Comets in the 21st Century

A personal guide to experiencing the next great comet!

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With a Foreword by Walter F Huebner

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To Michael Hockey and Artyom Ivakh, who, if luck holds, will see a Great Comet—T H

For my granddaughter, Alison Boice, who, at the age of 9, shows promising signs of becoming a Great Comet hunter and my wife, Panida Boonmasai, for her steadfast support in all of my endeavors.—D B

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Preface

I knew I wanted to study the heavens, ever since peering at Comet West seeming to hover above my home. When in the 1990s it became known that another Great Comet soon would appear in the sky, I wrote *The Comet Hale–Bopp Book: Guide to an Awe-inspiring Visitor from Deep Space* (1996 (Shrewsbury, MA: ATL)). The comet did not disappoint; I recall lecturing via bull horn to a thousand people standing in front of the Adler Planetarium, seeing the comet despite the bright lights of downtown Chicago.

The goal of that book was to introduce at the most basic level this cosmic sight to the millions who would watch it. While about Comet Hale–Bopp specifically, the work contained a lot of general information on comets that stood in its own right. (Some of this material appears in the present volume.) Of course, it is by now outdated—in rode co-author Dr Daniel Boice, whom I had known for nearly forty years and who, during that time, devoted himself to the investigation of comets, to provide the leap in comet science and observation that has occurred in more recent years. Thanks for his support of this project also go to Dr William Sheehan, astronomy author extraordinaire.

This present volume was created literally around the world: Boice writing from Thailand and I working in the United States. We hope our combined effort pleases the reader, regardless of whether they have had the opportunity to see a Great Comet themselves—or have yet to.—T H, Cedar Falls, December 2018

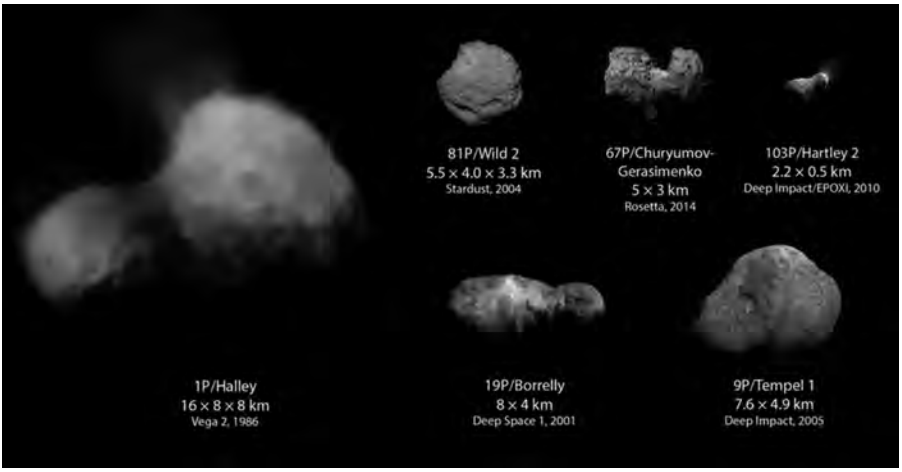
I was born at the dawn of the space age and was inspired by NASA's Apollo missions, which eventually landed 12 people on the Moon. Afterwards, my interest in all things astronomical grew, and I eventually bought my first telescope, a used 60 mm refractor, while attending high school in San Francisco, CA. I quickly graduated to an 8 inch Dobsonian reflector that I built myself under the guidance of the legendary John Dobson and joined the amateur ranks by enrolling in the historic San Francisco Amateur Astronomers. I have been very fortunate to follow my dream to become a professional astronomer and am deeply indebted to NASA and the National Science Foundation who have supported my career and to the opportunities provided by my employer of 26 years, Southwest Research Institute (San Antonio, TX). Ultimately, I must thank the American people for this funding and their trust that their money would be well spent!

Although primarily a researcher, my passion for teaching still burned. I was able to share my knowledge and enthusiasm of astronomy with students at University of Texas at San Antonio, San Antonio Community College, and Trinity University for over 20 years. Teachers learn a lot from their students. During this time, I was fortunate to supervise graduate students, our next generation of astronomers, and participate in many foreign collaborations.

I met my co-author Dr Thomas Hockey in graduate school at New Mexico State University. I graduated three years earlier and left for Los Alamos National Laboratory in 1985 where I was converted to comet science by Comet Halley and my mentor, Dr Walter Huebner. T H joined the faculty at the University of Northern Iowa to pursue his joy of teaching and historical astronomy. Our paths diverged for several decades, even though we are both members of the American Astronomical Society (AAS) and the International Astronomical Union (IAU). I took notice in 2017 when he won the prestigious Osterbrock Book Prize from the AAS Historical Astronomy Division for his four-volume reference work, *Biographical Encyclopedia of Astronomers*. Having the chance to co-author a book with him was a no-brainer.

Special thanks go to Dr Walter Huebner, retired Institute Scientist at Southwest Research Institute, and Professor Amaury de Almeida, Chair of the Astronomy Department at the University of São Paulo, Brazil, for reviewing our manuscript. Their insightful comments have significantly improved this book. Naturally, we are responsible for any remaining errors. I share my co-author's desire that you, the reader, will enjoy our work.—D B, Puan Phu, Thailand, December 2018

Frontispiece



Gallery of comet nuclei visited by space probes (to scale) with year of encounter. Courtesy of The Planetary Society.

Foreword

Comets are unusual objects in the sky that have aroused the interest and curiosity of many who have seen one. What are these objects, where did they come from, what causes their strange appearance, and what do we know about them? The authors of this book are much better known than these comets and much younger; they will reveal to us many of a comet's visual phenomena in familiar terms from everyday life without getting into deep scientific explanations.

The purpose of this book is to bring comets into the living rooms of general households, to familiarize politicians with these fascinating objects when they ponder funding for comet research, to teach children and young students, and to provide teaching tools about these very unusual objects in our skies. The presentation is very comprehensive in its description of orbits around the Sun, the development of the coma (escaping atmosphere) from a comet's nucleus and source of all activities, various types of comet tails, trailing as well as leading as a comet orbits our Sun, ancient beliefs and explanations of these phenomena, and the most recent discovery of the first interstellar comet. An interstellar comet is particularly exciting, because it has the potential to reveal data about a neighboring star without going there. For example, the stellar nebula from which the star formed may have been larger or smaller than the solar nebula (thus a different density), have a different radiation field and have a somewhat different composition. This would lead to different chemical reactions and thereby affect the conditions for the origins of life when compared to the conditions in our Solar System.

Daniel C Boice is a well-known astronomer, specializing in comet science, a discipline where professionals and amateur observers work hand-in-hand to study the mysteries of these celestial bodies. Thomas A Hockey is a professor of astronomy, specializing in the history of that field, and an award-winning author. We spoke recently about the allure of comets and the impression they make on people. Many astronomers, both professional and amateur, can name a comet that influenced their interest in the sky at an early age. For Boice, it was Comet West, which he saw light up the morning sky in 1976. For Hockey, it was Comet Bennett. Bennett was so shiny that he could even see it through his dining room window, in March 1970, the month of his eleventh birthday. 'Dan', Thomas suggested, 'sky lovers don't need to tell one another their age, only the name of their comet'. For me, it was the Great Comet Ikeya–Seki, the spectacular sungrazer of 1965.

Walter F Huebner, December 2018
Division of Space Science and Engineering
Southwest Research Institute
San Antonio, TX

Author biographies

Daniel C Boice

Daniel Boice is the principal astronomer at Scientific Studies and Consulting in San Antonio, TX. Prior to his present position, he spent 26 years in the Space Science and Engineering Division at Southwest Research Institute, TX, where he performed cometary research sponsored by NASA and the National Science Foundation. Concurrently, he held a joint appointment to the Department of Physics and Astronomy faculty at the University of Texas at San Antonio, where he taught undergraduate and graduate courses for 20 years. After receiving his BS in Physics at Brigham Young University in 1975, he obtained a PhD in astronomy at New Mexico State University in 1985. While a postdoctoral fellow in the Theoretical Division at Los Alamos National Laboratory, Dr Boice developed a computer model of cometary comas that has been successfully used to interpret spacecraft data and ground-based observations of many comets. He was a member of the science team for NASA's Deep Space 1 Mission to Comet P/Borrelly. His professional activities include over 75 peer-reviewed research papers, several hundred conference reports, and serving as Past Chairs of the Physical Studies of Comets Working Group (International Astronomical Union) and Space Related Studies of Small Bodies of the Solar System (Committee on Space Research (COSPAR)). In 2000, he became a Fellow of the Royal Astronomical Society. He has spent several years abroad teaching and working with colleagues in Germany, Japan, France, and Brazil. Dr Boice is continuing his comet research to assimilate information from ground-based observations and *in situ* spacecraft measurements to develop a better global understanding of comets. When not engaged in all things comets, Daniel loves collecting books and rock 'n' roll music, board gaming, and rice farming with his family in northern Thailand.

Thomas Hockey

Thomas Hockey is a professor of astronomy in the Department of Earth and Environmental Sciences at the University of Northern Iowa (UNI), where his research interests include studies of the history of planetary astronomy in light of the modern search for planets orbiting other stars, as well as the astronomy of solar eclipses and comets, and the archeoastronomy of pre-historic peoples. After receiving his BS in Planetary Science at the Massachusetts Institute of Technology in 1980, he ventured west to obtain an interdisciplinary PhD (Astronomy, History, and Philosophy) at New Mexico State University in 1988, specializing in History of Astronomy and Science Education. Professor Hockey enjoys teaching, having taught undergraduate and graduate courses at UNI for three decades. His professional activities include many peer-reviewed research papers and several books. In 2017, he received the

Osterbrock Book Prize from the Historical Astronomy Division (HAD) of the American Astronomical Society (AAS) for his four-volume tome, *Biographical Encyclopedia of Astronomers*. He has also served as the Editor-in-Chief of the *Astronomy Education Review* and Past Chair of the HAD/AAS.

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Daniel C Boice and Thomas Hockey

Chapter 1

Introduction

‘The comet is coming!’ The words are alliterative and compelling. We do not know the name of that comet yet. We do not know when it will arrive. However, eventually, another Great Comet will grace our skies—one that dazzles the naked eye and may even be seen in broad daylight. This means that you can have a one-on-one relationship with the comet, without the assistance of astronomers, television commentators, or anybody. Like others before it, the next Great Comet will be every person’s comet.

Typically, a brilliant comet makes an appearance in Earth’s sky every decade or so. Except for those who saw the difficult-to-observe Comet McNaught in 2007, the last Great Comet (figure 1.1), a generation grew up without really knowing what a comet is all about. We are overdue! This book is written to enhance your anticipated comet experience, or just to inform those who wish to know a little more about these celestial visitors.

Why should you make a point to experience the next Great Comet? A bright comet is an astronomical event. It is a ‘one-time offer’ from the heavens. Moreover, unlike eclipses or conjunctions (the alignment of planets in the sky), it is unique and usually cannot always be predicted. A comet is an awe-inspiring presentation of nature, on par with an erupting volcano, a mass migration, or a cyclone. Moreover, it is not nearly as dangerous to watch!

People have been looking up at comets for a long time, longer than we have recorded history. Comets are part of our culture; they are incorporated into our traditions and beliefs. Observations of comets are universal. They are a communal human experience. As you look up at it, perhaps from your back porch, you will be sharing it with persons around the planet, standing outside huts, mansions, pueblos, skyscrapers, yurts, condos, igloos, marinas, trailers, villas, and pup tents (figure 1.2).

A comet does not flash across the sky, as some individuals who confuse comets with meteors believe. You do not have to set your alarm clock and go to bed with

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Figure 1.1. Comet McNaught in 2007. NASA image.

Figure 1.2. Comet Ikeya-Seki in 1965. Photo taken at NASA's Jet Propulsion Laboratory (JPL) Table Mountain Observatory, reproduced with permission from James W Young, photographer.

your sneakers on to catch it. Depending upon how bright it gets, most people will be able to view a Grand Comet for weeks or months.

Furthermore, unlike the constancy of the full Moon or constellations of stars, a comet will change in appearance, perhaps night-to-night or even hour-to-hour.

The authors spoke recently about the allure of comets and the impression they make on people. Many astronomers, both professional and amateur, can name a comet that influenced their interest in the sky at an early age. For D B, it was Comet West, which he saw light up the morning sky in 1976. For T H, it was Comet Bennett (figure 1.3). Bennett was so shiny that he could even see it through his dining room

Figure 1.3. Comet Bennett in 1970. Copyright 1970 Fred Espenak, www.Astropixels.com.

window, in March 1970, the month of his eleventh birthday. ‘Dan’, T H suggested, ‘sky lovers don’t need to tell one another their age, only their comet.’

During the 1970s fad of ‘disaster movies’, T H watched his home town of Phoenix, AZ, ‘destroyed’ by a fluke comet in a television version of the genre. (With all that empty desert surrounding Phoenix, it was a remarkable shot!) Those cardboard models of familiar landmarks flying about looked silly, but foreshadowed evidence of real cometary cataclysms discovered in the 1990s.

In 1986, we joined astronomers around the world pointing out Comet Halley to the public (figure 1.4). That faint smear (no longer a Great Comet), seen through the telescope, never failed to disappoint. The fact that it was 4:00 A.M., and wintertime, did not help matters, either.

Would a bright comet ever come? Actually, there had been such a comet in 1976, Comet West (figure 1.5). However, West came less than two years after the ‘hype’ accompanying the fizzled Comet Kohoutek, the so-called ‘comet of the century’. Many did not wish to be fooled twice and remained skeptical. Thus, most folks missed a lovely comet. (Again, early morning prominence kept the audience low.)

It almost seemed as if the comets were impishly conspiring to mislead us. Then, suddenly, it was here! Comet Hale–Bopp was discovered in 1995. One year before Hale–Bopp, Comet Hyakutake danced overhead. Hyakutake was discovered less than two months before its peak brightness in the Earth’s sky in 1996. It came and went as Comet Hale–Bopp crept inexorably nearer for a 1997 performance (figure 1.6). In 2007, Comet McNaught became one of the brightest comets of the last century. Unfortunately, it remained in that portion of the Celestial Sphere only seen from far south. Thus, most of the world’s population had no chance of getting a good look at it.

Figure 1.4. Comet Halley in 1986. NASA image.

Figure 1.5. Comet West in 1976. J Linder/European Southern Observatory (ESO).

Lest we give you the impression that comets in general are very rare events, the above discussion centered on Great Comets, ones that can be seen with the naked eye, some in broad daylight. They outshine Venus, the third brightest object in the heavens (following the Sun and Moon). There have been only nine such comets (McNaught included) in the past three and a half centuries (on average one every 38 years). In 2013, Comet ISON was expected to be on this list (predicted to be almost as bright as the full Moon due to its expected proximity to the Earth), but it fragmented during its close approach to our home star. During the past century, there have been 14 brilliant, showpiece comets that could be seen by the naked eye at night or with a small pair of binoculars (on average 1.4 comets per decade). Notable

Figure 1.6. Comet Hale–Bopp in 1997. NASA image. Copyright 1970 Fred Espenak, www.Astropixels.com.

naked-eye comets in the past few years include Comet PanSTARRS (C/2011 L4), the three Lovejoy comets (C/2011 W3, C/2013 R1, and C/2014 Q2), and Comet 46P/Wirtanen[1]. Dozens of garden-variety comets are discovered each year, some bright enough to be seen with a small telescope, albeit most are out of reach for amateurs. Every night, a few comets are in the night sky to be studied by the pros. We may be awaiting the next Big One, but many comets can be enjoyed every few years or so.

You probably know that comets, like all other Solar System bodies, orbit our Sun so they periodically return to our skies when they get close to the Earth. Almost all observed comets follow elliptical orbits that penetrate well inside the orbit of Mars, some even cross the orbit of Mercury. In practice, you rarely see comets beyond Jupiter since they are very small and dim. Why this happens is explained in chapter 3.

What if comets were sentient beings or if aliens installed monitoring equipment on them; imagine the record of the Earth they would capture. Comet Halley would have an impressive photo album of the Earth taken at 76 year intervals, dating at least back from the ancient Chinese to the present. Major milestones would include:

- 240 BCE—Chinese ‘broom star’ seen during the Warring States Period, first historical record.
- 87 BCE—Babylonians record it in their province of the Parthian Empire.
- 12 BCE—‘Hung like a sword over Rome before the death of Agrippa’—historian Dion Cassius.
- 451—Defeat of Attila the Hun by the Visigoth/Roman alliance at the Battle of Châlons.
- 684—Seen by Europeans and later published in the *Nuremberg Chronicle.*
- 1066—Depicted in the Bayeux Tapestry, Battle of Hastings.

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[1] This comet nomenclature will become clear in chapter 5.

- 1301—Seen as the Star of Bethlehem in Giotto di Bondone's fresco *The Adoration of the Magi.*
- 1607—Observed by the famous German astronomer Johannes Kepler and published in his book, *De Cometis Libelli Tres*, in 1619.
- 1682—Sighted by Edmund Halley at Islington, 'Hence I dare venture to foretell, that it will return again in the year 1758'.
- 1910—Jack Johnson knocks out James Jeffries to retain his World Heavyweight Championship title, Boy Scouts founded, comet hysteria, and the first photograph of Halley.
- 1986—Challenger Space Shuttle disaster, Chernobyl catastrophe, first laptop computer from IBM (weighing 12 lbs), and international armada of space probes to Halley.

Maybe a few selfies would be thrown in, too. What will be seen in 2061 during its next return?

Is a mere comet worth all the fuss? For example, does it merit this book? You be the judge. For a few days in 1997, Comet Hale–Bopp was all the rage with TV meteorologists. (We guess weather and astronomy both involve looking up.) If you were one of those who wished that they would just get on with telling you whether it was going to rain, comets probably are not for you. On the other hand, if Comets Hale–Bopp or McNaught whetted your appetite for these celestial specters, this is the place to be. Here is what we know, so far.

Chapter 2

Roller-coaster comets

One does not need to know about pyrotechnics to appreciate a good fireworks show. Likewise, one does not need to know a lot about comets to appreciate the show they put on. However, for those of you for whom understanding enhances seeing, this chapter will give you a bit of background information on comets. If it piques your interest, you will want to read the rest of the chapters.

How do we define ‘comet?’ You may be surprised that astronomers have no official definition of this word. (You can find one in language dictionaries, but these are not meant for the specialist.) We accept the millennial-old traditions of our ancient relatives who noted that some ‘stars’ were fuzzy and had the appearance of ‘hair’ streaming from their ‘heads’. They also moved through the heavens relative to the surrounding stars. The Greeks used the word ‘κομήτης’, meaning long-haired. So when astronomers discover a small Solar System body that shows signs of actively producing a surrounding cloud, called the *coma*, and/or *tail(s)*, it is classified as a comet. This simplistic definition now leads to confusion since we have several objects that share the distinction of being both an *asteroid*[1] and a comet, i.e. they were originally discovered as asteroids but later showed signs of activity or vice versa (e.g. asteroid 2060 Chiron and Comet 95P/Chiron are the same object). Some small bodies were recently discovered in the Main Asteroid Belt that displayed *dust* tails and so were named ‘Main Belt comets’. Later several were shown to be activated by collisions with other bodies, not water ice *sublimation*[2] as is the case for comets, so are actually ‘active asteroids’, but still retain a comet designation. In fact, there may be a continuum of bodies between the inert asteroids and the active comets. Now that we have gathered details on thousands of these bodies using high-powered

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[1] Asteroids are small Solar System bodies primarily made up of rock and metal. Most are found between the orbits of Mars and Jupiter, a region called the Main Asteroid Belt. More on these space rocks can be found in chapter 3.

[2] Sublimation is the chemical term to describe the change of a substance from solid to gas and vice versa without passing through the liquid phase.

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telescopes and spacecraft, this observationally motivated definition needs a makeover, much like the definition of 'planet' was revised in 2006. Comets should be classified by their physical and chemical properties, time and place of formation in the Solar System, activation mechanism, and orbital properties. Hopefully, astronomers will remedy this rather embarrassing situation soon! If, after reading this book, you would like to propose a definition, please let us know.

2.1 The paths of comets

Comets are peculiar beasts. They seem to appear in the sky suddenly, unexpectedly. They move rapidly along paths unlike any other object in the sky. They do not look like anything else in the sky, with their fuzzy heads and long tails, and their appearance may change nightly. Then, after weeks or months, they go away, some coming closer to the Sun than any other Solar System object.

It was this mysterious behavior of comets that gave them their reputation. Comets often appear as swords or daggers in the sky. In days of old, comets were considered omens of things to come; unpredictable, they were thought to be celestial prophecies of the future. Most often, the events they 'predicted' were interpreted to be bad news: a famine, a plague, the death of a monarch (figure 2.1). As there always was something bad happening somewhere—alas, there always is—the 'predictions' were right much of the time!

Then, late in the seventeenth century, Englishman Edmond Halley (1656–1743) suggested that comets follow all the rules of motion that other celestial objects do (figure 2.2). If that were true, it took some of the mystique out of comets and the fear of comets out of the minds of people.

Until he tackled comets, Edmond Halley seemed destined by history to play Watson to the great scientist Isaac Newton's (1642–1727) Sherlock Holmes (figure 2.3). The two men were contemporaries. It was Halley who encouraged his eccentric and reclusive friend to publish Newton's world-changing theories of motion and

Figure 2.1. The Bayeux Tapestry illustrates the conquest of England by the Normans in 1066. Note the comet looming over losing King Harold's head.

Figure 2.2. Edmund Halley. NASA image.

gravity. These theories demonstrated that the Universe ran according to the same scientific laws of motion that, here on the Earth, caused the apocryphal apple to fall on Newton's head.

Halley embraced gravity wholeheartedly. Newton had shown that all objects in the Solar System[3] must revolve in orbits about the Sun, under the influence of the gravitational force between them and the Sun. What about comets? Comets did not seem to be a periodic phenomenon as regular as the orbit of a planet. Before Halley, each comet seen in the sky was considered a ‘one shot deal’; it appeared and disappeared, never to be seen again. Even the shifting of a comet from the evening to the morning skies (or vice versa), due to its passage around the Sun, was thought to be two different comets.

But Halley noticed, in the historical records, stories of a similarly appearing comet in the years 1531, 1607, and 1682. That was once every (about) 76 years! Maybe it was the *same* comet, thought Halley, coming near the Earth where we can see it, with that frequency.

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[3] Although moons revolve about their host planet, they still orbit the Sun.

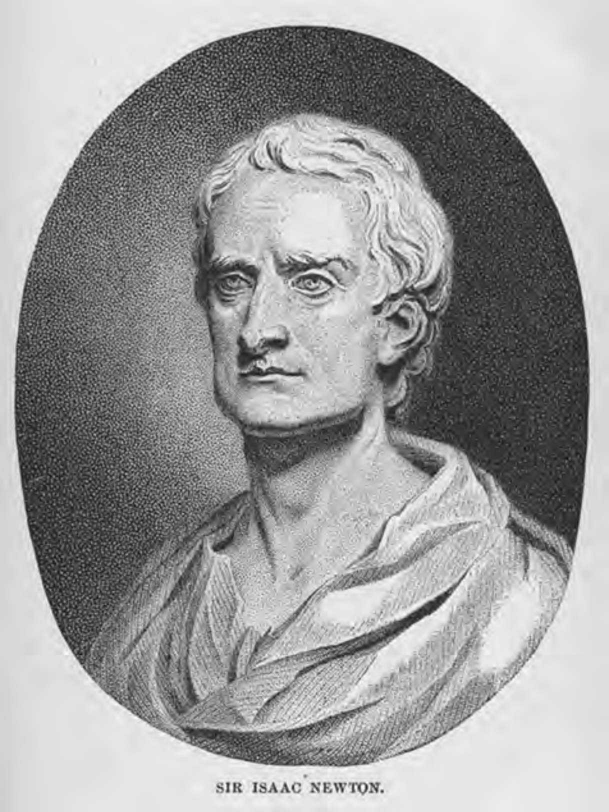

Figure 2.3. Isaac Newton. Reproduced from Bolton S K 1889 *Famous Men of Science* (New York: Crowell).

Halley used Newton's laws, and observations of the comet, to plot an orbit for it around the Sun. He then went out on a limb and predicted its return in the year 1758. Halley was dead by then, but his comet was very much alive and turned up—more-or-less on schedule—Christmas Day 1758, recognized by Nicolas-Louis de Lacaille (1713–62), a French astronomer, and the comet was named in Halley's honor in 1759.

It has been doing so ever since. Halley's Comet continues to appear in our sky approximately every 76 years. In the century just past, it put on a 'double feature', showing up in 1910 and again in 1986 (figure 2.4).

Now, we have just explained a popular misconception about Halley's Comet. Edmond Halley did not *discover* his comet. Further searches of historical records show that it was noticed as far back as the year 240 BCE. (Chinese and European sky-watchers recorded its every apparition since.) It is simply that everybody before Halley thought that it was a different comet each time. Halley did something more important than find a comet. He was the first to realize that comets orbit the Sun like planets, have periods of revolution like planets, and, in short, behave a lot like planets. Comets come and go, not as harbingers of death and obliteration, but on a regular schedule, like a celestial clock.

Figure 2.4. Comet Halley in 1910. From *Encylopaedia Britannica* (1911).

By the way, a personal quirk of T H: ‘Halley’ is pronounced like ‘alley’. Bill Haley and his Comets (‘Haley’ as in ‘Hale’) were a popular music group in the 1950s. They might have done a lot for rock-and-roll but had nothing to do with comets! There is even some evidence to suggest that Edmond himself said ‘Halley’ like ‘hallway’ without the ‘w’.

There is a good reason why it is easy to attribute the discovery of Comet Halley to Edmond Halley. Since his time, it has become the custom to name a comet after the first person, or persons, to set eyes upon it. (Alan Hale and Thomas Bopp spied their comet within minutes of each other.) The modern rule says that up to three people, anywhere in the world, can independently ‘discover’ a comet and still get their names attached to it as part of a hyphenated string[4]; hence, we English speakers have mouthfuls like Comet Honda–Mrkos–Pajdušaková.

Once the comet is confirmed, the name becomes official. No doubt as you read this, there are astronomers somewhere on the planet—mostly amateurs—scanning the skies with telescopes or binoculars. They wait for that first glimpse of a faint smudge against the blackness of sky, a new comet and their slice of immortality (figure 2.5). (A dozen or more are discovered each year.)

Why do comets need to be ‘discovered’ at all? Why can we not see comets all the time? After all, planets almost always can be seen in the sky, some with the naked eye, others by using a telescope. (The only exception is when they appear too near the Sun.) But planets travel around the Sun on paths that are very nearly circular. Their distance from the central Sun does not vary much. Because our planet Earth is comparatively close to the Sun, this means that the distance between us and another planet does not change greatly.

This is not true for comets. Comets travel in elongated elliptical paths. Their orbits are said to be eccentric. The ellipse is not centered on the Sun. Instead, the Sun occupies a point closer to one end of the ellipse. This point is one of two foci belonging to the ellipse. The other focus is empty.

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[4] More on comet discovery and naming in chapter 5.

Figure 2.5. Don Machholz, discoverer of eleven comets. Courtesy of Michele Machholz. The eye patch is an observer's tool to prevent eye fatigue, not indicative of a missing eye or a pirate!

In its orbit, an object's closest point to the Sun is called its *perihelion*; its farthest point is its *aphelion* (figure 2.6). The difference between perihelion and aphelion is small for most planets, including the Earth. For a comet, it can be immense, perhaps by a factor of a million or more.

(An extreme example is that of the sungrazing comets, which, as their name implies, either skim by the outer layers of the Sun or—in rarer cases—crash into it (figure 2.7). The Great Christmas Comet of 2011, another comet discovered by an amateur, Comet Lovejoy actually passed through the outermost atmosphere of the Sun, its *corona*[5], and survived at least for a few days, then seems to have fragmented and disappeared!)

Obviously, it is hard to see something when it is far away. Also, comets mainly shine by reflected sunlight. Not only is sunlight less bright far from the Sun, but any light that is reflected by a distant comet is dimmed as it travels the distance between the comet and our eyes. Importantly, comets change their appearance as they approach and recede from the Sun. Their surface temperatures cool to the point where water ice sublimation, the source of the comet's activity, ceases and the comet's brightness diminishes greatly. Beyond this point in the Main Asteroid Belt, the coma and tails gradually disappear and the tiny solid body, the *nucleus*, only a few kilometers in size, is all that remains. Occasionally we see unpredictable outbursts from the nucleus that may brighten and form a new coma and tail. Comet Halley displayed such an outburst at a distance past the orbit of Saturn, as did Comet Holmes in 2007 when it was mid-way between Mars and Jupiter and brightened by about half a million times in 42 h, making it clearly visible to the naked eye. More details of this behavior are given in chapter 3.

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[5] The corona is the hot but tenuous gas of electrically charged particles surrounding the Sun and extending millions of kilometers into space. It is best seen during a total solar eclipse.

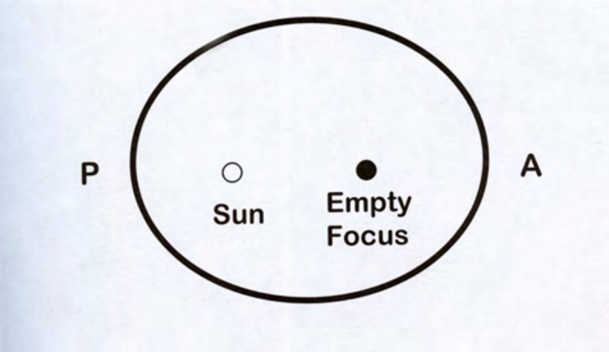

Figure 2.6. An elliptical orbit. P stands for perihelion, A stands for aphelion.

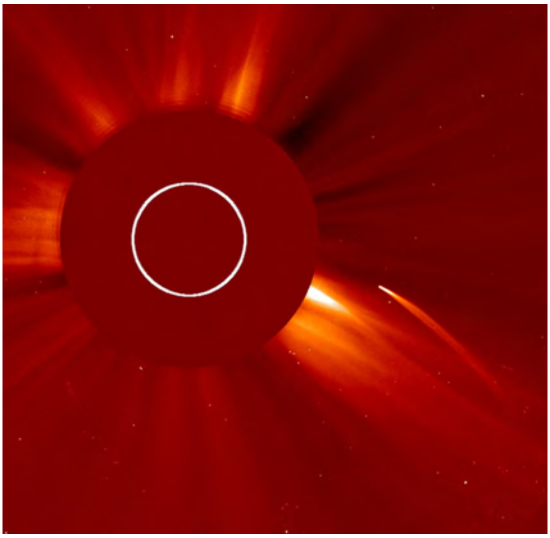

Figure 2.7. The brightest part of the Sun has been blotted out to reveal a nearby comet and the Sun's corona. NASA image.

2.2 Two kinds of comets

There are actually two types of comets based on their orbits: *short-period comets* and *long-period comets*[6]. (The *period* refers to the time it takes to orbit the Sun once.) Short-period comets may travel as far away from the Sun as Neptune, the most distant planet. Yet they also may get closer to the Sun than the Earth. As we said before, we cannot normally see comets as small nuclei when they are far away[7]. They only become visible to us when they are in our 'neighborhood', near the Sun.

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[6] The recent discovery of the first interstellar comet, Oumuamua, necessitates a third class, one that is not in orbit around the Sun and mentioned below.

[7] There are a few comets that we can track throughout their entire orbits, a testament to the incredible power of modern telescopes.

Figure 2.8. Periodic Comet Encke. Copyright F H Hemmerich.

Because objects travel much faster in their orbits when they are close to the Sun, comets spend proportionately more time far away and very little time close by. (Comets may travel as fast as one-hundred kilometers per second at perihelion, but only one-hundred meters per second at aphelion.) This is why comets seem to ‘appear’ in our sky quickly and just as quickly ‘disappear’. Short-period comets are defined—arbitrarily—as comets with periods of less than two hundred years. Other than their stretched-out orbits, short-period comets behave essentially like the major planets. They travel around the Sun within about 30° of the same plane as the Earth—this plane is called the *ecliptic*—and that of other planets. Thus, they may cross the orbits of the Earth[8] and the other planets. Short-period comets also (mostly) travel in the same direction as the major planets: counter-clockwise as viewed from the direction we call north. (Comet Halley is a rare clockwise one.)

Several distinctions are made within this group. Comets with periods of less than twenty years are known as Jupiter-family comets as their aphelia generally lie near Jupiter’s orbit with low inclinations and clearly have been influenced by the giant planet’s gravity. The comet with the shortest known period is Comet Encke: 3.3 years (figure 2.8). Its orbit does not reach Jupiter and is the prototype of the Encke-type comets, having orbits within Jupiter’s and decoupled from it. Comets having periods greater than twenty years and less than two hundred are known as Halley-type comets. Their orbits can be highly inclined to the ecliptic and can even be in retrograde (e.g. clockwise Halley as noted above). Only one-tenth of well-studied comets are short-period.

If short-period comets travel in elongated paths, long-period comets travel in *extremely* elongated paths (figure 2.9). Their orbits are said to be highly eccentric. These comets plummet almost directly toward the Sun and execute hairpin turns at their closest approach before hurtling away. While they may get nearer to the Sun

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[8] These near-Earth comets may present a collisional hazard to us and are the source of *meteor showers* as discussed in chapters 3 and 4.

