It is a spectacle pure and simple, the most magnificent free show that nature presents to man… not to view the coming one would be literally to lose the opportunity of a lifetime.

--On the Solar Eclipse of 1925, *The New York Times*

Introduction: From Omen to Awe

I am an astronomer; I have spent my whole life watching the sky. I've been to observatories all over the world and used every kind of telescope to image distant star clusters and massive galaxies. For me, every clear night is an opportunity to experience something amazing. I have seen comets stretch across the sky, sunlight glint off the dust that floats between the planets, and a Milky Way so bright that the glow of its billion stars has cast a shadow at my feet. But in all my life I have never seen anything as awe inspiring, as *awesome* - in the original definition of the word - as a total eclipse of the Sun. It is the only astronomical wonder that requires no telescope or fancy equipment to see and looks more spectacular to the eye than through the lens of any camera.

For an event that has at some point touched almost every place on Earth, remarkably few people have ever seen a total solar eclipse. The fact that *anyone* is able to see one is due to the coincidence that our Moon is exactly the right size and distance from the Earth to completely cover the Sun. More often than not, the alignment between the worlds isn't perfect and so the Moon only blocks a portion of the Sun and the eclipse is partial. At those moments, the Sun is still blindingly bright (literally) and so we are warned to use those little paper eclipse glasses that reward us with the strange sight of a Sun that is not fully there. Odds are you have probably seen a partial eclipse without making any special effort.

But on those much rarer occasions, when the alignment of Sun and Moon is perfect, and you stand fully within the shadow of the Moon, then a *total* eclipse occurs. The shadow on the landscape is small - maybe no more than a few dozen miles wide - yet the Moon's motion draws this darkness eastward for thousands of miles across our planet: the path of totality. For anyone on the ground, the experience can be either awe-inspiring or merely interesting, depending entirely on whether one is inside or outside that ribbon of darkness. Inside totality's path, the Sun turns black and the stars come out, outside the band and the Sun stays bright. It is literally the difference between night and day: ninety-nine percent totality is *definitely* not ninety-nine percent of the spectacle.

It is the most unnatural, natural event anyone can ever see.

Given this strangeness, it's perfectly reasonable that eclipses have been met with terror and dread throughout history. Yet we humans have responded with complex myths and complex rituals to allay our fears, describe what we're seeing, and bring the Sun back. In the process, we've discovered the cycles by which they occur, and over time used their appearance to measure our world and reveal the mysteries of the Universe. The story of astronomy is what we have learned from the shadows and light that reach between worlds. Today, people travel the planet to experience those few fleeting minutes of totality and when it is over, wonder when they can see another. Eclipses have made the transition from omens of doom to moments of awe. This is that story.

Skoll the wolf who shall scare the Moon

Till he flies to the Wood-of-Woe:

Hati the wolf. Hridvitnir's kin,

Who shall pursue the Sun.

--The Grimnismal, of the Eldar Edda

Chapter 1: A Day with Two Dawns and Midnight at Noon

It's not even lunch yet when something takes a bite out of the Sun. It's only a tiny notch at first, all but invisible without my cardboard eclipse glasses. Were it not for the shouts from the crowd around me on this August day, I never would have noticed. But now that I'm watching I can see the bite grow bigger. The bite is the edge of our unseen Moon; the Sun is being eclipsed.

It is no coincidence that cultures from all over the world witnessed this sight with some degree of dismay. The Greek origin of the word *eclipse* is *ekleipsis* meaning "omission" or "abandonment." Ancient Chinese eclipse accounts contain the characters for "ugly" and "abnormal." For the Aztec, the eclipsed Sun "faltered" and became "restless" and "troubled."[1] These reactions make perfect sense when you consider that the Sun is the giver of heat and life. When the Sun goes away without warning, it leaves behind the fear that it might not come back.

It takes forty minutes for the dark notch to grow so big that the Sun is now a crescent. I take off my glasses and see that in the shadow of the tree under which I've taken refuge from the heat, that same shape has become visible by the thousands. Every tiny gap in the leaves overhead acts as a *camera obscura*, a “pinhole camera” projecting a bright fingernail of light on the ground. Nearby children have spotted them too and begin to yell and giggle as they point and play amongst the tiny crescents. Had I not known what was happening before, this oddity would certainly have revealed the eclipse in progress above.

An hour has passed since this all began: only twenty minutes left until totality. The life-giving nature of the Sun is no longer an abstract concept: the sky is growing darker and colors are strangely wrong. The landscape is sapped of saturation. The worlds are aligning.

With ten minutes left, the conditions are changing fast. The world has turned to twilight. The shadows of trees and me are sharp as if lit by a single spotlight. All illumination now comes, not from a yellow Sun set amid a bright blue sky, but from only a narrow white crescent in a sky no longer bright.

I put my glasses back on for these final moments of the partial phase and can actually see the remaining crescent shrink as I watch. The crowd rises. Conversations hush and I notice for the first time that all birdsong has ceased; they have returned to their nests to sleep in the unexpected night. An unseasonably cool wind blows across my arm as the temperature drops this far into the lunar shadow and the eclipse officially becomes a multisensory experience of sight, sound, and touch. So little of the Sun is left that surely totality should begin at any second, but I can’t tear my eyes away to look at my watch. Even the passage of time seems affected as these last few seconds seem to expand rather than diminish.

Suddenly, the Sun’s thin sickle of light breaks apart into an array of brilliant specks that dance and shimmer along the Moon’s jet-black rim. They are called Baily’s Beads and they are the last rays of the vanishing Sun streaming through actual mountain valleys along the curved lunar surface. I finally remove my protective glasses to see them quickly wink away until there is only a single glistening star set in a band of white fire encircling the Moon: the glorious diamond ring.

And then the spot collapses upon itself and is gone.

Totality.

Where before there was light and heat, now there is only a cold, black hole in the sky surrounded by a ghostly crown. The corona, a ring of pearly tendrils, envelopes the darkness and stretches off into the sky in all directions. It is unimaginably beautiful, only ever visible during these few precious minutes of totality, and all around it are the brighter stars and planets invisible until now. It is a day that has become night at noon with Sun, Moon, planets, and stars overhead.

As an astronomer I know the mechanics of this celestial alignment, yet in this moment of totality I fully understand the difference between knowledge and feeling. The hair is raised on the back of my neck and my mind screams at the wrongness of what I am seeing. It is clear to me now why people throughout time did what they did to scare away the demons, chase away the jaguars, and slay the monsters they imagined devouring the Sun. The French astronomer and historian Jean-Pierre Verdet, has found this fear-fueled call to action was universal.[2]

<<Insert Eclipse-Types.tif here>>

But there has always been a purpose to this pandemonium. In Paraguay and Argentina, the roar of the crowds and barking dogs frightened the celestial jaguar that ate the Sun.

Norsemen yelled to frighten away Loki's demon dogs sent to hunt and feed upon the Sun and Moon. The Ojibwe of North America sought to help the beleaguered Sun by firing flaming arrows to help him regain his light. In India the people banged pots and pans to frighten Rahu, an immortal head who chased and ate both Sun and Moon.[3] If they were loud enough then Rahu would be startled, and drop the Sun from his jaws: totality would be averted and the eclipse would be only partial. For the Aztec, however, matters were more serious, where, "the common folk raised a cry, lifting their voices, making a great din, calling out, shrieking… People of light complexion were slain [as sacrifices]; captives were killed."[4]

Fortunately for any fair-skinned Aztecs, total solar eclipses for any one location are rare. Though eclipses happen roughly twice each year, each follows a different path across the planet. Every 18 years these patterns repeat in shape, but one third of the way around the planet and a little farther north or south than the one before. As seen from a location high above the globe these paths slowly spiral around the planet from pole to pole until eventually any spot on Earth can expect to see totality every 375 years on average.[5] Though three centuries is long in human terms, the different paths do cross, and a single person in a fixed location may periodically see multiple eclipses in as little as half a dozen years. For cultures that looked to the sky for omens, where every new star, comet, or eclipse could be the sign of the end-times, imagine what seeing two total eclipses in one lifetime would have meant?

A thousand years ago, in what would become the American Southwest, Chaco Canyon was the ceremonial center of the Ancient Puebloan people (who used to be called the Anasazi). There, on the side of a massive boulder is a pictograph unlike any other; one that may be a record of the total solar eclipse of July 11, 1097 that was one of *three* solar eclipses (two total and one annular) visible there over 58 years at the height of their culture.[6] It features a large circle pecked into the yellow sandstone surrounded by strange looping tendrils similar to the appearance of the solar corona, including an eruption of hot gas (called a coronal mass ejection) and Venus just where it would have been visible in the sky to the upper left.[7]

Imagine the effect such an apparition would have had for a sun-watching people at the heart of their ceremonial society during a decade of extreme drought when the climate was changing for the worse. For a people in the midst of extreme cultural and environmental crises, might such an eclipse have been yet another contributing factor in what made the Chacoans eventually wall up their monumental “Great Houses,” set them aflame, and ultimately abandon the canyon a thousand years ago?[8]

Even today, eclipses play on our fears. The American anthropologist, Ward Keeler, describes the event of June 11, 1983, when a total solar eclipse swept across Indonesia.

> [T]he air became very still and Java's lush vegetation glowed in the eerie light characteristic of sunset in the tropics. As at sunset, too, the horizon turned red, but it did so not only in the west but in all directions, and in the half-light distant volcanoes usually obscured by the glare of the Sun became visible. For the four minutes of total eclipse, the Sun, almost directly overhead, looked like a black ball surrounded by a brilliant white light. Most eerily of all, in one of the most densely populated rural areas in the world, there was no traffic on the roads, no movement in towns or villages, and no one watching the eclipse.[9]

For weeks prior to the event, newspapers, radios, and TVs had gone to great length to warn people about the event for fear that people would damage their eyes. Posters were prominently displayed in villages across the country bearing the message that watching the eclipse would cause you to go blind and were so effective that:

> [N]o one dared even to look outside, let alone look at the sky, for a period of about three hours before and after as well as during the eclipse. People stayed inside their houses, some watching the eclipse on television, others lying in bed, all thoroughly intimidated by what had come to be known as the Sun's "sharp rays."[10]

I know that fear first hand. The last total solar eclipse to touch the continental United States did so in Portland, Oregon on February 26, 1979. I was a boy, only nine years old then. In my fourth grade class we made clay medallions of the upcoming eclipse. While others painted black circles with yellow crescents in representation of the partial phase, I had found library books showing the corona and so carefully painted the billowing white ring around the central black hole. Yet on the morning of the eclipse, my school canceled classes and rather than go out and see the sight for myself I hid indoors with the curtains drawn. Local TV and radio stations had been inundated with the exact same messages of fear that would later be broadcast all over Indonesia. I hid indoors, terrified of the same mysterious rays with the power to make me go blind if I so much as got a glimpse of the eclipsed Sun.

Today I know that there are no special rays, sharp or otherwise. The Sun is just as bright on any ordinary average day as it is on the day of an eclipse. It is therefore only during the partial phase that the Sun is still bright enough that staring at it for even a couple seconds can cause permanent damage to the retina (just as it will do on any other day). For this reason, it is only during the partial phase that eclipse glasses are even necessary; when totality comes the Sun's light is as safe as it is awesome. Yet, in our zeal to be "safe" we flood the airwaves with our fears, never with our hopes. That is why, to this day, my first eclipse memory is of watching the events unfold on my RCA color TV (snapping photos off the screen with my plastic drugstore camera). My only direct experience of the event itself was noticing how dark the house became as totality passed unseen overhead. It would be thirty-eight years before a total solar eclipse would touch this country again and I have spent every one of those years wishing I'd turned around, gone to the window, parted the curtains, and simply looked up.

My career as an astronomer has taken me around the world since then, partly in pursuit of exactly that which I so narrowly missed when I was nine. Yet though I have seen multiple solar eclipses since, I will never be able to see the one that I missed that day. Every eclipse is different. The shape of the corona, the streamers and jets that are such a startling phenomenon of totality, is dependent on the conditions on the Sun at just that moment, and its exact shape is unknown until the instant of totality.

Astrological records of ancient eclipses in China claimed that while solar eclipses were a reflection of the quality of the king, the corona's appearance revealed the political plots at work behind the throne:

> (If the king) does not share his fortune with his subjects, the condition is called unstable. Then there will be a total eclipse with Sun being black and its

> light shooting outward…. If there are two ear-rings beside the Sun during eclipse while in the east, west, south, and north corners there are white clouds shooting outward, then the whole country will be in war.[11]

The search for meaning in celestial events is the purview of astrology. A comet appears in the sky? The king will be overthrown. A supernova (a new star) appears in the constellation of Leo? A new king will be born. The Sun is eclipsed? The king is wicked. When even I, a steely-eyed science-type, am moved to awe by such a rare and beautiful phenomenon, it makes sense to want to associate it with something of great importance.

It therefore follows naturally that if eclipses record momentous events, then a momentous event must require an eclipse. Both Ragnarok and the Rapture (as well as the Crucifixion in the gospels) are accompanied by the Sun turning black, often interpreted as total eclipses. Only slightly less momentous, to anyone not from Boston at least, is the fact that the Red Sox broke their 85-year long World Series curse only during the final moments of the total lunar eclipse of October 2004. At those moments when the Moon passes into the shadow of the Earth it takes on the reddish color of sunlight filtering through the Earth's atmosphere. Astrologers call it a "blood moon" for obvious reasons. Perhaps the Red Sox could only win by the light of a red Moon?

If eclipses were harbingers of end-times (at least for Yankees fans) then to call on one was a sign of one's power with the gods. In 1504, Christopher Columbus was in the midst of his fourth and final voyage to the New World when he became shipwrecked on the north shore of Jamaica. Even under the best of times, Columbus was a terrible administrator (he had already been removed as Governor of the Indies) so as the days turned to weeks on the beach, Columbus' crew grew tired and mutinied. They plundered the homes of the Jamaicans who had helped them and, in return, the locals revolted and attacked the stranded Europeans.

Caught between mutiny and rebellion, Columbus consulted the astronomical tables he used for navigation. In them he found that three days later, on the evening of February 29th there would be a total lunar eclipse. That night, Columbus told the local chieftains that God was angry at their rebellion and would make His displeasure known by causing the Moon to be "inflamed with wrath." When the Moon rose after sunset a dark shadow began to spread across its face. When the eclipse became total and the Moon turned red, the Jamaicans pleaded with Columbus to make it stop. Columbus went to his cabin claiming he would pray on their behalf, but in reality he went there to keep watch on his hour-glass. In addition to the date of the eclipse, his almanac had also revealed that totality would last for 48 minutes.

As the sand ran down and the time finally approached, Columbus stepped outside once more. God had answered his prayers, he said. He would forgive their rebellion provided they once more brought food for his men, and in the midst of the Jamaicans relief, the blood-red color drained from the face of the Moon and totality ended.

A little over three hundred years later another European thought he'd try the same trick. A doctor on the plains of the Dakota Territory in 1869 knew from his almanac that a total solar eclipse was about to occur. Eager to impress upon the Sioux the power of the White Man's magic and healing arts, he told them of the exact date and time that the eclipse would occur until he saw fit to have it stop.

When totality occurred, rather than cower in fear the men raised their rifles and fired into the air. When the Sun came out again they calmly stated that, “The doctor could predict the eclipse, but they could drive it away….”[12]

That eclipses can be predicted years in advance and all over the globe (and that people have done so for over a thousand years before modern computers) is amazing. Wish to see a total solar eclipse? Modern astronomy can now tell you the location and time of any future eclipse down to the mile and the second. More importantly, the proof of whether or not we are correct will be waiting for you when you get there: either you see the corona or you don’t. If you don’t, then we learn we didn’t understand the world as well as we thought and we seek to correct what we failed to get right. This is the power of science and the process by which we have learned everything we know about the physical Universe in which we live.

Astrology also makes predictions. Astrologers claim that the position of the Sun, Moon, and planets at the time of your birth influences your personality and fate. It identifies auspicious dates, opportune investments, and compatible mates. The one thing it does not do, however, is re-evaluate its assumptions when it’s wrong - the defining characteristic of science. Yet in a 2014 National Science Foundation survey, nearly half of all Americans (45%) responded that they believed there was some scientific basis to astrology. Imagine my disquiet when during my most recent trip to the doctor the nurse drawing my blood looked at my paperwork and said with a smile, “Oh hey, you’re a Scorpio too!”

The primal appeal of pseudo-sciences like astrology is understandable. Life is full of dangers and misfortune that plague us at random. Astrology gives us hope that there is a cosmic reason, a connection with the Sun, Moon, and stars, which gives order to the apparent chaos we encounter. Yet the science of astronomy reveals a far more direct way in which the heavens guide our lives on a daily basis.

The Sun gives us light, heat and food: those organisms that don't feed directly on sunlight, feed on other organisms that do. Our everyday concepts of position, direction, and time intimately depend upon astronomy. What is a "day" but the rotation of our planet? A "year" measures its orbital motion about the Sun. Even the orbit of the Moon is marked in the period of time we call a "month." Imagine every task, chore, rite, or celebration that happens on an annual basis and you will find a need for some astronomer in our past. Could civilization have arisen without astronomy? Might we all be the descendents of astronomers? Is there any evidence for where astronomy began?

Let's imagine a family tree of our distant ancestors. Four million years ago, our small *Australopithecus* ancestor first stood erect out on the African savanna. As the American astronomer Neil deGrasse Tyson has said, "Once we were standing upright, our eyes were no longer fixated on the ground." Out, away from the cover of trees, the night sky was more vivid than almost any sky current humans can see. We are not the only beings on this planet who have noticed the stars and Milky Way. Sea turtles, birds, and dung beetles all make use of the stars and Milky Way for navigating. We wouldn't call them astronomers. Use alone isn't science.

By 2.5 million years ago, our *Homo habilis* ancestors were following animal herds in their annual migrations. Evidence exists for seasonal camps during their travels. Did they plan them by noting the passing of the seasons with the changing Sun and stars in the sky, or did they merely set up new camps as they kept close to the animals upon which they depended? Lions follow herds, but they aren't scientists.

A million years later our *Homo erectus* forebears mastered fire which for the first time, extended the day's work into darkness. Perhaps the first constellations were made during those nights? If so, we have no record of them.

Only 60,000 - 100,000 years ago, the first *Homo sapiens* fed on shell fish from tide pools on the south coast of Africa. The tides are tied to the Moon and change each day, both in time and size as the Moon goes through phases. There'd be a benefit to understanding these patterns: those that did, got to feed themselves and their families; those that didn't got washed out to sea. Maybe this is where astronomy began?

But consider for a moment what is required to make these mental connections. The ocean tide is a direct physical effect; it gets you wet and reveals its food when it goes out. The Moon, by contrast, is so far away you can't touch it, hear it, or smell it. There's no reason these should be connected and what connection there is can only be revealed through observations over a long period of time, requiring memory, abstract pattern recognition, and a belief in an underlying order or connection.

The archaeologist, Steven Mithen refers to these skills as "cognitive fluidity": the ability to synthesize different forms of intelligence (the ability to build fires, tools, and weapons, along with the ability to interact in a group and structured society) and to combine these in ways that incorporate abstract ideas, myths, and long-term observations.[13] Evidence for this fluidity appears about this time in the first examples of representational art and bone-artifacts where a physical thing has been created as a representation of something else.[14] If this is the earliest time when science could arise, then it is not surprising that the first, most unambiguous evidence of human astronomical knowledge is more recent still.

Less than a mile from the Nile, in what once was ancient Nubia, is a complex of graves in which 58 bodies were found all buried on their left-side, head to the East, facing the rising Sun.[15] The simple fact that they face the East means that between 10,000 and 12,000 years ago someone knew how to identify one of the four cardinal directions. These directions are defined by the sky. The East is where the Sun rises, West is where it sets. The line joining north to south is where the Sun is at its highest during the day, and at night (at least in the northern hemisphere) the North is the direction around which all the stars turn. Here in the Nubian Desert is finally evidence of an astronomical knowledge and of its association with some abstract, intangible meaning.

When one first asks the question, “Why does the Sun rise in the East?” there are two paths to follow for an answer. One path leads to science, the other leads to religion. For most of human history these paths ran side by side and were often indistinguishable; the answer, “Because the gods make it so,” covers a lot of phenomena and is difficult to refute. This is what we see in the stories of eclipses. Demons and deities eat the Sun and Moon and do so for reasons only known to them.

This is a tricky path to follow because any phenomenon we don’t understand can always be blamed on the gods or God. Why does the Sun rise in the East and not fall from the sky? It’s the work of the god Apollo and his gleaming chariot. Why do the Sun, Moon and stars all circle overhead? Because God has placed the Earth at the center of the Universe around which all things move. In recent years this reasoning has been extended to biological evolution by those who believe the process is too complex to have occurred without an Intelligent Designer.

This explanation is called the “God of the Gaps,” a term first coined by Henry Drummond, a nineteenth-century Scottish evangelist. Over time, as we discover more about our world, the gaps in our knowledge grow smaller as does our need for miraculous intervention to explain what is seen. This is neither fair to science nor religion. For the religious-minded individual who looks for physical proof that God is at work in the cosmos, the duties of His job grow less consequential with every year. God gets demoted from being the Prime Mover of the heavenly firmament to merely twiddling the knobs on the values of a few physical parameters. It’s unfair to science because once a miracle is invoked (in essence to say what is unknown is unknowable), all further investigation stops. After the “Miracle Card” is played there is no reason to keep testing hypotheses.

So while the question “why” can be fraught with metaphysical traps, science also asks “how” - a question that has answers open to direct experimentation. How long is a day? How can I learn this from the changing position of the Sun in the sky? How do the locations of the Sun and the stars at night define direction and the passage of seasons?

For careful observers, the sky becomes a calendar easily used to predict the changing seasons upon which individual and complex society’s survival (and ultimately civilization) depend. It is, perhaps, no coincidence that the first signs of agriculture are found at the roughly the same period in time as the Nubian graves.

This transition from a chaotic world of seemingly random changes to a predictable world of returning stars, rain and food, is embodied in the story of eclipses. Like the ancient Chinese astrologers who courted palace intrigue, or even Christopher Columbus saving his own skin, whoever could understand the motion of the heavens and thus predict an eclipse had the power to declare why they occurred and impart order on chaos. In a modern world where twice as many Americans believe there is some science to astrology than there are that accept evolution, we are still in thrall to the cycles and patterns of the sky.

…

My attention returns to the black Sun overhead. A single needle of light bursts forth into a second diamond ring even more beautiful than the first. The light has returned too quickly and the Sun is once more too bright to behold. It is over and my first thought is, "When can I see another?"

That I chase eclipses where my ancestors feared them is not to say that they were foolish to fear the sky. Thanks to science, while we no longer blame demons and believe in omens, we do understand that ancient terrors like comet impacts and nearby supernova explosions could kill most life on Earth (and in some instances already have). And while eclipses themselves are without danger, how we react to them could be if we fail to take care of rudimentary eye-protection. Far more importantly, eclipses remind us of how dependent we, and all life on Earth, are upon the single star that is our Sun.

