APPENDIX 2: THE NATURE OF LIGHT

Appendix 2.1: Wave-Particle Model of Light—Models, Laws, and Theories

Science is more than just a collection of facts and observations. Models, laws, theories, and evidence all play an important role in understanding the nature of science. A scientific model is a conceptual representation (idea in your head) that stands for, and helps explain, other things. A model can be physical (a real thing), imagined (in my brain!), or mathematical (numbers and formulas). In science, we develop models that have explanatory and predictive powers (like the model of the universe) and we test these models in the world around us. If our model predicts our observations, we accept the model as a valid description of our world. However, if our model encounters discrepant events and fails to provide adequate explanations, we begin to modify our model or search for an entirely different model.

A good example of a scientific model is the model of the solar system. At one time it was thought that the Sun revolved around the Earth and this geocentric model of the universe was considered to be a "true" representation for many centuries. The model encountered a discrepant event when the retrograde motion of the planets did not exactly fit the epicycles of the geocentric model. A new model, the Copernican Sun-centred model, provided a simple explanation of the movement of the planets and it predicted the phases on Venus. Years later, the invention of the telescope permitted more sophisticated observations to confirm the predictions of the Sun-centred model.

Observations can be used to test models, both externally or by thought experiments, as we re-think and apply our model to new and sometimes discrepant situations. Our observations can lead us to identify regularities and patterns in nature. We call these regularities and patterns **scientific laws**. For example, a simple scientific law would be "what goes up must come down." We can also deduce laws, given a certain set of conditions. For example, if light is a wave, we can geometrically show that the ratio of the sines of the angles of incidence and refraction is a constant. We often represent laws as mathematical relationships (e.g., Snell's law, Ohm's law, Charles' law, or Newton's laws). Contrary to popular belief, laws are not absolute but are often constrained to certain conditions. Ohm's law is valid only for some materials and our pressure laws are constrained by temperature. Even Newton's laws are valid only in inertial frames of reference.

Scientific theories form explanatory systems for phenomena (and their corresponding laws) and may include presuppositions, models, facts, and laws. For example, Einstein's theories presuppose that the speed of light is constant in all frames of reference. In Einstein's world, Newton's laws, such as F = ma, hold only for objects that are moving much more slowly than the speed of light.

We must be very careful how we use the term “theory.” In everyday usage, the word theory often refers to an idea that is not proven. It’s partially true that some theories, like many cosmological theories, are speculative ideas and are based on little evidence. Additionally, children often hold simple or naive theories about why things float or why the sky is blue. Hypotheses, or proposed solutions, are also often speculative and we often seek to build support for them through predictions and observations. However, other theories, like theories of radiation, metabolism, or chemical bonding, have considerable evidential supports. It is impossible to “prove” our theories for every possible case, but robust theories explain a great deal and we sometimes literally “bet our lives” on them. Therefore, scientific theories lie along a spectrum from speculative hypotheses to robust explanatory systems. In science education, we often use early models or theories that are adequate for a less sophisticated understanding of a scientific concept. For example, Bohr’s model of the atom explains all the phenomena one might examine in an introductory chemistry program. More progressive theories require a more extensive background.

While it is important that our understanding of the nature of science is embedded in the context that the world is rational and can be understood, we never really know if we have achieved the most rational explanation. In science, truth is elusive but our beliefs must extend far beyond individual opinions. In science, we insist on an evidential argument.

The Theory-Evidence Connection

One of the main questions scientists are concerned with is the relationship between theory and evidence. It is not unusual in science education to make a knowledge claim in the form of “I know that...”. For example, while discussing health with your doctor, she might say that “lowering cholesterol level lowers one’s risk of heart disease.” To further the claim, support is found for that knowledge claim. We will call this support *evidence*. The nature of the evidence presented will depend on the background knowledge of the knowledge claimer (in this case a doctor). For example, she might stress the statistical evidence or discuss the latest hypotheses of the underlying mechanism that relates cholesterol level and platelet formation. Of course, one might simply quote a recognized authority, like the Department of Health, and not attempt to formulate an argument at all.

Since the background knowledge of the claimer and the intended audience may be different, an evidential argument must be given that “makes sense” to the audience and connects with their prior knowledge and experience. Consequently, a selection process (theory choice) is involved in deciding the adequacy of a given theory in terms of its ability to accommodate the available evidence. This selection process reviews and judges the characteristics of a good scientific theory. A good theory is accurate; the predictions the theory makes closely match the observations made to support the theory. However, accuracy is not the only characteristic of a good theory. When two theories are equally accurate, the better theory is often the simpler explanation. The Copernican model of the solar system was no more accurate than the Ptolemaic model, with a series of epicycles to account for the motion of the planets. In the face of equally accurate models, Copernicus' theory simplified the model of the solar system tremendously. Furthermore, a good scientific theory has explanatory powers that cover a broad scope. It explains a lot, even phenomena it was not intended to explain. The scope of a good theory also extends to bold predictions. Often these predictions, such as Einstein's prediction that light would bend near large bodies, are not confirmed until years later.

Implications for Science Teaching

In science education, teachers find that students are frequently "turned off" by science. This is not surprising when one considers that they are routinely asked to perform tasks on the basis of a theoretical model that is not connected to an evidential-experiential base that "makes sense." Solving problems based on a memorization of Ohm's law, or memorizing the valences of elements in order to balance chemical equations, are good examples of such tasks. Students should be encouraged to address such questions as "What are reasons to believe?" and "What is the evidence for?"

SLA
Student Learning Activity

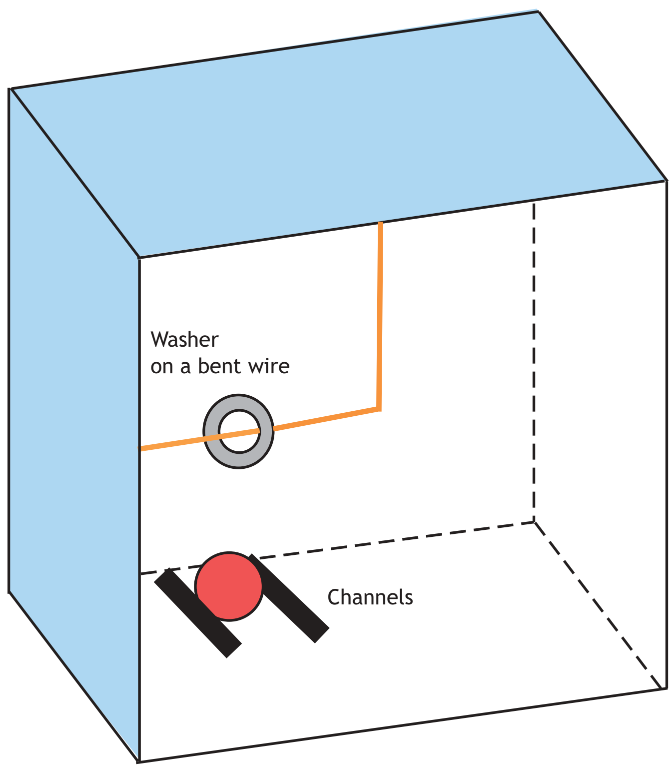
Appendix 2.2: The Mystery Container

The mystery container, sometimes called the black box, is an excellent activity for introducing the nature of science concepts for models, laws, and theories. Students' observations come from their sense data, but they must put meaning to these observations by inferring a model to explain the underlying mechanism of the mystery container. Regularities can be identified as simple laws, and a theory can be advanced that includes observations, inferences, a model, and laws to provide an explanatory system for the mystery container.

Mystery containers are easy to make but you might want to follow a few simple rules.

- No more than two distracters should be placed inside the box.
- Nature does not reveal the atom to us. We must still count on indirect evidence and our inferences to develop an adequate explanatory system. Therefore, the containers should be sealed (or the contents destroyed as in the IPS black box activity).

Diagram of a sample mystery container:



Examine, but do not open, your mystery container.

1. Carefully record your observations and make some inferences about the contents of your container.
2. Make a diagram of the contents of your container.
3. Make a list of the regularities and patterns that you find during your investigation.

Observations	**Inferences**
Regularities and Patterns	
Diagram of Contents	

SLA
Student Learning Activity

Appendix 2.3: Astronomy with a Stick

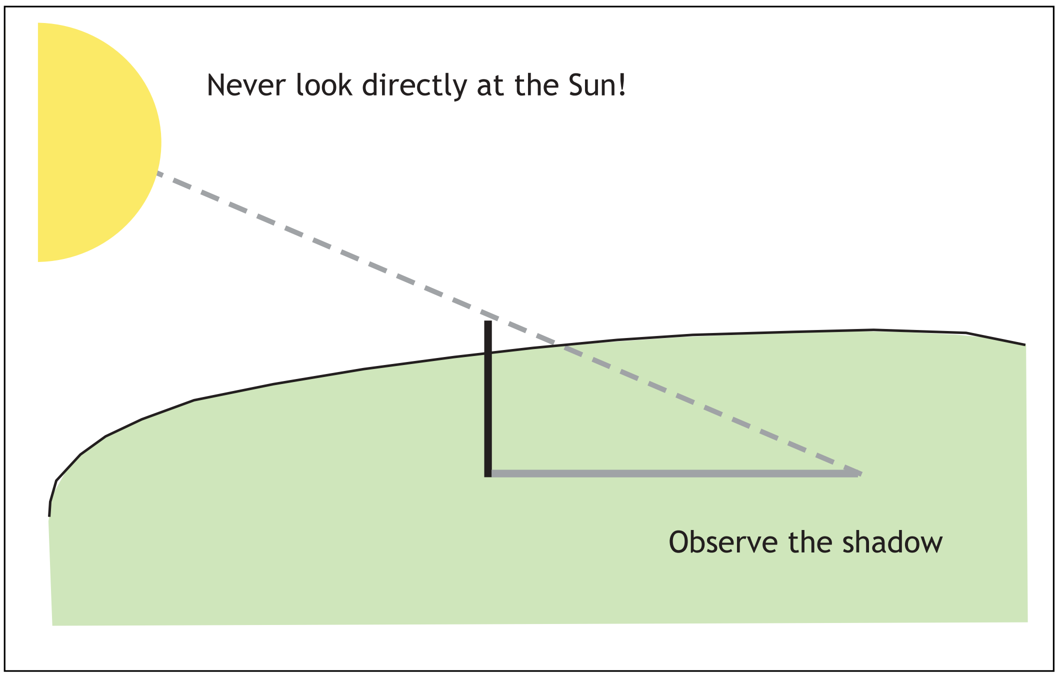
Apparatus: Five sticks of different lengths (e.g., 0.2 m, 0.4 m, 0.6 m, 0.8 m, and 1.0).

