Explaining the Motion of Heavenly Bodies: Part 5 - When do Solar and Lunar Eclipses Occur?

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In the previous four installments of this series of articles, we looked at the apparent motion of the Sun, moon and planets across our skies and how these can be explained by a) the earth rotating on its axis once every 24 hours; b) the revolution of the moon around the earth; and c) the revolution of the earth and other planets around the sun; each planet having its own period of revolution. But I have saved the most amazing phenomena for this last article – eclipses of both the Sun and the moon. We have been told that these occur when the shadow of the moon falls on some portion of the earth (solar eclipse) or when the shadow of the earth falls on the moon (lunar eclipse). In this last article I have planned to write on the topic of the motion of heavenly bodies, I hope to explain how and when these eclipses occur.

It is easy to have observed a lunar eclipse because there is usually at least one to be seen from wherever you live every year, these may be total or partial eclipses – in a total eclipse, for at least part of the time, the moon is entirely under the shadow of the earth while during a partial eclipse some portion of the moon remains brightly lit. Solar eclipses are much rarer occurences and most of these are only partial. Other than total eclipses (when for a very short interval the entire face of the Sun is covered by the moon), you have a phenomenon called an annular eclipse of the Sun where the moon does not cover the Sun fully, a bright ring all around the edge is visible with a dark circle in the middle. However fascinating solar eclipses are, looking at the Sun directly can damage our vision[1]. So when I talk about observing a solar eclipse, please not that I am not asking you to look directly at the Sun (which you should never do!).

Why don't we observe a solar eclipse every new moon day and a lunar eclipse every full moon night?

Whenever these three (the Sun, moon and earth) are in a straight line, the shadow of either the moon or the earth should fall on the other one. On a new moon day, the moon is between the Sun and the earth and we should be able to see a solar eclipse; and similarly, on a full moon night, the earth is between the Sun and the moon and we should see a lunar eclipse. Then why are these phenomena so rare? Since we don't have one solar and one lunar eclipse happening each month (remember that the moon takes roughly one month to go around the earth), it must indicate that these three bodies are not in a straight line twice a month. Why might this be so? The simplest explanation for this is that the plane of the orbit for the moon (around the earth) is not the same as the ecliptic plane (the plane of the orbit of the earth around the Sun). This can also be deduced from the fact that the moon rises from a different point each day. And if we observe the crescent moon near the horizon, and draw an imaginary line between the pointed tips of the crescent, this line will almost never be parallel to the horizon. Vijaya Varma gives a very brief explanation of how we would see the moon from different points on the earth in his Sandarbh article – chandrama ki kalaein (Sandarbh 26:70).

[1] Special darkened films are available through which we can look at the Sun during a solar eclipse. The coating on these films can get scratched if they are not stored carefully, so make sure that you test them first by looking at a bright light through it to check for any chinks of light. Another way to observe eclipses safely is to make a pin-hole camera and watch the image formed.

Activity 1: You need a torch, a globe and a small ball (the ball should be about half the size of the globe if possible, and certainly not bigger than the globe) to carry this out, and it is best done in a dark room. Fix the torch so that the light is steady, and the torch should be at the same height as the globe. Place the globe some distance from the torch such that the light from the torch falls on the globe, but there is still space between the torch and the globe so that you can make the ball (which represents the moon obviously) revolve around the earth. Now move the ball around the globe on different planes.
First - on a plane that is parallel to the floor or table surface on which you have placed the globe. Make sure that the ball (the moon) and the globe (the earth) are close enough for their shadows to fall on each other.
You can see that with the globe and the torch at the same height, when you move the ball around the globe on a plane which is parallel to the surface on which the globe has been placed, each time the ball is between the torch and the globe, you can see the shadow of the ball on the globe. You can also observe that this point corresponds to the new moon day since the lit portion of the ball (the moon) is facing away from the globe (the earth). This is the situation in which the people living in the shadow area will be able to observe a solar eclipse.
Similarly, when the globe (the earth) is between the torch and the ball, the shadow of the globe falls on the ball. This is the situation in which a lunar eclipse would be observed.

Second – move the ball around globe on a plane that is tilted with respect to the plane of the surface on which the globe is standing (see figure). In this case, for the given positions of the torch and the globe, you might not be able to find more than two planes where 'eclipses' would occur. Note the angle of this plane with respect to not just the globe, but also a couple of other items in the room. You will need this for the next activity.
You can see for both these planes too, each 'new moon' day would produce a solar eclipse and the 'full moon' night a lunar eclipse. So it would seem that you should still be observing a lot more eclipses than we actually get to see. Then what might be happening here?

The plane on which the moon revolves around the earth is actually tilted a little more than 5° with respect to the plane of the ecliptic. What happens to this tilted plane on which the moon moves around the earth as the earth moves around the Sun? Does this plane change the direction of its tilt as it moves around the Sun? Remember that whatever you guess, you need to check this against observations. And what are the relevant observations here? Namely that eclipses are rather rare phenomena.

