, located (as we see it) at the tip of the hunter's sword extending downward from the middle star on his belt. The light from these sibling stars, however, is already old by the time we get to see it. Indeed, located about 412 pc from the Sun, it takes over 1300 years for the new starlight to reach us. The light we see now left the nebula in our eighth century, at a time when the heroic poem of *Beowulf* was first being chanted by flickering firelight, the classical Mayan civilization was at its peak, the Venerable Bede was to complete his *Ecclesiastical History of the English People*, and Charlemagne was to be crowned the first Holy Roman Emperor. Much has happened on Earth since the light we now see from the newly formed stars in Orion started journeying outward.

Although the light from the Orion Nebula has been visible since humans first gazed toward the winter night sky, it was only recognized as being a cloud of glowing hot gas in 1864, when William Huggins, working from his Upper Tulse Hill, London, observatory, was able to resolve emission lines within its spectrum. This important discovery heralded the identification of the interstellar medium, and subsequent study by many generations of astronomers has revealed that our Milky Way galaxy is parturient with star-making gas and dust. Indeed, the disk of our galaxy, like an exuberant Rubenesque goddess, exudes great dimples and folds of interstellar matter, and it is the remarkable cyclical journey of this material, from gas cloud to star and back to gas cloud again, that this book will explore.

The Sun, the nearest star, is fundamental to life on Earth and humanity. It has nurtured our long chain of being, and it has, at least thus far, supported our faltering steps toward transcendence. Earth is our home, and our backyard is the Solar System. We currently live on the former, while the latter offers the opportunity of resources and possibly future domicile. The Sun dominates the Solar System; it is where virtually all the mass resides. Just 0.1 % of the Solar System's mass is tied up in the planets, comets, asteroids, and Kuiper Belt objects; the other 99.9 % is in the hot and roiling body that is our Sun.

However, the Sun is neither a typical star nor is it entirely located at random within the Milky Way galaxy. It is assuredly a special star. Nature mostly makes stars that are not like the Sun. Indeed, upon the galactic scale, the Sun is just one of hundreds of billions of stars, a rather massive star (but far from being the most massive star possible) but also a relative newcomer, being a mere 4.5 billion years old—a timescale that spans about the last one-third of the Milky Way's current age.

It is now well known, and readily stated, that without the Sun, there would be no life on Earth. But the story runs much deeper; without long-dead stars, there would be no hope for life anywhere in the universe, and without galaxies, those vast assemblages of stars that pepper the vast volume of the cosmos, there would be no planets and no ongoing star formation. Indeed, it is the self-gravity of our Milky Way galaxy that keeps the raw materials for the making of stars and planets, the interstellar medium, in place. Our existence depends not only upon the small things, our DNA, the rush of chemistry, and the slow-searching fingers of evolutionary adaptation. But it also depends upon the largest structures that we know of in our galaxy's disk, the giant molecular clouds and the stars that form within their glowing nurseries.

This book is about the unfolding story of star formation and how stars are intimately linked to the interstellar medium out of which they form and eventually die—literally as ashes to ashes and dust to dust. For certain, we do not know the full and detailed narrative of the star formation process, and we certainly have not, as yet, asked all the right questions of the phenomena so far discovered. But the journey of discovery continues apace; we are speeding onward, casting an ever-widening circle of exploration and understanding, and the vistas that are unfolding before our gaze are truly humbling and excitingly spectacular.

Regina, SK, Canada Martin Beech

REFERENCES

[1] See, for example, H. C. Ferguson's detailed article, The Hubble Deep Field, published in *Reviews in Modern Astronomy*, **11**, 83-115 (1998).

[2] This estimate accounts for the so-called baryonic matter – that is, matter made of three quarks – contained within stars. Observations indicate that at least five to ten times more matter again, is contained within the hot, diffuse intergalactic medium. The term observable universe is used here since this corresponds to what we can actually see – the universe may of course be much larger than we suppose. The topic of dark matter and the effects of dark energy have been discussed by the author in, *The Large Hadron Collider – Unraveling the Mysteries of* Universe (Springer, New York, 2010).

[3] In 10-point font size the *wingdings* square is about 3 millimeters on each side.

[4] This number is often called the Eddington number, after Arthur Eddington's famous calculation for the number of protons and electrons in the universe. Eddington, however, derived his value in an entirely different fashion, not actually based upon star or galaxy count data. The rather obscure reasoning behind Eddington's calculation is explained in chapter 11 of his posthumous text, *The Philosophy of Physical Science* (Cambridge University Press, 1939). Eddington argued that the number of protons in the universe was given according to the number $136x2^{256}$ – an 80 digit number that he evaluated by long-hand during a steamship crossing of the Atlantic.

Contents

1	**Reading the Sky**	1
	Invoking Buridan's Donkey	1
	Halley's Lucid Spots	2
	Wright's *Via Lactea*	4
	The Star-Gauging Siblings	12
	It All Begins with M1	18
	The Columns Arrayed Before Us	24
	An Evening with Norton	25
	Further Revelations from Norton	31
	The Gathering of Stars	36
	The Spectra of William Huggins	38
	The View Going Forward	42
	References	43
2	**In the Eye of the Beholder**	47
	Let There Be Light	47
	A Quantum Mechanical Aside	52
	Unweaving Light	53
	The Color of Excitation	59
	Seeing Red in Orion	63
	Tools of the Trade	71
	Colors of the Crab	76
	Coronal Gas and a Cosmic Onion	78
	Pulsars and Free Electrons	82
	References	87

3 The Dark Clouds Revealed 89
Kapteyn Tries Again 89
A System of Stars, or Many Star Systems 91
Trumpler's Dim View 96
Baade's Improbable Window 102
Seeing the Blues 106
Interstellar Extinction 114
References 120

4 The Hyperfine Split and Atomic Jitters 121
Star Noise 121
Dialing Radio HI 129
The Molecular Giants Emerge 133
Born of Stardust 149
The Pillars of Creation 152
Are GMCs Dangerous? 165
Life in a Molecular Cloud 172
References 176

5 In the Grip of Gravity 179
The Life and Times of a Molecular Cloud 181
Getting to Know the Stars 183
Making Stars the Lockyer Way 188
The Jeans Criterion 190
Young Stellar Objects 192
The Stellar Birth Line 198
Acquiring Stardom 202
B^2FH 209
The Engines of Evolution 212
First and Last 221
References 227

6 It's a Far Flung Life 234
References 253

Appendix The Magnitude Scale and Interstellar Extinction 256

Index 265

1

Reading the Sky

There, in the night, where none can spy,
All in my hunter's camp I lie,
And play at books that I have read
Till it is time to go to bed

—R. L. Stevenson

Invoking Buridan's Donkey

The year is 1692, and the reverend Richard Bentley, Master of Trinity College, Cambridge, has just asked Isaac Newton a deep and troubling question. An acclaimed theologian, Bentley was preparing to deliver the first of the newly endowed Robert Boyle Lectures. Open to the public, this series of eight lectures was to be delivered from the pulpit of St. Martin's Church, London, and the talks were to consider the role of Christian theology and the requirement of an active deity within the framework of natural philosophy (what we now call science) and specifically within the quest to understand the workings of the universe.

