
Rundetårn Observatory, Copenhagen, Denmark


1047-6938/09/07-8/0042/6-$15.00 ©OSA

# Ole Rømer and the Speed of Light

Patricia Daukantas

**While his 17th-century contemporaries were debating the nature of light, Ole Rømer was busy measuring its velocity. This little-known Danish scientist was the first to determine that light moves at a finite speed.**

In the 1670s, light was a popular topic of scientific inquiry. Natural philosophers did not know what light was made of, but they knew it when they saw it. In England at that time, Royal Society members Isaac Newton and Robert Hooke were bitterly debating whether light was a stream of particles or an ethereal wave.

Meanwhile, elsewhere in Europe, another aspect of light was just beginning to be explored. A Danish astronomer working with decades of careful solar-system observations published his discovery that light—whatever its form—travels at a finite, measurable speed. Although we take that fact for granted today, it was a groundbreaking concept in the 17th century. The prevailing view was that light did not travel at all; it simply existed.

Ole Christensen Rømer, a Dane educated at the University of Copenhagen, used the movements of Jupiter's moons to show that that wasn't the case. Although Rømer arrived at a highly imprecise figure—and some say that he only placed a lower limit on the velocity at which light can travel—he laid the groundwork for a major paradigm shift in the way scientists think about light and its properties.

Rømer wasn't aiming to make a scientific breakthrough that would reverberate through the ages. He and his co-workers had a far more pedestrian goal in mind: to measure European longitudes more accurately. The discovery of the velocity of light was more or less a by-product of the effort to create better maps.

## Rømer's early life

In 1644, Ole Rømer was born in Aarhus, a trading city on the east coast of Denmark's Jutland peninsula. (In some books and journals, Rømer is spelled Roemer, Römer or Romer.) His father, Christen Olsen Rømer, worked as a merchant and a skipper; his wife, Anna Olufsdatter Storm, was the daughter of an alderman. Historians know few details about their son Ole's early years.

At age 18, young Rømer entered the University of Copenhagen, which was at that time the only university in Denmark. Erasmus Bartholin (1625-1698), professor of geometry and medicine, became his mentor and took him into his home. Rømer lived with Bartholin for a number of years.

Bartholin had been entrusted with the task of preparing a manuscript that contained data from the Danish nobleman Tycho Brahe (1546-1601) for publication. Brahe had made copious naked-eye astronomical observations, so Rømer was able to learn mathematics and astronomy from the finest raw data set that had been compiled to that date.

Bartholin also delved into optics. In 1668, while Rømer was still living in his home, Bartholin examined a single crystal of Iceland spar (now known as calcite) that he had brought back from an expedition to that island. He noticed the double refraction of light—birefringence—through the crystal and was the first person to explain the phenomenon in a little-noticed publication the following year. Perhaps his mentor's experience inspired Rømer to think of light as a phenomenon worthy of study.

In 1671, Rømer accompanied Bartholin and the French astronomer Jean Picard (1620-1687) to the island of Hven, where, in the previous century, Brahe had built his magnificent, short-lived observatory of Uraniborg. Picard, whose passion was to measure the size of the Earth as accurately as possible, wanted to determine the exact position of the observatory (now in ruins) in order to calibrate Brahe's records for the French government.

**In September 1676, Rømer made a stunning prediction to the Royal Academy of Sciences: that the next eclipse of Io, which was supposed to take place on November 9 at 5:25:45 a.m., would be 10 minutes late. Sure enough, on that date, Io's eclipse was recorded at 5:35:45 a.m.**

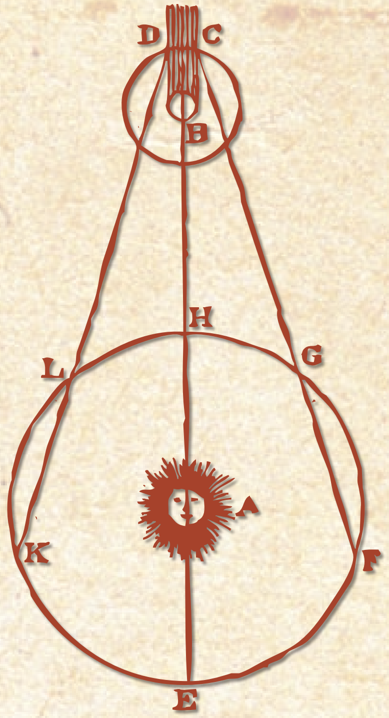


FIG. 70.