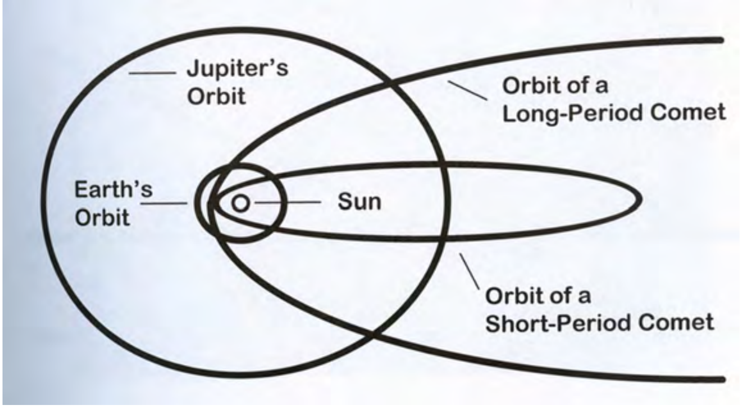

Figure 2.9. The orbits of a short-period comet and a long-period comet compared.

than any planet, at their most distant point, long-period comets are much, much farther away than Neptune. They often have periods of hundreds of thousands or even millions of years. It takes a long time to see a long-period comet twice. There are likely lots more long-period comets awaiting discovery than short-period comets. The reason is, simply, because the last time a particular long-period comet visited the inner Solar System and appeared in our sky, we were too busy keeping our cave fires lit and fending off saber-toothed cats to notice it!

Thousands of comets have been observed[9], but of the 3550 cataloged comets[10], 2723 (77%) are long-period comets. Furthermore, of the short-period comets, only 375 out of 827 have been observed more than once, a requirement to earn a number (e.g. 19P/Borrelly)[11]. Of the short-period comets, 675 are identified as members of the Jupiter-family, 99 are Halley-type, and 53 belong to the Encke-family. Great Comets like Hale–Bopp, with a period of around 2500 years, are long-period comets. On average, a dozen or so long-period comets are discovered each year (but most of these are seen only through telescopes and are quite faint). The general appearance of long-period and short-period comets in the sky is similar; differences in other properties, such as, composition, nucleus size, and shape, have not been convincingly established.

How far away do long-period comets get? When measuring lengths in the Solar System, miles or kilometers just do not 'cut it' anymore. The distances involved are too vast. Describing the expanses between the planets in kilometers makes about as much sense as quoting the distance from Chicago to Bangkok in inches! Such a number would contain a long string of zeros. A new 'yardstick' is called for.

Astronomers measure distances in the Solar System in terms of the Earth's average distance from the Sun. This distance (149 597 870.700 km exactly) is called

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[9] Including more than 3000 sungrazing comets spied by satellites in the vicinity of a fixed Earth–Sun position whose primary function is to observe the Sun.

[10] Comets for which an orbit has been determined. For the current number, see the JPL Small-Body Database: https://ssd.jpl.nasa.gov/sbdb.cgi#top (Accessed 24 December 2018).

[11] More on comet designation and naming in chapter 5.

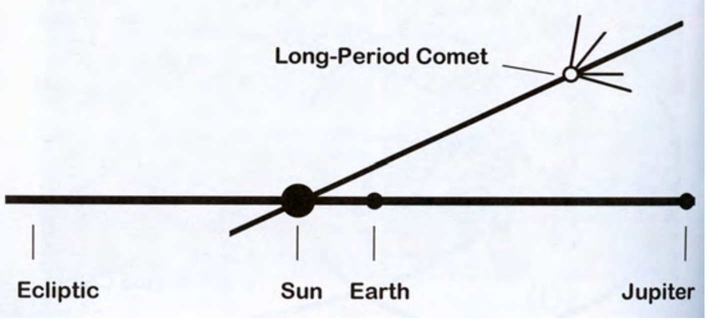

Figure 2.10. The orbit of a long-period comet may be highly inclined to the ecliptic.

one *astronomical unit* (au). It is a convenient and well-known length. Is it not sort of arbitrary to invent the astronomical unit? Yes. However, all distance units are really arbitrary—after all, somebody had to decide whose foot was exactly 'one foot' long!

Using this system, the planets conveniently range in average orbital distance from 0.4 au (Mercury) to 30.1 au (Neptune). Yet long-period comets stray so far from the Sun that even the number of astronomical units that they travel becomes huge. Long-period comets reach distances from the Sun of 50 000 au or more. Far from the limits of what many conventionally think of as the Solar System (actually the Planetary System), these objects travel up to one-fifth the distance to the next nearest star! If the Planetary System, Sun to Neptune, were the size of a baseball sitting on home plate, comets would travel beyond the outfield bleachers.

It is difficult to measure the shape of a comet's orbit based only on the small segment we can observe near the Sun. Some comet paths look like they never repeat, so-called parabolic or hyperbolic orbits, unbound to the Sun. These comets might not return at all—a cometary 'home run.' Indeed, the first interstellar comet was found in 2017, called Comet 1I/2017 U1 Oumuamua[12]. This interloper from beyond our Solar System confirmed our idea that comets may be expelled from planetary systems. A careful measurement of its motion revealed forces other than gravity arising from outgassing[13]. This raises the intriguing possibility of sampling material from other star systems without having to go there! Long-period comets do not necessarily stay in the ecliptic plane (figure 2.10). They can appear coming from any direction. Their orbits are randomly clockwise or counter-clockwise. (Hale–Bopp is a counter-clockwise comet, but it travels nearly perpendicular to the ecliptic.) Furthermore, they may be making their first visit to the inner Solar System with a fresh, frosty surface leading to greater activity and brightness. With few rules governing the orientation of their orbits, long-period comets are the 'bad boys' of the Solar System, challenging astronomers whose job it is to trace their courses. Now that we know these two types of cometary orbits, we will learn in chapter 3 that they

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[12] 1I/ is the first designation of an interstellar comet, a comet that originated in another star system. 'Oumuamua' is Hawaiian for scout or first distant messenger.

[13] Called non-gravitational forces, they arise from gas and dust jets emitted from the nucleus that impart a reaction force on it. See chapter 3 for more details.

indicate two different cometary reservoirs in our Solar System. But first let us describe how orbits work. Onward!

2.3 Celestial clockwork

The key to almost every aspect of a comet is its orbit about the Sun. Its orbit defines what kind of comet it is, how long it will last, and how it will appear to us and behave throughout its lifetime. Comets execute the sort of perfect figure in space of which Olympic skaters can only dream. A comet's orbit is truly a thing of beauty. Nevertheless, for some, it can be the most difficult aspect of comets to understand.

Indeed, the physics of orbits gives movement and life to the whole Solar System. For the remainder of this chapter, we will explain how orbits work. Orbital mechanics is mathematically elegant. In this book, however, we will restrict ourselves to a qualitative description of orbits, using comets as our principal example. We promise to refrain from using a single equation! Most basically, we hope to answer the question: 'How do those things stay up there, anyway?'

First, let us acknowledge two of astronomy's giants who started the scientific revolution that set in motion the work of those discussed below. In 1543, the Polish astronomer, Nicolaus Copernicus (1473–1543), proposed the radical idea (at the time) that the Sun was at the center of the Universe (our Solar System as we know it today) and that the Earth and planets orbit it. This heliocentric (Sun-centered) system broke from the millennially held geocentric (Earth-centered) belief of the Greeks that the Earth was at the center, causing great discord with the ruling religious establishment[14]. We have known about the heliocentric Solar System since kindergarten, but remember that it took the genius of Copernicus to overturn the notion held by all of the great intellects that preceded him. (By the way, that map of the Solar System from kindergarten is still under construction as we continue to learn more about our celestial neighborhood.) Following Copernicus, was the great mathematician/astronomer, Johannes Kepler (1571–1630). Through his arduous analysis of observations of Mars, he was able to describe all of planetary motion with three simple laws. Kepler's laws of planetary motion can be summarized as follows: (1) planetary orbits are elliptical with the Sun at one of the two foci (law of ellipses), (2) the speed of planets along their orbit constantly changes, being fastest at perihelion and slowest at aphelion (law of equal areas), and (3) the orbital period is related to the planet's average distance from the Sun, meaning that the farther from the Sun, the slower the motion of the planet in its orbit (harmonic law). This achievement earned Kepler the title, 'Lawgiver of the Heavens'. Kepler did not know why his laws described planetary motion, only that they fit the data well. In fact, we know today that Kepler's laws apply to any bodies in orbital motion, be it satellites orbiting planets, extra-solar planets orbiting their host stars, binary stars, galaxies orbiting each other, etc. Newton acknowledged these great minds when he stated, 'If I have seen further, it is by standing upon the shoulders of Giants.'

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[14] Aristarchus (310 BCE–230 BCE), a Greek, had formulated a heliocentric model some eighteen centuries earlier but this idea was rejected by his contemporaries.

To understand planetary and cometary orbits, we must begin by investigating two ideas. First, we need to look at motion itself. How does a thing—anything—move? Second, we need to look at a force called gravity.

2.4 A Universe in motion

In our busy modern age, motion seems natural. Is it? Aristotle (384–322 BCE), the Greek thinker who established the tradition of western science, believed not. He was not very impressed with motion. He felt that rest was the natural state of all things. Set an object in motion, and it eventually will come to rest, he observed.

Galileo Galilei (1564–1642), the arrogant and obstinate Renaissance genius, thought differently. He questioned whether either motion or rest were a 'preferred' state of objects. He did not think that there was anything more 'natural' about rest than about motion, or vice versa. This was embodied in his concept of inertia: the resistance of an object to any change in its position and state of motion. By eliminating preferred states, Galileo inaugurated the modern study of motion called dynamics. What a rebellious act to disagree with the great Aristotle whose idea held for almost two millennia.

Newton picked up where Galileo left off. (Quite literally, he was born within a year of Galileo's passing!) He adopted Galileo's concept of inertia and stated that an object at rest remains at rest and that an object in motion remains in motion—traveling in a straight line, at a constant speed. This is Newton's first law of motion: the law of inertia. The only way to put an object at rest into motion, stop a moving object, or change the speed or direction of an object already in motion is to exert a force, a push or a pull, on it. According to Newton, the change in motion produced by a force, occurs in the direction of the force and is proportional to its strength. This is Newton's second law of motion: the force law.

This makes sense. When you pick up and roll a bowling ball, it travels forward in the direction you threw it, not over your shoulder or someplace else. Furthermore, the harder you throw it, the faster the bowling ball is going to go.

What do we mean when we write 'change in motion'? The speed and direction of a moving object together are called its velocity. A change in velocity is an acceleration. So a force produces an acceleration, a change in motion.

We usually think of an acceleration as an increase in speed. It is. It can be just as easily a decrease in speed (commonly called a deceleration), however. We are less likely to think of a change in direction as an acceleration. However, a change in direction is just as much a change in velocity as is a change in speed. A given force can produce a change in speed, a change in direction, or both—depending on how the force is applied. We have all experienced this in our lives when we round a curve in a vehicle moving at a constant speed. We have to lean into the curve to oppose the force due to this change-of-direction acceleration, lest we be thrown to the outside of the curve. (This is called centripetal force.) Fortunately, our seat belt and door prevent this from happening.

Newton was on a roll and kept going. Acceleration is proportional to the force applied, declared Newton. It also is proportional to a property of every object, its mass. Mass is simply a measure of the amount of matter within an object. Given a certain force, if you try to change the motion of a large mass, you will get less acceleration than you would with a smaller mass. Even pushing very hard, it takes much effort to get a stalled car rolling. Yet, what happens when you use the same amount of force on a skateboard? Whoosh! A very rapid change in velocity results.

Do not confuse mass with weight. Weight is a force due to gravity's pull on mass. It is proportional to mass, but change gravity and you change your weight, not mass. A great recipe for weight loss is simply traveling to the Moon where your weight would decrease to 1/6 your Earth weight due to the lower gravity of the Moon. Of course, the object of weight loss is really mass loss.

Whew. That is a lot of Newton. Nonetheless, it works in our macroscopic world. These last few paragraphs describe every motion that you and we have ever seen. That is really complete, really powerful stuff. NASA uses Newton's laws[15] today to plot trajectories of spacecraft through our Solar System. Newton showed that motion is not capricious, that it follows relatively straightforward and describable rules. Newton's laws never fail us. You can bank on them because they cannot be broken. (At least this is true in the macroscopic world; it is altogether a different matter in the microscopic quantum realm, but you will need another book to learn about that!) They are also vital to understanding the orbits of comets.

Feel free to read over the last page or two again before going on. (We will wait!)

2.5 The gravity of the situation

Gravity is both simple and complex. In a sense, we all know what gravity is. Everyone who has ever fallen on his or her face has had an intimate relationship with gravity. Nevertheless, one can take an entire graduate physics course called Einstein's general theory of relativity without grappling with all the nuances of gravity.

For our purposes, gravity is simply a force, but a special kind of force. First, it is always a pull and never a push. Second, unlike most other forces, it can act at a distance, any distance. In other words, it is universal. This simple idea was extremely profound at the time. Newton had connected what we experience in our terrestrial world with what we see in the celestial one. (In the earlier example of acceleration, you had to place your hands on the rear bumper of the car to get it moving; gravity can accelerate an object without any direct physical contact between the objects.)

Gravity is produced by any object that has mass. As nearly everything that we know of (physically) has mass, this includes the whole Universe of objects! Between each pair of these objects there is the attractive force of gravity—the more mass in the pair of objects, the stronger the force. Think of that. Right now you (an object with mass) and a distant comet (another object with mass) are attracted to each other. Do you feel it? No, of course not. That is because gravity grows weaker the greater the distance between objects. It becomes infinitesimally weak at infinite distance, but never zero; we all are bound together in this Universe. What a profound notion. This could be the basis of world peace!

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[15] There is a third law, the reaction law, that will be discussed shortly.

To experience the force of gravity, one need only leap up. The velocity that you give yourself with your feet is quickly decelerated away. There is a moment of 'hang time,' and then you are accelerated down toward the massive object underneath you, the Earth. You do most of the moving because the Earth is much more massive than you, but the Earth has moved, too, in the opposite direction. This is Newton's third law of motion: for every action, there is an equal and opposite reaction[16]. Technically, the gravity produced by the mass of the Earth, since it is spherical, acts as if it is emanating from the center-of-mass of the Earth, a point at its middle, some 6400 km below you. Before you get there, though, another force, that exerted by the hard floor, stops you.

Now back to our original question: with all those bodies revolving around in the heavens—planets, satellites, comets, and asteroids—why does not everything fall down?

For centuries, people wondered what might propel the planets and comets in their paths. Some speculated that it might be a magnetic force, magnetism being a popular phenomenon to dabble with in the physics of the seventeenth century.

Then Newton described gravity and explained that the same force that works in day-to-day life on the Earth also affects the planets. That is, they move in a way that is totally consistent with a force proportional to the masses involved and inversely proportional to their distances from one another[17]. (That sounds a lot like gravity.) Newton's immortality rests in his realization that the force that runs the Solar System lies—literally—beneath our feet. Armed with his powerful ideas of motion and gravity, Newton focused on understanding the why of Kepler's laws of planetary motion. He was able to show that Kepler's laws derived from his basic laws of motion and gravity. He had to invent calculus to do so, but that is beside the point. In fact, when he examined Kepler's third law, he added the total mass of the orbiting bodies into the relationship between orbital period and average distance from the Sun. This important revision gives us the primary method of estimating the total mass of orbiting celestial bodies, a kind of cosmic balance.

Wait a minute. Has not our study of gravity backfired? Our intent was to tell why objects in the sky stay there, why they do not 'fall down'. We have invented a force that seems to require that they do just that—fall toward each other! There is an attractive force between the Earth and its Moon, between the Sun and a comet, and between all other objects as well: gravity. Read on.

2.6 Looping comets

'Why do the comets not fall?' we asked. They are falling—all the time! They have to be. Recall that in the absence of a force, an object is either at rest or moving at a constant speed in a straight line. That goes for any object, anywhere in the Universe.

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[16] In 1686, Newton published his three laws of motion in the *Principia Mathematica Philosophiae Naturalis*, considered by many to be the greatest scientific tome in history. If you get a chance to see an early edition, we highly recommend it.

[17] More specifically, gravitational force is inversely proportional to the square of the distance between attracting objects.

With no force acting upon it, a comet would either be static or traveling at a constant rate toward or away from us. If the latter were the case, the comet would either crash into something or disappear forever. No real comet behaves in this manner. Its speed and direction of travel are perpetually changing. (There are no 'straight' comets; their paths always curve, even if only a little.) No comet is stationary, of course.

If gravity is the force acting on the comet—and it must be—should not every comet collide with the Sun? This would be the case, if the comet started at rest. In other words, if you placed a new comet at rest with respect to (and some distance away from) the Sun, imparted no other force on it, and let it go, the comet would fall into the Sun. No question.

No, the comet can neither be unaffected by gravity nor lacking in original motion. Otherwise it would not behave as we observe comets to do.

What if the comet is not only attracted by the gravity between it and the Sun, but also has some initial velocity? If the direction of this velocity is toward or away from the Sun, it will not make any difference, but what if it is not?

We say that the direction toward or away from a center is radial. (Spokes of a bicycle wheel are aligned radially.) The direction perpendicular to this is transverse (figure 2.11). A comet that starts with a transverse velocity will be acted upon by the radial gravitational force of the Sun, perpendicular to the comet's transverse direction of travel. Its direction of travel will then change. (The comet is accelerated in the direction of the Sun by the force, but its transverse motion will be unchanged.) The path of the comet will be a curve.

The classic example is balls on a string (part of boleadoras in certain parts of the world). If you hold the balls motionless by the middle of the string, they dangle to the floor. If you give them a radial velocity (throw them), they move in a straight line (for a moment, at least). However, if you hold onto the string and give the balls a transverse velocity (perpendicular to the string, by twirling it), they travel in a curved path. The tension in the now-taut string takes on the role of gravity, in this analogy, by pulling at the balls radially in toward your hand. Yet the balls do not move inward. They stay at a constant radius from your hand (the half-length of the string). The balls continually accelerate, but never hit anything. In fact, they travel in a particular curved path that repeats itself over and over: a circle. They are constantly

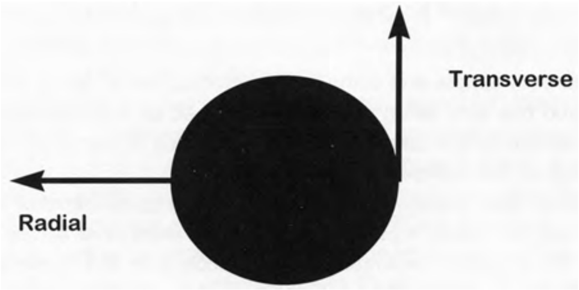

Figure 2.11. Radial and transverse motion.

'falling' to the center, but this fall is countered by their transverse motion. You could say that the balls are orbiting your hand.

To be sure, Newton's laws still apply. Just cut the string while twirling it and look at what happens. The balls take off. Invariably, they travel away in the transverse direction. We need both Newton's laws of motion and Newton's universal gravity to make an orbit.

An object moving in a curved path really is moving in two directions simultaneously: the radial direction and the transverse direction. Consider a giant pitching a baseball. Once he releases the ball, it flies at a constant speed parallel to the ground. There is no other force acting upon the ball in the transverse (horizontal) direction. (Ignore the frictional force with the air for the moment, i.e. no curve balls.) In the radial (vertical) direction, it is another story. Gravity pulls the ball to the ground. The ball accelerates radially until it hits the dirt. (It falls downward.) The two motions exist independently of each other. The ball would have been 'happy' to remain traveling at the same transverse speed indefinitely, had it not dug its chin into the ball field and come to a halt. (Except for a little deceleration caused by friction with the air, a fastball is moving at the same speed over the plate that it was leaving the pitcher's mound.)

What if the giant wants to throw the ball farther? He could give it a radial velocity during his pitch. This time, as the ball leaves his hand, it travels upward. Gravity must now decelerate this upward velocity to zero before accelerating the ball downward—this time from a good height—to *terra firma*. The ball takes much longer to strike the ground. Unfortunately, the ball makes no transverse progress across the field and falls at the pitcher's feet.

The giant's best bet is to throw the ball at an angle to the ground so that it has both transverse- and radial-velocity components. The radial component 'buys time', while the transverse velocity gains yardage.

Still, eventually, no matter what force the giant imparts on the ball, it will always 'bite the dust'. Of course, this assumes that the ground is an infinite flat plane and the ball does not achieve escape velocity, discussed below.

It surprises no one anymore to learn that the Earth is round; photographs of its globe, beamed down from space, have seen to that. But even the ancient Greeks knew about a round Earth, approximately the size we know today, by carefully measuring shadows at different locales throughout the year. Suppose our giant is really tall, so tall that he can see the curve of the Earth. He hurls the ball hard enough that, as the ball falls toward the ground, the ground curves away beneath it. The ball maintains its transverse velocity. It continues to be pulled downward (meaning toward the center of the Earth), but now that direction has changed. The ball still travels parallel to the ground. It continues to fall downward, and the ground continues to curve out from under it before the ball actually hits. If the giant has given the ball a sufficient initial transverse velocity, he had better look out! The ball will 'fall' all the way around the spherical Earth and hit him in the back of the head. If he ducks, it will continue to travel around the Earth, over and over (ignoring air friction). The ball is in orbit about the Earth. If the giant had used a slightly higher transverse velocity, the resulting orbit would have been elliptical instead of circular, and even more velocity would result in the ball permanently leaving the vicinity of the Earth (escape velocity) in a parabolic or even hyperbolic orbit. What goes up does not necessarily come down.

(When we watch the flame and clouds of smoke pouring forth from the engines of a rocket on its launching pad, all that thrust serves only one purpose: it is to impart on the rocket a velocity great enough so that the spaceship atop it will achieve orbit or beyond. This is another example of Newton's third law of motion. It is not the push of the rocket's thrust on the launch pad nor against the atmosphere that lifts the rocket upward.)

As comet nuclei coalesced in the *proto-solar nebula*, they acquired velocities that were the sum of the velocities of the material that formed them. Within this material, there was often a surplus of motion in the nebula's direction of rotation. This direction was transverse to the direction of the newly formed Sun, at the center of the nebula.

Notice that an orbit requires a precise combination of gravity and transverse velocity. Is it a coincidence that so many planets, comets, and other bodies achieved this necessary combination? Not really. We are seeing just the result of billions of years of Solar System evolution. Only those objects with the right velocities survived so that we can see them today. How many comets did not, and ended up falling into the Sun or were expelled? Probably quite a lot.

2.7 Orbits of your own

To help picture it, you can create a model of your own orbiting comet. The problem with doing so usually is that we cannot turn off the Earth's gravity to make the model! Everything falls to the floor. However, we can use the Earth's gravity to simulate the pull of the Sun on a comet using simple kitchenware. Here is how.

Get hold of a large, hemispherical-shaped salad bowl. (Glass or aluminum is best.) Mark the inside center of the bowl with a pen or sticker. This point will represent the Sun. The only additional thing you need is a marble to 'stand in' for the comet. Put both the bowl and the marble on the floor.

If you 'shoot' the marble across the floor, it will roll away from the bowl, in a straight line, at a constant speed. In other words, it will obey Newton's laws to the letter—just like any other moving object on the Earth or in space. The marble represents a comet (or anything else moving) not affected by the gravity of any other mass.

The marble in our demonstration eventually will slow and even stop. However, this is because of friction with the floor (an external force that negatively accelerates the marble). In space, there would be no such friction. You would lose your marble for good. (Colleagues have suggested from time to time that T H has lost all of his, already.)

In reality, it is impossible to avoid the gravity produced by other objects in the Universe. The salad bowl represents such an object: the Sun. Put the marble on the inside rim of the bowl. It 'falls' toward the central 'Sun.' It will do this, no matter where on the rim you place it. The salad bowl mimics the gravity of the Sun in that it causes nearby objects to be attracted radially toward a central point. The marble now simulates what would happen if a comet were placed, motionless, in the vicinity of the Sun. The real marble will overshoot the representation of the Sun, certainly. (There is really nothing in the middle of the salad bowl.) The real comet would hit, and be swallowed up by, the real Sun.

Let us try our experiment once more. This time, hold the marble on the inside rim of the bowl, and give it a little shot with your finger, in a direction more-or-less parallel to the rim. Because of the spherical shape of the bowl, the marble will 'orbit' the center of the bowl: the marble/comet will make many trips around the center/Sun (without going through it) until friction, again, decelerates it, and the marble comes to rest at the bottom of the bowl. Without friction, the marble would continue looping around forever.

This all may take a little practice. You will quickly see that the orbital speed you give the marble must be just right: if you give it too hard a 'flick,' the marble will leave the neighborhood of the Sun altogether (it will 'jump' out of the bowl). Too little force causes the marble to curve inward right away. It will not make even one orbit.

A physicist could rightly protest that the shape of the bowl does not exactly correspond to the way the gravitational force increases as you approach a massive body[18]. It still looks about right, though.

Notice that most random orbits are elliptical: the marble moves a little closer, then a little farther away from the center … a little closer, then a little farther away, a little closer … You get the point. The marble has a perihelion and aphelion with respect to the focus of its path. Slightly disparate initial trajectories will result in differently shaped ellipses. Let us leave our make-believe Universe of salad bowl stars and cometary marbles and return to the authentic Solar System.

A complication of the real Universe is this: we talk about a comet 'orbiting the Sun', but the Sun orbits the comet, too. Just as the comet moves under the grasp of the Sun's gravity, the Sun also is required to move under the influence of the comet's. Yet just as a gerbil on a seesaw with a hippopotamus does most of the moving, the comet does most of the work in its dance with the Sun. The Sun wobbles ever so imperceptibly as the comet whirls about it. Planets and comets orbit the Sun, and satellites like the Moon orbit planets, all for the same reason. Newton soon realized that planetary orbits are never circular nor elliptical, as stated by Kepler, due to these ever-changing gravitational tugs of all of the other planets, satellites, etc. As genius as Newton was, he could not accept that cometary motion could be described by periodic orbits; he preferred parabolic shapes so that the comet would never return. As we noted above, this notion would be changed by his friend, Edmund

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[18] The correct shape is like an inverted cone that tapers to its apex. You may have seen one at a museum for donations. Start a coin rolling around its surface, and it will orbit the apex until exiting through a hole at the bottom.

Halley, who predicted that comets followed elliptical orbits, like planets, that periodically brought them back into our night skies.

Though comet orbits can be extremely eccentric, they are physically no different from circular orbits. There are subtle non-gravitational forces acting on the comet, too, mainly due to the gas and dust *jets* emitted from the nucleus that perturb its elliptical orbit. These will be discussed in more detail in chapter 3. As we watch a periodic comet move through our sky, remember that it is constantly falling toward (or away from) the Sun. It just will never quite make it. An orbit is the ultimate example of 'falling—with style'.

Comets in the 21st Century

A personal guide to experiencing the next great comet!

Daniel C Boice and Thomas Hockey

Chapter 3

What comets are all about

A quiz:

What is a comet?

- A. A Lincoln–Mercury automobile.
- B. A vintage aircraft.
- C. A bathroom cleanser.
- D. A brand of beans.
- E. An ancient astronomical visitor of strange beauty.
- F. All of the above.

Here we discuss the anatomy and make-up of comets. We also will talk about their origin stories. By the end of the chapter, we are ready to take a virtual journey to a comet (and return). Buckle up, we are off to see a comet! By the way, the answer to the quiz is ‘F’, but we will focus on selection ‘E’.

3.1 Parts of a comet

No two comets are alike, somewhat like people. If we could view them in a line-up, they would share certain common features but they would all appear as individuals. These features constantly change as comets approach and recede from the Sun. Their appearance as seen from the Earth adds perceived differences as well (such as *antitails*[1], faint coma features, etc). Comets continue to surprise and amaze us, but we can draw some general conclusions about the parts of a comet, starting with the nucleus.

There is another reason why it is difficult to observe a comet when it is far away, besides the fact that its light is dim: far from the Sun, a comet is small. While planets have diameters measured in thousands or tens of thousands of kilometers, comet

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[1] An antitail refers to a tail that appears to point towards the Sun but is actually an illusion caused by observing the comet from a peculiar perspective, as discussed below.

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nuclei are at most city sized, not planet sized. They are too small to appear to us as anything more than a point of light. Estimates of their sizes come from various observations, including measurements from space probes made of a few comets that have come near the Earth. The most common method to estimate size is from the brightness (reflected sunlight) of the bare nucleus. Assuming the percentage of light that is reflected from the surface (albedo, see below), one can obtain the effective cross-sectional area, hence the size of an equivalent spherical object. Modeling Hubble Space Telescope images at far heliocentric distances can also extract the nucleus size. The close-approaching Comet Hyakutake's nucleus, for instance, was found to be merely 1–3 km across (figure 3.1). Based on these techniques, it seems likely that few comet nuclei are more than ten kilometers in diameter (although Comet Hale–Bopp at about 50–60 km is an important exception). The subtle distinction between the phenomenon we see in our night skies with its coma and resplendent tails ('comet') and the small solid body that gives rise to these magnificent features ('comet nucleus') is important and one that we adhere to throughout this book.

Like everything else in the Universe, comet nuclei also spin, giving them daytime and night-time. They rotate relatively rapidly, from a few hours to a few days. Some show complex rotational states where they wobble and tumble as they spin (like Halley). And their spin rate can speed up or slow down due to jet activity. Comet

Figure 3.1. Comet Hyakutake in 1996. Taken by Rick Scott and Joe Orman, near Florence Junction, Arizona. Courtesy of Night of the Comet.

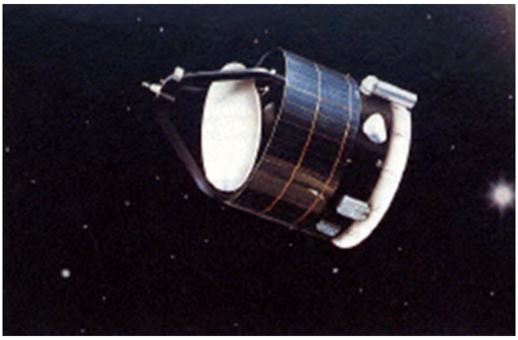

Figure 3.2. The Giotto space probe. NASA image.

Tuttle–Giacobini–Kresák holds the record, slowing its spin from 20 h to 46–60 h in a two month span during 2017.

Only a few comet nuclei have had their close-up picture taken, starting with Comet Halley. A fleet of space probes met up with Halley on its 1986 return. The Soviet Union's Vega 1 and 2 space probes, from 30 000 km away, took the first pictures of a comet nucleus, and found Halley to be oddly peanut shaped. The European Space Agency's (ESA) Giotto probe imaged the nucleus from only 600 km away[2] (figures 3.2 and 3.3). More recently (2001), the National Aeronautics and Space Administration's (NASA) Deep Space 1 encountered Comet Borrelly (at a distance of 2200 km) and sent back even better nucleus images (figure 3.4). Since then, three additional spacecraft have had close encounters with comets[3]: Stardust (NASA)—Comet Wild 2 in 2004 and Comet Tempel 1 in 2011; Deep Impact (NASA)—Comet Tempel 1 in 2005 and Comet Hartley 2 in 2010; and Rosetta (ESA)—Comet Churyumov–Gerasimenko in 2014. (Stardust and Deep Impact did double duty as NASA 'recycled' these spacecraft before their fuel was expended.)

Back on the Earth, we would probably miss most comets, if it were not for the spectacle they stage as they approach the Sun. Within about three astronomical units of our star, a bright cloud surrounds the comet nucleus. This cloud is called the coma or comet head (when including the nucleus). It can extend out to hundreds of thousands of kilometers in all directions. 'Coma' comes from the Latin word for hair, and, indeed, the coma gives the comet a diffuse, 'hairy' appearance. Now it is easier to see the comet. Not only is it closer, it is a bigger target. Comets are discovered after they have produced a coma.

Very close to the Sun, the comet grows its most distinctive and most impressive feature, its tails. Tails come in three varieties based on their composition: *ions*[4] (type I), *dust* (type II), and neutral atoms (type III). The dust tail is often a bright, curved

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[2] The Halley fleet also included two Japanese space probes, Suisei and Sakegake, and the repurposed NASA ISEE-3 satellite, recommissioned as the International Cometary Explorer (ICE), having first encountered Comet Giacobini–Zinner in 1985.

[3] ESA's Giotto spacecraft also visited Comet Griggs–Skjellerup in 1992 but did not provide images since its camera was damaged during the Halley flyby.

[4] Ions are electrically charged atoms and molecules.

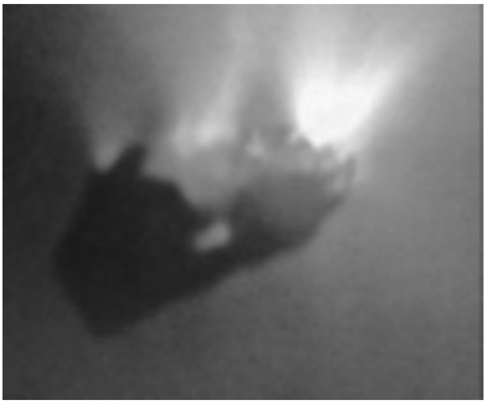

Figure 3.3. Close-up view of the Comet Halley nucleus by Giotto. ESA image.