Bentley's last three lectures struck to the core of his correspondence with Newton. By 1692 Newton's magnum opus, the *Principia*, had been in print for only 5 years, and while Newton's ideas and explanation of gravitational attraction were still new and hardly known beyond a small circle of the scientific elite, Bentley was interested in how this all-pervasive force might influence the stability of the universe. Specifically, Bentley asked that if gravity acts universally, and if stars are corporal bodies, then why are the heavens not alive with motion, with the stars streaming in every which direction? It was (and is) a good question, and Newton could offer only a vague and contrived answer. The reason why the stars appear static, Newton reasoned, was because the universe is infinite in extent and because the stars are uniformly arranged within its interior—the stars being set, to use a modern perspective, something like the atoms in a massive, continuously repeating crystal lattice. In short, Newton was suggesting that although every star did indeed feel the gravitational tugs from all of its nearest neighbors, the resultant pull, because of the uniform distribution, was equal in all directions and effectively summed to zero. The stars, just like Buridan's philosophical (and hard done by) donkey, feeling no compulsion to move one way or another, simply stay put.

M. Beech, *The Pillars of Creation*, Springer Praxis Books, DOI 10.1007/978-3-319-48775-5_1

Newton realized, however, that this arrangement must be highly unstable: it was a veritable house of cards. If just one star anywhere in the infinite depths of space shifted only slightly in its position, then the consequences would be fatal, and soon all the stars would be in chaotic motion. The perceived constancy, therefore, of the heavens and the apparent stability of the stellar system, from Bentley's and indeed Newton's, approved viewpoint, was a clear indication that an active, intelligent, and omnipotent Creator must be at play in the cosmos. Theology and the new physics of Newton combined, in the case of Bentley's Boyle lectures, to argue for a cosmos that was composed of a static and uniformly spaced infinite system of stars.

Halley's Lucid Spots

The first two decades of the eighteenth century were a remarkably productive time in the remarkable productive life of Edmund Halley. Halley turned a sprightly 44 years old as the new century began, having spent the last several years at sea as captain of HMS *Paramour*—a 6-gun pink of the Royal Navy. During his command of the *Paramour* Halley had sailed (not always with a harmonious crew) the South Atlantic seas, measuring variations in Earth's magnetic field [1].

Upon retiring his naval commission in 1703, Halley was elected to a professorship of geometry at Oxford University, and within short order he produced his *Synopsis of the Astronomy of Comets* (1705), learned Arabic and finished a translation of Apollonius's *Conics*, and outlined (1716) a method by which the size of Earth's orbit might be determined by viewing transits of Venus. In 1718 he made the monumental discovery of stellar proper motion—showing that stars[1] do indeed move relative to each other in the sky, and that they must also be moving through space. In 1720, along with antiquarian friend William Stukeley, Halley assisted in the first scientific attempt to determine a construction age for the great monoliths of Stonehenge, arguably one of the earliest custom-built astronomical observatories.[2] It was also in 1720, following the death of the cantankerous John Flamsteed, that Edmund Halley accepted the post of Astronomer Royal at Greenwich Observatory in London.

In between all these monumental works and activities, Halley also found time in 1715 to present an account to the Fellows of the Royal Society on "Several Nebulae or lucid Spots like Clouds, lately discovered among the Fixt Stars by help of the Telescope." Although arguably one of Halley's lesser papers—just three pages in extent when published in the *Philosophical Transactions*—his account drew attention to some of the new novelties that were then being discovered in the night sky. Halley writes, "[these] wonderful… luminous Spots and Patches… are nothing else but the Light coming from an extraordinary great Space of the Ether; through which a lucid *Medium* is diffused, that shines with its own proper Lustre."

---

[1] Halley specifically found that the positions of the bright stars Sirius, Arcturus, and Aldebaran had moved over half a degree on the sky since the compilation of the star catalog by Hipparchus circa 135 B.C.

[2] There is little doubt that Stonehenge was primarily constructed to accommodate the religious and funerary practices of a specific Stone Age society. It was not an astronomical observatory, although its geometry does indicate alignments with the rising and setting locations of the solstice Sun.

In total Halley's catalog of nebulae contains just six examples, of which he notes that there are undoubtedly more "not yet cometh to our Knowledge." The list of objects, while small, contains, in modern terms, a star formation region (or an HII nebula), a galaxy, three globular clusters, and one open cluster. Halley writes, "The first and most considerable is that in the Middle of *Orion's* Sword… [composed of] two very contiguous Stars environed with a very large transparent bright spot," and this, of course, is clearly the now famous Orion Nebula, first revealed as being a non-star-like object through the telescope by Christiaan Huygens in 1656 (Fig. 1.1a).

Third in Halley's list of objects is the Andromeda Galaxy (technically, at a distance of 2.54 million light years away, the most distant object visible to the unaided eye), described (Fig. 1.1b) as having, "no sign of a Star in it, but appears like a pale Cloud." Fourth in Halley's list is the globular cluster ω Centauri (Fig. 1.1c)—discovered, in fact, by Halley in 1677 while mapping the southern stars from the island of Saint Helena.

