Solar Eclipses

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Introduction

There are two basic types of eclipses: solar and lunar. A solar eclipse can only occur when the moon is new, and a lunar eclipse can only happen when the moon is full.

One of the objectives of this unit is to have students understand a little bit about the repetition of eclipses and eclipse terminology. The Babylonians understood these concepts at the latest, 200 years BCE. The repetition of eclipses is very mechanical, like drum beats. In this context, 'beats' refer to the rhythmic patterns that govern the occurrence of eclipses.

There are three distinct beats in understanding the repetition sequence. The major (most important) beat is the synodic period or the phase period of the moon, 29.5 days in length. There are also the nodical and anomalistic beats; both rhythms will be explained in due course.

Three students volunteered and started beating their hands on the tables with different rhythms, all starting off with a sharp slap on the wood. Students listened for the three beats to hit at the same time. Eventually, the three students slapped the table in the same instance, signifying the repetition of an eclipse.

Several beats ago, the volunteers hit the tables simultaneously, and then they started getting out of rhythm again. When the second simultaneous slap of the table occurred, another solar (or lunar) eclipse would have occurred.

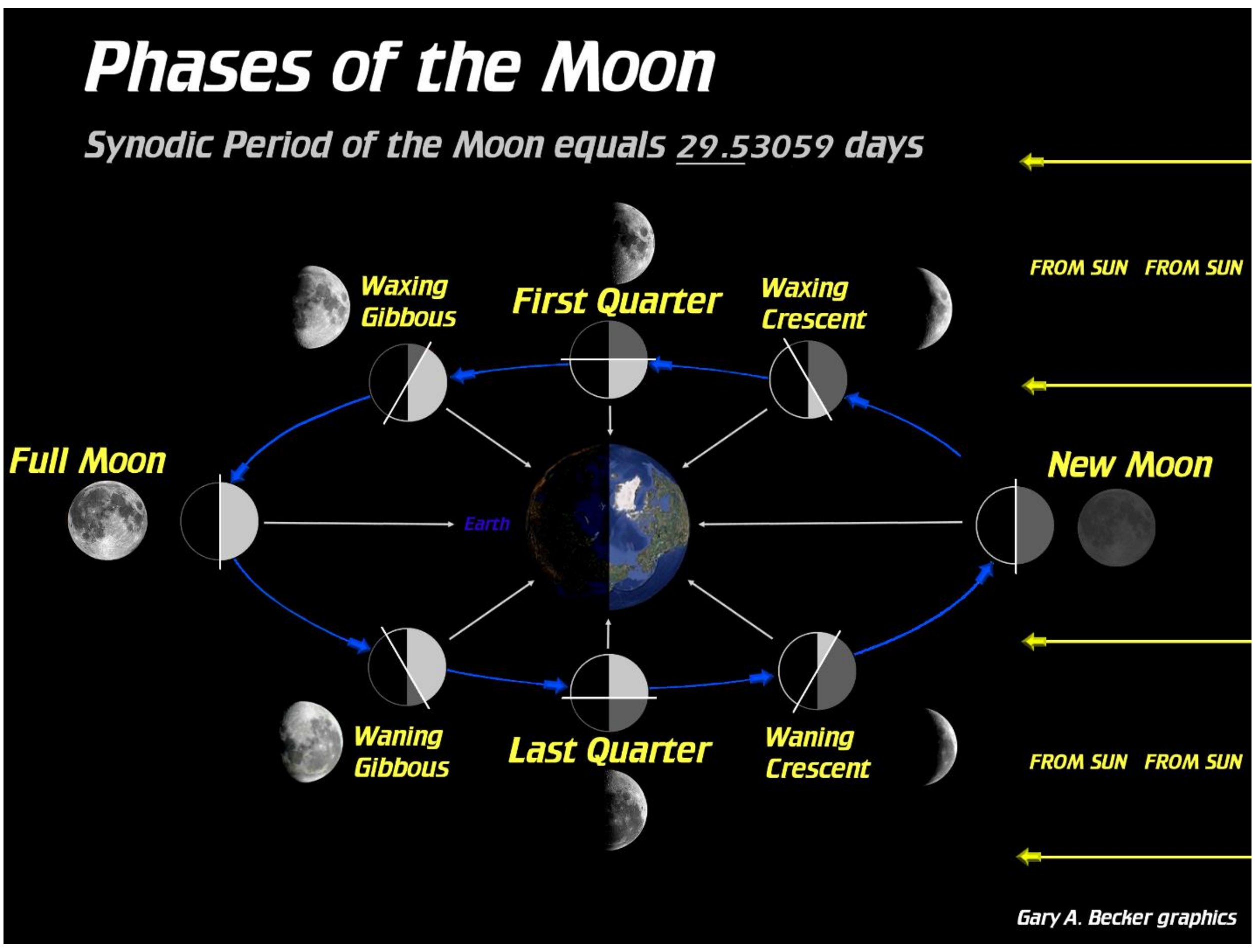
The most important beat of the three is called the synodic beat, which you know something about because that's the lunar phase period of the moon, which equals 29.5 days. Another beat is the nodical beat, while the third is the anomalistic period. All three beats must co-occur if there will be a solar or lunar eclipse. The synodic and nodical periods get out of synchronization, but eventually return, after 3.8 years, they come together to create another eclipse cycle that is not considered as significant. There must be another eclipse, but it may not be similar to the last eclipse of the cycle.

Ancient astronomers thousands of years ago were most interested in predicting total solar eclipses when the moon completely covered the sun. In this case, all three beats had to occur on the same day, and the last eclipse in the series also had to be a total solar eclipse. This discovery, made by some smart (Einstein) Babylonian who must have delved into thousands of years of records, led to the establishment of a repetition cycle that the Greeks named the saros.

If you don't put a total solar eclipse on your bucket list, I guarantee that when I die, I will make it my mission to harass you into seeing one. But I am getting a little ahead of myself. Let us talk about the language (the nomenclature) of eclipses. The experience of witnessing a total solar eclipse is truly awe-inspiring and something you won't want to miss.

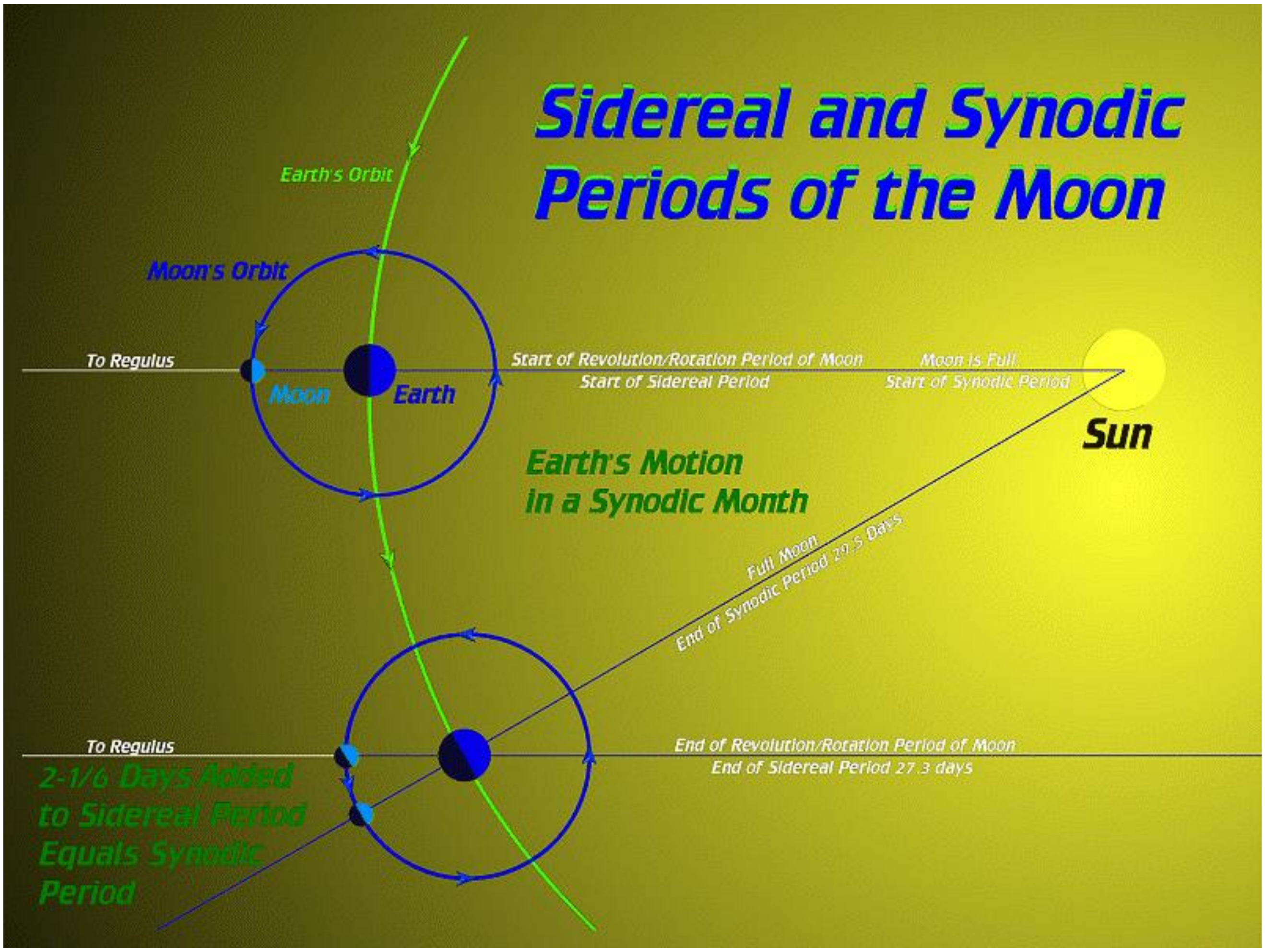
Eclipse Talk

Let's discuss a little bit about eclipse terminology. The 29.5-day synodic period is the governing beat for eclipses. This period is of utmost importance, as you cannot have any eclipse unless the moon is full or new. Understanding and appreciating the role of the synodic period is key to grasping the basic mechanics of eclipses.



Let's discuss again the difference between the synodic and the sidereal periods of the moon. We did this earlier in the semester, but it is an important concept worth repeating. The **sidereal** period is the time it takes the moon to complete one **revolution** around the Earth. The sidereal period of the moon is **27.3 days**. The **synodic** period is the time to complete one cycle of **moon phases**. This period transpires in **29.5 days**.

The synodic interval or phase period is critical because solar or lunar eclipses cannot occur unless the moon is new or full. In addition, the lunar phase period is easy to observe because the moon is bright and continuously changing in its brightness, as well as its position as it orbits Earth. The synodic period was also responsible for the first calendars. In the diagram found on the next page, sun, Earth, moon, and Regulus are all in a straight line. Regulus and the moon lie very close to the ecliptic, the plane created by the Earth as it revolves around the sun. The ancient Egyptians believed that Regulus was the star that, combined with the sun's power, produced summer's heat.

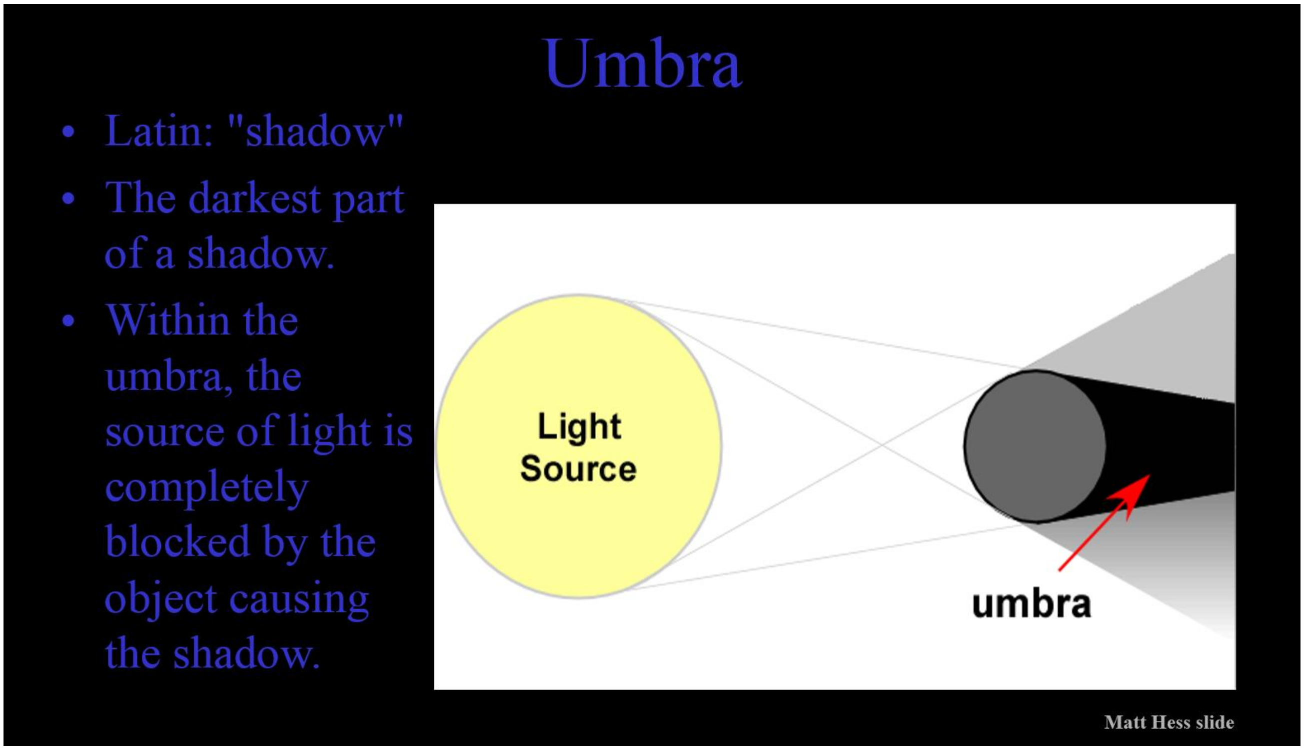


Start with all four of these objects in a straight line. When the moon passes, Regulus, for the second time, the sidereal period will have ended. **Sidereal** comes from the Latin meaning **star**. Once the moon passes the star for the second time, its orbital period, its revolutionary interval, has ended.