Figure 3.4. Comet Borrelly. NASA image.

fan-shaped appendage to the coma with a yellowish tinge. The ion tail is more straight, bluish in hue, and points in the opposite direction from the Sun (figure 3.5). Sometimes it narrows, bends, and then detaches from the comet entirely, only to grow back after some time like a lizard tail. Both may become over an astronomical unit long, giving them, for a short time, the distinction of being the largest structures in the Solar System[5]. Type III tails are only seen using special filters that isolate the light from specific atoms such as sodium. They are the straightest of all of the tails and also point anti-sunward. Some comets display all three types of tails, some only one and, in 2016, a comet was seen that had a well-developed coma but no tail, a Manx comet (named after the tailless cat).

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[5] The Ulysses spacecraft detected ions from the ion tail of Comet Hyakutake more than 3.8 au downstream.

Figure 3.5. A comet exhibiting both ionized gas and dust tails. NASA image.

Notice how long the comet tail is compared to the coma! Pretend that the coma is the size of a standard audio cassette tape. Now (in your imagination) cut the tape. Unwind it by pulling on the end, dangling the cassette behind. You will have to pull off one hundred meters of tape (more than half an hour's worth) to represent a long comet tail.

After a comet rounds the Sun, it heads back out into the remote recesses of the Solar System. Its tail fades, and then its coma disappears (figure 3.6). The comet's adornment was only very temporary. The comet now returns to its normal drab and dormant state in the outer Solar System. It is just an inconspicuous nucleus again, too small and too faint for even our largest telescopes on the Earth to see.

If you could follow a comet as it approaches the Sun, it would appear as it is most commonly illustrated: a fuzzy coma with a graceful tail or tails trailing it. If you continue to watch the comet after it passes around the Sun, however, it will look a bit strange. The tail will lead the comet. The ion tail is like a wind sock that always points in the direction of the wind (figure 3.7). (With comets, sometimes, the tail really does wag the dog!)

Space is not a fluid; it is virtually empty. Our mental picture of the comet tail, simply following in the wake of the comet, breaks down. So, what is going on?

The key thing you might have noted, as you followed the comet on its course, was that the tail stayed on the opposite side of the nucleus from the Sun, regardless of the comet's direction of travel. This is apparent from the Earth, as well. If a comet appears in the early evening sky, its tail will point eastward. If it appears in the early morning sky, its tail will point westward. This fact led astronomers to speculate that it is being blown back by something emanating from the Sun.

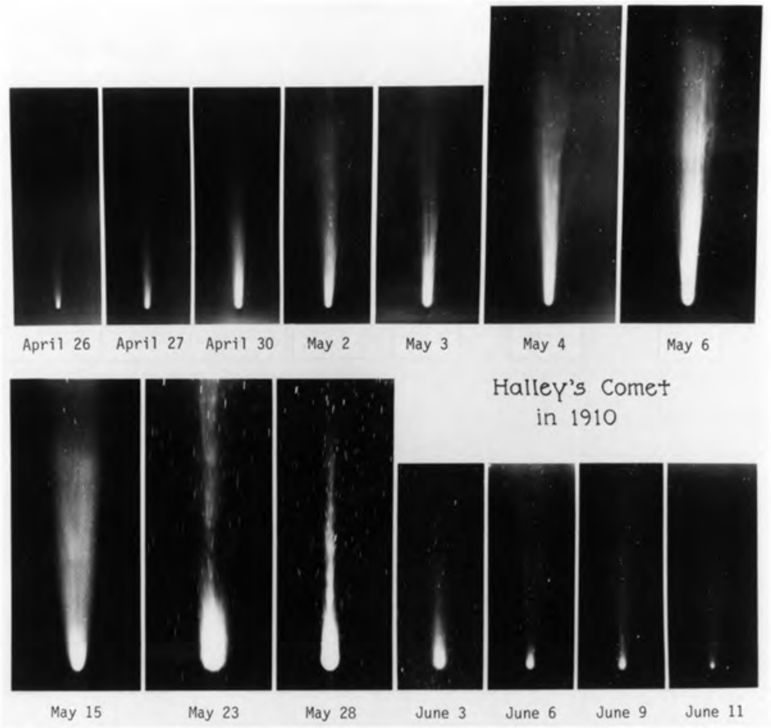

Figure 3.6. A sequence of images showing Comet Halley's ion tail lengthen and then shorten over time, as it approaches and then recedes from the Sun. 1910 apparition. NASA image.

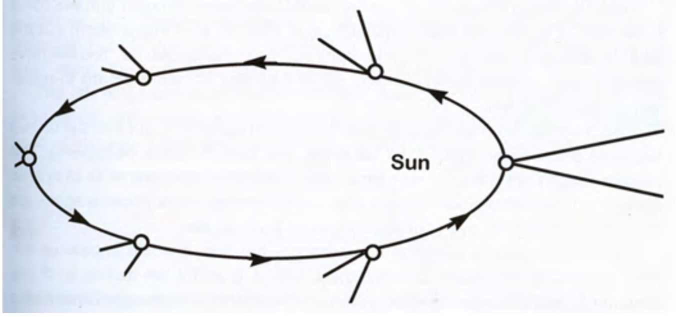

Figure 3.7. The orientation of a comet's tail with respect to the Sun.

The Sun is, of course, emitting light in all directions. We do not normally think of light as exerting a force on anything. (We do not feel a push when the car behind us turns on its headlights!) Still, light does exert a tiny force on every surface that it shines upon, though one much too small to be felt. It is this solar radiation pressure due to sunlight that pushes the dust and neutral atoms away from the Sun, forming the type II and III tails.

Figure 3.8. The aurora borealis. NASA image.

The pressure of sunlight alone is insufficient to account for the ion tail, which really does look like something being blown away from the comet by a wind. It is! In addition to light, escaping from the Sun at all times is a rarefied, but continual, stream of charged electrical particles (electrons and ions) called the solar wind, with an embedded magnetic field.

For a long time, occasional, sudden bursts of charged particles from the Sun were known to produce the aurora, or 'northern' and 'southern lights', when they interacted with the Earth's atmosphere (figure 3.8). Strong outbursts interfere with the Earth's radio communications and electrical power systems, although these are very infrequent events. The only hint that the solar wind is continuous came from comets. In 1951, the German astrophysicist Ludwig Biermann (1907–86) predicted the 'corpuscular' nature of the solar wind from comet tail observations. In the Space Age, space probes with instruments capable of detecting particle radiation and magnetic fields have proved what the comet tails have been telling us for generations, the existence of the solar wind. In 1957, the Swedish astrophysicist, Hannes Alfvén (1908–95), explained how ion tails form. Cometary ions present an obstacle to the solar wind and the magnetic fields embedded in it drape around the comet, stacking up in front and bending around the comet in the tail direction. The ions follow this draped field into the tail. He won the Nobel Prize in Physics in 1970 for his essential work in the study of *plasmas*[6], including comet ion tails.

Bends and knots in the ion tails of comets, long observed from the Earth, now can be explained, too. These phenomena signal that there has been a change in the solar wind or that the comet has moved to a different position with respect to the Sun, where the solar wind speed and orientation differ.

The ion tail points out behind the comet under the influence of the solar wind. This wind blows, on average, at 400 km s^{-1} (1 440 000 km h^{-1})! In comparison, the highest recorded wind speed ever measured in a hurricane is 300 km h^{-1}.

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[6] Plasma, often called the fourth state of matter, is a gas consisting of electrons and ions.

Figure 3.9. Comet Lulin exhibits an antitail. From: http://www.jacknewton.com/Comet%20Lulin.jpg. Used with permission from Jack Newton.

The liberated dust takes a more complicated route. A grain of dust is much bigger (thousands of times; its size can be measured in microns[7]—imagine something the size of smoke particles) and more massive (billions of times) than a molecule of gas. Each dust grain is influenced by the solar wind (comet dust often departs with a net electrical charge), the pressure of sunlight, and the gravity of the Sun and planets. The resulting forces cause each dust grain to follow a slightly different orbit around the Sun than the comet does. Thus, away from the coma, the comet's dust tail (traveling more slowly than the ion tail) separates from the ion tail and has a curved, but more uniform appearance.

Occasionally, the geometry of our point of view here on the Earth is just right so that we can see the tip of the dust tail appearing seemingly on the sunward side of the coma. It looks like another, 'backwards' tail on the wrong side of the comet. However, this antitail is just a projection effect. In reality, it is behind the comet and farther from the Sun than the coma (figure 3.9).

3.2 What is a comet made of?

What is the comet made of that blows away in the solar wind? Into the twentieth century, comets were pictured as flying, frozen sand piles in space. However, why should a bunch of rocky particles exhibit a coma and tail?

A new model for comets was called for. According to the one developed by Harvard University astronomer Fred Whipple (1906–2004) in 1950, comet nuclei are nothing more than 'dirty snowballs'. They are bodies made of an amalgamation of about 50–50 percent *ice* and dust. (They are now thought to have more refractories[8], dust; 'frozen mudball' might be a better analogy.) The dirty snowball model of a

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[7] 1 micron (micrometer) = one-millionth of a meter (0.000 001 m).

[8] *Refractory* material is a mineral that retains its form and properties at high temperatures, being quite suitable for making furnace bricks, as an example.

comet has now replaced the 'sandbag' model in the minds of astronomers. Moreover, recent evidence shows that nuclei are made up of many independent bodies (snowballs) loosely held together by gravity called 'rubble piles'. This is consistent with the low material strength exhibited by comets, resulting in the splitting of many nuclei (e.g. Shoemaker–Levy 9, to be discussed later). Rock and ice are common ingredients in the Solar System. In the inner Solar System, rock and metal are the principal building materials out of which planets are made. Our Earth is a fine example.

In the cold outer reaches of the Solar System, we find worlds very different from the Earth. These worlds have rock in them, but they also contain organic compounds and frozen gases (ices). The latter are made of *volatile* materials, under normal pressures, chemicals that turn to gas unless kept very cold. The planets Jupiter and Saturn, for instance, are mostly hydrogen and helium, not rock. Other worlds have layers of ice. The larger satellites that orbit the outer planets are made mostly of ice and rock. However, rock is denser than ice, so gravity has caused most of the rock to sink to the centers of these bodies, whereas the ice has floated to the outside. Hence, the surfaces of these worlds are very icy. So, it is not unusual to find ice in the Solar System.

The only difference with comets is that they are not very massive and, therefore, do not produce much gravity. Nothing sinks or floats. The dust and ice do not separate from one another. They remain a homogeneous mix. In other words, there is as much ice and dust in the outer layers of the comet nucleus as in its center—just like in a dirty snowball. (However, it must be conceded that nobody has ever tunneled into a comet nucleus to verify this.)

The snowball analogy is good in another way as well. Again, because comets have little mass, they do not produce enough gravity to compress themselves into a dense ball. Comets may be oddly shaped and very loosely held together. In fact, they often fragment or dissolve completely!

Density is defined as the mass of an object divided by the volume it takes up. The density of a spherical 'ice cube' should be about 0.9 g cm^{-3}. The density of an average comet nucleus is only half this (0.5 g cm^{-3}—the density of pine wood). Clearly, there is a lot of empty space in a comet nucleus. The material is fluffy.

We can now explain the appearance of the comet's coma and tail. As the comet nucleus nears the Sun, it warms up. It takes little heat to 'vaporize'[9] the ice near the surface of the nucleus. The ice does not melt and then boil. In the low pressure of space, the ice instead sublimates directly from solid to gas. (Solid carbon dioxide—'dry ice'—will do this at the temperatures and pressures normally encountered on the Earth (figure 3.10).)

To recap, as gas escapes the comet nucleus due to sublimation, it forms the coma cloud, mostly as neutral atoms and molecules. These are mixed with ions and electrons as the gas is ionized under the influence of solar radiation at a rate depending on the specific atomic and molecular properties. Dust freed by entrainment in this outgassing also escapes the low gravity of the comet nucleus.

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[9] At many places in this book, we loosely use vaporize and sublimate interchangeably, but, please remember, we always mean sublimate!

Figure 3.10. Sublimating carbon dioxide—'dry' ice.

Eventually, as the comet travels still closer to the Sun, around the orbit of Mars, the solar wind sweeps back the electrically charged ions of gas, and the pressure of sunlight pushes the dust particles away from the Sun. The comet tails are now formed as we described previously.

While dust is pretty self-explanatory, the term 'ice' needs some elaboration. Chemists call any solid made out of a volatile substance an ice. Much of the comet nucleus is in fact water ice, but other ices exist in the 'deep freeze' of the outer Solar System. Comets contain carbon-dioxide ice, carbon-monoxide ice, ammonia ice, methane ice, formaldehyde ice, and ices of other more complex chemicals, including a tincture of complicated organic molecules such as glycine, the simplest amino acid. (Given the preceding list, imagine what a piece of comet would smell like if thawed out on the Earth!) The exotic ices may bond loosely with the water ice as a hydrate or be trapped within a matrix of water ice called a clathrate.

Once turned to gas, many of these volatile chemicals glow in the presence of blue and ultraviolet light—the kind of light that makes a 'black-light' poster glow. In addition to visible light, the Sun shines in ultraviolet light. (Thankfully, our atmosphere shields the Earth from most of this potentially harmful radiation.) In space, the comet is bathed in this high-energy light and begins to glow, too. The process is called fluorescence. Photons (increments of light) of a wavelength we cannot see are absorbed by a coma molecule, and their energy is re-emitted as one or more photons of visible light. This makes the comet coma and ion tail even easier to see.

Most of the light we see from the coma actually comes from diatomic carbon (C_2) and cyanide (CN) molecules. Although they are very minor constituents of the coma, they fluoresce very effectively in sunlight, making them shine brightly. The parents of these molecules (i.e. the ices in the nucleus) are thought to be hydrocarbons (ethane C_2H_6 and acetylene C_2H_2) and small organic dust called CHON particles (CHON = carbon–hydrogen–oxygen–nitrogen-bearing molecules), respectively. An ion tail rich in carbon-monoxide ions (CO^+) can shine blue in absorbed and re-emitted sunlight.

Solar energy produces many interesting chemical reactions in the coma, transforming a dozen or so parent molecules (those contained in the nucleus ices) into a

Figure 3.11. The Moon's surface is largely dark, basaltic rock. However, a comet nucleus has even a lower albedo. (Not to scale: the comet should be about 800× smaller!) Courtesy of Robert Vanderbei, Princeton University.

plethora of thousands of siblings: reactive radicals, ions, and neutral atoms and molecules, which form from secondary gas-phase reactions. These reactions produce energy, heating and accelerating the coma gas. For instance, water vapor is broken up by sunlight into hydrogen and oxygen, forming an even larger part of the comet called the hydrogen envelope, a sphere roughly centered on the nucleus stretching more than a million kilometers in size (larger than the Sun). Hydrogen cyanide (HCN) is thought to be a molecule native to the nucleus (an ice), perhaps some in the form of a polymer associated with the dust. It is broken into hydrogen (H) and cyanide (CN), all of which can end up in the comet's tail.

This caused quite a stir in 1910, when it was announced that the Earth would actually pass through the tail of Halley's Comet. The Earth was about to be immersed in poison! Hucksters had a field day selling antidotes and gas masks to the public, but, of course, comet gas is so thin that it could never affect life on the Earth. Indeed, the Earth survived.

We have only scratched the surface of the chemistry that occurs in the coma. It is a chemist's delight to be able to study reactions that occur in the extremes of space, where vacuums and temperatures cannot be achieved in the laboratory. The study of comets is truly multidisciplinary.

3.3 More on the comet nucleus

That is it for the coma and tails. What does the comet nucleus itself look like? Astronomers refer to the ability of a surface to reflect light as a number called the *albedo*[10].

A shiny surface, like a mirror, has an albedo close to 1.0; a dark surface, e.g. black velvet, has an albedo close to 0.0. With all the ice present, you might think of a comet nucleus as a shiny, high-albedo object. It need not be (figure 3.11).

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[10] Albedo is the fraction of light reflected from a surface, ranging from 0 (total absorption) to 1 (total reflection).

If you live in a climate that experiences snow in the winter, you know how beautiful a street with newly fallen snow on it can look. On the other hand, now think of what that snow looks like a few days later! It becomes dark and unattractive. Is the street that dirty? If you take some of this dark, dirty snow home and melt it, you will find that there is very little dirt and soot in it. It is mostly pure water. It only takes a tiny quantity of dark material, mixed in with ice, to cover the faces of all the ice crystals and to drastically reduce the ice's ability to reflect light.

Most of the surfaces of the icy satellites in the outer Solar System are, in fact, very dark, though they are largely water ice (figure 3.12). Of the comets for which we have close-up space probe pictures, one of the surprises in these images is that the nucleus is almost black (typical albedo = 0.04)! It is darker than asphalt—blacker than practically anything else in the Solar System. Apparently, the outer layer of the comet has been preferentially depleted of high-albedo ice by repeated heating during many passages by the Sun. What is left is a crust of low-albedo dust, etc, pieces too big to be swept easily into the comet's coma and dust tail. Plus, repeated exposure to the Sun's ultraviolet rays has caused chemical reactions on the surface of the comet that combine volatile molecules into an organic sludge with an albedo less than that of coal.

Solar wind and cosmic radiation also can cause radiation damage to the surface material, especially on long-period comets, forming a radiation crust. Some darkness is caused by the fluffy nature of this surface, where light enters and cannot find its way out, like velvet!

For all the splendor of a comet in the sky, this frozen mix of dust and ice at the heart of a comet does not sound very exciting. Some might even call it ugly. Yet to planetary scientists who study the origin of the Solar System, it is more desirable than gold.

Figure 3.12. One of planet Jupiter's large icy satellites, Callisto. NASA image.

The problem with studying how the Solar System began is that it is difficult to get hold of the original stuff out of which it was made. It is believed that the proto-Solar System started out as a cloud of gas and dust that condensed and accreted into small bodies called planetesimals. These planetesimals collided into one another to assemble the planets. The planetesimal material still exists, but it has been changed so in the process of planetary formation and evolution that it is unrecognizable. The planetesimals themselves are gone now. Almost. Comets are thought to be 'original equipment' in the Solar System, leftover planetesimals that never participated in the construction of planets. In the cold locker of the outer Solar System, they remain just as they were more than 4.6 billion years ago. This primitive matter, not significantly altered by any astronomical or geological process, is a time capsule of the chemistry at the birth of the Solar System. Planetary scientists are like Solar System archeologists, digging back in time to its earliest days. They would love to get their hands on a piece of pristine comet.

In fact, they have. The Stardust space probe of 2004 flew through the coma of Comet Wild 2, within 237 km of the nucleus (figures 3.13 and 3.14). This was a short-period comet that recently had a gravitational interaction with Jupiter, changing its orbital period from 43 to about 6 years. Aboard Stardust was a tennis racket-shaped collector with an ultralight-weight, silica-based material named aerogel, in which comet dust particles became imbedded (figure 3.15). The collector was then returned in 2006 to the Earth (via parachute) for study. Everyone can participate in the analysis of the captured dust in a citizen science project at the website http://stardustathome.ssl.berkeley.edu.

3.4 Comet scene investigation (CSI) using chemical fingerprints

Time out. How is it that we think we know what comets might be made out of? The shape and motion of comets are evident from descriptions and photographs made from the Earth, but composition is another matter.

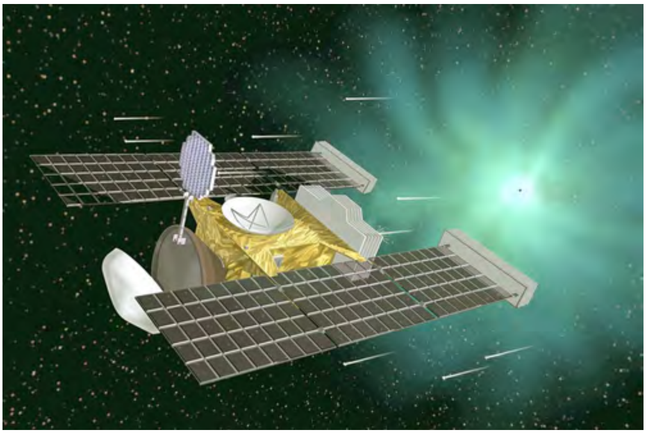

Figure 3.13. An artist's rendition of NASA's Stardust space probe rendezvousing with a comet.

Figure 3.14. Comet Wild 2 as imaged by Stardust. NASA image.

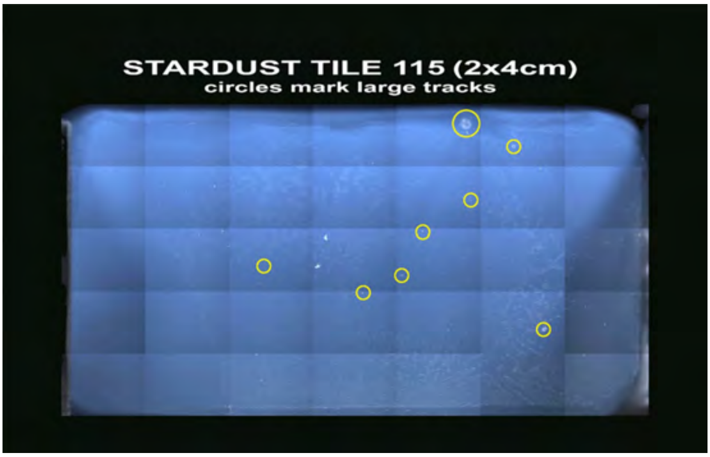

Figure 3.15. Comet dust grains captured in aerogel by Stardust. NASA image.

Astronomers are always at a disadvantage compared to their colleagues in other sciences. Chemists, geologists, or biologists can examine their subject matter up close, in a laboratory, conveniently displayed in test tubes and beakers. The subject of astronomy, the Universe beyond the Earth, is by definition detached. Except for meteorites (see below), small interstellar dust particles (IDPs) collected by high-flying aircraft and Earth-orbiting craft, and a few hundred kilograms of Moon rocks retrieved by astronauts, we cannot hold pieces of the rest of the Universe in our hand. All our information comes to us, indirectly, in the form of light and other kinds of radiation.

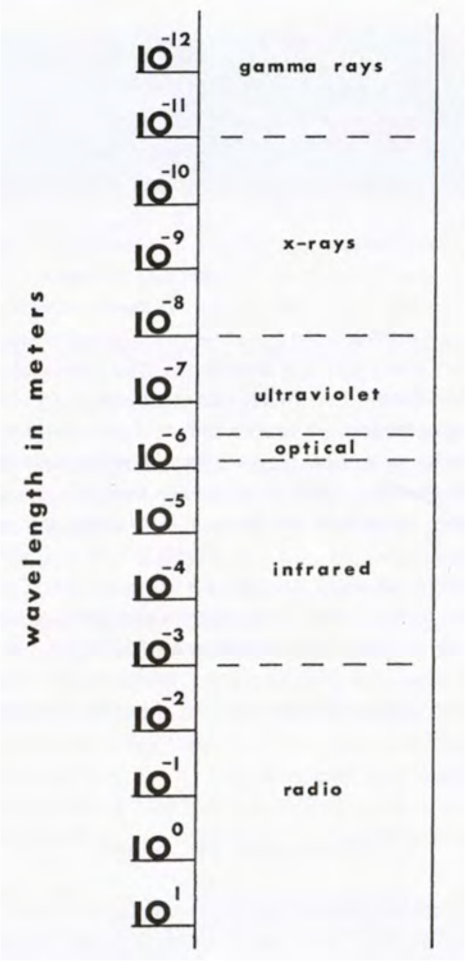

Figure 3.16. The electromagnetic spectrum. We can see only the optical portion.

Because they rely on light to such a great extent, astronomers must be intimately acquainted with the information imbedded in it. Here, we will hit the highlights. Formally, light is one type of electromagnetic radiation (figure 3.16). For our purposes, electromagnetic radiation is a wave that can travel through empty space without a medium to convey it. It does so at a constant speed (almost 300 000 km s^{-1}), the cosmic speed limit[11]. All electromagnetic radiation is alike except for its wavelength, defined as the physical distance between succeeding crests of the wave (or succeeding troughs). For instance, radio is a form of electromagnetic radiation. You and we think of radio as something very different from light. (We can see light, we cannot see radio.) Yet the only real difference is that radio has wavelengths

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[11] According to Einstein's special theory of relativity, nothing in our Universe can go faster than the speed of light.

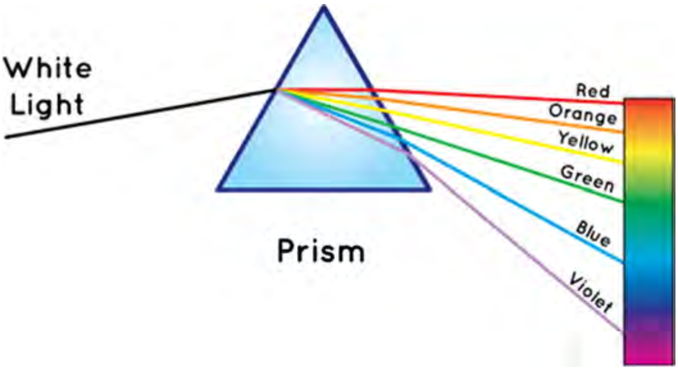

Figure 3.17. White light being dispersed into its component colors. NASA image. Illustration by: Simon Tuckett.

measured in millimeters or meters, while visible light has wavelengths measured in ten-millionths of a meter. (The wave crests are very close together.)

All visible light is not created equally. Sir Isaac Newton proved this when he shone white light through a prism. A prism separates white light into a spectrum of colors (figure 3.17). Each color has a slightly different wavelength. Another way of stating this is that wavelength is simply the quantity (number) scientists assign to the quality of color; so when you hear color, think wavelength and vice versa. There are really a tremendous number of colors, each distinguishable by wavelength, but the human eye and brain tend to group them into six ‘bins’ we call red, orange, yellow, green, blue, and violet. Newton described what he saw as a continuum of light but ended up using seven ‘bins’, including indigo between blue and violet. This conformed with the notion that seven was a ‘magic number’, like the seven notes of a western major musical scale.

The colors do not stop with either red (the longest wavelengths we can see) or violet (the shortest wavelengths we can see). Even longer than red is infrared (IR). Our eyes are not constructed to detect it, but our bodies are. Infrared is radiated heat. (Vipers (rattlesnakes), pythons, and boas can sense infrared from ‘pit’ organs on their heads—one reason you are at a distinct disadvantage when in a dark room with a rattlesnake!)

Even shorter than violet is ultraviolet (UV). The invisible ultraviolet rays of the Sun are notorious for causing sunburn and skin cancer. In a less deadly application, when you receive a re-admission hand stamp at the amusement park gate, it is made visible by an ultraviolet lamp. Honey bees can find nectar on flowers by sensing UV patterns unseen by human eyes; however, they do not enjoy beautiful sunsets since they cannot see red!

Any dense object that is heated will produce electromagnetic radiation. If it becomes hot enough, it will glow in visible light. The coil of an electric stove top will emit infrared light when set on ‘low’. (It looks dark, but you can feel the radiated heat with your hand.) If the stove is turned up, the coil will glow red and then orange. It is still producing infrared, and red light for that matter, but more energy is being emitted in those wavelengths we call orange than any other, so our eyes see the coil as orange.

Every temperature has its characteristic color. The shorter the wavelength of that color, the hotter is the object. Our Sun is glowing at the temperature associated with a 5500 °C body: the blend of all of the colors of sunlight is yellow. Remember, the Sun is producing light at many different wavelengths—a prism and sunlight will create a 'rainbow'—but actually more of the light is green than any other color. Is it a coincidence that the peak sensitivity of the human eye is in the green part of the spectrum?

The Sun's light shines on all the other bodies in the Solar System. There is no other significant source of light in the vicinity. We can easily see the planets, satellites, and comets because they reflect sunlight.

Not all the Sun's light reaches, and is reflected by, the comet. Thin, cool gas in the Sun's outer atmosphere absorbs specific wavelengths of light. Moreover, the atoms and molecules that make up this gas will absorb light of only these wavelengths. This absorption leaves dark lines (the absence of color) in the spectrum of sunlight (figure 3.18). We see these lines, too, revealed in the spectra of comets. The pattern is unique to the gas. It is a spectral 'fingerprint,' identifying the gas that the light has encountered.

Physicists and chemists in the laboratory have examined the pattern of absorption lines produced by all sorts of gases and have cataloged these patterns. They do this using an instrument called a spectroscope. A spectroscope is just a prism, or other device, which spreads light out into a spectrum (a process called dispersion) so that we can see what wavelengths are there and what wavelengths are missing. This branch of science is called spectroscopy.

A common misconception is that sunlight is composed of a continuous spectrum, all of the colors of the rainbow. Not so. As we have just learned, it contains up to 20 000 absorption lines where colors have been subtracted due to the cool gases in the outer layers of the Sun. In fact, the element helium (from ἥλιος, pronounced helios, the Greek word for Sun) was first discovered in 1868 by an astronomer analyzing the solar spectrum during a total eclipse, before it was found on Earth. This spectroscopy is powerful stuff!

When a thin gas is itself heated, it emits rather than absorbs light. However, it emits light only at its 'fingerprint' wavelengths. The result is a spectrum of bright emission lines alone, rather than a continuous spectrum with dark absorption lines

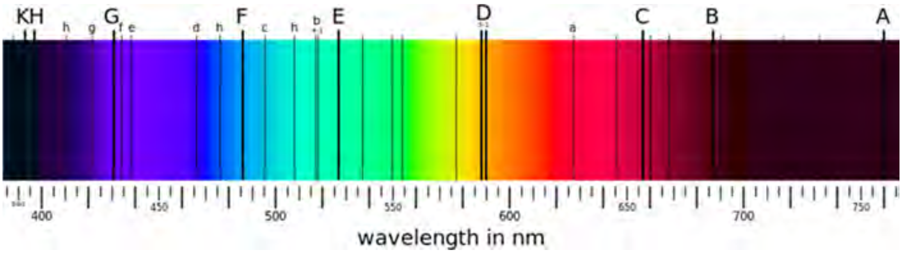

Figure 3.18. An absorption spectrum.

running through it. Mixtures of gases result in a superposition of ‘fingerprints’ that can be disentangled by carefully removing layer upon layer of each gas’s spectrum (figure 3.19).

Using these tools, comet detectives gather clues to understanding these bodies. When an astronomer causes comet light to pass through a spectroscope, in addition to the solar absorption lines, a pattern of emission lines is seen. These lines are produced by the comet. By comparing these patterns to the patterns of known gases, the gases present in the comet can be unmasked.

Spectral emission lines are only emitted by thin gases. It is lucky for those studying comets that there is so much gas associated with comets. While spectroscopy applies only to the coma and tail of the comet, we assume that the coma and tail gases come from the materials in the nucleus. That is, the nucleus must be made of chemicals that can generate those we see in the coma and tail. Therefore, we have a clue about the composition of the nucleus, too.

Spectroscopy does not work so well for comet dust. (Dust grains emit at infrared wavelengths.) Still, comet dust scatters sunlight just as surely as a dusty car window does. By studying the component of sunlight that is scattered and comparing it to the way dust in a laboratory scatters light, we can conclude, at least, what is the size of the particles involved, if not the particles’ exact chemical make-up.

In 2005 the Deep Impact space probe hurled a 370 kg copper projectile, almost 60% of the spacecraft’s total mass, into low-density Comet Tempel 1 (figure 3.20). (By way of comparison, Tempel 1 is a typical, short-period comet with a size of about six kilometers.) The comet and projectile collided at a speed of ten kilometers per second (or 37 000 km h^{-1}) delivering the equivalent energy of almost 5 tons of TNT (figure 3.21).

The explosive result broke through the comet crust, created a new 150 m-diameter crater, and hurled some 10 000 tons of fresh comet material into space, causing the comet to shine six times brighter. There it was studied by Deep Impact, the Hubble Space Telescope (HST), the Spitzer Ultraviolet Telescope, and by hundreds of Earth-based telescopes in a coordinated campaign that enlisted amateurs world-wide to collect important data about Tempel 1 prior to, during, and after the collision. In addition to taking pictures, spectroscopes revealed the presence of water, silicates, clay, and other (somewhat surprising) crystal minerals. Meanwhile, Deep Impact went on to visit Comet Hartley 2 as part of a mission extension called Extrasolar Planet Observation and Deep Impact Extended Investigation (EPOXI) that also searched for exoplanets (figure 3.22). NASA is always looking to recycle, reuse, and record eco-friendly spacecraft.

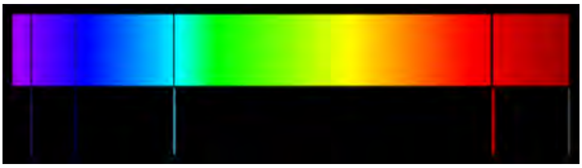

Figure 3.19. Top: an absorption spectrum. Bottom: the emission spectrum of the same element.

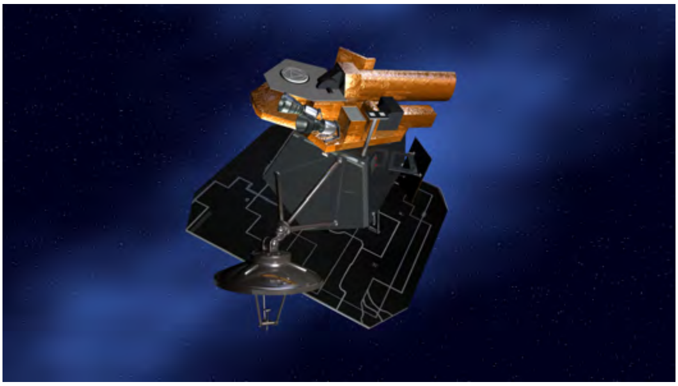

Figure 3.20. The Deep Impact space probe. NASA/JPL-Caltech image.