Over the last three millennia eclipses have made the transition from terrifying omen, to scientific tool, to benign tourist attraction. We will follow that story as shamans and astrologers divined their true pattern and perfected their prediction, to the philosophers and scientists who discovered their cause and used them to measure the world and explore the universe beyond. Eclipses on this world and others now reveal we are just one planet in an ever-growing family of planets throughout this galaxy in an ever-expanding universe. This is the story of science and ourselves, the path down which totality leads.

"The Eclipse of the Moon and Sun is a Thing throughout the universal Contemplation of Nature most marvelous, and resembling a Prodigy, and shews the Magnitude and Shadow of these two Planets."

--Pliny, History of Nature, Book II, Chapter X

Chapter 2: Two Worlds One Sun

The Sun shines on Mars as it does on Earth. But for the last billion years only dusty red rocks have cast shadows there. Over the last decade something new has been lit by the far-away Sun, its shadow slowly changing with the hours. There's a sundial on Mars.

Actually, there are three. Since 2004, each NASA rover has possessed a sundial (a Marsdial) that I and a small team of artists and astronomers designed to cast shadows across a plate of concentric grey circles and four colored squares. Scientists on Earth know what color they are and so use them on Mars to calibrate the colors of the eyes with which our robotic explorers see. Periodically the cameras are pointed where the Sun should appear. If the Sun's disk appears perfectly centered in the photos, then the rover must be located and oriented exactly as thought. It's a tiny example of the scientific method in action; a test of our ideas versus the actuality.

Now a sundial on a nuclear spacecraft, navigating by the sky, may be an odd combination of old and new (and an equally strange way to begin a story of eclipses) but we have depended on the Sun and its motion for as long as we have been human, no matter what planet we're on.

On both worlds, North is where shadows point when the Sun is highest (at least in the northern hemisphere) and East and West are where the Sun rises and sets on the equinoxes. A day is defined by how long it takes our planet to turn once on its axis (while a Martian day of 24 hours and 40 minutes is called a *Sol*) and a month is the time our Moon takes to orbit once about the Earth - think “Moonth.” Each planet’s axis is tilted, so each planet experiences seasons over the course of a year defined by the period of its orbit around the Sun.

For thousands of years, on Earth at least, the proof that the calendars we made kept accurate track of the days, months, seasons and years, was in their ability to stay synchronized with these celestial cycles. Eclipses were a benchmark for checking if we were right. Since eclipses are caused by the shadows the Sun casts on both Earth and Moon, eclipses should happen only when all three worlds are aligned. Lunar eclipses occur only at Full Moon, when Moon and Sun are on opposite sides of the Earth, visible to everyone on the shadowed side of Earth. A solar eclipse occurs two weeks (or half an orbit) later, when the Moon passes between Sun and Earth and its shadow falls somewhere on our planet. Only those fortunate to stand in the relatively small shadow get to see a solar eclipse.

Since it takes the Moon a month to orbit the Earth, it stands to reason that every month should see a lunar eclipse at Full Moon and two weeks later a solar eclipse when the Moon is New.

How I wish this were so.

Sadly, the Moon’s orbit is tilted by five degrees to our own around the Sun. For the majority of New Moons, the Moon passes without notice slightly above or beneath the Sun, and two weeks later similarly misses the shadow our planet projects out into space. Only when the alignment is right do eclipses occur.

Let's see how a person, without spacecraft or computers, with no knowledge of planetary orbits, or even knowledge of planets at all would have figured this out. It's the story of the scientific method that begins with simple observation.

We begin with what we can see.

Our lives used to depend on paying close attention to the cycles of the Sun; they told us when to hunt, plant, and harvest. Today, hardly anyone notices. But you can still see them for yourself if you look closely. Over the course of a year from winter to summer the Sun rises in the East and sets in the West a little farther north along the horizon each day. From summer to winter the pattern reverses. The farther south the Sun rises and sets the less time it spends in the sky and the shorter days bring colder temperatures: winter occurs. The opposite is true in summer when the days are long and the Sun is high overhead. This only happens because of the axial tilt of the Earth as it rotates in space.

All over the Earth there are buildings, petroglyphs and geographic alignments that ancient peoples used to mark the passage of time and the changing of the seasons. Every sundial, including those on Mars, reveals the seasons by the lengthening shadow cast by its gnomon as the noonday Sun gets lower in the sky each winter.[*] On Earth, the most famous ancient "observatory" is Stonehenge in southern England. Its most prominent feature is two concentric rings of massive standing stones with horizontal lintels on top. These date to at least

[*] Mars, by chance, currently has the same axial tilt as the Earth and so goes through its seasons too.

2300 BCE[†], though other surrounding features are older and radiocarbon dating of burnt pine wood reveals people have been in the area since as far back as the eighth millennium BCE.

Outside these rings stands a large pointed boulder called the Heel Stone. Archaeological evidence indicates that a similar boulder was once set into the ground beside it. From the center of the stone rings towards the point between the Heel Stone and its missing twin an observer 2300 years ago would be looking precisely towards the rising Sun at its northernmost point on the horizon, on the longest day of the year: the summer solstice.

I have personally seen a similar alignment of Sun and structure much closer to home. There, on the spring and fall equinoxes, the last rays of the setting Sun shine down a long passage to a doorway into which a crystal has been set. Through it the Sun's light is refracted in a rainbow of color across a small vestibule and through a large room where it shines directly onto a square niche imbedded into a wall. It's a magical sight that I have been lucky to see every spring and fall for the last decade - the fact that it's the living room in my own house in no way diminishes its power to delight me. I live in my own personal Stonehenge, and in a country where many city streets were laid out by surveyors precisely along the cardinal directions, there is an excellent chance that you do too.

One such alignment occurs in the heart of New York City, where the streets are arranged in a grid angled 29 degrees east of north. Twenty-one days before and after the summer solstice (typically on or around May 28th and July 12th) the setting Sun shines perfectly down the canyon of streets on the island of Manhattan. It is a phenomenon the

[†] BCE means Before the Common Era, equivalent to BC.

astronomer Neil deGrasse Tyson calls Manhattanhenge and there are actually people who will brave evening rush-hour commuters to dash out in traffic and photograph this alignment of city and Sun.

Whether Stonehenge was initially planned as an observatory, was an observatory by accident like the one in my house and New York, or was never an observatory at all, the fact remains that it works as one today and so too does it mark the movement of the Moon. It takes the Moon 29.5 days to complete one *lunation* (the time between two Full Moons[‡]). One of Stonehenge's stone rings features 30 archways, one of which is half as wide as all the rest. Outside this ring are two more rings of holes, one with 29, the other with 30. Is either of these symbolic of the Moon's 29.5-day lunation?[16] With enough boulders and holes, almost any astronomical connection can be found, but it is intriguing nevertheless.

What is known with certainty is that cultures all over the world continue to mark time by the sunrise, including the Hopi in the American Southwest, whose ancestors, the Chacoans built "Great Houses" that appear to have similar solar alignments of stones and pictographs as Stonehenge.[17]

In addition to where the Sun rises each day, the Sun also moves against the background stars with the seasons (and thus we see different stars at night in Summer and Fall). The path the Sun follows across these stars defines the plane of the Earth's orbit and is called the *ecliptic*. It crosses twelve prominent constellations through which the Sun passes approximately one every month. Perhaps you've heard of these constellations: Libra, Scorpius, Sagittarius, and so

[‡] This is slightly longer than the Moon's orbit around the Earth relative to the stars (27.3 days) since the Earth's motion around the Sun causes the Moon to have to go a little bit farther to once more align with the Sun.

on. Western astrology is based on the premise that whichever of these the Sun is in front of on the day you were born has some influence on your personality and fate. The prevalence of daily horoscopes says a lot about astrology's popularity if nothing about its accuracy.

Because of the Moon's orbital tilt, the Moon spends half the month above the ecliptic and half below. Where the Moon crosses the ecliptic marks a *node* (Latin for "knot"). As viewed from the Earth there are two nodes on either side of the celestial sphere. Through one the Moon passes upwards through the ecliptic, through the other it passes back down. When Moon and Sun both cross a node together, eclipses happen. Twice each year the Sun is close to a node when the Moon goes sailing by, and thus twice each year we see eclipses.

<<Insert Eclipses.tif here>>

If the Sun and Moon were mere points of light, they would have to perfectly cross the node at precisely the same instant for an eclipse to occur. But the Moon and Sun both span about half a degree on the sky. This produces a period of about 34 days, called an eclipse season, during which each body passes close enough to a node at Full or New Moon for an eclipse to occur, even if only partially.[18]

The direction the Moon's orbit tilts slowly changes over an 18.6-year period. The positions of the nodes therefore drift westward along the ecliptic and so the Sun and Moon encounter them slightly more often than every six months. Lunar eclipses therefore happen either every 5 or 6 lunations (every 148 or 177 days) with a solar eclipse occurring two weeks before or after each one.

We see ancient knowledge of this pairing between lunar and solar eclipses in a narrative from the Pomo people, a Native American tribe in Northern California. They explain eclipses by a bear that walks the Milky Way. When he comes upon the Sun, the Sun refuses to step out of the way. For his impertinence, the two wrestle and the great bear bites the Sun; “Sun got bit bear” is the meaning of the word the Pomo used to describe an eclipse. After his battle with the Sun, the bear comes upon the Sun’s sister: Moon. She too, refuses to step aside and again there is a great fight in the sky.[19]

Back in Stonehenge there are 56 “Aubrey Holes” in a giant ring around the standing stones. The British astronomer Fred Hoyle hypothesized that these pits could be used to keep track of when lunar and solar eclipses occur. By periodically moving a series of four stones from one hole to another at different rates, one for the Moon, one for the Sun, and two stones always kept a half circle apart representing the nodes, an eclipse is possible when the Moon and Sun stones fall on either the same node stone (a solar eclipse) or opposite node stones (a lunar eclipse). With little more than these a person could keep track of the phase of the Moon, and the times of eclipses under Britain’s cloudy skies and remain remarkably accurate for years.[20]

The Mayans too were aware of eclipse seasons. One of the few remaining Mayan books, called the Dresden Codex after the city where it now resides, reveals multiple entries warning of 148- and 177-day intervals.[21] Helpfully, the Mayan artist/author/astronomer who composed each page placed an elaborate half-black and half-white figure at the center of each numerical tally. One such figure reveals an enormous snake about to devour this possibly eclipsed Sun or Moon.

There are other numbers that reveal ancient knowledge of solar eclipses over time. Total solar eclipses can only happen at New Moon (every 29.53 days), during eclipse seasons (every 173.3 days), when the Moon is nearest to the Earth in its non-circular orbit (every 27.3 days). How often does it take for each of these cycles of different lengths to come around again like hands on a clock? It happens that every 6,585.3 days (18 years, 11 days and 8 hours) the Moon will fully eclipse the Sun at the same node, at the same time of year, and with the Sun and Moon in nearly the same constellations as it did before. For no shorter period of time do all of these three cycles of differing lengths coincide.[§]

This is the Saros cycle.

Eclipses separated by this amount of time are said to be of the same Saros, and each Saros is numbered. The first total solar eclipse I saw was of Saros 145 on August 11, 1999 in Hungary. The eclipse in the United States on August 21, 2017 is 18 years and 11 days later (if it were visible in Hungary it would be August 22) and therefore must be Saros 145 again.

The difference in location between Europe and North America is due entirely to the remaining 8 hours (0.3 days) in the Saros cycle. Between two eclipses of the same Saros, the extra 8 hours means the Earth will have rotated an extra third of its day, moving the eclipse a third of the way around the Earth to the west.

[§] 6,585.3 days is exactly 223 lunations, 38 eclipse seasons, and 239 orbits of the Moon.

After 3 cycles of 18 years (called an *Exeligmos*) totality once again happens at the same longitude on Earth. But now 33 extra days have passed and the Sun is a little higher (or lower) in the sky depending upon the season, shifting the path of totality a little farther north or south depending on whether the Moon is ascending or descending through the node. Over time, total eclipses of a single Saros will begin at one pole of the Earth, slowly leave tracks spiraling around the planet, cross the equator, and after 1,300 years "retire" the Saros as it produces its last eclipse at the other pole. The solar eclipse of August 21, 2017 is the 6th total eclipse of Saros 145. There will be 35 more before it is done with us in 2143.[22]

To notice cycles that repeat only after nearly decades hints at cooperation over generations requiring careful record keeping. The first unambiguous record of the Saros cycle, comes from the Chaldeans, who in 626 BCE ruled an empire containing the ancient city of Babylon and extending from the Mediterranean eastward to the Persian Gulf and from the Red Sea northward into modern Turkey. What we know of their astronomy comes largely from the writing of later Greek astronomers, and a handful of small clay tablets full of closely spaced cuneiform markings that record the names of kings and dates of their reigns.

For centuries, possibly extending back to the 8th century BCE, they kept daily astronomical diaries recording the positions of the Moon and planets relative to the stars. As far back as the 7th century these daily diaries also kept track of the weather, and economic and political events.[23] I can imagine a Chaldean astronomer making note of everything he saw each day in hopes of identifying patterns that might indicate what phenomena bode well for the king, and what omens or occurrences were bad.

One pattern that becomes obvious in what are now referred to as the Saros Cycle Texts are multiple tables of kings' reigns and dates arranged in columns of 5 and 6 lunar months with columns precisely laid out 223 lunar months apart. 223 months add up to 18 years. Though no mention is made of eclipses, modern calculations show almost perfect agreement with lunar eclipses visible in Babylon during that time.[24] The fact that these dates were given with the names of known kings implies, of course, that the tablets were written after these eclipses would have come to pass.

What evidence is there that after noticing these cycles, ancient astronomers made the connections necessary to predict their future occurrence? Today we would refer to that as forming an hypothesis. If similar eclipses happen every 18 years, then the next should occur… when?

The earliest account of a solar eclipse's prediction at an exact time and place is from the Greek historian Herodotus. In his *Histories*, written around 450 BCE, he describes a five-year-long war between the Lydians and Medes a hundred years earlier in what is now Turkey.

> In this war they brought about a battle by night; and the engagement came about in the sixth year when they were still contending with each other at war on an equal basis, when it happened, as the battle was beginning, that day suddenly became night. (Thales the Milesian predicted to the Ionians this change [of day to night] would come about, setting beforehand the favorable period in which the ominous event did indeed happen.) When the Lydians and Medes saw

> it become night instead of day, they quit the battle and rather made haste on both sides that peace came about.[25]

Historians and astronomers, as early as Pliny the Elder in 77 CE, have interpreted this "day turned to night" as a solar eclipse.[26] Unfortunately, the only solar eclipse that appears to have occurred during this time, in the correct place (28 May, 585 BCE), would have been partial from the plains of the ancient Anatolian capital of the Medes, certainly not enough to have turned "day to night."

Nevertheless, Thales could have been aware of the Saros cycle and heard of its previous occurrence on May 18, 603 BCE over Egypt and the Persian Gulf. Aware of the Saros cycle, Thales would have known the day such another eclipse would have been likely, though it is unlikely he would have known where.

Still, there are astronomers who would like to see the site of the ancient battle declared a World Astronomical Heritage site to help preserve its place in the history of science.[27] At the very least, whether Thales actually predicted a solar eclipse or the story is a complete myth, the fact that writers of the time believed it was possible to predict an eclipse means that these amazing spectacles were no longer the results of demons or gods, but firmly in the realm of natural phenomena.[28]

Chinese court astrologers, like their colleagues in Babylon, recorded virtually every eclipse over a period of more than 3000 years.[29] If an eclipse occurred as predicted it meant you understood the periods of the Sun, Moon, and Earth and thus your calendar of months and years accurately reflected the seasons, and successfully identified the dates of holy days important to unite your people, praise your rulers, and appease the gods.

Holidays like Christmas that occur on the same date every year are essentially tied to the period of the Sun (or, more accurately, the period of the Earth *around* the Sun). But each of the three main monotheistic religions has holidays that float from date to date because they are tied to the period of the Moon. Ramadan is the ninth month of the Islamic calendar where each month begins at the first sighting of the crescent new Moon after sunset.

Passover, like Ramadan, is also tied to the Moon. It occurs on the 15th day of the Jewish month of Nisan, which like in the Islamic calendar begins at dusk with the new moon. Since 15 days is almost equal to half of the lunar cycle, Passover occurs at the full moon, and to keep it in the spring it has become the first Full Moon after the Spring Equinox.

In Christian tradition, the last supper of Jesus was a Passover Seder, after which followed the crucifixion and resurrection. So Easter is now set as the first Sunday after the first Full Moon after the Spring Equinox.

In our modern world we may no longer worship the Sun and Moon, but our worldwide religions are still tied intimately to their motions. At the very least, each year individuals celebrate life's victories and tragedies by the number of trips around the Sun that we have made since their occurrence. Ours is a world enumerated, regimented, illuminated and measured by astronomy.

But what do these millennia of observations, these innumerable cycles of Moon and Sun, traveling nodes, recurring eclipses, and repeating Saros reveal about our Universe? If we derive our notions of direction from the Sun and stars, then what do the Sun and stars tell us about our place among them? And how do we know they are correct?

Stand in the Piazza San Marco at the heart of Venice and a giant model of the heavens in beautiful gold and lapis blue tolls the hours from the Torre dell'Orologio. This spectacular clock dates from the 1490s and shows a golden Earth at the center of its massive wheel. Around it spins the Moon, its half blue and half gold sphere slowly rotating with the lunar phases over a period of 29-and-a-half days. Farther out, an ornate golden Sun glides across the 12 constellations of the zodiac, in keeping with its actual position among the stars. Only in the very last ring are 24 giant roman numerals arrayed revealing the time of day by their alignment with the Sun.

During the Middle Ages clocks like these could be found all over Europe, although few as grand. For those who were no longer attuned to the patterns of the sky (including the modern crush of tourists madly snapping photos of every pigeon and gondolier in Venice) they served as a direct visual reminder in the heart of each community that there was, astrologically speaking, a comforting order to life.

The other thing these clocks provided was a model of the Universe in which we are reassuringly at its center. Around us the Moon, Sun, and planets (in that order) move against the background stars. For the natural philosophers concerned with understanding the nature of reality (who would one day be known as scientists) eclipses were a means to an end. They were a tool to use to understand if our model of the universe was correct.

The Greek philosopher Aristotle saw that during a lunar eclipse the shadow that the Earth projects on the Moon is always curved. From this he reasoned the Earth must be round (two thousand years before Columbus). Since we do not feel the Earth move under our feet (nor are we blown off the Earth like a rider's hat on horseback) he reasoned we alone must be stationary. The Moon, Sun, planets and stars must orb it the Earth in perfectly uniform circles because the circle is the most perfect shape and the only logical place for the center of the Universe to be is at the center of these circles. We are therefore the center of the Universe.

This geocentric (Earth-centered) model of the Universe explained a lot and in many ways is a very good scientific theory. It explains what most of us see on a daily basis and ties together a variety of phenomena. It even does an excellent job of predicting what we'll see in the future. Go to any planetarium and you can see the Universe circle around you on the surface of a giant celestial sphere, just as it appears in reality. It works, but that doesn't change the fact that it is wrong (although a 2014 survey by the National Science Foundation reveals 1 in 4 Americans is not aware of that).[30]

Even during Aristotle's day, astronomers noticed that the planets didn't seem to move across the background stars in a simple way. We can see this today, most easily when watching Mars. Every 26 months Mars completes a loop-the-loop across the background stars: stopping, moving backwards, then stopping and moving forwards again. Each of the planets performs a similar type of retrograde motion at some point in its orbit. Yet Aristotle and others refused to reject a good idea for unfortunate observations: the Heavens were perfect and so were circles. The solution was to add complicated layers of overlapping circles to each planet's orbit causing them to spiral along in their paths through the heavens.

In the second century AD, the mathematical astronomer Claudius Ptolemaeus (better known as Ptolemy) of ancient Alexandria in Egypt, took the geocentric model and using the ancient eclipse observations of the Babylonians made detailed calculations for predicting the positions of the Moon, Sun and planets within this complex geocentric system. His *Almagest* ("great compilation") published in 150 CE was the definitive word on what every astronomer needed to know up to the time of Galileo. Think about that for a moment: for 1500 years this was the most widely used astronomy textbook in the history of the western world.

During this time it was unheard of to question the correctness of either Ptolemy or Aristotle before him. Add to their infallibility the fact that the new Christian Church had adopted their Earth-centered universe as proof of our special status in God's Creation, and any question of their astronomy took on the added burden of heresy. Without the freedom to question anyone's conclusions, new discoveries die and a single astronomy text can hold sway for over a millenium.

But there were those who rejected this philosophy. They believed that no matter how elegant the hypothesis, it's the experiment that determines what's right.

Almost forgotten in the West today is the work of the 10th Century Islamic mathematician and scientist Ibn Al-Haytham. From him we have one of the earliest statements of what today we recognize as the scientific method:

> [T]he seeker after the truth is not one who studies the writings of the ancients and, following his natural disposition, puts his trust in them, but rather the one who suspects his faith in them and questions what he gathers from them, the one who submits to argument and demonstration, and not to the sayings of a human being whose nature is fraught with all kinds of imperfection and deficiency. Thus the duty of the man who investigates the writings of scientists, if learning the truth is his goal, is to make himself an enemy of all that he reads, and, applying his mind to the core and margins of its content, attack it from every side. He should also suspect himself as he performs his critical examination of it, so that he may avoid falling into either prejudice or leniency.[31]

Abū ʿAlī al-Ḥasan ibn al-Ḥasan ibn al-Haytham, known in the West as Alhazen, was born in Basra in 965 AD in what is now Iraq. While learning in Europe was stifled during the Middle Ages, with even the learning of the ancient Greeks suppressed, the acquisition of knowledge was considered an Islamic virtue. Early in life he turned his mind to the study of religion but was dismayed by its many contradictions and conflict. Believing that these disagreements lay in human interpretation and misunderstanding he turned his eyes instead to mathematics. In the world of numbers, no matter what your beliefs, no matter where you were from, mathematics always worked. The fact that he thought mathematics could be used to describe God's creation was a revolutionary idea: one that would come to be called physics.

Alhazen skills became known beyond Basra when he claimed to have calculated how to damn the Nile River that flooded each year causing massive destruction and death. Unfortunately, when the powerful Caliph of Egypt had Alhazen brought to him and was shown the mighty river first hand, Alhazen realized he was wrong. This was a difficult spot to be in with a Caliph, who though a patron of the sciences, was also a supremely dangerous man. What could you possibly do?

In the end Alhazen did the only logical thing: he pretended to go insane.

The Caliph had him confined to a house where he stayed for the next ten years, freed only upon the Caliph's death. Though his body was imprisoned, his mind was free to work on the mathematical exploration of the world around him: specifically the questions of sight and the nature of the bright Egyptian light pouring in through his windows.

In *The Book of Optics*, written during his time of home confinement, Alhazen used his experiments to "dispel the prevailing confusion" of how we see (and what we see) by rejecting the writings of authority and instead beginning with what was actually known and observed. From that starting place he used mathematics and logical induction to develop laws of optics and vision that could actually be tested.

He refuted the prevailing claim (by Ptolemy and others) that we see by our eyes sending out some "flux" that interacts with the world then reflects back to our eyes.[32] If the eye was going to depend on receiving information from its surroundings, why not save a step and just propose that objects emit or reflect light, and the eye is merely the organ by which we receive that light? Experimentally it makes sense, since it is easily demonstrable that the eye can be hurt by looking at incredibly bright sources, like the Sun (the perennial fear during eclipses).

