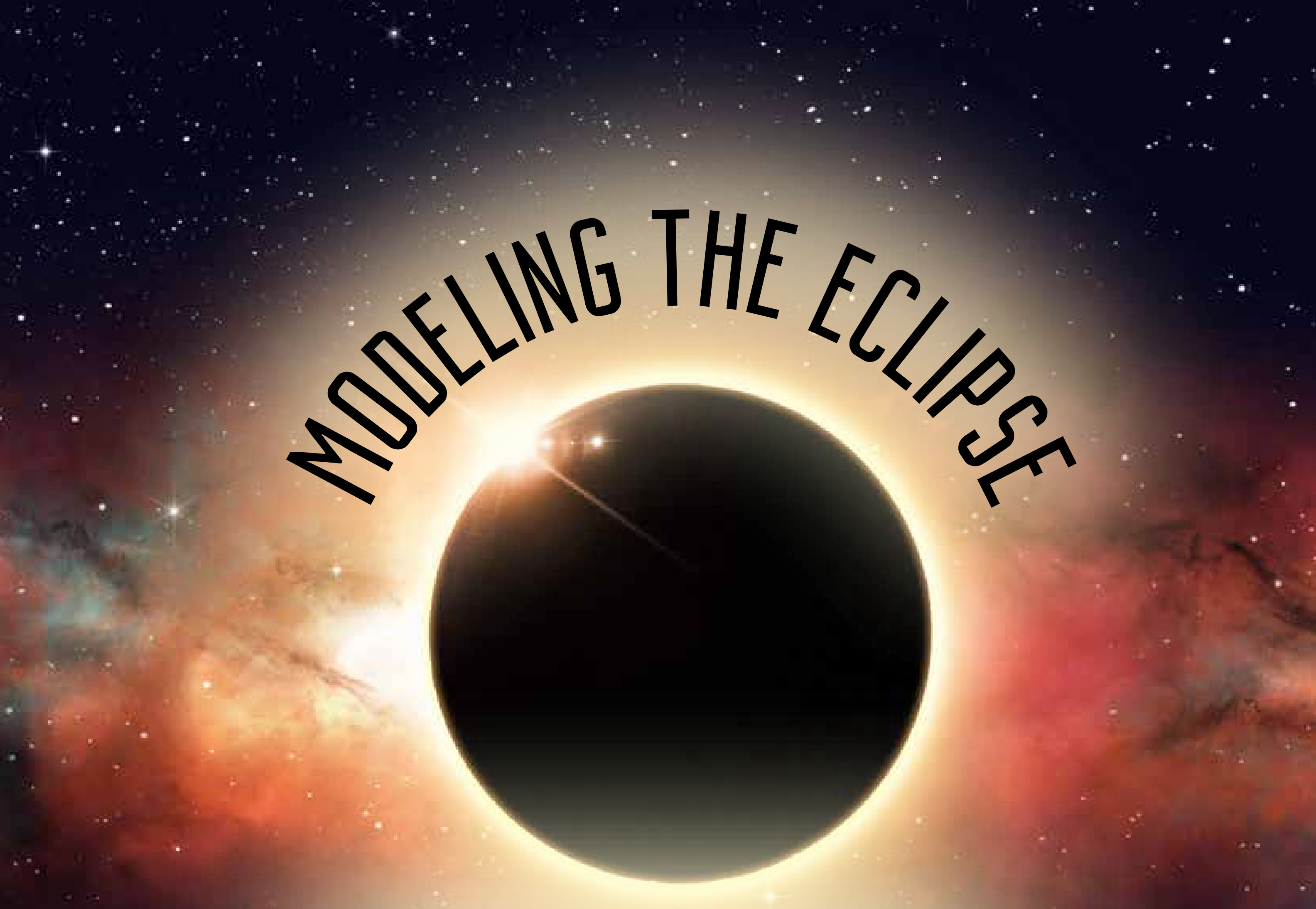

MODELING THE ECLIPSE

USING VARIOUS MODELS AND PERSPECTIVES TO HELP STUDENTS VISUALIZE THE SOLAR ECLIPSE

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This article describes a unit in which students investigate total solar eclipses, such as the one coming August 21, from several perspectives. It incorporates mathematical thinking and aligns with the *Next Generation Science Standards* (NGSS Lead States 2013; see box, p. 51).