Figure 3.21. The explosive collision between the Deep Impact projectile and Comet Tempel 1. NASA image.

3.5 The demise of comets

Once vaporized gas and dust leave the comet nucleus, they are gone for good. Therefore, each passage of a comet near the Sun depletes the nucleus since it has no means to replenish these substances along its orbit. Every perihelion, meters of a comet's outer crust may be eroded away. The coma and tail that make a comet such a magnificent sight in our sky ultimately mean the demise of the comet. It has been

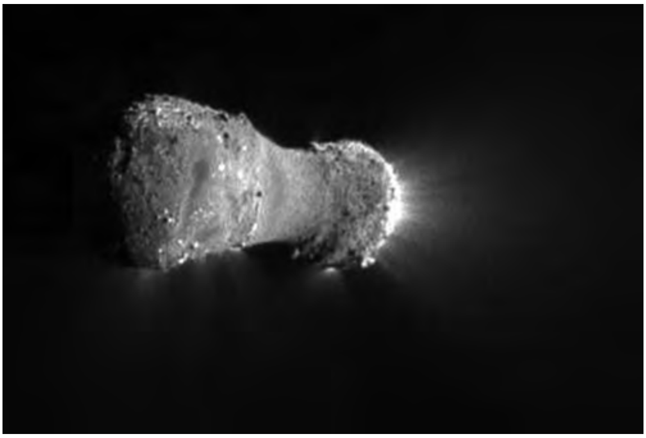

Figure 3.22. Comet Hartley 2. NASA image.

Figure 3.23. Drawing of Comet Biela. The comet split in two after its 1826 apparition.

estimated that a comet can only make one hundred to a thousand such near-Sun trips, on average, before there is nothing but grit left. The comet nucleus will expend its available volatiles before this, and with no glowing coma or tail to mark its presence, will be lost from view. Alternatively, some dust particles may fall back onto the nucleus forming a thick, insolating mantle that prevents the Sun's heat from reaching lower layers where volatiles may still exist. These dormant comets may be reactivated by a collision that breaks through the mantle, exposing volatiles in the interior. Short-period comets last, at most, half a million years.

This is not just theory. Comet Biela was discovered and charted so that its return time could be predicted with great precision (figure 3.23). Still, at the appointed time, no comet appeared.

Comets also have been observed to break up, often near the Sun. Gravity becomes weaker with distance. A comet venturing very near the Sun will experience a noticeably stronger gravitational pull on its 'front' than on its 'back'. This difference in attractive force, called a tidal force, is sometimes strong enough to tear the comet asunder. Maybe rapid sublimation at certain places on the comet nucleus has left structurally weak spots, such as exposed cavities and cracks, along which the nucleus is pulled apart. If the nucleus is a ‘rubble pile’, an aggregate of smaller bodies in the hundred meter range, tidal forces may overcome the self-gravity that holds them together. The result: two or more smaller comets, traveling in more-or-less the same path. Recent examples of this were Comet ISON in 2002, which broke up very near the Sun, and Comet Schwassmann–Wachmann 3 in 2006. (The latter’s fragments went on to fragment themselves.)

Long-period comets tend to put on better performances in the sky than short-period comets. It is they that have the potential to become a Great Comet. The reason is that they have made far fewer trips to the purlieu of the Sun, in the course of their lives, than have their short-period cousins. While the short-period comets have had their volatile materials significantly depleted, long-period comets still have much fresh ice to produce a bright coma and long tail.

All that comet dust does not just vanish, of course. If you go out at night, just long enough after sunset for the sky to become completely dark, you may see an extremely faint glow in the west. (Your best chance to see this is to avoid city lights and choose a time when the bright Moon is not in your sky.) This glow may look like a tapering pyramid reaching up into the sky from where the Sun set. The pyramid does not stand straight up, however. It follows a path across the sky coincident with the ecliptic. You are seeing the *zodiacal light* (figure 3.24). It is called that because it appears in the zodiac, the set of twelve star constellations along the ecliptic. You can see the same thing in the East, in the early hours before sunrise. Moonless evenings in February, March, and April are the best times to see the zodiacal light in the Northern Hemisphere. (Change evenings to mornings for the Southern Hemisphere.)

Zodiacal light is produced by sunlight reflecting off dust particles in the ecliptic plane. These particles will eventually fall into the Sun. The fact that the zodiacal light is always present means that the dust must be continually replenished. The most obvious source is comets.

Figure 3.24. The zodiacal light. A Fitzsimmons/European Southern Observatory (ESO).

What happens when a comet dies? It may break into pieces, like the last sliver of a bar of soap left on the shower floor. Ironically, at this point the comet may brighten as more area of fresh ice is exposed. Perhaps, it may go out more quietly, simply fading from view. What is left then?

Besides comets, there are small rocky and metallic bodies in the Solar System called asteroids (figure 3.25). Most asteroids are thought to be leftover planetesimals (or collisional fragments thereof) created in the inner, hotter part of the proto-Solar System cloud. Most known asteroids now reside in the Main Asteroid Belt, between the orbits of Mars and Jupiter. They formed when the temperature cooled enough to allow high-melting-point refractory elements to solidify. (Examples of refractory materials include silicon, calcium, titanium, aluminum, iron, and compounds that contain these elements.) Most asteroids are mere points of light in the sky, even through a telescope. They do not exhibit a coma or tail.

If a comet has one or more large pieces in it, made of rock or metal, these pieces will go on, even after the volatile components of the comet have been exhausted. We may never see them. They may continue to follow in the comet's orbit long after the comet itself ceases to be. In short, this devolatilized or dormant cometary body may become one or more asteroids. Some asteroids on comet-like orbits are thought to be dormant comet nuclei.

However, the leftover pieces of rock may be much smaller and more numerous. The corpse of the comet may travel through space as a dissociated rubble pile. This swarm cannot be seen in visible light, but it is there, filling the orbit of what was once the comet's. We may encounter this debris if the Earth's orbit happens to cross the path of the former comet.

Meteoroids are small bits of extraterrestrial rock and metal that can strike the Earth, much smaller than asteroids (less than about three meters in size). When they do so, they are traveling at terrific speeds. During their short flight through our atmosphere, on the way to the ground, they compress the air in front of them incredibly quickly, heating it to a high temperature that is transferred to the meteor

Figure 3.25. Ida, a typical asteroid, about 60 km in the long dimension. NASA image.

causing it to glow and possibly leaving a trail of hot vapor in its wake. We can see their fiery deaths as quick, often momentary, streaks of light in the night sky. We call them 'shooting stars' or 'falling stars', but because they have absolutely nothing to do with stars, a better name is *meteor*. Many meteors are the size of grains of sand and completely burn up in the atmosphere. Larger ones may survive their fall, and can be recovered as meteorites.

Meteors appear in the sky randomly all the time. Human beings spend little time looking up at the sky; therefore, when one does happen to glance up and catch sight of a meteor, it is considered a sign of good luck, something to 'wish upon'. Yet, several times each year, the number of meteors in a night increases, in some cases significantly (figure 3.26).

Such a meteor shower is misnamed. The frequency of meteors during these days or weeks is usually not as great as the word 'shower' implies: it is one every one-to-fifteen minutes, on average. (Maybe 'meteor sprinkle' would be better!) Still, the effect is real. At one time, meteors were believed to be a strange weather phenomenon and to have nothing to do with bodies in space. Then it was noticed that shower meteors all seem to be coming from the same point in the sky. Each streak diverges from this point, called the shower radiant.

The effect is the same if one watches a line of cars, side by side, traveling toward you on the highway. At the horizon, the cars all seem to occupy a single point, but as they get closer, they appear to move outward from this point. (When this happens, it would be a good idea to stop standing in the middle of the road! Run away!) Also see figure 3.27.

The fact that shower meteors have a radiant suggests that they are produced by objects approaching us from far away. The Earth travels through the same place in its orbit at the same time each year. The fact that meteor showers are annual suggests that there are meteoroids present at this location always. Putting what we know about meteor showers and comets together, we can guess that the meteoroids that produce these showers are the spent remains of comets, a trail of comet dust so

Figure 3.26. Time-lapse image of a meteor shower. Thomas W Earle.

Figure 3.27. Both the telephone poles and the canal appear to diverge from a common, distant radiant.

to speak, expanding from the comet's path, and now intercepting the Earth. Indeed, the paths of shower meteoroid swarms have been calculated and matched up with the orbits of known comets. Meteor showers are some comets' last 'hurrah'.

When an especially dense part of the meteor swarm (the comet *trail*) is intersected by the Earth, the frequency may rise to as many as one thousand meteors per hour—a true meteor storm! Major meteor showers like this occurred in the Novembers of 1966, 1996, 2001, and 2002; they are called the Leonids after the constellation in which their radiant appears. They are due to Comet Tempel–Tuttle that had recently rounded the Sun and replenished its debris trail. The Leonids also contain many fireballs, very bright meteors that exceed the brilliance of Venus. What happens if the comet is crossing our orbit when we arrive? A spectacular collision, of course, but more on that in chapter 4.

Do not confuse the meteoroids that produce shower meteors with meteorites found on the Earth. These larger objects from space survive their hot passage through the atmosphere to land nearly intact. However, these falls are random; they do not coincide necessarily with any annual meteor shower. High-flying aircraft have been successful in capturing bits of meteor-producing grains. Analysis of the material shows it to be chemically different from meteorites. This well-traveled dust is nearly our only sample of 'comet stuff'.

Because we are always losing comets, there must be a source of a fresh supply. Where?

3.6 The origin of comets

We know what becomes of a comet that spends too much time near the Sun. But where do comets come from in the first place? What is their origin? They must have formed outside the snow line, the distance from the Sun at which ice remains frozen, currently at the distance of Jupiter's orbit.

According to Dutch astronomer Jan Oort's (1900–92) theory from the 1950s, the answer lies in the average distances of long-period-comet aphelia. That almost all go out to 50 000 au in random directions is more than a coincidence. Oort envisioned a vast shell of dirty snowballs surrounding the Solar System at that distance up to 150 000 au (more than half the distance to the nearest star and at the limit of the Sun's gravitational boundary). This shell is a reservoir of potential comet nuclei—more than a trillion of them. Today we recognize a doughnut-shaped Inner Oort Cloud (or Hills Cloud), extending from about 2000 to 20 000 au, surrounded by the Outer Oort Cloud, the spherical shell envisioned by Jan Oort (figure 3.28). By far, most of these bodies stay in the *Oort Cloud* (figure 3.29). They slowly move around the Sun, always at this vast distance, in nearly circular orbits. They are as cold as space gets: about 3 K (−270 °C). Here we make an important distinction between the Solar System and the Planetary System. Oort showed that the influence of the Sun (due to its strong gravitational pull) extends to at least 50 000 au, far beyond the realm of planets (about 30 au). So when you hear someone (like NASA) claim that a certain spacecraft is at the edge of the Solar System or has left it, they actually mean that it has left the Planetary System (at 30 au) or at best the influence of the solar wind (about 120 au). Please remind them that it has quite a ways to go before leaving the Solar System!

Figure 3.28. Astronomer Jan Oort. Copyright the Leiden Observatory, reproduced with permission.

Occasionally, however, something disturbs these loosely bound objects in the Oort Cloud. (Such a thing would have to come within 100 000 au of the Sun to produce a noticeable effect.) It may be the gravity of a traveling nearby star, an event that occurs once every 3–10 million years, or that of a wandering interstellar cloud of gas or even galactic tides[12]. (The star Gliese 720 actually will pass *through* the Oort Cloud—in a million years.)

Our Sun, along with hundreds of billions of other stars, slowly revolves around the center of a huge disk of stars called the Milky Way Galaxy. Every time the Sun passes through a dense part of the disk, the disk's gravity may nudge the Oort Cloud. Any of these mechanisms could supply us with enough comets for 10 000 years.

Regardless, nuclei are bumped out of the cloud. Some escape the Solar System entirely. It even may be possible for such a comet to travel from the influence of one star to another. (Remember, Comet Oumuamua that we discussed earlier in chapter 2? Some argue that Comet Hyakutake is a captured interstellar comet.) More likely, however, the nucleus plunges inward. The result is a long-period comet. These objects did not start out at such great distances from the Sun. They probably formed out of the denser gas and dust present in the proto-Solar System cloud, at about the distance of Neptune (30 au) and in the ecliptic plane. The modern theory of the origin of our Solar System, called the Nice model[13], posits that the giant planets originally formed much closer to the Sun and then migrated outward, unleashing a flood of comets throughout the Solar System as part of the Late Heavy Bombardment era (about four billion years ago) and formed the Oort Cloud among other Solar System features. Some have suggested that five giant planets were originally formed, and one was ejected in a case of planetary musical chairs. The Grand Tack Hypothesis suggests that Jupiter originally migrated inwards, before interacting with Saturn and reversing its course to its present location, solving some of the limitations of the Nice model. With all of this exciting work, there remains so much that we do not know about the history of our Solar System, but comets certainly provide many important clues.

Some meteor dust contains hydrated minerals, those that incorporate water. These are common on the Earth; an example is olivine. This dust must have formed nearer the Sun and then somehow migrated out to the realm of the comets. That comets contained both 'fire and ice' materials was a major finding of the Stardust Mission.

As was mentioned earlier, many of the objects so formed (planetesimals) collided with and joined the outer major planets as they grew. The left-overs were subjected to the gravitational pull of the now-massive planets and were banished to the distance of the Oort Cloud or farther.

There also remain potential comet nuclei between Neptune and about 50 au out (with the densest part lying between 40 and 48 au). This is the *Kuiper Belt* (figure 3.29), named after a pioneer planetary scientist of the 1940s and 1950s, Gerard Kuiper (1905–73). (Not the fancy belt worn by D B as one student noted on his exam!)

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[12] Galactic tides are tidal forces exerted by the Milky Way Galaxy on our Solar System. Tidal forces are explained in chapter 4.

[13] It is a nice model but the name actually comes from the French city, Nice, where it was originally developed.

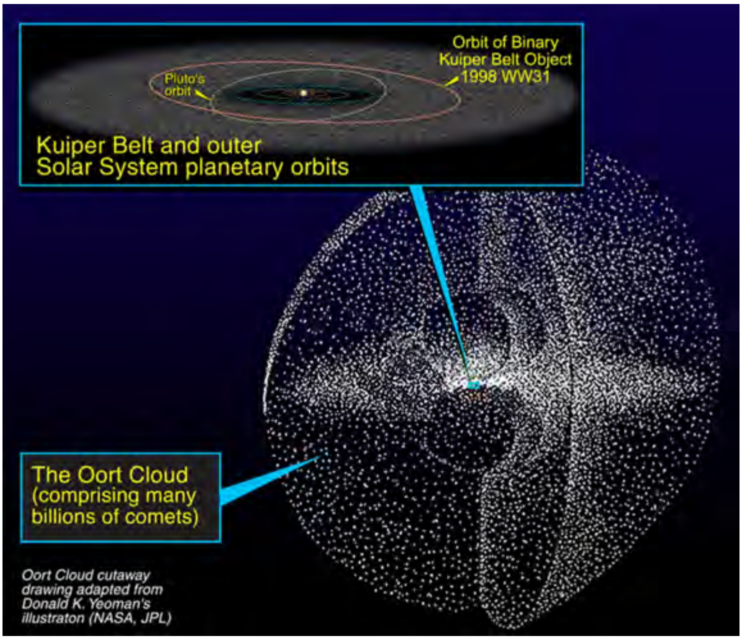

Figure 3.29. Representation of the Oort Cloud and Kuiper Belt. NASA image.

He thought of it in 1951 after asking a simple question: why should the Solar System end at Pluto (then a planet)? He could find no reason why it should. Originally considered a hypothetical hiding place for would-be comets, beginning in 1992, large Earth-based telescopes finally imaged larger members of the Kuiper Belt. The total count now is more than one thousand. Because we expect large nuclei to be rare compared to smaller ones, the Kuiper Belt, like the Oort Cloud, must be a repository for a great number of comet bodies, maybe more than 100 000 with a diameter greater than 100 km. (It is hard to tell the size of these objects, most point-like in appearance from the Earth, because we do not know their albedos.) Indeed, telescopic survey images (e.g. by Hubble, figure 3.30) suggest that hundreds of thousands more Kuiper Belt Objects (KBOs) await to be detected by telescope, while hundreds of millions more remain invisible. Moreover, it is improbable that the space between the Kuiper Belt and Outer Oort Cloud is devoid of objects, hence the Inner Oort Cloud that smoothly joins these two. The mass of the Kuiper Belt may exceed that of the main asteroid belt by hundreds of times (but still only 1/10 of an Earth mass). KBOs have satellites: one of them has three, and Pluto[14] has five. The New Horizons space probe, having flown by Pluto, will attempt to visit another KBO, 2014 MU_{69} (nicknamed Ultima Thule), on January 1, 2019 (figure 3.31). (The first results from New Horizons' successful encounter with Ultima Thule can be found in the Postscript.) During the elaborate Kabuki dance of the Giant Planets

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[14] Pluto is a Dwarf Planet but is also considered to be a KBO, in a special class, called Plutinos; these are in synch with Neptune's orbit.

Figure 3.30. The Hubble Space Telescope. NASA image.

Figure 3.31. Launch of the New Horizons space probe in 2006. It flew by Pluto in 2015 and is now headed to a KBO, ignominiously named (486958) 2014 MU_{69} (nicknamed Ultima Thule). NASA image.

predicted by the Nice model, Uranus and Neptune shepherded the Kuiper Disk to its present location and may have even traded places. Also formed was the Scattered Disk, overlapping the Kuiper Belt and extending beyond 100 au, containing objects with very elliptical orbits and higher inclinations. The Scattered Disk is now thought to be the principal source of short-period comets.

There is a population of small bodies with characteristics of both asteroids and comets between the orbits of Neptune and Jupiter called *Centaurs*. Interactions with the outer planets make their orbits inherently unstable. Some are thought to be short-period comet nuclei from the Kuiper Belt or Scattered Disk making their way progressively into the inner Solar System. 95P/Chiron was the second Centaur discovered in 1977, joining a list now totaling over 500 objects.

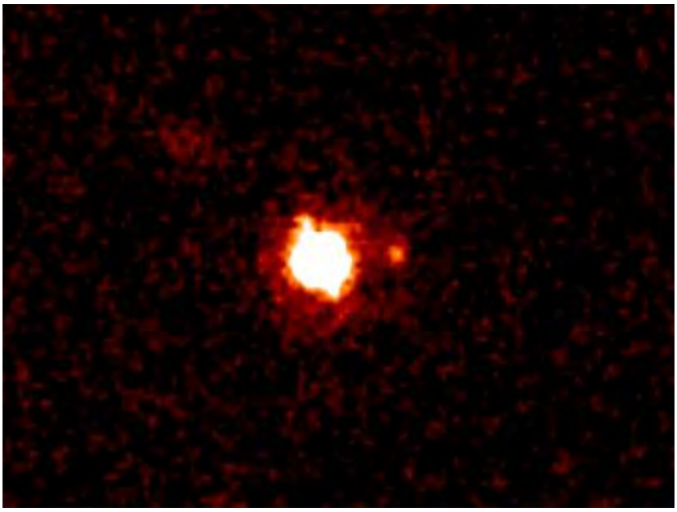

Figure 3.32. Distant KBO Eris is slightly smaller than Pluto but is more massive. Note its satellite Dysnomia on the right. Image courtesy of W M Keck Observatory.

Another place in the Solar System where comet nuclei may be sequestered are the *Trojan asteroids*. These small bodies are located at the orbit of Jupiter, in two groups about 60° ahead (Greek node) and 60° behind (Trojan node) its orbit, trapped at stable points. All are classified asteroids but many may be comet nuclei that were captured by Jupiter in the early history of the Solar System. To date, 7040 Trojans have been discovered. In 2021, NASA will launch the Lucy Mission to visit six Trojans between both groups, arriving in 2027.

In 2006, a Great Debate was held at the International Astronomical Union meeting in Prague about the definition of a planet. What precipitated the debate? It was the discovery of Eris in 2005 (figure 3.32), initially thought to be larger than Pluto (figure 3.33) and at twice its distance from the Sun. If Pluto was a planet, then surely Eris was also. Experts in the field suggested that there could be hundreds of other Plutos in the Kuiper Belt. (We now know of an additional two[15], Haumea and Makemake, joined by the largest asteroid, Ceres, in the Main Asteroid Belt.) The issue was settled by vote and 76 years after its discovery by United States astronomer Clyde Tombaugh (1906–97), Pluto lost its status as a planet, being reclassified into a new category of ‘dwarf planet’. Do not let the adjective fool you; Pluto is not simply a small planet but an entirely new creature. For one thing, Pluto is small for a planet (smaller than our Moon!) and only one out of three made substantially out of ice (in addition to ice giants Uranus and Neptune; Pluto is thought to be 70% rocky, 30% water ice but without the deep hydrogen–helium atmosphere). It does have sufficient mass to pull itself into a round shape, like a planet. It also has the most noncircular orbit of them all—it crosses the orbit of Neptune. It is more inclined to the ecliptic

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[15] There are four dwarf planet candidates in the Kuiper Belt as we go to press: Sedna, Quaoar, Orcus, and 2014 UZ224.

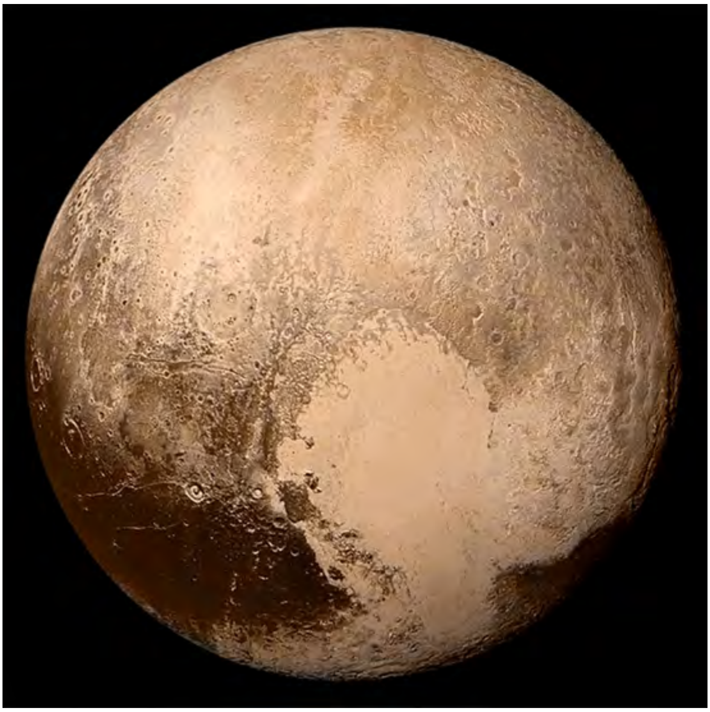

Figure 3.33. Pluto as seen by the New Horizons space probe. NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute image.

than other planets. Finally, it inhabits a crowded region of the Solar System, unlike planets that have largely cleared the region of their orbits. All these things sound more like ‘comet’ than ‘planet’. We now recognize that Pluto has been reclassified as the first of the KBOs. Pluto is not the smallest planet.

May it be the largest comet? While Pluto does sublimate a thin atmosphere when near perihelion, it never gets close enough to the Sun to form long ion and dust tails. Moreover, Pluto is too massive to allow gas and dust to freely escape its gravitational pull as is characteristic of a comet. So, we must add to our definition of a comet: a small body that cannot bind the sublimating gas and attendant dust. Pluto also has the uncometary characteristic of a large natural satellite, Charon, and four smaller ones (Hydra, Nix, Styx, and Kerberos). It is unlikely that school children will be required to unlearn this quixotically named dwarf planet any time soon.

Rather than mourn the demise of Pluto, we should celebrate our new found knowledge. This is a prime example of the scientific method at work, causing us to constantly review and revise previously held notions as new discoveries are made. In any event whether you agree with Pluto’s reclassification or not, Clyde Tombaugh summed it up best: it doesn’t matter what you call Pluto, it remains an important and fascinating body!

Occasionally, a long-period comet, on its trip into the Planetary System, will come near one of the major planets. Comets have so little mass that they are easily

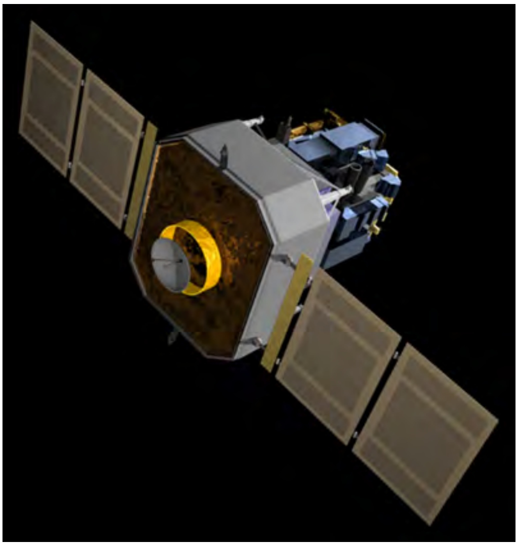

Figure 3.34. ESA’s Solar and Heliospheric Observatory (SOHO). NASA drawing.

diverted from their courses by the gravity of these worlds. Oort had to account for these course changes first before he could see that the original orbits of long-period comets share a common aphelion in the Oort Cloud. Often the affected comet will be drawn in toward the Sun or discharged from the Solar System entirely.

The Solar and Heliospheric Observatory (SOHO) in space watches the environment near the Sun (figure 3.34); it has discovered well over three thousand sungrazer comets—comets that get up to seventy times closer to the Sun than the planet Mercury. Bright Comet ISON came within two solar radii of the Sun in 2013, before disintegrating (figure 3.35). SOHO’s images also show dozens of comets plummeting *into* the hot Sun each year. Sometimes these suicidal comets come in groups. Were they once parts of a single, larger comet? Current thought points to a parent Great Comet, possibly seen by Aristotle in 371 BCE, for the origin of many fragments.

An example of a gravity altered orbit is that of the recent Comet McNaught, which had an initial orbital period of 6 500 000 years, but because of gravitational interactions with the other planets on its recent pass, its orbit was changed to a hyperbolic one that will eventually relax to a period of about 90 000 years, becoming a member of the Inner Oort Cloud.

Sometimes, however, the comet’s orbit will be made more circular by these interactions. Its period will shorten, and it will visit the realm of the planets more frequently. There, it will have more opportunities to be affected by the planets’ gravity. Eventually its orbit will be ‘beaten down’ near the plane of the ecliptic. The result is a short-period comet. Halley’s Comet is thought to have evolved this way.

Short-period comets may also come directly from the Scattered Disk. Here, an occasional nudge from Neptune, or gravitational interactions or collisions between the KBOs themselves, change their orbits.

Figure 3.35. Comet ISON. In a comet image, the camera follows the moving comet thereby making it appear as if it is the backgrounds stars that are moving. TRAPPIST/E Jehin/ESO.

We can even explain why most short-period comets orbit the Sun in a counterclockwise direction: a comet orbiting in the same direction as the motion of the planets will spend more time near a planet than will a comet whirling by the 'wrong way'. Thus, counterclockwise comets will have more time to be diverted gravitationally by the planets than will clockwise comets.

Massive planet Jupiter is particularly effective at influencing comets. Most short-period comets have aphelia out to about the orbit of Jupiter (5.2 au). Clearly, Jupiter has modified the orbits of these comets, the so-called Jupiter-family comets.

On the other hand, there is a very strange body that goes nowhere near Jupiter. The Centaur Chiron—not to be confused with Charon, Pluto's satellite—spends most of its time between the orbits of Saturn and Uranus (average orbital radius of 14 au). It originally was classified as an asteroid, but asteroids do not usually venture this far out. Chiron seems to be an icy body. The line of demarcation between these two categories of bodies becomes fuzzier. At perihelion in 1996, Chiron formed a coma! With an orbit much more circular than normal, is chameleon-like Chiron the ultimate short-period comet? If so, it is a big one; Chiron is two-hundred-kilometers across and nearly at the boundary of having a gravitationally bound atmosphere!

3.7 A visit to a comet

A Great Comet is one that we can see easily without optical aids (figure 3.36). They are as bright as planets; some can be seen in the daytime. They are invariably long-

Figure 3.36. An example of a Great Comet from the past.

Figure 3.37. Comet Holmes' outburst in 2007, visible in the daytime!

period comets because these comets have not developed a significant mantle from too many passages around the Sun.

Obviously, most comets are dim objects, seen only through a telescope. However, comet brightening is unpredictable. In 2007, Comet Holmes was a run-of-the-mill comet, that is, until it became half a million times brighter in only 42 h (figure 3.37). What happened? Did a meteoroid impact excavate fresh material and fling it into the coma and tail? Was a pocket of fresh material suddenly exposed, with the same result? We just do not understand comet brightening and dimming well, making it difficult to predict what will become a Great Comet and what will not. Even well-known Comet Halley became brighter on its last *outward* path from the Sun at 14 au. We may see what changed when it revisits us in 2061.

But let us now not restrict ourselves to telescopic views from the Earth. Let us take an imaginary spacecraft voyage to a newly discovered comet. As we approach the comet, we aim toward the bright center of its head. This is not necessarily the nucleus. It is just the densest part of the coma. No one has ever gotten a good view of the nucleus of a comet from the Earth. When near us, the nucleus is always hidden by the coma. We have only space probe images of the nuclei of certain comets to guide us (see the frontispiece). They may be atypical, but this is an imaginary encounter, so let us continue.

Closer, we enter a cloud of hydrogen gas surrounding the comet, ten million kilometers in diameter. This cloud is invisible to our eyes. We detect it with ultraviolet sensing instruments. It is our first warning that the comet looms ahead.

Now we begin to be bombarded by cometary dust particles in the outer coma. Being hit by a dust grain does not sound very violent. But dust particles traveling at the speed of a comet may be moving orders-of-magnitude faster than the bullet of the highest-power rifle. These granules could easily pass right through us at such speeds. However, we have matched speed with the comet and are creeping up on it at a leisurely rate. Shielding built into our spacecraft further protects us.

As we enter the dusty, thickest part of the coma, the nucleus can be made out. We are used to seeing round planets and satellites. However, our comet is oddly out-of-round. It does not contain enough mass for its own gravity to have squeezed it into a space-minimizing ball.

Ours is a dense comet nucleus. (Comet densities are less than that of ice, varying between 0.1 to 0.6 g cm^{-3}; we measure the mass of our comet by how its gravity affects the course of our spaceship.) From our point of view, accustomed to the comparatively mild topography of the Earth, there may be absurdly high mountains jutting out of the comet nucleus, or impossibly deep fissures cutting into it. There are craters produced by still smaller bodies smacking into it during its long journey around the Sun. The internal strength of our compressed comet material is strong enough to support such features.

We might have ended up at a low-density comet. Here, the nucleus may not even be one solid piece; it may consist of separate pieces barely in contact with one another. Or the whole thing might be the consistency of a fluffy new fallen snow, one with porous cavities within it (porosity up to 75%)—in other words, a body that scarcely holds itself together.

Our comet nucleus rotates underneath us, with a period measured in days. As it does so, each place on the surface experiences day-time and night-time just as places on the rotating Earth do each day. On the daylight side, jets of gas and dust erupt into the comet's sky, at speeds of a thousand kilometers per hour, and feed the coma. At night they shut down. These jets come from isolated 'active spots' on the nucleus's surface, where freshly exposed ice, from a slope exposed by a landslide or small porous holes in the comet's crust, is being rapidly sublimated away by the Sun's heat. With so little gravity, this material easily escapes into the coma.

Wait a minute. Is something wrong here? The day side of the comet nucleus is facing the Sun; the night side is facing the comet's tail. No, it is true that the jets point toward the Sun, but quickly the gaseous material expands to fill the vacuum of space and flows in all directions. Ions produced by photoionization of cometary neutrals by UV sunlight are caught up in the solar wind, blowing far faster than the

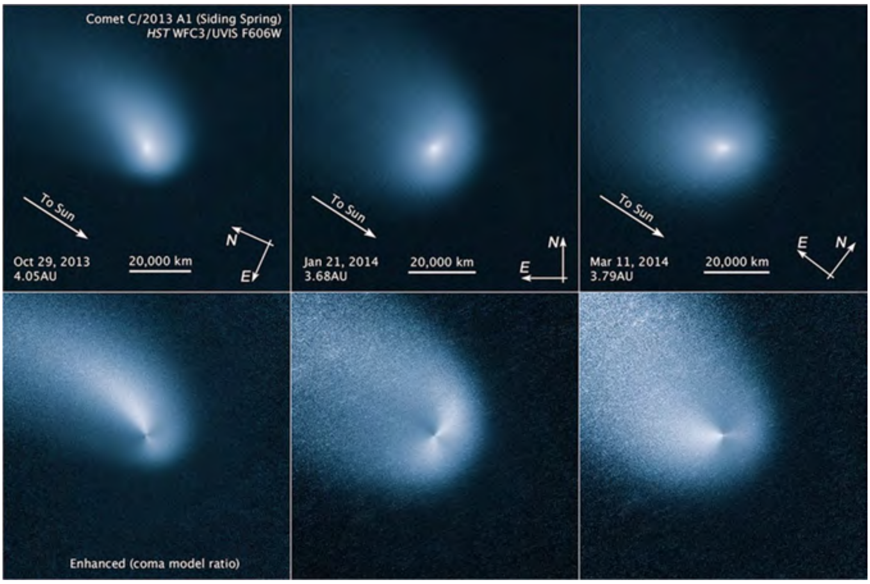

Figure 3.38. Active, rotating jets, on a comet's nucleus, in this time sequence (top—comet image; bottom—coma dust model). NASA/ESA/J-Y Li (Planetary Science Institute) image.

comet itself moves, and are turned around to blow back in the direction of the ion tail, away from the Sun.