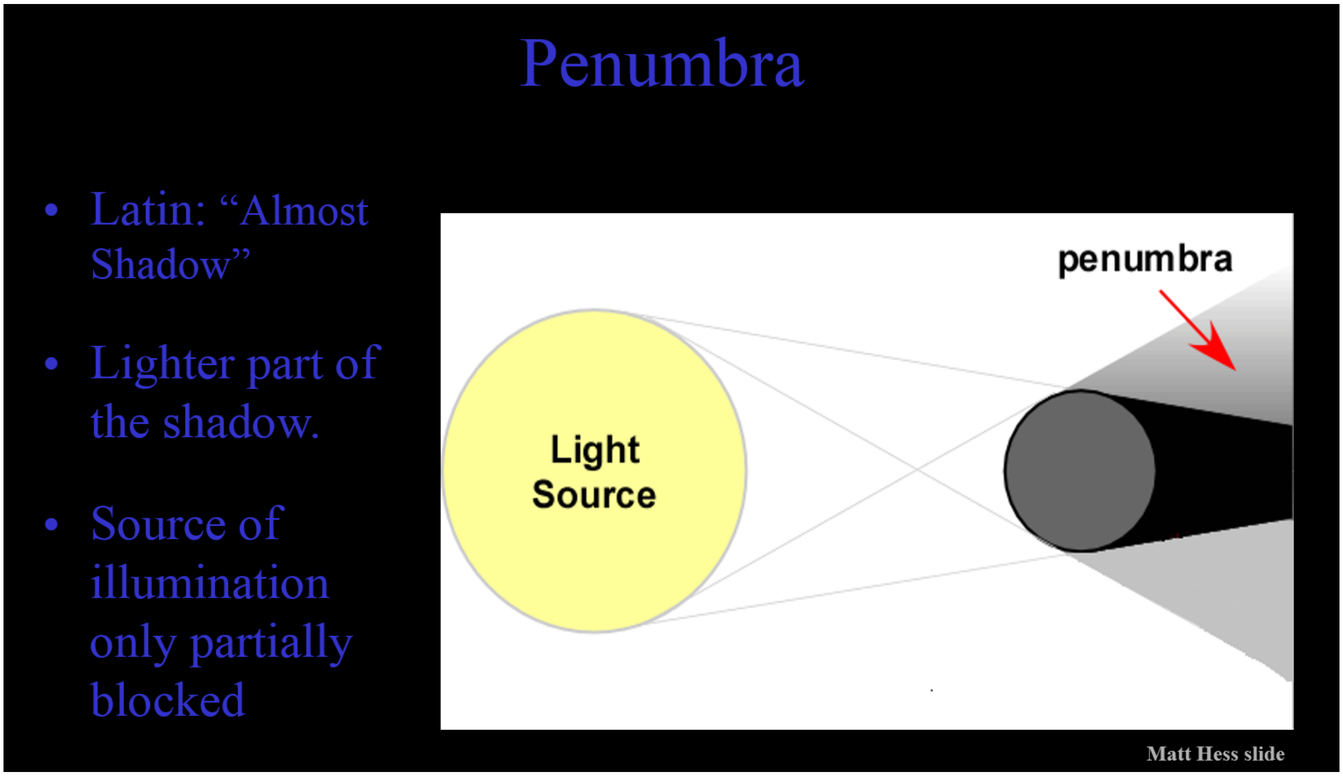
Imagine a precise dance of celestial bodies. We mentally cue the moon to begin its graceful revolution around the Earth. The Earth, in turn, starts its elegant orbit around the sun. This celestial ballet continues until the Earth, moon, and Regulus are again aligned in a straight line, marking the end of the sidereal period. If we map this out in days, we find that it takes 27.3 days for the moon to complete one full orbit.

Observe the moon transitioning from a waxing gibbous phase to a full moon. It's a gradual process, taking a little longer than the sidereal period for the moon to align perfectly for the full phase.   On average, it takes about 2-1/6 days for the moon to move through that small angle and reach the full phase, aligning once again with the moon-Earth-sun line.

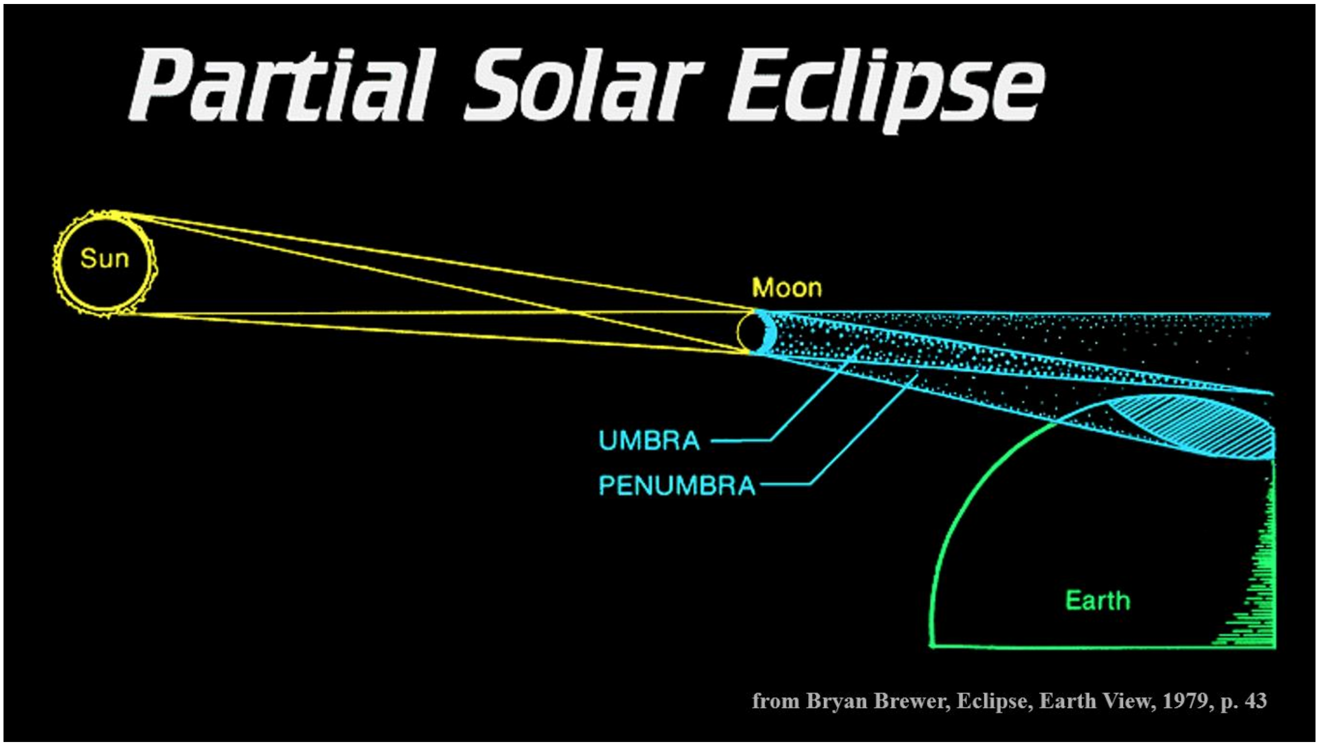
In the slide, notice that the terminator is perpendicular to the line from the center of the sun through the center of the Earth through the center of the moon. We have reached the end of the synodic period. Two and one-sixth days (2-1/6) plus 27-1/3 days equals 29-1/2 days for the phase (synodic) period of Luna. Keep in mind that the synodic period does vary a little. If the Earth is covering more orbital ground like it is in the wintertime, when Earth is closer to the sun, then the time to catch up to complete the synodic period will be a little longer. If it is in the summertime when the Earth is slowest in its orbital motion, the moon will have a smaller distance to travel; hence, the synodic period will be slightly shorter. The takeaway from this slide is that the orbital and phase periods of the moon are not the same.



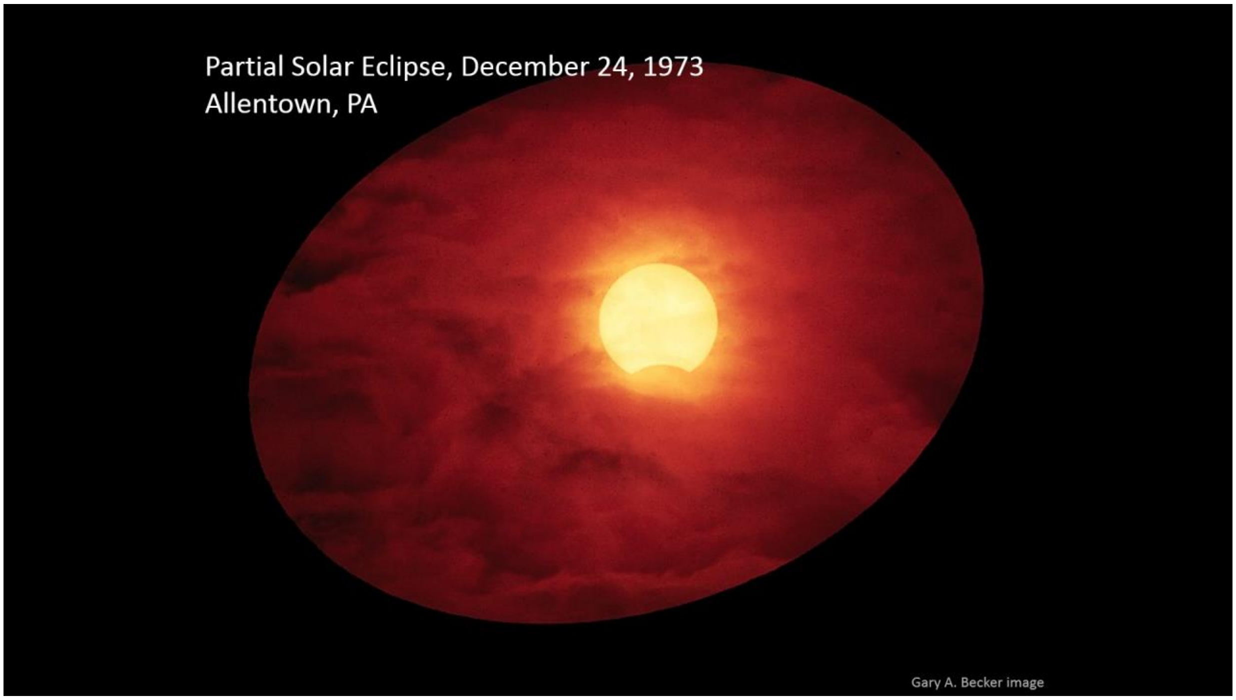
Let's go through some eclipse terminology. An object illuminated by an extended source like the sun will always produce two shadows, the umbra and the penumbra. Whenever you are in an eclipse situation, the actual shadow created by the occulting body is called the umbra. When you are in the umbra, the light source will be invisible because the object producing the shadow is opaque, hiding the light source. Umbra comes from the Latin meaning shade. If you move away from the umbra, you will encounter the penumbra, Latin for light shade.