Figure 1 (p. 48) lists instructional tasks for the unit numbered in the recommended sequence. The first three tasks review patterns and teach students the relationship between the phases of the Moon and eclipses. The final tasks are more complex, linking observations from Earth with space phenomena. The technology resources listed in Figure 2 (p. 49) include immersive visualizations from websites and free downloadable software that can strengthen student understanding. Students should already have studied foundational Earth-Sun-Moon interactions before high school, so the introductory material in this unit can be used for review and to assess students' prior knowledge.

Types of models

This article refers to physical, virtual, and mathematical modeling. *Models* include anything useful for thinking about and understanding science. For our purposes, *physical modeling* involves physical objects, such as a lamp representing the Sun. *Virtual modeling* refers to planetarium visualizations or software models such as those in the Celestia and Stellarium programs (Figure 2). *Mathematical modeling* refers to mathematical approaches to understanding phenomena such as relative speed.

Instructional tasks

1. Patterns in the lunar cycle (Earth-based perspective)

Direct observations

Begin reviewing patterns in the sky by having students document sunrises, sunsets, and Moon phases. Students can sketch in their science notebooks how the Sun and Moon move in the sky over the course of a day or night as well as the visible shape of the Moon over longer periods. A compass (or compass app) will help them note orientation. Students will notice a pattern if they make observations at the same time daily. They should add predictions and "I wonder" questions and statements when they notice something of interest. Ask students basic formative assessment questions such as, "In what direction does the Sun rise or set?" and "Where does the Moon rise and set?"

Then, encourage students to think more deeply by asking them, "Why do these objects rise in the east and set in the west?" Although lunar phases and their cause are taught in middle school, teachers can reintroduce students to the appearance of the Moon from Earth, the phase names, and the position of the Moon in relation to the Earth and Sun during the lunar cycle.

Teachers can assess students' direct observations through their science notebook sketches and questions answered during class or in their notebooks.

Point out that the Sun's and Moon's respective diameter-to-distance ratios from the Earth are similar, which means the two appear to be about the same size when viewed from Earth. This helps explain how the Moon just barely fully blocks the Sun during a total solar eclipse.

As an extension, students can think about the Moon slowly moving away from Earth (at a rate of about 4 cm per year), due primarily to the energy drain from constant tidal pulling on Earth. Given that today, the Moon appears to be approximately 4.6% larger than the Sun, students can compute how long it will take for the Moon to move approximately 4.6% (16,700 km) farther away. This works out to about 418 million years before the Moon's apparent size is too small to cover the Sun completely—preventing total solar eclipses from ever occurring again.

Planetarium and virtual modeling

A planetarium complements students' real-world observations, allowing the educator to control variables such as time and date to help make patterns apparent. An alternative is simulation software such as Stellarium (Figure 2), which also enables students to quickly gather data about patterns in the sky. Using a planetarium or simulation software avoids real-world observational issues such as clouds.

FIGURE 1

Overview of instruction

The recommended instructional sequence is shown numerically along with an estimated time for each modeling experience.

Earth-based perspective	Space-based perspective
Grounded in observation and predictable patterns through modeling. Includes mathematical and computational thinking to generate data to construct explanations and engage in argument from evidence of systems and system models to understand the scale of size and distance. 1. Patterns in the lunar cycle (monthly and annual) • Lunar cycle: One month of observations and sketches of visible shape, individually or as a class. Revisit over time so students can observe a repeating pattern of Moon phases throughout the year. 3. Solar eclipses • Types of eclipses and when they are observable (30 min.) • Shadows produced during a total solar eclipse—why do they occur west to east? (45 min.)	Emphasis on modeling the dynamic interactions of the Sun, Earth, and Moon (rotation, revolution) through systems and system models. Scale of phenomena can be emphasized. 2. Earth's rotation causes movement patterns in the sky, and the positions of the Earth and Moon relative to the Sun lead to lunar phases. • Identify the cause of the east-west patterns as seen from Earth's surface (30 min.) • Identify the cause of changing Moon phases (30 min.) 4. Eclipses and frequency of phenomena • Identify how eclipses occur and why eclipses are not regular events (45 min.) • Observe the movement of objects in space to identify the direction of shadow movement (30 min.)