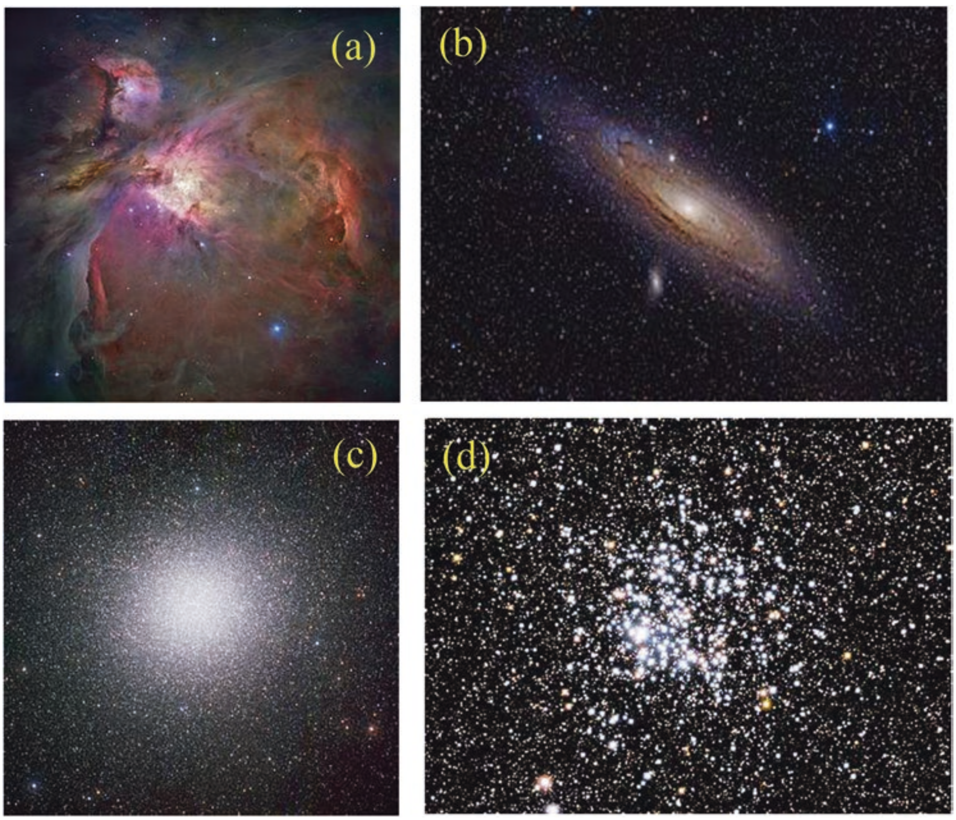

Fig. 1.1 (**a**) The Orion star formation nebula. (**b**) The Andromeda Galaxy—a spiral nebula, (**c**) ω Centauri globular cluster. (**d**) The Wild Duck cluster. Images a, b and d courtesy of NASA. Image c courtesy of ESO

The fifth entry in Halley's list of nebulous objects is known to present-day astronomers as the Wild Duck cluster (in the constellation Scutum), and it is an example of a rich, galactic cluster of stars (Fig. 1.1d).

To Halley, and to all of his contemporaries, the clouds and spots identified in his 1715 catalog (Fig. 1.1a–d) were objects of curiosity, and while they were clearly not stars, they nonetheless moved within the stellar realm. Halley notes, "[S]ince they have no Annual Parallax, they cannot fail to occupy Spaces immensely great, and perhaps not less than our Whole Solar System." Halley was certainly correct in his surmise about the vast size of nebulae regions, but he was woefully off with respect to the true scale; the nebulae occupy regions of space vastly larger than our Solar System.

In his short catalog of nebulae Halley makes no attempt to relate them to any specific stage in the life of a star. Indeed, Halley knew that new stars (the supernovae of 1572 and 1604) did appear from time to time, and he also knew that some stars (e.g., omicron Ceti, or Mira, Algol and χ Cygni) were variable in their brightness. But to the question of star formation and star death he, like his contemporaries, remained steadfastly silent. Importantly, however, by the early to mid-eighteenth century it is apparent that astronomers were becoming increasingly aware of oddities in the sky: luminous clouds, new stars, and stars that showed periodic changes in brightness. What such observations and objects implied about the structure of the cosmos was then unclear, but the notion that the stars were immutable, ageless objects, and that the spaces between the stars was entirely empty, was being brought into question.

Although silent on the issue of star origins, Halley did question Newton's 1692 proclamation that the universe was infinite in extent and contained an infinite number of stars. His argument was "rather of a Metaphysical than Physical Nature," and revolved around the use of the word "infinite," Halley essentially noting that to produce an infinite number of stars in an infinitely large universe would presumably require an infinite amount of time, and this ran counter to the then accepted wisdom. Accordingly he asserted that the number of stars must be finite. Interestingly, as well, Halley ponders the question, but provides no answers or conclusions concerning the psychological consequences of residing in a region of space illuminated by a cloud of "lucid medium." He notes in particular that, "In all these so vast Spaces it should seem that there is a perpetual uninterrupted Day, which may furnish Matter of Speculation, as well to the curious Naturalist as to the Astronomer." Indeed, the question is not an entirely idle one, and we shall come back to consider the consequences of living in a dense molecular cloud region at a later point.

Wright's *Via Lactea*

A broad and ample road whose dust is gold,
And pavement stars, as starts to thee appear,
Seen in the Galaxy, that milky way,
Which nightly, as a circling zone thou seest,
Powder'd with stars

—John Milton, *Paradise Lost* (Book VII)

The picture of an infinitely repeating pattern of equally spaced stars within an infinitely large universe is not an unholy construct (and is no more bizarre than some of the more rococo cosmological models that have been presented in recent years). The minds-eye view is simple enough, easy to visualize, and it certainly has the feel of a well constructed arrangement. The problem, of course, is that the picture is entirely wrong. Newton and Bentley erred in their impeccable, though rather contrived logic.

From a modern perspective (with the benefit of several hundred years' worth of hindsight at our disposal), we can raise any number of objections to the proposed cosmological scheme developed by Newton. Firstly, it assumes that all stars must be of the same mass, and that the star formation process, even if regressed to sometime in the near infinite past, must have been extremely rapid, the stars congealing at their lattice points so rapidly that they did not have time to move before their surrounding closest neighbors formed to enforce equilibrium. Still the main problem, of course, is that the model as suggested simply looks nothing like the star distribution we actually see on the sky. The stars are not uniformly spaced from each other, and they seem to be dotted at random across the celestial sphere. Even if we use brightness as a proxy for distance, the fainter (and therefore further away [2]) stars do not spread into an all-enveloping all-sky glow.[3]

Even though we do not see any obvious order within the distribution of stars in the sky, there are nonetheless features that betray structure. Indeed, the one very obvious feature that stands out above all others on the night sky is the Milky Way (Fig. 1.2).