During one such solar eclipse a hole in his window shade projected the crescent image of the partially covered Sun into his darkened room. Experimenting with candles and pinholes, he discovered how to calculate the size and positions of the images they projected onto screens, thus inventing the camera obscura. Today, a popular (and safe) method of observing a partial solar eclipse is still by building a box with a pinhole in one end and a screen at the other.[33]

Today, though physics students around the world still use his methods of drawing light rays, most of us in the West aren't very familiar with Alhazen or much of the role that early Islamic scholars played in Europe's rise out of its intellectual Dark Ages. But we can see this influence every night when we look at the sky. Our bright stars are still known by their Arabic names: Aldeberan, Altair, Alcor, and Alberio. Their *altitudes* and *azimuths* (which determine their position in the sky) are Arabic in origin and are represented by Arabic numerals including the very concept of zero. The manipulation of these new numbers gave us *algebra*.

The Latin translation of Alhazen's *Optics* was read widely in West. But while European scholars would credit Alhazen's discoveries in their own research, credit for developing the method that achieved those results was not. As a result, when we think of the modern scientific method and its role in discovery it is Johannes Kepler, living 600 years after Alhazen, who most often comes to mind.

Kepler was well aware of Alhazen's work and was fortunate to be living in a time when brave thinkers dared to finally question the universe of Aristotle and Ptolemy (and by extension the Church). Alhazen had recognized that Ptolemy's universe of crystal spheres spinning within spheres, turning with uniform circular motions, was too complex to work in reality.

> The undoubted truth is that there exist for the planetary motions true and constant configurations from which no impossibilities or contradictions follow; they are not the same as the configurations asserted by Ptolemy; and Ptolemy neither grasped them nor did his understanding get to imagine what they truly are.[34]

But what that truth was, even Alhazen had no idea. Six hundred years later, the heliocentric model of the solar system proposed by Nicholas Copernicus and championed by a new generation of experiment-minded scientists like Kepler and Galileo, proved vastly more simple than Ptolemy's complex cycles upon cycles. If all the planets, including the Earth, went around the Sun, then retrograde motion was simply the effect of the Earth passing other planets. Day and night were nothing more than the Earth spinning on its axis.

But what determined the order of the planets and why was each found where it was? Kepler thought he'd discovered the solution by hypothesizing that the space between each planet's orbit was determined by the shapes of five perfect Pythagorean solids. Kepler was instantly famous for reading the celestial blueprints of God.

Yet, just like Alhazen before him, Kepler believed that the ultimate arbiter of what was true was what was seen. Sadly, when applied to Mars: what was seen was not what he predicted. His model was exceptionally beautiful but unquestionably wrong. The statesman and scientist Benjamin Franklin once wrote, “In going on with these Experiments, how many pretty systems do we build, which we soon find ourselves oblig'd to destroy!” How painful it must have been for Kepler to discard what had made him so well known, but in the act of intellectual honesty that has become one of the defining examples of the scientific method, he threw it all away until it was right, though it took him a decade to do so.

What he finally found were three laws of planetary motion that though constructed specifically for the orbit of Mars, are now known to apply to all the planets about the Sun, the Moon around the Earth, and every star in orbit around any galaxy in space. They are:

1. All planets orbit the Sun in an ellipse with the Sun located off center at one focus (a circle is just a special case of an ellipse).

The Moon orbits the Earth in an ellipse. This is why we occasionally have so-called *supermoons* where a Full Moon occurs when the Moon is at its closest to us. This is also why a solar eclipse two weeks before or after a supermoon is an annular eclipse. The Moon is now at its most distant point from the Earth and too small to fully cover the disk of the Sun.

2. A planet travels around its orbit at a rate that will always sweep out equal areas of space in equal amounts of time.

In other words, planets speed up when they are closest to the Sun, and slow down when they are farther away.

3. The time it takes the planet to complete one orbit around the Sun is related to the average distance between the planet and Sun.

The constant that relates them is a product of nothing more than their mass. As a result wherever we see two or more objects in orbit around one another somewhere in the Universe we can measure their mass. The discovery of supermassive blackholes at the center of galaxies and that the mysterious dark matter that is the overwhelming component of the Universe is entirely thanks to Kepler’s Third Law, and the scientific method that produced it.

And what is the proof these laws are correct?

Engineers from one world have launched spacecraft to another, each following its own “Keplerian” orbit between the worlds. One of those is roving across Mars exploring magnificent mountains and valleys using a sundial to track the Sun and help photograph what it sees. Like that clock in Venice, each Marsdial bears a small heliocentric solar system on its face with a representation of the Sun at its center surrounded by the elliptical orbits of Earth and Mars.

On August 19, 2013, NASA controllers had one of the rovers turn its cameras towards the Sun. Though they had performed this maneuver many times before to verify their location, on this day, at precisely the moment predicted by Kepler’s Laws, a tiny notch in the Sun appeared. Just a small one at first, but as the rover continued to snap images, an irregular blob began to appear against the glare of the Sun’s disk. Eventually, the strange silhouette stood out perfectly against the surrounding Sun: the silhouette of Phobos, a moon of Mars. After five thousand years of marveling at solar eclipses on Earth, of deducing their cycles, predicting their appearances, and revising our hypotheses for why they occur, at that instant our robot emissaries stood in the shadow of a Martian moon and beheld an eclipse on an alien world.

"On Thursday, February 29, 1504, when I was in the Indies on the island of Jamaica in the port which is called Santa Gloria, … there was an eclipse of the Moon, and because the beginning was before the Sun set, I was able to note only the end, when the Moon had just returned to its brightness, and this was most surely after two and one-half hours of the night had passed by, five sandglasses most certainly."

--Christopher Columbus, Libro de las profecias

Chapter 3: Shadows Across a Sea of Stars

As a kid visiting the Oregon coast I often wondered, "How wide is the ocean and what is there beyond the horizon?" As I grew older and turned my sights to the night sky, I wondered something very similar, "How far away are the stars and are there other planets there?" Of course, even though very few of us have ever circumnavigated the globe, and no human being has ever ventured into space beyond the Moon, we do know some of the answers to these questions. Immensity isn't immeasurable. While these vast numbers may make little sense in our daily lives, we at least know they are known.

Consider what it must have been like to live in a world where this was not true; where the sense of immeasurability, the certainty of the unfathomable, was commonplace and the thought that the world could be known was new.

The philosopher Anaxagoras was born about 500 BCE in the eastern Mediterranean on what is now coast of Turkey. It was a time when philosophy had only recently turned its eye to the natural world. Less than a hundred years before, Thales of Miletus supposedly predicted a solar eclipse that ended a war, thus implying that our world is predictable and events are not just the random whims of the gods.

In such a world of physical phenomena Anaxagoras was the first, as far as we know, to understand that eclipses occur when one heavenly body blocks the light from another. This rejection of gods and dragons as the causes of eclipses is a revolutionary thought by itself, but Anaxagoras took it further. If solar eclipses happen only because the Earth has moved into the shadow of the Moon, then the size of the shadow must tell us something about the size of the Moon. Additionally, since the Moon covers the Sun, the Sun must be farther away. Yet to appear nearly the same size, the Sun must be larger still.

The logical conclusion from these observations is that the shadow cast by the Moon upon the Earth must be shaped like a cone where its base is as large as the Moon and tapers towards the Earth. Measure the extent of the shadow sweeping across the Earth and you know the Moon must be at least as big and the Sun even larger still. This is the power of scientific thought, because if eclipses occur when a demon devours the Sun, there is no reason to believe that any measurement we make here on Earth should reveal the demon’s size.

On February 17, 478 BCE, the shadow of an annular eclipse spread across the Mediterranean Sea and crossed the Greek islands of the Peloponnesus, creating a “ring of fire” in the sky, visible for almost six minutes. Anaxagoras, living in Athens, would have been living along the midline of annularity and surely would have seen the sight, but in only six minutes would have had no way to measure the size of the shadow across the countryside.

In a stroke of genius, Anaxagoras found the answer by simply going down to the seashore and asking arriving sailors what they had seen. At that time, Athens was the center of trade for ships from all over the eastern Mediterranean. If sailors at sea had seen a ring of fire in the sky, they'd remember where they were when they saw it. The locations of all those who did and did not see the spectacle revealed the extent of the shadow across the surrounding seascape.[35] Without going farther than the local seaport, Anaxagoras measured the Moon.

While we do not have Anaxagoras' own words as to what he concluded, we do have the writing of those who came after. Five hundred years later, the Roman historian Plutarch wrote, "Anaxagoras [says that the moon] is as large as the Peloponnesus,"[36] while Hippolytus of Rome, a third-century father of the Christian Church wrote in his *Refutation of All Heresies* that, according to Anaxagoras, "The sun exceeds the Peloponnesus in size.[37]"

The story of Anaxagoras standing on the beach measuring the size of the Moon is the story of astronomy. We are a species confined to our own world (or at best, our own solar system). Yet from this one vantage spot we have had to survey the Universe on whose shores we stand. To do so has required eclipses, transits (when small things move in front of big things), and occultations (when big things move in front of small). Astronomy is made possible, in part, by the shadows that span the stars.

Standing on the celestial seashore, let's pace out our Universe, starting from the world we see by day to the stars we see at night. At each step we will learn where we are and how far we've come.

What is the simplest way to measure distance? Walking works. We measure it in feet (at least in the United States) and it's no accident a foot is about the size of our own feet. How far can a person measure precisely by walking? In the Mediterranean of the third century BCE, *bematists* were men who could walk at a precise and constant pace and it was they who could be paid to accurately measure long distances across the landscape.[38]

One place their services were in use was along the Egyptian Nile that each year flooded and erased what few features marked the boundaries between fields. Bematists were particularly suited to pace off the long, flat, featureless landscape south from Alexandria to Syene, which they found to be 5000 *stadia* apart (around 520 modern miles, depending on the exact definition of *stadia* used). We know this distance because sometime around 240 BCE, Eratosthenes of Cyrene, the chief librarian of Alexandria, used it to find the size of the world.

Eratosthenes had heard that on the summer solstice the noonday Sun shown straight down a well in Syene, casting no shadow. He knew no such thing happened in Alexandria on that or any other day, so one of two possibilities must be true: either the Earth was flat and the Sun was very close (much like a cloud that hangs over one town appears far to the south as seen from another), or, the Sun is far away and the Earth is round.

The answer can be found by looking at the Moon during a lunar eclipse. Aristotle himself noted a century before Eratosthenes' experiment that during every lunar eclipse the Earth's shadow looks like a circle. No matter where the eclipse occurs in the sky, the shadow the Earth casts never changes. The only figure that looks the same from any direction is a sphere.

Since the Earth's shadow already confirmed the Earth was round, the only explanation for the different lengths of the Sun's shadows in Syene and Alexandria was the curvature of the Earth. From the difference in shadows, and the distance between them, the circumference of the Earth is revealed.

Here's how this works: imagine that one day in the Hawaiian islands, you notice your own shadow directly at your feet while flag poles and tiki totems cast no shadows at all. You look overhead and there is the Sun at the zenith, the highest point in the sky. Hawaiians call it *Lahaina Noon* after the name of a town on the island of Maui where this happens twice each year. You immediately call your friend in Puerto Rico who is unimpressed, as right at that instant she is watching a spectacular sunset with the Sun touching the waters of the Caribbean on the horizon. The difference in position of the Sun in the sky between the two of you is 90^o, exactly one quarter of a circle ($90^o/360^o$ = ¼). You must therefore be a quarter of a circle, a quarter of the Earth's circumference, away from one another. Measure the distance between you, multiply by four, and you know the full distance around the Earth.

This is precisely what Eratosthenes did. The different lengths of the shadows meant a difference of 7.2 degrees between the position of the Sun in Syene and Alexandria. This difference meant the two cities were $7.2^o/360^o$ or 1/50th of the way around the Earth from one another. Since the distance on foot between them was 5000 stadia, the entire Earth must be 250,000 stadia around.

Depending on the precise length of a stadia, Eratosthenes' value for the Earth's circumference may be as close as 2% of the actual value we now know.[39] More important than this precision, however, is the very idea that it could be done.

For Eratosthenes' method to work it was vital that two distant observers be looking at the same thing (the Sun, in this case) at exactly the same time and see its different position forming different shadows in different places. But how can we be sure that any two people on Earth are looking at the same thing in the sky at exactly the same moment? Simple: use a lunar eclipse.

As early as 150 BCE, the astronomer Hipparchus suggested using lunar eclipses to determine longitude (locations east and west) around the Mediterranean. To do this accurately, though, required paying attention to time.

The reason why is that the Earth is a sphere that is constantly spinning. The moment at which the Sun is highest in the sky (local noon) changes as you move westward around the world. It takes a full 24 hours to turn 360^o, so the Earth must turn 15^o every hour. When the Moon moves into the shadow of the Earth and is eclipsed, everyone on the night-side of Earth sees it happen at the same instant. The *local time* at which each person sees the eclipse occur depends solely on their location east-west across the nighttime Earth. If I see the eclipse begin at 10:00 in the evening while my friend sees it start at 1:00 in the morning, the difference in local time is three hours. Since every hour of difference means we are 15^o of longitude apart, a difference of three hours places us 45^o around the world from one another.

Once Eratosthenes measured how many miles (or stadia) there are per degree, then a difference in local time between two observers becomes a difference in miles around the planet. For this reason an especially valuable tool for navigation would be some means of precisely calculating the times of eclipses in a known location for comparison with local observations. Just such an eclipse calculator was found in 1901 in the remains of a shipwreck off the Greek island of Antikythera. What is now called the Antikythera Device is an intricate mechanism of bronze gears that have been shown to calculate various astronomical quantities, including the position of the Sun against the zodiac (and thus the date), the phase of the Moon, and the date and time of solar and lunar eclipses using dials that appear to track the Saros and Exeligmos cycles of eclipses.[40] From analyzing the patterns of eclipses they predict and the dates of known eclipses in the ancient world, scholars have dated the device to sometime around the third century BCE, 1500 years before metal gears would once more be used in Europe to make clocks for telling time and modeling the heavens.[41]

It's unknown if there was ever more than a single calculator like the Antikythera Device, but in the centuries that followed navigators set sail with books and scrolls filled with detailed astronomical tables filled with the positions of Sun, Moon, and stars and the times of their eclipses. Christopher Columbus was just such a navigator.

Thanks to Washington Irving's 1828 biography of Columbus, most Americans learn that it was Columbus, alone, who believed the world was round and that the East could be reached by sailing west. In truth, it wasn't his beliefs about the shape, but rather the size of the Earth which set Columbus apart from his contemporaries.[42]

By a combination of wishful thinking, selective observations, and a confusion of Roman for Arabic miles, Columbus believed the Earth was a quarter smaller than Eratosthenes had found. He also thought the distance from Europe to Asia was so great, greater than anyone else believed, that the open sea between the Canary Islands off the coast of Africa and Japan was no more than 2400 nautical miles (only 1/6th the way around the world). The actual distance along the route he had planned is closer to 10,600 nautical miles, over half way around and pretty close to what the best minds of the day had calculated.[43]

It's no wonder everyone else thought he was mad. By all rights Columbus should have been sailing out into an ocean spanning over half the planet; it was only by luck that he found the Caribbean approximately where he expected to find the eastern reaches of Asia. It must have been so confusing when nothing he found was as he expected.

On his fourth voyage to the Caribbean Columbus found himself shipwrecked on the north coast of Jamaica. He used a lunar eclipse predicted in his almanac to scare the local populace and save his crew from starvation. But the eclipse on the night of February 29th, 1504 should have also revealed his mistake of where he actually was. Columbus thought he was somewhere off the coast of China, 107^{o} of longitude from Spain across the sea.[44] Since the world turns 15^{o} per hour, there should be about 7 hours and 15 minutes of difference between his local time and clocks back in Spain. In reality Columbus was only about 71^{o} west of Spain and so the difference in time would have been about 4 hours and 44 minutes.[45]

Through a combination of error in reading his almanac and the difficulties of keeping accurate local time using sand in an hour-glass, the eclipsed Moon rose over the eastern ocean almost exactly when he expected.[46] Had he really been 7 hours west from Spain, Columbus would have discovered Arizona. Columbus would go to his grave never knowing how lost he actually was. Not until Sir Walter Raleigh observed a lunar eclipse from Roanoke Island off the coast of Virginia in 1584 was the width of the Atlantic Ocean actually known.

Over the next three hundred years explorers continued to map North America using the sky. President Thomas Jefferson had Captains Meriwether Lewis and William Clark trained in astronomy to find their way across the continent.[47] On the night of January 14, 1805, in the village of the Mandan tribe in modern North Dakota, Lewis wrote in his journal:

> Observed an Eclips [sic] of the Moon. I had no other glass to assist me in this observation but a small refracting telescope belonging to my sextant, which however was of considerable service, as it enabled me to define the edge of the moon's immage [sic] with much more precision than I could have done with the natural eye.[48]

Using his astronomical almanacs, Lewis calculated his correct longitude to within 85 miles.[49]

Solar eclipses were even better tools for finding one's locations (owing to the dramatically instant onset of totality). The logs of 18th and 19th century solar eclipse expeditions are full of detailed, and rather tedious, tables of times and positions on the sky of eclipses against which the towns, rivers and mountains of continent-wide countries and globe-spanning empires were measured.

In 1869, Major John Wesley Powell and the men under his command became the first Europeans (and possibly first people ever) to navigate the Colorado River by boat and to map the last remaining blank spots in America. Powell's almanac predicted a solar eclipse on their journey but the day of the eclipse found the one-armed Civil War veteran at the bottom of the 2000-foot-deep Grand Canyon. George Young Bradley, boatman and geologist on the expedition wrote in his private journal that:

> Major & brother have climbed the mountain to observe the eclipse but think it almost or quite a total failure for it has rained almost or quite all the P.M. We could see the sun from camp when it was about half covered but it clouded immediately and before the cloud passed it was behind the bluffs. Major has not come in. Cannot tell whether he saw it or not. If he did we shall have our Longitude.[50]

Thanks to the typical summer monsoon clouds of the canyon country, it didn't clear and so his exact position would remain a mystery. If only the Earth had more moons, making for more frequent eclipses.

Sadly the Earth doesn't, but Jupiter does.

In January of 1610, Galileo had discovered four large moons around Jupiter, each one about the same size as our own Moon. The closest of these Galilean satellites, Io, orbits Jupiter once every 1.8 days and each time around is eclipsed, or more accurately occulted, by Jupiter's disk. Galileo himself realized that these occultations happened with such regularity that they could be used to find longitude on Earth. Construct a table of eclipse times as visible from Paris, for instance, and Jupiter turns into a tiny clock in the sky. No matter where you may be, observe a Jovian eclipse through a telescope and you immediately know the time back in Paris to compare with your own.

When King Louis XIV sought to make France the world leader of science in the late 1600s, he employed astronomers to use Jupiter's moons to make the world's most precise map of France. His astronomers traveled all over the country with their telescopes, recording their Jovian eclipses and calculating their distance from Paris. It was the most accurate map ever produced up to that time, and it revealed that many roads and distances were actually shorter than had been believed. Dava Sobel in her history of longitude writes that upon seeing the new map the king "complained that he was losing more territory to his astronomers than to his enemies."[51]

In 1793, Alexander MacKenzie and his team of ten men lugged a telescope across the breadth of what would become Canada (a decade before Lewis and Clark would do the same in the U.S.) and found their location along the Pacific Coast by seeing the tiny eclipse of Jupiter's largest moon Ganymede.[52]

Over a decade later, as Lewis and Clark were on their way back from the Pacific, President Thomas Jefferson commanded Lieutenant Zebulon Pike to determine the position of the Rocky Mountains in Colorado by means of Jupiter's moons, even though the Rockies were still under Spanish rule.[53] Spanish troops captured Pike and his men in 1806 and before letting them go, confiscated all their astronomical observations. Pike's Peak in Colorado is named in his honor and, fittingly, anyone now can drive to its top, navigated there by a GPS unit triangulating its position from satellites in space. Two hundred years later we still know where we are and where we are going by means of astronomy.

These methods using triangulation and eclipse aren't limited to distances here on Earth. The same techniques Anaxagoras used so long ago reveal the cosmos is much larger than anyone had ever believed. To understand how big, let us turn our eyes back to the shadow our planet casts and look again at a lunar eclipse.

Two hundred years after Anaxagoras wrote that the Moon was larger than the Peloponnesus islands, another Greek philosopher, Aristarchus, realized that when the Moon entered the Earth's shadow we instantly see its size in comparison to our own. Aristarchus measured the curve of the umbra (the darkest part of the Earth's shadow) as it crossed the face of the Moon and concluded that between 2.5 and 3 Moons would fit side by side across our shadow.[54]

When at last Eratosthenes measured the size of the Earth, so too by extension did he measure the Moon. But Aristarchus went farther; in his *On the Sizes and Distances of the Sun and the Moon,* written around 280 BCE, he showed that if you know the actual size of the Moon then you can determine how far away it must be to appear as small as it does in the sky. We do this today with high school trigonometry.

And the distance to the Sun? Aristarchus imagined a triangle formed between the Earth, Sun, and Moon when exactly half the Moon was lit by the Sun (and so a 90^{o} angle exists at the corner with the Moon). Measure the angle at the Earth (the angle between Moon and Sun on the sky) and if you know the distance to the Moon then, from trigonometry, you know the distance to the Sun. Sadly the distances were so vast, and the angles so close to 90^o (and his ability to measure positions on the sky so imprecise) that there was no way his method would work.

<<Insert SunDistance.tif here>>

In the end, his calculations pointed to a Sun 20 times farther away than the Moon and consequently 20 times larger since both appear the same size in the sky. The reality was different, off by a factor of 20, but the fact that that it revealed a Sun very much larger than the Earth was profound. If the Sun is so much larger than the Earth, then why would the Sun orbit the Earth and not the other way around? It was an early argument for those who believed in a heliocentric Universe.

One proof geocentric proponents gave for why this was impossible stated that if the Earth really did move through space then the constellations should change size and shape with the seasons as we orbit the Sun and draw close to some stars and move away from others. But no one had ever seen this happen.

How much the stars should change their positions depends on two things: the distance to the nearest stars (whose position should change the most compared with those that are father away) and our distance from the Sun – how far we actually move through space as we change position from one side of the Sun to the other (January to July, for instance).

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But no one knew how far away the Sun actually was. In fact, everything we know about the size of the solar system, including even the actual size of the planets, depends on knowing their distance from us. As of the 1800s all of these distances were simply known in relation to the distance between Earth and Sun. For this reason, this distance was called the Astronomical Unit (AU) and its calculation was one of the great questions of astronomy in the centuries after Galileo.

Sir Edmund Halley was the first to suggest a means to solve this problem using a phenomenon called parallax on the planet Venus. On those rare occasions when Venus passes directly between Earth and Sun (creating a tiny eclipse called a transit), different observers at different location on Earth see Venus take slightly different paths across the solar disk. For observers at opposite ends of the Earth, the greater the path difference, the closer Venus had to be.