FIGURE 2

Resources

Planetarium (both Earth- and space-based perspectives, with emphasis on the latter)
The immersive environment of a planetarium is ideal for engaging students in exploration of these complex, large-scale phenomena. Offerings of different planetariums vary, so investigate what is available near your community.

Eclipse simulations

Eclipse of the Century: *http://bit.ly/2glHDF8*
A video of the 1991 "eclipse of the century" filmed from Hawaii.

Eclipse Interactive: *http://bit.ly/2gc19pm*
Students can manipulate size and distance to observe both lunar and solar eclipses. Note that in the total solar eclipse, the shadow moves from west to east across the South American continent.

2017 Total Solar Eclipse: *https://svs.gsfc.nasa.gov/4314*
This simulation allows students to view the total solar eclipse's path across the United States on August 21, 2017. They can watch the path of totality move from the West Coast to the East Coast and identify how the eclipse will look from various locations across the country.

Solar Eclipse from Space: *http://aol.it/2gDBZvH*
A series of photographs taken by NASA shows a solar eclipse from the space perspective, looking toward Earth. This shows how eclipses happen in other parts of the world and how the shadow moves from west to east.

Stellarium (free; Earth-based perspective): *www.stellarium.org*
The best non-planetarium option for the Earth-based perspective. This software shows a realistic sky from any home coordinate (latitude and longitude) you enter. The software shows what you would see from Earth's surface if you could have unobstructed sightlines. It is possible to set up and observe eclipses.

Celestia (free; space-based perspective): *http://celestia.sourceforge.net*
This software allows you to fly throughout the solar system and beyond the galaxy.

2. Earth's rotation causes movement patterns in the sky, and the positions of the Earth and Moon relative to the Sun lead to lunar phases (space-based perspective).

Physical modeling

Students can create physical models that help them understand the patterns they noticed in the first task. As described elsewhere (e.g., Kruse and Wilcox 2009; Schatz and Fraknoi 2016; Taylor 1996), a basic model that uses a lamp to represent the Sun, students' heads to represent Earth, and a foam ball to represent the Moon can model motions and interactions so that students can make predictions.

Students often struggle with the direction of the Earth's rotation. Have students hold a transparency of the outline of the United States in front of their face and look out into space (toward the lamp/Sun). Through observations and questions, guide them to understand that Florida is on the left ear because they are looking out from inside the Earth. Thus, students discover that they should rotate their left shoulder counterclockwise (from the perspective of the North Pole).

To determine the direction of the Moon's orbit around the Earth, students must first understand the origin of the Earth-Moon system. Approximately 4.5 billion years ago, a shockwave in space set our young solar system—mostly a cloud of gas and dust—into motion. As it gained momentum, the dust flattened into a disk. Over hundreds of millions of years, the planets formed and inherited their motion from the early solar system. According to the favored scientific hypothesis, the Moon then formed from a collision between our planet and a Mars-sized protoplanet named Theia. This collision released large amounts of material from the early Earth, which swirled around in the same direction as Earth's rotation and then coalesced into our Moon (Mackenzie 2003). Students should model the Moon's orbital revolution in the same direction as the Earth's rotation. Later, this will help explain why the shadow of the total solar eclipse moves from west to east.

Planetarium and virtual modeling

In a planetarium or using the software simulation Celestia (Figure 2), students can see the rotation of Earth while hovering in space, looking back at our planet. Students note the day/night cycle as Earth rotates, including the fact that the Eastern United States comes into sunlight first (because the Sun rises in the east). Being "inside" the model strengthens one type of student thinking, and shifting perspective to outside the model, from afar, helps students think about the phenomenon in another way.