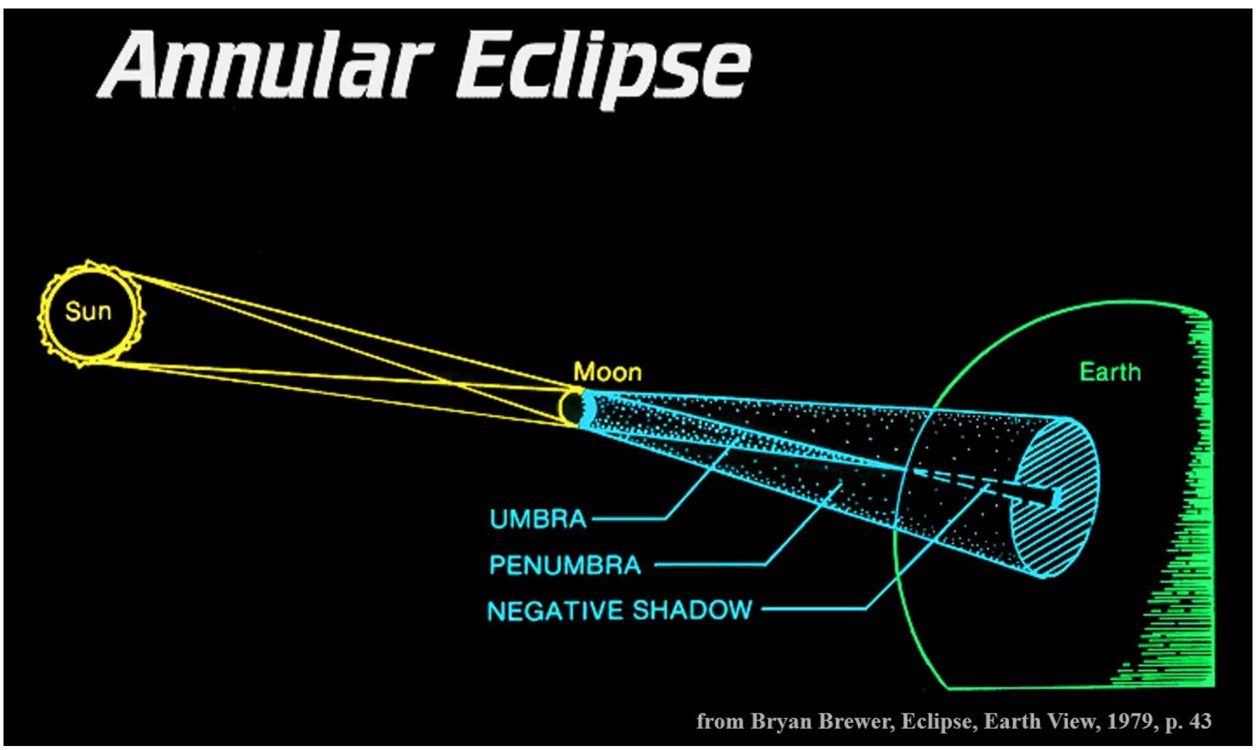
Let us pretend you are at the tip of that red arrow in the penumbra slide. You would see the occulting body in the direction of the light source. The opaque body covers up a good part of the light source but not all of its light. Some of that sunlight is getting into the penumbra, which means that the penumbra cannot be as dark as the umbra. If an observer moves closer to the umbra, more and more of the sun's light is blocked, and the penumbra becomes darker until the person gets to the umbra, where all light from the source is blocked. The penumbra should go from a nearly invisible boundary to very dark at the umbra penumbra boundary. I have never seen a slide duplicate that situation, so you will have to deal with uniform greyness within the penumbra, as shown in all diagrams.



There are four types of solar eclipses: partial, annular (broken annular), hybrid, and total eclipses. Every solar eclipse has a partial aspect where the observer is not close enough to the umbra to see the moon completely cover the sun's disk. In this case, the umbra misses the Earth completely, and all observers are in the penumbra. Nobody on the surface of the Earth sees a total or annular eclipse. It is a partial solar eclipse everywhere where any shadow reaches the ground. Partial solar eclipses are the standard types of eclipse in a series of eclipses called a saros cycle when that cycle begins and ends.   They often occur near the poles of the Earth. Again, we'll discuss saros cycles later in this lesson.



This is an image of a partial solar eclipse that occurred throughout much of North and South America on December 24, 1973. The next slide shows the geometry of an annular eclipse.



In an annular eclipse, a unique celestial dance unfolds. The moon's distance from the Earth is such that the umbra, the darkest part of the shadow, doesn't quite reach our planet's surface. This condition, where the observer is within the penumbra of the moon's shadow, is visible in all areas where the eclipse occurs. The moon's umbra, the fully shaded inner region of a shadow, doesn't quite stretch to the Earth's surface, creating a spectacle that can tell us something about the moon's orbit.

There is an area called the negative shadow zone, which lies under the umbra and is where a smaller moon can be seen silhouetted against a larger sun. If viewed safely filtrated, the sun would appear as a ring of sunlight surrounding the darker, opaque moon. This ring of the sun is called the annulus, Latin for ring. This type of eclipse is named an annular eclipse. Remember, safety comes first when observing an annular eclipse. Proper filtration is necessary for observations of the entire event.

The sun is 864,000 miles in diameter but also 93 million miles away. The moon is about 2160 miles in diameter but only about 240,000 miles away. The moon is about 1/400 the diameter of the sun, but it is approximately 400 times closer to Earth than the sun. The sun is about 400 times the moon's diameter but 400 times farther away. The net result is that the sun and the moon look about the same angular size (about 1/2 degree) in the sky. It just turns out that the moon and the sun have almost a perfect inverse relationship between distance and size. The Earth and the moon revolve around the sun, and both objects are in elliptical (oval-shaped) orbits. With changing distance comes changing size. If I approached you, I would look bigger; if I moved away from you, I would look smaller. The sun looks biggest in the sky when we are closest (perihelion) in early January and smallest when we are farthest away (aphelion) in early July. These conditions will be discussed shortly.

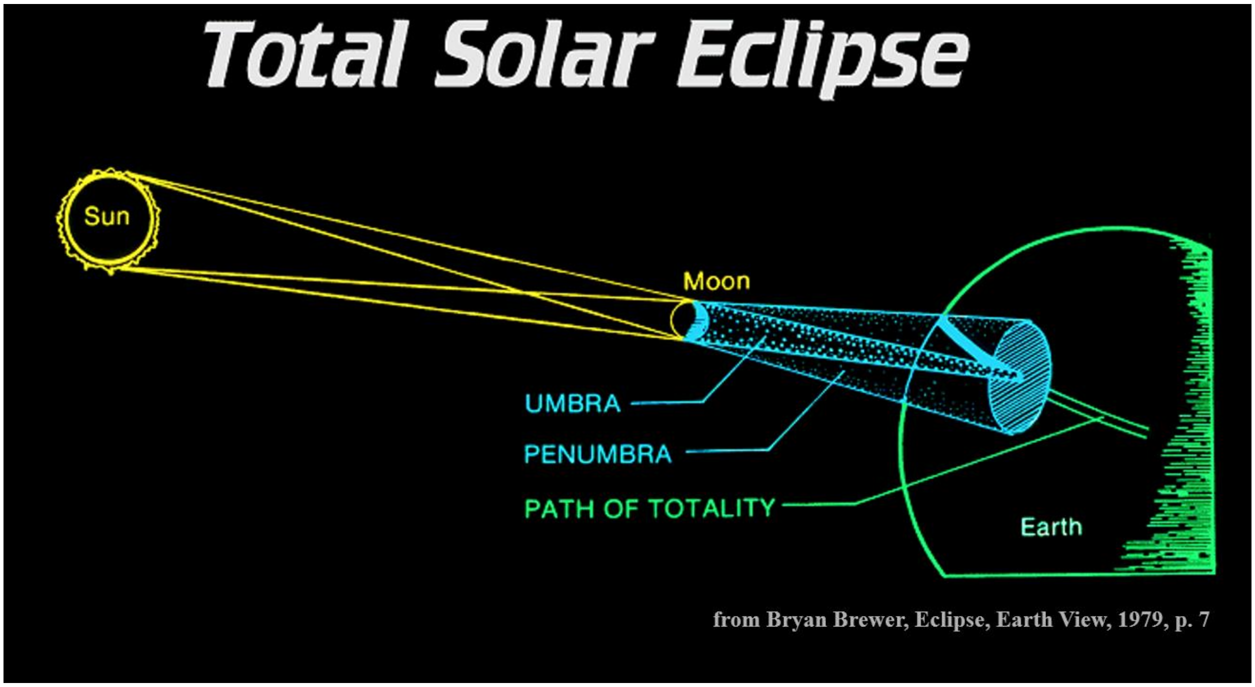
Here (next page) is an annular eclipse photographed on May 10, 1994, in Canutillo, Texas. I had students along on that trip. The image shows second contact, the beginning of the annular portion of the eclipse.

During an annular eclipse, several key events occur. When the moon makes contact with the sun at the beginning of the eclipse, it is called first contact. The second contact happens at the start of the annular portion of the eclipse when the sun appears as a circle of light around the moon. The third contact ends the annular portion of the eclipse. At fourth contact, the moon is tangent to the sun's disk, and the eclipse is concluded.

In the next slide, I am in Osceola, North Carolina on May 30, 1984, imaging a broken annular eclipse.

There was a broken annular eclipse in Osceola on May 30, 1984. The size of the angular diameter of the moon and the angular diameter of the sun were so close to each other that when the center of the moon passed in front of the center of the sun, the mountains on the limb of the moon briefly occulted parts of the limb of the sun, breaking the sun's circumference into a beaded structure. Pearls of sunlight streamed from the valleys of the moon. The beaded structure is called Baily's beads, named for the Englishman Francis Baily, who first explained the phenomenon in 1836 during an annular eclipse. The three images on the right show the mountains jutting just beyond the sun's limb, breaking the sun's light into Baily's beads. The broken annular part of the eclipse lasted only seven seconds. You can learn more about this eclipse in my astronomy text. It is a fun story called *The Great Eclipse Chase*, which introduces readers to the excitement of chasing an eclipse.

Finally, the type of eclipse I want you to see is a total solar eclipse. If you also have a desire to see an annular eclipse, that would also be fine, but it is a dangerous eclipse to look at, and during annularity, it does not get dark. So are the partial phases of any solar eclipse. You need special filtration to see all aspects of the event. Most recently, an annular eclipse on October 14, 2023, crossed the southwestern part of the United States. I was near Hanksville, Utah see that one.



The eclipse I want you to put on your bucket list is a total solar eclipse. A total solar eclipse is one that you will never forget and will last in your memory as long as you live. The visual effects are spectacular. After the total solar eclipse of August 21, 2017, I remember calling my wife because the solar eclipse was partial here in the Lehigh Valley. It is also ongoing at the time of my call. When Sue answered my cell, she was so excited for me. When I heard her voice, I just started to cry. The beauty of a total solar eclipse is such an emotional event that I just broke down and cried. It is nature at its most mysterious.

Remember that the eclipse is dangerous to view anytime the sun is visible. You must use filters, but when totality occurs, the entire moon hides the sun, the sun's corona becomes visible, and the eclipse is entirely safe to view with any instrumentation. The landscape can be as dark as if there were three to six full moons in the sky. Planets are visible, and sometimes even brighter stars.

The moon's shadow falling upon the surface of the Earth is a dynamic situation. The moon orbits the Earth at about 2000 miles per hour, but the Earth also rotates in the same direction as the moon. There is only a very small strip of territory over which the shadow will pass, the path of totality. That strip may extend for only four or five thousand miles, and chances are that it will not go through your town or city.

Concerning these different motions, the moon is moving in the same direction as the Earth is rotating. And that's favorable for eclipses, particularly if the path of totality is nearer to the equator and the shadow mainly moves west to east.

The moon's orbital speed is about 2000 miles per hour. If the Earth were not rotating, the shadow would move across the surface of the Earth with a minimum speed of 2000 miles per hour. However, this is not the situation because both Earth and moon are traveling in the same direction,

Think of the Earth-moon motions. The Earth's axis goes into space at the North Pole and heads towards the North Celestial Pole, which is very close to the North Star. In a 23-hour, 56-minute interval, it will complete one rotation and circle an observer around once. If there is a total solar eclipse at the North Pole, the moon's shadow moves past that position at

Luna's orbital speed of 2000 miles per hour because all an observer is doing is spinning. It is a little more complicated than that, but total solar eclipses at the poles do not last very long.

What happens to the speed of the shadow if it is near the equator of the Earth? Think about this for a moment. The equator is where the Earth is at its widest. If you consider the Earth's diameter to be 8000 miles and you multiply this number by pi (3.14), let's say three, to make it a mental calculation, you will obtain the circumference, which is 3 x 8000 or 24,000 miles. This part of the Earth must complete one rotation, just like the north or south poles, in just under 24 hours. This speed and time to complete one rotation mean the equator travels approximately 1000 miles per hour. The real number is closer to 1050 miles per hour.

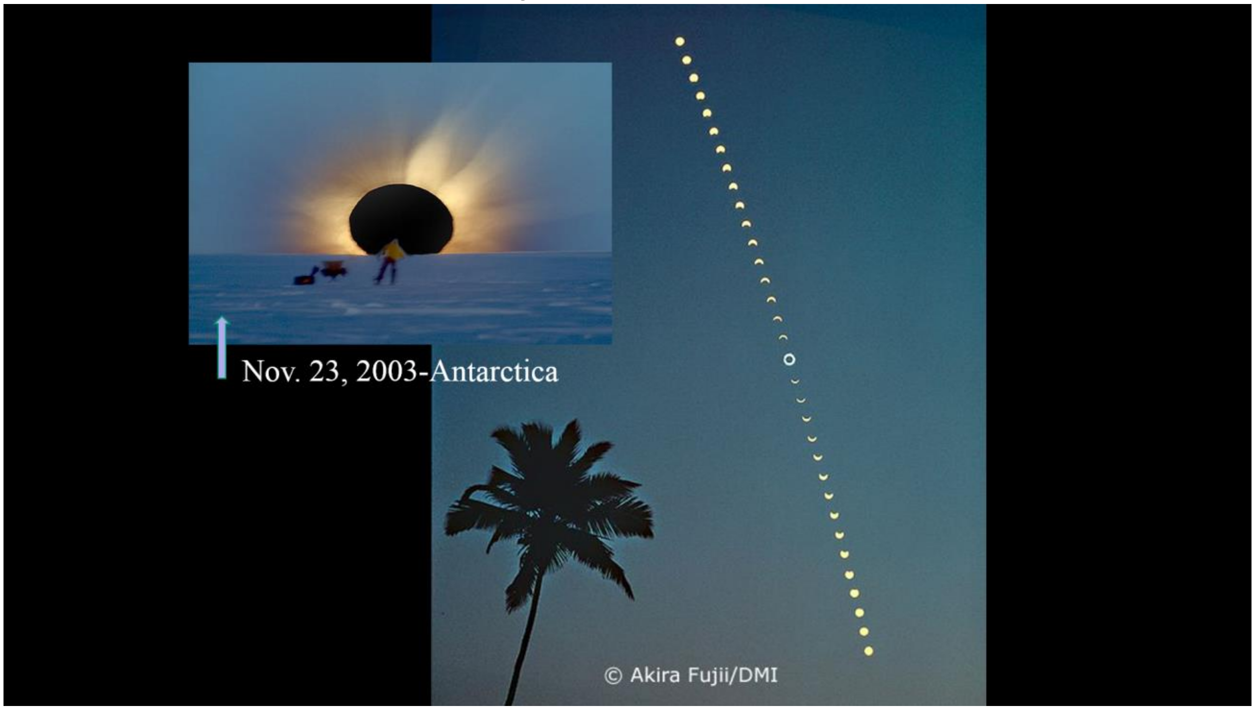
Think of it this way. If I am driving a car going 60 miles an hour and I want to pass someone traveling at 30 miles per hour, how fast will I pass the slower-moving vehicle from the driver's perspective in the faster-moving car? I will move out into the passing lane to get around that person going 30 miles an hour. I'm going 60 miles per hour; the car is going 30 miles per hour. We are both moving in the same direction. Thirty miles per hour is the correct answer. My speedometer still says 60 miles per hour, but I passed the car moving at 30 miles per hour relative to the slower-moving vehicle.