The true path of the dust entering the coma is a spiral. The rotation of the nucleus acts like a spinning lawn sprinkler. This spiral structure sometimes can be seen within the coma of a comet from the Earth (figure 3.38). Such was the case with Comet Hale–Bopp.

Nuclear jets help explain a long-standing mystery about comets. The laws of celestial orbits are incredibly precise. It is possible to predict the position of an orbiting planet millennia in advance. This is not true of comets, however. Comets are notorious for not returning to perihelion on schedule. Sometimes they are a little late, sometimes they are a little early. Even when the perturbing effects caused by the gravity of nearby planets are considered, a comet orbit seems to change with time.

The jets are the solution to the mystery. According to Newton, for every action there is an opposite reaction. (This is the classic sailor-steps-off-boat-onto-dock/boat-moves-away-from-dock/sailor-falls-into-water effect.) As material flies off the nucleus in a jet, the comet itself is pushed a little in the opposite direction. We call this a non-gravitational force.

The gas and dust have little mass but lots of momentum. A bullet does not weigh a lot, but, if traveling fast enough, can knock over an elephant. This is the same principle upon which a rocket engine works. Hot, expanding gas, moving at high velocity, comes out of the bottom of the rocket, and the rocket moves upward. That is one explanation of how comets change their orbits: comets are rocket propelled!

In reality, a jet of gas pointing toward the Sun will not greatly affect the comet's orbit. The comet must be accelerated or decelerated in the direction in which it is traveling. However, the jets do not point directly toward the Sun. The nucleus' rotation swings the jets around to point a little forward or backward, depending on the sense of the comet's rotation compared to the comet's direction of travel. If the jet acts to speed up the nucleus a bit, the comet's orbit will increase in size, and the comet will be tardy for perihelion. If it happens to retard the nucleus, the comet's orbit will become smaller, and the comet will arrive at its appointment with perihelion ahead of schedule. We notice that the northern pole of our comet is in

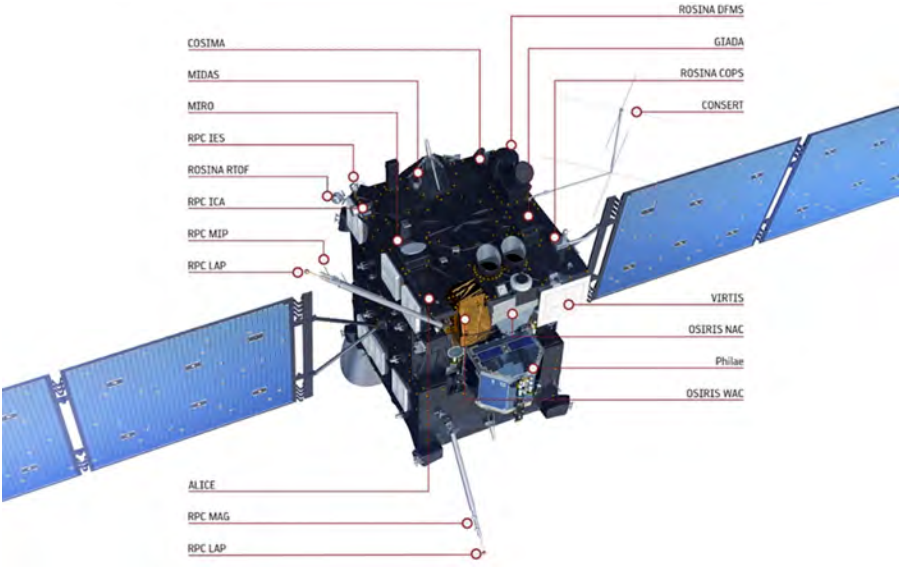

Figure 3.39. The Rosetta space probe. ESA image.

Figure 3.40. Comet Churyumov–Gerasimenko imaged by the Rosetta spacecraft. ESA/NASA image.

constant daylight. It is summer in the north. Tilt of the comet's rotation with respect to its orbit (called the obliquity) causes seasonal effects. So as the comet rounds the Sun, new, fresh surfaces are illuminated causing changes in the gas and dust production.

We are now so close to the comet nucleus that we could reach out and touch it. Should we step out of our spacecraft and plant a flag, claiming its territory as our own? Well, there are international treaties that prevent that sort of thing, but we will not even try.

There is no air to breathe on the surface of a comet, and we would be exposed to the cold and radiation of space. (For all the fuss about the comet coma, at its thickest its density still approximates a good laboratory vacuum; that of the ion tail is even thinner: a few hundred molecules per cubic meter.) Even if we properly attire ourselves in spacesuits, it is likely that the force of planting the flag is enough to propel us backwards away from the comet and our spacecraft, never to return. (With so little gravity, we would be nearly weightless standing on the nucleus of a comet.)

What is more, we might have arrived at a low-density comet. The consistency of the comet ice may be such that our meaningless flag gesture would merely result in pieces of comet flying apart, like a sneeze over talcum powder. We may also be able to achieve superhuman feats such as breaking the comet apart with our bare hands since the material strength is thought to be that low.

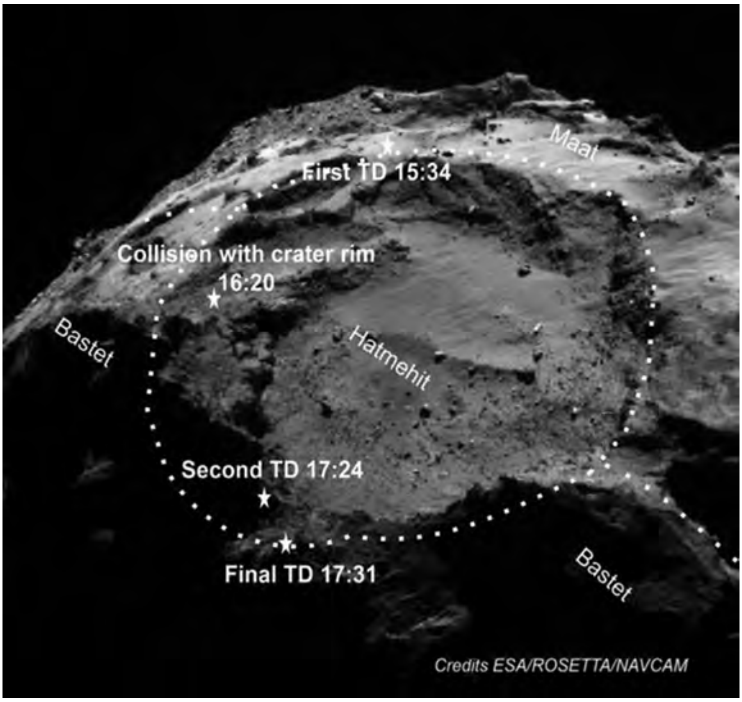

Figure 3.41. Philae's landing. ESA image.

Figure 3.42. A view from Philae. ESA image.

No, standing on a comet might be a tricky proposition. In 2014, ESA's Rosetta space probe (figure 3.39) flew along with Comet Churyumov–Gerasimenko, after zipping past Mars and a couple of asteroids. It found a dumbbell-shaped comet nucleus, perhaps the merger of two separate comets (figure 3.40).

Accompanying Rosetta was a lander named Philae. The idea was for Philae not so much to land as to grab onto the comet nucleus. For this it was equipped with harpoons and screws. However, Philae's landing failed when it could not stick to the comet properly (figure 3.41). It apparently hit a relatively hard surface just beneath the crust. Instead of coming to rest, Philae bounced across the comet terrain, and its solar energy collectors probably were left in shade (figure 3.42). Its batteries ran out shortly thereafter. Two instruments did return valuable results about the surface material, detecting 16 organic compounds, four for the first time.

At its very nucleus, we are too close to appreciate the magnificence of the whole comet. We cannot see the forest for the trees. The Earth provides the near perfect perspective from which to enjoy a comet. It is neither too close nor too far away. Moreover, we do not need an imaginary spacecraft to get us there!

Now, it is time for us to return to the Earth but not before scooping up a handful of comet material for analysis on the Earth. As we depart, we take a moment to look back at the night side of the comet. There, above the horizon and out of the shadow of the nucleus itself, we see hovering in the sky a short column of light. It is the tail of the comet, foreshortened because it is pointing almost directly away from us. Only at its top do we see it begin to split into two wisps, one faintly blue (the glowing ion tail), the other yellow-whitish (the dust tail reflecting the color of sunlight). And not a minute too soon, as it appears that a sizable part of the nucleus is splitting off and heading in our direction … Beam me up, Scotty!

Chapter 4

Comet crashes

Let us begin by stating that none of the comets we have mentioned will strike the Earth. That is worth repeating. They and all other known comets are not on track to hit the Earth—or any other planet, for that matter. Recently, the 2013 Comet Pan-STARRS came within about nine times the distance to the Moon—not very close (figure 4.1). While there are many natural threats to our lives and property, currently a comet is not among them. However, in the long run, we know that it is not a question of if a comet (or asteroid) will hit the Earth, but when it will occur. Comets have collided with the Earth in the past and will do so again at some future dates. Will we have the technology to first find them and then mitigate the threat? Read on!

We can say this with a certainty that we reserve for few other things because of the utter predictability of gravitational orbits. While comet orbits do change, they usually do not do so significantly within a single orbit, and no comet's present orbit takes it anywhere near us.

Be that as it may, a slight apprehension is understandable. Beginning at an early age, we were all admonished of the dangers presented by heavy, flying objects. The sky is falling! Do you remember the story of Chicken Little (Henny Penny)? A comet is such an object, and it is traveling very, very fast. Moreover, in our collective subconscious we may carry with us the vestiges of that primordial fear of comets as agents of mischief.

All this is not completely irrational. Some comets do end their lives prematurely. We can see the artifacts of their early deaths all over the Solar System. If a comet and a solid planet (or satellite) try to be in the same place at the same time, a collision must occur. The modern Solar System is huge and mostly empty space; but, over long intervals of time, such collisions on very rare occasions do happen. The low-mass comet is the big loser. It is destroyed in the collision, and an impact crater forms on the planetary surface. It is these craters that we see covering all the ancient exposed surfaces in the Solar System. We need only look at the round features all over our moon to see that impacts are an important geological feature on other

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Figure 4.1. Comet Pan-STARRS. The name comes from Panoramic Survey Telescope and Rapid Response System, a pair of telescopes located on the island of Maui, Hawaii, designed specifically to look for moving celestial objects such as comets. Courtesy of Ignacio Diaz Bobillo, www.pampaskies.com.

worlds. Many of these craters are caused by asteroids, not comets. When either body strikes, it is going at such a high speed that a violent explosion results. Little visible evidence is left indicating the nature of the impacting body. However, the population of asteroids decreases in the outer Solar System. Most of the craters we see on the icy satellites of Jupiter, Saturn, Uranus, and Neptune surely must be the result of comets (figure 4.2).

Have you ever been to the beach and thrown a stone into the wet sand? If so, you have noticed that the stone is buried in the sand (one end may be above surface), a small depression ('crater') is formed, and some sand is blasted out of the hole. Imagine what would happen if you threw the stone at an angle, say 45°, to the beach. The resulting 'crater' would be oval in shape with most of the excavated sand splashing ahead of the stone. Since impactors on solid planets and their satellites arrive at various angles to the surface, we would expect craters to have a variety of shapes, from circular to highly elongated ovals, if our beach analogy is correct. This is not what we observe. Impact craters are all nearly circular. What went wrong? The energy of the beach impacts was much, much lower than those in the Solar System. The hypervelocity speeds of asteroids and comets range from ten to more than one hundred kilometers per second, resulting in energies greater than nuclear explosions (in some cases many times greater than civilization's entire stock of nuclear bombs).

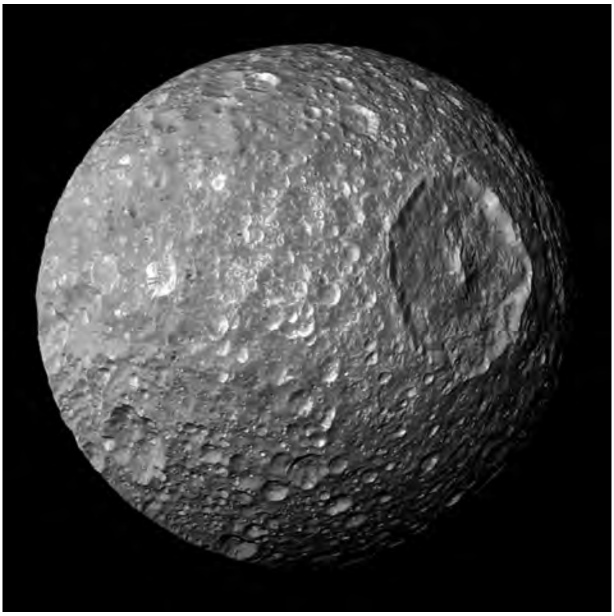

Figure 4.2. Mimas, a heavily cratered satellite of Saturn. Had the object that created the huge crater on the right, named Herschel, been any more massive, Mimas might have been destroyed in the collision. NASA image.

A better analogy would be throwing sticks of dynamite at the wet sandy beach. Caveat: do not try this at home!

We generally divide crater formation into three stages: (1) contact with and compression of the surface resulting in the vaporization of the impactor and much surface material (less than a second), (2) excavation and ejection of material forming crater rims and rays of material streaking radially away from the crater and a mushroom cloud growing above the impact site if an atmosphere is present (minutes to hours), and (3) modification of the nascent crater by crater wall slumping and slippage, possible crater floor rebound forming a central peak, and others depending on the size of the crater (hours to days). A general rule of thumb is that the crater size is about ten times larger than the size of the original impactor.

The outer layers of Jupiter, Saturn, Uranus, and Neptune themselves are made mostly of gas. They have no solid surface on which to form as lasting a record of comet collision as a crater. Still, these large planets must certainly be targets, as well.

In July 1994, astronomers watched a comet named D/Shoemaker–Levy 9 [SL-9] crash into Jupiter. It was the ninth comet discovered by the team of Eugene Shoemaker, Carolyn Shoemaker, and David Levy. (The D/ preceding the comet's name indicates that it is deceased.) Before this, Jupiter's prodigious gravity broke SL-9 into 21 large pieces during a close approach and temporarily captured these pieces as 'moons' on a collisional trajectory (figure 4.3). As the fragments struck, monstrous explosions were recorded by Earth telescopes and robotic space probes (figure 4.4). They left impressive, if transitory, dark spots in the atmosphere of

Figure 4.3. Comet Shoemaker–Levy 9. NASA/ESA/H Weaver and E Smith (Space Telescope Science Institute) image.

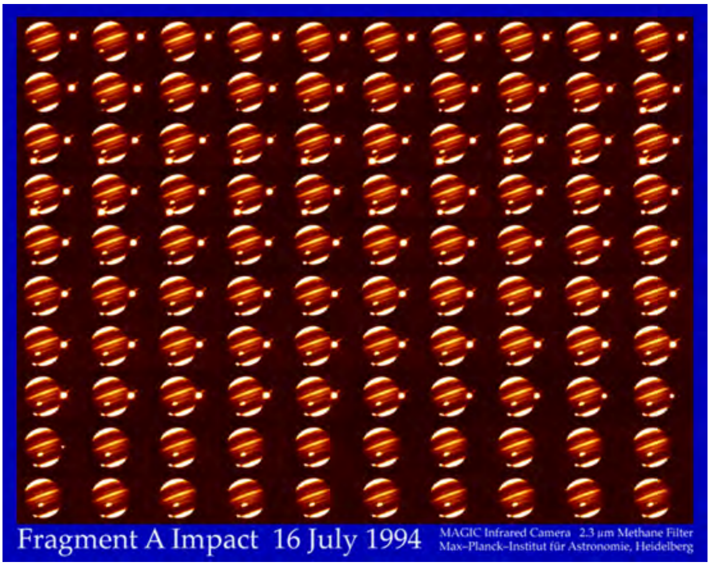

Figure 4.4. A time sequence of Shoemaker–Levy 9 fragment 'A' explosively colliding with the planet Jupiter. Movement is due to the rotation of the planet. NASA image.

Jupiter (figure 4.5). These were easily visible from the Earth, even through a small telescope.

A spectacular comet collision happening in our lifetimes was incredibly serendipitous. It was the first time the astronomers who theorize about impact processes could actually see a collision first hand—'up close' but not 'too close'. Predictions varied wildly from a 'big bang' to a 'whimper'. We learned a lot from this event and have a much better understanding of cometary impacts. (They are 'big bangs!') Since SL-9, observers (primarily amateurs) have witnessed other—presumably—comet impacts on Jupiter[1]. This reinforces the notion of Jupiter as a 'cosmic vacuum cleaner' providing increased protection for the Earth from possible collisions with

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[1] Similar 'flashes' have been seen on the Moon by the Moon Impacts Detection and Analysis System (MIDAS) at https://www.uhu.es/josem.madiedo/obs/e_midas_intro.html. Many are probably impacts from comet particles since they occur during meteor showers.

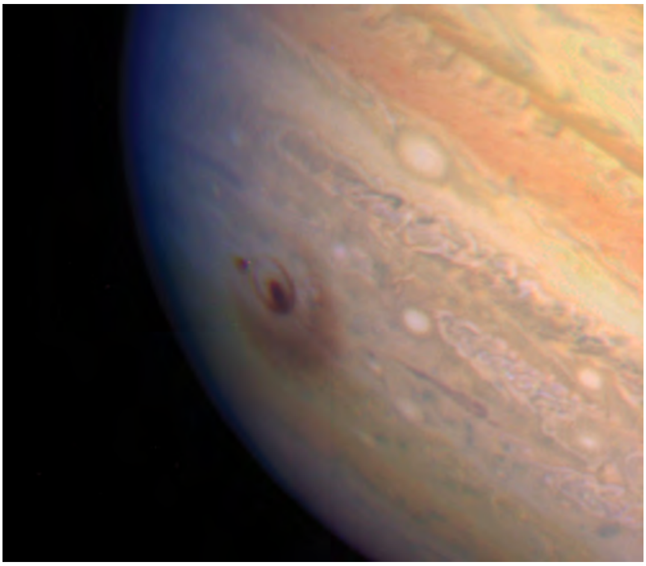

Figure 4.5. The temporary spots produced by Shoemaker–Levy 9 fragments ‘D’ (left) and ‘G’ (right) striking Jupiter in 1994. This was the first time we witnessed a collision between two Solar System objects. NASA/ESA image.

these small bodies. In 2014, Comet C/2013 A1 (Siding Spring) had a close encounter with Mars, coming within 140 497 km. Although the nucleus did not hit Mars, the planet ‘flew’ through the inner coma, resulting in a strong meteor shower, tons of vaporized dust in the atmosphere, and additional ions added to Mars’ ionosphere. These effects were recorded first hand by the international suite of spacecraft now deployed at Mars that were unaffected by the passage.

4.1 What if?

What about collisions with our planet, the Earth? Have we been spared? A several-kilometer-wide comet really colliding with the Earth would bring unimaginable ruin to our home world. We have never seen it happen. Nothing like this has occurred in historical times. Yet what is unlikely on short time scales may be inevitable over much longer time scales.

Imagine that it is a nice warm Saturday. You have the grass mowed just so. You look forward to spending the rest of the afternoon in your hammock, watching The Game on TV.

Suddenly, an errant comet tears into the atmosphere above your head, traveling 100 000 kilometers per hour. This massive an object, about 10 km across, is barely slowed at all by the Earth’s atmosphere in the second or two it takes the comet to reach the ground. It undergoes an airburst at an altitude of 90 km, fragmenting into several pieces. When the blast wave hits the surface, it does so with a force equal to more than 7500 times that of the nuclear arsenal of the human race, generating an earthquake of 10th magnitude on the Richter scale. A fireball more than

200 kilometers across is seen, two hundred times brighter than the Sun, at a distance of 500 km from the impact site. The people, trees, houses, and very rock of your city are vaporized, and a cloud of debris expands outward faster than the speed of sound. This cloud heats the local atmosphere to a temperature that ignites forest fires for more than one thousand kilometers. A crater more than one hundred kilometers across and more than a kilometer deep is carved out. Nitrogen and oxygen, the gases out of which our atmosphere is made, are chemically united to form a smog of nitrous and nitric oxides. Pulverized rock and dust are thrown upward into space. Most of it falls back, however, to deposit the equivalent of a centimeters-thick layer of dust over the entire atmosphere of the Earth, thereby blocking out sunlight. The artificial night lasts for months resulting in 'impact winter', a precipitous drop of temperature that freezes the surface. The smog is spreading meanwhile, of course. By now these noxious chemicals have combined with atmospheric water to form nitric acid. The result is a global acid rain, the strength of automobile battery fluid.

The good news? The Earth is barely disturbed and loses negligible mass. There is no noticeable shift in Earth's orbit nor its axial tilt nor rotation. And an event of this magnitude only occurs every 90 million years on the average.

Still, you thought when you awoke this morning that the only thing you had to worry about was whether the mower would start! Obviously, you should have been listening to the news since a comet of this size would have been spotted months prior to impact.

Is this story simply the rattling of a pessimist? Unfortunately, no. It is based on computer simulations performed at various research institutes and probably accurately describes what could happen if a large body encountered the Earth[2]. The catastrophe would be similar to the much-feared nuclear winter after an all-out war.

We already know that one hundred tons of interplanetary material arrives weekly on the Earth. This is in the form of harmless meteoroids and wafting dust. Large bodies are much rarer in the Solar System than small bodies. But one-in-a-million odds are no comfort if this happens to be the one-in-a-millionth year.

Scientists take this threat seriously enough to propose that a more systematic search for Earth orbit-crossing asteroids and comets be made, so that we have advanced notice of their imminent arrival, especially those large enough to inflict significant local damage (size greater than 140 m—some much greater) and that make extremely close approaches to Earth (within 19.5 lunar distances) in the next one hundred years, called potentially hazardous objects (PHOs). The United States Congress listened and, in the 1990s, mandated that by 2008, NASA find at least 90% of the celestial objects crossing the Earth's orbit larger than one kilometer (causing a global cataclysm) and funded several telescopic surveys to accomplish that goal. Since then, the search has continued for smaller, more-distant objects (still larger than 140 meters and capable of inflicting a large-scale local catastrophe). To date, about 95% of the larger objects (about 1000 including 157 PHOs) and more than

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[2] Online impact simulators can be found at https://impact.ese.ic.ac.uk/ImpactEarth/index.html and http://simulator.down2earth.eu/planet.html?lang=en-US. Go ahead, play with them!

17 000 smaller ones (including almost 2000 PHOs) have been found and are undergoing characterization. It is important to know the physical properties of these objects if we hope to mitigate their hazards. Know your enemy! These lists are dominated by asteroids (since we are in the inner Solar System), but more than one hundred near-Earth, short-period comets are known.

After detection, do we have the technology to eliminate the threat by either destroying or deflecting it from a collision with the Earth? Researchers have devised a toolbox of mitigation strategies based on the matrix of warning times versus object sizes; including standoff, surface, and subsurface explosions (conventional and nuclear); hypervelocity impactors; gravitational tractors; mass drivers; laser ablation; ion beams; focused solar energy; and a host of others. Working with the Department of Defense, efforts are underway to implement the most promising strategies under the direction of NASA's Planetary Defense Coordination Office. NASA has funded the Double Asteroid Redirection Test (DART) to be launched in 2021 as a proof of concept for the kinetic impact technique to deflect asteroid (65803) Didymos in 2022.

With enough forewarning we might be able to use a nuclear-tipped missile to divert the trajectory of the incoming projectile. (This is the only good use we can think of for such a missile.) We would have to be careful, however. If we simply broke the comet into many pieces, the result could be a rain of comet chunks upon the Earth, rather than a single impact. The devastation could be made greater! Of course, we could assemble Bruce Willis and his team at the Cape … Oh drat, we do not have any more space shuttles …

Would a seek-and-destroy plan for comets be worthwhile? Is this 'know thy enemy' philosophy a responsible use of funds in otherwise fiscally tight times? We do spend money and time to avert other natural calamities: for instance, warning of and protection against tornadoes. Of course, every year we hear about a few people killed by tornadoes. The peril seems more immediate. Yet what if a deadly comet or asteroid strikes only once per million years-but kills a few million people? The odds are the same. (The odds of comet impact are calculated best by estimating how often comets have already struck the Earth in its remote past; see below.) This is clearly an international issue so an effort enlisting as many international partners is being undertaken. We are all sailing in this planetary boat together!

Perhaps we should continue to search for and study comets on such an undertaking's own scientific merit, too. Comets are intrinsically fascinating and potentially tell us a lot about our Solar System's past and possibly the origins of life on the Earth. The long history of observing comets and interpreting them, as part of our cultural heritage, tells us something about ourselves.

4.2 The comets come to Earth

All of the above sounds a little bit hypothetical. Have real comets struck the Earth in the past? The answer is that they must have. The Earth is fundamentally no different from any other planetary body with a surface. If comets and other objects have crashed down upon worlds like the Moon, there is no reason to think that the Earth should be spared. In fact, the Earth's stronger gravity should do a better job of attracting wandering comets.

Why then is the Earth's not a cratered and gouged surface like that of the Moon? Ah, 'fundamentally' no different from the Moon? Yes, but in the details there are certainly dissimilarities between our world and its satellite. These details make all the difference when it comes to searching for a record of impacts on the Earth.

First, the Earth possesses an atmosphere. Weathering—wind, water, and other forms of erosion (including life)—will eventually obliterate an impact crater on the Earth, whereas it will remain unspoiled on the dry, airless Moon.

Second, the Earth is a geologically active place. We experience earthquakes, volcanoes, and the inexorable shift in location of land masses called continental drift. This latter force of nature, in particular, changes the appearance of our planet over the eons. Pieces of the Earth's crust are always being destroyed while others are being created. (Most of this activity takes place, out of view, under the Earth's deep oceans.)

In contrast, the Moon is a geologically dead body. A globe of the Earth fabricated by imaginary navigators one hundred million years ago will do us no good today. The continents and ocean basins have changed. However, the Moon looks today much as it did a billion years ago.

Geological activity on the Earth destroys comet and asteroid impact craters. If they form at some fairly constant rate, the number that will exist on the Earth at any one time is limited. On the Moon, the craters keep piling up. With no efficient mechanism to get rid of them, the Moon just becomes more and more pockmarked.

So it is reasonable that today the craters on the Earth should be the most recent (in terms of geologic time) and, therefore, there should be relatively few. However, 'few' is not the same as 'none'. Where are they?

Well into the past century, no impact craters were recognized on the planet closest to us—the Earth. Of course, no one was looking for them! While comet impact, as a means of creating landforms on the Earth, was recognized as a theoretical (but inconsequential) possibility by geologists, it was a somewhat distasteful subject. The catastrophic nature of an impact—one moment there is no crater, the next moment there is—went against the grain of the predominant geological principle, uniformitarianism.

This principle states that changes in the appearance of the Earth are slow, approximately constant, and predictable. Uniformitarianism was a hard won concept. It was claimed on the intellectual battlefield of the nineteenth century, when political and religious forces maintained dogmatically that the Earth was created pretty much 'as is'—suddenly and with finality, in the recent geological past. This older idea was catastrophism. To many geologists, even in the 1970s, comet impacts ranked right up there with archaic deluges—irrelevant to the overall history of the Earth. With no evidence to the contrary, who could blame them?

The only impact crater recognized by the geological community at this time was the Barringer Crater in Arizona, USA (figure 4.6). It is particularly fresh (50 000 years old) and not very big. (You can visit it, right off of Interstate 40.) Compare it to the much larger lunar crater Tycho (figure 4.7).

The problem is that we are too close to the subject. Literally. It is quite easy to see the craters on the Moon from our vantage point—the ultimate bird's eye view from

Figure 4.6. The Barringer impact crater in Arizona, USA. It is almost 1.2 km in diameter and about 170 meters deep. United States Geological Survey image.

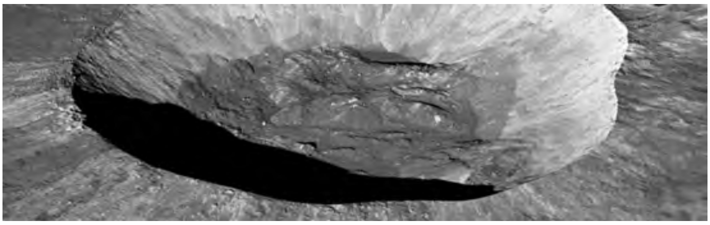

Figure 4.7. Compare the Barringer Crater to 85 km-wide crater Tycho on the Moon. NASA image.

the Earth. We do not have that perspective of our own world. Your authors have stood in the middle of a *bona fide* terrestrial impact crater. It was formed by the collision of a comet or asteroid with the Earth, fifteen million years ago, and is located in that place on the Earth we now call Germany. Yet if it had not been pointed out to us, we might never have recognized it. The Ries Crater looks like any other Bavarian valley (a little flatter than usual, maybe), surrounded by a 'coincidental' ring of hills. Since it formed, rivers have run, forests have grown, castles and villages have been built, and wars and plagues have been won and lost, all within its basin. It looks nothing like the impact craters on the Moon—today.

The scale of large impact craters can cause them to escape our notice. It was only when humans achieved the same 'overhead view' of their home planet as they had of the Moon that a number of round features began to attract notice. This became possible at the beginning of the Space Age, when artificial satellites were first launched to look down on and photograph the Earth. The intent was not to search for impact craters, but they found them anyway (figure 4.8).

Admittedly, there are other ways to produce roundish features on the Earth: volcanic calderas, salt domes, sink holes, etc. It remains necessary to inspect the sites of possible craters for the 'ground truth' of their impact nature—rocks shocked by sudden, immense blows. By this method, even if the crater has been so eroded that it no longer resembles the circular, raised, bowl-shaped feature we associate with a crater, it can be identified.

(The geology of impact craters got a boost in the cold-war era from the study of craters produced by nuclear detonations. These craters were recognized to be very similar to those produced by impacts, and the effect on the surrounding rock is much

Figure 4.8. Ring-shaped Lake Manicouagan in Canada is actually an impact crater formed over 200 million years ago. It is one hundred kilometers in diameter. NASA/Goddard Space Flight Center/LaRC/JPL/Multi-angle Imaging SpectroRadiometer Team image.

the same. This idea was championed by the United States geologist, Eugene Shoemaker (1928–97) who first showed that Barringer Crater was formed by an extraterrestrial impact.)

Today, satellites and aircraft aloft with cameras, and geologists on foot with their rock hammers, have verified 190 impact craters on the Earth[3]. (Again, it is not possible to say how many were produced by comets, and how many by asteroids, inasmuch as the parent body disintegrates in the explosive impact.) The largest is the Vredefort crater in South Africa at more 300 km across and dated to be about 2 billion years old. The number keeps growing every year. Indeed, a map of the impact sites on the Earth shows a curious density distribution matching that of the human population of the Earth. Do comets aim for people? No, more likely there are impact craters in the sparsely inhabited areas of Earth, too. These places simply have not been explored as well. That is just the land. Ocean covers 7/10 of Earth's surface. There surely must be many more impact craters waiting to be discovered, once the sea bottom has been explored.

While uniformitarianism, the slow unyielding rise of mountains and gradual erosion of valleys and silting of oceans, is the primary mechanism for change on the Earth, the geology of today recognizes that Earth's history has been punctuated by sudden, brief episodes of catastrophism: cometary and asteroid impacts[4]. These events are extremely rare. When they do happen, though, they create land features in a few minutes that would ordinarily take millions of years to excavate by uniformitarian forces.

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[3] Earth Impact Database maintained by the Planetary and Space Science Centre, University of New Brunswick, Canada (http://passc.net/AboutUs/index.html).

[4] Volcanoes and earthquakes also cause sudden changes.

The craters come in all sizes: from tens of meters to more than 100 km across. The smallest impact crater (13.5 m in diameter) resulted from a three-meter body that crashed in Peru in 2007. Villagers witnessed the fall and accompanying fireball. Tremors shattered windows, racked buildings, and threw a man from his bicycle.

Other than the very recent small craters, they generally date from two billion years to 'merely' tens of thousands of years ago. Their rims have been knocked down. Their floors have been filled with sand, water, or jungles. Nevertheless, they are there. The Earth cannot escape the rain of comets. The craters are their monuments.

4.3 The killer comet

If this reads like so much ancient history, consider the Tunguska Event. The name is intentionally vague. On 30 June 1908, something happened in a largely uninhabited region of Siberia, something that has become one of the great puzzles of planetary science.

The story is told of a colossal blast at 07:14 that morning that knocked people 60 km away to the ground and caused a herd of reindeer to vanish entirely. The pressure wave in the atmosphere was dutifully recorded by weather instruments across Europe. For many evenings, strollers as far away as London commented on an unusually bright sky.