3. Solar eclipses (Earth-based perspective)

Physical modeling

Students can use a revised physical model from the previous task to construct explanations for eclipses. As students look into "space," they should notice that the Earth, Moon, and Sun

FIGURE 3

Path of the August 2017 eclipse shadow across the United States.

NASA

can be aligned to depict the various Moon phases. Ask students assessment questions: "When would solar or lunar eclipses occur [and have students demonstrate with the model]?" "How often do total eclipses occur?" "Why don't eclipses happen twice every month?" Highlight the fact that all models have limitations, such as the physical model incorrectly suggesting that a lunar and solar eclipse occur every month.

To clarify eclipse events, introduce into the model the scale of the diameters and distances in the Earth-Moon-Sun system. On this scale, if students' heads represent Earth, the Sun would be over 2 km away and 21 m in diameter (your thumb held at arm's length would easily cover it up; students will have to imagine this part of the model). The Moon would be a tennis ball about 6 m away from the Earth/head, and it too could be covered by a thumb held at arm's length. Students can also compare the actual numbers: Although the Moon is about 400 times smaller than the Sun, it's about 400 times closer to the Earth than the Sun and can therefore, at times, block our view of the Sun from Earth.

It helps to add to the model the 5° tilt of the Moon's orbit relative to the ecliptic plane; at 6 m away, 5° means that the Moon is about 0.5 m higher than the Earth-Sun line. Taking the model outside helps students better grasp this concept. Set up the model and identify a six-story building (or a tall tree) about 2 km away to represent the Sun. Using these scales and the tilt of the Moon's orbit, students can see why an exact alignment that leads to a total solar eclipse is relatively rare.

4. Eclipses and frequency of phenomena (space-based perspective)

Physical modeling

Because the student's body often blocks light from the "Sun," some students have difficulty understanding why eclipses don't occur every lunar cycle. To help, remove students from the model by putting the Moon on a stick or wire and use another foam ball on a stand, instead of a head, as the Earth model. Then, students can move the Earth and Moon while keeping their bodies out of the light.

If in this model students don't rotate the Earth, they may notice that the Moon's shadow moves from west to east on the Earth. This may lead to a question about how a real eclipse shadow moves, once Earth's rotation is taken into account. Looking at the August 2017 eclipse path across the United States (Figure 3) may make students wonder why the solar eclipse shadow moves from west to east, because the apparent motion of objects in the sky is east to west. Using a mathematical model can answer the question.

Connecting to the *Next Generation Science Standards* (NGSS Lead States 2013).

Standard **HS-ESS-1: Earth's Place in the Universe**		
Performance Expectation The chart below makes one set of connections between the instruction outlined in this article and the *NGSS*. Other valid connections are likely; however, space restrictions prevent us from listing all possibilities. The materials/lessons/activities outlined in this article are just one step toward reaching the performance expectation listed below. **HS-ESS1-4.** Use mathematical or computational representations to predict motion of orbiting objects in the solar system.		
Dimension	**Name and *NGSS* code/citation**	**Specific connections to classroom activity**
Science and Engineering Practices	**Developing and Using Models** Develop a model based on evidence to illustrate the relationships between systems or between components of a system. **Using Mathematical and Computational Thinking** Use mathematical or computational representations of phenomena to describe explanations. **Engaging in Argument From Evidence** Evaluate evidence behind currently accepted explanations or solutions to determine the merits of arguments.	Students use models of Earth-Sun-Moon interactions to observe how and when eclipses can occur. Students use computations from models of interactions of the Earth, Sun, and Moon, including spatial scale (sizes, distances), to explore eclipses and related phenomena. Students use evidence to argue the rarity of eclipses from observations and mathematical calculations involving interactions in space.
Disciplinary Core Idea	**HS-ESS1.B: Earth and the Solar System** Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the Sun.	Students use models to explore how the orbital motions of the Earth, Sun, and Moon lead to the phenomenon of solar eclipses. These models set the stage for students to explore Kepler's laws in extension activities.
Crosscutting Concepts	**Patterns** Empirical evidence is needed to identify patterns. **Scale, Proportion, and Quantity** Algebraic thinking is used to examine scientific data and predict the effect of a change in one variable on another. **Systems and System Models** When investigating or describing a system, the boundaries and initial conditions of the system need to be defined and their inputs and outputs analyzed and described using models.	Students use a physical model to observe the patterns that occur in space. Students explore how the scale of the Earth-Sun-Moon system leads to the phenomenon of eclipses but only on an intermittent schedule. Students also investigate how the difference between rotational and linear speed between the Moon and Earth's surface account for the west-to-east movement of a total eclipse shadow. Students use a physical model to demonstrate how eclipses occur due to the interactions between the Earth, Moon, and Sun.