A metre stick or measuring tape.

A sunny day! (**Note:** Never look at the Sun directly!)

In this experiment, you must collect your data quickly (in less than 10 minutes).

1. Place the stick on the ground outside and measure the length of its shadow.
2. Graph the height of the stick versus the length of its shadow.



Nature of Science Questions

1. Can you describe a simple law that relates the height of the stick to the length of its shadow?
2. State a mathematical law that relates the height of the stick to the length of its shadow.
3. What does "the slope of the height versus length graph" mean?
4. Compare your results with data that are collected over a long period of time (such as an hour).
5. Are there any constraints to your mathematical law?
6. Will your mathematical law be the same tomorrow? Next year?

BLM
Blackline Master

Appendix 2.4: Chart for Evaluating the Models of Light

Accuracy?
Explanatory Power?
Simplicity?

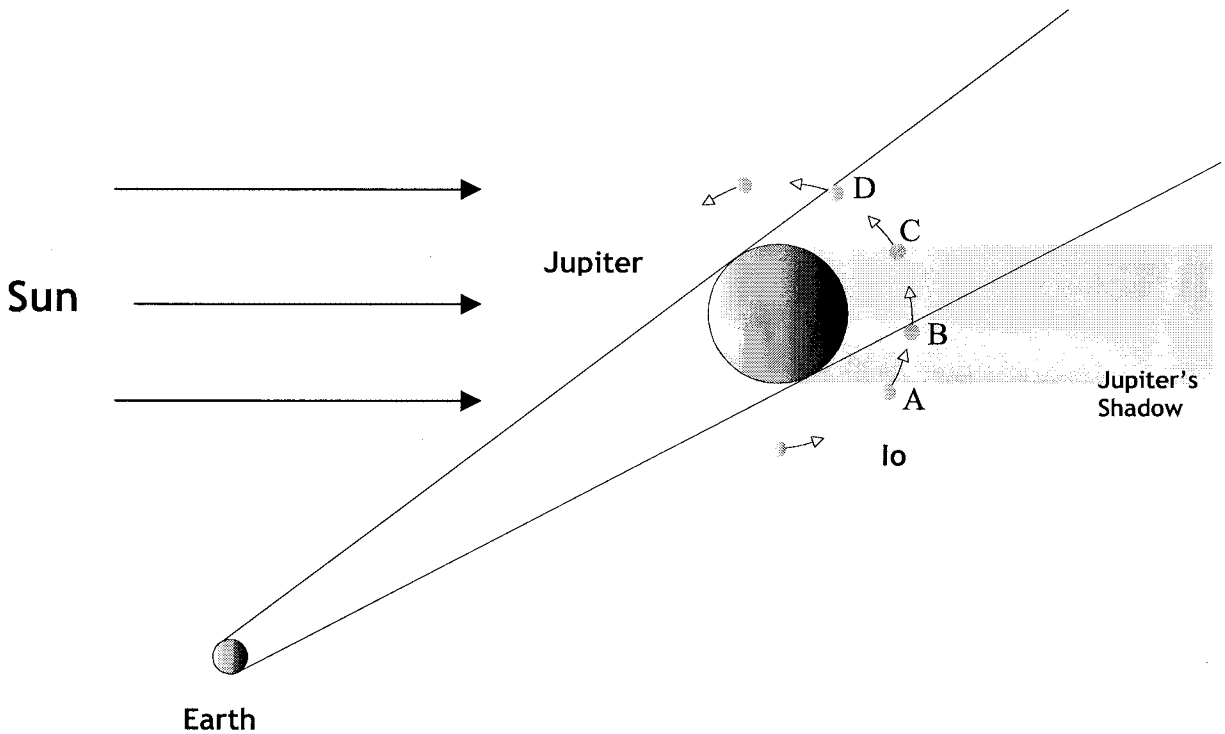
Model ______________________

Phenomena	Supporting Arguments	Counter-Arguments
Rectilinear Propagation		
Reflection		
Refraction		
Dispersion		
Diffraction		
Partial Reflection/ Refraction		
Speed of Light		

BLM
Blackline Master

Appendix 2.5: Jupiter and Its Moon Io

Watching Io as It Passes into Jupiter's Shadow (Umbra)



BLM
Blackline Master

Appendix 2.6: Ole Christensen Rœmer: The First Determination of the Finite Nature of the Speed of Light

A Rœmer Timeline…

1. **Dates**
   Born: Aarhus, Denmark, 25 Sept 1644
   Died: Copenhagen, 19 Sept 1710
   Dateinfo: Dates Certain
   Lifespan: 66

2. **Father**
   Christen Pedersen Rœmer
   Occupation: Merchant
   It is known that when he died (1663 at the latest) he left Ole a great many navigational instruments and books; it appears then that he must have been, at the least, fairly wealthy.

3. **Nationality**
   Birth: Aarhus, Denmark
   Career: Copenhagen, Denmark, and France
   Death: Copenhagen, Denmark

4. **Education**
   Schooling: Copenhagen
   In 1662, he was sent to the University of Copenhagen, where he studied with Thomas and Erasmus Bartholin.

5. **Religion**
   Affiliation: Lutheran

6. **Scientific Disciplines**
   Primary: Astronomy, Optics
   Subordinate: Physics

7. **Means of Support**
   Primary: Academia, Government, Patronage

   He lived and studied with Erasmus Bartholin, who was impressed enough with his work to entrust to him the editing of Tycho Brahe's manuscripts. From 1664 to 1670, he edited Tycho's manuscripts.

   In 1671, he accompanied Bartholin and Jean Picard to Hveen to observe the position of Tycho's observatory. Then, in 1672, he accompanied Picard back to Paris where he was assigned lodgings in the Royal Observatory and worked under the auspices of the Académie. It is generally assumed that he was a member of the Académie. Louis XIV appointed him to tutor the Dauphin in astronomy, and Rœmer travelled around France, making observations at the behest of the Académie.

   In 1677, the Professorship of Astronomy in Copenhagen was designated for him.

In 1681, he became Professor of Mathematics at the University of Copenhagen. He was also appointed Astronomer Royal and director of the observatory. In addition, he served in a number of advisory roles to the king, as master of the mint, harbour surveyor, inspector of naval architecture, ballistics expert, and head of a highway commission.

In 1688, he became a member of the privy council.

In 1693, he became the judiciary magistrate of Copenhagen.

In 1694, he became chief tax assessor.

In 1705, he became mayor of Copenhagen. Later, he became prefect of police.

In 1705, he was named a senator.

In 1706, he was named head of the state council of the realm.

8. Patronage

Types: Scientist, Court Official

The first part of his life, he was supported by scientists: first Bartholin, then Picard, who remained his patron after he settled in Paris. Some connection through the Académie probably allowed him to be appointed as Louis XIV's tutor. In 1704, long after his return to Denmark, he built his observatory on land owned by Erasmus Bartholin.

The major patron in his life was Christian V of Denmark, who appointed him as Astronomer Royal and was responsible for the numerous appointments he held.

After Christian V died, Frederick IV assumed his patronage, first giving Rœmer an appointment in 1705.

9. Technological Involvement

Types: Instruments, Civil Engineering, Hydraulics, Cartography

In Paris, part of his duties involved making instruments. He built clocks and other devices, including a micrometer for differential measurement of position. In Copenhagen, as director of the observatory, he continued his innovation in instrumentation. He was perhaps the first to attach a telescopic sight to a meridian transit.

He also invented a new thermometer and was active in the science of thermometry, passing some ideas to Gabriel Fahrenheit, whom he met in 1708.

Rœmer reordered Denmark's system of measuring and registration and introduced a new, rational system for numbers and weights. The number and weight reforms were especially important because the previous system was confusing and hampered trade. Rœmer combined weight and length, a system that only occurred in other lands more than a century later (with the metric system).

While Copenhagen was growing rapidly in these years, Rœmer was in charge of laying out streets, lighting, water supply and drainage, fire standards, and lesser affairs.

In 1699, he revised the calendar, so that Easter was scheduled according to the Moon.

10. Scientific Societies

Memberships: Académie Royale, Berlin Academy

He corresponded with Leibniz, Fahrenheit, and others.

Hoefer and Leksikon indicate he became a member of the Académie in the early 1670s, but the verbal records of the Académie for this period are missing and this piece of information is not generally mentioned in secondary sources.

Honourary member of the Berlin Academy.