You can see this for yourself by holding your thumb a few inches in front of your face. Look at it with first one eye and then the other: your thumb shifts against the background wall depending on which eye you use and how far away you hold your thumb. The closer you hold it, the larger the shift. Our brains are hard-wired to interpret the different sized shifts as differences in distance and thus we have stereo vision that renders our world in 3-D.

Halley proposed that astronomers travel as far as possible across the globe and each record the path of Venus’ transit across the Sun. Afterwards, comparison of observations from far flung observers would determine the distance to Venus using simple trigonometry. Since

Kepler's Third Law provided the distance between all the planets in terms of Astronomical Units, once one distance was measured, all the rest become known.

Venus orbits the Sun once every 225 days. In principle that means that Venus should lap us in our race around the Sun at least once every year. But like the Moon's orbit that is tilted around the Earth, the same is true for Venus' orbit around the Sun. Over a century goes by between moments when Earth, Venus, and Sun align and transits become possible. Halley concluded the next would not be visible until 1761 (followed eight years later by another) - long after he would be dead. Writing in Latin so as to reach as wide an audience of scientists as possible, Halley wrote in 1716:

> I would have several observations made of the same phenomenon in different parts [of the world], both for further confirmation, and lest a single observer should happen to be disappointed by the intervention of clouds from seeing what I know not if those either of the present or following age shall ever see again; and upon which, the certain and adequate solution of the noblest, and otherwise most difficult problem depends. Therefore again and again, I recommend it to the curious strenuously to apply themselves to this observation.[55]

All over Europe scientific societies answered his call and, as each transit opportunity approached, launched expeditions that sailed the world for astronomy. One of the most successful transit expeditions was that of Captain James Cook who in 1768 set sail on his first voyage into the Pacific. His destination was the island of Tahiti where he and his crew established a small observatory at a place still known as Point Venus.

> Saturday, 3rd [June 1769]. This day proved as favourable to our purpose as we could wish. Not a Cloud was to be seen the whole day, and the Air was perfectly Clear, so that we had every advantage we could desire in observing the whole of the Passage of the planet Venus over the Sun's Disk.[56]

On this voyage Cook would go on to explore New Zealand and the east coast of Australia where his botanist, Sir Joseph Banks, discovered a multitude of plants and animals unknown to western science. This voyage and the two that came after made Captain Cook a hero in England and the subject of local history studies for school children, including myself, all over the Pacific Ocean and on multiple continents.

At the other end of the spectrum, and other end of the world, one of the most unsuccessful transit expeditions was surely that of the French astronomer Guillaume-Joseph-Hyacinthe-Jean-Baptiste Le Gentil who at the behest of the French Academy of Sciences set out for the Indian Ocean to observe the transit of 1761.

Le Gentil's destination was Pondicherry, India, a site specifically suggested by Halley himself. When he arrived in the Indian Ocean he found war had broken out between England and France, the British had captured Pondicherry, and storms blew his ship off course resulting in weeks spent wandering the Indian Ocean and Arabian Sea. On the day of the transit, he was nowhere in sight of land and unable to make any of his measurements accurately from the deck of a rolling ship.

Rather than go home to France in defeat, Le Gentil resolved to try again for the next transit eight years later. He set sail for Manila in the Philippine Islands where his calculations predicted the conditions would be best for the transit of 1769. Again he was beset by misfortune. The suspicious Spanish governor there accused him of forging his letters of introduction and made it clear he was not welcome. Sailing once more for Pondicherry, now back under French control, he built his observatory and spent the time until the transit studying the local flora, fauna, and Indian astronomy. Unfortunately, a storm arose on the long-awaited day of the transit and he once more missed everything. It was perfectly clear back in Manila.

Dejected, Le Gentil packed up his samples and returned to France, but came down with dysentery and on his way home his ship was wrecked in a hurricane. By the time he finally reached France he had been away for eleven years, six months and thirteen days. His heirs had declared him dead and fought over his estate. His wealth was gone, his specimens sent from India never arrived, and his chair in the French Academy of Sciences had been bestowed on another man.

According to the Canadian astronomer Helen Sawyer Hogg, who translated Le Gentil's journals, his voyage "is probably the longest astronomical expedition in history. In fact, it is quite possible that, except for interplanetary travel, there will never be astronomical expeditions to equal in duration and severity those made for that particular pair of transits."[57]

One hundred and five years later when the next two transits occurred, the world was better prepared than before. In 1874 Russia would launch 26 transit expeditions, Britain 12, the United States eight, France and Germany six each, Italy three and Holland one.[58] Every country with scientific aspirations joined in the worldwide endeavor. In the United States, the composer John Philips Sousa even composed the "Transit of Venus March."

From all these transit expeditions astronomers calculated a distance for the AU of 92,885,000 miles,[59] within 0.07% of what we now know to be the true value. This one number, acquired from observations made at far-flung points around the globe, at last revealed the extent of the solar system and each planet's size.

The numbers were huge.

Let's bring these literally astronomical dimensions to a more manageable scale. Imagine we were to shrink the solar system to the size where the Sun is a grapefruit, five inches (10 cm) in diameter. On this scale, the Earth, no bigger than a tiny candy sprinkle a millimeter in size, is 16 yards (or meters) away. Jupiter, a pebble a half inch in size (1 cm), is another 60 yards away. Pluto and the Kuiper Belt, at the edge of the observable solar system, are grains of sand a third of a mile (500 meters) away from our tiny planet.

In 2006 humanity launched the New Horizons spacecraft, the fastest machine ever created, and it took nine years to reach Pluto. Nine years to travel the third of a mile in our model solar system. Yet even light, the fastest thing in the Universe, still takes almost five hours to travel that distance. The speed of light may be fast, but it isn't infinite.

For centuries philosophers debated whether light even had a speed. Some, like Alhazen in his treatise on optics, said yes, arguing that nothing could be in two places at once.[60] Others argued no. The French philosopher Rene Descartes wrote that if light took time to travel during a lunar eclipse then it would take time for the Earth's shadow to fall upon the Moon and an equal amount of time for the sight of it to travel back to us. By the time we saw the eclipse occur it might already be over and surely such a thing was impossible.[61]

Descartes was wrong, of course. Or rather he was right; he just had the wrong moon. To truly see this effect, he needed to look for an eclipse around another planet.

In 1676, Ole Roemer's job was to measure the period of Jupiter's moon Io for the task of mapping France. He found that rather than having a constant rate, the time between Io's eclipses grew less as the Earth approached Jupiter and longer as it travelled away.

This is so because while the Earth approaches Jupiter, the light from each little eclipse travels progressively shorter distances to reach us. As the Earth moves away from Jupiter the distances increase and the "news" of each eclipse has farther to travel. The maximum difference in distance is the diameter of the Earth's orbit (twice an AU). From the maximum difference of 22 minutes in Io's orbital period, Roemer found that light travels roughly 11 minutes per AU.[62] This is terribly fast from our terrestrial experience but not instantaneous.

As our measurements have improved for both the speed of light and the distance to the Sun we now know the Earth lies 8.3 light-minutes from the Sun. We see the Sun as it was 8.3 minutes ago. Pluto as it looked almost five hours ago. And the stars? How far is it to the stars?

Once the length of the AU was known, astronomers could use the parallax of nearby stars to reveal their distance. The closer a star, the more its position moves back and forth against the distant stars each year (remember the motion of your thumb when looking with one eye then the other). Because even the closest stars are so distant, the first parallax motion wasn't observed until 1838, long after anyone still needed proof that Copernicus had been correct that Earth really moves around the Sun.

The star was 61 Cygni and its parallax shift was only 1/12,000th of a degree, near the limit of what even telescopes today can measure without being sent into space. The result places 61 Cygni almost 658,000 AU away from the Earth, meaning the light we see from it tonight took 10.3 years to travel here.[63] On the scale of our model solar system, 10.3 "light-years" is the distance between Los Angeles and Paris. For comparison, the farthest human beings have ever traveled into space is the orbit of the Moon, no bigger in our model than the width of a thumbnail.

For more than a century now, astronomers have used this technique (and others that have built upon it) to erect a distance ladder out into the universe, where each step is based upon the one before. From the distance between cities in Egypt we measure the circumference of the Earth and the locations of far-flung explorers around the globe. Their positions reveal the distance to Venus and the Sun, from which we calculate the vast distances between stars. From them we learn that we live in a vast spiral disk more than 100,000 light-years across containing more than two hundred billion stars.

And in all that vastness, are there other worlds around other suns? Less than a quarter century ago, anyone asking how many planets there are would have been told nine (including Pluto). The number of solar systems was one: ours. Today the answer is thousands of planets around other stars with hundreds of multi-planet solar systems. New ones are being discovered so rapidly that before I write an exact number, it is almost certainly out of date.

The technique that has discovered the most planets depends upon detecting their silhouettes as they pass in front of their Suns. In essence we look for shadows spanning the distances between stars during momentary eclipses (or more precisely, transits). The first transiting exoplanet (the term used for planets orbiting other stars) was discovered in 1999 around the star HD209458. For three hours every 3.5 days it blocks enough light from its star that astronomers on Earth can tell it is two and half times larger than Jupiter and size.

In 2009 NASA launched the Kepler Mission, a space telescope designed specifically to look for transits around stars in a tiny patch of the sky towards the constellation of Cygnus. Kepler found thousands of planets with thousands more waiting to be confirmed. While many of these are the size of Jupiter and Saturn, astronomers poring through the vast backlog of data are finding increasingly smaller planets. In 2015 one was found that was dubbed "Earth 2.0," a planet only 60% larger than the Earth in an orbit about the same as ours around a sun only slightly brighter than our own.[64]

The successor to Kepler is the Transiting Exoplanet Survey Satellite (TESS) set to launch in 2017, the same year as the Great American Solar Eclipse. Unlike Kepler, it will search the entire sky for transiting planets. When they find candidates, they'll look for ground-based observatories to conduct follow-up observations, using technology now available to small universities and even amateur astronomers. My students and I, using a telescope no bigger than the first one my father bought me when I was a boy, have watched as a planet three times the mass of Jupiter orbits its star every three nights placing us briefly in a shadow more than 300 light-years long.

The question now is whether any of these planets are suitable for life. One benefit to transits is that at the moment a planet passes in front of its star, some tiny portion of the starlight we see has filtered through the planet's atmosphere. Atoms in the planet's atmosphere absorb a tiny amount of this starlight, each element absorbing a different combination of colors. The starlight we receive during a transit therefore bears the chemical fingerprints of the gasses in the planet's sky. We are no longer simply discovering other worlds, we are learning the compositions of their atmospheres. We are effectively sniffing alien air.[65]

Astronomers applied this technique to our own world. Observing our Moon during a total lunar eclipse, they were able to detect the chemical signature of oxygen, ozone, and water vapor in sunlight that had filtered through our own atmosphere before falling upon the lunar surface.[66] These molecules, together, mark our planet as a potential abode for life. It's only a matter of time before we detect the same from stars.

And that is where our steps through the universe have lead, from the shores of the Peloponnese, to the sands of the Nile, from the islands of the Caribbean, to the village of the Mandan, from Tahiti, to the Moon, the Sun, and the inky depths of the sea of space beyond.

Someday, maybe farther in the future than Anaxagoras is in our past, the first ships will set sail for the stars. When they do, the stars that are their destinations will be the ones with worlds discovered during this generation. And they will have been discovered the way we have discovered the universe around us, by following the light and shadows of distant worlds.

"By this time the light had visibly diminished: objects appeared as if lighted by the moon. The decisive moment drew near, and we waited for it with great anxiety. This, however, did not affect our intellectual powers: they were rather over-excited, and this feeling was amply justified by the grandeur of the phenomena nature had prepared for us, and by the knowledge that the fruits of our great preparations and a long voyage depended entirely upon the observation of some moments' duration."[67]

--M. Pierre Jules Janssen, 1869 eclipse expedition to India

Chapter 4: As Below, So Above

The Moon and Sun haven't always been *places*. For the majority of the last two millennia, the prevailing view was that stars and planets were mere points of light and the Moon and Sun just ethereal spheres. These spheres were eternally bright and moved each day in perfect circles above the corruptible Earth where everything falls and decays. In matter and motion there was nothing similar between Heaven and Earth. In the world before Copernicus, the Earth was the only *world*.

This separation of Heaven from Earth, Man from the gods, is attributable to Aristotle more than twenty-three hundred years ago. It's an idea that makes a certain amount of sense: we see rocks tumble, yet the Sun rises. Wood burns like the Sun, but the Sun seemingly burns forever. In fact, according to Greek mythology, we humans only have fire on Earth by the gift of Prometheus who stole it from the heavens, fueling our civilization.

From myth to modern astrophysics, the Sun is the unifying thread in the story of our position and origin in the Cosmos. Understanding its fire has revealed that the heavens, Earth, and we ourselves, are all subject to the same forces and composed of the same substances. This story, that we are the heavens made manifest, is one we know from eclipses.

It is a story that begins with the Moon.

Look up at the Moon and though the rest of the sky is full of pinpoint stars and a (blindingly) featureless Sun, the Moon has obvious features. All over the world people have seen these dark markings as a Man, a Woman, or even a Rabbit. Yet up until only the last four hundred years, had you asked a learned philosopher about the nature of the Moon he would have told you that it too was a perfectly smooth, unblemished sphere.

According to various European thinkers these markings were simply the mirror-like reflection of the imperfect Earth. Other philosophers posited that though smooth, the Moon was composed of a translucent crystal with pockets of different density. Yet others proposed that the Moon wasn't solid at all, but rather a cloud of spherical vapor through which light was more or less easily passed.[68]

The unifying theme was that the Moon, as a celestial orb, must remain a perfect sphere that shared no common feature with a physical place like the corruptible Earth. Which hypothesis was correct, our eyes had no way to tell for certain; our eyes could only tell us so much. That changed in November 1609 when Galileo Galilei pointed a telescope at the sky and beheld the Moon with a magnification beyond that of our own biology. What he saw through his eyepiece was a complex array of light and dark features even smaller and more intricate than the face we see in the Moon each month. But what could they be?[**]

From the time of Leonardo da Vinci, Italian artists endeavored to create realistic representations of the natural world in drawing and paint using geometry and perspective. Galileo, raised in the heart Renaissance Florence, was intimately aware of these techniques including that of *chiaroscuro*, the interplay of light and shadow across solid surfaces under a variety of illumination.[69] Looking through his eyepiece he instantly recognized the three-dimensional reality that had been hidden there for so long:

> [I] have been led to the conclusion that we certainly see the surface of the Moon to be not smooth, even, and perfectly spherical as the great crowd of philosophers have believed about this and other heavenly bodies, but, on the contrary, to be uneven, rough, and crowded with depressions and bulges … like the face of the Earth itself which is marked here and there by chains of mountains and depths of valleys.[70]

Galileo does not say what curiosity made him first point his telescope at the Moon.[71] It is therefore impossible to say what he expected to see. But as an astronomer who has had the pleasure to use a new telescope with new capabilities never before available, I can say that this is the most exciting moment in any scientist's life.[72] To look with new eyes at new worlds, where every sight is a source of surprise is science at its most exciting.

[**] The British mathematician, Thomas Harriot, actually pointed a telescope at the Moon four months before Galileo. But he made no more than a rough sketch of what he saw, noting the data and time and nothing more. What he thought about the light and dark regions he saw he wrote in no journal nor shared with any colleague. As a result his name remains little more than a footnote in the history of astronomy.

But Galileo went farther: If the Moon had mountains, then he should be able to measure their height. To understand how this is possible, imagine standing in a meadow before dawn, with mountains behind you to the west. Long before you see the sun rise, the mountains peaks behind you are lit; where the first peaks to be touched are the tallest. Galileo saw the same phenomenon on the Moon. He measured how far into the lunar night a mountain could be and still have its peak lit by the Sun. Simple geometry told him they were comparable in height to our own.

Eighty years later, when Sir Isaac Newton published his mathematical laws of gravity, he proved that the exact same force that causes stones to fall also keeps the Moon in orbit around the Earth. The same physical force is therefore at work both here and in the sky. The Moon was now a place where any scientist or artist could imagine standing and watching the sunrise.

And what about the Sun? Using a telescope to project an image of the Sun upon a piece of paper, Galileo saw that it had spots. The Sun, like the Earth and Moon, was blemished.

Galileo and his contemporaries were not the first people ever to see sunspots. On occasion sunspots can grow to over ten times the size of the Earth (as large as the planet Jupiter). When this happens, they are large enough to be seen without a telescope, especially through thick haze or when the Sun is low on the horizon.[††] Chinese records going back to 165 BCE tell of naked-eye sunspots.[73] The 14th century Indian *Kashi Khanda* text describes a Sun

[††] In 2003 a dozen major forest fires raged around Southern California. I was living under one of the smoke plumes and still remember looking up through the ash-darkened sky to see a blood red Sun with two black sunspots for eyes looking back down at me. It was the eeriest thing I've ever seen.

whose face was covered by dark snakes, almost certainly sunspots, a sight that would have been visible as the morning Sun rose through the mist of the River Ganges.[74]

Thanks to the blinding light of the Sun's photosphere (literally, its surface of light), sunspots are the only feature of the Sun that we can ever see under normal circumstances. But solar eclipses aren't normal circumstances. Like holding a hand up to block the glare of a street lamp at night, suddenly we see more for having less light to hide what is there. Solar eclipses have been the greatest tool for understanding the geography (the heliography?) of the Sun.

Before the 19th century, eclipses were primarily interesting for what their occurrence and duration revealed about navigation and timekeeping on Earth. In the early 1800s, the English astronomer Sir Francis Baily was more interested in what eclipses revealed about the Sun and Moon. And while most astronomers merely observed eclipses that happened to pass over their homes (making drawings later to record what they could remember) Baily was willing to go wherever necessary to see what he could discover and record those discoveries on the spot.

Born in 1774, Baily was the son of an English banker. He was a studious young man and interested in science, but as soon as his mercantile apprenticeship was over, he left London for adventure in the United States. His letters from this time read like a Robert Louis Stevenson novel: a harrowing shipwreck on the high seas, disgust at the slave trade in the West Indies, boating and canoeing down the Ohio and Mississippi Rivers to New Orleans, and then walking back to New York overland through 2,000 miles of Indian-filled wilderness.[75]

For a while he thought of staying in America (there was a rumored romance according to his friends back home), but eventually he returned to England. There he attempted to continue his life of travel by seeking service with the East India Company in Turkey, then the Africa Association to explore the far-off Niger River. In the end it came to nothing, and so finally he accepted a position in London as a stock-broker.[76]

Baily's intelligence led him to write revolutionary papers on the mathematics of interest and annuities (the first to do so using algebraic equations and symbols). But in time his interests turned once more to science and in 1811 he used his mathematical skill to calculate the date of the first known total solar eclipse in history: that of Thales of Miletus (which he concluded occurred on September 30, 610 BCE)[77]. Twenty-five years later, in 1836 and now President of the Royal Astronomical Society, Baily's mathematics revealed that the Moon's shadow would sweep across Europe on July 18, 1842.[78] It would be the first total solar eclipse to cross the continent in 118 years, and so a sight virtually no living European could claim to have seen.

Baily had already seen an annular eclipse. In 1836 he traveled to Scotland with his telescope to observe the event and in the process reported an unusual sight. At the precise moment that the Moon moved fully in front of the Sun, when the thin crescent of light wrapped itself around the Moon to become a ring, a complicated pattern of bright "beads" come into view where the two "horns" of the crescent were about to touch.[79]

Baily was not the first to see these "beads." The Reverend Samuel Williams of Harvard University had seen something similar in 1780 during a total eclipse of the Sun on the coast of Maine. He had traveled there to set up telescopes and chronometers to measure the time and duration of totality. Unfortunately, whether through errors in his maps or his math, Williams' expedition just barely missed totality's path by a matter of miles. So close was he, though, that he recorded the appearance of multiple bright points of sunlight moving along the thin edge of the Moon where at maximum obscuration it skirted the edge of the Sun.[80] Williams' failure to reach totality meant his observations were not widely read, but some astronomers have suggested that Baily, during his American wanderings might have become aware of these and so made special efforts to see these bright points of light for himself in Scotland.[81]

The phenomena are now called "Baily's Beads" and they form at the first and final moments of totality, when sunlight streams through mountains and valleys along the edge of the Moon. Those mountain peaks Galileo first discovered break up the Sun's light into rays that shimmer in and out of existence until the bright disk finally disappears. Without Galileo's discovery, there is no explanation for what everyone sees at the moment of totality.

It was this phenomenon that Baily was most interested in seeing again in 1842 from Pavia, Italy, where representatives from the local university had put at his disposal anything the school had to offer. Having brought his own telescope he informed them that all he wanted was a room with a view of the Sun where he could be left alone, free from distraction, to make his observations.[82]

The next day the weather dawned clear and beautiful. As the eclipse began, Baily commenced recording his observations noting everything he saw. Then, as the Sun vanished and the beads finally appeared:

> I was astounded by a tremendous burst of applause from the streets below, and at the *same moment* was electrified at the sight of one of the most brilliant and splendid phenomena that can well be imagined. For, at that instant the dark body of the moon was *suddenly* surrounded with a *corona*, or kind of bright *glory*, similar in shape and relative magnitude to that which painters draw round the heads of saints….
>
> I had indeed anticipated the appearance of a luminous circle round the moon during the time of total obscurity: but I did not expect, from any of the accounts of preceding eclipses that I had read, to witness so magnificent an exhibition as that which took place.[83]

One of those previous accounts of the corona of which Baily wrote was by Sir Edmund Halley, who in 1715 observed a total solar eclipse in the sky above London (the first over England in more than 500 years). During totality he beheld “a pale whiteness” with color of pearl and iris surrounding the Moon that “in all Respects resembled the Appearance of an enlightned [sic] Atmosphere viewed from far,” much like steam from a coffee cup backlit by the Sun on a cool winter’s morning. “But whether it belonged to the Sun or Moon I shall not at present undertake to decide.”[84]

The Spanish astronomer Jose Joaquin de Ferrer was the first person to call this radiance the *corona*, Spanish for crown, when he saw it during the total solar eclipse of 1806 from the banks of the Hudson River in upstate New York. Ferrer measured the corona’s extent across the sky and calculated that if it *was* a lunar atmosphere it must extend 348 miles out into space, 50 times higher than our own.[85] And though that seemed unlikely to him, like Halley he had no idea if it were true.

Unfortunately, prior to the invention of photography, what one person beheld could be conveyed to another only through word or art. And for those, with no idea what to expect, what the eye and brain fail to comprehend the hand is severely hindered in reproducing. Consider the words of one observer for the total solar eclipse of 1858, that for anyone who has seen totality, rings true more than 150 years later: “Every effort has been made by the artist to represent in the accompanying lithograph, drawn from the sketch and notes, the scene then before me, and which still remains strongly impressed upon my memory…. It was a far more imposing sight without than with the telescope; and long as has been my experience in the observation of celestial phenomena, and calm and unimpassioned, at such times, as my temperament has become, the sublime majesty of the scene thrilled me with excitement and humble reverence.”[86]

Even today it is difficult to do an eclipse justice as no photograph captures the corona exactly as the human eye sees it. Yet as spectacular as the corona was, Baily found another sight even more remarkable: three large red “protuberances” surrounding the disk of the Moon.[87] Though he felt sure they were associated with the corona, once again, whether a part of the Sun or Moon he could not say.