The diagram, from Ole Rømer's 1676 article, of Jupiter (B) eclipsing its moon Io (DC) as viewed from different points in Earth's orbit around the sun (A). Rømer observed that Io's orbits appeared shorter when viewed when Earth is traveling toward Jupiter (from F to G) than when it is moving away from Jupiter (from L to K).

Wikimedia Commons

Over several months, Rømer and Picard observed about 140 eclipses of Io, the innermost of the four moons of Jupiter whose discovery by Galileo in 1610 had roiled the geocentric world view of Europe. At the same time, Giovanni Domenico Cassini (1625-1712), the newly appointed director of the Paris Observatory, was observing the same eclipses from the French capital. Later, by comparing the times of the eclipses, Cassini and Picard could calculate the difference in longitude between Paris and Uraniborg.

Picard brought the promising 28-year-old Rømer to the Paris Observatory in 1672, the year after the institute opened. The Dane threw himself into a productive round of building instruments, including planispheres (adjustable star charts) and a micrometer that, according to Rømer biographer I. Bernard Cohen, "was so superior to any designed previously, that it was speedily adopted for general use."

## Geometry and reasoning

At the time, the French Royal Academy of Sciences had a practical problem to solve: how to produce more accurate maps of Europe using a new technology, the pendulum clock invented by Christian Huygens (1629-1695). If two observers—one at a place of known longitude and the other at a location whose longitude was yet to be determined—could observe the same astronomical event, they could use their timings to calculate the difference in longitude between the two locations.

As a practical matter, the astronomical event had to recur often enough that it could be observed frequently. The motions of Io, which circles Jupiter in just under 42.5 hours, fit the bill. Cassini and others assembled timetables of the motions of Jupiter's moons—the "immersions," or times when the satellite disappeared behind the major planet from Earth's viewpoint, and "emersions," periods when it emerged. But the timetables were not always accurate.

In particular, Rømer noticed that, when the Earth was moving toward

Jupiter (as from F to G in the diagram on the facing page), Io's apparent orbital period would be shorter than predicted. Likewise, when the Earth was moving away from Jupiter (as from L to K), Io's emergence from the shadow of the giant planet would be increasingly delayed. The only explanation Rømer could find for this anomaly was that it was taking longer for the light from Io to reach Earth when Earth was farther from Jupiter.

In December 1676, Rømer published an explanation for this *mora luminis*, or "delay of light," in the *Journal des Sçavans*, the first scientific periodical printed in Europe. The article is pithy by modern standards—only six paragraphs—and written in the third person, a frequent 17th-century convention.

Rømer never actually gave a value for the velocity of light—which is ironic considering he is famous for being the first to measure that speed! However, what he did put forth was the qualitative idea that light travels at a finite, though mighty fast, speed. (See box on right.)

Eleven years ago, geologist James H. Shea analyzed Rømer's report from the perspective of modern scientific publishing. He pointed out that Rømer omitted most of the details that a peer referee would need to evaluate the paper, including:

- The value he used for the synodic period of Io
- The mathematical calculations he performed
- The accuracy and precision of his timekeeping and telescopic instruments
- Dates and times of his key observations, and
- A test of his hypothesis against a mathematical model.

In the few places where Rømer did actually use numbers, he didn't get them right. He wrote: "In a duration of 42½ hours, in which this satellite [Io] undergoes approximately one full revolution, the distance from the Earth to Jupiter changes, in both quadratures, by at least 210 diameters of the Earth." As Shea noted, our home planet actually moves approximately 330 Earth diameters during one of Io's orbits—Rømer underestimated the distance by nearly 60 percent.