If I'm near the equator and a total solar eclipse occurs, the shadow is moving at 2000 miles per hour, but the Earth is rotating at approximately 1000 miles per hour. I can slow down the shadow to about 1000 miles per hour, and the eclipse will last longer. Suppose there is an Eclipse that is near the equator. In that case, chances are that it will be a much longer totality event than if the eclipse were occurring at a higher latitude where the rotation of the Earth would not have as much effect in dampening or slowing the motions of the moon's shadow.

Think about this. What are the conditions that would create a very, very long totality in a solar eclipse? The longest duration of totality in a solar eclipse is 7 minutes, 31.5 seconds. Based on what we just said, where would you want to be? Bethlehem, PA, London, England, Aruba, Jamaica, "Oh, I want to take you…"

Aruba would be the correct answer because it is the site closest to the equator, where Earth would move faster than Allentown, London, or even Jamaica. Secondly, what time of the year is the Earth farthest from the sun? Summer is correct. In the summertime, the sun appears the smallest in the sky. Every 27.6 days, the moon is as close as it can get to the Earth and, therefore, as big as it can get in the sky. For a long duration of totality, you would want to be near the equator in early July when the sun had the smallest angular diameter and when the moon was at or near perigee, which would present to an observer Luna's largest angular diameter). I saw an eclipse on

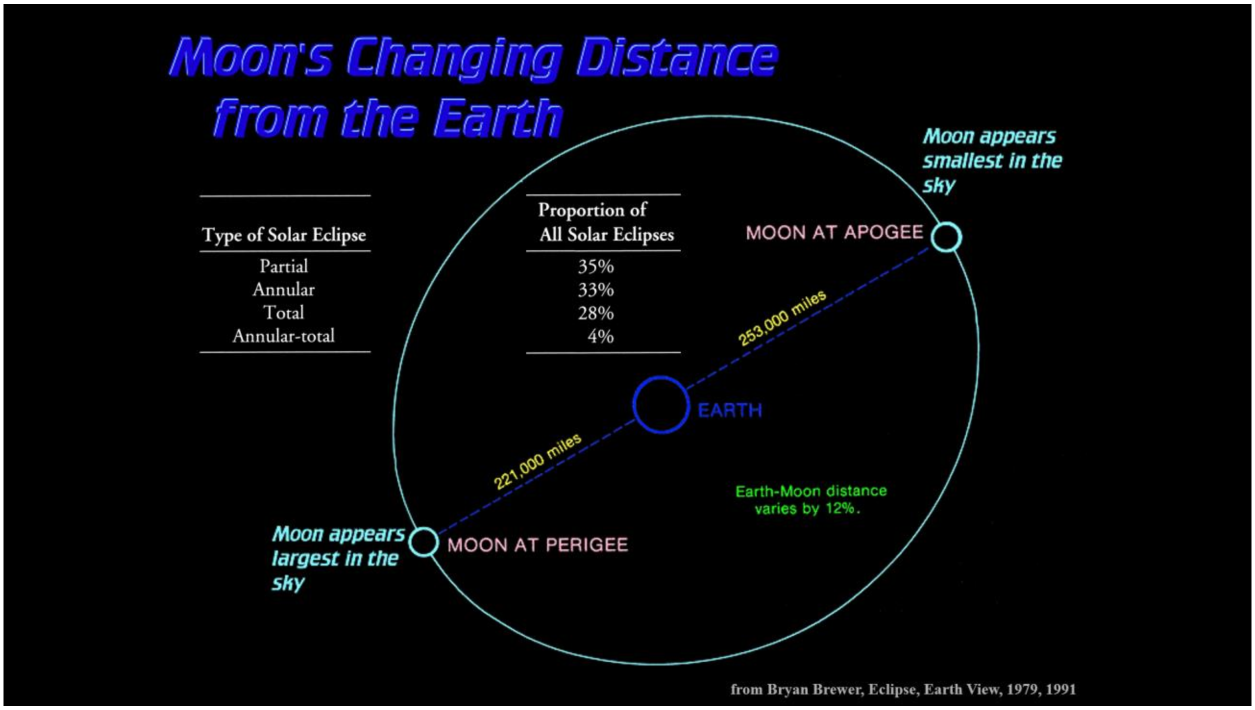
June 30, 1973, off the coast of Africa, where totality lasted 6 minutes, 39 seconds. In central Africa, people were in the moon's shadow for 7 minutes and 3 seconds. There was another very long total solar eclipse on July 11, 1991. I also saw this one, but I was not at the optimal location. I was in Hawaii, where totality lasted for just over 4 minutes. At the tip of Baja California, people were immersed in the moon's shadow for 6 minutes, 59 seconds. Baja, California is that part of Mexico that extends southward of the US state of California. The Gulf of California is in between Baja California and Mexico.



On the right is a compilation of many images of a single total solar eclipse. The picture contains 33 images separated by approximately 10 minutes each. The central image, totality, is the most significant as it captures the corona (solar atmosphere) surrounding the dark moon eclipsing the sun. After the sequence of eclipse images was completed, Akira Fuji, a world-renowned astrophotographer, snapped one last photo of the scene containing the palm tree. On the right is a picture of a total solar eclipse in Antarctica. I remember a friend of mine, David Levy, actually saw this eclipse. The plane landed on the ice, and people got out and set up their equipment. The tour agency put up tents so participants, if they chose to, could rest if they were tired. Temperatures were probably above zero. Remember that even in the summertime, Antarctica is still very cold. The highest recorded temperature was 69.35 degrees Fahrenheit in 2020, confirming that the Earth is warming.

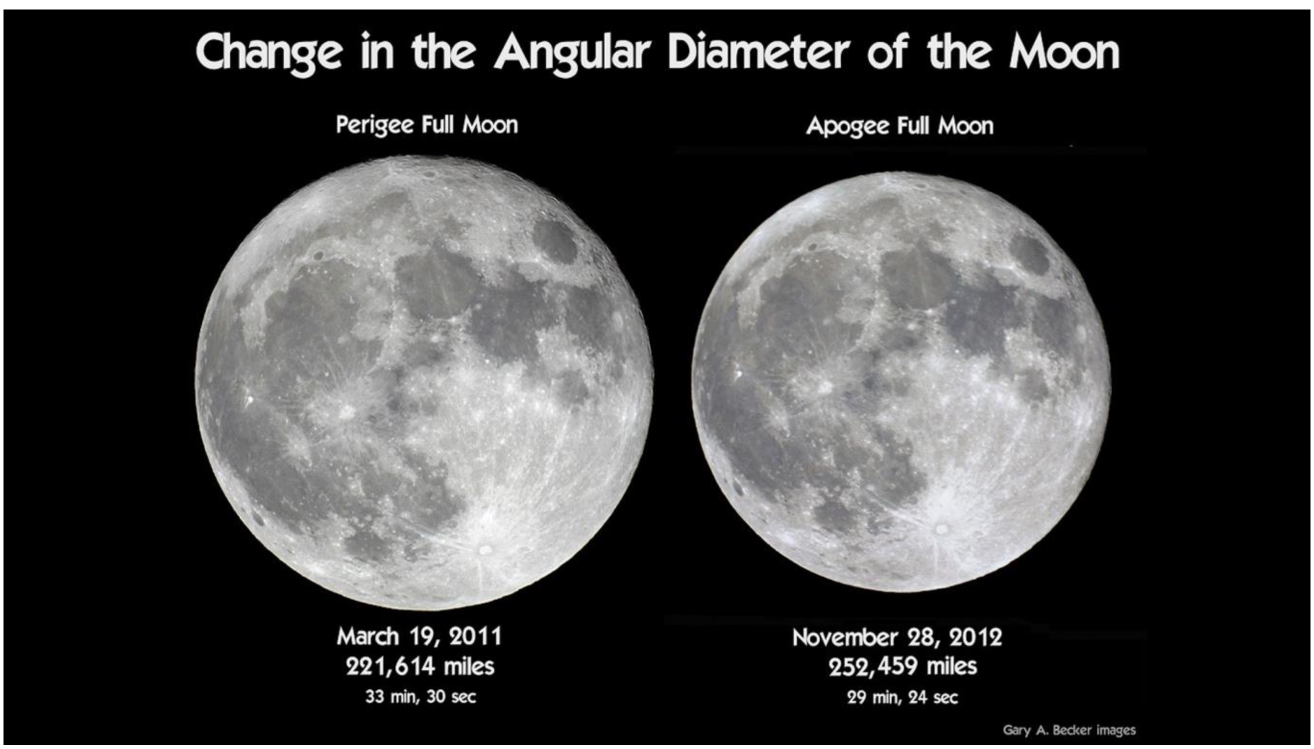
Below is my picture of the total solar eclipse I saw on August 21, 2017, in Guernsey State Park, Wyoming. This eclipse trip was a culmination of a year's worth of planning and I will have more to say about that eclipse when we discuss how to plan an eclipse trip.

Let's consider how distance affects eclipses. By now, you should have some feelings about this important factor. Note that as the moon orbits the Earth, it is not inscribing a circle but rather an ellipse (oval). The moon travels faster in its orbit when it is closer to Earth and slower when it is farther away from our planet.



The moon's elliptical orbit has an eccentricity of about 12.5 percent. It gets to a position in its orbit closest to the Earth, a location called perigee, from the Greek, peri meaning close, and gee meaning Earth. As the moon moves to the opposite side of its orbit, it reaches its farthest position in its path, called apogee. Again, from the Greek, the apo means far or great, while the gee signifies the Earth.

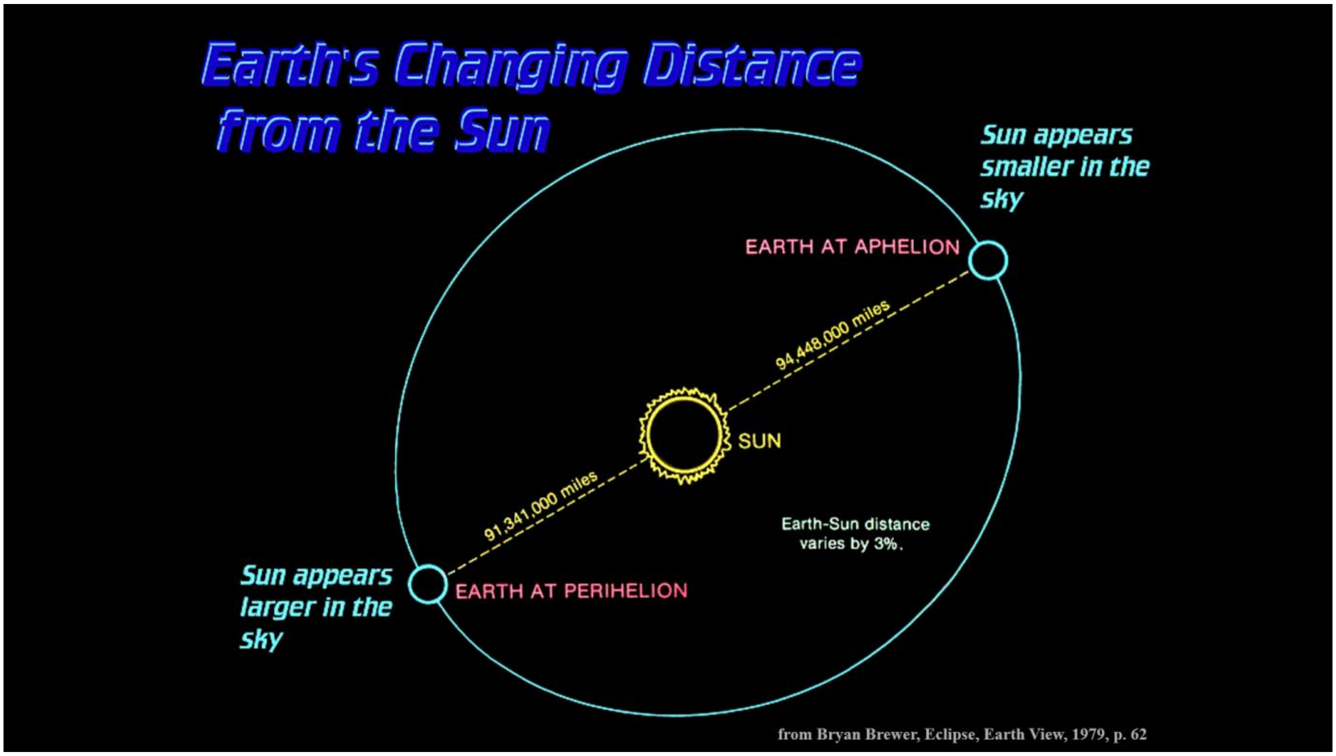
These two positions, perigee and apogee, are crucial in understanding the moon's orbit and its effects on solar eclipses. Their positions are opposite along a line segment called the major axis, or the line of apsides if referring to eclipses.   The major axis connects the closest and the farthest positions of the orbiting moon around the Earth. Because the moon's orbit is an ellipse, distance from Earth is not fixed but continuously changes, altering the moon's angular size or how big the moon appears in the sky. With their close angular sizes, this dynamic relationship between the Earth and the moon determines the type of central (annular, broken annular, or total) solar eclipse that will happen.