As with Galileo’s experience before him, the interplay of expectation and surprise in what Baily saw is one of the greatest delights in any scientific investigation.[‡‡] Thanks to Baily’s

[‡‡] The most exciting statement a scientist can utter is, “Huh, that’s odd.”

meticulous observations, astronomers from all over Europe and the New World were now eager to see if they too could discover something new about the Sun and Moon and these strange phenomena. To do so, according to Baily, was no longer possible by a single observer. Rather, the job of accurately recording all that there was to be seen during an eclipse required a team, each with his own independent piece of equipment dedicated to a particular phenomenon. Most importantly, if the Sun was to be understood, these teams of careful observers would need to travel the world to wherever new eclipses occurred.

Expeditions from England, France, and the United States would travel to every continent by commercial steamships, government gun-boats, newly constructed continent-spanning railways, and even hot air balloons. The astronomers who lead them would climb high in the mountains of Peru in 1858, conduct observations in the Indian Himalayas in 1868, make beachheads on remote islands of the South Pacific in 1883, and travel across the sands of Algiers in 1900. Virtually every total solar eclipse that touched on solid land would be the subject of scientific expeditions for the next 90 years.

One British solar eclipse expedition in 1860 would mark the beginning of astronomy as most astronomers practice it today. Warren de la Rue was a pioneer in applying the newly invented technology of photography to astronomy and he was determined to prove that the camera could capture the phenomena of totality just as well as the human eye. Through photographs the mysterious features could finally be available for everyone to study and measure at leisure without depending on the artistic (or literary) abilities of the observer.

Perhaps at last their origin would be discovered: were the corona and red “flames” features of the Sun, or of the Moon?

The expedition was a major undertaking. His primary equipment was a special solar telescope with a custom built cast-iron mount and 48 glass plates that he and his assistants carefully cleaned and packaged in London before departure. At their destination in Spain, the entire apparatus would be housed in a specially designed observatory that would double as a darkroom for developing plates. In the event the photographs were a failure (for no one had any measure for how bright the corona and prominences were, and therefore for how long to expose the plates) the expedition also carried a 3-inch telescope to use for drawings.

To this equipment were added boxes of developing chemicals, distilled water, engineers’ and carpenters’ tools, lanterns, oil, stove, kettle, and provisions in case the local countryside should be deficient in food (it was not). The entire expedition equipment list could be broken down into 30 boxes weighing a total of 4,133 pounds, transported by the British Admiralty ship *HMS Himalaya* from Plymouth, England to Bilbao on the coast of Spain and then by train to the interior town of Rivabello .[88]

It was a long way from Galileo and Baily and their simple pens and paint brushes.

Fortunately, De la Rue’s photographs during totality were a complete success. From photographs taken at the start and end of totality it was obvious that Moon moved relative to the corona and prominences. The conclusion was clear: the red “flames” and corona belong to the Sun and at that extreme distance they must dwarf the Earth in size.

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As much as it was a success for solar astronomy, De la Rue's photographs were also a success for the impartial, mechanical, eye of the camera over the artistic skill and transitory experience of the astronomer. The American astronomer H. C. Russell wrote about this change with some trepidation: "In many cases the observer must stand aside while the sensitive photographic plate takes his place and works with the power of which he is not capable... I feel sure that in a very few years the observer will be displaced altogether."[89]

Other intellectuals were sure that even with new technology there were natural limits to what we could learn about these worlds beyond our atmosphere. In 1835, the prominent French philosopher, Auguste Comte, wrote in his *Course de la Philosophie Positive*:

> We can imagine the possibility of determining the shapes of stars, their distances, their sizes, and their movements; whereas there is no means by which we will ever be able to examine their chemical composition, their mineralogical structure….[90]

This attitude seemed eminently reasonable given the astronomical distances between us and the stars, planets, Sun and even our closest neighbor, the Moon. Without ever being able to travel to the heavens, the best we could ever hope to have is their light and once you had seen (or later photographed) all that there was to be seen, what more could possibly be known?

Two hundred years earlier, Newton discovered that hidden within sunlight were all the colors of the rainbow. All that it took to unlock them was passing the light through a simple glass prism. In 1800 William Herschel found that if you place a thermometer just beyond the red end of the rainbow there is an unseen "color" there that contains a tremendous amount of heat: we now call it the infrared. A year later the ultraviolet was discovered beyond the blue.

Over the next two decades, tiny gaps were discovered all across the solar spectrum where no color fell. Because the spectrum was best viewed when light passed through a narrow straight slit, these dark gaps were called "lines" and in 1859, just 24 years after Comte made his grand pronouncement, chemists Kirchoff and Bunsen discovered that these lines were the fingerprints of the natural elements. Discover what fingerprint goes with what element and suddenly anyone can sample the composition of the stars, no matter how far away.

We live in a world composed of apparently endless variety. Yet everything we see is simply made of molecules that are a combination of about 100 different types of atoms. Even simpler, each of those atoms is nothing more than a combination of just three components: protons, neutrons, and electrons.

Every atom consists of a nucleus composed of one or more positively charged protons, (with some number of neutrally charged neutrons) circled by one or more negatively charged electrons. One proton circled by one electron is all that you need to make hydrogen, the lightest element there is. Six protons, fused together with six neutrons and encircled by six electrons, and you form carbon, the primary component of our bodies. Eight protons, eight neutrons, and eight electrons produce the most important constituent of the air we breathe: oxygen.

We picture electrons orbiting the nucleus as if they were tiny planets orbiting a sun. But unlike planets, electrons can only occupy specific orbits carrying specific amounts of energy. Any change from one orbit to another therefore requires a similarly specific change in energy. When changing from a higher energy to a lower one, the excess energy is given off as light. The wavelength, or color, of light is simply a matter of its energy. Since each element has a unique set of energy levels for its electrons, each element emits or absorbs a unique spectrum of colors – its own elemental fingerprint.

Astronomers Pierre Jules Janssen and Norman Lockyer[§§] independently designed instruments to study these spectral lines from the Sun during eclipses. Of particular interest were the nature and composition of the mysterious red prominences. They found that the light of the prominences, rather than being a rainbow of light like the photosphere, was instead composed of just four distinct lines: two bright red and blue lines and two weaker yellow and green.

Three of those lines, red, green and blue, had previously been discovered in the spectrum of the simplest element of all: hydrogen. August Comte had been proved wrong. Without leaving our planet Lockyer and Janssen discovered the composition of a world out in space and rather than some celestial aether (the dream of the ancient Aristotleans) it was

[§§] Lockyer was also the first person to study ancient temples and monuments, including Stonehenge, for astronomical alignments.

nothing more than the simplest of all elements found right here on Earth. Solar prominences are great geysers of hydrogen gas, erupting off the surface of the Sun.

And the other spectral line? When Lockyer found no element or conditions under which hydrogen emits the remaining bright yellow line in the solar prominences, he proposed a new element named after the Sun god Helios: helium. It would take another 25 years before this new element was discovered on Earth.[91]

Helium, composed of two protons, two electrons, and two neutrons, is the second most abundant element in the Sun (right after hydrogen) and like hydrogen, Lockyer and other astronomers found it in the spectra of stars and gaseous clouds throughout space. The fact that we see the exact same spectral lines from the most distant galaxies, the galaxies whose light has been traveling towards us since soon after the Universe formed, means that the same laws of matter and light (what we now know as quantum physics) hold true throughout the universe and throughout time. It's the logical progression from when Newton first found the same laws of physics at work on the Moon as hold true on Earth.

That we see the presence of these common elements throughout space is a key clue to the life-cycles of stars and the origin of just about everything. To understand why, it is important to step back and first wonder why the Sun, like the stars at night, continues to shine. Is the Sun really is on fire and the light we see is due to the breakdown of molecular bonds? Chemists of the 19th century knew well what kind of energy molecular bonds release when they break and, given the rate at which the Sun shines, found that if this were true, the Sun would run out of fuel in no more than a few thousand years.

Such a short lifespan for the Sun was not a problem for a biblical origin of the Earth only 6000 years ago. But the 19th century also saw expeditions other than those for eclipses. Charles Darwin's 1830s expedition in the *HMS Beagle* produced his work proposing the slow evolution of species over millions of years. This agreed well with his calculation presented in the *Origin of Species* that erosion would need 300 million years to create the geologic landscape he saw back home in England.[92] It makes sense that the Earth should be older than the life that inhabits it, but impossible that it is older than the Sun that sustains it. The Sun can't be on fire.

Does the Sun shine, instead, by the energy it released from its formation? Drop a rock from a high building and there is no doubt that its impact releases energy. An entire Sun's worth of mass falling together from a distance spanning the solar system would release enough energy to light the Sun for nearly 20 million years. Yet even that is still too short compared to the Darwin's geologic history.

No adequate answer for why the Sun shines was known until the dawn of the 20th century. Only then did the discovery of radioactivity and the components of the atom finally reveal a previously unknown energy source: fuse small atomic nuclei together to form larger ones and the energy released per mass is more than almost any other reaction.

But the nucleus of the atom is where the positively charged protons reside. To force them together you need to overcome the tendency of like-charges to repel. Only incredibly high pressures and temperatures can fuse even the smallest atomic nuclei together. In 1920, the British Astronomer Sir Arthur Eddington (famous for his own eclipse expedition the previous year) accurately proposed that the only place these conditions are found naturally is in the hearts of the stars. Fusion is what fuels the Sun.[93]

Our Sun is a mass of hydrogen gas a million times greater than the Earth. Gravity, the force that draws all things together, tries to cause the Sun to collapse. But as it does, the pressure at it its center grows until the hydrogen that's found there fuses to form an atom of helium and release a tremendous amount of nuclear energy. The gas heats up and swells like a hot air balloon until the gravitational collapse is countered. Our Sun, like every star in the sky is in the midst of a delicate balance between gravity pushing in and nuclear-driven heat pushing out.

Eventually the heat from the core, radiating our through the Sun, bubbles to the surface in enormous convection cells like a rolling boil of water heated from beneath on a kitchen stove. The tops of these cells radiate their energy away into space as light. This is the photosphere that we see.

On Earth we are familiar with everyday things like oven coils and charcoal fires that give off light because they are hot. We call this thermal radiation. You and I are warm enough to give off infrared light, but not so warm that we glow at night with the lights off. The Sun, stars, and the filaments inside incandescent light bulbs are. And that is why they light our world. The Sun's photosphere is at a temperature of nearly 10,000^o F (5,500^o C) and thus radiates light in the visible part of the spectrum.[***]

[***] Cooler gasses just above these convection cells absorb their characteristic fingerprints of color from the light streaming by and thus are the source of the solar absorption spectrum observed on Earth.

The dark sunspots Galileo first saw are slightly cooler places within the photosphere. They form as different parts of the Sun rotate at different speeds (gas at the poles takes 30 days to make one trip around the Sun, while gas at the equator takes 24). The Sun's magnetic field twists and knots during this differential rotation until kinks pop out of the surface like a rubber-band twisted too much. Where this happens, the magnetic fields push the flowing hot gas aside and we see down into comparatively cooler, darker gas beneath.

Hydrogen atoms stream along the magnetic field lines that loop out of these spots, emitting the bright red line of hydrogen gas that first revealed their composition during eclipses. These are the prominences that together with sunspots increase in number as the kinks in the Sun's magnetic activity ebb and flow over an 11-year cycle. See an eclipse during solar maximum (around 2014 and 2025, etc.) and you have the chance to see lots of bright red prominences. Eclipses half way between those years tend to have not as many.

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The source of the hydrogen we see in the prominences is a thin atmosphere of excited gas just above the photosphere. The red light of excited hydrogen gives this layer its color which is also sometimes visible during solar eclipses, and is why we call it the chromosphere: *chromo* is Greek for color. Strangely, the chromosphere grows hotter the farther it extends from the Sun. Why it does so is still a subject of research. The leading hypothesis says energy flows upwards along the magnetic fields and is funneled into the upper atmosphere, particularly the corona above it that can reach a temperature of millions of degrees.

Spectral lines given off by iron atoms that have had thirteen of their electrons ripped from around them are evidence of the extreme temperatures found in the corona. Until relatively recently no lab on Earth could produce the conditions necessary for these lines. Astronomers at the turn of the last century thought they had discovered yet another new element in the Sun, which they called "coronium."[94] Only with the new understanding of atomic physics developed during the early 1900s was the true origin of these lines, and thus the enormous temperature of the corona, made clear.

Think about what these temperatures mean. Every star you see in the sky is glowing because it is a few thousand degrees hot. The very hottest stars are a few tens of thousands of degrees. But when you see a total solar eclipse, that corona you witness is millions of degrees hot; it is the hottest thing the human eye will ever see in nature. Yet it comes from a place so diffuse that the light it gives off is too faint to be seen unless the rest of the Sun's light is extinguished.

This is what our Sun is: a nuclear fusion reactor that has been producing helium and energy (and giving us life) for almost five billion years and that will continue to do so for another five billion more. But then what?

The British astronomer Fred Hoyle (who also hypothesized the eclipse-predicting-potential of Stonehenge's Aubrey Holes) was the first to propose that once a star has run through its hydrogen fuel, the inward force of gravity eventually forces the fusion of helium into carbon, oxygen, and other elements in the periodic table. Since each new element requires even greater temperatures and pressures to force them to fuse, eventually no new fusion is possible. For a star like our Sun, its core collapses into a white dwarf star, a tiny ball of carbon atoms no larger than the Earth, while all the rest of its gasses are blown out into space.

For the most massive stars this death is accompanied by an explosion as bright as a billion stars shining at once. During this supernova explosion the atoms in the star collapse then rebound, ripping the star apart from the inside out. For a fraction of a second it becomes the Universe's largest particle collider, producing the other naturally occurring elements in our periodic tables. The star's explosion scatters all of these into space to eventually become incorporated into new stars (and the planets that form around them).

The spectral lines of carbon, oxygen, and iron that we see in the Sun are only there because other stars lived and died long before ours ever formed. They are the source of the lead in our batteries, the silver in our banks, and the uranium in our warheads. The iron in our blood was formed in the ancient hearts of stars and with every breath we take we breathe in the oxygen those stars left for us. They are a part of us; every atom in your body, other than hydrogen, was once an atom in the heart of a star. All of us are the Universe on Earth.

This is a revelation both uplifting and humbling. It is the dream of the astrologers that we are intimately tied to the stars at an atomic level. At the same time it is a disquieting thought that the physicists who discovered this cosmic connection are many of them the same ones who found another, less uplifting use for nuclear processes. The physicist Hans Bethe who discovered how helium is fused, went on to become the head of the theoretical branch of the Manhattan Project developing the first nuclear bomb in World War II. Edward Teller discovered the energies produced in the nuclear fusion at work in stars and then went on to do the same for the even more powerful hydrogen bombs.

The fathers of stellar fusion are the fathers of the atomic and hydrogen bombs – bombs that for a brief moment unleash the conditions at the core of our Sun on the surface of our tiny planet. How appropriate then that Zeus, in his anger at Prometheus for stealing the celestial fire, sent evil into the world locked in a box we opened in our curiosity.

But, there is also another use for nuclear fusion on Earth. Should we ever find a way to sustainably fuse the hydrogen from water, we will unleash the power of stars and the Sun using a process that leaves behind no radiation or greenhouse gasses, using a fuel that is found everywhere, virtually free and practically limitless.

Sir Arthur Eddington was prescient when he spoke about nuclear power in 1920. "If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfillment our dream of controlling this latent power for the well-being of the human race -- or its suicide."[95] It is important to remember, then, that though evil may have escaped from Pandora's Box, the one thing that didn't was Hope.

"I wish to again put on record, that, during totality of the solar eclipse of 1878 at Denver, Colorado, I saw two new stars which I have reason to think were intra-Mercurial planets…These are facts, and the world is challenged to disprove them."

--Lewis Swift, American amateur astronomer, 1883[96]

Chapter 5: The eclipse that changed the world

The first planet discovered since antiquity was found by mistake. Its discovery resulted in the greatest triumph of Newton's clockwork universe yet eventually led to its greatest failure at the hands of German patent clerk. Out of the ashes of that failure a new paradigm would rise, not just for scientists, but for the world we now know, and it was a solar eclipse that provided the proof.

On a clear night in 1781, William Herschel, a musician and self-taught astronomer born in Germany but raised in England, pointed a telescope he had designed and built himself at a relative unremarkable piece of sky. In his eyepiece he saw a faint bluish ball that he at first took to be a new comet. But as other astronomers turned their telescopes towards the new object, its changing position revealed motion more like a planet around the Sun, than a comet plunging in toward it. They named the new planet *Uranus*, after the Greek god of the sky.

Yet something about Uranus wasn't quite right. No single orbital solution to Newton's Laws fit all of its observed positions. At the Paris Observatory, Urbain Jean Joseph Le Verrier, was given the task of reconciling these observations. Le Verrier was a brilliant young mathematical astronomer (what today we might call a theoretical astrophysicist) and in 1846 he published a paper with a startling hypothesis: Uranus was not alone.

For almost 200 years Newton's laws of motion worked spectacularly well at explaining the motion of everything from a cannon ball's arc to the movement of the Moon and stars. Everything about gravity was mathematically predictable. According to Le Verrier's calculations, the only way Uranus could move as it did was if it was being influenced by an as yet undiscovered planet even farther from the Sun.

To assert was one thing; to reveal, another. Le Verrier worked backwards from effect to cause and on August 31, 1846 announced the precise celestial coordinates where astronomers should turn their telescopes to reveal the unseen planet. Less than a month later, Neptune was found precisely where Le Verrier said.[97]

Neptune's discovery was the highest triumph yet of Newton and science and confirmation of the contemporary assertion by philosophers that if one could but know all the "forces that set nature in motion, and all positions of all items of which nature is composed," then the future and past could be predicted with infinite precision.[98]

And such a world of mathematical precision it was. Life in the 19th century was accelerating rapidly, fueled by the new technology of iron and steam made possible by the physics of heat and motion. Smoking mechanical ships now crossed the seas in mere days while locomotives raced across continents for the first time moving people faster than any creature could walk or run. In Europe and the Americas, electricity and the telegraph made the world smaller than its physical geography and connected any two points at the speed of light (or at least the speed of a telegrapher's typing). In this world Le Verrier's name, along with those of other French luminaries of science and technology, would be engraved in the steel girders of the tower Gustave Eiffel would eventually erect over the city of Paris.

But Le Verrier's work didn't end with Neptune; at the other end of the solar system he saw there was something wrong with Mercury. Like the planet Venus, Mercury periodically passes in front of the solar disk. But where a transit of Venus is rare (only occurring in pairs every century or so), Mercury's transits are common, happening at intervals between three and 13 years apart. Le Verrier realized that for all of Mercury's transits, the times that had been predicted didn't *quite* match what had actually been seen. The differences were small, only a few seconds – easily explained by errors in an individual observer's clock. The problem was that nearly every observer reported this error, and all in the same direction (always starting early). What's more, over the century that they'd been observed, the discrepancies had been growing.

For the man who was Newton's champion, the mathematical solution was clear: our solar system must contain yet another planet, this time one hidden in the glare of the Sun. And just as Mercury's transits revealed its influence, perhaps transits of the mystery planet would reveal its existence.

Almost immediately upon announcing his conclusion, Le Verrier received word that the mystery planet had already been seen. Dr. Edmond Modeste Lescarbault, an obscure French physician living outside Paris claimed to have seen just such a small circular spot pass across the Sun. Visiting Lescarbault incognito, Le Verrier cross-examined the doctor:

> … whose means of observation were certainly of the scantiest. His telescope was a small one of only two or three inches aperture; as a time-keeper he had only an old watch with no second-hand, so that he was obliged to use a pendulum consisting of a bullet at the end of a string for counting seconds, and to save paper he made his calculations on boards which he planed off whenever he wished to erase an old computation and make way for a new.[99]

At the end of his visit, Le Verrier announced to the world that his predicted planet had been seen and named it *Vulcan* after the Greek god of fire. Using Lescarbault's time and duration of transit, Le Verrier calculated that it must circle the Sun once every 19 days and 7 hours, and that during roughly half of all solar eclipses it would appear within 8^{o} of the Sun as bright as a first magnitude star (one of the brightest in the sky). In addition, twice each year - around April and October - it would be visible transiting across the solar disk.

The next transit would occur on or about March 22, 1860, just two and half months later. To find such a planet, astronomers all over the world would need to monitor the Sun constantly without any gaps in their observations lest the planet pass across the Sun unseen. By telegraph the news went out to far-flung observers but no such transit was ever seen. Even worse, an astronomer in Brazil published a paper claiming to have observed the Sun at exactly the same time as Lescarbault and to have seen no transit at all.

It would be a pattern repeated over and over again for the next 50 years. For every astronomer (noted and otherwise) who chanced to see a dark dot on the Sun "exactly" as Vulcan would appear, another reported fruitless hours spent looking for any such spot.

Detecting Vulcan during a total solar eclipse proved no easier.

On August, 7th 1869, the *Sioux City Daily Times* reported that a party of four astronomy enthusiasts in St. Paul County, Iowa, claimed to have seen a "star" one-sixth the size of Mercury near the totally eclipsed Sun. However, the *Des Moines State Register* announced that a professional astronomer who had set up his observatory in the path of totality, had "searched that region thoroughly, and found nothing that would indicate the existence of planets of that kind."[100]

The disagreement over Vulcan's existence eventually became so absurd that according to the *New York Times*, a positive opinion of Vulcan was a dangerous matter for any young astronomer. The planet Vulcan had become "an astronomical sea-serpent." And though it might exist, the older, more established astronomers, would scoff, that, "Professor So and So never saw it," and then they would hint, "with sneering astronomic smiles, that too much tea sometimes plays strange pranks with the imagination, and that an astronomer who cannot tell a planet from a fly that walks across his object-glass is no sort of man from whom any discoveries of moment need be expected."[101]

But all that appeared to change on July 29, 1878, when two independent astronomers claimed to see Vulcan during a total solar eclipse from two widely separated locations within minutes of one another. Reporting from Rawlins, Wyoming Territory, Professor James Craig Watson of the University of Michigan reported that:

> I had committed to memory the relative positions of the stars in the neighborhood of the sun, and I had placed the chart of the region conveniently before me for ready reference, whenever required…. The object which I had in the field shone with a ruddy light, and it certainly had a disc larger than the spurious disc of a star.[102]

Meanwhile Lewis Swift, the famous discoverer of no fewer than 13 comets (including Comet Swift-Tuttle, responsible for the annual Perseid meteor shower each August), reported from totality in Denver, Colorado, that in searching for Vulcan, "about one minute after totality I observed two stars, by estimation 3^{o} S.W. of the sun … by careful comparison, they appeared exactly of the same magnitude, and both as red as Mars. I looked closely for twinkling, but they were as free from it as the planet Saturn. They both, at the time, seemed to my eye and mind, to have a small round disk, about like the planet Uranus."[103]

Upon this news the Princeton astronomer, Dr. C. A. Young wrote that "One brilliant discovery will probably develop from this occasion, and hold a conspicuous place in the annals of science. The planet Vulcan, after so long eluding the hunters, showing them from time to time the only uncertain trace and signs, appears at last to have been fairly run down and captured."[104]

But given the brightness of the new planet, Young calculated Vulcan's size could be no more than 400 miles in diameter.[105] This was tiny enough to have escaped detection for so long, but too small to cause the change in Mercury's orbit in the way that was seen. Perhaps there were multiple Vulcans? In fact, it soon became clear from comparison of Watson's and Swift's notes that their locations didn't match – they couldn't possibly be reporting the same planet.[106]

When no subsequent transits appeared, both were adamant that what they had seen were real.[107] *The New York Times* wrote, "Prof. Swift arrived in town to-night, and in an interview with a reporter stated that he had no more doubt that he discovered Vulcan than that he had been to Colorado."[108] In time, Swift was sure that the new photographic technology being used by eclipse-chasers like Pierre Janssen would confirm his discovery. When they didn't, Swift was ready to explain that this was not surprising as their photographic emulsions were more sensitive to blue light and not the red color he'd seen Vulcan display.