Long known to ancient astronomers, the *Via Lactea* (Milky Way) appears as an irregular, faintly luminescent band, marked with dark and tendril-like blotches, that stretches around the entire celestial sphere. Less easy to see for modern city-dwelling observers but very obvious to anyone under remote, clear-sky conditions, the key question to ask about the Milky Way is, is it a band of luminescent matter, or is it made up of myriad faint stars? To the ancients the answer was unknown, and indeed, for them, unknowable, but with the introduction of the telescope in the early seventeenth century, it began to become increasingly clear that the Milky Way, far from being a strange collection of luminous matter, was really the accumulated light from a multitude of faint and remote stars seen through a trelliswork of obscuring mater.

March 12, 1610, is one of those days in which the human perception of the cosmos changed. It is the day that a then relatively unknown mathematician in Padua signed off on a small booklet given the deliberately aggrandized title *Siderius Nuncius*. The mathematician was Galileo Galilei, and the booklet, *The Sidereal Message,*[4] was to change the very practice of astronomy.

---

[3] This problem is usually described under the guise of Olber's Paradox [3]. And, this paradox is only resolved under the constraint that we live in a universe of finite age.

[4] It is clear from Galileo's correspondence of the time that he intended the Latin word *nuncius* to mean *message* as opposed to *messenger*, and indeed, it is via the former term that Galileo refers to his work when describing it in his native Italian. The *tradition* of referring to the booklet as the *Sidereal Messenger* was apparently started by Johannes Kepler in his *Dissertatio cum nuncio sidereo* (published April 19, 1610).

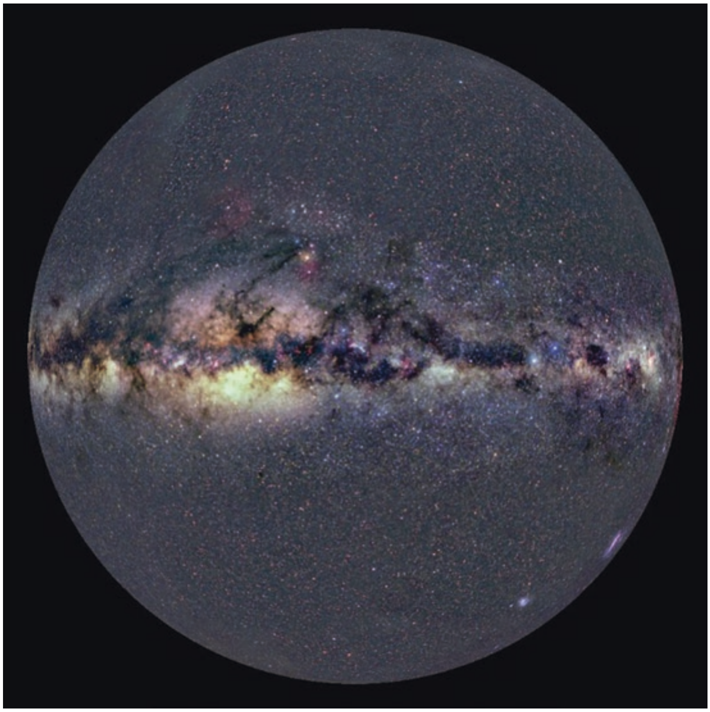

Fig. 1.2 The arch of the Milky Way is revealed in this half-sphere image of the sky. Towards the center of the image are the gas and dust clouds in the direction of Sagittarius. Antares, the brightest star in Scorpius, is located just above and slightly to the *left* of the image center. Alpha and beta Centauri shine prominently about two-thirds of the way along the band of the Milky Way to the *right* of the image. Just to the *right* of these two stars in the image is the dark macula of the Coalsack Nebula, which is nestled within the lower corner region of Acrus, the Southern Cross. The two luminous clouds to the *lower right* in the image are the Small and Large Magellanic Clouds. Image courtesy of NOAA Science on a Sphere

Word of Galileo's work spread like wildfire. Within 2 weeks, news of its publication had reached southern Germany, and within 5 weeks it had reached the shores of remote England—a distance of some 1100 km as the crow flies. Indeed, by 1615 *Siderius Nuncius* was available in translation format in China.

Within the pages of the *Sidereal Message*, Galileo somewhat hastily describes the observations he had made of the heavens with his newly constructed telescope. The iconic instrument of astronomy, the telescope, had dramatically appeared, seemingly out of nowhere and essentially fully developed, in northern European markets in late 1608. Galileo heard of the new device in the summer of 1609, and having rapidly developed his lens grinding skills he turned his new device, with a magnification of about 20 times, to the night sky. What he found revolutionized astronomy, and it also made Galileo famous.

In relation to our narrative, the first important result that Galileo presents is given in his introduction where he notes that, "[I]t seems of no small importance to have put an end to the debate about the Galaxy or Milky Way and to have made manifest its essence to the senses as well as the intellect, and it will be pleasing and most glorious to demonstrate clearly that the substance of those stars called nebulous up to now by all astronomers is very different from what has hitherto been thought." Galileo later explains that with the aid of the telescope the Milky Way, "that for so many generations [has] vexed philosophers," is "nothing else than a congeries of innumerable stars distributed in clusters." Galileo further presents maps of the fainter stars that he has resolved in the Pleiades, Orion and Praesepe. Perhaps surprisingly Galileo makes no mention of the nebular region in Orion, nor does he mention the Andromeda nebula (which is distinctly visible as being nebulous to the naked eye).

Although Galileo rushed his *Siderius Nuncius* into print, no doubt with the intent of cementing his priority on his new discoveries, he made no attempt to speculate upon what he had actually observed. His account was matter of fact, and while he later used his observations to challenge accepted orthodoxy, the primary role of the work was to reveal the newly observed phenomena.