Let's look at these images of the moon at apogee (far) and perigee (close). On the right, we have an apogee photograph captured on November 28, 2012, when the moon was approximately 252,500 miles from Earth. The image on the left, taken at perigee, shows the moon at its closest distance of 221,500 miles from Earth. Notice how it appears larger than the moon on the right, a visual testament to the moon's varying distances.

What determines the moon's orbital speed as it moves closer or farther from the Earth? The answer lies in the gravitational forces at play. At perigee, the Earth and moon are locked in the strongest gravitational tug-of-war, with each body exerting its maximum force on the other. This gravitational attraction causes the moon to speed up in its orbit. Conversely, the gravitational forces are weakest at apogee, resulting in the moon's slowest orbital speed.

If the moon is at apogee and a central solar eclipse occurs, the eclipse will always be annular. If the moon is at perigee, a central eclipse will always result in a total solar eclipse.

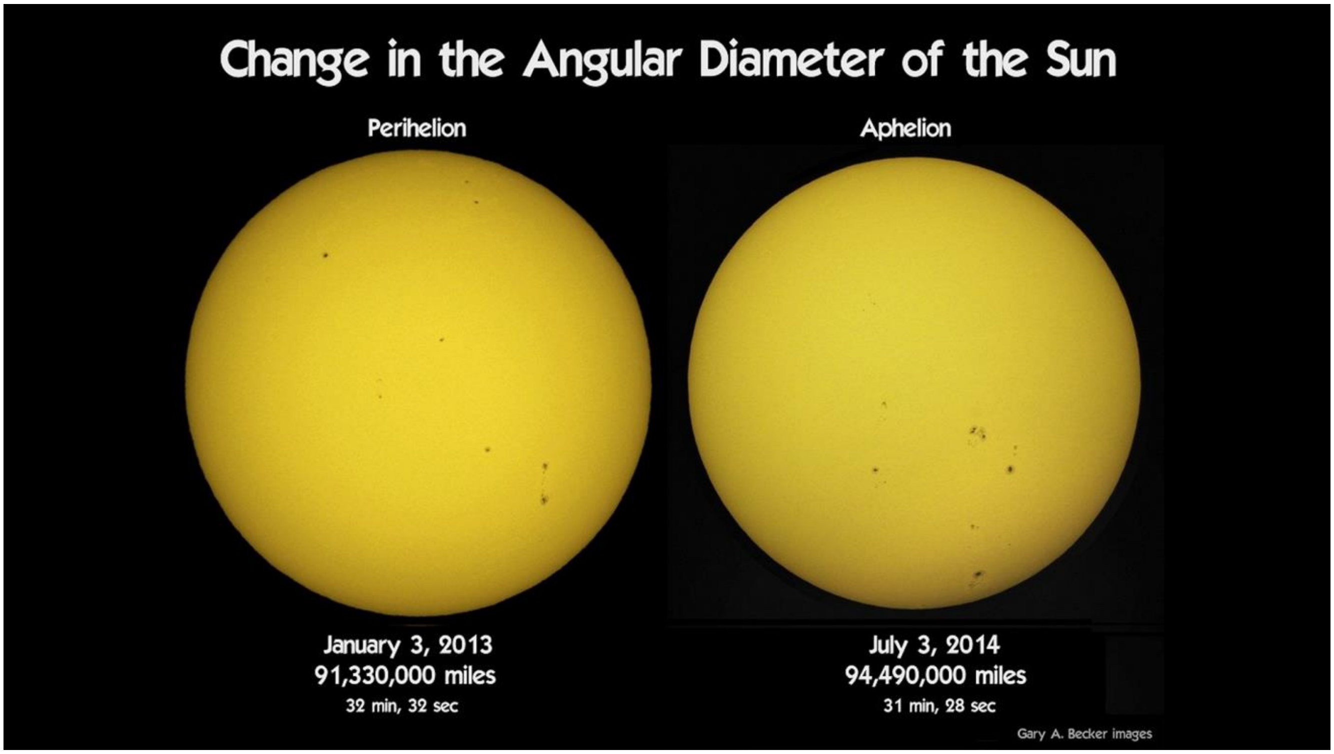


The other consideration is the Earth's revolution around the sun. Our orbit around Sol is also elliptical by about three percent. This elliptical orbit is significant in understanding solar eclipses because it affects the distance between the Earth and the sun. That means that Earth's distance from the sun constantly changes, varying by roughly three million miles from the Earth being closest and farthest from the sun. In early January, the distance is about 91.5 million miles. By early July, that distance has increased to approximately 94.5 million miles.

We have words to express the Earth's extreme positions from the sun. If we are closest, that location in Earth's orbit is termed perihelion, a word derived from the Greek' peri' for near and 'helios' for the sun. If we are farthest, the Earth is at aphelion, a word also derived from the Greek 'ap' for far and 'helios' for the sun.

If you are a gambler and you were going to bet on central solar eclipses as to whether more would be total or more would be annular, which type, annular or total, would be more common? Let's say there are 100 central solar eclipses, which are eclipses where the moon's center passes precisely in front of the sun's center somewhere on the Earth. Remember that there are two flavors of central eclipses, annular and total, governed by their distance from the objects they orbit. As a betting person, which eclipse type would you always bet on if you did not know what type of eclipse would be occurring? If you lived long enough, you'd make a fortune. Which central eclipse type is more common, annular or total solar eclipses? The annular type is correct. Out of 100 eclipses, there might be 46 or 47 total and 53 or 54 annular.   Knowing that fact, you would walk away with some great money.

You would always bet on the annual eclipses because annular eclipses only occur when the moon is farther away and when the moon is moving slower in its orbit around the Earth.

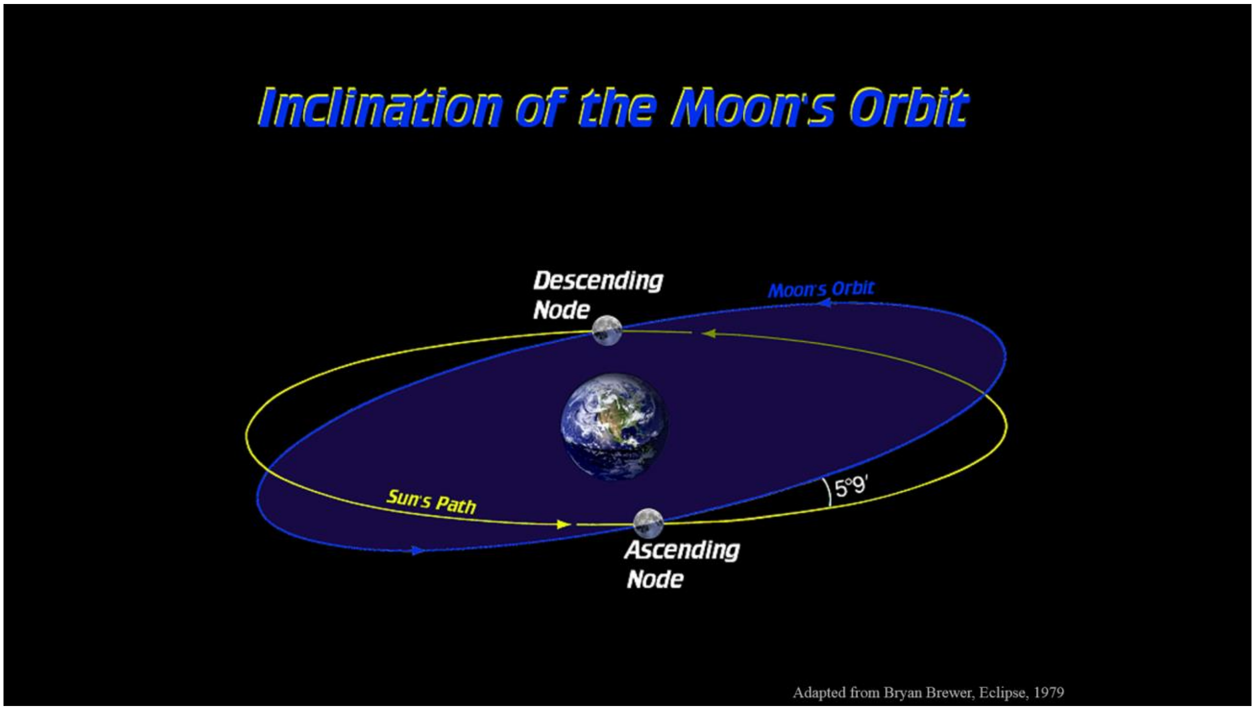


This slide documents the sun when Earth was at perihelion (left—closest to the sun) and at aphelion (right—farthest from Sol). Perihelion in 2013 was actually on January 2 that year, but unfortunately, it was cloudy that day. We were at 91,330,000 miles. The aphelion image on the right side of the slide was snapped on July 3, 2014, eighteen months later, within several hours of aphelion. At that time, we were at a distance of 94,490,000 miles from the sun. You have to look more critically, but a difference can be seen. Which sun appears larger?

Here are all four images for comparison: two of the sun and two of the moon when Sol and Luna were at their extreme distances. These are the same images seen in the previous slides but reduced in size, so they fit into the boxes, which are the same size. The photos were taken with the same telescope and camera to create an exact scale.

Please understand that everything I say about solar eclipses applies to lunar eclipses. I am hyping solar eclipses because they are visually more spectacular. I also want you to see a total solar eclipse sometime during your life. You will never regret your choice, guaranteed.

Repetition of Eclipses



Here, a slide shows how the moon's orbit (blue) is tilted to the Earth's orbit (yellow). The blue represents the plane of the moon's orbit. The yellow represents the plane of the Earth's orbit around the sun. Pretend the sun is off to the right of the slide but in the ecliptic plane. The moon's orbit is tilted 5 degrees, 9 minutes to the ecliptic plane. Students will only have to remember 5 degrees. It is a small tilt, but since the moon and the sun are only a half degree in diameter, a separation of even just one degree would not result in an eclipse occurring, let alone 5 degrees.

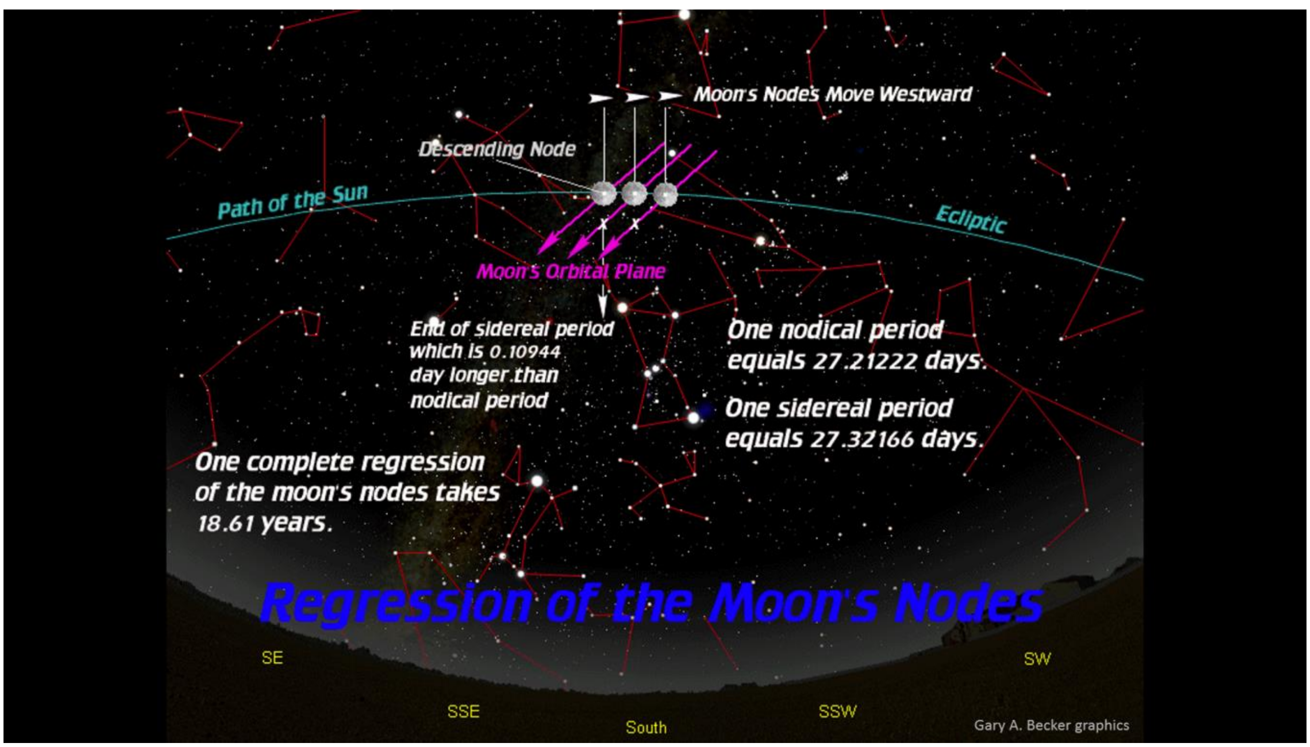
How large is a half degree? Just look at the moon when it is full in the sky. It is not very big. Remember that from one horizon to the zenith to the opposite horizon is 180 degrees. Five degrees is not that big of an angle. Because the moon is only a half-degree and the sun is only a half-degree, when Luna is either new or full, it will pass over or under the sun or Earth's shadow, and no eclipse will arise. But what happens if the moon crosses the ecliptic, in other words, if the moon is at or near a node (see next paragraph), and the moon is either full or new? Can you see that an eclipse must happen because the Earth and sun define the ecliptic? The moon must either pass in front of the sun or pass through the shadow of the Earth.