Sources

1. Hoefer, "Rœmer," Nouvelle biographie universelle, 42 (Paris, 1862), cols. 495-7. [ref. CT143.H6]
2. I.B. Cohen, *Rœmer and the First Determination of the Velocity of Light* (New York, 1944). [QC407.C67]
3. Rene Taton, *Rœmer et la vitesse de la luminière* (Paris, 1978). [QC407.R63]
4. Kirstine Meyer, "Rœmer" [in Danish], *Dansk Biografisk Leksikon*, 20 (Copenhagen, 1941), 392-400. [CT1263.D2]

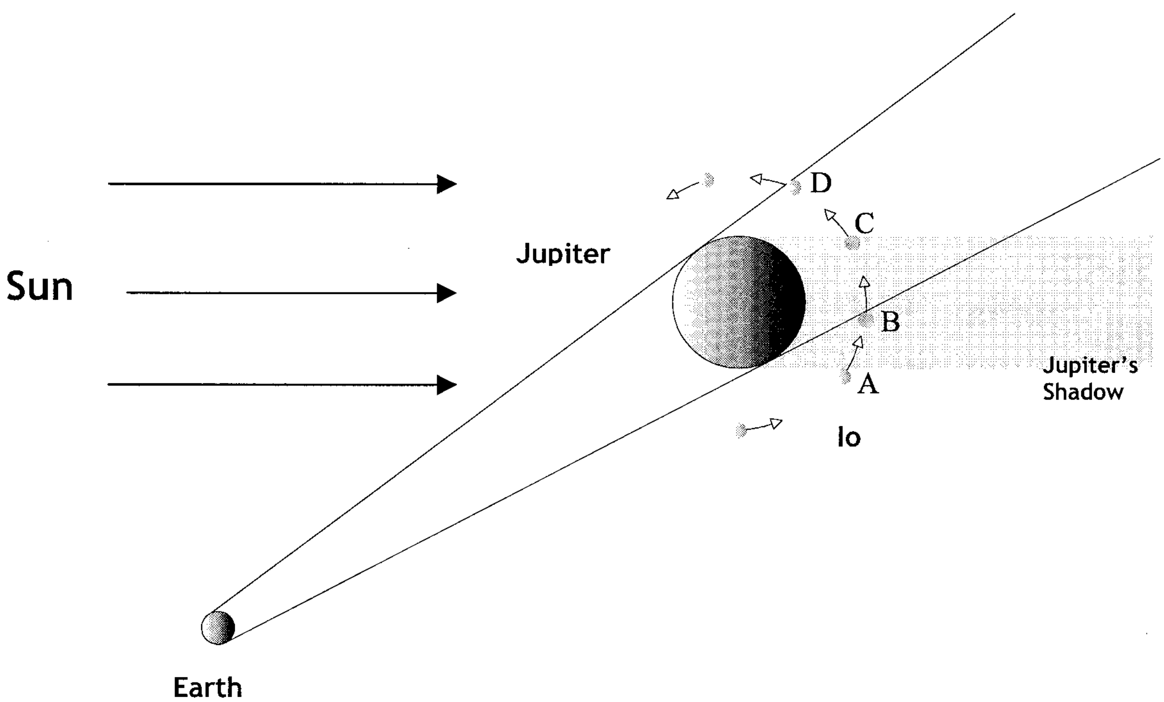
Rœmer, Ole Christensen: Compiled by Richard S. Westfall, Department of History and Philosophy of Science, Indiana University. Reproduced from http://es.rice.edu/ES/humsoc/Galileo/Catalog/Files/roemer.html.

SLA
Student Learning Activity

Appendix 2.7: Ole Rœmer and the Determination of the Speed of Light

Natural philosophers have demonstrated an interest in the nature of light since the time of the Greeks. Fundamentally, the nature of light was linked to our understanding and explanations of vision. Early theories of light (or vision) maintained that light emanated from the eyes and its propagation was instantaneous. Hero of Alexandria claimed that the speed of light was instantaneous, noting that if you keep your eyes closed, look to the stars, and then suddenly open your eyes, you will see the stars. Since no time elapses between the opening of your eyes and the sight of the stars, then the speed of light must be instantaneous.

In the 17th century, mapmaking and navigation inspired a great search for the determination of longitude. Galileo discovered the four largest moons of Jupiter in 1610, and immediately recognized that the regularity of the period of these moons could easily be used as a “clock.” The orbital period of a moon of Jupiter can be calculated by observing the successive eclipses of the moon. The diagram below illustrates the geometry of observing an eclipse of the moon Io. An eclipse begins when Io enters the shadow of Jupiter (point A).



Questions:

1. When the Earth is in this position, can we observe when the eclipse begins? ends?
2. Describe how you would start and stop a clock to measure the orbital period of Io.
3. Draw a diagram of Jupiter and Io, making the disk of Jupiter about 3 cm across, showing where Io would be when an observer no longer sees it in a telescope.

Using *Starry Night* Software to Calculate the Period of Io

Starry Night is a planetarium program that you can download and demo at http://www.space.com. It is available through the Manitoba Text Book Bureau (stock #MS 8420).

During the period 1668–1678, Ole Rœmer timed eclipses of Io over 50 times. Not all the observations were true eclipses, however, with Io passing into Jupiter's shadow behind the planet. Occasionally, Rœmer was timing what is called a **transit**, where the moon Io actually passed in **front** of Jupiter as seen from Earth.

Some of the early observations from the period 1668–1672 took place at Tycho Brahe's famous Uraniborg ("city of the Heavens") observatory near Copenhagen, Denmark, and were done in partnership with the astronomers Jean Picard and Giovanni Domenico Cassini of France. Over the period 1672–1678, observations were made from the Paris Observatory. For some of Rœmer's observations, Earth was moving towards Jupiter. However, for the majority of the eclipses of Io, Earth was moving away from Jupiter. This was likely done to accommodate observing Jupiter during "prime time" in the hours from sunset to midnight when Jupiter was an easy-to-see object in the evening sky. The table on page 53 of Appendix 2.10 shows the timings of these eclipses of Io as recorded in Ole Rœmer's handwritten notes. Note the times of his observations, and see his preference for "prime time" observing after sunset.

The Orbital Period of Io

Calculate the average value of the orbital period of Io for each set of values when the Earth is moving towards Jupiter and when the Earth is moving away from Jupiter. Compare these values.

Rœmer found that the orbital period of Io was always slightly longer when the Earth was moving away from Jupiter compared to when the Earth was moving toward Jupiter. Rœmer concluded that the speed of light was the reason for this discrepancy of time. The drawing of Rœmer's observation on page 37 of this appendix shows the Earth-Jupiter system that he may have used to calculate the speed of light.

We know:

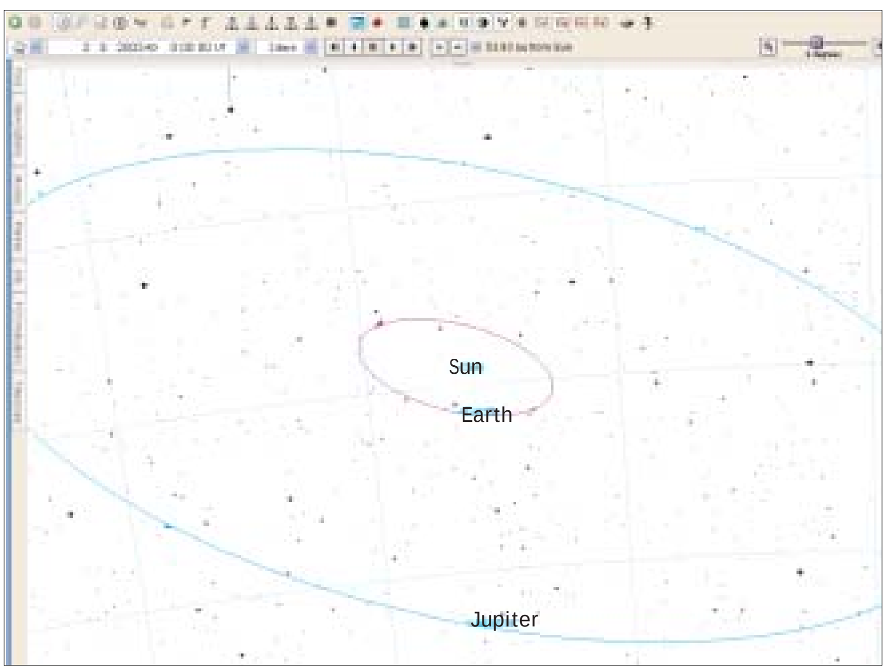
$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{\Delta d}{\Delta t}$$

Therefore, the speed of light will be the extra distance that light travels divided by the time that has elapsed over that distance. We calculate this twice: when Earth is moving away from Jupiter, and when Earth is moving towards Jupiter, and then we compare our data. For a first approximation, we assume that Jupiter does not move at all over such a short period of days to weeks, and motions of Earth and Jupiter occur in the same plane.

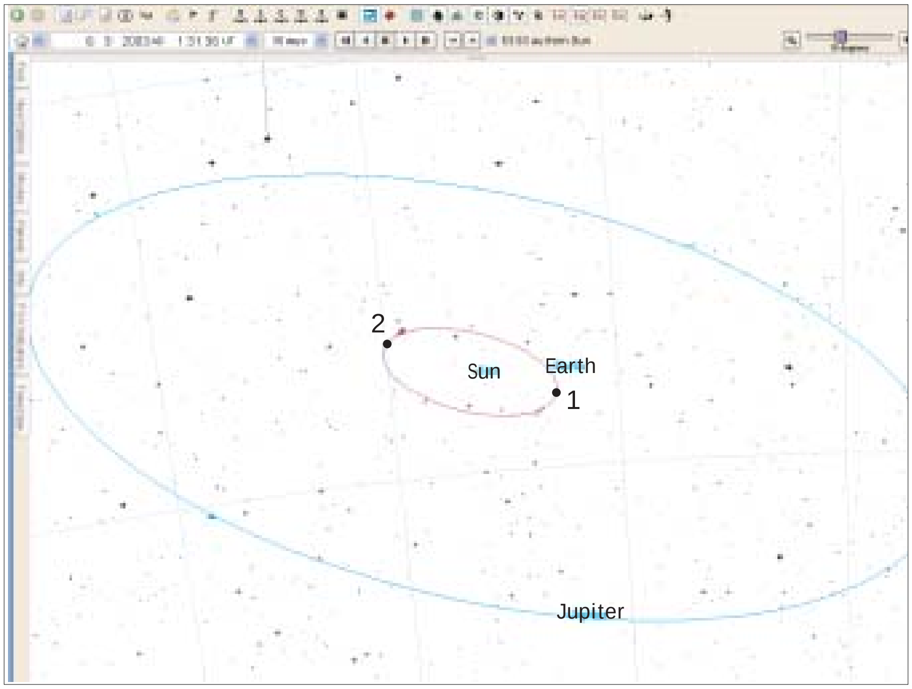
1. Find the date for a Jupiter-Earth opposition. For example, on February 3, 2003 @ 00h UT (Universal Time).
2. Convert this date to the Julian Date (2452673.50000). The Julian Date (JD) is the number of days since noon on January 1, 4713 BCE, according to the Julian calendar. By clicking on the arrowhead icon to the right of the UT symbol in the time window, *Starry Night* will make this conversion for you.

