RØMER AND THE SPEED OF LIGHT

1. Røomer measures the orbital period of Io

The date was April 29, 1676. The place was the Royal Observatory in Paris. The Danish astronomer Ole Rømer was observing Io, one of the moons of Jupiter. He had been measuring the orbital period of Io since at least March 7. This can be done quite accurate to the nearest second, by noticing the exact moment at which Io enters or leaves the shadow of Jupiter. In other words, for half of each orbit, Io is eclipsed by Jupiter; one second you see it, the next second it enters Jupiter's shadow and you don't see it. Or, one second it is invisible, and the next second you see it, as it emerges from Jupiter's shadow. These two events are called *eclipses* and *emergences*.

Io takes about 42 hours to orbit Jupiter. From Earth, in any given week, you can see several emergences, or several eclipses, but usually not both, as if an emergence is visible, the eclipse will take place when Io is on the other side of Jupiter from Earth. To measure the orbital period, you measure the timing of successive eclipses or emergences. To improve the accuracy, you measure, for example, ten successive eclipses and take the average time.

The reason Rømer was measuring the orbital period of Io was this: he wanted to show that the speed of light was finite. The idea is this: sometimes Earth is moving *towards* Jupiter, and sometimes Earth is moving *away* from Jupiter, depending on the time of year. Let d be the distance that Earth moves (toward or away from) Jupiter during one orbit of Io. If the speed of light is finite, it will take light a certain time T to travel the distance d, and our measurement of the orbital period of Io will be off by the amount t. It will be shorter by t when Earth is moving towards Jupiter, and longer by t when Earth is moving away from Jupiter. So if we compare the measurements at different times and get different answers, we can conclude that the speed of light is finite.

Rømer did this, at two different times of the year, sometime before 1676, and found no difference in the orbital periods. Therefore, the speed of light is very fast! If it took one second to travel an Earth diameter, we would expect the two measurements to differ by seven minutes, so light must travel hundreds of Earth diameters per second (or perhaps the speed is infinite).

But Rømer realized that, if the speed of light is finite, the effects should pile up over many orbits. There is a certain time when the Earth is exactly between the Sun and Jupiter; then Jupiter is said to be "in opposition" (it is on the opposite side of Earth from the Sun). Right at the opposition, Earth is not moving either towards or away from Jupiter, but in a perpendicular direction. Therefore, right after the opposition, you should get an accurate orbital period measurement, regardless of the speed of light. But if you wait a while and measure again, you should get a different orbital period, due to the accumulation of errors due to the speed of light.

Rømer made these measurements after the opposition of March 2, 1672. The first four orbits gave an average period of 42 hours 28 minutes and $31\frac{1}{4}$ seconds. After thirty orbits, the average period was 42 hours 28 minutes and 3 seconds. That was 32 seconds shorter, or about one second per orbit. Thus, luckily for Rømer, the error that was too small to be seen in one orbit could be seen after 30 orbits.

Rømer then calculated (using trigonometry, especially the law of cosines, on the triangle formed by the Sun, Jupiter, and Earth) that light would travel a distance equal to the radius of Earth's orbit in eleven minutes, and would reach Earth from Jupiter in about ten minutes (at the distance Jupiter was in April, 1672). The actual speed of light could not be determined at that time, since the radius of the Earth's orbit was not yet known. But at least, it was finite!

2. Longitude and the Moons of Jupiter

How did a Danish astronomer come to be working at the Royal Observatory in Paris, and why was he being paid to measure the moons of Io? It was *not* because of curiosity about the speed of light–that was what we now call a "spin-off". The real issue was the search for a way to determine longitude at sea, which was a vital issue for navigation in the Age of Discovery.

To determine longitude, it would be enough to observe the time of sunset or sunrise, which can be predicted a year in advance; if the sun where you are is going down one hour earlier than in Greenwich Observatory, then you are 15 degrees of longitude west of Greenwich (because 15 is one twenty-fourth of 360). So all you need is a clock.. But in 1672, there were no clocks that could keep accurate time on board a tossing, turning ship. Pendulum clocks worked only on land. So accurate navigation was extremely difficult. You could try to estimate the ship's speed by letting out ropes and counting the knots going by, but if there were ocean currents, which there were, you would not account for their effects.

Galileo had proposed using the moons of Jupiter for a clock; but it seemed to be too difficult to observe the eclipses of the moons from on board a ship. However, the method might work on land, and this method had been pioneered by the Italian astronomer Giovanni Cassini. Cassini was invited to France by King Louis XIV to establish the Royal Observatory. It opened in 1671, with Cassini as director. He immediately sent Jean Picard to Uraniborg, Denmark, the island where Tycho Brahe's observatory was. The idea was that Cassini in Paris and Picard in Uraniborg would measure the times of the eclipses of Io, and the difference of times would enable them to compute the difference in longitude of Paris and Uraniborg. That was the reason for the interest in the accurate measurement of the orbital periods. Rømer was a young assistant to Picard, and he must have been a good one, since Picard arranged for him to come to Paris and work at the Royal Observatory. Røomer had already been observing the eclipses of Io since at least 1668, so he probably showed Picard how to do it!

3. Reception of Rømer's work

Cassini was not immediately convinced, and apparently neither was Picard. Therefore Rømer, who was in a junior position, did not publish his work. The reason for Cassini's caution was that there are several other possible causes of discrepancies in the orbital periods. The orbits of Earth and Jupiter are not circular but elliptical, and each of these causes a variation in the orbital period. Those could be calculated and corrected for; and even after correcting for the speed of light there still remain discrepancies; those turned out later to be because of "orbital resonance" with the other moons of Jupiter (Europa and Ganymede in particular), but that explanation didn't come for another century.

In any event, after four years further measurements must have established the discrepancies more convincingly. Cassini announced on August 22, 1676, that henceforth the tables of predicted eclipse times would incorporate a detection for this "new, not previously detected, inequality." However, the corrections that Cassini made were not the same for each of Jupiter's moons (as they should have been if they were due to the speed of light), so apparently Cassini still regarded this as an empirical correction. But in England, Rømer's idea was accepted by Astronomer Royal John Flamsteed, as well as Edmond Halley and Isaac Newton, although Robert Hooke did not accept it, believing that the movement of light was "virtually instantaneous". Final confirmation of Rømer's work did not come until 1727, when James Bradley succeeded to measure "stellar aberration". That, however, is another story.