The economy and politics of Russia, as well as the remoteness of the site, necessitated a nearly twenty-year delay before the first serious investigation of the Tunguska Event (figure 4.9). In 1927, a Russian scientist named Leonid Kulik (1883–1942) fought his way through dense woods, swamps, and vicious swarms of mosquitoes to visit the spot. There, he found evidence of a great forest fire and trees tipped over like bowling pins, but radially, in every direction away from the site, flattening some 2000 km^2, about the size of New York City. Yet there was no tell-tale crater.

Figure 4.9. The Tunguska site.

The Tunguska Event sounds like a twentieth-century comet impact. The glowing European skies seen as noctilucent clouds easily can be accounted for by scattered light from the sudden influx of icy particulate material from a vaporized comet. (Astronomer Fred Whipple suggested in 1930 that the glow in the sky was caused by the dust of disintegrating Comet Encke.) Where is the crater, however?

Maybe there does not have to be a crater. A small comet plummeting toward the Earth's surface could reach a point where the atmosphere is thick enough so that the comet is impeded sufficiently to blow up before hitting the ground. The result would be much the same as an above-ground nuclear test—without the radioactivity. While there would be great destruction, there would be no new crater.

It seems that a comet did hit within our great-grandparents' lifetimes. That is recent! It was not a major impact. Even so, had the Tunguska Event happened over an inhabited place, such as a city, the death and damage would have been horrifying. Luckily, it did not. There was not even a well-placed eyewitness. One wonders how many other Tunguska-like events have drawn no notice?

Something much smaller (an about 20 m near-Earth asteroid) exploded over Chelyabinsk, Siberia, in 2013. Recorded by many car dashcams as brighter than the Sun, it underwent an airburst due to its shallow angle of entry into the atmosphere. The shock wave from the explosion (equivalent to several hundred kilotons of TNT) broke windows all over the city. What is the deal with Siberia? Answer: it is geographically large[5]!

While a Tunguska Event can kill locally, a large comet impact could radically affect all life on the Earth. There is evidence that it has done just that.

Lately, popular books and media have renewed our interest in dinosaurs. (It seems that dinosaurs, of course, have been a favorite subject of eight-year-olds since time immemorial, including your trusted authors.) Moreover, the great mystery associated with these great creatures is not why they lived, but why they died. The dinosaurs ruled the Earth (or the top of its food chain, anyway) for 140 million years. (Compare this performance to *Homo sapiens*' measly half-million years so far.) Then they vanished 66 million years ago, leaving only their fossilized remains. Suddenly. Forever. Why?

Among paleontologists who study fossils, there are as many theories for the extinction of the dinosaurs as there are Godzilla movies. Maybe it was disease. Maybe it was supervolcanoes. Maybe it was normal climatic change to which the dinosaurs could not adapt. Maybe they did not go away at all, but instead evolved into something else. (Birds?)

How about this? It was the unique father/son team of scientists Walter (1940–) and Luis Alvarez (1911–88), a Nobel-prize winner in physics, who first brought attention to an unusual rock layer in the Earth. This layer is thin, but it is everywhere

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[5] NASA has released a map of bolides (commonly referred to as fireballs) due to small asteroids impacting our atmosphere. It shows a random distribution around the globe: https://www.jpl.nasa.gov/news/news.php?feature=4380. You can follow fireball sightings at https://www.datastro.eu/explore/dataset/nasa-fireball-and-bolide-reports/table/?sort=peak_brightness_date_time_ut.

Figure 4.10. The K–Pg (Cretaceous–Paleogene, formerly known as K–T) boundary, marking the end of the dinosaurs' reign on the Earth. Courtesy of Mark A Wilson, the College of Wooster.

and contains high amounts of the element iridium—unusual for the crust of the Earth[6], yes, but not for comets and asteroids. The Alvarezes proposed that this iridium-enriched debris was laid down globally when a gigantic impactor struck the Earth. The depth of the impact layer points to a date 66 million years ago (figure 4.10).

66 million years ago? That is a familiar number. A comet impact that deposited remains of itself over the entire world is fully capable of precipitating a global disaster even greater than the one imagined at the beginning of this chapter. Before settling, the dust would have choked out sunlight for the world's plants and animals. The ecological system would have collapsed, and hardest hit would have been the mighty dinosaurs.

It is a frightening, and at the same time, fascinating scenario—dinosaurs populate the whole Earth and then are wiped out after millions of generations, on some random Tuesday afternoon. It is a lesson for us in the conceit of species.

However, there are loopholes in the theory. The fossil record does not tell us whether the dinosaurs disappeared in a given year or a given hundred thousand years. We cannot establish if they all died out at once or over a very long interval of time. So we cannot know for sure that the impact was the cause of the dinosaurs' demise; but the punch did land, and it surely did them no good. The impact may have been one more straw in a sequence of events that ultimately did in these behemoths.

Still, if a comet had something to do with the extinction of the dinosaurs, we should thank this lucky 'fuzzy star'. It wiped the ecological slate clean. The removal of the dinosaurs allowed a new type of creature to ascend—the mammals. (The mammals, which were smaller and could burrow and hibernate, were better suited to survive the impact-induced global winter.) That is, it opened the way for us.

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[6] The rare-Earth element, iridium, is thought to be more abundant in the Earth's interior, where heavy elements sank when the early Earth was in a molten state (called differentiation).

If all this is so, the comet (or, to be fair, maybe asteroid) impact of 66 million years ago was an important event in (future) human history. It would be interesting to know the site of this roll-of-the-cosmic dice that 'came up sevens' for us (at the expense of the dinosaurs). The search was on for the crater.

For some years, the only known crater that dated from approximately 66 million years ago lay beneath T H's present home state of Iowa. (Much more recent glaciers bulldozed the crater flat; only well drilling accidentally revealed the presence of an impact feature beneath the unremarkable corn fields of Calhoun County.) However, that crater is rather too small and old to be the 'killer', and the density of the impact fallback points more to a larger crater in the Caribbean. The Iowa crater could at best be the result of a small piece of the comet breaking off and producing a precursor crater.

Then oil geologists in Mexico realized that there was an enormous ring-like structure in the Yucatán. It had eluded attention before because only part of it was on land. The rest extended into the Gulf of Mexico. The 180 km Chicxulub (CHEEK-Shoo-loob) impact crater has been dated to 66 million years ago. It may be the 'smoking gun' of the most famous comet impact of all time.

There have been other episodes of mass extinction in the Earth's history, besides the one of 66 million years ago. Each of these was followed by a flourish of evolutionary activity, replenishing the ecosystems with species. Natural calamities are, in fact, 'natural'.

Some scientists have proposed that there is a 26 million year periodicity to mass extinctions. If this were true, it would be tempting to look for a common periodic cause for them. If the Oort Cloud was nudged regularly with this frequency, sending a myriad of new Hale–Bopps (a particularly big comet) each time into the inner Solar System, the odds of cometary collisions with the Earth would increase dramatically every 26 million years. What could cause a periodic disruption of the Oort Cloud? Periodicity suggests some sort of orbit. Suppose the Sun has a faint companion star (as many other stars do). If such a companion were in an eccentric orbit, it might be far away most of the time, but periodically (every 26 million years?) would swoop through the Oort Cloud and initiate a storm of comets. The postulated companion star even has been given a name, Nemesis.

It is a neat chain of reasoning: a variation in the number of species seen in the fossil record leads to speculation about comet impacts and, ultimately, an unseen companion star to the Sun. The problem is that the 26 million year periodicity is by no means statistically proven. Furthermore, a careful search for Nemesis by powerful infrared telescopes has turned up nothing (and it should have been found). Regardless, while the hypothesis may be completely wrong, it is a fine example of the cross fertilization of scientific ideas between different disciplines (paleontology, biology, astronomy) that has marked the 21st century.

Long ago, comets and their tails were seen as cosmic swords hanging over the Earth. It was thought that the comet sword would inevitably bring harm to people and societies. Our modern theory of comets shows that there was a hint of truth in that medieval view. Still, are comets always to be considered harbingers of annihilation?

As we suggested earlier, rapid change on the Earth (some might say destructive change) is not always bad. Sudden, altered conditions may accelerate evolution and lead to the advancement of life and increase in the variety of species on the Earth, known as punctuated evolution. In other words, a totally safe Earth might be a very dull Earth, evolutionarily speaking.

Also controversial is the idea that comets had a role in providing the environment on the Earth capable of sustaining life in the first place. During the Earth's formation, it was much too hot for water to exist since it would have been vaporized into space. Why then do we have an abundant supply of water on the Earth's surface? Astronomers have suggested that comets coming to the Earth may be responsible for much of the Earth's supply of life-giving water[7]. Like we import much of our goods from China today, the Earth may have imported its water from the outer Solar System. This water (in frozen form) would be delivered by comets that struck the ground billions of years ago. To further investigate this idea, we must look for subtle differences in ocean water and comet water. Not all water is equal! One tell-tale indicator is the relative amount of water's hydrogen (H) atoms to its *isotope*[8], deuterium (D), called the D/H ratio. The first measurements of cometary D/H were quite different from that of Earth's oceans but these came from long-period comets. Results from two short-period comets (much more likely to deliver water to Earth) were similar to ocean water, but the recent Rosetta Mission found a higher value in the short-period Comet 67P/Churyumov–Gerasimenko. Since our statistics are small (only a dozen comets), the origin of Earth's water is still an open question.

A radical suggestion is that the very organic molecules that would (one day) unite to create life on this planet were not indigenous to the Earth; they were transported here by comets! We know that comets do contain moderately complex organic molecules. (The Stardust and Rosetta space probes have recently found the simplest amino acid, glycine, in comets.) These are the kinds of molecules found in living organisms. It is unclear, however, how many of these delicate molecules could withstand the passage through the Earth's atmosphere intact. Alternatively, they could be forged by chemistry in the fiery aftermath of the collision.

These conjectured connections between comets and life on the Earth are far from conclusive. Yet they provide a plausible argument for thinking of comets, not only as the destroyers of worlds, but also as—just possibly—sowers of life.

The scientific fact that Comet Lovejoy (just to pick one or any other comet we know about, see figure 4.11) will not endanger the Earth did not, of course, stop various supermarket periodicals from proclaiming that it would. When any new natural phenomenon is discovered, it is the habit of tabloid journalists to search for some way in which it might imperil the average citizen. (Of course, their goal is to increase sales, not accuracy.) The conjured carnage resulting from a comet falling

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[7] An alternative idea is that water was sequestered in subsurface hydrated minerals that release water vapor when brought to the surface by volcanic activity.

[8] Isotopes are variants of elements with different numbers of neutrons in their nuclei but generally have the same chemical properties. Add a neutron to a hydrogen atom and you have deuterium, a heavier atom. Make water with deuterium and you have 'heavy water'.

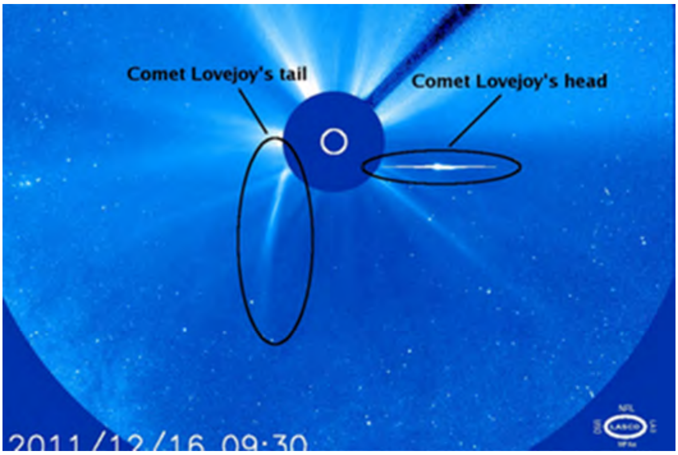

Figure 4.11. Comet Lovejoy rounds the Sun. NASA image.

from the sky is too good to pass up. One vivid example could be found on any checkout lane during the week of 9 January 1996. There, perusers of the *Sun* read in a front page headline of a 'giant comet of century hurtling for head-on crash with Earth!' Sure enough, on inside pages, after reading that a 'werewolf girl is on the loose in the Amazon jungle' and that 'mutant killer rats threaten the US', we came to the article about the comet 'threatening the very existence of humanity'. (This Earth shattering news was modestly placed on page 16, after the article about 'wine on a stick'.)

The prediction was attributed to Johan Oftebrau of Oslo, Norway, a 'top astronomer'. 'Of course, I pray my calculations are wrong', Oftebrau is quoted in the *Sun*, 'but I've been a scientist for a long time.' Such are the claims of pseudoscientists (figure 4.12).

Everyone is entitled to make a prediction. The world of ideas is open to anyone, and the *Sun* has every right to publish its unique perspective on comets. But it is up to us to use our critical thinking skills to keep us from being fooled! As the Nobel Prize-winning physicist Richard Feynman (1918–88) said, 'The first principle is that you must not fool yourself and you are the easiest person to fool.'

The trouble comes when we are asked to select between competing predictions. How to choose? One way is to ask which prediction is the most specific (and therefore most easily could be demonstrated to be wrong, sometime in the future). The orbits calculated for comets are the product of scores of independent observations and calculations. These calculations predict, to many decimal points, where a comet will be at any given time. The methods and results of the scientists who compute these orbits are available for public inspection and critique. Most importantly, observations continue. These observations objectively verify the specific predictions of the calculated orbit. (Another way of saying this is that no one has succeeded in disproving the orbit.)

The same cannot be said for the predictions that have foretold calamitous results from comets. (No doubt there were alarms sounded in Australia at the time of

WEEKLY WORLD

NEWS

RUSSIA JOINS U.S. IN FRANTIC BID TO BLOW IT OUT OF THE SKY!

HUBBLE FINDS DOOMSDAY COMET

. . . AND IT'S SPEEDING TOWARD EARTH!

HOW YOU CAN PREPARE FOR THE 20TH CENTURY'S WORST DISASTER

Figure 4.12. Another dubious headline.

Comet McNaught, as well.) In fact, the doomsayers' theories fail the test. All this sounds funny, until we read of a cult in California that committed mass suicide in response to Comet Hale–Bopp's approach.

Lastly, some have asked: if a comet did represent a threat to humankind, would the astronomical community tell us? Such a question is, perhaps, inescapable in a time when conspiracy theories are all the rage. Still, the answer must be a qualified 'yes'. On the one hand, not only would these individuals (many of whom have spent their lives studying comets) want to be the first to sound the claxon, it may be impossible to shut them up. As we have seen, planetary scientists readily accept the fact that comets do hit the Earth and, moreover, that such events are inevitable. But scientists are fallible, too, so they may 'jump the gun' with incomplete data or erroneous analysis. Fortunately, cooler minds have prevailed about this serious responsibility so we now have many checks and balances before an announcement to the press occurs. We do not want to cry 'the sky is falling'. Too many false positives would numb the public to the real next big one. There is an established protocol for announcing such a discovery to make sure that the orbit and risk are reliably assessed. If verified, the discovery goes up the chain of command through NASA to the President and the Federal Emergency Management Agency (FEMA). The Office for Outer Space Affairs (UNOOSA) of the United Nations also is notified. (UNOOSA coordinates with the International Asteroid Warning Network

(IAWN) to disseminate information concerning an extraterrestrial impact.) The final word resides with the White House. It is a distinct possibility that they may know there is one headed our way that cannot be avoided but will not let the public know due to the ensuing mass panic. D B always asked his students what they would do if the world was going to end next week. Would they still come to class? (A resounding ‘No!’) Would the fabric of society unravel (riots, lawlessness, etc)? Would many people want to finish their bucket lists quickly regardless of the law? There may well be a comet out there with ‘our name on it’. But astronomers worldwide likely have not found it yet.

Astronomers have pondered the best way to assess the risk of impact and communicate it to the public. In 1999, they introduced the Torino Impact Hazard scale. It consists of a color-coded number between 0 (we are in the clear) and 10 (‘Houston, we’ve got a problem,’ the end is near)[9]. Currently, all Near-Earth Objects (NEOs) are at Torino scale 0[10], but we have had some causes for alarm. In 2004, the 370 m sized asteroid (99942) Apophis was discovered and initial orbit calculations gave it a 2.7% chance that it would hit the Earth on 13 April 2029. Further observations showed only a close encounter on this date but raised the possibility that the Earth’s gravity could bend Apophis’ orbit and result in an impact seven years later on 13 April 2036. Did we mention that both of these dates fall on Friday the 13th and that the asteroid was named for an Egyptian deity of destruction? (This would be much scarier than the movie franchise.) Fortunately, we can now rule out an impact with Apophis, but it still holds the record for the highest Torino scale rating of 4.

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[9] The Torino Impact Hazard Scale: 0 (white, no hazard), 1 (green, no unusual hazard), 2–4 (yellow, merits attention by astronomers), 5–7 (orange, threatening with close encounter), 8–10 (red, collision is certain).

[10] NASA’s Sentry System tracks the risks of newly found NEOs and can be found at https://cneos.jpl.nasa.gov/sentry/.

Chapter 5

Observing comets

Here we offer some practical advice for observing comets. It applies to any faint astronomical object or constellation as well. We cannot describe to you exactly how a comet will appear in our sky. Both you and we may be glimpsing something last seen by the ancient Egyptians! Despite that, it is possible to make a good guess based on the appearance of previous comets.

5.1 Eye on a comet

The comet will first show up as a fuzzy star to the naked eye. (Those with telescopes or binoculars will catch sight of it earliest, obviously.) Stars always appear point-like; they have no shape. As you look among the stars for the comet, search for one that seems diffuse and has some apparent size.

‘It looks like a cotton ball’ is the description one onlooker gave us of Hyakutake, the Great Comet of 1996. Indeed, the fuzzy patch that is the comet coma will be more-or-less round. It likely will appear brightest at a central condensation and will become radially fainter. This was the appearance of the Christmas Comet Wirtanen that D B spied using binoculars in December 2018, with a distinct greenish hue.

Because of this, the coma will not have a well-defined edge. Its size will depend on the darkness of the sky. The phase of the Moon can play a large role in sky brightness. It is best to observe during a new (or nearly new) moon or after moonset/before moonrise. Comet Hyakutake had an apparently large coma because it was so close—yet it was only about the size of the full moon to the naked eye. There are other astronomical objects with similar appearance to the naked eye: do not confuse a comet with the Milky Way, Andromeda Galaxy, or Large and Small Magellanic Clouds (if you live in the Southern Hemisphere).

How can you distinguish a comet from a cloud? A small, isolated cloud is uncommon. Still, if there are distant clouds in the sky while you are observing, you will readily see why the ancients were confused about whether comets belong to the Earth’s atmosphere or beyond. The proof that you are sighting a comet will come

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with its lack of immediate movement on the Celestial Sphere. Clouds likely will move with respect to the background stars within twenty minutes or so. The comet's motion during this time will be negligible.

Now that you have found the comet, does it appear to have any structure? A trick astronomers use to bring out faint detail in an object is averted vision. The retina of the human eye is less sensitive to light at its center. By glancing slightly away from an object but keeping your attention to the center, you can use the more sensitive outer retina to make it look brighter.

Can you see a tail? Remember to look for it in the direction opposite the Sun. The tail may be many times longer than the diameter of the coma. It will appear brightest near the coma and become fainter farther away. How far away from the coma can you see the tail? How wide is it? Is there one tail or are there several? Are there breaks in the tail?

What is the color of the tail and coma, and does it vary? Do not be too disappointed if you do not see color in a comet. Individuals' color perception varies markedly (and you will need a bright comet). If you cannot see color in the stars, you are unlikely to see it in the comet.

Of course, if you are using binoculars or a telescope, the comet will appear brighter, larger, and more colorful. (A certain amount of light is needed to trigger your color vision; this is why your bedroom looks gray when you wake up in the middle of the night.) You also will be able to distinguish more detail. Look for structure or asymmetry in the coma. The nucleus of the comet remains hidden, but look for jets of material, originating at the nucleus, heading out into the coma.

There is a 'downside' to telescopes or binoculars, too. With a telescope or binoculars, you may not see an entire Grand Comet at once! This, we think, diminishes the effect. Therefore, no matter how sophisticated the optical aids you use are, be sure to spend some time peering at the comet with your eyes alone. The darker the site, the better. In addition, there is a certain magic about seeing the unfamiliar comet in a sky set against the silhouettes of familiar trees, mountains, or buildings. As you do so, remember that, except for a little air, there is nothing between you and the titanic comet (figure 5.1).

The following applies in particular to telescope and binocular observers: be patient. The quality of your view of a comet will change minute-to-minute and night-to-night. This is because you are looking through the Earth's blanket of atmosphere. The air is constantly in motion. Even if there is no wind at ground level, there are air currents high above you. As cells of different air density pass over you, the direction of the light passing through them is bent this way and that. This phenomenon causes the stars to vary in brightness and is called *scintillation*. Yes, stars do twinkle, but only to those of us watching them from the Earth's surface. Astronauts (e.g. aboard the International Space Station) see stars as steady points of light.

Astronomers use a not-very-technical-sounding term to describe this effect. They call it *seeing*. On some nights, the atmosphere between you and the comet changes more quickly and more drastically than on others. Thus, astronomers refer to nights of ‘bad seeing’ and ‘good seeing’. On nights of bad seeing, stars dance around in the telescope, or appear to go out of focus for an instant.

(Think of a fish tank. It is a lot easier to see objects through it clearly when the water is still than when someone is stirring up the water.)

Seeing does not affect the view of an object with apparent size (such as a comet or planet) as much as it does the stars. The effects of bad seeing on different points on the comet tend to average out. (The comet will not twinkle.) Still, if the seeing is bad when you are observing the comet, your view will be degraded. It is worth waiting for a moment when the seeing settles down. In this moment the comet will suddenly appear much clearer. You may see more detail in this one instant than in minutes of previous viewing.

The transparency of the air also can vary from night to night. By ‘transparency’, we do not mean whether it is cloudy or not. Even on a technically clear night, there can be a thin layer of material in the atmosphere, material that makes celestial objects appear dimmer or with less contrast. Your best bet, most assuredly, is to observe for as long and on as many nights as possible, to increase your chances of a very good view.

When you first detect the comet, note its location with respect to several nearby stars, preferably located in a triangle centered on the comet. Later in the evening, see if you can discern its motion in relation to these stars. As you watch the comet from night to night, this movement will become more evident. It is the true movement of the comet through the heavens.

Whatever its real motion, a comet’s tail gives it a continuous sense of motion in the sky. It looks like a dynamic entity. Thus, although you know that comet tails always point away from the Sun, a comet’s real direction of travel (after perihelion) may surprise you.

During a night, or over a set of nights, look for changes in the shape of the comet itself. It will get brighter as it approaches, and fainter as it recedes, of course. However, it may alter physically as well. New outbursts from the hidden nucleus can change the appearance of a comet quickly. Remember that some comets even have split into fragments before our eyes!

For anyone artistically inclined, attempting to draw the comet is a pleasant pastime. Make sure you note the date, time, location, seeing, etc. Include a few reference stars as context. Until the advent of astronomical photography a little more than one hundred years ago, drawing was the way astronomers recorded what they saw. An added benefit of drawing is that it requires a concentration that may ultimately cause you to see more characteristics of the comet.

(Astronomical photography of the comet is outside the scope of this book. Producing a photograph of a faint comet that matches its visual appearance is a challenge; a camera with manual exposure and aperture settings and a steady support are essential. Still, if you are a camera buff, it is worth a try! If you have a smart phone and a telescope, try aligning the camera with the eyepiece and snapping a photo. It takes some practice, but you will get a quick and simple image of the comet.)

Lastly, astronomical observing, like anything else, takes practice. If your initial view of the comet is disappointing, try again. Be an active observer. (You may want

Figure 5.1. A comet painting. Courtesy of Richard Baum.

to develop your astronomical viewing skills ahead of time by looking at other celestial objects.) For instance, fix at first on just one thing. Study the brightness of the comet and how that brightness varies. Next, concentrate on the shape and structure of the comet. Spend another session trying to decide color.

And so forth. You may be surprised that you can see more the second (third, fourth, fifth) time you see the comet than you did the first time. This might be so, even if the optimum view of the comet has passed. It is actually possible to train the eye to see more.

5.2 Where to go?

We cannot stress enough the importance of choosing a dark location from which to inspect a comet. By 'dark' we mean one far from artificial illumination of any kind. Those who were 'let down' by, for instance, a bright comet like Hyakutake usually were those who did not make the effort to find such a site.

These days, finding the ideal viewing location is not as easy to do as it once was. Even though Comet Halley was not as favorably placed in our sky in 1986 as it was during its previous 1910 apparition, expectations ran high. After all, our grandparents told us what a sight it was and not to miss it. However, our grandparents had an advantage over us that had nothing to do with the comet.

All over the world, skies were darker in 1910. Outdoor lighting in this age was in its infancy. We were much more a rural civilization. It was easier to find a dark place back then; it might even have been your front yard.

Today, we are losing the dark of night. For most urban dwellers, even the stars have all but disappeared. They have not gone anywhere—the fault lies in street lamps, spotlights, glowing fast-food signs, etc. Astronomers call this problem *light pollution*.

Now, we do not have anything against light. Light so that we can find our way at night is good. It gives us a degree of security and keeps us from running into each other! We have no wish to return to the days when we were virtually prisoners in our homes, once the Sun had set.

Everything is fine as long as artificial illumination is directed where it is intended: down onto the ground. However, too much of this lighting is directed carelessly upward. This includes lights intentionally beamed up for advertising purposes and, more commonly, improperly aimed street and yard lights. This escaped light does not just disappear as it shines upward. It scatters in the Earth's atmosphere and makes the sky glow, thereby obscuring faint astronomical objects.

Photographs of the Earth at night, taken from space, show this problem clearly. North America and Europe particularly are ablaze with light (figure 5.2). The location of every city and village can be pinpointed. The paths of interstate highways can be traced just by the glow of roadside rest stops!

This light is not doing anyone any good. It is totally wasted. Need we add that it takes energy to illuminate the stratosphere superfluously? Energy conservation begins above our heads! More pragmatically, all this light that never reaches the ground represents wasted money. In the case of public lighting, it is most often at the taxpayers' expense.

Do not get us wrong. We understand the need for security lighting to make our public spaces safe. Notwithstanding, more light is not synonymous with better light.

Figure 5.2. World-wide light pollution.

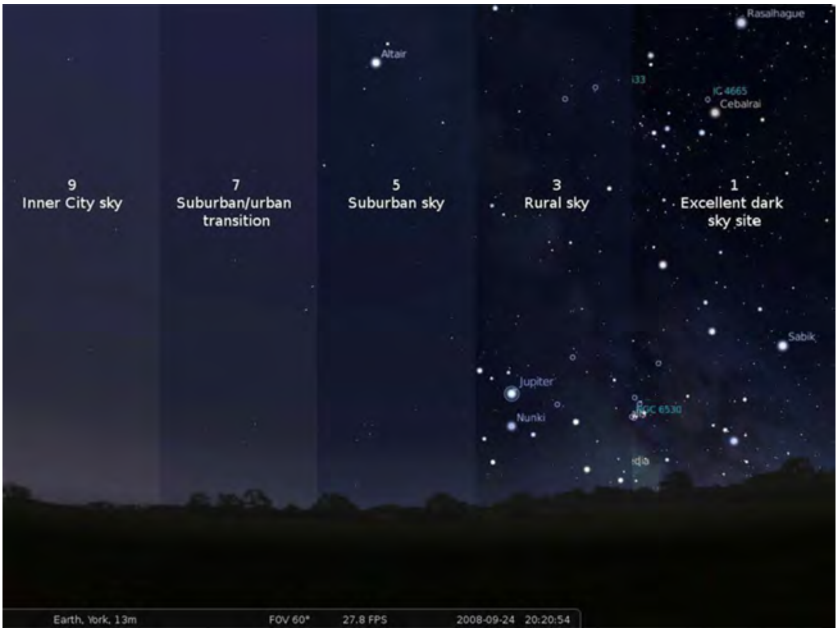

Figure 5.3. A light pollution scale. Raj Chanian.

Efficient illumination involves putting enough light where it will be useful, and no light where it will not.

The irony of light pollution is that, unlike many other forms of pollution, the problem is so easy to cure. Often, that cure is as simple as placing a reflector over the lamp to bounce light back down instead of beaming it up. Meanwhile, though, light pollution continues to rob us of a birthright no less legitimate than clean air and water—the right to enjoy a truly dark and beautiful night sky (figure 5.3).

As we dismount our soap box, let us address the subject of how to deal with light pollution: you can fight or flee. To fight light pollution in the 'big picture', you can encourage governments and businesses to install responsible illumination. More locally, you can make sure your own house is in order by inspecting lighting on your property. Are the tops of bulbs exposed? Are your lights on unnecessarily in an hour when no one is about? Do any lights shine into a neighbor's yard? (She or he may be trying to observe a comet!)

Alternatively, try this experiment. Stand under an outdoor lamp. Can you see the bulb from another lamp? If so, the lamps do not have enough shielding. (The light from the second lamp should not be reaching you; it is not required where you stand because you are, after all, standing beneath a lamp![1])

In this way, you can reduce the light pollution coming from your home. For comet watching, you can even turn everything off. You can do a great deal to

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[1] More light pollution experiments can be found at https://www.globeatnight.org/dsr/. We urge you to join the growing ranks of advocates to preserve our dark skies.

improve your view of the sky by avoiding just a few nearby lights. Ultimately, however, you have little control over more-distant but more numerous lights, strung around your city or town.

For most people, their best bet for a very dark sky will be to flee—out of town, or away from any source of nocturnal illumination. Luckily, there still are such places, though citizens of major cities may have a fairly long trip. Regardless, it will be worth the effort. You will be amazed at how many stars you can distinguish at a non-light-polluted site. (An added benefit of this detour is that it may get you away from urban smog, which adversely affects the transparency of the sky.) A convenient test of your site is the Milky Way: if you can make out this band of light, you are seeing the sky as the ancients did—after they extinguished their camp fires.

If you cannot avoid light completely, find a site that has a relatively dark, unobstructed horizon in the direction of the comet. Once there, do not introduce your own light pollution! After you are settled, turn your headlights or flashlights off.

If you require a little illumination (for instance, to consult a sky chart), try putting a red filter over your flashlight. Red light does not disturb your night vision as much as other colors do. (This is the same strategy used in lighting airplane cockpits.) While you can buy special red LCD flashlights, a piece of red cellophane will do. We also have succeeded at making our own ‘red light’ by painting the bulb of a penlight with red fingernail polish.

Clearly, comet viewing takes a bit of planning ahead of time. This is time well spent. Why look at a cool comet from a crummy site? It is like watching the Super Bowl from the highest row of bleachers. Remember, a comet is almost certainly a ‘one shot’ opportunity. Few of us will be available to inspect it on its next apparition, say in the year 4018!

5.3 When to look?

A word about time: while its flowing tail gives the impression of something flying through the heavens, in reality, a comet seems to move slowly against the stellar background. This is for the same reason that a distant airliner gradually works its way through our field of vision, though we know that it is cruising at hundreds of kilometers an hour. It is very far away. Comets travel much faster than aircraft, but they are also much, much farther away. You may not notice much motion in the comet during a given night, though you will see its position changing from night to night. This is still fast for a celestial object. Only the Moon normally appears to move through the stars at a rate measurable to the naked eye in days, rather than weeks.

The final arbiter of your view during these nights of the comet will be the weather. There is little that can be done about clouds, besides crossing one’s fingers. Even so, the comet will be visible long enough that all but the most dreary locales are unlikely to be clouded out altogether. (There will be comet enthusiasts aboard ships who will navigate their route to avoid overcast skies!)

Assuming the night is clear, when should you look? The simple answer is: look whenever the comet is above the horizon! Remember, however, that twilight must be ended totally (or not yet begun) to have the darkest achievable sky. Still, since comets are brightest and most well-developed when closest to the Sun in their orbit, some of the most spectacular views appear in the pre-dawn hours or evening twilight skies.

If you cannot avoid light pollution entirely, there is a certain practical advantage to observing comets after midnight. (This assumes, of course, that one is above the horizon at this time.) The reason is that more outdoor lighting is turned off as one heads into the early hours of the morning, and your sky will be a little bit darker.

All else being equal (weather, seeing conditions, atmospheric transparency, phase of the Moon, etc), the optimum time to observe a comet on a given night is when it is highest in the sky. By 'highest,' we mean farthest from the horizon. This is true even at a totally dark site. Why? It is the atmosphere again. The atmosphere always dims our view of a comet to some extent. (It would be considered a complete nuisance to astronomers if it were not for the fact that we need the atmosphere to breathe!) Astronauts, cosmonauts, and tychonauts aboard their space stations will have the ultimate view of the comet.

The Earth's atmosphere is a layer of gas surrounding the solid globe. It is, effectively, only about one hundred kilometers thick. Thus, it is very thin compared to the size of the Earth. From our point of view, then, although our geography books have taught us that the world is 'round', we can picture ourselves as standing at the bottom of a flat 'dish' of air. The 'dish' is wider and longer than it is tall. We want to stare upward through as short a column of obscuring air as possible. This path is directly overhead.

Astronomers call the width of the atmosphere they are looking through the *air mass*. Observing a celestial object at any angle with respect to the zenith (the point directly overhead) means that your air mass increases as a celestial object's angular distance from the zenith increases (figure 5.4).