Activity 2: Not just does the moon go around the earth, but the earth is also revolving around the Sun. Let us try and recreate this using our torch-globe-ball model. The exact plane of the moon's orbit which gave us both solar and lunar eclipses had been noted in the earlier activity. Now move the globe so that in its imaginary orbit around the torch, it is now in a position which is three months later. You will have to turn the torch so that its light still falls on the globe (see figure). Now move the 'moon' into position and make it orbit the globe in a plane that is at the same angle as before (see figure).
Do you still find the shadow of the ball falling on the globe in the 'new moon' position and the shadow of the globe falling on the ball in the 'full moon' postion? For this to happen, you will see that you need to change the ball's orbital plane.

Hence, if the plane of the moon's orbit around the earth were to 'wobble' as the earth-moon system moved around the Sun, we would be able to see many more eclipses than we actually do. In the third article in this series, when we were talking about the tilt of the earth's axis as it moves around the Sun, I had mentioned that the conservations of angular momentum also argues against the earth's axis changing its direction as it revolves around the Sun. Similarly, here too the same principle keeps the plane of the moon’s orbit tilted at a constant angle as the earth-moon system moves around the Sun.

Shadows formed by various sources of light:
a) Point source of light – If we have a point-source – that is, where light radiates ourwards from a point, these rays will be diverging from each other, so the size of the shadow of any object which is in the path of these light rays will depend on how close it is to the source of light. We can see this even if the source of light is not exactly a point, but the light still rays diverge as they travel from the light source.
For example, if we light a candle and observe the size of our hand’s shadow on the wall, we can see that the shadow grows bigger when we take our hand closer to the candle. (figure)

b) Parallel rays of light – Suppose we were to do this same experiment using the Sun as the source of light – we will see no discernible variation in the size of the shadow if we move our hand away or towards the screen (that is, we are moving our hand closer to the Sun or away from it respectively). So we often come across the statement that the light rays coming from the Sun are parallel. In this article, we shall see the limitations of this statement. (figure)

c) Extended source of light – In reality, it is difficult to find a point source of light, most sources we come across are something different – take for example a tubelight. If we look at our hand’s shadow formed on a wall by a tubelight, especially if we keep our hand slightly away from the wall, we will see that the ouline of the shadow is blurred, and the farther our hand is from the wall, the more blurred the edges get. (figure)
The dense part of the shadow is called the umbra and the lighter portion is called the penumbra. Basically, no light from any part of the light source is falling the area called the umbra while the penumbra is partially lit – light from part of the light source is falling in this area, but not from other parts. (figure)
While explaining the course of an eclipse, we need to consider the Sun as an extended source of light and we shall see how the umbra/penumbra comes into play with total and partial eclipses.

(See Eklavya’s module on Light for a detailed discussion on various concepts in optics.)

The Sun as a Source of Light:
Whether we consider the Sun to be a source of parallel rays, a point source, or if we have to treat it as an extended source of light depends on the scale of the phenomenon we are trying to explain. On the surface of the earth, when we are looking at the shadows of small objects, then the rays’ deviation from the parallel is negligible enough to be ignored. But when we are studying the shadow formed by the moon or the earth, then the Sun needs to be considered as an extended source of light sending out light rays which are not parallel to each other.

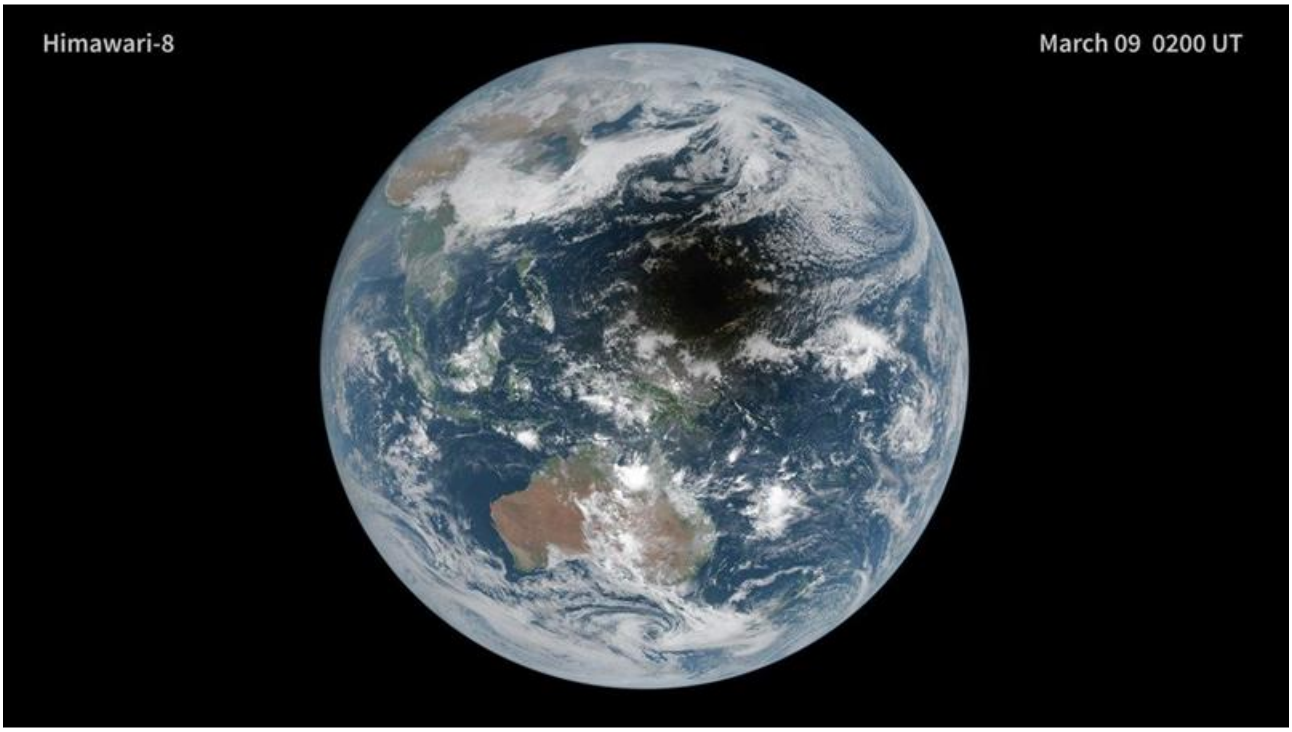
Umbra and Penumbra during eclipses:

Simple observations show the existence of both umbra and penumbra in the shadows of both the earth and the moon during lunar and solar eclipses respectively. The effect that we see is slightly different in both cases. During a solar eclipse, we are in the shadow of the moon, while during a lunar eclipse, we are watching the shadow of the earth travel across the face of the moon.

During a lunar eclipse, the moon passes through the penumbra of the earth's shadow before it enters the umbra portion of the shadow. In the penumbra, since some light from the Sun is falling on the moon, the shadow will not be so dense and we normally observe it as a reddish colour moving across the face of the moon. But once the moon enters the umbra portion of the earth's shadow, there is no sunlight falling on the moon at all, and so it is totally dark. Then the moon once again passes through the penumbra portion of the shadow on the other side and appears reddish in colour before regaining the glory of the full moon. (figure)

During a solar eclipse, what we observe is a black arc moving across the face of the Sun till it covers it entirely. The total eclipse lasts only for a few minutes, and then we see the black arc retreating across the face of the Sun. That is, during the period of totality, we are in the umbra of the moon's shadow. When we can see a portion of the Sun, we are in the penumbra of the moon's shadow where light from part of the Sun is reaching us while the rest is blocked by the moon coming in the path of the light.

But if we look at a satellite picture which will allow us to look upon the earth the same manner in which we look at the moon during an eclipse, we would see that a portion of the earth is covered by the moon's shadow which is lighter along the edges (see photo). The people in the dark portion of the shadow will be experiencing a total solar eclipse.



You might wonder why solar eclipses are only visible from certain parts of the earth each time; and as you can see from the satellite photo, the moon's shadow is falling on only a small area of the earth's surface while the entire moon comes under the earth's shadow during a lunar eclipse. Well, don't forget that the moon is much smaller than the earth!

Why do we get total and annular solar eclipses?

Hark back to the second article in which we discussed the elliptical nature of the earth's orbit around the Sun, that is, it is not at the same distance from the Sun throughout the year. At times it is closer to the Sun (in January) than at others; and this variation in the earth-Sun distance is about 1%.

For all practical purposes, this difference in the distance between the Sun and the earth has no effect on the amount of solar radiation falling on the earth, and there is no discernible difference in the size of the Sun that we can observe through the year either.

But the same eliptical orbit of the moon around the earth causes a perceptible change in size of the moon. This is especially noticeable during the full moon when sometimes the moon being at its closest approach to the earth looks bigger and is called a ‘super moon’. This variation in the apparent size of the moon also has an effect on eclipses. If a solar eclipse takes place when the moon is close to the earth, its apparent size is big enough to cover the entire disc of the Sun and we get a total solar eclipse. But if the moon is farther away, then it will be relatively smaller. In this case, the moon will not cover the entire Sun, and when it is exactly at the centre, there will be a bright rim of the Sun showing all around the dark shadow of the moon, and then we observe an annular eclipse.

During a total solar eclipse, since the moon blocks all the light coming from the Sun, it becomes quite dark (not pitch dark as the night though). I remember the birds causing a commotion during the total solar eclipse in 2009 which took place early morning. Poor birds had just woken up and suddenly it started becoming dark again, they must have wondered what happened to the day and were probably expressing their angst at not having had even one proper meal!

Even during an annular eclipse, the day dims to a great extent, though it does not get dark. What is remarkable is the reduction in temperature with most of the solar radiation blocked suddenly in the middle of the day; as it happened during the annular eclipse which was visible in Kanyakumari in January 2010.

Human beings should enjoy all the total solar eclipses possible – soon we will have only annular eclipses since the moon is slowly moving farther away from the earth. Of course, here the ‘soon’ refers to time on a cosmic scale. The last total solar eclipse is expected to take place around 650 million years from now. To put this into perspective, it took about the same amount of time for multicellular life to evolve into human beings, so it is quite likely that there won’t be any humans around to shed a tear over the end of total solar eclipses :-)

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