IOP Concise Physics

Comets in the 21st Century
A personal guide to experiencing the next great comet!
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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

[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

[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.

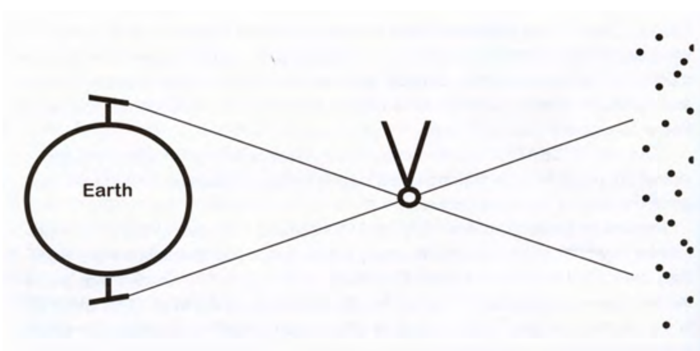

Figure 6.1. A modern measurement of parallax for a nearby comet. The angle is highly exaggerated.

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,

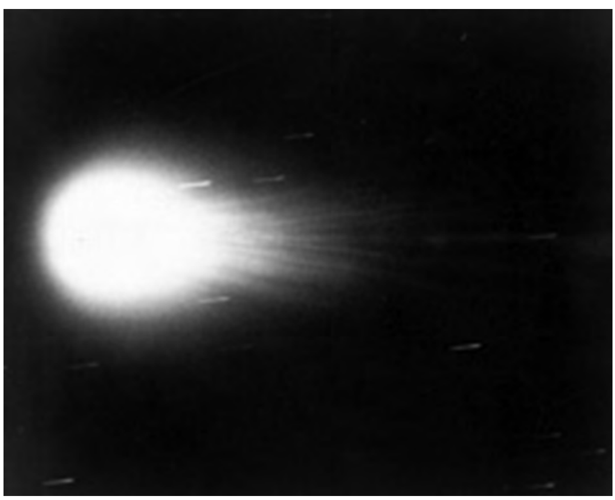

Figure 6.3. Comet Kohoutek in 1973. NASA image.

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

[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

[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,

[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

[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

[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

[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!

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