FIGURE 4

Mathematical calculations of linear speed.

Object	**Diameter**	**Circumference** (2πr or πd)	**How many km in one day** (divide by 28 days)	**How many km each hour?** (divide by 24 hours)
Earth's surface at the equator	12,742 km	40,030 km	**	1,668 km/hr
Moon's orbital diameter	726,600 km	2,282,681 km	81,524 km	3,397 km/hr

Mathematical modeling

The Earth has a greater angular velocity than the Moon's orbital velocity as seen from Earth. The Earth rotates 360º in one day, compared to the Moon orbiting 360º in approximately 28 days.

However, the Moon's shadow, which is projected on the Earth during a solar eclipse, moves at a speed related to the Moon's linear velocity compared to the linear velocity of the Earth's surface. Imagine a car moving at 90 km/hr passing a truck moving at 80 km/hr. If the Sun casts the car's shadow on the side of the truck, that shadow would move along the truck at a speed that is the difference between the speeds of the two vehicles (10 km/hr in this example). For the Moon and Earth, NASA reports the Moon's linear velocity as 3,400 km/hr and the Earth's *surface* at the equator as 1,670 km/hr, which means that the lunar shadow moves at approximately 1,730 km/hr from west to east at the equator (Young 2006).

Students can make these computations for themselves, calculating the circumference (2πr or πd) for the Earth and Moon and kilometers traveled per rotation or revolution (Earth rotation = 1 day, Moon revolution = ~28 days). Next, students calculate how many kilometers the Earth and Moon travel in one day, which can then be converted to the distance each travels per hour (Figures 4 and 5). This is a necessary conversion for a direct linear velocity comparison because the total solar eclipse will cross the United States in a matter of hours (Figure 5).

To compute eclipse shadow speeds at Earth latitudes other than the equator, students must calculate, using spherical geometry, the smaller circle traveled at these other latitudes over the course of a day and use that smaller Earth surface speed in computations.

FIGURE 5

Mathematical calculation of the lunar shadow.

Moon's orbital linear speed (km/hr) – Earth's linear speed at the equator (km/hr)	= Speed of the lunar shadow (km/hr)
3,397 - 1,668	= 1,729

Planetarium and virtual modeling

In a planetarium or using simulation software, students can observe an eclipse from Earth and then "fly" into space and view the same event from a space perspective. This allows students to consider the tilt of the Moon's orbit through reorienting their perspective, and the objects can be represented to scale on the planetarium dome. These technology-enabled models incorporate correct spatial scale, orientations, rotation, and revolution, and the tilt of Earth's axis and the Moon's orbit relative to the plane of the ecliptic. From these observations, students can construct explanations for the direct observations they make and experience firsthand on Earth. ■

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References

Kruse, J., and J. Wilcox. 2009. Conceptualizing Moon phases: Helping students learn how to learn. *Science Scope* 32 (5): 55–59.

Mackenzie, D. 2003. *The Big Splat, or How Our Moon Came to Be*. Hoboken, NJ: Wiley.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states*. Washington, DC: National Academies Press.

Schatz, D., and A. Fraknoi. 2016. *Solar science: Exploring sunspots, seasons, eclipses, and more*. Arlington, VA: NSTA Press.

Taylor, I.J. 1996. Illuminating lunar phases. *The Science Teacher* 63 (8): 39–41.

Young, A. 2006. Sun–Earth day: Frequently asked questions. *http://go.nasa.gov/2jj9qV6*.