   Note: From this point forward, all Julian Dates in brackets (e.g., 2452673.5) represent possible answers for each step in our procedure.
3. Using the *Starry Night* “outer solar system” view (GO→SOLAR SYSTEM→OUTER SOLAR SYSTEM), zoom in until you can see both Jupiter and Earth on the same screen. You will have to click on the “Find” tab and toggle “on” the orbit of Earth. Toggle “off” the orbit of Mars so that only the orbits of Earth and Jupiter are traced on the screen.
4. Find the approximate point of **maximum elongation** (this is often called **quadrature**, meaning “one-quarter the way around”). In one year (365.25 days), Earth orbits the Sun. Therefore, the point of maximum elongation is the date of opposition plus 365.25/4 = 91.3125 (JD 2452673.50000 + 91.3125 = JD 2452764.8125). This, of course, neglects the relative motion of Jupiter during this same period. See the following screen shots, and note the positions of Jupiter, Earth, and the Sun at the points called “opposition,” when Jupiter-Earth-Sun form a straight line. Also note “quadrature,” when these objects form a 90-degree angle. In the diagram, this is point “1”.

   Opposition



Quadrature



5. In order to work with an appropriate time interval on Earth's orbit, we will identify **two specific points on either side of quadrature**, and call these 'A' and 'B' (refer to the diagram on page 37). Point A represents a position for Earth that is about 20 periods of Io before quadrature, and Point B represents a position that is about 20 periods of Io after quadrature.

   Calculate the Julian date (JD) for points A and B (this timespan A→B, represents a total of 40 intervals of Io's orbital period). Rœmer had calculated that Io orbits Jupiter, on average, in 1 day, 18 hours, and 28 minutes (1.769 days). Therefore, back up 20 x 1.769 = 35.380 days from the point of quadrature to get to Point A. Using only the significant digits of interest to us in the Julian dates (we call this a Modified Julian Date, or MJD), Point A is at MJD 764.8125 – 35.380 = 729.4325. In a similar way, calculate the MJD for point B (MJD is 800.1925).

6. Using *Starry Night*, find the exact Julian date for the eclipse of Io at Points A and B, which represent timings of eclipses when Io exits Jupiter's shadow. We call such an eclipse an "emmersion" event. Remember, Earth is moving away from Jupiter during this time interval (MJDs are 729.21667, 800.01597 respectively).

7. Calculate the interval of time between the eclipse at Points A and B (70.7993 days).

8. Calculate the arc length AB (1.8×10^{11} m). To simplify, we will take this arc length and consider it a straight line (to accommodate the rectilinear propagation of light).

   Radius of Earth's orbit = 1.496×10^{11} m (not known with precision in Rœmer's time)

   For example,

   The sector angle traced out in one day for Earth orbiting the Sun

   $= 2\pi/365.25$ radians

   $= 0.0171937$ radians

   Arc length = radius x sector angle (in radians)

   $s = r \cdot \theta$

   $= (1.496 \times 10^{11} \text{ m})(70.7993 \times 0.0171937)$

   $= 1.821 \times 10^{11}$ m

9. Calculate the Julian date of quadrature at Point 2 on the other side of Earth's orbit (see diagram on page 37), and repeat steps 5-8 for Points C and D that represent timings of eclipses when Io enters Jupiter's shadow. We call such eclipses *immersion* events, as did Rœmer himself. Remember, Earth is now moving towards Jupiter.

   (Point 2 at MJD 947.4375, Point C calculated as MJD 912.0575, and Point D calculated as MJD 982.8175.)

10. Using *Starry Night*, find the exact Julian date for the eclipse of Io at Points C and D that represent timings of eclipses when Io **enters Jupiter's shadow**. We call such an eclipse an "immersion" event. Remember, Earth is moving toward Jupiter during this time interval (MJD 911.41722, 982.20361 respectively).

11. Calculate the interval of time between the eclipses at Point C and D (70.78639 days).

12. Calculate the total difference in the intervals of time for Earth moving away and moving towards Jupiter. This is the amount of time it takes light to travel the interval AB + CD.

    Total difference in intervals of time = 70.7933 days – 70.78639 days

    = 0.00691 days

    = 9.9504 minutes

    = 597.024 seconds

13. From your data, calculate the speed of light.

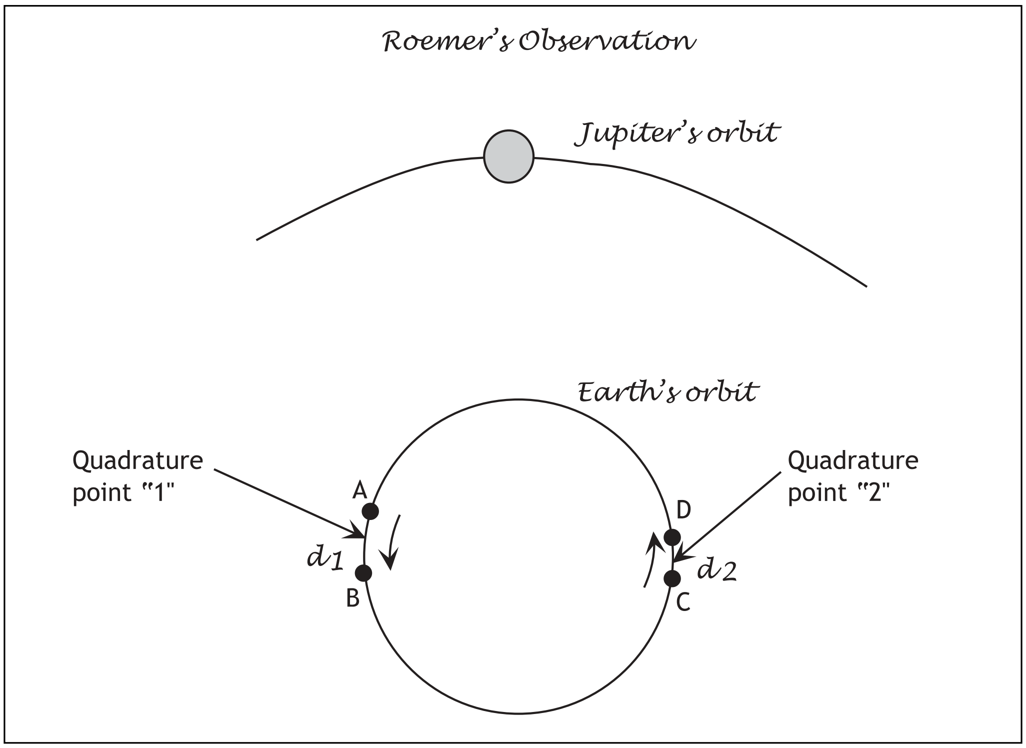
$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{\overset{\frown}{AB} + \overset{\frown}{CD}}{t_1 + t_2}$$

$$= (2)(1.821 \times 10^{11}\ \text{m})/597.024\ \text{s}$$

$$= 6.100 \times 10^{8}\ \text{m/s}$$

This value for the speed of light is in the same *order of magnitude* as the modern value.