In September 1676, Rømer made a stunning prediction to the Royal Academy of Sciences: that the next eclipse of Io, which was supposed to take place on November 9 at 5:25:45 a.m., would be 10 minutes late. Sure enough, on that date, Io's eclipse was recorded at 5:35:45 a.m., in perfect confirmation of his hypothesis.

When presenting those results to the Academy on November 21, 1676, Rømer stated that it took about 22 minutes for light to cross the diameter of the Earth's annual orbit (a value also published in the *Journal des Sçavans*).

How did Rømer arrive at the 22-minute figure? Historians were unsure about that until the summer of 1913, when they discovered a manuscript folio that contained a list of jovian moon eclipses in Rømer's handwriting from 1668 to 1677. Apparently, Rømer had intended to publish a more complete version of his work, with more data to back up his hypothesis, but he never got around to it. Huygens recorded in his own writing that Rømer presented additional results to the Academy in 1677.

In his December 30, 1677, letter to Huygens, Rømer wrote that he had collected more than 70 observations of Io, both his and Picard's, since 1668. In calculating the moon's orbital period, he had grouped the emersions and immersions together for study. He found, in Cohen's words, that "the mean period is always greater when calculated on the basis of emersions than when calculated on immersions."

Rømer and Picard made more than half of their observations from 1671 to 1673, and Rømer chose those data to come up with the 22-minute figure because Jupiter "offered, during this period, comparatively few variations in its movement and distance from the sun; this because 1672 marked the aphelion passage of Jupiter," Cohen wrote.

## History of a Velocity

Ancient Greeks debated whether light had any motion at all. Their general conclusion was that, if light did move, it did so at an infinite velocity. Only Empedocles of Acragas, who lived in the fifth century B.C.E., thought that light was an ineffable substance with a fast but finite speed. Aristotle reasoned that light has substance but no motion, and his thinking held sway with scholars for centuries.

In the 11th century, Ibn al-Haytham (Alhazen) proposed that light travels very fast but slows down in denser bodies. Christian Huygens (1629-1695) adopted the hypothesis that light had a finite speed, but he did not do much to promote the idea; he merely used the concept to account for the phenomena in which he was interested.

In France, prevailing opinion favored the view of René Descartes (1596-1650), who argued strenuously for the instantaneous transmission of light. The Dutch physicist Isaac Beeckman (1570-1637) tried to convince Descartes that light has a finite speed that could be measured experimentally, but to no avail. Educated society's high regard for Descartes hindered the widespread acceptance of Rømer's work for years after his death. Like Descartes, Johannes Kepler (1571-1630), who figured out the laws of planetary motion, also hypothesized that light traveled infinitely fast.

Galileo (1564-1642) proposed an experiment to measure the speed of light. Two experimenters would practice uncovering and covering their lanterns until the second could uncover his lantern the instant that the light from the first reached him. He tried this himself at a distance of roughly a mile from his assistant. Not surprisingly, he failed to notice any "observable delay."


Rundetårn ("Round Tower") Observatory as it appears today in downtown Copenhagen.

## The Cassini controversy

Initially, Rømer's hypothesis about the velocity of light was met with resistance among the French scientific elite. The opposition was led by Cassini, who refused to accept that light had a finite speed, despite having flirted with the idea earlier in his career. Instead, he attributed the irregularities in the eclipse timings, which he had noticed while compiling his tables, to irregular motions of the planets or other causes that were yet to be revealed.

In an interesting twist, some modern researchers, including Laurence Bobis and James Lequeux of the Paris Observatory, have asserted that it was actually Cassini, and not Rømer, who first proposed the "successive motion" of light. At the very least, these scholars contend, the hypothesis was a joint effort.