Johann Kepler, on the other hand, as was indeed his way, made every attempt to speculate on the greater meaning of Galileo's new discoveries. Within 2 weeks of receiving a copy of Galileo's *Siderius Nuncious*, Kepler had penned a lengthy letter (published a few months later in pamphlet form) of reply. Entitled "Conversation with the Sidereal Messenger," Kepler set down his thoughts on Galileo's work, and though his letter oozes with praise and congratulations, Kepler also brings Galileo to task on many points. With respect to Galileo's observations on the Milky Way, Kepler writes, "You have conferred a blessing on astronomers and physicists by revealing the true character of the Milky Way. You have upheld those writers who long ago reached the same conclusion as you: they are nothing but a mass of stars." This is a gentle correction of Galileo's claim for complete novelty concerning his ideas about the structure of the Milky Way, and it is by no means Kepler's only correction and/or objection to Galileo's matter of fact writing. A copy of Kepler's "Conversation" was handed to the official Tuscan couriers on April 19, 1610, and Galileo is known to have received and read the letter, but he never penned a reply.

Itinerant lecturer Thomas Wright of Durham was one of the first astronomers to attempt an interpretation of what the Milky Way was in terms of a vast accumulation of stars. Writing in "An original theory or new hypothesis of the universe," published in 1750, Wright reasoned that the appearance of the Milky Way indicated that the Solar System must be located within a flattened, disk-like distribution of stars. The system was disk-like since the Milky Way stretched around the entire sky, and flattened since it was a localized band of concentrated starlight. Indeed, Wright draws a visual analogy with the planet Saturn and its extensive ring system. At play was an "optical effect." When an observer looked into and along the disk, many stars would be seen, but when looking at right angles, and therefore out of the disk, a relative dearth of stars would be evident.

Wright actually vacillated in his ideas about the potential distribution of stars, suggesting that the same optical effect and appearance of the Milky Way could be achieved if the Solar System was located within a vast, thin shell of stars (Fig. 1.3). Wright came up with two very different models to describe the shape of the stellar universe partly because he insisted that at the center of the universe was (naturally) the "Abode of God."

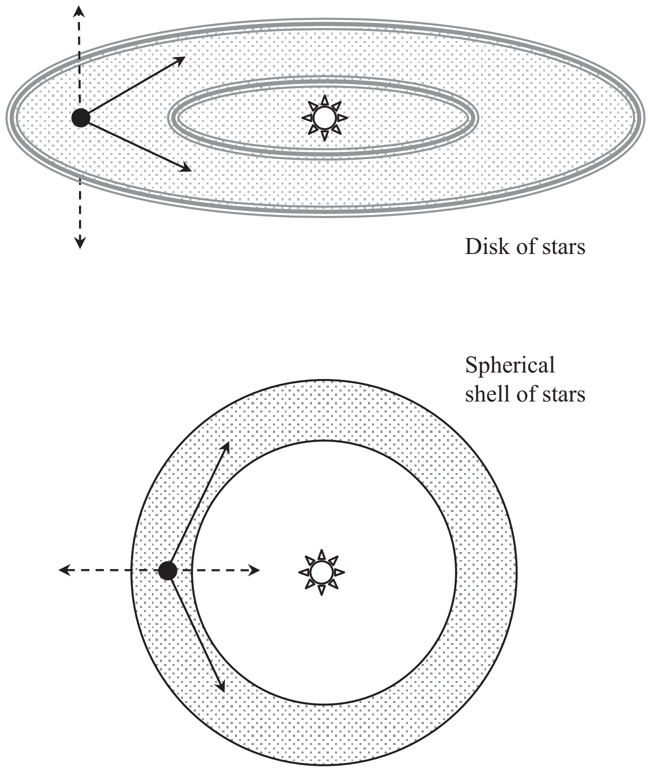

Fig. 1.3 Thomas Wright of Durham's two possible interpretations for the stellar configuration necessary to reveal the Milky Way. In the direction of the *dashed-line arrows* an observer would see many stars systematically arranged in a flattened distribution on the sky, while in the direction of the *dashed-line arrows* an observer would see few, and randomly distributed, stars. The Abode of God, which is remote and unknowable, is located, according to Wright, at the center of each construction

Although by present-day standards Wright's invocation is not a required pre-requisite for a cosmological model, it nonetheless required Wright to consider the consequences of Newton's universal gravitational attraction. Indeed, Wright adopted the stance that all stars must be in motion. This was not an entirely new idea, and indeed, Edmund Halley, in 1718, had already shown that at least a few stars had distinct and measurable proper motions on the sky [4]. Again, though Wright's ideas have a decidedly modern ring to them, his reasoning is suspect, and stellar motion was invoked so that the stars could never fall to the core of the universe and thereby impinge upon the "Devine Centre." Were the stars arranged in some motionless configuration, Wright argued, invoking the idea first raised by Richard Bentley some 58 years earlier, they would simple collapse under their mutual gravitational attraction to a common center. For Wright, the stars were put in motion about the Devine Center at the time of the Creation, and this implies that the stars were all formed at the same time.[5] Wright's ideas are decidedly idiosyncratic, but they at least initiate the important cognitive step that takes us towards the idea of a dynamical universe (or galaxy as we would call it) with the stars preferentially arranged according to an identifiable structure.

Almost immediately after publishing his "An original theory," Wright began to backtrack on his ideas, and he eventually sold out to classical ideas, suggesting that the, "starry firmament might well prove to be no other than a solid orb … And the fixed stars no more than perpetual lamination or vast eruptions." History has mostly relegated, if it appears at all, Wright's ideas to the foot- or end-note sections of modern cosmology texts. It sits on the uncomfortable divide between what we now recognize as being real scientific enquiry (undertaken in order to explain an observed phenomena) and the dogmatic inclusion of assumed starting conditions.

For all this, however, Wright was partly on the right track in his interpretation of the observed phenomena of the Milky Way and for his realization that gravitational attraction required that stars must be in motion. The universe, whether infinite or not, was dynamic and slowly changing. When (and again if) Wright is ever mentioned within modern astronomical texts it is because of a statement he makes about other "Divine Centers" and what lies beyond the body of stars that we can see. With respect to his favored spherical shell model, Wright argued that beyond the confines of the Milky Way shell was the domain of "outer darkness," where the damned were exiled. More importantly for our historical theme, however, Wright argues, "the many cloudy spots, just perceivable by us … may be external creations, bordering upon the known one (the Milky Way), too remote for even our telescope to reach." Here is the first mention by Wright of diffuse nebulae, and while it is difficult to interpret his thinking, Wright appears to be suggesting that these "cloudy spots" are other universes apparently centered on distinct and separate Devine Centers.