If you are peering through a greater air mass, your view is dimmed, and effects of bad seeing are amplified. As you gaze closer to the horizon, the view deteriorates quickly. Try looking at the stars overhead and compare them to stars near the

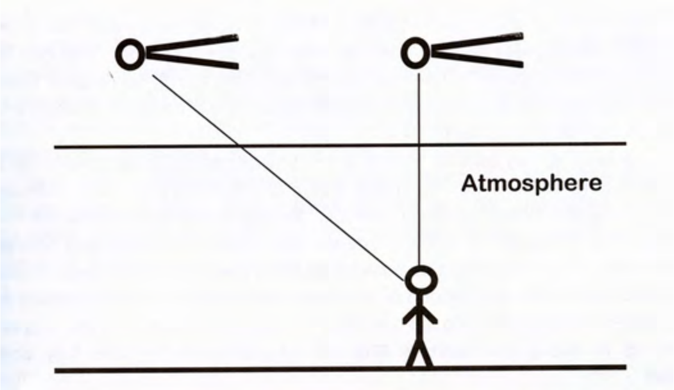

Figure 5.4. We must look at greater air mass to see the imaginary comet on the left than we do to see the imaginary comet on the right.

horizon. The ones at the horizon twinkle much more. Indeed, it is feasible to see only the brightest astronomical objects (the Sun, the Moon, and Venus) at the horizon. Even an extremely bright comet will not be visible immediately upon ‘comet rise’ nor just before ‘comet set’.

Few people will be at a latitude such that a comet looms directly overhead. Still, the view is potentially best when the comet is halfway between rising and setting, on a line running North–South across the sky through your zenith. This line (or semicircle, really) is called your *celestial meridian*. The comet reaches its maximum apparent distance from the horizon when it crosses the meridian.

This often will occur during the day, of course. Nevertheless, if the comet is visible in the western sky, you know that its zenith angle is increasing and that the air mass is growing. Conversely, if the comet is in the eastern sky, this angle is decreasing and the air mass is shrinking.

There is one other factor that will affect your view of a comet, to which we have alluded to a couple of times before. It is the Moon. The Moon is a fascinating astronomical object to study in its own right. However, for comet watching, moonlight is worse than a bright street light. The Moon is a natural source of light pollution. It goes through its cycle of phases (new, waxing crescent, first quarter, waxing gibbous, full, waning gibbous, third quarter, waning crescent) once each month. You cannot do anything about this other than plan your comet observing session with the Moon in mind. This is easy around the time of the new moon. The Moon is not visible in the sky at all then. The full moon, however, is a disaster as far as viewing faint comets is concerned. It is up all night and very bright. The first and third quarter moons, those times when we see half of the Moon’s disk illuminated, are not quite as bright as the full moon and can be avoided. The first quarter moon sets around midnight; the third quarter moon does not rise until that time. (Many calendars denote the phase of the Moon with a small symbol near the date.)

In conclusion, it may be that exactly when you observe a comet is not as important as the time you spend with it. If you have just come outdoors from a brightly illuminated building or vehicle, the iris of your eye has shrunk to a small size. Not much light is entering through your pupil. To discern faint objects, it is necessary for as much light as possible to strike the retina in the back of your eye, within the thirtieth of a second or so it takes the human brain to construct an image. When you first step into the darkness, it takes a while for your iris to open. In fact, up to twenty minutes are required for people to become fully dark adapted.

Not waiting for dark adaptation is the second most common cause of ‘comet disappointment’. Plan to spend at least half an hour or so looking at the comet to make sure that your eyes become fully light-sensitive. Remember that dark adaptation is reset each time your eye is exposed to bright light, so resist the temptation to use your smart phone as a flashlight (or check your social media account) during an observing session.

Here is the ‘final test’ of your comet viewing: we know something best when we attempt to point it out and describe it to others. Make sure to compare your comet experiences with someone else. That other person may be a member of your family, a neighbor, a new friend, or someone halfway around the globe on the Internet. Remember, the world is small to a comet.

5.4 Expectations

As you can tell by now, astronomers toss around words like ‘spectacular’ and ‘bright’. These words are meaningful in the context of astronomical events. Today, however, movies and television have ‘cranked up’ the threshold of what people perceive as spectacular. Frankly, we need many sensory stimuli to be excited about an event these days. (You cannot merely have a car crash in today’s movies; it has to be a whole lot of cars-or at least a bus … in 3D.) The media bombard us with light and color. This is quite a bit for any natural phenomenon to have to compete with. However, it is the very actuality that comets are completely natural events in our Universe, putting on their display with no help from—and with indifference to—humankind, that makes them remarkable.

Astronomers inadvertently raise expectations, too. We like to publish our ‘scrapbook’ pictures of the heavens. Amazing ‘shots’ of distant astronomical objects can be found in books, magazines, and online-in color, and with extraordinary detail. (Some of these pictures appear in this book.) However, such images were built up with sensitive detectors, over long exposures, using huge telescopes. Sometimes they are computer-enhanced.

Your view of a new comet almost certainly will be subtle. Remember, however, that what you are looking at is real. It is not recorded and edited for your consumption as is so much of what we experience today. You are watching the Universe ‘live’.

Chapter 6

Hunting comets

‘Hung by the heavens with black, yield day to night!
Comets, importing change of time and states,
Brandish your crystal tresses in the sky…’
Henry V, I.i, William Shakespeare

6.1 Who discovers comets?

Until very recently, most new comets were discovered by amateur astronomers. Now, the term ‘amateur astronomer’ may suggest to you something taken lightly, something done naively, or worse. Certainly, a phrase like ‘amateur biologist’ conjures up images of Doctor Frankenstein. ‘Amateur nuclear physicist’ sounds even scarier—the word ‘crackpot’ comes to mind as a synonym!

Yet, unlike many other sciences, astronomy holds the word ‘amateur’ in high regard. Amateur astronomers often are very serious and well educated about their avocation. Moreover, in these tight times, when professional jobs are exceptionally hard to come by, the classical distinction between amateur and professional—whether you are being paid or not—is beside the point. Few professional astronomers would argue that there are ‘amateurs’ who know their way around their telescopes better than some of their ‘pro’ colleagues[1].

Amateur astronomers occupy an important niche in the discipline. Reductionist sciences such as physics or chemistry concentrate on a few underlying principles. (These principles are both beautiful and profound, but exploring their subtlety takes years of graduate study and, for the experimentalists, outrageously expensive

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[1] Nowadays, many rightly refer to ‘amateurs’ as ‘citizen scientists’.

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equipment.) Astronomy is messier! We have to deal with the real Universe, which is inhabited by all sorts of strange and differing celestial bodies.

Contrary to popular misconception, most professional astronomers do not spend their nights patrolling the entire night sky on alert for new comets. Nothing could be further from the truth since doing so would take too long! With uncommon exceptions it is inefficient for these few professionals to spend precious hours of large telescope time (not to mention the expense) with only the hope of making some as-yet-unimagined discovery. It is too risky for their careers. Professional astronomers, for the most part, study known bodies, with the hope of bettering their understanding of these objects. Large telescopes are focused on a tiny patch of sky as part of a specific scientific investigation (rarely involving comets), leaving the rest of the sky open for discovery.

This is where amateurs come in. Compared to the professionals, amateurs have more time (because there are so many more of them). They have more telescopes (because they use smaller, cheaper instruments). Their telescopes have greater fields-of-view than the enormous ones of professionals—all the better for surveying the sky. Perhaps most importantly, amateurs have less to lose if they fail (because their after-work hours are their own)!

Amateurs are well suited for frontline search-and-discovery. While small telescopes and modest instrumentation restrict them to brighter objects, it is exactly these suddenly brighter objects for which the sky continually must be monitored: new comets, asteroids, and stars that vary abruptly in luminosity.

Professional astronomers are indebted to amateurs for mounting this celestial posse. These efforts take a long time to pay off. The greatest tool of the amateur astronomer is perseverance.

A typical comet hunter might begin scanning the sky shortly after sunset. He or she will be on the lookout for a faint 'wisp' against the near-black sky. Hours before moonrise particularly are coveted. Do not bother telephoning serious comet seekers the night of the new moon—they will not answer!

There are 'fuzzy' objects in the sky, other than comets, of course. Distant star clusters, nebulae, and galaxies sometime mimic comets. The early French comet-seeker Charles Messier (1730–1817) catalogued the fixed locations of a little over one hundred of these objects. He did so precisely to avoid the nuisance of repeatedly *confusing* them with comets. Our amateur, however, is very familiar with the sky and recognizes these old friends. She or he is looking for something that does *not* belong there.

As Earth revolves around the Sun, the Sun appears to move through the Celestial Sphere during the year. That portion of the Celestial Sphere that is in the sky after sunset and before sunrise slowly shifts. Each night, a thin new swath of dark sky emerges from twilight. It is here that our comet hunter searches, in the predawn hours, for comets that have become bright while the Sun prevented us from observing them.

Back and forth the observer scans with a telescope or binoculars, occasionally consulting a star chart. The process is meticulous and systematic; some may even call it boring. Notwithstanding, it works. Some amateurs have discovered multiple comets (or rediscovered ones that were lost).

It is not always a lonely enterprise. There are frequent star parties. Maybe not as festive as their name implies (but just as fun), ‘star parties’ are gatherings of amateur astronomers and their telescopes, held outdoors under a (hopefully) clear, dark sky. At a star party, one can ‘mingle’ from one telescope to the next, stopping to look at whatever that particular ‘scope happens to be aimed at. A star party is a veritable buffet of astronomical delights.

Once a comet is discovered, a call goes out for confirmation observations. A comet cannot be attributed to its discoverers until it is impartially observed.

The International Astronomical Union’s Central Bureau for Astronomical Telegrams (IAU-CBAT) is located in Cambridge, MA, at the Smithsonian Astrophysical Observatory. CBAT is the *Guinness Book of World Records* for astronomy. By world-wide consensus, all claims to astronomical discovery rest on the official distribution of the *IAU Circular*[2], announcing a discovery and when, where, and by whom it was made. CBAT is non-profit and funded through subscriptions to the *Circulars*. It operated under the auspices of the IAU until 2015 when the IAU was reorganized.

(The name ‘CBAT’ is anachronistic today. Astronomical information streaming in and out of CBAT now is transmitted largely by electronic mail. Telegrams have gone the way of the Pony Express.)

Reports of a new comet cause CBAT to implement a system for initially designating comets[3]. Pretend we discovered a comet. It is written down by the year (2019) and the half month of that year in which it was discovered (‘H’ for latter April) and 1 (for the first comet discovered in this two-week period), 2 (for the second comet discovered in this two-week period), 3 … etc. Put it all together and our comet is the alphanumeric 2019 H1. (The letter I is skipped insofar as so many confuse it with the Roman numeral for ‘1’.) Later, a C/ is attached if it turns out to be a long-period comet, a P/ is attached if it is a short-period one, and the family names of up to three discoverers are added: Comet C/2019 H1 (Hockey–Boice). But we do not kid ourselves. If one of us had been clouded out, stuck with a flat tire, or laid up in bed with the flu, there is no doubt that others would have found the comet in ensuing nights. And the comet would have a different name. Comets do not ‘sneak up on us’; there are too many astronomical sentries on alert.

6.2 Where is our comet?

We all know how big a skyscraper ought to be, so we can judge our distance from it by sight. Astronomical bodies vary in size dramatically, and human beings had no first-hand experience with them before the Space Age. Anything that was permanently out of arm’s reach (like the Moon) could be huge, but then again might just as well be the size of a pizza. How would our ancestors know?

Tycho Brahe knew. Tycho (1546–1601) was a Danish aristocrat who operated the first modern astronomical observatory in Europe worthy of the name on a sparsely

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[2] http://www.cbat.eps.harvard.edu/services/IAUC.html.

[3] We describe the current system adopted by the IAU in 1994, see https://www.iau.org/public/themes/naming/#comets. If you see other designations, they are from an older, outdated system (e.g. Comet 1969i (Bennett)).

inhabited, royally owned island. It was probably just as well that it was lightly populated. Tycho seems to have mistreated pretty much anybody he came into contact with whom he did not consider his equal—and that was just about everybody. A notable exception was a young Polish assistant named Johannes Kepler who, as detailed in section 2.3, translated Tycho's magnificent data tables into a simple means of describing planetary orbits.

Tycho (usually remembered by his 'toy-sounding' first name[4]) did not know how to play well with others, but he did know comets. He 'discovered' one when he was a young man. This was at a time when there were no official records of comet discoveries. It was a naked-eye comet[5], and many people spotted it independently. Still, Tycho studied the comet, and it eventually bore his name: Tycho's Comet of 1577.

We claim that Tycho was the original comet scientist. He was the first to prove that comets are celestial bodies and not simply some sort of temporary meteorological phenomenon, contrary to the belief that went back to the ancient Greeks. Because of this, he was the earliest scientist to consider comets astronomical objects and not apparitions of doom. This is how he did it.

First, a demonstration. Hold your thumb out in front of your face. Compare it to distant objects, such as furniture across the room, or trees and houses if you are outside. (Your thumb will appear very large in comparison!) Now, blink slowly, by opening just one eye, and then just the other. (You will feel silly doing this, but nobody is watching you, and it is for a good cause.) The background objects appear no different. However, your thumb looks as if it moves back and forth. It is not really going anywhere, of course, attached to your body as it is. This apparent motion is the result of seeing your thumb alternately from two places (your left eye and your right eye). These two vantage points are separated by a distance, the distance between your eyes (about ten centimeters).

Now stretch your arm out so that your thumb is farther away from you. Repeat the blinking. What happens to the apparent shift in location of your thumb? It gets smaller. Believe it or not, behind this funny exercise you will find the basis for finding the distance to comets, as well as to planets and stars.

The farther away an object, the less *parallax* it will exhibit. Parallax is the angle through which an object seems to move when viewed from two disparate places, as reckoned against some more-distant background. If you know the distance between the two measuring stations (a distance called the baseline), you need no more than to measure the parallax angle in order to calculate the distance to the object.

The calculation requires only simple trigonometry. We will admit that if 'trig' is a word you tried to avoid in high school, the word 'simple' may not seem an appropriate adjective with which to describe it now! We will not do the calculation

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[4] Every language seems to pronounce Tycho's name differently. In Danish, it is pronounced 'tee-Koh Brah,' in Latin it is 'tee-Koh Bra-Hay,' and in German it is pronounced 'two-Show Brah.'

[5] Remember that Brahe's observatory did not contain a single telescope; it was not invented yet! His observatory consisted of a large quadrant, sextants, and other instruments to make precise measurements of the positions of astronomical objects.

here. Nevertheless, in the grand scheme of mathematics, it is a reasonably straightforward application of the properties of right triangles.

This method is used routinely by surveyors: If you have seen one person standing along the highway (in an orange vest holding a pole) and another some distance away (squinting at him or her through a small telescope), measuring parallax is what they are doing. We still find it amazing that we live in a geometrically well-behaved Universe in which we can measure the distance to objects without ever touching them with the end of a tape measure.

The surveyor does not wink back and forth, of course. You noticed when you did the parallax demonstration that objects much farther than your thumb did not appear to change location perceptibly. This was because the baseline distance (inside your head) was too small. The parallax angle can be exaggerated by increasing the baseline distance. If you quickly dodge back and forth across the room, you can make more-distant objects appear to shift their position, while the farthest objects still keep their relative place. (The surveyor picks up her or his telescope and moves it to another station along a pre-measured baseline.)

Objects in the sky are farther still. As you might guess, the baseline distance has to be great to see any astronomical parallax at all (figure 6.1).

This brings us back to Tycho (figure 6.2). Tycho measured the position of the 1577 comet very precisely against the background of extremely distant stars. He then compared his determination to those made by astronomers elsewhere in Europe. (He foreshadowed the international observing campaigns that are common today.) There was no difference! A cloud-like thing anywhere between the Earth and the Moon (where the celestial domain traditionally was considered to begin) would have exhibited a parallax. Because he could find no parallax shift, Tycho could not really measure the distance to the comet. However, he could state with certainty that the distance must be on the order of that of the planets (which also did not exhibit a parallax with the angle-measuring techniques of his day). Therefore, Tycho reasoned, comet distances must be far away.

Tycho was the first to suggest that comets should be thought of like planets and treated like planets. He conceptually pointed the way to applying Newton's and Halley's science of orbits, to comets.

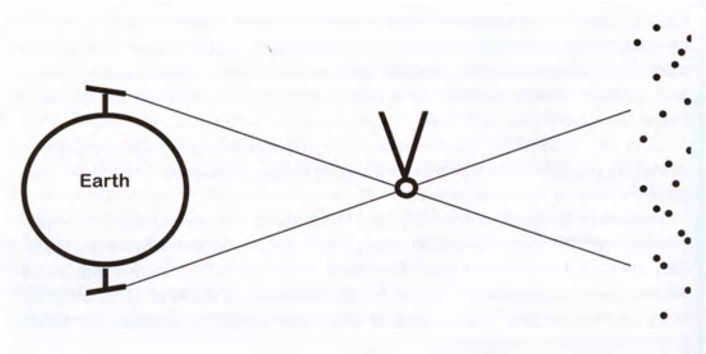

Figure 6.1. A modern measurement of parallax for a nearby comet. The angle is highly exaggerated.

Figure 6.2. Tycho Brahe at his observatory. A close inspection reveals a peculiar nose. In fact, it is prosthetic, made of brass (or gold or silver, depending on the story). Tycho lost his nose in a duel. Obviously, he was a much better astronomer than swordsman.

Tycho's comet observations had a philosophical implication, too. According to the natural science theories of the ancient Greeks (still going strong after more than fifteen-hundred years), the heavens were perfect, orderly, and unchanging. This made the realm above far removed from happenings below on the Earth, where things are often ugly, chaotic, and unpredictable! Comets, however, seem to show up and then disappear haphazardly. Maybe things in the celestial canopy were not so immutable and unlike the Earth after all. Maybe there was a commonality between the heavens and Earth—we are all part of one Universe.

When observers all over the world send CBAT measured positions of a comet, they are repeating an experiment with great historical significance. Since Tycho's time, however, some improvements have been made in the parallax technique.

First, the baseline can be longer. The distance between, say, New Mexico and Japan is a significant fraction of the diameter of the Earth! And if we are willing to wait six months, the Earth's revolution about the Sun will move us by a baseline distance of 2 au.

Second, we now can measure very small parallax angles, those that would have been imperceptible to Tycho. The reason for this latter technology is that we have a device to aid the naked eye, the astronomical telescope—a tool invented just some years after Tycho's death!

With a telescope, it is possible to measure angles in seconds of arc (or smaller). An arc second is one-sixtieth of one arc minute: 1/3600 of one degree!

Comet parallaxes now are measured routinely. Still, at the time of its discovery, no parallax was observed initially for Comet Hale–Bopp! Hale–Bopp must have been very far away. In fact, Hale–Bopp was discovered while it was beyond the orbit of the planet Jupiter (5.2 au average orbital distance). No comet had ever before been found by amateur astronomers this far from the Sun.

Once you know where a comet is in space at different times, it becomes possible to calculate its orbit. Because elliptical orbits are geometrically simple, you might think this an easy task. After all, we already know that the figure of the orbit is an ellipse, right? It is not quite that simple. One has to learn both the size of the orbit (perihelion or aphelion distance) and its shape (the ellipse's *eccentricity*). We cannot stop there. It is also necessary to compute the orientation of the ellipse. Which way does the imaginary line through the foci of the ellipse go? Because this line can point in any direction on the Celestial Sphere, two numbers are required to describe it uniquely. The ellipse still can rotate an infinite number of ways about the axis that is this line. This rotation must be specified, too.

(We have not even mentioned distortions from the true ellipse, caused by the gravity of Solar System bodies other than the Sun. Nor have we mentioned non-gravitational forces, due to the comet 'jets' exerting forces that can be counter to or in concert with the usual elliptical motion. This results in the slowing or speeding up of the comet during its orbit.)

Calculating the orbit of a comet begins to sound a lot like that nightmare algebra problem you tried to solve in school—you know, the one with trains leaving all sorts of stations at all sorts of different times and speeds! With this bad memory, you might think that the comet would have to be observed many places in its orbit in order to forecast with certainty where it will be in the future. In reality, by pulling a couple of mathematical tricks, you can get by with just a few observations.

It helps if these observations are spaced out in time. In the case of Comet Hale–Bopp, it was possible to obtain observations *back* in time. After learning of its discovery, Robert McNaught (who would later have his own name-sake Great Comet of 2007) rummaged through some photographs of the sky taken at the Anglo-Australian Observatory two years earlier. These photographs were made for purposes that had nothing to do with the still-unknown Comet Hale–Bopp. Serendipitously, Hale–Bopp happened to be in the frame of one of the pictures! Nobody would have recognized the inconspicuous comet in the image if they were not looking for it.

Once an orbit is determined, one knows where the comet will be at any time, and it is time to figure out how close it will get to the Sun and Earth, distances that will help estimation of its peak brightness. Now that the comet's period is known, one can establish whether it is a C/ comet or a P/ comet. Remember that long-period comets usually put on a flashier show.

6.3 How bright a light?

When discovered, Comet Hale–Bopp was more than a thousand times brighter than Comet Halley at an equal distance. If the lights of an oncoming truck seem bright while still far away, it is reasonable to conclude that they will be very bright when the truck passes you. However, what if, when you glanced at the distant truck, the driver had happened to 'flick' on and off its high beams? Your estimate of the lights' future brightness will be biased. The lights might not be all that bright when the truck passes you, running on its normal headlights exclusively.

Comets can 'flick.' They undergo episodic outbursts as fresh material from the nucleus is inserted into their comas. This material shines brightly until it dissipates. For a while, the comet is much brighter than it normally would be at a given distance from the Sun.

The most notorious comet of the 1970s was Comet Kohoutek (figure 6.3). Like Hale–Bopp, Comet Kohoutek was found far from the Sun. This led to speculation that it would be extremely bright in our sky when it neared the Sun. Unfortunately, Kohoutek happened to be eyed during an outburst. Soon after its discovery, the comet faded. It never achieved remarkable brightness in our sky.

Comet brightness is predicted by way of a mathematical function. It takes into account distance from the Sun and Earth, the albedo of the comet, and the behavior of comets in the past. Scientists call this method an empirical equation; others might call it an 'educated guess'. Obviously, only the first item on the list is well known.

The behavior of past comets is a real problem because no comet is really canonical. When, and the rate at which, comets 'turn on' (produce comas) depends on how an individual comet is made. Different ices, under different conditions,

Figure 6.3. Comet Kohoutek in 1973. NASA image.

outgas at different distances from the Sun—and each fluoresces uniquely! Dust plays a major role in coma brightness too, of course, but you must convert ice first to liberate reflective dust. Dust comas are exclusively seen at large heliocentric distances, detection of gas is only seen closer to the Sun. This can lead to misidentification of new objects as comets since only dust is seen and no gas. Our current thinking is that a significant amount of ice (gas) needs to be present for an object to be a comet. Some 'Main Belt Comets', displaying dust tails, have later been found to be the result of asteroid collisions, not comets at all!

The outburst mechanisms are still unknown but the leading candidate is gas-pressure build-up in interior voids that eventually overcomes the mechanical strength of the overlaying surface material, producing an eruption. Another is the penetration of the solar heat wave deep inside the comet, converting amorphous water ice to crystalline water ice, an exothermic process that releases a large amount of energy. A third mechanism involves cometary avalanches (landslides) that expose fresh, volatile-rich surfaces, as recently observed in Comet 67P/Churyumov–Gerasimenko, the target of the Rosetta Mission.

We now understand that 'first timers' (comets not known to have passed this way before) are particularly quick to brighten at far distances and then fade as they near the Sun (e.g. Kohoutek in 1973 and Austin in 1990). They are thought to have accumulated a surface frost of very volatile ices such as carbon dioxide (CO_2) and carbon monoxide (CO) during their cold storage in the Oort Cloud that sublimates quickly, resulting in very rapid brightening. A middle-aged comet is a nice find; it has passed the Sun before, but not so often that it is nearly worn out (like Comet Halley). Quite the contrary.

When a comet brightens (forms a coma) too distant for water ice to have sublimated, it must be the result of the sublimation of ices that do so at a lower temperature. We expect these ices to be less plentiful than water ice. Thus, the comet should be 'saving itself' for the inner Solar System (and us).

There is not always a direct link between the size of a comet nucleus and the comet's brightness. Only a small part of the nucleus's surface area is actively producing coma gas and dust at any one time. A small nucleus with a proportionately large active area could produce as impressive a coma as a large nucleus with a proportionately smaller active area, such as Comet Hartley 2 with an active fraction exceeding 100%, the excess water production coming in the form of icy dust particles that release water as they travel away from the nucleus. Still, all else being equal, it is natural to correlate the *magnitude*[6] of a comet's light with the size of the nucleus itself.

Only a few comets have been visited by space probes. How do we measure the size of something that is a mere point as seen from the Earth? If you can see the coma cloud, it should be possible. The Hubble images of Comet Hale–Bopp reveal a coma cloud that increased in brightness as one radially approached the center. The center is where the hidden nucleus is presumed to be. If the nucleus really was a mere

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[6] Astronomical magnitude refers to the brightness of an object. The smaller the magnitude number, the brighter the object.

mathematical point, the coma brightness would decrease smoothly as a function of radius. But sometimes it does not. There may be a slight light 'bump' at a radius near the center. By assuming that this represents the light of the nucleus itself, the coma light can be subtracted out by computer techniques to reveal a rough view of the nucleus. It is not possible to discern shape, but some appraisal of size can be made.

Rotation is a fundamental property of all Solar System bodies. It is one of the first things that gives the object itself a unique character (as opposed to properties of its orbit). A uniform comet nucleus is like a white cue ball. You can spin it fast. You can spin it slowly. It does not matter. With no marks or number on the ball, it is difficult to prove whether the sphere is turning at all. This goes for a billiard ball on the table beside you! Imagine the difficulty in deciding the rotation period of a featureless, far-off comet nucleus. Again, we are talking about all those comets that have not been visited *in situ*.

A 'jet', marking the location of a sublimation active region on the nucleus, turns the comet into an eight ball. Now there is a reference mark for timing the rotation period. Every time you see the numeral '8' rotate in front of you, one rotation period has elapsed. Simple counting tells you whether the ball is spinning fast or barely turning. Similarly, charting the angular motion of a fixed 'jet' on the comet nucleus will yield the nuclear rotation rate.

Timing the rotation of a billiard ball is more difficult, however, if the numeral happens to be at the very top or bottom of the ball. Now, even if the ball is turning very rapidly, the numeral does not seem to move much because it is so near the rotation axis of the ball. So it goes with the comet nucleus.

Still, the 'jets' reveal where the pole of the comet is. Unless the comet's axis is perpendicular or parallel to our line of sight, the 'jets' are more foreshortened on one side of the comet, compared to the other. This means that they tilt alternately a little toward and away from us.

A pinwheel will always look completely symmetrical if you face its axis—a direction perpendicular to the stick. However, its blades, too, will be foreshortened on one side if you look at the pinwheel from any other direction.

To complicate matters, no single rotation period may fit the observations of all of the 'jets'. Does a region of activity get up and walk around the surface of the comet nucleus? Not likely! The comet might not be spinning in a single mode. It might be wobbling, as well as rotating. If that were not bad enough, the nucleus may skip eruptions. That is, the nuclear vent may not produce a 'jet' each time it rotates into sunlight. Fickle is the comet.

6.4 Eureka! I've found a comet!

Do you want to discover a comet? If so, this section is for you. In it, we give you professional tips to aid you in your attempt. Your reward? It is having a celestial body officially bearing your name in the history books. Amateurs have played an important role in comet discovery and continue to do so as detailed in section 6.1. In recent years, smaller, automated telescopes have been dedicated to survey the skies for unexpected visitors to Earth's neighborhood, looking for Near-Earth Objects

(NEOs). In 1992, the United States Congress directed NASA to be on the lookout for small Solar System bodies (mainly asteroids) that might be on a collision course with the Earth, definitely bad news for us. (Think dinosaur extinction some 66 million years ago.) This is where amateurs (you!) come into play. But you better act fast, since the current professional surveys and those on the planning books[7] are set to dominate the discovery scene in the near future.

Do you live in a major urban area without dark skies or just want to avoid those pesky mosquitoes? Then discover a comet from the comfort of your indoors armchair. Several dedicated amateurs have done just that (and continue to do so) using the live online feed from the SOHO satellite that monitors our Sun. Occasionally, a previously unknown small sungrazing comet will enter the field-of view of the SOHO/LASCO instrument[8]. If you are the first to spot it (and report it), you have discovered a comet. Unfortunately, the rules of this game normally do not allow you to attach your name to it. Alternatively, the comet bears the name of the SOHO spacecraft. But hey, you just bagged a comet! These armchair comet hunters are very competitive, so your discovery will take a lot of patience and persistence like most accomplishments in life (unless you are just plain lucky).

Do you feel lucky? Look through online archives of night sky images for evidence of a comet that others have missed. These images are processed without regard for hunting moving objects. Such large repositories are managed by the Catalina Sky Survey, the Faulkes Telescope Project, Planetary Resources, and the Zooniverse[9]. There are automated telescope networks[10] with serious telescopes that offer online access for a small fee. It does not take any special technical knowledge to do this. After some practice, you are off and running. Discovering a comet can also enrich your pocketbook. The Edgar Wilson Award[11], overseen by the CBAT, annually awards up to $20 000 with a plaque for the discovery of comets by amateurs. Comet discovery can be complex and confusing for the novice, so we try to carry you up the learning curve as quickly as possible! We have provided additional resources in the appendices that give further details and instructions for the serious observer with modest resources.

6.5 Starting your comet quest

i. *Select an observing site*. The motto of the Scouts is ‘Be Prepared’ and this certainly applies to comet hunting. As the great French scientist Louis Pasteur said: ‘Chance favors the prepared mind.’ As a first step, you want to find a location with dark skies. As we discussed in section 5.2, light

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[7] The Large Synoptic Survey Telescope (LSST), scheduled for ‘first light’ in 2019, is expected to discover 10 000 comets in its first year of operation. Every night the LSST will collect 30 terabytes of data.

[8] The Large Angle and Spectrometric COronagraph (LASCO) instrument is a set of three coronagraphs aboard SOHO that image the Sun’s corona from 1.1 to 32 solar radii. A coronagraph is a telescope designed to produce an artificial solar eclipse, blocking the brightness of the Sun’s disk, to reveal the extremely faint light surrounding it, called the corona.

[9] https://www.zooniverse.org/projects/mschwamb/comet-hunters.

[10] For example, Slooh (https://www.slooh.com) and iTelescope (https://www.itelescope.net).

[11] http://www.cbat.eps.harvard.edu/special/EdgarWilson.html.

pollution, the combined effects of night lights on urban skies, is a major problem in modern times for those of us wanting to make a personal connection to the night sky. The ancients had more access to dark night skies and were more connected to them, not only for personal satisfaction but because their existence depended in part on nightly observations to mark the time, seasons, location, etc. (Today, we use ‘high tech’ devices such as clocks or smart phones, calendars, and GPS systems.)

If you live in an urban area, then you will need to find a dark site outside the city limits for your observations. How can you judge the extent of light pollution in your area? If you are in the Northern Hemisphere and can find Polaris (the North Star), a member of the constellation Ursa Minor (the Little Bear or Dipper), then follow this procedure—remember, it is important to let your eye adapt to the dark (about twenty minutes) and to use minimal lighting afterwards (a red-light flashlight or one with a red filter). Do not use your smart phone as a flashlight as it will destroy your night vision and you will need to wait another twenty minutes or so to re-adapt. Now look for the two end stars of the dipper, Kochab and Pherkad. If you cannot see these stars, you are not far enough away from the city! Next, try to fill in fainter stars between Polaris and Kochab that outline the dipper. If you can make out all seven stars in the dipper, you have skies sufficiently dark to start your comet search (limiting to 5th magnitude[12]). (Ideally, you want 6th magnitude.) Keep in mind this technique works for the northern part of the sky but darkness can vary with the cardinal points. For example, you may have driven north of the city so that the southern skies at your observing location may still suffer from light pollution. You can usually judge the other parts of the sky once you have made the dipper estimation. Keep in mind that there can always be clouds blocking the stars that cannot be seen directly at night. And then there is the phase of moon.

ii. *Become familiar with the night sky*. Learn the constellations. They are your guides to the night sky. If you have an interest in Greek/Roman mythology, you will have the added pleasure of connecting the myths to the sky[13]. There are many books for doing so (e.g. *The Stars* by H A Rey[14] or the classic *Norton’s Star Atlas*, now in its 20th edition), as well as online materials (e.g. www.SkyMaps.com); smart phone apps (e.g. *Google Sky Map* for Android and *Star Walk* for Apple iOS devices); and planetarium software (e.g. *Stellarium*, etc) for your home computer. After some basic knowledge, more parts of the sky can be learned by ‘star hopping’, going from a known bright star to an unknown nearby bright star following the star chart. Up to now,

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[12] We are referring to the astronomical magnitude system as was described earlier. More details on finding the limiting magnitude and reporting it to a world-wide campaign can be found at https://www.globeatnight.org/5-steps.php.

[13] Did you enjoy the movie, *Clash of the Titans* (either version)? All of the major characters from that legend are memorialized in the autumn evening skies.

[14] Yes, that is the same Rey who wrote the *Curious George* books!

we have only used our naked eyes for observing. This is sufficient for making a discovery since several important comet discoveries in modern times have been made with the unaided eye. But binoculars and telescopes will enhance your chances and increase your enjoyment of the night skies.