According to Suzanne Débarbat, a historian of science at the Paris Observatory, Cassini briefly believed in the finite velocity of light, but he changed his mind when no one could detect such a delay in the eclipses of the other three Galilean moons of Jupiter. He could not admit that a hypothesis that was valid for one of the four moons did not work for the other three. (Remember, nothing was known about the nature of the jovian system at that time or the gravitational attraction among the bodies.)

The Royal Academy's meeting records are missing the minutes from mid-July to mid-November 1676. However, the institution's first secretary, Jean-Baptiste Du Hamel (1624-1706), wrote in 1698 that Cassini had warned the Academy in August 1676 that the tables of the jovian satellites' motions were inaccurate and that the eclipse of November 16 would be delayed by about 10 minutes.

Could the 75-year-old Du Hamel have been mixed up, especially given the 22-year lag between the warning and the account of it? In a never-published history of the Paris Observatory, Joseph Nicolas Delisle (1688-1768) and his collaborators used some of the now-missing minutes to credit Cassini with the warning of the delayed eclipse—and the attribution of the delay in time it took for light to travel to Earth.

The existing minutes for 1676 note for November 21 that "Rømer read to the Company an account where he shows that the motion of light is not instantaneous…. He will confer with Messieurs Cassini and Picard in order to insert this report in the first Journal." The minutes also state that Academy members discussed the findings on November 28 and allowed Cassini to present his views on the subject on December 5.

In an obscure 1862 text, Urbain Le Verrier, a Paris mathematician, wrote: "This is Roemer's discovery. Its extreme simplicity does not decrease its value. The contemporaries have first dismissed it; later, they attempted to divert a part of the merit to Cassini. It seems that in this respect the scientific habits are the same today as they were in that time."

## Gaining acceptance

Hooke, that early champion of the wave nature of light, maintained that Rømer's estimation was not conclusive. In his 1680 "Lectures on Light," the English physicist called the Dane's idea of light speed "so exceeding swift that 'tis beyond Imagination" and added, "and if so, why it may not be as well instantaneous I know no reason."

Except for Hooke, English scientists proved receptive to Rømer's work, especially after Rømer visited England in 1679. Rømer explained his findings to John Flamsteed, the first Astronomer Royal, who accepted them and started correcting his tables of the eclipses of Jupiter's satellites.

Huygens, another wave theorist, and Isaac Newton (1642-1727), a proponent of his corpuscular theory of light, both embraced Rømer's finding. In the early pages of his classic 1704 treatise *Opticks*, Newton seemed to present both sides of the light-velocity issue:

> Mathematicians usually consider the Rays of Light to be Lines reaching from the luminous Body to the Body illuminated,

Rundetårn Observatory, Copenhagen, Denmark

> and the refraction of those Rays to be the bending or breaking of those lines in their passing out of one Medium into another. And thus may Rays and Refractions be considered, if Light be propagated in an instant. But by an Argument taken from the Equations of the times of the Eclipses of *Jupiter's Satellites*, it seems that Light is propagated in time, spending in its passage from the Sun to us about seven Minutes of time: And therefore I have chosen to define Rays and Refractions in such general terms as may agree to Light in both cases.

As Cohen noted dryly, "It will be remembered with what dread Newton viewed controversies." However, late in the second volume of *Opticks*, the English physicist credited Rømer with the proposition that "Light is propagated from luminous Bodies in time, and spends about seven or eight Minutes of an Hour in passing from the Sun to the Earth."

It was another English astronomer, James Bradley (1693-1762), who drove the nail into the coffin of the instantaneous-light theory a half-century after Rømer's work. While searching—fruitlessly—to measure stellar parallax, Bradley ended up discovering the aberration of light from the stars.

Just as raindrops appear to fall straight down when one is standing still but at a slight angle when one is walking forward, the apparent position of the stars is dependent on the velocity of the observer, Bradley reasoned. When the effect happens to light, it is only about 1/200 of a degree of arc—a very small angle—but one that Bradley was able to measure with the instruments available to him in 1728.