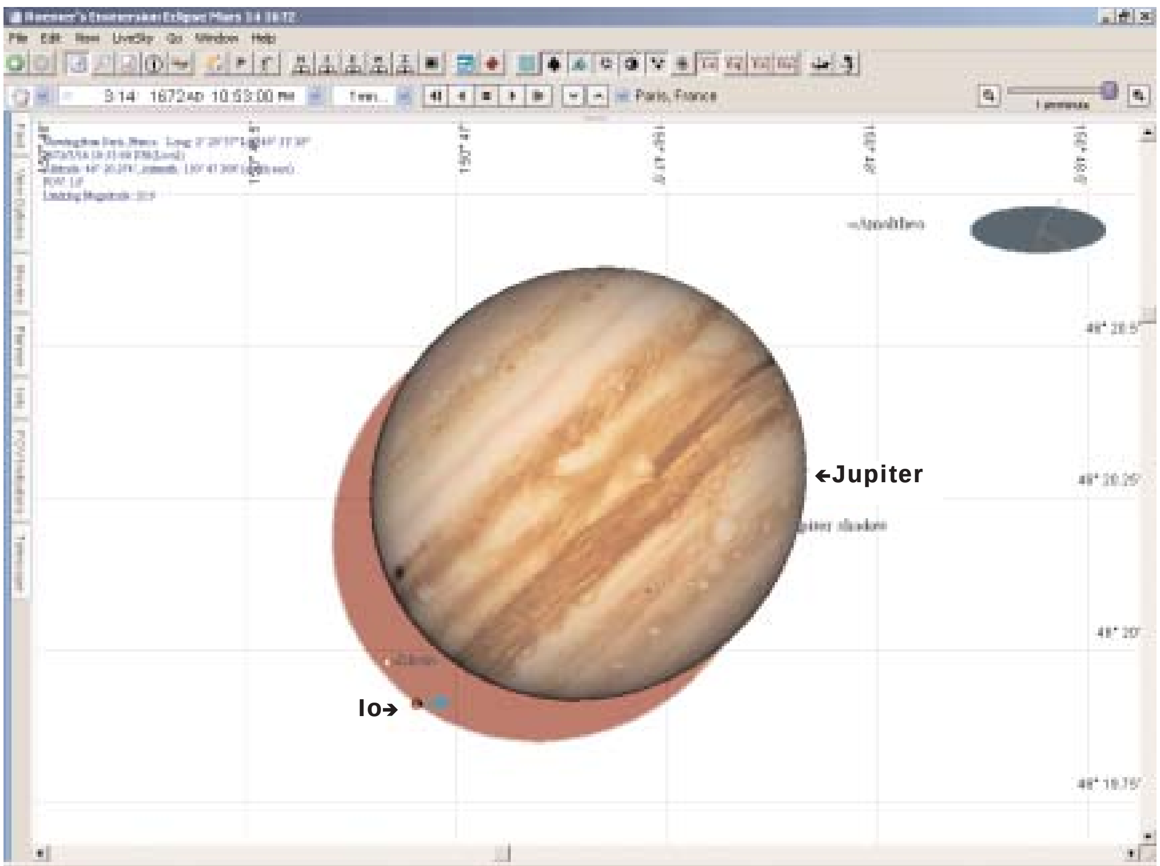
Note: The sketch that follows shows the relative positions of Jupiter and Earth at the two **quadrature** positions. The arc lengths **AB** and **CD** in the previous equation would be equivalent to d_1 and d_2 in the diagram.



An Alternative Method Using Rœmer's Own Data

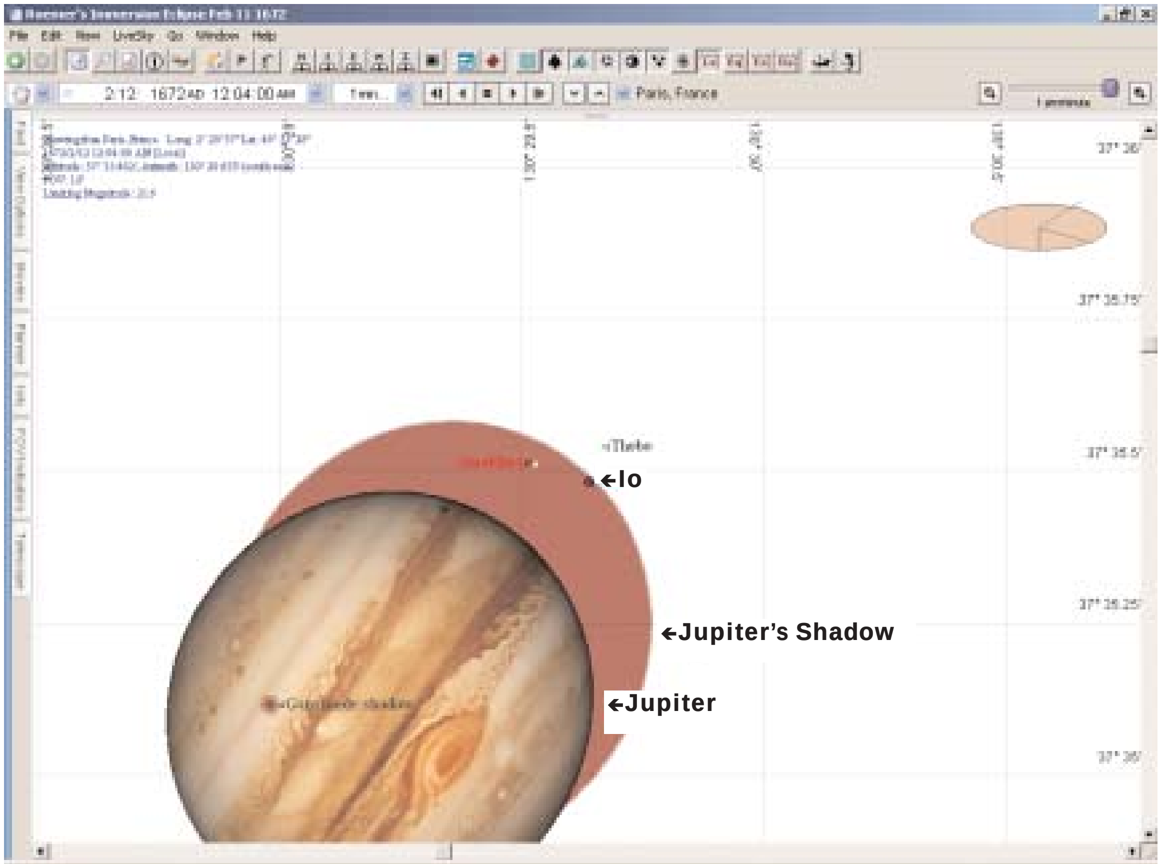
In this alternative method, we will use two pairs of eclipses from Ole Rœmer's own notes (and rely on Rœmer's times too!). One pair will come from an interval when Earth was receding from Jupiter (*emmersion events*), and the other pair will be from an interval when Earth was approaching Jupiter (*immersion events*). See the images below for an example of each type of event as they could be seen in modern telescopes from the Paris Observatory.

"Emmersion" Event: Io Exits Jupiter's Shadow



Graphic 1

"Immersion" Event: Io Enters Jupiter's Shadow



Graphic 2

Rather than use the **arc lengths** AB and CD, as was done in the previous example along Earth's orbit, we will use direct distances from Earth→Jupiter from the *Starry Night* software. As was found in the previous technique, using pairs of eclipses that are about 70 days apart introduces a significant error in the distance measurement. Light propagates in a straight line to the observer, not along an arc. By taking arc length distances as the distance travelled by light, we introduced a very large systemic error in the calculation of the speed of light. One way to reduce this error significantly is to take pairs of Io eclipses that are very close in time (a few days at most).

1. "Emmersions" at	1672 March 14	JD 2331819.41180
	1672 March 23	JD 2331828.26250
	Interval	8.8507 days
"Immersions" at	1672 February 11	JD 2331787.46111
	1672 February 20	JD 2331796.31041
	Interval	8.8493 days

As we would expect, the second interval (when Earth is approaching Jupiter) is less than the interval when Earth is moving away from Jupiter. It was these irregularities that first intrigued Ole Rœmer, and had him consider what such a *mora luminis* ("delay in the light") could mean for determining longitudes.

2. Now, determine the difference in the time intervals from (1) and (2) above:

   8.8507 days – 8.8493 days = 0.0014 days = 120.96 seconds

3. At this point, we need to "modernize" our method, and consult *Starry Night* in order to determine the Earth→Jupiter separation for each of the times listed in parts (1) and (2). Accurate measurements, such as those in *Starry Night* or the *Astronomical Almanac* tables, would not have been available to Rœmer.

   Earth→Jupiter separation at

1672 March 14	(JD 2331819.41180):	4.4526 A.U.
1672 March 23	(JD 2331828.26250):	4.4956 A.U.
Increase in distance		0.0430 A.U.

   Earth→Jupiter separation at

1672 February 11	(JD 2331787.46111):	4.4964 A.U.
1672 February 20	(JD 2331796.31041):	4.4529 A.U.
Decrease in distance		0.0435 A.U.

   Adding these two distances together: 0.0865 A.U.

4. The result from Step (3) above allows us to calculate the speed of light. Light, from our simulation in *Starry Night*, appears to have taken 120.96 seconds to travel a distance of 0.0865 A.U.

   This means the light requires 120.96 seconds/0.0865 A.U. = 1,398.38 seconds to traverse 1 A.U. (the average distance from the Earth to the Sun) or 1.496 x 1011 metres.

   $$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{1.496 \times 10^{11}\ \text{m}}{1{,}398.38\ \text{s}} = 1.07 \times 10^{8}\ \text{m/s}$$

   This result is only ~36% of the modern value of approximately 3.00×10^{8} m/s, but clearly demonstrates that Rœmer's eclipse data can be used to show that light has an extreme velocity when compared to moving objects, such as planets.

Refining the Technique Using Eclipses of Io Close to Quadrature

Up to now, we have relied upon two techniques that have resulted in unsatisfactory values for 'c'. It remains to attempt one more set of calculations using the Earth-Jupiter distance techniques (Steps 1–4 above) for pairs of eclipses that are very near to quadrature. The reason for this is simple: at these points, the relative speeds of Jupiter and Earth reach their maximum, and the shadows of Jupiter are most pronounced. This allows us to compare this technique with that used earlier in this activity.

Repeat Steps 1–4 from the procedure outlined above (the "Jupiter-Earth" distance technique), but choose pairs of eclipse events that satisfy the following conditions:

a) The two eclipse events used are about 4–6 weeks apart

b) The pairs of eclipses occur ~6 months apart near the quadratures

1. "Emmersions" at

	2001 February 4	JD 2451945.16458
	2001 March 12	JD 2451980.56528
	Interval	35.4007 days

2. "Immersions" at

	2001 September 17	JD 2452169.85069
	2001 October 22	JD 2452205.24583
	Interval	35.39514 days

3. Now, determine the difference in the time intervals from (1) and (2) above:

   35.40070 days – 35.39514 days = 0.00556 days = 480.4 seconds

4. Earth→Jupiter separation at

2001 February 4 (JD 2451945.16458):	4.7037 A.U.
2001 March 12 (JD 2451980.56528):	5.2691 A.U.
Increase in distance	0.5653 A.U.