"Happily the time is not far distant when the problem can be settled," wrote Swift in 1883, "The great eclipse of 1886 will afford an admirable and comparatively easy opportunity, if rightly managed, to dispel every doubt….. Until then let us hold the matter in abeyance. My faith in their existence was never stronger than to-day."[109]

But the eclipse of 1886 revealed nothing about Vulcan, and as the 19th century gave way to the 20th the triumph of Newtonian physics that had led to the discovery of Neptune was now producing nothing but failure. With each eclipse that revealed no sign of the elusive planet, further excuses and refinements were required to explain away Mercury's motion. What began with a single planet had already been modified to multiple planets, which in turn became a plethora of planetoids, a belt of debris between Mercury and Venus,[110] and finally nothing more than a simple ring of dust.[111] Nothing ever fit, yet still Mercury moved.

Maybe the fault was not in our stars but rather our physics? The astronomer Asaph Hall, discoverer of Mars' two moons, suggested an unsettling possibility for the first time in the summer of 1894. Maybe gravity doesn't work the way we thought?[112] Is it possible Newton was wrong?

For scientists, the defining characteristic of our field is the experiment. If an experiment's results do not confirm our hypothesis, it is the hypothesis that must change. This is an ideal that depends on there being a simple, crucial experiment whose result all involved agree will be the deciding factor of which idea is correct.

The reality is never this simple.

It is always easier to add an extra parameter to a previously successful theory, than scrap the whole thing and start from scratch: Mercury doesn't move as expected? Simple, just keep adding ever tinier planets. But the question arises, when do you stop making excuses and look for a new hypothesis?

Occam's Razor is the supposition that the simplest explanation that fits all the data is usually the correct one. Unfortunately, there is rarely any agreement on what explanation is "simplest," and "usually correct" is not the same as "always correct."

In his book *The Structure of Scientific Revolutions*, the philosopher Thomas Kuhn explains that science does not progress by a constant stream of crucial experiments where scientists constantly evaluate all of their assumptions and successes with each new experiment. Rather, we scientists use the results of previous experiments to build a framework, or paradigm, upon which we hang all of our new experimental results to construct a picture of the universe. Based on this picture, scientists think of new experiments to perform and decide how to interpret their results. The majority of the time we are simply filling in the missing pieces of a picture we have inherited from those who came before.

When experiments don't provide the results we expect (e.g., when the planet Vulcan fails to appear) we look for reasons that allow us to keep as much of the framework as we can, even if the details of the picture become more complicated than we would like (e.g., rings of Vulcanoids specially oriented to affect the planet Mercury and no other).

Eventually, someone comes along who suggests a totally different framework that creates an entirely new picture, a new paradigm, by which to interpret our previous results. Whether this new paradigm is "simpler" than what came before, thus satisfying Occam's Razor, is rarely agreed upon by the scientists of the time. According to Kuhn, scientists during these scientific revolutions rarely have a rational reason for choosing one framework over another.

For instance, Copernicus proposed a new paradigm in which the Earth was only one planet among many planets in orbit around the Sun. When Galileo's telescope revealed moons orbiting Jupiter and that our Moon, Sun and planets all had features of their own, it refuted a tenet of the old paradigm that all motion must center on the Earth, while confirming a central aspect of the new paradigm that the heavenly spheres were physical places just like the Earth.

Yet, Copernicus' model of planets orbiting the Sun in perfect circles did not predict the positions of the planets as well as Ptolemy's complex systems of celestial spheres within spheres. Understandably, a reasonable a person could choose the old complexity over the new simplicity when simplicity didn't work. But new paradigms suggest new hypotheses with new experiments that might make no sense under the old framework.

The parallax motion of nearby stars over the course of a year is a phenomenon that makes no sense in a universe where the Earth doesn't move. Likewise, a universe where the Earth is simply another planet fairly requires that the Moon, planets and Sun also exhibit features and turn on their axes just like we. In time, all of these phenomena were revealed through the ever-increasing magnification of telescopes, while the physical laws of Kepler and Newton revealed that the same force that causes an apple to drop here on Earth makes the planets orbit the Sun in elliptical, not circular, paths producing even better agreement to observations than Ptolemy's crystalline spheres.

Whatever the reason individual scientists have for accepting one framework over another, eventually no serious scientist is left to propose new additions to the old paradigm and the scientific revolution is complete. From that moment onward, it becomes the task of new scientists to understand the implications of news laws within the new framework.

At the dawn of the 20th century, astronomers believed they understood the framework of Copernicus, Galileo, and Newton so well that the well-respected astronomer A. A. Michelson could write:

> The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. Nevertheless, it has been found that there are apparent exceptions to most of these laws, and this is particularly true when the observations are pushed to a limit, i.e., whenever the circumstances of experiment are such that extreme cases can be examined. Such examination almost surely leads, not to the overthrow of the law, but to the discovery of other facts and laws whose action produces the apparent exceptions.[113]

By this reasoning, since the famous astronomers of the 19th century were doing nothing more than filling in details of well-established laws, then perhaps it is no coincidence that today almost no one remembers their names.

By contrast, the 19th century was the greatest time of discovery for forces that had apparently little to do with planets or gravity: electricity, magnetism, and optics. In 1865, while astronomers were busy looking for Vulcan, the Scottish physicist James Clerk Maxwell unified these phenomena into a set of simple equations that reveal light is a wave of changing electric and magnetic fields.[†††]

We tend not to think of electricity and magnetism outside of the electronics that powers our daily lives, yet every sense with which we perceive the world - taste, touch, sound, and smell - are just the interactions of atoms and molecules via their electric fields (while sight is the direct detection of light). Albert Einstein was different, though. In 1895, at the age of 16, he thought very deeply about light and the ramifications of the laws that govern it.

For instance, he wondered, what would a person see if he could ride a beam of light? A person on a beach sees waves crashing one after another on the shore, the water waving in and out. But a person surfing on a wave, traveling at its speed, rides a constant crest that no longer appears to "wave." Maxwell's equations provide no solution for this possibility with light. They require that for light to be "light" it must move precisely at the speed of light. In fact, Michelson and other astronomers had verified this experimentally: no matter where you look or how you move, light always moves past you with the same speed.

It so happened that Maxwell's equations have other problems with moving observers: charged particles in motion produce magnetic fields while stationary ones don't. Depending on whether I am standing next to a proton or moving by one at a constant rate, I will see it produce different fields. This may not seem like a profound problem but it puzzled Einstein and would eventually lead him to solve the mystery of Mercury, and in the process overturn how we understand the nature of time and space.

[†††] Every generation of physics students is aware of "Maxwell's Equations" while the astronomers of the 19th century are largely forgotten.

The reason this is so puzzling is that the Relativity Principle, which has its origins in Galileo's efforts to prove that the Earth can move without us feeling it, states that there is no experiment that can reveal whether a person is at rest or in constant, uniform motion. This principle must be true since even when we are at rest in a laboratory, any experiment we do there is really flying at tremendous speeds as the Earth hurtles through space. Everything is always in motion relative to something. But Maxwell's laws don't satisfy this principle.

Let's say I hold two protons while standing inside a rocket moving at a constant speed. I open my hand and, because we are at rest with respect to one another, all I see is a repulsive electric force between them (their like charges repel). They fly apart and take exactly one second to hit the surrounding wall. But to a friend standing outside the rocket, she sees me and the two protons in motion. There is now an additional magnetic force of attraction between the protons that causes them to move apart slower. By her watch, the same protons now take *two* seconds to hit the wall. But by the Relativity Principle we can't both be correct; otherwise, measuring the time it takes the protons to fly apart would be a simple test to determine who was in motion and who was not.

Einstein found that both observers could be correct, provided that time passes differently for people at different velocities. Moving clocks run slowly compared to those at rest, and the closer they approach the speed of light the slower time runs. The answer to Einstein's original question is the reason a person moving at the speed of light sees a light wave stop waving is because time has stopped altogether.

Einstein was not the first to propose a solution where space and time were relative. Henri Poincare, the French mathematician and philosopher had done so in his book, *La Science et l'hypothese* which was widely read among the intelligentsia of turn-of-the-century Europe. Einstein was influenced by Poincare (as apparently was the artist Pablo Picasso).[114] Einstein, however, took these radical ideas to their natural mathematical conclusions and had the courage to declare that this is how reality works no matter how much it might disagree with common sense (common sense, according to Einstein, being just the collection of prejudices someone acquires by the time they are 18).

In 1905, Einstein published his special theory of relativity specifically looking at how motion at constant velocity (a "special" case of motion) solves the problems with Maxwell's equations. The only way for the laws of electricity, magnetism, and light to work for any observer traveling at any constant speed is if the following are true:

1. Moving clocks run slowly compared with clocks at rest.
2. Moving meter-sticks are shorter compared with meter-sticks at rest.
3. Events that are simultaneous for observers at rest need not be simultaneous to observers moving by at a constant speed. Simultaneity is relative.

As revolutionary as these ideas were, Einstein realized his relativity theory was incomplete. What about *any* motion, including those where an observer is accelerating? It was this question that brought Einstein into the realm of Newton when he realized that an extension of the Relativity Principle to acceleration requires that any physical phenomenon that happens while accelerating must also happen in a sufficiently large gravitational field.

If you have visited Disneyland you have probably experienced this "Equivalency Principle" for yourself. There is a ride where you sit in a room and feel as if are you are zooming through space in a rocket. When the view out the front "window" shows the rocket blast off, hidden hydraulics tip the room backward letting the Earth's gravity pull you back into your seat. The pull of gravity is indistinguishable from an acceleration and the reason the ride works. The same principle is at work in movies like *2001: A Space Odyssey* or *Interstellar*, where a spinning space station produces an acceleration which the characters experience as "artificial" gravity.

Einstein spent another decade working through the mathematics of this more "general" theory of relativity. When completed in 1915 it resulted in two more strange phenomena:

1. Gravity is a curvature of the fabric of a four-dimensional "spacetime" (three dimensions of space and one dimension of time).
2. Clocks close to a massive object run more slowly compared with those farther away.

Gravity is no longer a force between objects with mass, as Newton discovered, but a warping of the fabric of both space and time that reproduces all the planetary motion predicted by Newton's and Kepler's Laws. If you've ever seen a coin roll into one of those giant plastic funnels at a science museum you will see it sweep in and out of the "gravity well" at the bottom in a way that reproduces the elliptical orbits and changing velocities of planets around the Sun.

But very close to a massive object like the Sun the warpage in spacetime causes planetary orbits to curve a little more than what Newton and Kepler predict. The added curvature causes a planet to overshoot the point where its orbit began and each new orbit begins a little farther along than the one before. As a result its orbital axis shifts a tiny amount each trip around and traces out a shape like a flower with each orbit a petal (rather than a single constant ellipse). A person on a more distant planet like the Earth sees a planet like Mercury cross the Sun earlier than otherwise predicted and over time, the discrepancy grows.

Announcing his new General Theory of Relativity to the Prussian Academy of Sciences on November 18, 1915, Einstein stated, “In this work, I found an important confirmation of this radical Relativity theory; it exhibits itself namely in the secular turning of Mercury in the course of its orbital motion, as was discovered by Le Verrier. Namely, the approximately 45 arcseconds per century amount is qualitatively and quantitatively explained without the special hypotheses that he had to assume.”

So much for Vulcan.[‡‡‡]

“Furthermore,” continued Einstein, “it shows that this theory has a stronger (doubly strong) light bending effect in consequence through the gravitational field,” than what could be explained by Newton’s gravity alone. In other words, just like with Mercury, light traveling close to a massive object has its path deflected by the curvature of spacetime more than could be accounted for by Newton’s Laws alone.

The mark of a successful scientific theory is one that ties together a wide range of physical phenomena, explaining accurately what is already seen, and predicting results for experiments yet to be performed. General Relativity did exactly that. It tied together space, time, motion, light, electricity, magnetism, matter and gravity. It explained what more than 50

[‡‡‡] Almost no one remembers the hypothesized planet today. In 1962, the American television writer, Gene Rodenberry, was drafting a story for a new science fiction TV show and his main alien crew member was labeled a “Martian.” Roddenberry later changed this to something more exotic. What caused him to instead make Star Trek’s Mr. Spock a Vulcan, he never said.

years of transit and solar eclipse observations had failed to verify, and suggested a result for a new test: the bending of starlight passing near a mass like the Sun. When could such a phenomenon be tested?

The answer was during a total solar eclipse.

The change in light would be subtle. Starlight passing through the Sun's warped gravity field would cause the light to reach Earth from a slightly different direction than if the Sun were not present. Stars near the Sun on the sky would all appear slightly shifted away from its disk when compared to their known positions. A photo of the totally eclipsed Sun will record the faint light of all the stars that are momentarily visible. Compare these positions with a photo of the same star field without the Sun (perhaps taken as little as a couple months after the eclipse) and the change in the stars' positions should reveal any gravitational influence of the Sun.

<<Insert GReclipse.tif here>>

The first attempt to measure this deflection of starlight during a solar eclipse in 1912 failed due to bad weather.[§§§] The next opportunity occurred on August 21, 1914 from southern Russia. Unfortunately, the assassination of Archduke Ferdinand in July of that year led to the German invasion of Russia on the first of August and the start of the First World War. Einstein's colleague, Erwin Freundlich, who traveled there specifically to measure the deflection of starlight, found himself instantly converted from visiting astronomer to enemy alien. He had all of his instruments confiscated, and was instantly arrested by the Russians.[115] As the United

[§§§] The astronomer, C.D. Perrine, director of the Observatory in Cordoba, Argentina reported rain before, during and after the eclipse; "we... suffered a total eclipse instead of observing one."

States remained officially neutral, a group of astronomers from California's Lick Observatory was allowed to remain, but ran out of luck when the weather turned bad and Russian officials impounded their instruments for the rest of the war.[116]

The First World War hindered the proof of Relativity in more ways. While today we may forget Einstein was German, scientists of the day did not. A British zoologist included in his paper of 1918 a note that "No quotations from German authors published since August, 1914, are included. '*Hostes humani generis.*' [enemies of the human race]."[117] The Director of the Observatory of Turin in Italy gave lectures on the nature of "German science and Latin science" exhorting his audience to not look to German scientists, "for bold initiative, for flashes of genius, for fruitful ideas, for results expressed in a brilliant, clear, comprehensive, and simple formula, as are all the laws of Nature….[118]

Even where hatred of Germany wasn't evident, many of the Allied scientists who heard of Einstein's theory of gravitation were sure it must be wrong. The American astronomer Heber Curtis was the leader of Lick's efforts to search for both Vulcan and any deflection of starlight. The photographic plates he acquired during the 1918 total solar eclipse in Washington State produced nothing but ambiguous results (in part because of thin clouds, but mostly thanks to cobbled together equipment replacing those still impounded in Russia). Yet still he thought them worth publishing, so that, "When the Einstein theory goes into the discard, as I prophesy it will go within ten years, these negative or indecisive results will be more highly regarded than at present."[119]

Ironically, by war's end it was a British astronomer, Sir Arthur Eddington, who was the unofficial spokesman for the German theory of relativity. Thanks to a colleague in Holland, Eddington had the only copy of Einstein's paper to reach England during the war and he was the primary person spreading word that the mystery of Mercury's orbit had been solved. As much as Allied scientists may have been loath to accept the broader implications of Einstein's theory, the solution to the problem of Mercury could not be ignored.

As a devout Quaker, Eddington was a pacifist like Einstein during a time when pacifism was not a popular position on either side of the war.[120] In England, those who refused to serve on the basis of conscientious objection faced possible imprisonment. According to Eddington's student, Subrahmanyan Chandrasekhar, it was a social disgrace to even associate with a conscientious objector and the view amongst the older faculty at Cambridge University where Eddington taught was that it would bring disgrace upon the institution to even have one in their midst.

To avoid such a scandal, and to protect Eddington from the draft, "They therefore tried through the Home Office to have Eddington deferred on the grounds that he was a most distinguished scientist and that it was not in the long-range interests of Britain to have him serve in the army…. Eddington was deferred with the express stipulation that if the war should end by 1919, then he should lead one of the two expeditions that were being planned for the purpose of verifying Einstein's prediction with regard to the gravitational deflection of light."[121]

The eclipse on May 29, 1919 would be the best opportunity yet to test the deflection of starlight as the Sun would be passing before the Hyades star cluster, resulting in numerous bright stars visible beside the Sun. Totality would cross the Atlantic Ocean, touching land in northern Brazil and once again on the island of Principe, off the coast of western Africa. By 1919 the war had ended, but astronomers from nearly every nation that would normally mount such an expedition were out of money or simply too busy recovering from the devastation of war. England, alone, found itself prepared to set sail to test this new theory of gravity.[122]

Eddington and an assistant from Cambridge would head to Principe while the Astronomer Royal, Frank Dyson, sent two of his assistants from the Greenwich Observatory to observe the eclipse from Brazil. Each team would take along two instruments for photographing the eclipse. Their task was to capture photos of the eclipse, as well as comparison plates of the same region of sky without the Sun present. Any change in the positions of the background stars would reveal the effects of Sun's gravity on light.

But the observations and their analysis would be difficult. The deflection Eddington was looking for was tiny: only about an arcsecond in size (an acrsecond is 1/1800 of the solar diameter as seen from the Earth). Any temperature, focus, or mechanical changes in the telescope could skew where the individual stars fell on a photographic plate by at least that amount. This required taking even more comparison photos.

For the team in Brazil, where the eclipse occurred soon after sunrise, they would remain for two months so that they could photograph the same grouping of stars as the eclipse (with the telescope in exactly the same position) but after the Sun had moved away and those stars were now visible in the darkness before dawn.

In Africa, where the eclipse occurred near noon, it would take nearly half a year for the same stars to be photographed in the same position by night. As a compromise, comparison plates were taken back in England before the expeditions set sail. This was not an ideal arrangement, but then again, both groups were already making do with make-shift equipment cobbled together from parts available in the aftermath of war. The end result was that a difficult experiment would be performed under difficult conditions where the final results, though simple in principle (a deflection of 1.75 arcseconds would confirm Einstein, a deflection of half that would support Newton), in practice would be anything but.

To prepare the public for the results of an experiment testing the implications of a theory that even professionals couldn't claim to fully understand, Eddington, Dyson, and their assistants implemented a public relations program aimed at both the general populace and the scientific community.[123] It was an effort without clear precedence. For the public, they published explanatory newspaper articles about the experiments in *The Times* of London, gave public talks. For the scientific community, they wrote scholarly articles in *Observatory*, a leading professional journal of which Eddington was the editor.

These articles continued through the launch of the expedition and to the day of the eclipse itself with breathless reporting from the astronomers on station as the eclipse commenced:

> Astronomer Royal (Sir Frank Dyson) informs us that he received yesterday a cablegram from Professor A. S. Eddington and Mr. Cottingham from Princes Island [sic], West Africa, stating that the eclipse of the sun was observed there

> through clouds, but they are hopeful of obtaining good results (The Times of London, June 4^{th}, 1919).

A day later, *The Times* informed readers that "further telegrams from the British astronomers who observed the total eclipse of the sun last week report that the photographs taken at Sobral, Brazil, were quite successful, and the negatives already developed show all the stars that were expected to be recorded."[124] Upon their return, further articles highlighted their busy work over the glass plates to tease out the results that would determine which great mind, Newton or Einstein would prevail.

During this time the public weren't the only ones that needed to be properly prepared. Einstein's mathematics and its implication were so complex that even Dyson could write that "The result was contrary to my expectations, but since we obtained it I have tried to understand the Relativity business, & it is certainly very comprehensive, though elusive and difficult."[125] Prior to making any official announcement of their results, Eddington first quietly presented their findings to a leading group of British mathematical physicists. Only with their favorable reception were Eddington and Dyson confident to announce what they'd found at a Joint Meeting of the Royal Astronomical and Royal Societies, two weeks later.[126]

On November 6, 1919, in front of over a hundred members of the scientific community (as well as one reporter from *The Times* of London) Dyson and Eddington announced that Einstein's theory had been confirmed.[127] Upon hearing their analysis the President of the Royal Society declared, If the results obtained had been only that light was affected by gravitation, it would have been of the greatest importance…. But this result is not an isolated one; it is part of a whole continent of scientific ideas affecting the most fundamental concepts of physics…. The difference between the laws of gravitation of Einstein and Newton come only in special cases. The real interest of Einstein's theory lies not so much in his results as in the method by which he gets them. If this theory is right, it makes us take an entirely new view of gravitation. If it is sustained that Einstein's reasoning holds good – and it has survived two very severe tests in connection with the perihelion of Mercury and the present eclipse - then it is the result of one of the highest achievements of human thought.[128]

The next day the headlines blared out from *The Times*,

REVOLUTION IN SCIENCE. – New Theory of the Universe. – Newton's Ideas Overthrown.[129]

The groundwork Eddington laid for Relativity's favorable – even ecstatic – embrace in London caught the attention of the American media that had not been subjected to Eddington's public relations onslaught of the preceding year. The headline in the next day's *New York Times* read:

LIGHTS ALL ASKEW IN THE HEAVENS – Men of Science More or Less Agog Over Results of Eclipse Observations – EINSTEIN THEORY TRIUMPHS – A Book for 12 Wise Men: No more in All the World Could Comprehend it, Said Einstein, When His Daring Publishers Accepted It.[130]

Eddington made Einstein a genius, but the American press made Einstein a star.

Thanks to the 1919 total solar eclipse we now live in a world where Einstein's name is universally known and synonymous with brilliance, where everyone knows that black holes "suck in" light, that science fiction starships fly through space using their "warp" drive, and that "everything is relative."

No scientist or philosopher predicts any longer that everything that can be known is known, or even that what is known now will always be known to be true. Even our language has changed as scientists are careful now to talk about scientific "theories" instead of "laws" even when, like the General Theory of Relativity, it has withstood nearly a century of repeated experimentation.

That repeated questioning and testing of Relativity has been vital to its success. In the years since, there have been those who have claimed that given Eddington's public (and not so public) support for Relativity that he cooked the books on his "decisive" experiment; that he threw out data that didn't match the answer he wanted.[131] It's true the observations were not all that anyone could have wanted in a decisive experiment. Errors introduced in the stellar positions due to focus, tracking, temperature, and travel were not easily, or obviously removed by all the comparison plates, and Eddington *did* throw out data he felt were not trustworthy.