In modern terms Wright is almost invoking the idea of a multiverse [5]. Theologically such daring notions would not, at that time, be well received. Indeed, writing anonymously in 1755, philosopher Emmanuel Kant (working from a lengthy book review rather than Wright's original text) misunderstands Wright's intended ideas. Incapable of believing that Wright was actually invoking the notion of individual creations, each centered upon its own divine core, Kant stumbles upon the more useful notion of "island universes," not so much as distinct and separate creations but as remote stellar systems (galaxies in the modern vernacular) within one large cosmos. With Kant we also begin to see a solidification of the idea that the fixed stars are not scattered randomly throughout space but are arranged in a dynamical and systematically ordered fashion.

At the same time that Kant was speculating on the possibility of island universes, French astronomer and deacon to the Church, Abbé Nicholas Louis de Lacaille was recently returned from his travels abroad. At the age of 37 years Lacaille had ventured to the southern hemisphere, and working from a make-shift observatory established at the Cape of Good Hope, on the southern tip of Africa, he set about observing and mapping the antipodean stars. From March 1751 to March 1753 he measured the positions and

---

[5] From *Genesis* 1:14, which would have been Wright's overriding authority, we have, on the fourth day, "Let there be luminaries in the vault of the sky."

cataloged some 9800 stars, and he made careful observations of the Moon and planetary positions. Combing the latter positions with simultaneous observations made by Jerome Lalande back in France, new estimates were made for the distance to the Moon and the Sun. His southern star catalog, *Coelum Australe Stelliferum*, was published posthumously in 1763, and it was Lacaille who proffered names for most of the then new, and the now accepted, southern hemisphere constellations. During his survey of the southern stars, Lacaille inevitably came across oddities, and these he described in a catalog, *On the Nebulous Stars of the Southern Sky*, published by the Royal Academy in Paris in 1755. Lacaille's catalog contained entries on 42 nebulous objects that he divided into three kinds. Objects of the first kind were described as being nebulae without stars; the second kind constituted nebulous stars with clusters, while the third kind were described as stars accompanied by nebulosity. Somewhat ironically, from a modern perspective, objects listed by Lacaille as being of the first kind included several globular clusters, a few open clusters and one galaxy. The remarkable nova-like star Eta Carina was introduced as an object of the third kind, and so, too, is the interstellar cloud and star formation region M8, also known as the Lagoon Nebula (Fig. 1.4).

With the publication of Lacaille's catalog we are also introduced to the Coalsack Nebula (Fig. 1.5). This remarkable dark interstellar dust cloud located close to the Southern Cross constellation Crux had long been noticed by explorers of the southern seas, but with Lacaille's description we begin to perceive a sense of its mystery. Lacaille writes, "One can yet mention among the phenomena which strike the view of those who look at the Southern sky, a space of about three degrees in extension, in all directions, which appears dark black in the eastern part of the Southern Cross. The appearance is enhanced by the vivid whiteness of the milky way that enshrouds the space on all sides." [6].

Fig. 1.4 The Lagoon Nebula (M8) is located in the constellation of Sagittarius. Located some 5000 light years away, the nebula was first described by Italian astronomer Giovanni Battista Hodierma in 1654 and is just visible to the unaided eye. Image courtesy of the European Southern Observatory, ESO

Fig. 1.5 A portion of the Coalsack Nebula. Image courtesy of the European Southern Observatory, ESO

Different, and at odds with the bright glow of the stars and bright nebulae, what is the Coalsack Nebula? Easily visible to the unaided eye, it is a dark macular on the otherwise glowing abundance that delineates the Milky Way. However, does the absence of starlight in this small patch of the sky indicate a true dearth of stars, and a literal hole in the heaven's fabric? Are we really seeing the darkness, the coal-black darkness, of space, or is there something else going on? Is this one of Newton's feared-for regions in which the balance of stars has moved beyond the impotency of Buridan's donkey—a void created by the veritable crashing of stars and the rolling of heavenly spheres?

Perhaps it is a European, Old World, way of seeing things, but not every culture has viewed the Milky Way solely in terms of the nebulous light that it exudes. Indeed, the significance of the Milky Way, in many cultures around the world and through history, has been cast in terms of its voids and dark regions. For such cultures the story of the cosmos and creation of the world is defined in terms of what is framed by the stars, rather than the actual distribution of the stars themselves. For the ancient Babylonians and the ancient Greek astronomers, in fact, right through to the modern era, the night sky is delineated by the pointillist outlines of heroes, gods and mythical beasts, their helical rising and setting being used to determine the time of the seasons and the passage of the years.

For numerous Australian aborigine clans, however, the heavens are described according to the subtle sky shadows of creatures from the Dreamtime. Rather than the deep-socket of darkness and starless void seen by early European explorers, the Coalsack Nebula, to the aborigine eye, is the head of *Tchingal*, the Emu, with its aphotic body, neck, and feet stretching through the constellations of the Acrux, Centaurus, and Scorpio. In another interpretation the Coalsack is the hiding place of *Bunya*, the possum, who has climbed to the top of a sky tree after being chased by hunters. To the ancient Inca in Peru, the Coalsack Nebula formed part of *Tinamou*, the partridge. *Tinamou* lies nestled between *Hatun llamaytoq*, the Mother Llama (her body the dark clouds of the Milky Way stretching through Scorpius, her eyes the glowing orbs of α and β Centauri), the toad *Hanp'atu* (another distinct dark cloud), and the Snake, *Mach acuay,* which extends through Vela and Pupis, its head arching towards Sirius.

The Milky Way is the optical backbone of the celestial sphere, and it winds around the world as a star-studded braid, divided and crossed, according to culture and background, by constellations and dark maculation, the yin and the yang of perception, that are the ancient shadows of distant mythology.

The Star-Gauging Siblings

Although it is difficult to dismiss the beauty of the mythical heavens created by the human imagination, the Milky Way will only reveal its true secrets by detailed examination, and indeed, it is only through the deep searching of the Milky Way with a telescope that its true structure will be delineated—its saucy looks teasing out the very weave of its fabric. When exploring the heavens with a telescope, however, two basic approaches can be taken. Either set the telescope to view a random spot and see what turns up, or systematically scan the heavens, working in a methodical fashion, covering specific and well-defined swaths of the sky.