Earth→Jupiter separation at

2001 September 17 (JD 2452964.50834):	5.3512 A.U.
2001 October 22 (JD 2452994.59236):	4.8146 A.U.
Decrease in distance	0.5365 A.U.

Adding these two distances together: 1.1018 A.U.

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{(1.496 \times 10^{11} \text{ m/A.U.})\ (1.1018 \text{ A.U.})}{480.4 \text{ s}} = 3.43 \times 10^{8} \text{ m/s}$$

At this speed, the light travel time across the diameter of Earth's orbit (i.e., 1 A.U.) would be:

Light time = 1.496×10^{11} m / 3.43×10^{8} m/s = 436.15 s = 7.27 minutes

(The accepted mean value for light time across 1 A.U. is ~8.28 minutes.)

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Appendix 2.8: Why Were Eclipse Events at Jupiter Important to 17th-Century Science?

Jupiter's satellites and the measurement of longitudes in the 17th century

In 1610, Galileo 'discovered' the four largest satellites of Jupiter: Io, Europa, Ganymede, and Callisto. Initially, he named them the *Medicean Stars* in order to honour the family of his most generous patron, the Archduke Ferdinand de Medici. Today, we often refer to these four bodies as the "Galilean Satellites of Jupiter."

The orbits of these satellites have very small eccentricities (they are nearly circular) and are close to the equatorial plane of Jupiter.

Jupiter's equator and its orbit are not much inclined to the plane of the ecliptic.

At the end of the 16th century, the determination of longitudes could not be done very accurately because of the lack of stable and accurate timekeepers—particularly on ships at sea. Galileo then had the idea of using Jupiter's satellites as time indicators: their motions are practically circular and regular; their periods are short enough (on the order of days); and the instants of mutual eclipses do not depend on the location of the observer. This last point is crucial in order to have reliable standards.

This idea—that of using eclipses of Jupiter's largest moons—was taken up again by Cassini in 1668. It eventually met with success, due to the perfection of observational instruments and the invention of a clock that had precision on the order of seconds (by Christiaan Huygens in 1657).

During the winter of 1671-1672, Picard and Rœmer (viewing from Uraniborg on the island of Hveen in present-day Sweden, the site of Tycho Brahe's observatory), and Cassini (from the Paris Observatory) observed simultaneously the moments of eclipses of Io by Jupiter. From these measurements, they measured the difference of geographical longitude between Uraniborg and Paris.

From 1672 on, Rœmer worked at the Paris Observatory and continued his observations of the eclipses of Jupiter's satellites. Particular emphasis was placed on timings of what was called "the first satellite of Jupiter"—Io.

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Student Learning Activity

Appendix 2.9: Becoming Familiar with Ionian Eclipses

The following are some exercises that are related to Io's motion around Jupiter, which put you in a position similar to that of Rœmer.

The Ionian Phenomena

Examine the figure below. The Earth is between a conjunction and an opposition. The radius of the orbit of Io is equal to six times the radius of Jupiter. The angle SJE = *a* is always smaller than 11°.

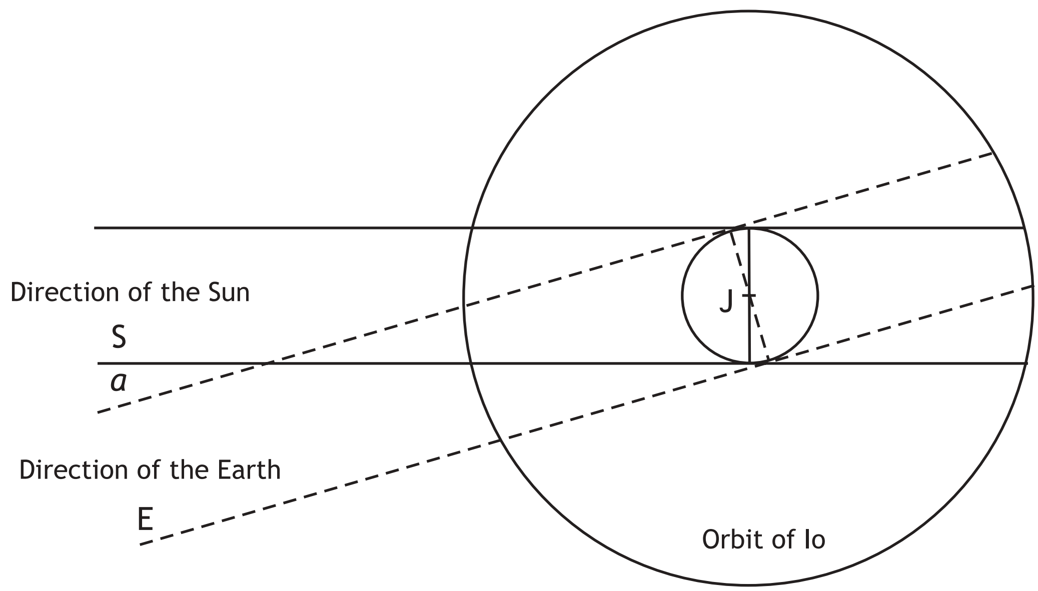
a) On the figure below, indicate, using the labels E_1, E_2, O_1, O_2, Sh_1, Sh_2, and P_1, P_2, the beginning and the end of the following four phenomena:

Eclipse: The satellite enters the shadow of Jupiter.

Occultation: The satellite, as seen from Earth, goes behind Jupiter.

Shadow: The shadow of the satellite is seen on the planet.

Passage: The satellite, as seen from Earth, passes in front of the planet.



b) Now explain why only the beginnings of the eclipses can be observed from Earth, as seen in the previous diagram.

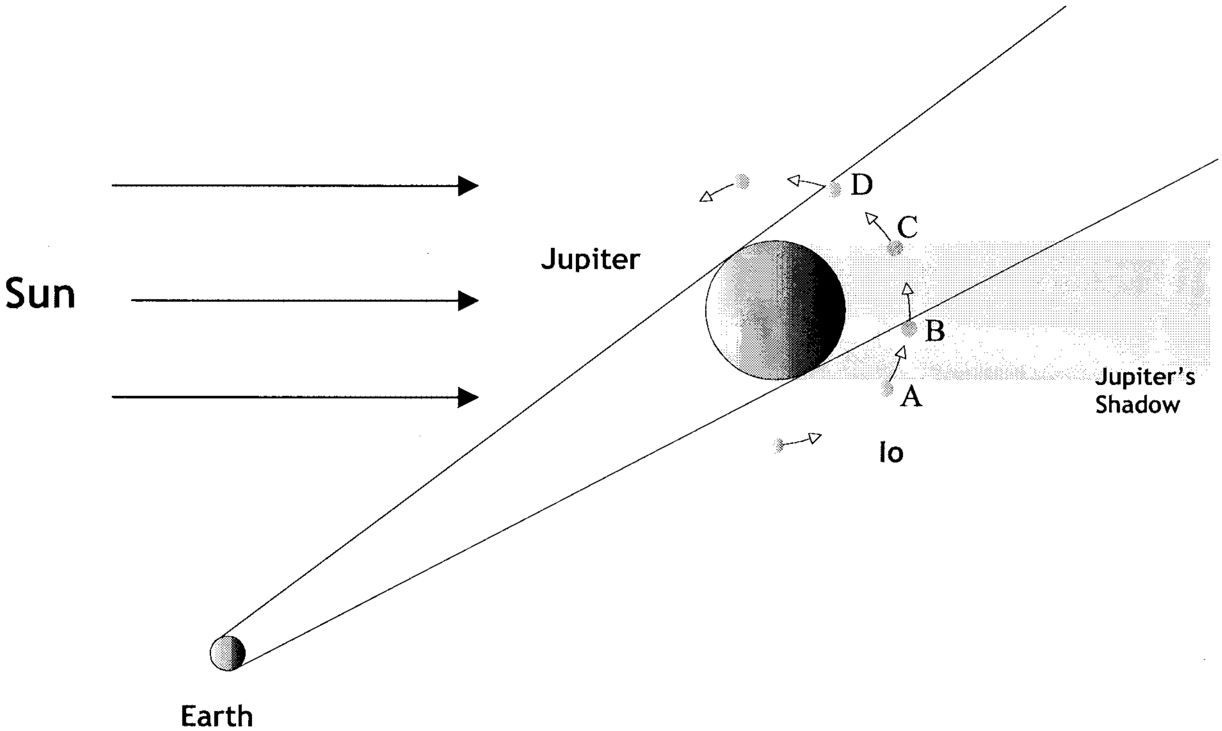
c) Research what happens when the Earth is close to a **conjunction** with Jupiter and the Sun. Draw a diagram showing the positions of Earth, Sun, and Jupiter when this event occurs.

d) Can we see Jupiter at this time? Why or why not?

e) Research what happens when the Earth is close to an opposition event with Jupiter and the Sun. Draw a diagram showing the positions of Earth, Sun, and Jupiter when this event occurs.

f) Draw another figure that shows what happens when the Earth is between an opposition and a conjunction (this occurs twice per calendar year). Explain why only the end or the beginning of the eclipses of Io can be observed from Earth.

Reviewing Some Planetary Geometry . . .



g) Label the above diagram with the following: Direction to the Sun, Earth, Jupiter, Io, Jupiter's Shadow (or umbra).

h) What events occur at the following points? (Don't peek back!)

A ____

B ____

C ____

D ____

SLA
Student Learning Activity

Appendix 2:10: Simulating Rœmer's Eclipse Timings Using *Starry Night Backyard*

Note: In order to proceed with this portion of the activity sequence, you will need access to *Starry Night Backyard* (or *Starry Night Pro 4.x*).

A table of Rœmer's eclipse timings appears at the end of this activity for ease of removal.