Let's reinforce the concept of a node, simply an intersection point where two planes cross. In this case, it is where the ecliptic plane crosses the moon's orbital plane. The descending node is located where the moon travels from above the ecliptic to below the ecliptic. If the moon moves from below to above the ecliptic plane, that point of intersection is called the ascending node.

There are seasonal nodes, such as the vernal equinox, where the ecliptic plane crosses the plane of the celestial equator. The autumnal equinox is the intersection point where the sun traveling along the ecliptic plane moves from above to below the plane of the celestial equator.

If the moon is at or near a node and new, the moon's shadow must be on the ecliptic, pointing directly towards the Earth. If the moon is full and at a node, it must intersect the Earth's umbra because the Earth's shadow must always lie on the ecliptic. No eclipse can occur if the moon is significantly above or below the ecliptic plane and in a new or full position. That is what happens in most months. The moon's crossing position doesn't have to be exactly in the plane of the ecliptic. There is some wiggle room because the Earth presents a fairly large target for the moon's umbra and penumbra to strike, and the Earth's shadow presents a sizable target for the moon to enter. **The moon must be near or at a node and either full or new for an eclipse to transpire**.

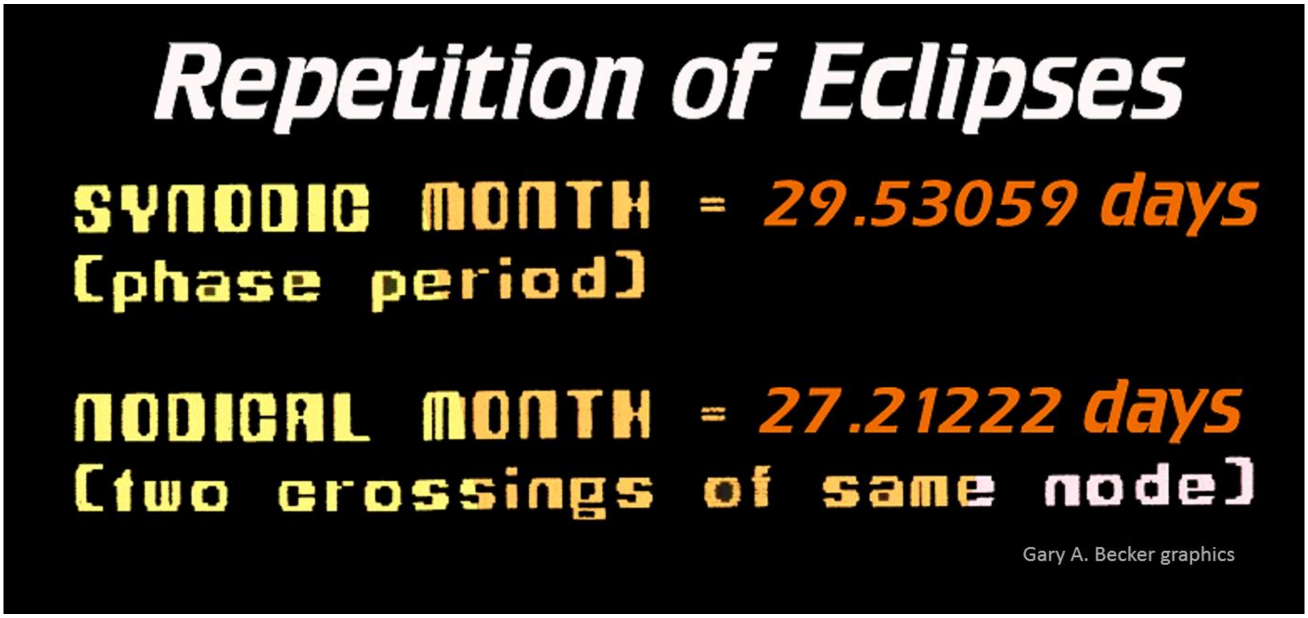
In a perfect world, the time it would take for the moon to cross the same node twice should be the same as the sidereal period of the moon, 27.3 days. But this is not a perfect world. The time it takes the moon to cross the same node twice is called the nodical period, and its interval is 27.3 days. Why is this?



Let's delve into this concept using the slide on the last page. Here, the moon is positioned on the ecliptic and at its descending node. The tilt of the moon's orbit, though exaggerated here, is just over 5 degrees. When we give the signal, the moon starts its journey, moving to the left and eventually returning to the ecliptic. However, its crossing position will be slightly to the right of its previous intersection. This westward motion of the nodes, known as a regression of the moon's nodes, is a regular feature of the Luna's orbit. The node has shifted to the right (west). When the moon crosses the ecliptic (the node) the next time, it will happen to the west of its previous crossing before it passes the position (now slightly lower) where its orbital motion ends the sidereal period. The sidereal period of the moon is 27.3 days, while the nodical period of the moon, the time it takes to cross the same node twice, is 1/10th of a day shorter or 27.2 days.

Students will need to know these periods, sidereal (27.3 days), synodic (29.5 days), nodical (27.2 days), and anomalistic (27.6 days), to one decimal place to the right of the whole number, as stated in this paragraph.

Let's turn our attention to the eclipse repetition cycle, as illustrated in the next slide.



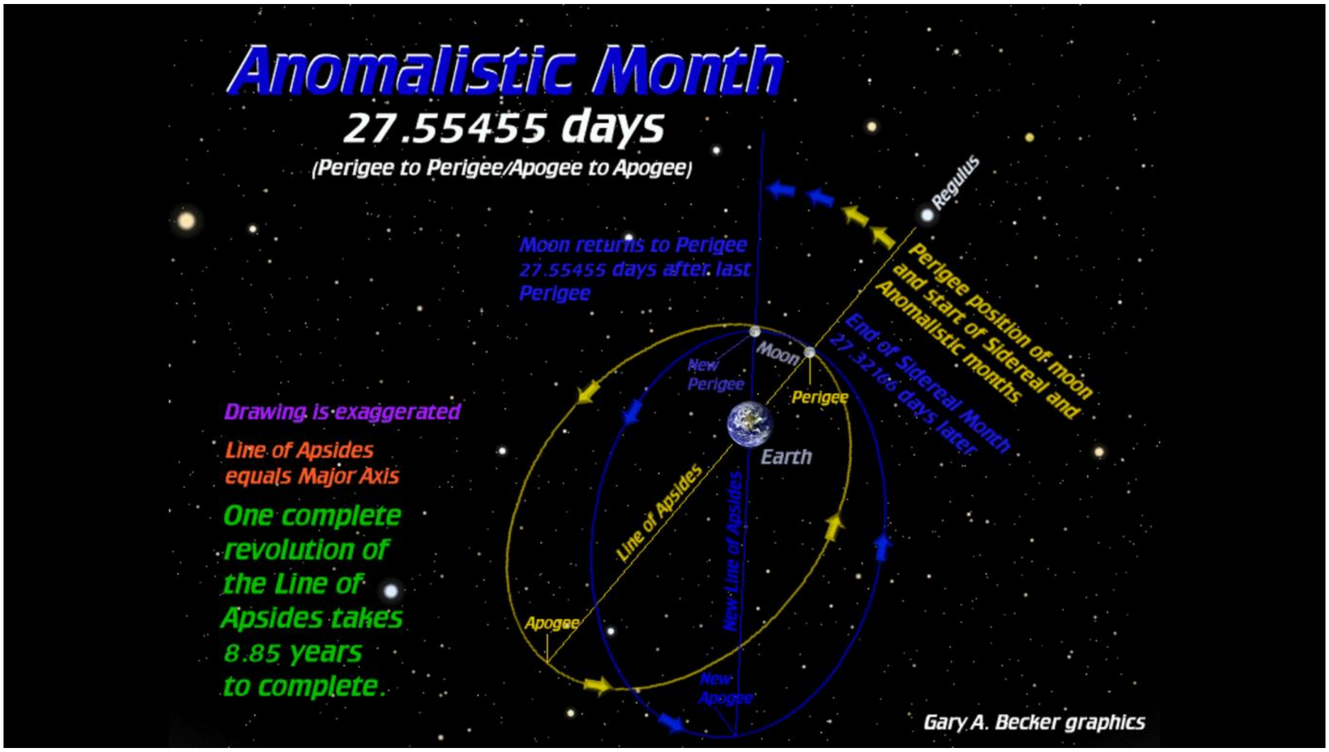
Our two drum beats, the synodic period of 29.5 days and the nodical period of 27.2 days, are crucial in predicting solar eclipses. **If an eclipse occurs today, the next one will occur when a whole number X, multiplied by the synodic period, equals the same number of whole days as a different whole number Y multiplied by the nodical period.** When synchronized (x times the synodic period and y times the nodical period) with the same number of whole days, these two drumbeats indicate the occurrence of another eclipse. When they become synchronized again, another solar eclipse will occur. Forty-seven x 29.53059 days equals 51 x 27.21222 days, yielding the same number of whole days, 1387.

If a solar eclipse occurs today, it means that the synodic and nodical periods have aligned. In subsequent time, they will start getting out of phase again. However, 47 synodic months equal the number of whole days as 51 nodical months. During this interval, the moon will return to the same phase and must be at or near a node. Another eclipse of the same type, solar or lunar, must ensue. The information that will not be available if the event is a solar eclipse is whether the eclipse will be total, annular, or partial.

Here is the rub. Ancient cultures were not interested in partial or annular eclipses because they were essentially invisible to them. They were not as interested in lunar eclipses either because the moon was not as important an object as the sun. Unless the moon covers the sun to about 99.9 percent, the dark disk of Luna will not be visible against the sun. People were interested in total solar eclipses where the moon "swallowed " the sun.

If the sun and moon were gods independent from human affairs, there was no reason to suspect that the sun would ever return if a total solar eclipse occurred. I am not trying to indicate that a deep partial or annular eclipse would not make the landscape look weird—weak shadows on the ground, the sky looking greyish blue, the landscape yellow, but that would not be close to the visually spectacular effects of the moon producing a total solar eclipse. There's one early story about two Chinese astronomers who were unable to predict a total solar eclipse and were beheaded for their lack of knowledge. It was a mistake they could not have foreseen because the eclipse that led to their demise was the first solar eclipse to be witnessed in a new cycle of eclipses called the saros.

We want to know when the next total solar eclipse will occur. Those are the really important eclipses. I still need a new moon, and I will still need the moon positioned in its orbit at or very near a node. In addition, because I want to predict a total solar eclipse, I need the moon to be at a similar distance from the Earth to create the same type of eclipse (total) as the last one viewed.



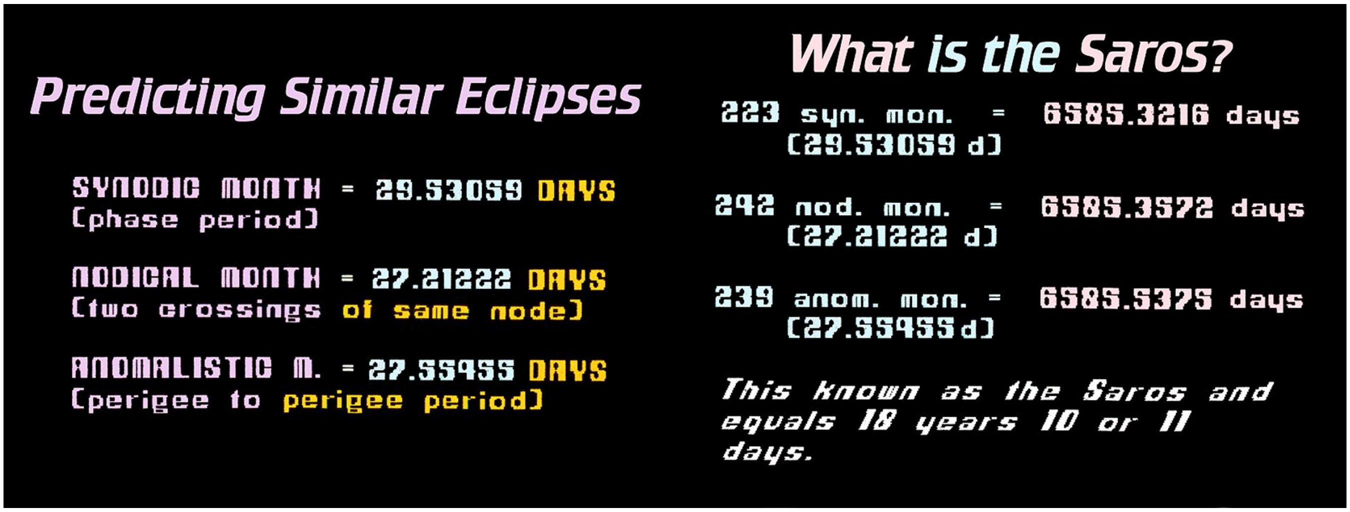
This next slide shows a view of the moon's orbit. While not as exaggerated as the drawing, its orbit is still an ellipse. If you looked at the moon's orbit, you would see a shape that is more circular than oval, especially if the Earth was covered. However, it is an ellipse, and I must emphasize that. Also, I don't want to be too simplistic, but on the other hand, I cannot demonstrate this unless I highly exaggerate what I am about to explain.