Yet, in a 1979 reanalysis of the plates using modern automated measurement software, the Greenwich Observatory confirmed the earlier results of 1919.[132] More importantly, however, even after the results of 1919, the scientific community as a whole (including Eddington and Dyson) recognized the need to confirm these results during subsequent eclipses. At the next optimal eclipse in 1922, the skeptical astronomers at Lick Observatory successfully acquired results that confirmed those of Eddington, yet the testing and re-testing didn't end there. Such is the tenacity of science that the last professional eclipse expedition to measure the deflection of starlight was in 1973, led by a University of Texas team looking to test Einstein's theory against an even newer alternative.[133]

Since then, radio astronomers have been able to measure the same deflection of light around the Sun but now using quasars, distant supermassive black holes, to a precision far higher than Eddington could have ever dreamed.[134] And still, General Relativity continues to have its details subjected to experimentation (even earning two astronomers a Nobel Prize in Physics in 1993) in the hopes of learning more about its strengths and limitations. Like the orbit of Mercury a hundred years ago, any future weaknesses discovered in Einstein's gravity will raise new questions, spurring new experiments, and in time lead to even deeper understanding of the strange new and magnificent universe in which we live.

"The perfect golden ring of light with a blazing jewel set in it was a sight that will never be forgotten by those who had the good fortune to see the eclipse yesterday morning from a place of vantage…. The astronomers may have further advice about the Einstein theory, or whisperings of a planet nearer the sun than Mercury, or word of a new element in the sun. But the great lesson of the eclipse to the masses of those who saw it is that one little unusual phenomenon in the skies makes us realize how closely akin we all are in this common planetary boat out on an ethereal sea that has no visible shores. "

--The New York Times, January 25, 1925

Chapter 6: Saros Siblings

The Faroe Islands are a tiny archipelago of 18 glacier-carved islands that float on the cold, grey waves of the North Atlantic. Their jagged mountains stretch out of the sea to catch the rain-filled clouds blown over from far-off Iceland. Everywhere I look water tumbles down treeless slopes of volcanic rock, gathering into pools and waterfalls that pour back into the surf below. When the Sun finally does break free from the overhead gloom, the cascades come alive and burst with rainbows while sunbeams race across the mountain tops. The British, no strangers to harsh weather, call this the Land of Maybe. Upon arrival, I have a hard time believing this is where I've come to see a total solar eclipse.

It won't be the first total eclipse seen here by the descendents of the Norseman who once fished these waters. One of the oldest stories the islanders know tells of four brothers from the island of Suðuroy who may have witnessed the total eclipse of May 30, 1612.

> They were brave and strong, but they were constantly quarrelling and fighting, and sometimes even threatening to take each other's lives. One day, when they were out in the hills tending their sheep, darkness suddenly fell upon them. They were terrified and promised God that if they survived they would change and become better men. Soon afterwards, the sun came out again, and legend has it they hugged each other and never fought nor quarreled again for the rest of their lives.
>
> -National Museum of the Faroe Islands

Having experienced the power of an eclipse with full warning of what to expect, I can believe its power to change lives when wholly unexpected. The eclipse this time will be far from a surprise to the 50,000 people who call these islands home. Over the last three days an additional 11,000 eclipse-chasers have descended upon the islands; each one eager to see what was once a subject of terror, but what is now one of tourism.

The lone total solar eclipse of 2015 has not made it easy for the ever-growing throngs of "coronaphiles" to reach their moment in the Moon's shadow. Totality touches land in only two places this time, the Faroe Islands at latitude 62^{o} North, half way between Scotland and Iceland, and the even more remote islands of Svalbard, 80^{o} North latitude off the coast of northern Norway (total population: 1200, not including the polar bears).

Based on the latest weather broadcast from Denmark (the only one I'm getting with English subtitles), the omnipresent clouds are forecast to break sometime around the moment of totality, give or take an hour. I'm told the chances are better in the northwestern part of the islands, the direction from which the winds blow, so I have positioned myself on the literal edge of the archipelago as far north and west as one can go. I am sitting on a wooden bench built to stare out to sea along the dramatic thousand-foot-tall volcanic cliffs teaming with seabirds that drop to the surf below. The sense of being at World's End is profound – it's as if here the Creator ran out of rock and simply quit. Beyond my perch nothing more than a few rocky islands dot the northwestern horizon, while beyond them is the sea.

For most eclipse-chasers, the goal for picking a spot to see an eclipse is a combination of clear skies and proximity to the central line of totality to maximize their minutes, and even seconds, of darkness. But in this land of tall mountains and deep valleys, it's crucial to find a spot where the morning Sun is guaranteed to be above the surrounding hills while eclipsed. Michael Zeiler, an expert in systems of graphical information, has created gorgeous maps of the Faroes revealing the sunlight and shadow across the landscape at the moment of totality. I've seen them everywhere on the islands these last few days, and locals and tourists alike each pore over them debating the perfect spot from which to see the Sun. I've found my sunny spot at the top of a sheep meadow overlooking the tiny town of Gasadalur on the western island of Vágar. Whether it will be free of the clouds is beyond the power of Zeiler's maps to promise.

It's an article of faith amongst eclipse-chasers that the best eclipse-viewing spots are those with access to easy mobility so that viewers can quickly drive in one direction or another depending on the clouds. My meadow, unfortunately, sits at the end of a one kilometer-long, one-lane tunnel through the surrounding mountains. Quick movement is out of the question. Besides, the weather changes so quickly here that expert eclipse-chaser, and psychologist, Dr.

Kate Russo claims the best strategy is to find your place and stick with it: “This eclipse will be for those with nerves of steel,” she warned after spending a month in these islands watching the changing weather each day at exactly the moment of totality.

As I sit at my perch, I look over my shoulder to see yet another squall come ashore; it drenches me and at two hours until the eclipse begins, I remind myself: nerves of steel.

It took me more than 25 hours of non-stop air travel on progressively smaller airlines to reach these islands and then drive my rental car (one of the last available) to the house of my host, Lis Mortensen, a curator at the National Museum of the Faroe Islands in the nation’s capitol of Torshavn. Mortensen has created an exhibit on solar eclipses, their causes and local history, “I felt it was important and that people would want to come learn about the eclipse,” Mortensen told me. “Now that the eclipse has gotten close, it’s set attendance records. Everyone wants to know what they’ll see and where to go to see it.”

It’s important to remember how recent a change this is. For all but the last few hundred years of human history, solar eclipses were seen only by those who happened to live within totality’s path. The Faroe Islands are no exception. When a total solar eclipse crossed these islands in 1954 the population was still largely isolated from the rest of the world; radio had only recently come to the islands, and if not for the work of Niels Pauli Holm, a Faroese ophthalmologist, no one would have known what was about to happen and how to observe it.

As an expression of this uncertainty and confusion leading up to the 1954 eclipse, Mortensen quotes in her museum exhibit the experience of a then-young Faroes girl:

> I went home and my mother asked me to collect the clothes from the clothes-line. She was afraid that the clothes would burn. People were talking about total destruction, and I remember that people frequently visiting us talked about it. We were asked: “What are you going to do?” We didn’t have any answer to this, looking uneasily at each other….[The old people] were afraid the houses would be destroyed.
>
> --National Museum of the Faroe Islands

The mood is noticeably different now as the streets are filled with tourists and restaurants and bars all over town feature signs offering special limited edition solar eclipse beer and fish burgers with homemade tartar sauce. These signs are in English and Dutch as well as Faroese, a language spoken only by the people who live in these islands. It is one of many languages in danger of disappearing in our modern global-internet age and the eclipse has posed a problem, as there are no words for a number of the phenomena associated with the eclipse. Wary of letting the language adopt too many English (or Heaven-forbid, Danish) words and losing its heritage altogether, they search for analogous Icelandic words, its nearest linguistic relative, so as to express what we’ve all come to see: *Solarmyrking*, the solar eclipse.

Sitting on my bench in this meadow, I am astounded by the number of languages I hear from the eclipse-chasers: Greek, German, French, and more that I can’t identify. The Greek eclipse-chasers comment that after a week in the islands I am the first American they have heard. The joy they show seems to indicate I’ve given them an advantage in some sort of nationality-bingo game to which I am not privy. My 25 hours of flying also appears to be a record for this crowd. But once you've seen totality, traveling half way around the globe just isn't too far to see it again.

The very first person to travel to see a total solar eclipse, the world's first eclipse-chaser, appears to be Monsieur le Chevalier de Louville, Member of the Royal Academy of Sciences at Paris. He traveled to London to see the total solar eclipse of April 22, 1715 that was predicted by Sir Edmund Halley.[135] Halley was famous for using his friend Sir Isaac Newton's laws of motion to predict the courses of the Moon and comets as well as the dates, times and places of eclipses both future and past. According to his calculations, this would be the first eclipse to pass over London in 575 years; as one of the first to have its exact time and location predicted (not counting the stories of Miletus of Thales two thousand years before), odds are this was the first one for which an avid enthusiast could make definite travel plans to see it.

At that time, before the invention of the widespread availability of telescopes and cameras that coronaphiles are setting up around me, the most common instrument the public had at their disposal for recording an eclipse was the pendulum clock. Halley used this fact to perfect his orbit for the Moon which would allow him to make even better eclipse predictions. In the weeks before the eclipse, Halley sent out broadsides to be posted across the country asking for anyone who could see totality to record its duration using their clock and let him know their results. The map of those who saw totality (as well as the time and duration of its occurrence) would determine the exact position and motion of the Moon's shadow and thus its path around the Earth.

The public was asked to take part in an almost identical act of citizen-science 210 years later in New York City. On the morning of January 24, 1925, a total solar eclipse was predicted to sweep across the state of New York, with the southern edge of its band splitting the island of Manhattan into those who could see totality and the solar corona and those who couldn't. Astronomers from several northeastern universities, including Yale, Princeton and Cornell, sought to refine the size and distance to the Moon and so possibly solve some as yet unexplained discrepancies in the time and duration of recent eclipses. Articles filled the local newspapers urging the public to go out and witness the celestial event from their rooftops, street corners, wherever they had a view of the Sun. The headline and story in *The New York Times* for the morning of January 20th read:

> **SCIENTISTS ASK AID OF LAITY IN ECLIPSE**
>
> **Public's Observations Along Edge of Shadow Counted On for Important Data.**
>
> **MAY SOLVE MOON'S SHIFTS**
>
> If the weather is clear, one of the features of greatest interest for Manhattan will be the determination of the exact line which separates the total eclipse from the partial eclipse. This line is expected to occur somewhere between 110th Street and Seventy-second Street. An observer north of the line will see

> everything - the complete blackening of the sun's disk, the piercing through of the brighter stars and planets, the thin red rim about the sun, the delicate tree-like scarlet "prominences" outside on the red rim and the pearl-tinted lines of the corona extending in all directions away from the sun.
>
> Amateur photographers and observers in Manhattan will have a chance to help clear up one of the most difficult scientific questions about the eclipse. By fixing the exact line which separates the total eclipse from the partial eclipse, they can establish the exact diameter of the moon and the exact course of the moon….
>
> While the observer is surer of seeing all the heavenly sights by taking a position north of 110th Street, he will have the excitement of engaging in cosmic detective work if he stays in the doubtful zone between Seventy-second Street and 110th Street and studies the shadow effects from his rooftop.

The article claimed that not since the invention of the camera for astronomical use had the edge of totality crossed a great population center like New York City. The result was that never before had so many people with so many cameras photographed an eclipse from along totality's edge, capturing in the process a phenomenon that though seen innumerable times before had never been named. Whether as a result of the wealth on display in Manhattan's shops for the more well-to-do, or merely a reflection of the roaring excess of the 1920's itself, the name they gave was perfect and continues to be used to describe what for me is the highlight of every eclipse: the diamond ring.

<<Insert NewYork1925.tif here>>

Witnesses that day remarked in great numbers on the incredible beauty of that final instant before the Sun is totally extinguished. At that moment, one last ray of the solar disk shines down a lunar valley along its limb and produces a brilliant pinprick of light set in the luminous ring of the just-emerging corona. A headline in *The New York Times* three days after the eclipse read:

THAT 'DIAMOND RING' IN THE SUN'S ECLIPSE

A Remarkable Photograph Taken at Saugerties Seems to Prove it No Illusion[136]

Each total eclipse displays two such rings, one at totality's start, the other at its conclusion; to my mind the second always seems most beautiful as a final punctuation on the spectacle just finished. Of the roughly 6 million people living in New York City in 1925, those in Manhattan right along the southern edge of the shadow would have seen a totality of no more than an instant - consisting of a single diamond ring - the jewel-like gleam of the Sun never fully hidden.[****]

[****] In 2017, the residents of St. Louis and Kansas City, Missouri will get the opportunity to see this same phenomenon in exactly the same way, as each city is split in half by the eclipse's path.

Because winters are cold in New York and the forecast was for snow the day of totality, an unusual plan was put in motion for a fleet of 25 airplanes (including a dirigible) to take to the sky with cameras and other instruments to record the moments of totality and broadcast their results through a constant stream of radio commentary to the public below. A reporter for *The New York Times* captured the drama of the largest formation of airplanes to fly across New York since the end of the Great War only six years before:[137]

> As the machines winged toward their destinations, the shadow [of the Moon] grew larger, while Major Hensley, his lips only an inch or two from the microphone, told the millions within radio distance what was going on.… Looking from the cockpit of [his] airplane, the observers saw the shadows deepening over Long Island Sound and the Connecticut shore. Far off on the horizon, at the extreme northerly edge of the shadow, a play of soft green, purple and deep blue light could be seen… Then came totality and with it the darkness of night…. Higher and a little to the right the planets Mercury, Venus and Jupiter glowed with a soft blue light as they burst into prominence with the dimming of the greater luminary…. The pilots of the machines, though their minds were intent on their jobs, found times to gaze on the spectacle. The scientists in the cockpits were enraptured. They saw the eclipse under conditions that no others had ever experienced.[138]

The novelty of the eclipse would also be communicated to the public through moving pictures taken from Yale Observatory in New Haven, Connecticut, and then sent by airplane to New York City so that they could be playing in theaters on Broadway by that afternoon.[139]

Airplanes play an even larger role in eclipse-chasing today. As I sit here I can see blue sky coming over the horizon but I can only pray it gets here in time. Above me, however, are thirty specially chartered airplanes full of passengers with no need to worry about what the weather will bring. Three of them are Boeing 737 jet airliners that took off from Iceland to be here at totality, while three private nearly-supersonic jets have flown from Paris and Geneva, Switzerland. At the moment of totality they will literally turn to chase the Moon at nine-tenths the speed of sound; fast enough to prolong totality from the two minutes and 20 seconds that I will, hopefully, see on the ground to almost four minutes in the air.

They are not the first to prolong totality in this way. The record for the longest duration of darkness is held by the supersonic Concorde that as a mere prototype in 1973 was chartered by a group of international scientists to streak across Africa at twice the speed of sound at an altitude of 55,000 feet. From that height the sky was black and the curvature of the Earth was clearly visible as was the shadow of the Moon beneath them. At a speed of almost 1300 miles per hour, the same as the speed of the Moon's shadow moving across the Earth, the Concorde stretched what was normally an exceptionally long seven minutes on the ground to an astounding 74 minutes of totality in the sky.[140]

Older coronaphiles tell me that the 1970s was the decade when commercial eclipse chasing really began. The first public cruise ship chartered to see a total eclipse of the Sun occurred in 1972 (900 miles off the coast of New York in the western Atlantic) the same year as the release of the Carly Simon song, “You’re So Vain” in which the un-named subject of the song flew “your Learjet up to Nova Scotia to see the total eclipse of the sun.” The first commercial flight for amateur solar eclipse-chasers was an Ansett Airlines flight chartered out of Perth, Australia in 1974 where all the seats were removed from the left side of the plane so photographers could set up cameras and telescopes to look out the small windows.

Public interest in eclipse chasing has gotten exponentially larger in the decades since. In 2001, Doug Duncan, an astronomer, educator, and long-time eclipse chaser planned to charter the Concorde to reproduce the extreme-duration 1973 eclipse but this time for members of the general public who could afford the cost. At $10,000 a seat it was only marginally more expensive than a typical Concorde flight, but given the position of the Sun low in the sky, passengers would see totality perfectly framed in the Concorde’s tiny windows for the entire hour and a half flight across the Atlantic. Unfortunately, the Concorde he was in the process of chartering was the one that crashed upon take-off in 2000, after which the fleet was grounded, never to fly again.

Chartering cruise ships for eclipse-chasing was no less difficult. “They wouldn’t give me the time of day for two years,” Duncan told me when he tried to find a Mediterranean cruise line that was willing to alter course by a hundred miles to intersect totality off the Greek Islands in 2006. “Then finally, a year before the eclipse, they came back and said to me, ‘We don’t understand why, but a lot of people want to be on a ship going to where you want to go. So we'll let you have a third of our ship. Send us a non-refundable deposit of $100,000 by the end of the month and it is yours.'" Duncan had to take all of his savings and another mortgage on his house, but he paid the deposit. "I ended up taking 402 people, I hired 10 astronomers to speak, and I ran a kids program for 50 people and all the kids were flying kites off the back of the cruise ship. It was glorious."

Today, every eclipse that crosses any sizeable body of water is almost guaranteed to pass over a cruise ship carrying an array of expert speakers for the crowds, including astronauts astronomers, and scientific authors. In fact, there are nine ships in and around the Faroe Islands today for this eclipse.

The most dramatic solar eclipse I've ever seen was on just such an eclipse cruise across the Atlantic for which I was a speaker in the fall of 2013. It was from the deck of a four-masted luxury sailing ship, the *Star Flyer*, sailing from Spain to Barbados. Nearly the entire ship had been booked, just like Duncan had done in 2006, and so they agreed to alter course and intercept the moon's shadow for all of the 42 seconds totality would be visible from off the coast of Africa 20 degrees north of the equator.

It took a full week of sailing out of the Canary Islands under nothing more than billowing white clouds and baby-blue skies. In an almost eerie counterexample to what I am experiencing today, the day of totality was the only day that dawned cloudy and in the final ten seconds of masterful sailing by our captain he managed to reach the lone break in the clouds. The Sun disappeared behind the Moon at the exact instant we crested a wave and broke free of the clouds. Clutching the rigging with one hand and my hat with the other, the moment was made all the more special by its brevity and a horizon circled with storm clouds and rain in every direction but the one that mattered.

Back in the Faroes, one of the people in the air overhead is Bárður Eklund from the Visit Faroe Islands tourism board. He hangs from the open door of a helicopter photographing the Moon's shadow racing across the cloud-tops. Dr. Russo, the eclipse-chasing psychologist, has been working with the tourism board and others on the islands for over a year using her experience to help prepare the community for what is about to happen here.

Eclipse chasing scientists haven't always had a very good record of sharing the beauty of what they have come to see with the people who actually live there. The Faroes eclipse of 1954 took place during the start of the Cold War, when the islands were a NATO-early warning station. A small team of American scientists traveled here to study the eclipse and the only record they left is a tiny plate on a stone in the village of Lopra with the inscription: "Solar Eclipse Expedition 30 June 1954 US Air Force."

And that is par for the course for many of the solar eclipse expeditions stretching back through the 1800s where local populations were viewed as a source of free labor (at best) and potential source of danger and theft (at worse).

Alex Soojung-Kim Pang is a former deputy editor of the Encyclopedia Britannica who has researched the intersection of Victorian Era eclipse expeditions, tourism, and the people they encountered. He sums up the attitude of many Western scientists when on expedition, writing that "Before an eclipse, [local] crowds were merely troublesome, but during an eclipse they were far more dangerous: stirred up by jealous priests, shackled by ancient superstitions, constitutionally incapable of the same kinds of self-control on which Europeans prided themselves, they threatened to revert to savagery under the enormous emotional pressures of totality."[141]

The solar astronomer Norman Lockyer wrote of his 1871 eclipse expedition that his observations would have been ruined by 'the smoke of [Hindu] sacrificial fires…, if there had not been a strong force of military and police present to extinguish them; and in Egypt, in 1882, without the protection of soldiers, a crowd of Egyptians would have invaded the camp."[142]

This was the era that saw the beginning of a professional travelling-class. The new tourists, economically prosperous, who could afford months, if not years on the road, were well moneyed, well educated, and well read. They were encouraged to read about the geology, flora and fauna (and occasionally the people and customs) of their exotic destinations. The same railroads and steamships that made world-wide travel possible (as well as the rise of institutions like tourist-hotels, travel agencies, and travel literature that catered to the large numbers of Victorian tourists when they arrived) were indispensible for the new eclipse expeditions, the members of which were often drawn from the same well-connected leisure class.[143] The attitudes of the scientists towards the local inhabitants they encountered therefore mirrored the attitudes as a whole of the Victorian Age.

> It is not at all probable that one of the dusky lookers-on at our preparations had a remote idea of the approaching phenomenon, and certainly not of the objects of our arrangements… No effort could have given them the

slightest comprehension of the causes of the unusual darkness, nor why the white man should come so far to look at it.

-- Eben J. Loomis, 1896, *An eclipse party in Africa: Chasing summer across the equator in the USS Pensacola*[144]

Having seen multiple eclipses myself, it is my fervent belief, as it is others', that eclipses should be enjoyed by everyone fortunate enough to be in the path of totality, not just the scientists, or even the dedicated tourists who have come to see them. Today, Dr. Russo is leading this charge to share totality's beauty beyond the crowds of already excited eclipse chasers. Back in 2013, two years before the eclipse that has brought us both here, she arrived in the islands to work with local officials and spread the word on what was about to occur. "I really thought it was important to be a part of the community, being here, building it up, sharing it with the community, not just being an eclipse-chaser, coming in, seeing it, and going."

She'd experienced what it was like to be a part of the local community during an eclipse in 2012 when totality touched her native Queensland on the northeastern coast of Australia. Living abroad, she'd returned there to promote her book, *Total Addiction*, about the psychology of seeing an eclipse. "I had gotten there a month before and I was doing a survey of people before the eclipse and after the eclipse," Russo told me. "There was nobody on the ground in North Queensland who had actually seen an eclipse before." People who lived there were talking about leaving, not even staying to see the eclipse because they were so worried about the influx of tourists. "Oh no," Russo thought. "This is coming to your community; you need to be here."

She started going to markets, community groups, and schools to give talks. She made herself available for radio and TV interviews as someone who had seen what an eclipse was like. “And the more I did, the more interest there was, because once you’ve seen an eclipse and start talking about it you can’t help but become excited.” The great fear for Russo, as it is for me, is that for those who talk about eclipses without ever seeing one - the local officials, radio hosts, and TV reporters that flood the airwaves in every metropolitan community before totality - they just don’t understand the passion with which the experience grabs you as a physical thing. They can leave the public with a distorted view of what an eclipse can be. At best, they may suggest it is some sort of scientific novelty, an educational event that is worth seeing if you are free at the time. At worst, they may leave their viewers with the impression that eclipses are for oddballs, and that making the effort to see an eclipse is something only slightly demented people do. This is understandable, if you haven’t seen one yourself, you can’t help but not understand the experience.