Both methods will reveal new phenomenon within an observer's eyepiece, but the latter method does away with good fortune and makes discovery inevitable. The systematic approach, in which specific regions of the sky are surveyed, is the powerful working methodology that has long been adopted by the comet hunter. Certainly chance and good fortune govern the discovery, but repeatedly looking in the right part of the sky at the right time (the pre-dawn or post-sunset regions of the eastern and western sky) will maximize the chance of catching a new wayward comet.

Eighteenth-century French astronomer Charles Messier knew this observing rule well, and he applied it with great success, discovering in his lifetime 13 new comets. What Messier also found in the sky, however, were nebulous clouds and faint star groupings that, at first glance, might be confused with a comet. These nebulae had no specific interest for Messier, but he diligently cataloged such objects when he came across them, and by 1774 his first catalog was published in the journal of the French Academy of Sciences. Several revised versions of Messier's catalog appeared in subsequent years, with the final version, *Catalogue des Nebuleuses & des amas d'Etoiles*, seeing print in 1781. The final edition contained some 103 entries [7]. From a modern perspective, among the objects contained in Messier's catalog are some of the most spectacular sights that can be found in the night sky, and his list reveals galaxies, genuine nebulae, supernova remnants, planetary nebulae, galactic star clusters, and globular clusters (recall Fig. 1.1). This modern labeling, of course, was not available to Messier or his contemporaries, but the key point in our present narrative is that nebulae, of one shape or another, were being found in relatively large numbers by astronomers, equipped, again by modern standards, with relatively small telescopes. Messier was using a modest 4-inch refracting telescope to conduct his studies, and prior to 1785 the largest telescope in the world was the 29.5-inch diameter reflecting telescope[6] constructed by the reverend John Mitchell in Yorkshire, England.

Pushing the light-gathering power of telescopes to the limits of available materials and technology, and then using this advantage to systematically gauge the sky, was the great passion of William Herschel; and it is Herschel that takes our story of discovery in new and innovative directions. In the same year that Messier's final catalog appeared, Herschel secured a permanent place in the history of science by discovering the planet Uranus—an object that, when he first swept it up in his eyepiece, he thought was a comet. The discovery of Uranus was monumental, and it brought Herschel fame and royal patronage, with the latter importantly enabling him to concentrate on building larger and better telescopes with which to explore the heavens.

With new-found fame and money at his disposal, Herschel set about moving himself and his somewhat reluctant sister Caroline to a new home, eventually named Observatory House, in Slough. It was from there, beginning in the early 1780s, that William and Caroline set about the systematic study of the heavens. Having received a copy of Messier's catalog in 1783, the Herschel siblings became interested in finding more such objects, and by 1802 the brother-sister duo had cataloged some 2500 new nebulae. Their method of discovery was highly systematic, and consisted of using a sky-drifting technique. Accordingly, the telescope would be set to some prescribed and fixed altitude, and then, as Earth's spin carried the telescope's field of view slowly across the sky, a long ribbon of the celestial sphere could be examined. When a new nebula was sighted, William, at the eyepiece, would call out a description when it crossed the center of his eyepiece view, and Caroline would then dutifully record the time and details.

Herschel became fascinated with nebulae, and he gamily strove to understand what they were and what they were telling us about the heavens. In 1782 Herschel found his first planetary nebula, and this discovery alone resulted in a long-running struggle to understand the connection between nebulosity and stars. Did new stars form in nebulous regions, or did they simple drift into them? Cataloged as NGC 7009 (Fig. 1.6) Herschel noted that he saw, "a star surrounded by a cloud of (true) nebulosity," and he speculated that the nebula might represent a star caught in the process of assembling.

---

[6] It was in 1785 that William Herschel began the construction of what was to be his great 40-foot telescope—an instrument that utilized a 47-inch diameter mirror to capture starlight. This giant telescope was paid for with funds provided by King George III, and saw first light on February 19, 1787, when Herschel observed the Orion Nebula—object number 42 in Messier's catalog (Fig. 1.1a).

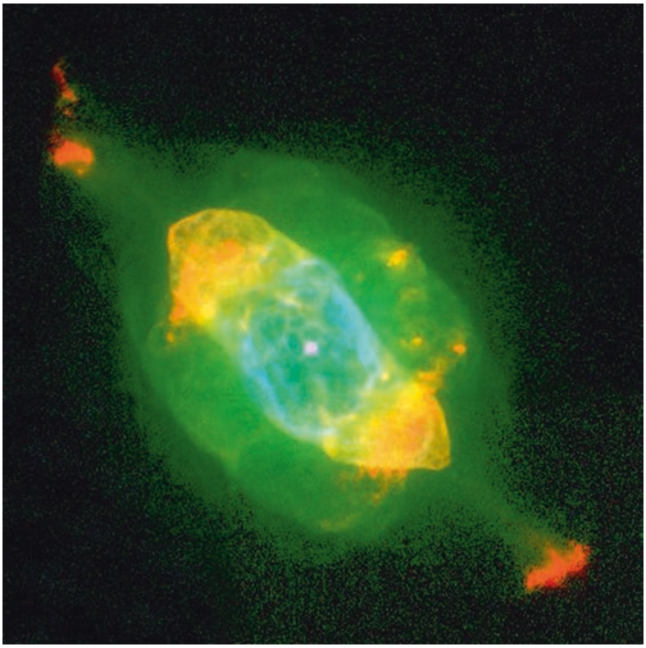

Fig. 1.6 NGC 7009, William Herschel's first planetary nebula. Named the Saturn Nebula by William Parsons (Lord Rosse) in the 1840s, NGC 7009 is located some 3000 light years away. A *cylinder-shaped* nebulosity surrounds the central star, with two jet-like streams moving away from the central region, along the system rotation axis, to terminate in two bright ansae. Image courtesy of NASA/HST

Such objects had, in fact, been observed earlier by Messier in the 1760s, but it was Herschel that coined the name planetary nebula in the mid-1780s in response to their observed round(ish) shape and smoky-green color. Although in 1784 Herschel asserted that nebulae were likely composed of some form of shining or fiery fluid, in agreement with the earlier ideas presented by Edmund Halley, he backtracked on this notion in a paper read before the Royal Society of London in 1785. Indeed, Herschel noted that wherever he looked in the zone of the Milky Way he had always found that it was composed of stars. Likewise, he observed, globular clusters could be resolved into myriad stars, and, he speculated, that they were possibly formed by gravitational clustering around a large central star. As to the diffuse nebulae, Herschel asserted that they were probably distant star clusters.