Let's start with the yellow orbit of the moon. Once again, we have the moon lined up with the star Regulus, but we also have the moon at perigee, its nearest position to the Earth. We can predict when the moon's next perigee position will occur. I say go, and everything swings into motion. The sidereal period has started, but I have also begun another cycle called the anomalistic period—perigee to perigee, apogee to apogee. The moon starts revolving around the Earth. As it continues, I will change my position from the yellow orbit to the blue orbit. As the moon comes around, it is located on the path of the blue orbit. If you look closely, you can see the blue orbit is now in front of the original perigee position of the moon when it was in the yellow orbit. That is important because when the moon passes Regulus for the second time, ending the sidereal period, it has not yet reached its new perigee position. The moon will chug, chug along its orbit until it gets to its actual perigee location, which is the place along the line of apsides (major axis) to the left of its original position.

Here is the important part. The moon comes around and passes Regulus, ending the sidereal period, but then the moon continues to chug along its orbital path until it reaches its next perigee location. The anomalistic period (perigee to perigee/apogee to apogee) is a longer interval of time than the sidereal period. The anomalistic period is 27.55455 days. Let's make it 27.6 days so we don't go too crazy.

We have these three periods to consider. They are the synodic period of **29.5**3059 days, the nodical period of **27.2**1222 days, and the anomalistic period of **27.5**5455 days. Those are the three beats that have to come into synchronization to produce a similar eclipse. When all three beats coincide, in other words, when they are multiplied by three different whole numbers to produce the same number of whole days, the moon will be new, the moon will be at or near a node, and the moon will be at a similar distance to the Earth as it was at the time of the first eclipse. Another solar eclipse must occur.

It is the same concept as the two-beat repetition of the eclipse cycle, but it now involves three beats. What whole number X multiplied by the sidereal period, what whole number Y multiplied by the nodical period, and what whole number Z multiplied by the anomalistic period will result in the same number of days? The slide below shows those numbers, which lead to an 18-year, 10, or 11-day period known as the saros in which, during that time, a similar eclipse will be repeated.



Please do not memorize these numbers except for the first numeral to the right of the decimal. Understanding the concept is essential to your success in this unit on eclipses. It's the key to unlocking the mysteries of the saros cycle and eclipse occurrences.

If a total solar eclipse occurs today, I can confidently predict that in 6585 days, the moon will be new, the moon will be at or near a node, and the moon will be at a similar distance as the last eclipse of that saros sequence. Another solar eclipse similar to the previous one in the saros cycle must occur. The length of this period is 18 years, 10 or 11 days. It is more accurately 18 years, 9, 10, 11, or 12 days, depending on the number of leap year days within that 18-year saros period. You will need to remember 18 years, 10, or 11 days, but the 9 and 12 days are rare occurrences.

These interconnected eclipses form a distinctive saros cycle that can endure over a millennium before alignments deteriorate and the cycle ends.

I need to step back and regale you with another piece of eclipse information. If a total solar eclipse occurs today, will the next total solar eclipse happen in 18 years, 10 or 11 days? The answer is no. There are well over two hundred saros cycles running simultaneously, giving someone interested in observing eclipses multiple opportunities to view solar and lunar eclipses each year if that person is willing to travel.

Because there are two nodes, a descending node where the moon is traveling from above the ecliptic to below the ecliptic and an ascending node where the moon is moving from below the ecliptic to above the ecliptic, there must be at least two solar eclipses and two lunar eclipses occurring each year. However, as many as seven solar plus lunar eclipses can occur in a year. There could be two lunar and three solar, five lunar and two solar, three lunar and three solar, etc. There must always be two lunar and two solar eclipses in a year, but there can be as many as five of one type of eclipse, seven eclipses total, during that same time interval. Below, I am showing you one complete saros cycle, a unique sequence of eclipses from the first partial eclipse that occurred at the South Pole to the last partial solar eclipse that will happen at the North Pole. Study it for a moment to understand the evolution of the different types of eclipses that occur as alignments become better and deteriorate.

A Complete Saros Cycle

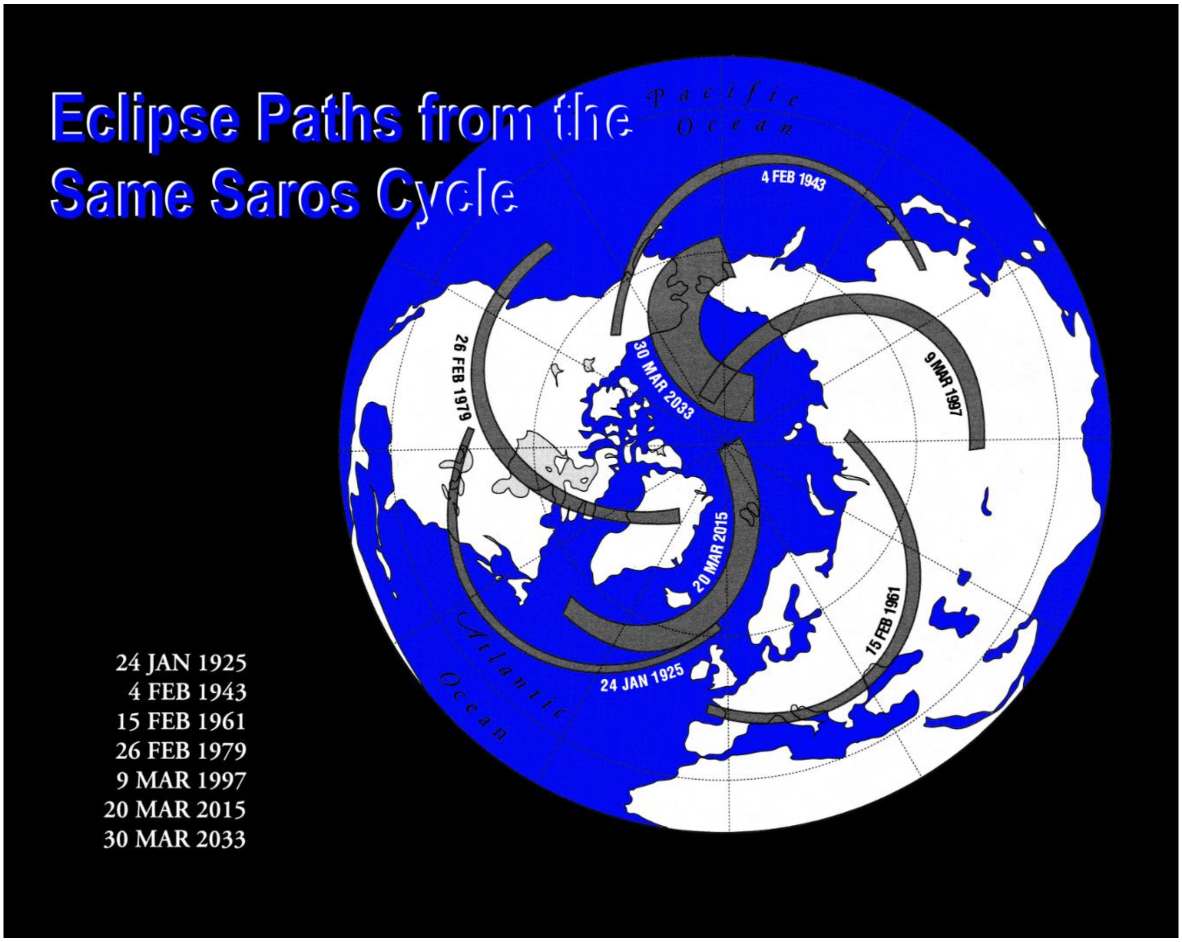
Date	Type	Date	Type
933 May 27	Partial	1582 June 20	Total
951 June 7	Partial	*1600 July 10	Total
969 June 17	Partial	1618 July 21	Total
987 June 28	Partial	1636 Aug. 1	Total
1005 July 9	Partial	1654 Aug. 12	Total
1023 July 20	Partial	1672 Aug. 22	Total
1041 July 30	Partial	1690 Sep. 3	Total
1059 Aug. 11	Annular	1708 Sep. 14	Total
1077 Aug. 21	Annular	1726 Sep. 25	Total
1095 Sep. 1	Annular	1744 Oct. 6	Total
1113 Sep. 11	Annular	1762 Oct. 17	Total
1131 Sep. 23	Annular	1780 Oct. 27	Total
1149 Oct. 3	Annular	1798 Nov. 8	Total
1167 Oct. 14	Annular	1816 Nov. 19	Total
1185 Oct. 25	Annular	1834 Nov. 30	Total
1203 Nov. 5	Annular	1852 Dec. 11	Total
1221 Nov. 15	Annular	1870 Dec. 22	Total
1239 Nov. 27	Annular	1889 Jan. 1	Total
1257 Dec. 7	Annular	1907 Jan. 14	Total
1275 Dec. 18	Annular	1925 Jan. 24	Total
1293 Dec. 29	Annular	1943 Feb. 2	Total
1312 Jan. 9	Annular	1961 Feb. 15	Total
1330 Jan. 19	Annular	1979 Feb. 26	Total
1348 Jan. 31	Annular	1997 Mar. 9	Total
1366 Feb. 10	Annular	2015 Mar. 20	Total
1384 Feb. 21	Annular	2033 Mar. 30	Total
1402 Mar. 4	Annular	2051 Apr. 11	Partial
1420 Mar. 14	Annular	2069 Apr. 21	Partial
1438 Mar. 25	Annular	2087 May 2	Partial
1456 Apr. 4	Annular	2105 May 14	Partial
1474 Apr. 16	Annular	2123 May 25	Partial
1492 Apr. 26	Annular	2141 June 4	Partial
1510 May 8	Annular-total	2159 June 16	Partial
1528 May 18	Annular-total	2177 June 26	Partial
1546 May 29	Annular-total	2195 July 7	Partial
1564 June 8	Total		

*Begin dates from Gregorian calendar

Why do eclipses change their types when a saros cycle is supposed to predict similar eclipses? Each of these beats, with its fractional component, operates over a gradual process, causing the saros cycle to slowly shift in and out of synchronization, leading to an eventual end to the cycle.

Eclipse after eclipse in the same saros cycle is not quite the same. The synodic beat decimal of 0.3216 day, a predictable factor, indicates that the next eclipse in the sequence will happen about 1/3 of a day later. This extra eight hours means the path of totality will be about 8000 miles to the west of the previous total solar eclipse. If an eclipse is visible in Africa, the next eclipse of that same saros cycle, 18 years, 10 or 11 days later, will occur over the Pacific Ocean.

Given that the primary beat for eclipses is the synodic period, the difference in the decimal remainders between the synodic/nodical and the synodic/anomalistic periods indicates that the moon's position relative to the node and its distance from the Earth are slowly shifting over time. A saros cycle commences at either the north or south poles, progresses over time to produce a lengthy series of total solar eclipses, and then gradually falls out of phase to generate a series of partial solar eclipses at the opposite pole of the Earth as it concludes.



This slide highlights a few of the paths of totality from the same saros cycle you just viewed. We are looking at the eclipses of 1925, 1943, 1961, 1979, 1997, 2015, and 2033. The moon's shadow runs west to east across the surface of the Earth if you want to follow the paths in their correct directions. However, please notice how the totality paths are moving toward the North Pole as this saros cycle nears its end.

My father saw the total solar eclipse from Allentown on January 24, 1925, as a very deep partial eclipse. It was 98 percent total. My grandfather took a barrel and filled it up with water. Then he took a piece of glass and smoked it with a candle. They held the glass in front of their eyes, looking at the sun's reflection in the water. This eclipse occurred when my dad was nearly six years old. My father remembered this event vividly, which may have influenced his desire to become a science/mathematics teacher in Pennsylvania public schools. It's pretty cool regarding my grandfather's ability to create a safe view of this eclipse; however, it's important to note that viewing the partial stages of a solar eclipse directly, even with a smoked glass, is still very dangerous. This eclipse was total in Scranton, PA and continued across Manhattan in New York City.

Manhattan Island, as you may well know, runs north-south. The eclipse path was almost exactly west-east. In Manhattan, volunteers were stationed on the rooftops of buildings to determine the exact location where the eclipse became total. In other words, these people were trying to determine the southern limit of the eclipse. It turned out that the eclipse became a total solar eclipse north of 86th Street and was a deep partial eclipse south of that location. This eclipse became known as the 86th Street Eclipse.