In conducting his research, Bradley came up with a new value for the speed of light: 298,000 km/s in modern units. Amazingly, he was within 1 percent of the currently accepted value of 299,742.458 km/s in a vacuum! Certain details of the matter were still not settled—notably, the presence or absence of a "lumiferous ether." However, from 1728 onward, the question of light's velocity became about just how accurately we could measure the speed of light, not whether light traveled at all.

**Jean Baptiste Joseph Delambre used a century's worth of increasingly precise observations of Io's eclipses to revisit the topic. He calculated that light travels from the sun to the Earth in 8 minutes and 12 seconds.**

## Rømer's legacy

By 1728, Rømer had been dead for 18 years; he passed away a few days before his 66$^{th}$ birthday in 1710. He made his final observation of Io in January 1678, returned to his homeland in 1681 and busied himself with other scientific and civic activities thereafter.

Physicists continued to make evermore precise measurements of the speed of light. In 1809, French astronomer Jean Baptiste Joseph Delambre used a century's worth of increasingly precise observations of Io's eclipses to revisit the topic. He calculated that light travels from the sun to the Earth in 8 minutes and 12 seconds. Depending on the value of the astronomical unit, Delambre's work placed the speed of light at just over 300,000 km/s.

In the middle of the 19$^{th}$ century, Hippolyte Fizeau and Leon Foucault devised earthbound instruments to measure light's velocity, and James Clerk Maxwell combined the astronomical and earthbound speed calculations to bolster his argument that light was an electromagnetic wave. Cavity resonator wavemeters took light-speed accuracy to new heights in the 20$^{th}$ century, culminating with the definition of *c* as exactly 299,792.458 km/s in a vacuum.

As the biographer Cohen wrote: "That Rømer's figure [for the transit time of light between the sun and Earth] was too large, a little less than a third larger than the most recent value, is of little or no discredit. At a time when the general belief was that the velocity of light was instantaneous, he offered a means of contradicting that belief that convinced the major portion of the scientists of his time. If his figure was a little large, it was, in any case, of the right order of magnitude."

With the question of whether light travels at a finite speed settled, the great minds of the 18$^{th}$ and 19$^{th}$ centuries moved onward to investigate diffraction, interference, polarization and other phenomena that laid the foundation for the study of optics as we know it today. ▲

Patricia Daukantas (pdauka@osa.org) is the senior writer/editor of *Optics & Photonics News*.

**[ References and Resources ]**


- The classic English-language essay on Ole Rømer is I.B. Cohen's article "Roemer and the First Determination of the Velocity of Light (1676)," originally published in 1940 (Isis **84**, 327) and reprinted by Burndy Library of New York in 1944. Other sources:
- The October 1676 paper describing Rømer's work (translated by Dmitri Rabounski) is online at zelmanov.ptep-online.com/papers/zj-2008-01.pdf.
- A. Wróblewski. "de Mora Luminis: A spectacle in two acts with a prologue and an epilogue," Am. J. Phys **53**(7), 620 (1985).
- J.H. Shea. "Ole Rømer, the speed of light, the apparent period of Io, the Doppler effect, and the dynamics of Earth and Jupiter," Am. J. Phys. **66**(7), 561 (1998).
- S. Débarbat. "The Galilean Satellites of Jupiter from Galileo to Cassini, Römer and Bradley," in René Taton and Curtis Wilson, eds. *Planetary Astronomy from the Renaissance to the Rise of Astrophysics* (Cambridge: Cambridge University Press, 2003).
- L. Bobis and J. Lequeux. "Cassini, Rømer and the Velocity of Light," J. Astron. Hist. Heritage **11**(2), 97 (2008).
- I. Newton. *Opticks*, fourth ed., online at books.google.com.
- E. Poulsen. "Biography of Ole Rømer (1644-1710)," Abraham Zelmanov Journal, **1** (2008); online at zelmanov.ptep-online.com/papers/zj-2008-b1.pdf.
- Visit OPN's Web site (www.osa-opn.org) for additional biographical information and references.