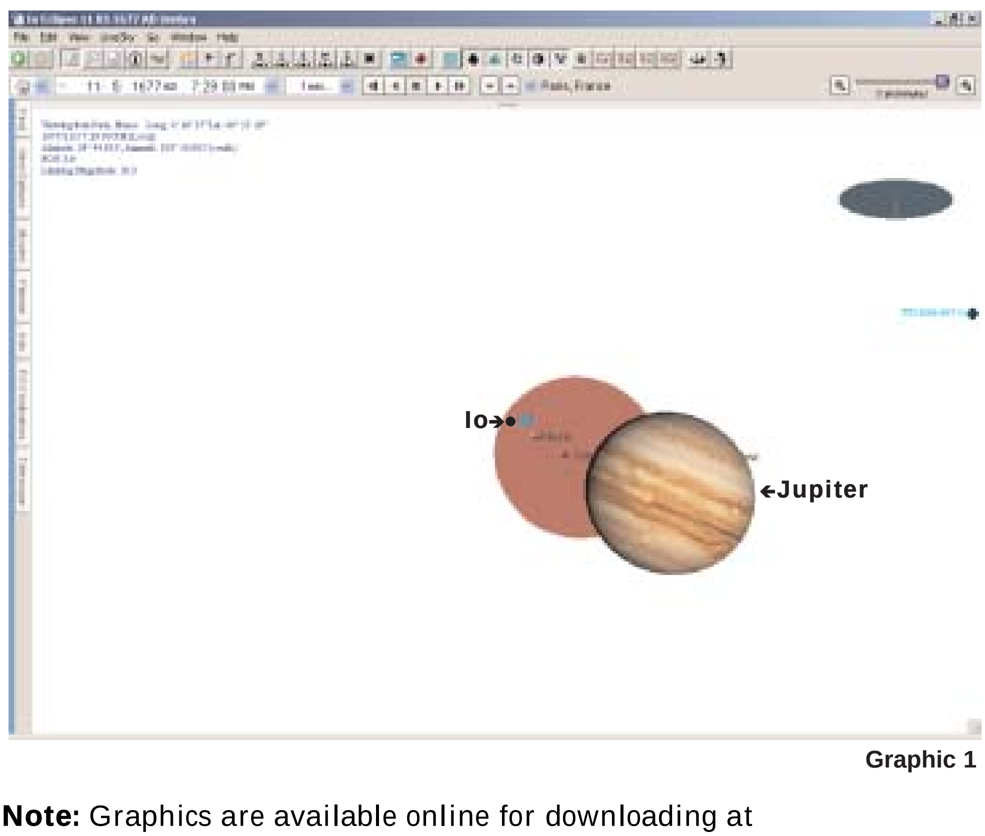
Procedure for Setting Up an Eclipse in *Starry Night*

Step 1

Set the location for Paris, France. Set the TIME of the eclipse you wish to view (consult the chart at the end of this activity) by making adjustments to the toolbar as required. Ensure that the software is "stopped." (You can do this by selecting the ■ button on the time increment buttons.)

Step 2:

Use the PLANET LIST or Find feature to "lock onto" Jupiter. Once you have locked Jupiter, use the ZOOM feature in order to get Jupiter to be about the size of a "toonie" on the screen. Your screen could look something like this (in *Starry Night Pro*):



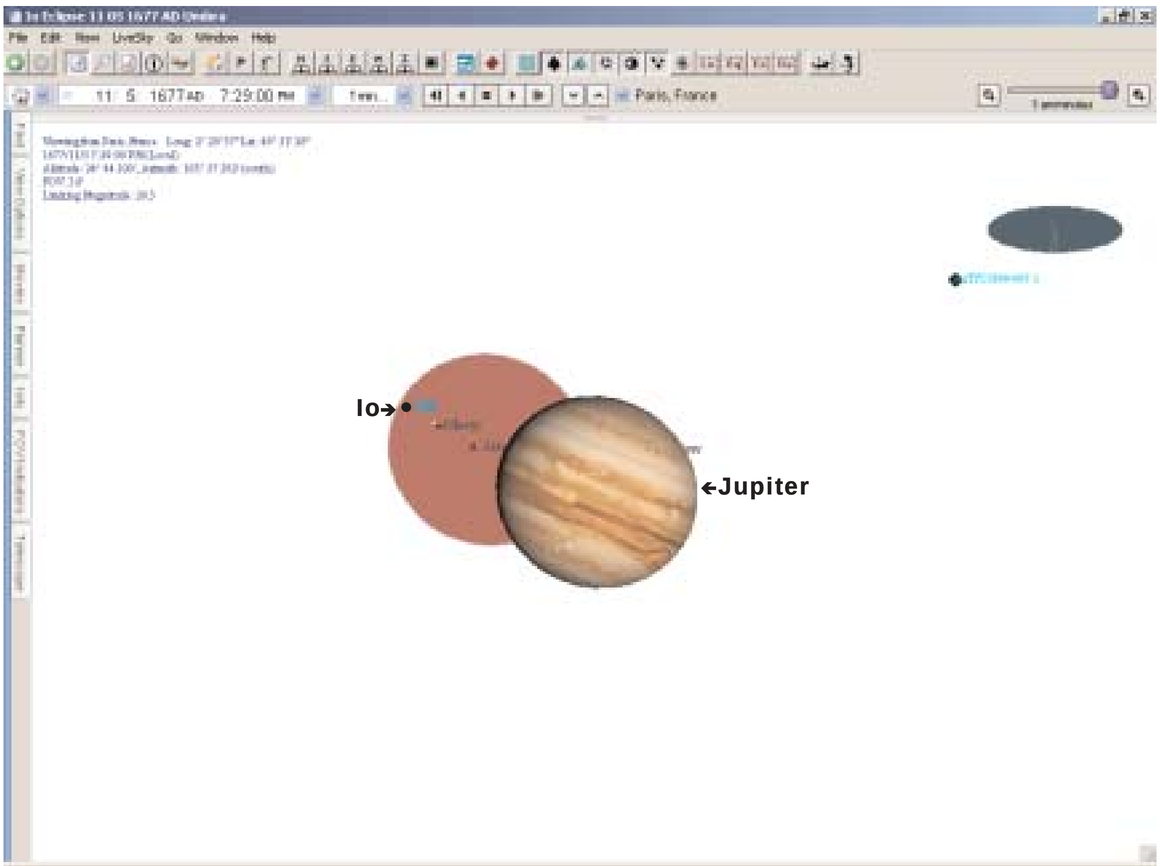
Graphic 1

Note: Graphics are available online for downloading at <http://www2.edu.gov.mb.ca/ks4/cur/science/default.asp>.
Navigate to Physics 30S through the "Curriculum Documents" link.

Step 3

Using the ▶ or the ◀ keys on the time panel, and with the time increment set to “minutes,” try to determine the exact moment that Io emerges from the shadow (umbra) of Jupiter. Astronomers call this moment **egress**. You will likely see Io brighten suddenly when this moment occurs.

Your screen could look like this:

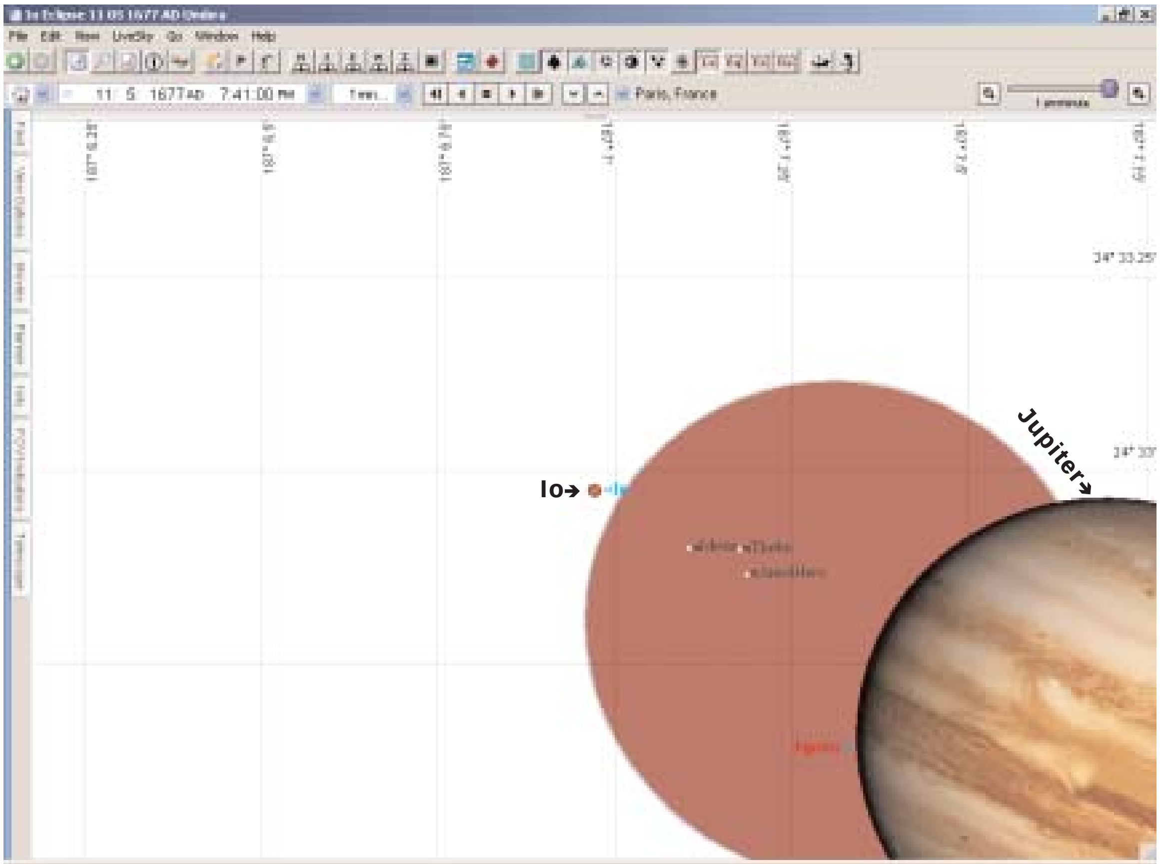


Graphic 2

Step 4

Locking on Io and observing Jupiter's shadow

Use the PLANET LIST or Find feature in order to "lock onto" Io. Once you have locked on this moon, use the ZOOM feature in order to get Io to be about the size of a "small disk" on the screen. Your screen could look something like this:



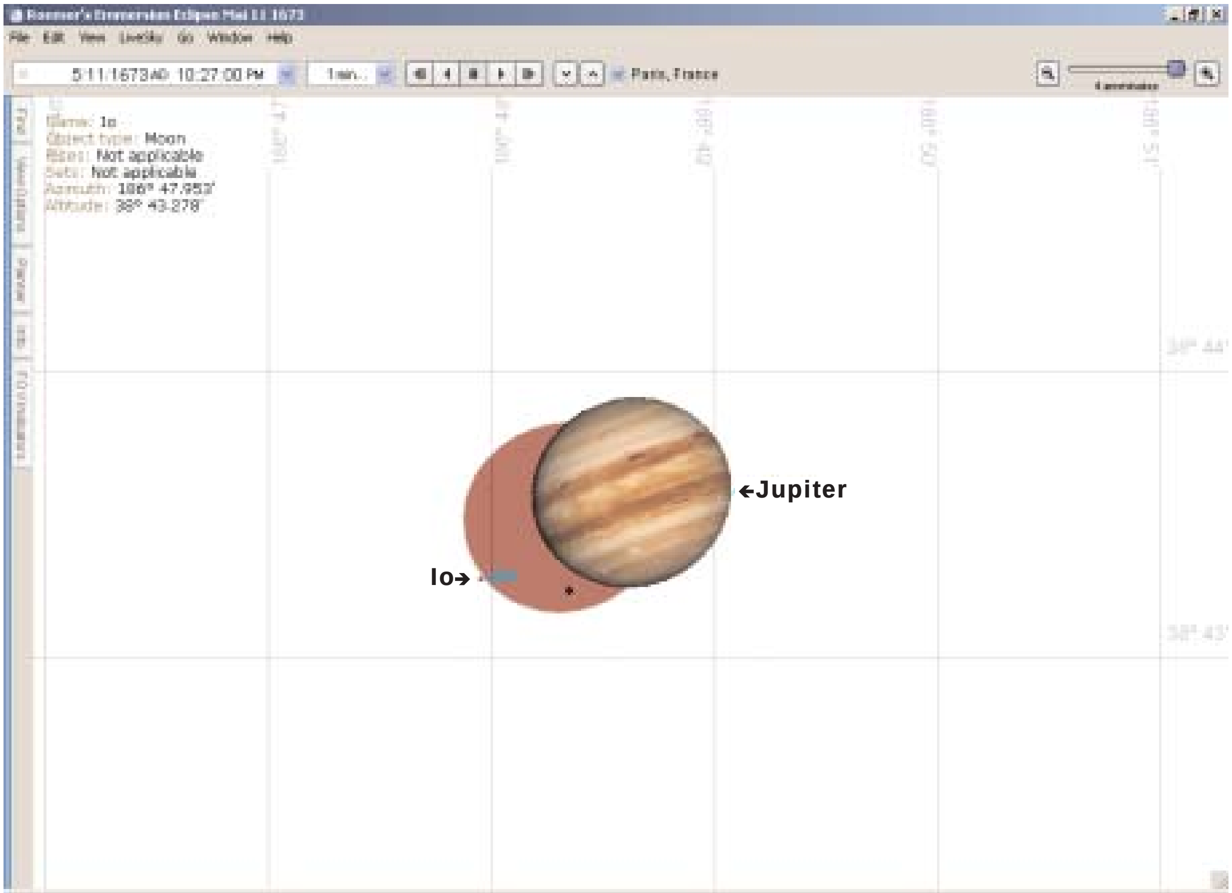
Graphic 3

Now, using the time buttons on the toolbar, try to find the exact moment when the shadow of Jupiter crosses the "face" of Io. Fill in the chart on pages 31–32.

Check this time with that of Rœmer's (from the table). Do the two times agree?

What possible explanation could be given if the times do NOT agree with each other?

In another mode (known as "White Sky," and only available with *Starry Night Pro 4.x*), you can get a good look at Jupiter's shadow.



Graphic 4

Step 5

Observing a number of eclipses from Rœmer's notebook data

The information that appears in the chart at the end of this activity includes eclipse timings that are from Ole Rœmer's own notebook. (See Summary of Eclipse Data, pp. 53–54 of this appendix.)

Experiment with some of these to see if there are some "problems" with his data. For instance, could he have been observing the wrong moon (i.e., not Io)? Did an eclipse of Io even occur on the date indicated?

You can record these data in the chart that follows.

Event Date	Transit/ Eclipse	Immersion/ Emmersion	Rœmer's Observed Time at Paris Observatory	Observed Time (*Starry Night*)	Timing Discrepancy (Rœmer vs. Simulation)	Rœmer's Timing Early (e) or Late (l)
October 22, 1668	eclipse		10:41 PM			
November 26, 1669	eclipse		11:26 PM			
March 19, 1671	eclipse		10:01 PM			
April 27, 1671	eclipse		7:42 PM			
May 4, 1671	eclipse		9:41 PM			
February 11, 1672	eclipse		10:57 PM			
February 20, 1672	eclipse		8:20 PM			
March 7, 1672	eclipse		7:58 PM			
March 14, 1672	eclipse		9:52 PM			
March 23, 1672	eclipse		7:18 PM			
March 30, 1672	eclipse		8:14 PM			
April 6, 1672	eclipse		10:11 PM			
April 29, 1672	eclipse		10:30 PM			
March 13,1673	eclipse (Europa)		5:00 AM			
May 11, 1673	eclipse		9:17 PM			
May 18, 1673	eclipse		11:32 PM			
August 4, 1673	eclipse		8:30 PM			
July 31, 1674	eclipse		10:19 PM			

Event Date	Transit/ Eclipse	Immersion/ Emmersion	Rœmer's Observed Time at Paris Observatory	Observed Time (*Starry Night*)	Timing Discrepancy (Rœmer vs. Simulation)	Rœmer's Timing Early (e) or Late (l)
July 20, 1675	eclipse		8:26 PM			
July 27, 1675	eclipse		10:17 PM			
October 29, 1675	eclipse		6:07 PM			
August 7, 1676	eclipse		9:49 PM			
August 14, 1676	eclipse		11:45 PM			
August 23, 1676	eclipse		8:11 PM			
November 9, 1676	eclipse		5:45 PM			
August 26, 1677	eclipse		11:31 PM			
September 11, 1677	eclipse		9:14 PM			
September 18, 1677	eclipse		9:41 PM			
September 18, 1677	eclipse		11:51 PM			
November 5, 1677	eclipse		6:59 PM			
January 6, 1678	eclipse		6:25 PM			

Summary of Eclipse Data from Rœmer's Notebooks—For Teachers

Event Date	Transit/ Eclipse	Immersion/ Emmersion	Rœmer's Observed Time at Paris Observatory
October 22, 1668	eclipse	immersion	10:41 PM
November 26, 1669	eclipse	immersion	11:26 PM
March 19, 1671	eclipse	emmersion?	10:01 PM
April 27, 1671	eclipse	immersion	7:42 PM
May 4, 1671	eclipse	immersion	9:41 PM
February 11, 1672	eclipse	immersion	10:57 PM
February 20, 1672	eclipse	immersion	8:20 PM
March 7, 1672	eclipse	emmersion?	7:58 PM
March 14, 1672	eclipse	emmersion	9:52 PM
March 23, 1672	eclipse	emmersion	7:18 PM
March 30, 1672	eclipse	emmersion	8:14 PM
April 6, 1672	eclipse	emmersion	10:11 PM
April 29, 1672	eclipse	emmersion	10:30 PM
March 13, 1673	eclipse (Europa)	emmersion	5:00 AM
May 11, 1673	eclipse	emmersion	9:17 PM
May 18, 1673	eclipse	emmersion	11:32 PM
August 4, 1673	eclipse	emmersion	8:30 PM
July 31, 1674	eclipse	emmersion	10:19 PM

Event Date	Transit/ Eclipse	Immersion/ Emmersion	Rœmer's Observed Time at Paris Observatory
July 20, 1675	eclipse	emmersion	8:26 PM
July 27, 1675	eclipse	emmersion	10:17 PM
October 29, 1675	eclipse	emmersion	6:07 PM
August 7, 1676	eclipse	emmersion	9:49 PM
August 14, 1676	eclipse	emmersion	11:45 PM
August 23, 1676	eclipse	emmersion	8:11 PM
November 9, 1676	eclipse	emmersion	5:45 PM
August 26, 1677	eclipse	emmersion	11:31 PM
September 11, 1677	eclipse	emmersion	9:14 PM
September 18, 1677	eclipse	immersion?	9:41 PM
September 18, 1677	eclipse	emmersion	11:51 PM
November 5, 1677	eclipse	emmersion	6:59 PM
January 6, 1678	eclipse	emmersion	6:25 PM

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Appendix 2:11: Contributions to the Determination of the Speed of Light

Name of contributor:	Lifespan (years):	Nationality:
Method(s) used:	Observations:	Inferences:
Value for 'c' determined by method:	Calculation of percentage error based on modern accepted value:	Interesting point about this person's life:

NOTES