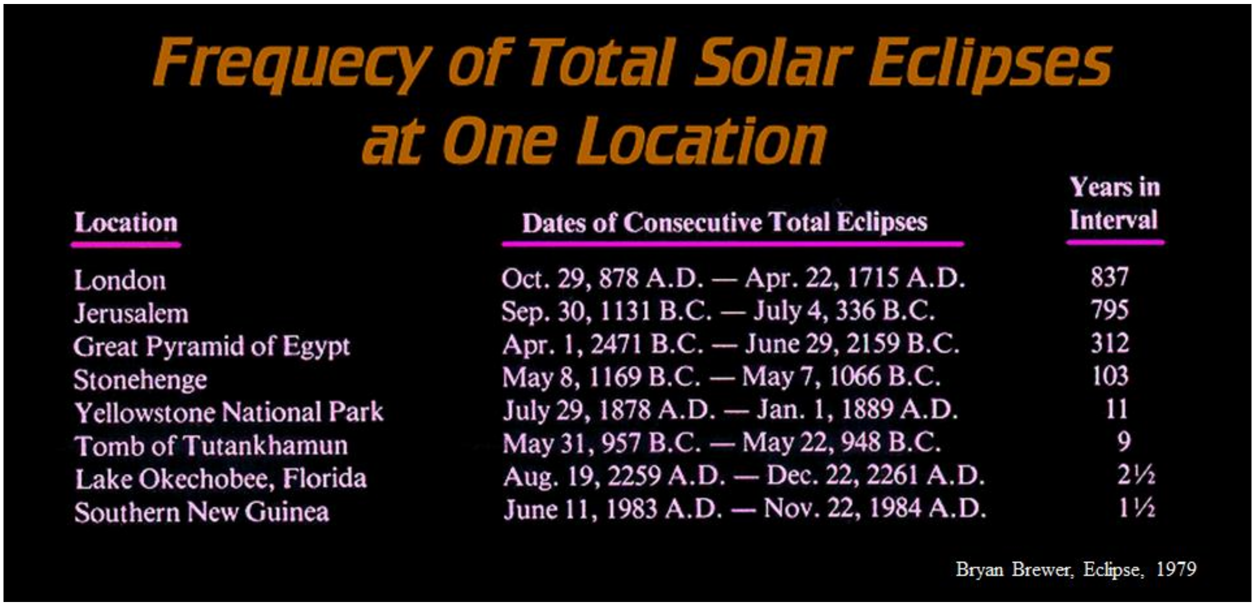
Another interesting fact about this eclipse was that it occurred on a Saturday. The NYC Transit Authority did not consider that many interested folks might want to go uptown that day to see the eclipse. The subways were on a light Saturday schedule, and tens of thousands of people were caught below street level waiting for a train to transport them north, uptown.

Look at the path of totality on March 20, 2015. Can you see it ends just at the North Pole? March 20 is the vernal equinox, the first day of spring, when the sun is just rising at the North Pole. On your next exam, I will have a question about this eclipse, dealing with Santa, and how his toy production was affected.

You can see how this saros cycle spirals towards the North Pole by looking at the 1925 path of totality and comparing it to the path of the moon's shadow in 2033. After 2033, the eclipses become partial, and after 2195, even the penumbras will not touch Earth's surface anymore, thus ending this particular saros cycle.

No total solar eclipse has gone through Allentown, Pennsylvania, or the Lehigh Valley for several hundred years. The next total solar eclipse that the Lehigh Valley gets to experience occurs on May 1, 2079, where totality happens when the sun's disk has just fully become visible on the eastern horizon.

If you never plan to travel to see a total solar eclipse, remember that chances are that no eclipse will pass over your area. In a 1000-year study of the totality paths of solar eclipses across the continental US, there were locations, particularly in the Southwest, where the moon's shadow never touched the Earth.

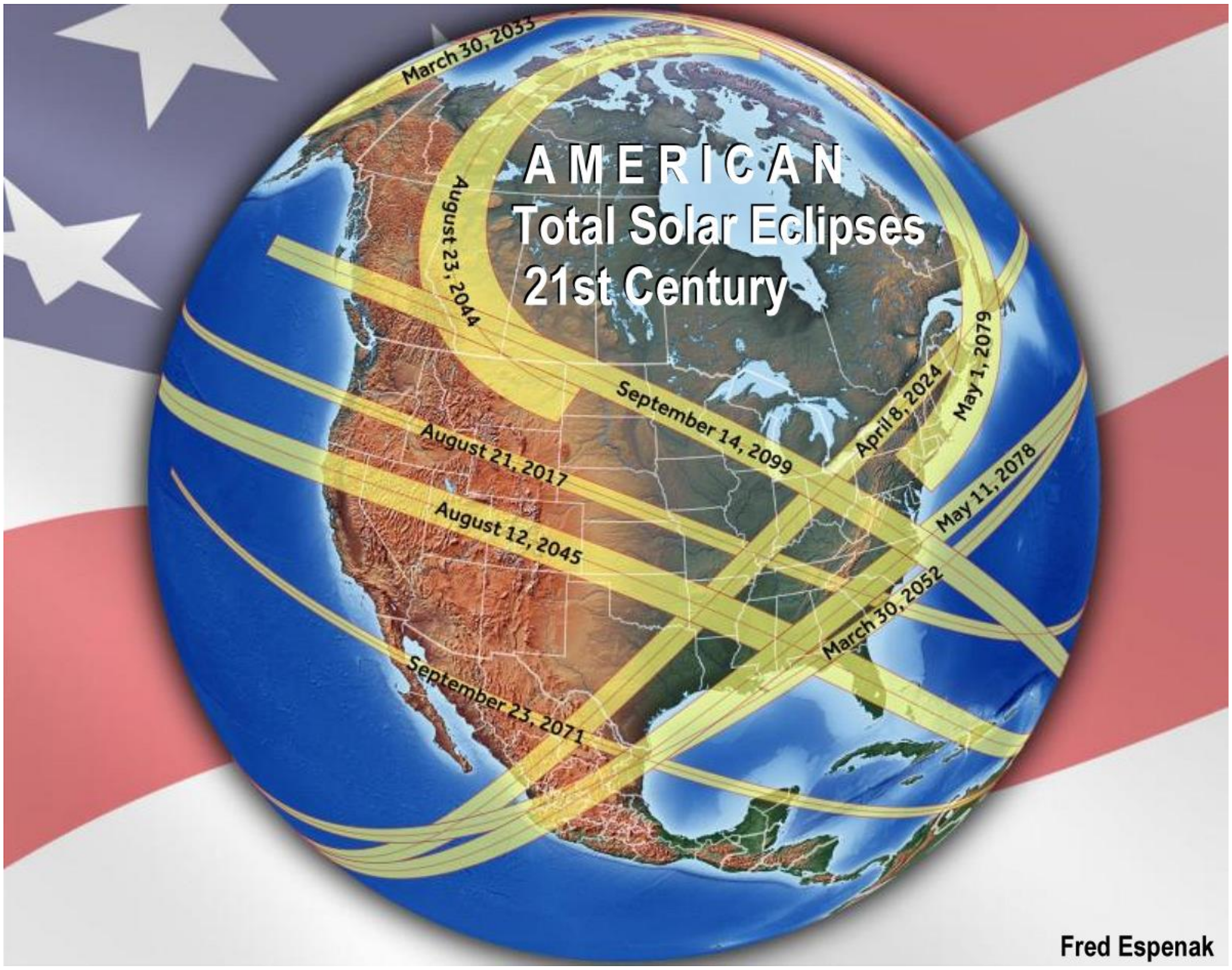


Frequecy of Total Solar Eclipses at One Location

Location	Dates of Consecutive Total Eclipses	Years in Interval
London	Oct. 29, 878 A.D. — Apr. 22, 1715 A.D.	837
Jerusalem	Sep. 30, 1131 B.C. — July 4, 336 B.C.	795
Great Pyramid of Egypt	Apr. 1, 2471 B.C. — June 29, 2159 B.C.	312
Stonehenge	May 8, 1169 B.C. — May 7, 1066 B.C.	103
Yellowstone National Park	July 29, 1878 A.D. — Jan. 1, 1889 A.D.	11
Tomb of Tutankhamun	May 31, 957 B.C. — May 22, 948 B.C.	9
Lake Okechobee, Florida	Aug. 19, 2259 A.D. — Dec. 22, 2261 A.D.	2½
Southern New Guinea	June 11, 1983 A.D. — Nov. 22, 1984 A.D.	1½

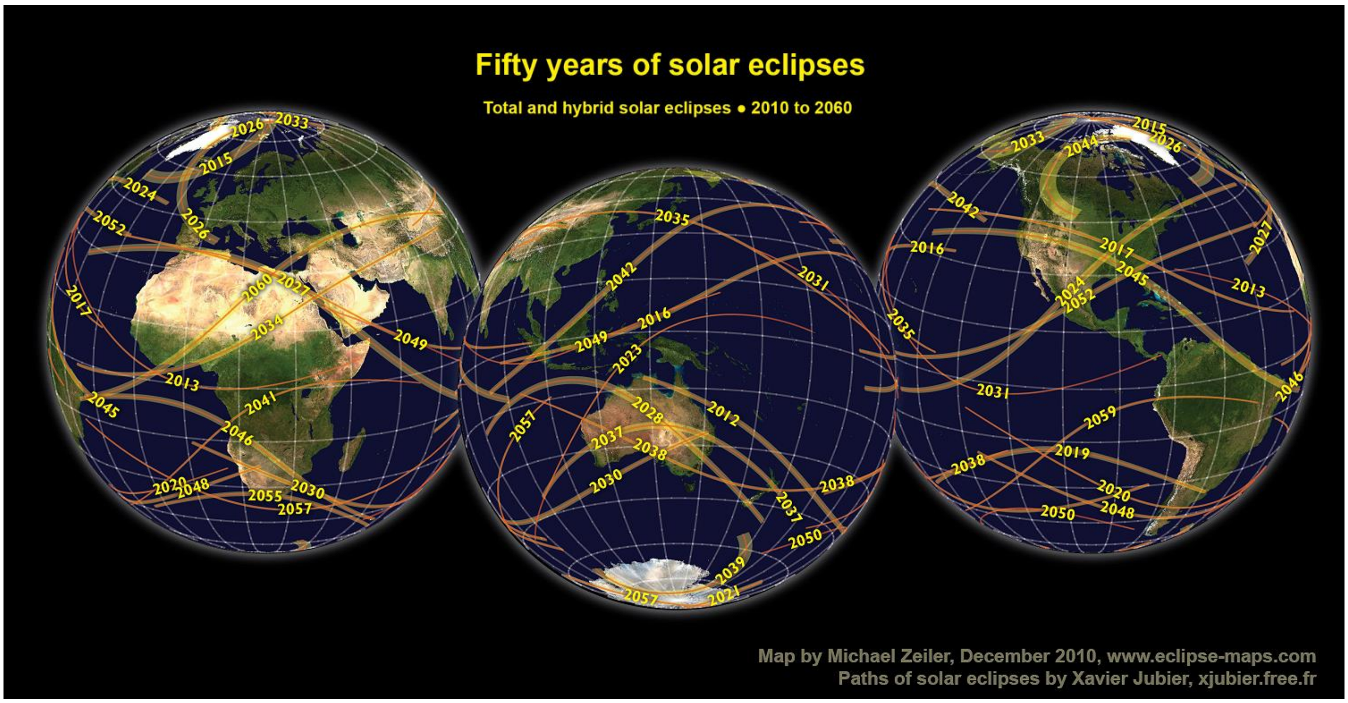
Bryan Brewer, Eclipse, 1979

In this slide, we can see the intervals between total solar eclipses at specific locations. Remember that the path of totality is relatively narrow, on average about 115 miles wide. The interval between the path of totality passing over the same area twice is about 375 years. But it can be much longer, such as in London, England, where the time between two total solar eclipses was 837 years, from 878 AD to 1715 AD. However, you do not have to wonder why the "natives" in Southern New Guinea, north of Australia, might have become slightly restless. Only a year and a half went by between two total solar eclipses in that location. Most likely, your location will not be graced by two solar eclipses occurring in a short time or even a lifetime.



The kids growing up in Carbondale, Illinois, will think that eclipses are incredibly frequent because an eclipse occurred there on August 21, 2017, and another total solar eclipse happened on April 8, 2024. After 2024, the US mainland will have to wait with bated breath until August 22, 2044, and August 12, 2045, before experiencing another total solar eclipse that crosses the continental US. I guarantee that you will never regret traveling to see a total solar eclipse. Most people who take the opportunity to see one, will want to see more.

By studying the map below, which shows the paths of total solar eclipses from 2010 to 2060, you can travel the world to see a total solar eclipse. The thickness of the paths through the mid-latitudes gives some idea of the length of totality. The thicker the path, the longer the totality will last.



Look to Australia for a truly unique and thrilling experience-witnessing a solar eclipse. The 2023 hybrid eclipse was fascinating. The beginning and end of the central path produced an annular eclipse. However, as the Earth's surface bulged outward, the umbra quickly made contact with the Indian Ocean, creating a short totality that lasted only 61 seconds at its greatest duration. The eclipse path only touched the end of the western tip of the North West Coast of Australia, about 500 miles north of Perth, where I saw it on board the Pacific Explorer. But look at all of the others. It would be a great excuse to visit one of the countries with the friendliest people in the world. You may not want to leave. Just remember, the seasons are reversed. However, since the paths of these eclipses all occur in the Southern Hemisphere, they will happen during Australia's summertime.

Get ready for the upcoming eclipses and the thrill they will bring. Note the thickness of the path of totality of the August 21, 2017 eclipse. It was thin, indicating that the totality duration was short. I saw that eclipse in Guernsey State Park in SE Wyoming. Its duration was 2 minutes and 22 seconds at the location where I observed it. Note the thicker path of totality for the total solar eclipse on April 8, 2024. Totality lasted longer. The duration of totality during that eclipse was just over four minutes in central Texas, where it turned out to be mostly cloudy. I saw this one near the Canadian border in Derby Center, Vermont.

Stay tuned for our next meeting, where we'll delve deeper into the fascinating world of solar eclipses by visually looking at the different types of eclipses and the equipment needed to see one successfully. We will also discuss lunar eclipses.

March 7-9, 2021
August 23, 2021
December 20-22, 2024