It’s for that reason Russo now travels to eclipse communities to help share her knowledge of what the experience is like. A year before the eclipse, she and Geoff Sims, an eclipse-chaser with a PhD in meteorology from Australia, set up a citizen-science project asking local Faroese to photograph the sky where they live at exactly 9:40 a.m. (the time of the eclipse) every day for a month to compare with local weather statistics to gauge the chances of clear skies at different points across the islands on eclipse day.[145]

In February 2015, a month before totality, Russo returned to the islands to work with the tourism office as well as local media, schools, museums, businesses, and artists. Their goal was to develop and disseminate information for tourists and locals alike on where to go, what to look for, how to see it safely, and how to insure as many people as possible could share in the moment together. “A year ago,” she tells me, “even when they were thinking that maybe no more than 5,000 people would be traveling to the islands to see the eclipse, that still left 50,000 people here who needed to know what was happening.”

In my week before the eclipse, I heard her efforts first-hand on the local radio. I learned about one community where a hospital scheduled no surgeries so staff could pop outside for 20 minutes to see the lead up to totality. Elsewhere, schools made plans to let students stay home with their family to enjoy the experience together, while in other communities, the local schools became the center of the community event.

Russo became interested in eclipse-chasing in 1999 when she witnessed her first one on the coast of France, having travelled there by bus from Belfast to see it. At that same moment I too was experiencing my first total eclipse but a little farther along totality’s path in central Hungary. For both of us it was a profoundly moving experience. She calls us “Saros Siblings,” a term she’s coined for those of us having shared in this new experience during the same eclipse. It’s no accident the first hotel room in the Faroes was booked for this eclipse back in 1999 almost immediately after that event. Evidently another Saros Sibling of ours felt the need to see the corona again and didn’t want to miss out on a chance to get a room. In 2017, there will be at least 9 million new Saros Siblings as people flock to totality’s path in the United States.

…

Back in my meadow, sitting on my wooden bench there are now more than a dozen of us, more than I have seen in any one location in my week here in the Faroes. We've set up our cameras and are swapping stories of eclipses seen and missed due to weather. It's no one's first eclipse: five, eight, one gentleman has even seen 17 total eclipses in his travels around the world. And far from satiating their desire, like checking off an item on a bucket list, it leaves each wanting to see more. What will it be like in the U.S. when instead of a dozen we have ten thousand all gathered in one location?

The blue sky is suddenly upon us and as the clouds part overhead, we can see the eclipse is already underway. The excitement is palpable; it's what makes the experience so memorable for each person in their own way.

Geoff Sims saw his first total solar eclipse in 2002 in southern Australia. An avid photographer, he had read all about eclipses: what to expect, and how to photograph them. He piled all of his equipment in a car that he drove for three days across the continent to reach a point near the center of totality. What he experienced there was more than he'd expected: "On face value it is everything that you read about but the excitement during the lead up, the chills that you get when the Sun gets covered and you realize totality's eminent, that kind of excitement I could never have imagined. Then when you see the corona, it just blew me away. Because you can't describe exactly how that appears in the sky and photos just don't do it justice. You can never anticipate what it will really be like for the light to just disappear so quickly." His photographic work on eclipses has now taken him all over the world and it was thanks to his scouting locations here a year ago that he was able to put me in contact with the people I've met.

David Makepeace is a filmmaker from Toronto, Canada, who like the growing number of eclipse-chasers worldwide is in no way a scientist. His first total solar eclipse was in 1991 in Baja California, Mexico. A girlfriend invited him down to see the eclipse, "I had taken an astronomy course at the University of Toronto so I had some kind of basic understanding of what would happen, but I went there primarily to see her; the eclipse on the beach would be secondary. Then we saw it and it totally blew my socks off. I was silent for two days afterward, sitting on the beach staring off at the Sea of Cortez wondering about my existence, wondering what I was doing here on this big rock flying through space." Today he works on films and planetarium programs to share this experience with the public.

…

I look up and see that my sky overhead is now a race between scattered clouds and the Moon. One minute it's clear, the next minute it's cloudy. Each time the Sun reappears it is a little farther gone and the colors are even stranger. The Sun is now so small that the shadows are sharper, cast by a single white spotlight.

Everything is happening so fast now. The light fails, the temperature drops, and suddenly new clouds form over the mountains around us. Just 30 seconds before totality begins, clouds seal the sky shut and then it goes black. Each one of us is no more than a silhouette under a sky now darker than any day I have ever experienced. The clock begins: two minutes is all we have.

All we need is a momentary break in the clouds any time in the next two minutes and we will easily see the corona with our fully dark adapted eyes. Even for a cloudy day, this darkness is unnatural. I can understand the fear of those early quarrelsome brothers in the ancient Norse story. It's absolutely obvious that above these clouds something strange is happening.

We wait. We look all around at the unbroken blanket overhead. Just a single break is all we need. One minute gone. Sixty seconds left. Is it slightly clearer over there? No?

The horizon grows light, the Moon's shadow is leaving… and then a second dawn breaks as the clouds everywhere grow bright and drift apart. Once more we are in Sun.

I missed it.

I fold up my tripod and put away my camera to occupy my thoughts for just a little while. We all joke that we'll see one another next time in Indonesia, or the United States. It helps dampen the disappointment.

Later, at the dinner table of Lis and Andras, with their family gathered from across the islands, we tell stories of what we'd seen, and in time, we laugh. We talk about who was clouded out and who wasn't. On the roof of the hotel the staff saw totality, while the tour group staying there who traveled to a special location for the event did not. As we talk we all agree that the sense of having shared in something awe-inspiring in the darkness truly made this day unique for everyone (even under the clouds).

Súsanna Sørensen of the Visit Faroe Islands tourist board told me later about her own experiences, after all the work of helping others to see the eclipse: “We had invited my family and my husband’s family to early breakfast at our house. It was a very special morning, with an exciting atmosphere prior to the eclipse. The weather was not too good and it was fantastic when we saw first contact; it was finally here and we could see at least parts of it. Breakfast had to wait and we all went out on our balcony. It was a very strange feeling when totality began, how the light disappeared, like turning off a switch. It was a really beautiful light with a yellow rim at the horizon.” Though she, like me, was clouded out for totality itself, she was philosophical about it: “There was a small hole in the clouds where you could see the blue sky and we knew that somebody else probably saw totality through that hole.”

For those who did, and even those who didn’t, we all saw and shared something that day and felt lucky to have experienced what we did. A month later I received an email from Súsanna who told me that even now, “It has been the talk of every social gathering I have been to since, even this weekend, when we were out with friends. The dramatic light is something that everybody talks about and how it made us all feel small and at the same time part of something bigger.”

And like everyone else, she is now thinking about where she can go next to see another. In some sense the answer to that question is easy. Unlike many other natural spectacles, there is no question on exactly what date and what moment the next total solar eclipse will begin. All that is in doubt is if we will be there to see it and with whom will we be fortunate enough to share the experience.

"[W]hen I had once turned my eyes on the moon encircled by the glorious corona, then on the novel and grand spectacle presented by the surrounding landscape… I mentally registered a vow, that, if a future opportunity ever presented itself for my observing a total eclipse, I would give up all idea of making astronomical observations, and devote myself to that full enjoyment of the spectacle which can only be obtained by the mere gazer."[146]

--Warren De La Rue, 1862,

First man to photograph a total solar eclipse.

Chapter 7: The Great American Eclipse and Beyond

Totality's eerie light bathes the ring of massive monoliths as robed figures chant and burn their sacrificial offerings. Around them, the gathered throngs raise their voices in joy and smile for the cameras of the CBS Evening News. It is 1979 and the scene is a bizarre roadside recreation of Stonehenge overlooking the Columbia River in western Washington State. Neo-pagans and curious onlookers have amassed to witness the rare event unfold overhead, and this being Washington (and the 1970s), it's clear that not all the smiles and good vibrations are due solely to the solar eclipse.

Back in the studio, Walter Cronkite tells us there will not be another total solar eclipse to touch the continental United States this century. Not until the far-off date of 2017 will totality once more be so visible to so many on this continent.

I’ve been waiting to see this eclipse ever since.

The 1979 eclipse only touched a corner of the U.S. before swinging up into western Canada, and not even half the population of the United States today was alive for it. A continent-spanning eclipse hasn’t happened in the United States since 1918, almost a hundred years before what is being called the Great American Eclipse of 2017. While this may seem like a long time, consider that when Bailey saw his first totality in 1842, Western Europe had gone 109 years without seeing the solar corona at all. Halley’s eclipse in 1715 marked the end of a 500-year drought for England. Australia is currently in the midst of seeing eight total solar eclipses in a period of 64 years (1974 to 2038) but only after having seen none for the previous 52 years.[147]

While any one spot on Earth will experience solar totality every 370 years on average, remote Baker Island in the Pacific Ocean is in the midst of a 3000-year gap between totalities. Over time, these cycles of bounty and absence come and go as every place on Earth is crossed eventually. For human beings with our limited lives and limited means of travel, these vagaries of celestial alignment mean the majority of people on Earth have never seen a total solar eclipse.

The 2017 Solar Eclipse

The first total solar eclipse most Americans will have ever seen begins the morning of Monday, August 21, 2017, two seconds before 10:16 Pacific Daylight Time. At that moment the dark shadow of the Moon touches the Pacific Coast at Yaquina Head lighthouse outside the coastal town of Newport, Oregon. There is no doubt about this. Astronomers have a bad reputation when it comes to predicting amazing sights for the public. Too many "Comets-of-the-Century" turn into faint fuzzy duds that disappoint in the darkness. Too many meteor "storms" wind up being no more than a drizzle once you've woken the family at 2:00 a.m. But this eclipse is happening, in the middle of the day, exactly on time, and in exactly the places that are predicted. It is as certain as the sunrise.

The only question is a matter of clouds, and even those can be predicted with some certainty. The region with the best chance of clear skies all along the path of totality on that date is eastern Oregon, which the Moon's shadow reaches at 10:19 and 36 seconds PDT as it crosses the Cascade Range and flies eastward at a speed of 2,265 miles per hour. The shadow then crosses into Idaho, including the southern tip of Montana where no roads lead into the Beartooth Mountains.

At 11:34:56 Mountain Daylight Time the shadow reaches Jackson Hole Airport in the middle of Wyoming's Grand Teton National Park. This is one of two national parks totality touches and the only one in the high mountain air west of the Mississippi. Summer storms can be an issue, though. The weather for the week of August 21, 2014 (exactly three years before the eclipse) included rain and sleet while a year later, August 21, 2015 was mostly-clear and sunny. The eclipse crosses the state diagonally almost entirely along the line of Highway 26. For those looking to avoid any clouds and reach potentially clear skies in their cars, this could be the ideal racetrack for whichever direction it's necessary to drive.

The lunar shadow then sweeps across the plains, reaching the border of Nebraska at 11:46 a.m. and the northeast corner of Kansas at 1:02 p.m. Central Daylight Time. Twenty-two minutes later, totality engulfs Kansas City, Missouri (the largest city yet along the path) right after lunchtime. A little farther east, at the University of Missouri in the town of Columbia, residents are expected to gather in the 71,000-seat Faurot Field football stadium. It will likely be the largest single gathering of spectators to see totality on the continent this day.

Totality reaches the Mississippi River south of St. Louis at 1:17 and eight seconds CDT. People living in Missouri's largest city will see the Sun disappear above their homes but only if they live south and west of the line between Creve Coeur Park and the Missouri Botanical Gardens. For those wishing to see totality from Forest Park, home of the famous 1904 St. Louis World's Fair, only the extreme southwestern corner of the park is within the path and totality there lasts no more than 20 seconds.

At this point, onlookers all along the midline of the path have had at least 2 minutes of totality, but those residents of Carbondale, Illinois will get to experience the eclipse's greatest duration at 2 minutes and 40 seconds. These folks are luckier still, as the very next total eclipse to touch the continent will sweep over their houses, allowing them to see two eclipses in seven years from their very own doorsteps.

From Illinois the path leads over Kentucky and then crosses into Nashville, Tennessee – the largest city completely within the shadow of the Moon at 1:27:28 CDT. As totality leaves Tennessee it crosses the southern half of Great Smoky Mountains National Park, the most visited national park in the United States. In 2010, 9.4 million visitors came to this park, more than twice the number that visited the Grand Canyon that year.[148] The highlight of the park is Cades Cove, a spectacularly beautiful valley set amidst the hardwood forests and rushing streams of the Great Smoky Mountains. Totality reaches here at 2:34:20 Eastern Daylight Time and is visible in the park from much of (but not all of) Newfound Gap Road as it crosses from Tennessee into North Carolina.

At 2:47 EDT, one hour and 33 minutes after coming ashore on the Pacific Coast, the Moon's shadow crosses out into the Atlantic just north of Charleston, South Carolina. In that time it will have touched 13 states, five state capitals, and 9.7 million residents, not counting the millions that will travel into the path to see it. For that one day, every man, woman, and child in North America will share in a phenomenon of wonder and joy. Though totality will take only 93 minutes to cross from sea to shining sea, during that time, everyone on the continent will be within at least the partial shadow of the Moon and experience the eclipse together.

But not all views are equal.

Though the entire continent will witness at least a partial eclipse, the real show is within the zone of total darkness. You must get into the *umbra*, the darkest part of the Moon's shadow where the disk of the Sun is totally covered. That's where the eclipse is total. Those in totality's path see the diamond ring, Baily's Beads, the corona, and any prominences visible on the solar limb. Day becomes night and the brighter stars and planets such as Venus and Mars become visible near noon. You will understand the true meaning of awe.

While those near the midline of totality will see the longest darkness, those near the edge, but still just within the umbra, have the chance to see more edge effects such as Baily's Beads and the deep red chromosphere (including prominences) as the Sun just skirts behind the lunar edge.

Those barely outside totality's path may still see some Baily's Beads (if within just a few miles of the band); but, though the day will grow dark and colors will change, day will not become night and no stars or planets will become visible. Here, outside the path of totality, the Great American Eclipse will be only partial and special eclipse glasses will be needed for the entire event.

Make no mistake: The difference between being inside and outside the path of totality *is* the literal difference between day and night.

A Guide to Safely Viewing a Solar Eclipse

I saw the 1979 eclipse, my first, in complete safety: in a darkened room, with all the windows covered, watching it on TV. I missed experiencing the greatest awe-inspiring wonder that Nature has to offer because my local school officials felt it was too dangerous for children and didn't want to be held liable in the event of an injury. Whether those school administrators were right to be wary, not a year has gone by since then that I haven't felt cheated out of a life-changing experience.

Observing a solar eclipse *can* be dangerous if proper precautions are not taken. In that regard, viewing a solar eclipse is no different from many other sporting activities in which families and schools regularly take part. But unlike bicycle helmets, football pads, or lifejackets, the equipment needed to safely view a solar eclipse costs no more than a dollar or two and you may even have it sitting around your house already.

First, you may be wondering what the potential harm is. The un-eclipsed Sun is visible every day, yet we don't warn children to stay indoors on sunny days. While it is true that the Sun doesn't emit any special rays during an eclipse, how we behave toward the eclipsed Sun does change. On a typical day very few people willingly stare at the Sun for a prolonged period of time. Our eyes and brains know it isn't good for us to shine that much light through the lenses of our eyes and focus it on our retinas, so we instinctively look away.

The concern by over-worried health officials is that during an eclipse we are motivated to stare at the Sun, particularly close to totality when the Sun may look like a crescent. People want to see this phenomenon and so they will look longer than normal at a particular sharp feature, placing its image for prolonged periods of time on a single part of the retina. Since there are no pain receptors in the retina, the damage that takes place as it burns produces no discomfort. For all its painlessness, the damage is permanent. And for particularly young children with clear pupils that have not become dulled with age, the increased amount of light received by their retina does make for more danger compared with adults.

The solution to this problem is simple: never look directly at the partially-eclipsed Sun without proper eye protection. Either look through specially-designed filtered glasses (or cards) or project an image of the Sun on a screen using a pinhole projector made from items found around the house or naturally outdoors. These two methods of seeing the partial phase of a solar eclipse are cheap, safe, and in the case of finding naturally-occurring pinhole-projections, an enormous amount of fun.

Filters: The most widely available device for viewing the partial phase of a solar eclipse is simple, commercially-available plastic or cardboard safety-glasses. These glasses are inexpensive (typically $1 or $2) and are available from a number of websites and local stores where total eclipses occur (see the end of this chapter for licensed suppliers).

You should be unable to see anything through the “lenses” of these glasses other than the Sun. The special solar filter in these glasses can be delicate. Any holes or scratches they develop make them instantly worthless and potentially dangerous. Keep them protected. If you have any doubts, hold them up to a light bulb: if you see any light at all coming through the “lenses,” throw them away and use another pair.

What not to use: Stay away from people offering to let you look through make-shift items like dark beer bottles, silver candy wrappers, CDs or DVDs, smoked glass, or dark sunglasses. These may make the Sun look dim, possibly even dim enough to look at without discomfort, but they may do nothing to block infrared or ultraviolet radiation that will also cause permanent damage to the retina and possibly lead to blindness.

Projection: The cheapest, simplest, and absolute safest method of watching a partial solar eclipse is to find a piece of cardboard and poke a small hole in it. Hold this outside and the sunlight passing through the hole produces an image of the Sun wherever the shadow of the cardboard falls. Place a sheet of paper on the ground or on a wall and everyone can see the eclipse progress together. Do not look through the pinhole at the Sun.

<<Insert Projection.tif here>>

One of the most enjoyable parts of watching a partial solar eclipse (or spending time outside in the Sun waiting for totality to begin) is looking around for natural pinhole projectors. You can use leafy trees, woven hats, interlaced fingers, or any other place that tiny holes occur through which the eclipsed Sun shines, casting myriad crescents into their shadows.

Whether using filters or projection, once totality begins with the first diamond ring, put the filters and glasses aside and feel free to look at the Sun with the naked-eye in complete safety until the second diamond ring marks totality’s end.

Photographing Solar Eclipses

My simplest recommendation for photographing a total solar eclipse is: Don’t do it! Typically you will have no more than two minutes or so of totality. That’s 120 seconds. Why spend those precious seconds looking down at your camera’s instruction menu, trying to get your camera to focus, or working to get the exposure right? Reread the quote at the opening of this chapter. Even the very first person to ever photograph a total solar eclipse wished he had the chance to see another without the bother of equipment. If this is your first eclipse and you absolutely need a photo, someone else will take one and it will probably be better than yours.

If none of that dissuades you, here are a few tips to keep in mind for taking solar eclipse photos. There are links to specific websites with more detailed information at the end of this book.

1. During the partial phase of the eclipse, do not point your camera at anything you wouldn’t look at with the naked-eye. You may be able to safely look at the monitor

on the back of your digital camera, but your camera lens is focusing the Sun's light on your sensitive camera optics. If you need a filter for your eyes, so does your camera.

2. If you are using a filter for your camera during the partial phase, remember to take it off during totality or you won't capture anything.
3. During totality the sky darkens enough for the brighter stars to appear. In the days before totality, go outside immediately after sunset and wait until the first, brightest stars appear. This is a fair approximation to how dark it will be. Experiment with taking photos at this time. How do they come out? Do you need a tripod for your camera to successfully take sharp, non-blurry, non-grainy photos under these conditions? If so, this will be another piece of equipment you will need to handle during those precious seconds of totality.
4. It will be dark during totality; do not use a flash. It will blind everyone around you at exactly the moment you and everyone else want to see the most. Turn all flashes off.
5. The Full Moon is about as bright as the corona. Try taking photos of the Full Moon to see how long you need to expose for the Full Moon to be properly exposed. Again, does this need a tripod?
6. The Full Moon is also the same size as the Sun and will be the size of the "hole in the sky" during the eclipse. Practice using your camera to photograph the Full Moon. How big does it appear in your image? Is this worth taking a picture of? Many of the

best eclipse photos that show details of the corona and prominences use telephoto lenses with focal lengths of at least 500 mm, but they cost thousands of dollars.

Future eclipses.

If you miss the total solar eclipse of 2017 (or, having seen it, you catch the bug and absolutely must see another) don’t worry, there are many more coming. The next total solar eclipse to touch the continental United States is April 8, 2024. On that day in mid-afternoon the path of totality starts in Mexico, travels northward into Texas and then crosses the central United States before passing through eastern Canada. The citizens of southern Illinois in the United States are the lucky individuals to see two total solar eclipses in seven years without having to travel anywhere.

Perhaps the most spectacular views that day will come for those on the U.S. side of Niagara Falls. From the railing beside the water, the totally eclipsed Sun will hang directly above the crashing falls for 3 minutes 30 seconds in what is sure to be a wild sensory-overload spectacle of sight and sound. Assuming it is clear at that time of year, of course.

For those who love to travel there are some exotic destinations for future solar eclipses that are tantalizing in the opportunities they afford. In July 2019, totality will sweep off the Pacific Ocean and across the Chilean Andes. The path will cross one of the great original southern hemisphere astronomical observatories, the La Silla Observatory at 7,900 foot elevation (2400m) operated by the European Southern Observatory. This is one of the darkest locations on Earth and since solar eclipses happen at New Moon, those who travel here for the eclipse should stay to see the glories of the southern Milky Way high overhead throughout the night. It is a view unlike any other available to us in Europe or North America, particularly with regards to darkness of night and grandeur of our galaxy.

<<Insert Table: “Total and Annular Solar Eclipses Worldwide (2017-2030)” here>>

On December 4, 2021, at the height of the Southern Hemisphere summer the totally eclipsed Sun will be visible from Antarctica and no other continent. The Sun and Moon will glide horizontally, no more than about 20^{o} off the gleaming ice – about the distance spanned by your thumb and little figure extended at the end of your arm.

Surely one of the most awe inspiring sights will be to see the total eclipse of August 2, 2027 from amidst the Temple of Luxor in Egypt. Totality will last over 6 minutes, the longest for the next 30 years, and hang in the darkened sky almost at the zenith, directly above the stone pillars and statues below.

For those who can’t get to Egypt on that day, this particular path first touches ground passing precisely over the Strait of Gibraltar and the Pillars of Hercules (the Rock of Gibraltar in Spain, and Jebel Musa in Morocco). Totality lasts for about four and a half minutes here before continuing over northern Africa to Egypt and across the Red Sea.

The solar eclipse of July 22, 2028 passes directly over Sydney, Australia affording three and three quarters minutes of totality, while South Australia is visited by totality just two years later on November 25, 2030.

Lest we forget total lunar eclipses, there is a special beauty to going out under a night sky brightly lit by a Full Moon. What begins with only a few stars visible against the glare of the

Moon slowly turns into a thousand points of light as the eclipsed Moon darkens. By the time totality occurs the sky is ablaze with stars; and if totality occurs near the peak of a meteor shower, the dark-red Moon can be surrounded by shooting stars for the duration of totality. This I experienced in August 2007 from Grand Teton National Park immediately after the Perseid Meteor shower and with the Milky Way arching overhead, it was one of the most magical moments I've ever experienced.

<<Insert Table: "Total Lunar Eclipses Worldwide (2017-2030)" here>>

For such a night, consider the total lunar eclipse of July 27, 2018. Occurring two weeks before the peak of the Perseid shower, a few meteors may be visible as the blood-red Moon hangs beside the brightest portion of the Milky Way for witnesses in Europe and Africa through Asia. To find more possibilities, and see the places you'll need to go to follow the path of totality, visit any of the websites at the end of this book.

Beyond 2030 I run into the conundrum that all eclipse chasers eventually face: how many more will life allow me to see?

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