A good challenge is the Messier marathon—attempting to view all 110 unique Messier objects in a single night. In the Northern Hemisphere, it is best done in mid-March to early April, around the time of a new moon. To prepare for the marathon, spot a few Messier objects every week so that you know what to look for. You will need at least a six-inch-aperture telescope to complete the list. (The faintest is M95, a barred spiral galaxy, at 11.4 magnitude.) Otherwise, 100 mm binoculars under optimum sky conditions can find all but M95. Using your naked eyes, you will be lucky to see 30 objects.

iii. *Choose an instrument*. Naked eyes, binoculars, or telescope, that is the question. The answer is largely determined by your budget. The larger the instrument, the brighter and more detailed the image will be. To begin, resist the temptation to go all in—do not buy too much since you may decide later that it is not for you! Start small and develop your interest. Remember that your instrument serves a general purpose to enjoy the splendor of the night skies, not only comet spotting. If you do choose a telescope, go for as large an aperture[15] as your budget will allow to see the faintest possible objects (highest limiting magnitude). This means obtaining a reflecting telescope (reflector), preferably with a low *f*/ratio (<5) and accompanying large field-of-view. It goes without saying that optical quality is essential, so go with a reputable manufacturer. Typical ‘scopes in this class are called Schmidt–Cassegrain or rich-field telescopes. (5–6 inch apertures are good starters.) Objects will appear brighter. In addition, great views of the Milky Way, galaxies, nebulae, etc are afforded. Use a low magnification eyepiece initially for a larger field-of view, then switch to higher magnification eyepieces as practical. Both authors attended graduate school with Alan Hale, the co-discoverer of Comet Hale–Bopp (*the* Great Comet of the 20th century), who used his 16 inch reflector for the discovery. (Incidentally, the amateur astronomer Thomas Bopp used a 17 inch reflector.)

A sturdy mounting is a necessity. A simple ‘cannon’ mount, the most common known as a Dobsonian, can be operated manually to follow the diurnal motion of the sky. More sophisticated ones, called equatorial mountings, align one axis of motion with the celestial pole. A small motor geared appropriately will move the telescope about the other axis at the appropriate rate, called sidereal tracking. If you plan on becoming an astrophotographer, this arrangement with a CCD camera is essential for long-time exposures. Of course, nowadays quick photos can be snapped using the camera in your smart phone. Simply align with the eyepiece and

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[15] This is the diameter of the mirror (reflecting telescope) or lens (refracting telescope).

shoot away. Post the best ones to your favorite social media account and watch for the reactions! An adaptor to keep the phone still can be added for a small cost.

Any pair of binoculars will give great sky views. Of course, going for larger aperture and lower magnification are best for celestial scanning (e.g. 50–80 mm, 7–25× magnification) and have wide fields of view. There are specialized binoculars for comet hunting (100 mm and larger), but these are for the serious amateurs and usually exceed the beginner's budget.

iv. *Practice with known comets*. Where can you find comets currently in our night skies? Due to Newton, we have great knowledge of celestial motion, including that of comets (thanks to his contemporary, Halley). Pick up a copy of *Sky and Telescope* or *Astronomy* magazines and look for their night sky sections. There are several online resources detailing the positions of comets currently in our night skies, too. Try these websites: https://in-the-sky.org/newsindex.php?feed=comets&year=2018&month=9&day=5&town=1690313, https://www.skyandtelescope.com/observing/celestial-objects-to-watch/comets/, https://theskylive.com/comets, and https://www.cfa.harvard.edu/skyreport. (More can be found using your favorite web browser.) Most have finder charts to help identify the comet among the stars. You can make your own finder charts—just make sure that they are up-to-date since the comet is in constant motion[16]. The orbit of a new comet may be slightly inaccurate due to lack of observations, so it pays to scan around its predicted location. Remember, non-gravitational forces also may cause deviations from the predictions.

Next, check the magnitude to see if it can be seen in your instrument. Comet magnitudes overestimate their visibility since their light is spread out, resulting in low surface brightness. Therefore a 4th magnitude comet may appear as a 6th magnitude object. Use averted vision for the faint ones! Our naked eyes are limited to 6.5 magnitude when fully dark adapted under optimum skies. Comets fainter than about 8th magnitude will only be seen in large binoculars (>50 mm), and modest telescopes (>6 inch) are needed to detect 11th magnitude comets with great sky conditions. If several comets can be seen that night, start with the brightest and work your way to down to the faintest. Recall our discussion at the beginning of chapter 5 about the comet's appearance, usually a bright central point with a surrounding diffuse, roundish cloud (coma) and perhaps the hint of a tail. Make your own estimation of the comet's brightness by comparing it to nearby stars. With practice, you can report your measurements to the International Comet Quarterly where they are published and you are credited. Estimating comet magnitudes is a very important activity for amateurs. These visual magnitude estimates (either by eye, binoculars, or telescopes) are used by the pros to augment their data since amateurs report with greater frequency on

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[16] You can delve deeper into locating the comet using its *ephemeris*, a table with celestial coordinates (right ascension, declination), expected magnitude, and other information for a given night. Check out NASA's Horizons System for more details: https://ssd.jpl.nasa.gov/horizons.cgi.

a near-nightly basis. World-wide campaigns have been organized in support of spacecraft missions to comets and the authorship of scientific publications that resulted was shared with the amateurs[17].

After a few hours, look for motion of the comet relative to the background stars. Make sure you keep records of your observations (with sketches or photos) so you can compare the comet night after night and to others.

v. *Happy hunting*! Now you are ready to scan the skies for interlopers (those not seen on the star maps and not known to us). Start in the twilight, just before sunrise, as this is the part of the sky that is newly revealed after being blocked by the Sun for many months. Do your search systematically by scanning adjacent swarths of the sky (and with low magnification if using a telescope). When you do find the comet, you will experience the thrill of discovery at that moment and the satisfaction of successfully finding it by yourself. In the meantime, stop to 'smell the roses', to wonder and appreciate the beauty of the objects that are part of the celestial zoo. Clyde Tombaugh (1906–97), while searching for Pluto and other planetary candidates, discovered a comet (274P/Tombaugh–Tenagra), many asteroids, hundreds of variable stars, and a few star clusters and galaxies. Good luck. But, again, persistence and determination are most important.

You can also become a member of a comet hunting team. Check with your local astronomy club. It can be a great resource for those beginning their nightly adventures and have a variety of telescopes for you to test drive at a star party before deciding on your own. You also may find similar-minded people online with a few simple searches (e.g. Zooniverse) and in groups like the Planetary Society[18], the world's largest and most influential non-profit space organization, co-founded by astronomer Carl Sagan (1934–96) in 1980.

vi. *How to report a discovery*. If you do find an object you suspect to be a new comet, you will need to report it to be recognized as the discoverer. Time is of the essence; keep in mind that hundreds of other comet hunters worldwide also are scanning the skies! However, you must strike a balance between relative certainties—make certain that your discovery is real (confirming motion, appearance, etc). Reporting too soon will cause unnecessary effort if the sighting does not pan out and may hurt your credibility. Report too late, and you may lose the discovery. A brief message can be sent that you suspect a discovery to keep your foot in the door with a more detailed message to follow if confirmed later that night or the next. Whom do you contact? The Harvard-Smithsonian Minor Planets Center (MPC) is the official office that represents the International Astronomical Union (IAU) in the discovery of comets, asteroids, and other transient

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[17] Astrobiologist Karen Meech (University of Hawaii) organized such a campaign in 2005 to coordinate observations of Comet Tempel 1, the target of NASA's Deep Impact Mission.

[18] http://www.planetary.org.

objects in the night sky (novas, supernovas, variable stars, etc). The MPC manages the Central Bureau for Astronomical Telegrams (CBAT) to do so. Send your report to the CBAT via email at cbatiau@eps.harvard.edu. (Telegrams are no longer accepted.) You also may use their web interface at http://www.cbat.eps.harvard.edu/DiscoveryForm.html. Your report should include the following information, or it may be rejected: your name and contact information; date and time of observation; method (naked eye, binoculars, etc); details of instrument used, if any; observational site; and the comet's position, motion, and appearance[19]. If one of the first three to report before it is officially announced, you get naming rights (in chronological order of the report), e.g. Comet (your name)–Boice–Hockey!

6.6 Epilogue

This completes our introduction to comets. We hope that you share our enthusiasm and passion for these fascinating objects that grace our skies, either as a fun pastime or for serious observation. This book is just the iceberg tip of our knowledge about comets. For some, it may be a springboard to dive into more advanced comet texts (ones that may even have equations). (See appendices F and G for suggestions.) We might even have planted the seeds for someone to become a professional comet astronomer. We do not know when the next Great Comet will appear, but now you are prepared to discover it and participate in the thrill of comet observations with a multitude of others around the world who share your interests. Who knows? Maybe you will write a book chronicling your many comet discoveries in the years to come. Good luck and clear skies!

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[19] More details on reporting comet discoveries can be found at http://www.cbat.eps.harvard.edu/CometDiscovery.html.

Chapter 7

Postscript

On 1 January 2019, the New Horizons spacecraft flew by the first small body encountered in the Kuiper Belt, MU_{69} (nicknamed Ultima Thule), at a distance of 3500 km (a veritable 'cosmic hole in one'), returning many scientific treasures. It captured the first images of a primordial comet nucleus (figure 7.1), one that has never had a near encounter with our fiery star and has been in cold storage in the Kuiper Belt since the dawn of the Solar System. Preserved in this pristine state, it provides clues about our early history, some 4.6 billion years ago. This sensational mission revealed a two-lobed body joined by a small 'neck', a contact binary, like another contact binary, Comet 67P/Churyumov–Gerasimenko, much eroded and transformed by successive close encounters with the Sun. This shape likely resulted from a slow collision where the two separate bodies stuck or a collision that fragmented a larger body and two large fragments came back together. Its size was measured to be about 34 km in the longest dimension, slightly larger than the average comet nucleus (but certainly smaller than Hale–Bopp), with a spin period of 16 h or so. It shows surface properties consistent with comet nuclei (very dark with some albedo variations and a brighter ring at the neck, mottled and ruddy terrain) and similar features (hills, slopes, plateaus, and craters) but with less relief due to its unprocessed nature. Its surface is slightly reddish from irradiation of ices during its long storage stint, similar to other Kuiper Belt Objects. Its detailed composition has yet to be determined but ices of water, methanol, and organic molecules have been identified spectroscopically on its surface, mixed with rocks. At its distance of 43.4 au from the Sun, surface temperatures are frigid, about 40 K, but hypervolatile ices of carbon monoxide, molecular nitrogen, molecular oxygen, and methane have sublimated from its surface. Data will continue to be returned until August 2020 so stay tuned for more revelations about this spectacular body and perhaps a cousin, since NASA may decide to send New Horizons to another Kuiper Belt Object!

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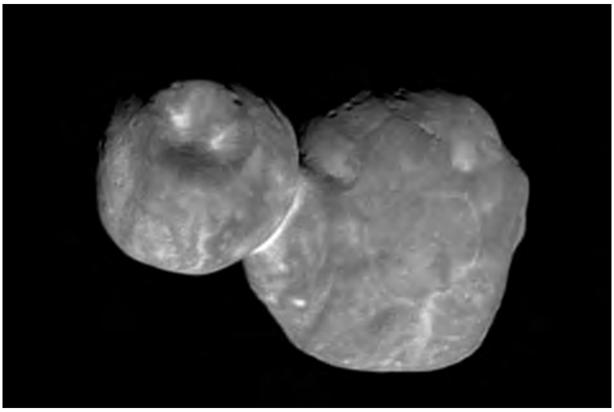

Figure 7.1. ‘Cosmic snowman with a necklace’, the primitive comet nucleus, MU_{69} (Ultima Thule). Its shape is that of a contact binary, two roughly round but flattened bodies joined by a neck, with a size of 34 km along the long axis. The ‘necklace’ is thought to contain fine grains that tumbled there by gravity or from the initial lobe merger. (NASA/John Hopkins Applied Physics Laboratory, Southwest Research Institute.)

Appendix A

Lesson suggestions for teachers

A.1 Comet orbits and tails

To illustrate the orbit of a comet about the Sun, use a table fan, Styrofoam ball, and a lightweight ribbon (such as the tape inside an old audio cassette). Pin various lengths of cut ribbon to the same point on the ball. The table fan represents the Sun. Its breeze plays the role of the solar wind. (The real solar wind should blow in all directions, of course.) The ball represents a comet nucleus surrounded by its coma. Place it at a distance from the 'Sun'. No tail (the ribbon strips) blows back away from the Sun. The ribbon hangs toward the floor and for now should be ignored. Carry the comet/ball almost directly toward the fan. Such is the appearance of a high eccentricity orbit. As the ball approaches the fan, strips of ribbon will begin to blow back away from the *faux* Sun. In other words, a comet tail grows longer the closer the comet is to the Sun. Upon reaching the fan, whip the ball quickly behind it and retrace its path, now away from the fan. The tail gradually shortens and then disappears as it retreats from the Sun, just as a real comet behaves. However, there is a difference: because the ribbon must always be blown away from the Sun, the tail now leads the comet instead of trailing it (the antitail) as it did on its inward passage. This, too, mimics the behavior of a real comet tail.

A.2 Recipe for a comet

To illustrate the physical nature of a pristine comet nucleus, use a large, glass bowl, crushed ice, some dirt, and a big spoon. Pour crushed ice into the bowl and then a layer of dirt, in roughly a 3:1 ratio. The dirt represents the refractory (dust) portion of a comet. Now comes the important part: stir the mix rapidly with the spoon. Comets, unlike planets, are not differentiated (layered). A comet is a homogeneous compilation of various ices and a refractory component. The 'comet' mix quickly

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and almost magically changes from bright, white ice to dark as each ice crystal becomes coated with a thin layer of 'dust.' It takes little dust to darken a comet drastically. Unintuitively, bodies made principally out of ice can have very low albedos. (Optionally, you can add some ground coal and dry ice to the mix. Now the 'comet' becomes darker and sublimates!)

A.3 Light pollution

Join the growing ranks of advocates to preserve our dark skies by estimating the sky darkness (limiting magnitude) at your designated observing site or at the students' homes (as homework). This can be done on any clear night; however, global campaigns are organized twice a year with instructions on submitting your results to the web. Students will gain familiarity with constellations during this exercise. This and more light pollution experiments can be found at: https://www.globeatnight.org/dsr/. See chapter 5 and section 6.5 for more details.

A.4 Learn constellations

This exercise builds on the previous one as more constellations of the night sky can be filled in. Monthly sky maps can be downloaded at: http://www.skymaps.com/. Since constellations are seasonal, concentrate on the prominent ones visible in the current evening skies. Make sketches or photos and label the bright stars and any planets that might be visiting. Zodiacal constellations are best to start with along with popular ones (e.g. Orion, Ursa Major, Ursa Minor, etc). Optionally, students can research the myth associated with each and other important facts. Section 6.5 has more details for your lesson plan.

A.5 Observations of the Moon

Observe the Moon's phase for an entire month with the naked eye using sketches or photographs from a smart phone camera. Note how the phase progressively changes and the motion of the Moon in the night sky relative to the constellations. Have the students estimate the position of the Moon in the sky (e.g. NE about 30° above the horizon). This will help you verify that the student actually made the observation rather than copying from the Internet. The students will soon notice that the Moon rises later each day so records must be taken accordingly. Learn the proper terminology to describe the phase (e.g. first quarter, not half moon; waxing gibbous vs waning gibbous, etc). Observations can be organized on a common calendar, making sure to record the time of observation also. (Optionally, if a student has knowledge of star charts, the phase and position can be recorded with respect to the stars.) Remember, some observations can be made during the day!

A.6 Observe a planet(s)

After consulting the website https://theskylive.com/planets (or another appropriate reference), chose a planet or planets that can easily be seen in the evening or morning skies with the naked eye (i.e. Mercury, Venus, Mars, Jupiter, or Saturn). Have the students make a sketch (or snap a photo) of the planet with respect to a few surrounding bright stars and the horizon (if appropriate), noting date, time, place, and general sky condition of the observation. (If exercise A.3 has been assigned previously, they can estimate the limiting magnitude. If A.4, they can identify the surrounding constellations.) Repeat this observation at later dates to note the motion of the planet relative to the stars. (Mercury and Venus—every few days; Mars—every week; Jupiter and Saturn—every month.) Observing during retrograde motion will heighten this experience.

A.7 Observe a comet

Exercises A.3–A.6 have prepared the students for their comet adventure. Consult the Internet for a bright comet (magnitude 4 or lower) that can be seen with the naked eye or with binoculars during the academic year (e.g. https://theskylive.com/comets). Make sketches noting the comet's position and brightness relative to the surrounding stars. A camera can be used if available for more accurate records. Hold the camera very still using a tripod or leaning against a steady object. Repeat the observation every night for a week or so, noting the comet's motion through the sky. Consult chapters 5 and 6, in particular sections 5.3 and 6.5, in making your lesson plan.

A.8 Observe a meteor shower

After selecting a prominent meteor shower from appendix B, depending on your academic calendar, consult the Internet for details of the shower (location in sky, best dates and times for observing, phase of the Moon, etc). This activity is best done with a small team to completely cover the sky. Assign each team member with a portion of the sky. Count how many meteors are seen every 10 min for one hour in the evening and, optionally, repeat for an hour in the early morning. Estimate the limiting magnitude (exercise A.3) every 10 min as well. This is important to determine the sky darkness (the darker the sky, the more meteors seen) and any changes in sky conditions that may occur during the one hour observation. This activity is best done lying on the ground or using lawn chairs, just don't fall asleep!

Appendix B

Approximate dates for some famous meteor showers

The shower can begin a few days before this date and last a few days after. Meteor showers are named after the constellation or nearest star from which the shower radiant appears. The IAU recognizes 112 established meteor showers.

Name	Peak night	Hourly rates	Parent object
Quadrantids	January 3	25	2003 EH_1[a]
Lyrids	April 21	10	C/1861 G1 (Thatcher)
Eta Aquariids	May 4	10–60	1P/Halley
Perseids	August 11	50–75	109P/Swift–Tuttle
Orionids	October 21	15–20	1P/Halley
Leonids	November 16	15[b]	55P/Tempel–Tuttle
Geminids	December 13	60–75	3200 Phaethon[a]

[a] Asteroid.

[b] Meteor storms (greater than 1000 meteors/hour) were seen in 1999, 2001, and 2002, but are not expected again until 2099.

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Appendix C

Typical comet visibility rates

In a typical year:

- Around a dozen comets reach perihelion.
- Tens of comets are visible to sky-watchers on the Earth.
- Two or three of these comets will be visible to amateur astronomers with small telescopes.
- One comet discernible to the naked eye will grace the sky.

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Appendix D

The brightest comets since 1935

Peak magnitude[a]	Name
(−10)	C/1965 S1 (Ikeya–Seki)
(−5.5)	C/2006 P1 (McNaught)
−3.0	C/1975 V1 (West)
(−3)	C/1947 X1 (Southern comet)
(−1)	C/1948 V1 (Eclipse comet)
(−1)	C/2011 S3 (Lovejoy)
−0.8	C/1995 O1 (Hale–Bopp)
(−0.5)	C/1956 R1 (Arend–Roland)
(−0.5)	C/2002 V1 (NEAT) (figure D1)
0.0	C/1996 B2 (Hyakutake)
0.0	C/1969 Y1 (Bennett)
(0)	C/1973 E1 (Kohoutek)
(0)	C/1962 C1 (Seki–Lines)
0.5	C/1998 J1 (SOHO)
1.0	C/1957 P1 (Mrkos)
(1.0)	C/2011 L4 (PANSTARRS)
(1)	C/1970 K1 (White–Ortiz–Bolelli)
1.7	C/1983 H1 (IRAS–Araki–Alcock)
(2)	C/1941 B2 (de Kock–Paraskevopoulos)
(2.2)	C/2002 T7 (LINEAR)
2.4	1P/1982 U1 (Halley)
(2.4)	17P/Holmes [October 2007]
2.5	C/2000 WM$_1$ (LINEAR)

(*Continued*)

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2.7	C/1964 N1 (Ikeya)
2.8	C/2001 Q4 (NEAT)
2.8	C/1989 W1 (Aarseth–Brewington)
2.8	C/1963 A1 (Ikeya)
2.9	153P/2002 C1 (Ikeya–Zhang)
3.0	C/2001 A2 (LINEAR)
3.3	C/1936 K1 (Peltier)
(3.3)	C/2004 F4 (Bradfield)
3.5	C/2004 Q2 (Machholz)
3.5	C/1942 X1 (Whipple–Fedtke–Tevzadze)
3.5	C/1940 R2 (Cunningham)
3.5	C/1939 H1 (Jurlof–Achmarof–Hassel)
3.5	C/1959 Y1 (Burnham)
3.5	C/1969 T1 (Tago–Sato–Kosaka)
3.5	C/1980 Y1 (Bradfield)
(3.5)	C/1961 O1 (Wilson–Hubbard)
(3.5)	C/1955 L1 (Mrkos)
3.6	C/1990 K1 (Levy)
3.7	C/1975 N1 (Kobayashi–Berger–Milon)
3.9	C/1974 C1 (Bradfield)
3.9	C/1937 N1 (Finsler)

Source: *The International Comet Quarterly*. Published by the Earth and Planetary Sciences Department at Harvard University. Updated 17 November 2013. Accessed 25 May 2016.

[a] On the astronomers' magnitude scale, a smaller (more negative) number represents a brighter comet. Peak magnitudes in parentheses are uncertain.

Figure D1. Comet NEAT in 2003. NASA image.

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Appendix E

Notable comets in history

Year	Comet	Comments	Year	Comet	Comments
1066	Halley	Portent of William the Conqueror	1106	X/1106 C1	Widely visible in day—Europe and Orient
1145	Halley	Well documented by Chinese	1264	C/1264 N1	Poured out smoke like a furnace
1378	Halley	Recorded by Chinese, Koreans, and Japanese	1402	C/1402 D1	Comet visible in broad daylight
1456	Halley	Comet was excommunicated by the Pope!	1531	Halley	Orbit computed by Halley
1556	Heller	Great fiery unusual-looking star	1577	Tycho's Comet	Observed by Tycho Brahe; tail 80° long
1607	Halley	Orbit computed by Halley	1618	C/1618 W1	Tail 104°
1661	Hevelius	6° tail and multiple nucleus structures	1680	Kirch	Maximum tail arc of 90°
1682	Halley	Epoch of Edmund Halley's observations	1689	C/1689 X1	Discovered at sea, tail 68°
1729	Sarabat	Large perihelion distance	1744	De Cheseaux	Remarkable appearance with six tails
1759	Great Comet	Passed 0.07 au from the Earth	1769	Messier	Tail length exceeded 90°
1811	Flaugergues	Unprecedented 17 month visibility	1823	Great Comet	Large sunward antitail

(*Continued*)

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1835	Boguslawski	Star-like nucleus and a broad tail	1843	Great Comet	Sungrazing comet
1858	Donati	Most beautiful comet on record	1861	Tebbutt	Daytime 'auroral glow' reported
1874	Coggia	Unusual jet features	1880	Great Southern Comet	Orbit resembles comet of 1843
1881	Great Comet	Only comet spectrum observed before 1907	1882	Great Comet	Orbit resembles comet of 1880
1887	Great Southern Comet	Orbit resembles comet of 1843	1901	Great Southern Comet	Brightness rivals that of the star Sirius

Courtesy of Karen Meech and Gary Kronk's *Cometography,* volumes 1 and 2.

Appendix F

Books on historical comets

Heidarzadeh T 2008 *A History of Physical Theories of Comets, from Aristotle to Whipple* (New York: Springer)

Metz J 1985 *Halley's Comet, 1910: Fire in the Sky* (Saint Louis, MI: Singing Bone)

Schechner S J 1997 *Comets, Popular Culture, and the Birth of Cosmology* (Princeton, NJ: Princeton University Press)

Seargent D 2009 *The Greatest Comets in History: Broom Stars and Celestial Scimitars* (New York: Springer)

Stephenson F R and Walker C B F (ed) 1985 *Halley's Comet in History* (London: British Museum)

Van Nouhuys T 1998 *The Age of Two-faced Janus: The Comets of 1577 and 1618 and the Decline of the Aristotelian World View in the Netherlands* (Leiden: Brill)

Yeomans D K 1991 *Comets: A Chronological History of Observation, Science, Myth, and Folklore* (New York: Wiley)

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Appendix G

Intermediate and advanced books on comets

Brandt J C and Chapman R D 2004 *Introduction to Comets* 2nd edn (Cambridge: Cambridge University Press)

Crovisier J and Encrenaz T 2000 *Comet Science: The Study of Remnants from the Birth of the Solar System* (Cambridge: Cambridge University Press)

Festou M C, Keller H U and Weaver H A (ed) 2004 *Comets II* (Tucson, AZ: University of Arizona Press)

Krishna Swamy K S 2010 *Physics of Comets* 3rd edn (Singapore: World Scientific)

Kronk G 1999–2017 *Cometography* vols 1–6 (Cambridge: Cambridge University Press)

Meierhenrich U 2015 *Comets and their Origin: The Tool to Decipher a Comet* (New York: Wiley)

Sagan C and Druyan A 1997 *Comet* (New York: Ballantine)

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Glossary

(The first occurrence of each entry in the text has been italicized.)

Air mass	The ‘width’ (or path length) of the atmosphere through which an observation is made.
Albedo	The fraction of light reflected from a surface, ranging from 0 (total absorption) to 1 (total reflection).
Antitail	A dust tail that appears to point towards the Sun but is actually an illusion caused by observing the comet from a particular perspective from the Earth.
Aphelion	The farthest point from the Sun in an orbit.
Asteroid	A small Solar System body primarily made up of rock and metals. Recent work shows that many also contain water in some form or other, making their distinction from comets less clear. Most are found between the orbits of Mars and Jupiter, a region called the Main Asteroid Belt (MAB).
Astronomical unit (au)	The average distance between the Sun and Earth during its orbit, being 149 597 870.700 km exactly.
Celestial meridian	The imaginary line running from an observer’s north point on the horizon, through the point directly overhead (zenith), to the south point. It divides the hemispherical sky into eastern and western parts. Objects in the east rise during the night, achieve their greatest distance above the horizon as they cross the meridian, and set in the west.
Centaurs	Small bodies with characteristics of both asteroids and comets between the orbits of Neptune and Jupiter (e.g. 95P/Chiron), now totaling over 500 objects. Some are thought to be comet nuclei from the Kuiper Belt or Scattered Disk making their way progressively into the inner Solar System.
Coma	A constantly escaping cloud of gas (including ions) and dust surrounding an active comet, its ‘atmosphere’.
Corona	A hot but tenuous gas of electrically charged particles surrounding the Sun and extending millions of kilometers into space. It is best seen during a total solar eclipse.
Dust	Small grains (less than about 1 μm) composed of refractory materials (silicates, carbonaceous substances, carbon–hydrogen–oxygen–nitrogen (CHON) material, rocks, metals), some with ices.
Eccentricity	The degree of ‘flattening’ of an ellipse (or orbit), ranging from 0 (circular) to near 1 (highly elliptical).

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Ecliptic	The plane of the Earth's orbit in the Solar System.
Ephemeris	A table of celestial coordinates (right ascension, declination) giving the sky positions of celestial bodies. Comet ephemerides can be found online at NASA's Horizons System, https://ssd.jpl.nasa.gov/horizons.cgi.
Ice	Any solid made out of a volatile substance, e.g. water, carbon dioxide, etc.
Ion	An electrically charged particle caused by adding or removing electrons from a neutral atom or molecule.
Isotope	A variant of an element with a different number of neutrons in its nucleus but generally having the same chemical properties (e.g. adding a neutron to a hydrogen atom yields its heavier isotope, deuterium).
Jet	A stream of sublimating gas with dust emanating from a specific surface area (active region) usually on the day-time side of the nucleus. Jets exert non-gravitational forces on the nucleus that changes its orbit and spin state.
Kuiper Belt (KB)	A doughnut-shaped disk of small bodies, including three dwarf planets, at 30 to about 50 au from the Sun, first postulated by Gerard Kuiper in 1951. The first Kuiper Belt Object (KBO), other than Pluto, was found in 1992. Now more than one thousand KBOs are known. It overlaps the Scattered Disk which extends out to at least 100 au and is the source of most short-period comets with very elliptical orbits and higher inclinations.
Light pollution	The combined lighting that illuminates the night sky, mainly in urban areas, including street lamps, spotlights, glowing fast-food signs, automobile lights, house lighting, the phase of the Moon, etc, making it difficult to see stars and other astronomical phenomena.
Long-period comet (LPC)	Comets with orbital periods exceeding 200 years, up to about a million years, at random directions and angles to the ecliptic, forming a roughly spherical cloud surrounding the Sun (the Oort Cloud).
Magnitude	In astronomy, the system used to measure the brightness of an object, the smaller (more negative) the number, the brighter the object. A difference of five magnitudes is a hundred-fold change in brightness. Examples: the Sun is −26.7 in magnitude, the full Moon is −12.6, Venus at its brightest is −4.4, Sirius (the brightest star) is −1.6, the faintest object seen by the unaided eye under the darkest skies is 6.5, the limit of the Hubble Space Telescope is 31.5, and the limit of the James Webb Space Telescope (Hubble's replacement to be launched in 2021) is 34.
Meteor	Small pieces (less than about three meters in size) of extraterrestrial rock and metal that enter the Earth's atmosphere traveling at very high speeds, and are heated to a high temperature, causing them to glow and possibly leaving a trail of hot vapor in their wake. We can see these streaks of light in the night sky, which many call 'shooting stars'. Many meteors are the size of grains of sand and completely burn up in the atmosphere. Before atmospheric entry, they are called meteoroids and if they survive to hit the ground, we call them meteorites.
Meteor shower	An increase in meteor activity over several consecutive nights each year, with meteors that appear to radiate from a common point in the night sky. The frequency of meteors can vary from a dozen (a sprinkle) to more than one thousand per hour (a storm). The source of these meteors is the dusty debris trail of comets whose orbits intersect that of the Earth.

Nucleus	The tiny solid part of a comet, measured in tens of kilometers down to a few hundreds of meters, with a typical size being about 10 km. It is composed of ices and refractories, being very dark and very porous (fluffy). It is the source of all activity that gives rise to the coma and tails.
Oort Cloud (OC)	The outer region of the Solar System containing long-period comet nuclei, first postulated by Jan Oort in 1950. It consists of the doughnut-shaped Inner Cloud (Hills Cloud) from about 2000 to 20 000 au that smoothly joins with the Kuiper Belt and the spherical Outer Cloud from about 20 000 up to 150 000 au (the limit of the Sun's gravitational boundary). Several thousand long-period comets are known to have originated from the Oort Cloud. They have extremely elliptical orbits with random orientations to the ecliptic plane.
Parallax	The angle through which an object seems to move when viewed from two disparate places, as reckoned against some, more-distant background and is inversely proportional to its distance. It is the basis for finding distances to comets, asteroids, planets, and stars.
Perihelion	The closest point to the Sun in an orbit.
Period	The amount of time to complete one orbit.
Plasma	A gas consisting of electrons and ions, often called the fourth state of matter since it behaves very differently to an ordinary (neutral) gas.
Proto-solar nebula	The interstellar gas and dust cloud out of which the Sun and its Solar System formed some 4.6 billion year ago.
Refractory	Minerals that retain their form and properties at high temperatures, such as rocks and minerals.
Scintillation	The variation in brightness of a point-like astronomical object, such as a star, when seen through Earth's atmosphere, i.e. twinkling or flickering. Extended objects, such as planets and comets, do not flicker appreciably.
Seeing	A measure of the 'blurring' of astronomical objects due to the atmosphere, principally due to scintillation, light pollution, and cloud cover.
Short-period comet (SPC)	Comets with orbital periods less than 200 years. They travel near the ecliptic plane of the Solar System and generally in the same direction as the planets, most originating from a doughnut-shaped region surrounding the Sun (the Kuiper Belt and Scattered Disk). They include Jupiter-family comets (JFC) with periods less than 20 years, Encke-type comets (ETC) with the shortest known periods whose orbits do not reach Jupiter, and Halley-type comets (HTC) with periods between 20 and 200 years. About 10% of well-studied, short-period comets (observed more than once) fall into this latter category.
Sublimation	The chemical term to describe the change of a substance from solid to gas and vice versa without passing through the liquid phase.
Tails	Long appendages made up of ions (type I, atomic and molecular ions affected by the solar wind), dust particles (type II, affected by sunlight), and gas (Type III, neutral sodium atoms affected by sunlight) that stream away from the comet's head in the inner Solar System, generally in the direction away from the Sun. Comets may exhibit one or more tails simultaneously. A Manx comet was seen in 2016 that had no tail.

Trojan asteroids	Small bodies at the orbit of Jupiter, in two groups about 60° ahead (Greek node) and 60° behind (Trojan node) its orbit, trapped at stable points. They are classified as asteroids but many may be comet nuclei that were captured by Jupiter in the early history of the Solar System. To date, 7040 Trojans have been discovered.
Volatile	Under normal pressures, chemical substances that turn to gas unless kept very cold, e.g. carbon dioxide, methane, molecular oxygen, molecular nitrogen, etc. Water ice is also considered to be a volatile.
Zodiacal light	Sunlight reflected from comet dust in the ecliptic plane, most easily seen in the western sky after sunset as an elongated cone extending up from the horizon.