To Herschel, the stellar realm was very much a dynamic place, and he argued that the stars were initially arranged with some degree of regularity (as advocated for by Newton) but that they moved and clustered together under their mutual gravitational attraction. In addition, he noted, "there will be formed great cavities or vacancies by the retreat of stars towards the various centers," and anticipating a final universal crash of stars, he argued that the globular and open clusters might be the "laboratories of the universe, wherein the most salutary remedies of the decay of the whole are prepared." In an attempt to establish the distribution of stars in space Herschel employed a star-gauging methodology, and literally counted the number of stars that he could see in various directions around the sky.

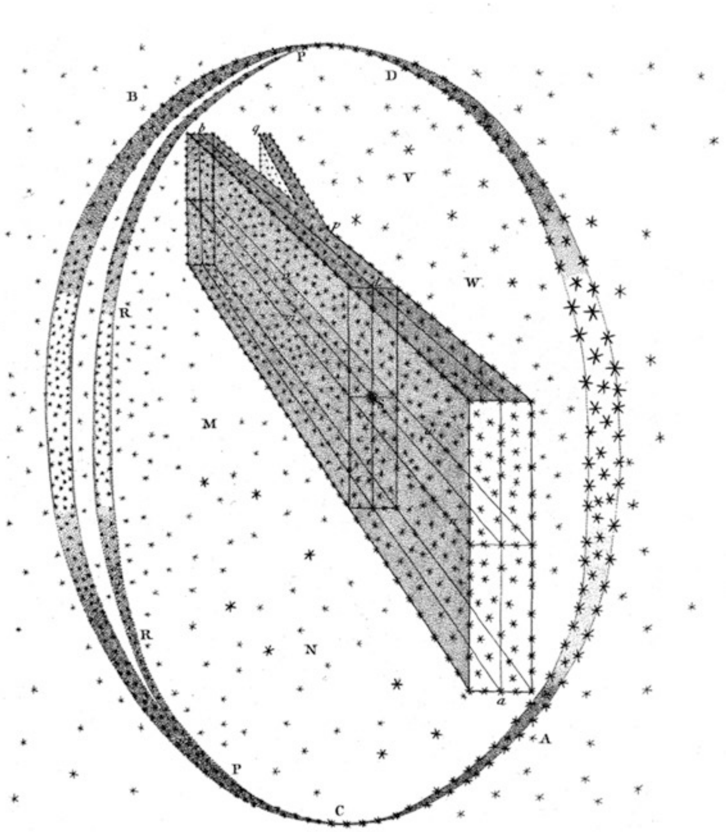

Fig. 1.7 The distribution of stars in the stellar realm as deduced by William Herschel in 1785. The stars are distributed in the form of a flattened disk, cloven in half (in the direction of Sagittarius and Scorpio), with the Sun at the center

Presenting his results to the Royal Society in 1785, Herschel argued that his gauges (to be described in more detail below) indicated that the stars were arrayed in a flattened disk, or stratum, with the Sun located at the center (Fig. 1.7). This distribution is similar to the disk-like structure evoked in 1750 by Thomas Wright of Durham, who had no more than the visual appearance of the stars on the sky to work with (recall Fig. 1.3). The stratum containing the stars, however, was not uniform but cloven—Herschel remarking that "some parts of the system indeed seem already to have sustained greater ravages of time than others." Herschel estimated that the stratum of stars had a diameter that was some 1000 times larger than the distance to Sirius, and some 100 times the distance to Sirius across. Taking, as Herschel did, the distance between the Sun and Sirius[7] to be a typical star separation distance, his estimate for the size of the stellar stratum translates to being about 9700 light years across and 970 light years in depth.

---

[7] Isaac Newton in his 1687 *Principia Mathematica* estimated that Sirius was 615,670 AU from Earth.

Fig. 1.8 The Crystal Ball Nebula. This infrared image of NGC 1514 was obtained with the WISE spacecraft, and it reveals an intriguing set of dust rings situated about the central binary star system. The nebula is located some 2200 light years away. Image courtesy of NASA/JPL—Caltech/UCLA

By the early 1790s Herschel once again changed his mind on the possible constitution of at least some nebulae. Viewing the Orion Nebula (M 42) with his newly constructed 40-foot reflector, Herschel argued that it was, "an unformed fiery mist, the chaotic material of future stars," and this viewpoint was further strengthened by his discovery, on November 13, 1790, of NGC 1514 (Fig. 1.8). Herschel described NGC 1514, now known as the Crystal Ball nebula, as "a most singular object," and he further noted that, "the nebulosity about the star is not of a star nature." In a paper read before the Royal Society of London, on February 10, 1791, Herschel discussed the topic of "Nebulous Stars, properly so called," and argued, from his extensive observational notes that some stars are truly "involved in a shining fluid, of a nature totally unknown to us." This "shining fluid," he further suggested, can even exist in space without the presence of a central star, the Orion Nebula being described as one such example where there was distinct nebulosity but no apparent connection with any specific star or stars. Herschel did note and record the four bright stars that make-up the so-called Trapezium cluster in M 42 (Fig. 1.9), but he asserted that they were unrelated to the nebulosity. It is now known that this cluster of young bright stars is responsible for illuminating most of the surrounding nebula.

Moving deeper into the 1790s Herschel began to direct his observational efforts towards objects other than nebulae—his ensuing publications relating to the study and observation of new comets, planets, planetary satellites, and stellar motion, along with the description of his new telescopes and the discovery of infrared radiation (see Chap. 2). In 1800, however, among the 30 papers he read to the Royal Society in that year, Herschel released a catalog of 500 new nebulae, to which he added some "remarks on the construction of the heavens." Indeed, from this time forward, Herschel has his sights firmly set on decoding the sky—how are the stars set out in space and what kinds of nebulous matter exist between and around the stars.