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Paris 1676: The discovery of the velocity of light and the roles of Rømer and Cassini

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Abstract

It is often claimed, that the 1676 discoveries at the Paris Observatory of a new irregularity in the orbit of Jupiter's first satellite and of the velocity of light were not due to Rømer alone, but that Cassini played a major role or even that Rømer took over these ideas from Cassini. These claims indirectly accuse Rømer and Cassini of dishonesty. We investigate the foundations of these allegations through an analysis of apparent contradictions in the primary, historical sources. The minutes from a meeting of the Academy on 22 August 1676 are especially important. Our analysis shows no reason to believe that Cassini took part in the discoveries, but his criticism incited Rømer to argue his case better. We conclude that the discoveries were due to Rømer alone and that the accusations against the two scientists of dishonesty are ill founded.

Keywords

Velocity of light, Rømer, Cassini I

Introduction

That the propagation of light takes place with a finite velocity was discovered in 1676 at the Paris Observatory and published soon after by Ole Rømer (1644-1710).[1] Many years earlier, René Descartes (1596-1650) had looked in vain for a light-time effect in a lunar eclipse and therefore concluded that light propagation had to be instantaneous.[2] The discovery was important in several ways. Philosophically, it proved the dominating Cartesian view wrong and paved the way for a better understanding of optics. From a practical point of view, it was important for the prediction of astronomical phenomena that were used for geodesy and navigation. Outside France the discovery was very well received, while Jean-Dominique Cassini (1625-1712), the leading astronomer at the Paris Observatory, soon rejected it and in fact never accepted it again.

Many papers discuss the discovery and the role of Cassini, and we will just give a few examples. Cohen says that Cassini announced a new irregularity in the eclipses of the satellites of Jupiter in August 1675[3] saying this irregularity seemed to be the result of the velocity of light and that light needs 10-11 minutes to cross the distance from the Sun to the Earth. However, because of Cassini's strong objections to Rømer's presentation of the discovery to the Academy in November 1676, Cohen concludes that "To him [Cassini] can be given no credit for the discovery – for a moment he entertained a hypothesis (one among others) but merely to discard it immediately". Van Helden subscribes to Cohen's view, stating a bit bluntly that "Roemer adopted Cassini's stepchild".[4] More recently, Bobis & Lequeux are on the same line but more subdued: "Cassini abandoned the hypothesis while leaving Rømer free to publish it."[5] A different idea was suggested by Nielsen, namely that Cassini anticipated Rømer.[6] Either way, one or both the two gentlemen stand accused of misconduct: Cassini by anticipating Rømer or Rømer by giving no credit to Cassini whatsoever and Cassini for disowning his own discovery.

We will below look into the events in 1676 in the context of Cassini's and Rømer's publications and in the context of Rømer's correspondence with Huygens, aiming to settle this curious dispute about priority and misconduct. The case is particularly curious because Rømer and Cassini were close collaborators at the same observatory and they are not known to have had any disagreement on the matter.

Because the discovery was based on a study of eclipses of a Jovian satellite, we will first describe the difficulties involved in predicting and observing such eclipses.

The eclipses of Jupiter's satellites

For an observer on the Earth, a full eclipse of a Jovian satellite can never[7] be observed. When the Earth is approaching Jupiter, i.e. in the months prior to opposition, only the initial contact – the immersion – can be observed as the satellite disappears into the shadow. Conversely, in the months following opposition, as the Earth recedes from Jupiter, only the final contact – the emersion – can be observed, as the satellite reappears from the shadow. Accurate knowledge of the orientation of the shadow cone, especially its angle with the satellite orbit, is therefore very important for making reliable predictions of the phenomena. Had we been able to observe both the start and end on an eclipse, this would have mattered less, because the mean of the start and end is insensitive to the cone orientation.

When the Académie royale des Sciences, here simply called the 'Academy', was founded in Paris in 1666, Christiaan Huygens (1629-1695) compiled a list of 30 science goals in the physical sciences that the Academy should work upon.[8] They cover many areas of physics and astronomy. Item 10 on the list says to observe the motions of the Jovian satellites and construct tables,[9] while item 11 says to observe the eclipses of the satellites here [i.e. in Paris] and in other places of the world in order to establish their longitudes and improve the maps.[10] Further down Huygens' list comes an apparently unrelated task, item 16, suggesting to observe if light is transmitted over distances instantaneously.[11] A finite velocity of light was necessary for Huygens wave theory of light, so he had a strong interest in this question. Producing good maps and finding reliable means of navigation were problems of great economic importance and some countries had offered significant rewards[12] to those who could solve them. The idea of using the eclipses of the Jovian satellites as a universal clock goes back to their discovery in 1610 by Galileo Galilei (1564-1642). It required two things in order to work: reliable clocks adjusted, e.g., to the apparent, local solar time, and reliable tables of upcoming eclipses. If an eclipse could be observed simultaneously in two different places, the difference in local solar time would directly give the longitude difference. Huygens had already solved the first problem through his invention of the pendulum clock in 1656, but predicting the eclipses remained difficult. The leading authority in this field was Giovanni Domenico Cassini in Bologna, who had published the best tables till then in 1668 and who was therefore invited to join the Paris Observatory in 1669, where he became Jacques-Dominique Cassini and the first of a dynasty of astronomers.

Predicting and observing the eclipses

The Moon orbits the Earth at a distance of 60 Earth radii and the orbit is inclined more than 5 degrees to the ecliptic. Lunar eclipses therefore require the Sun to be near the nodes of the orbit and only happen about once a year. The four large satellites of Jupiter are similar in size to the Moon, but gravitationally dominated by their planet. Their orbits are close to the equatorial plane, which is inclined just three degrees to the orbital plane of Jupiter. This means that during Jovian equinox, the shadow cone of Jupiter will lie in the orbital plane of the satellites, while at Jovian solstice, the cone will be inclined by three degrees, and the satellites will traverse shorter sections of the cone.

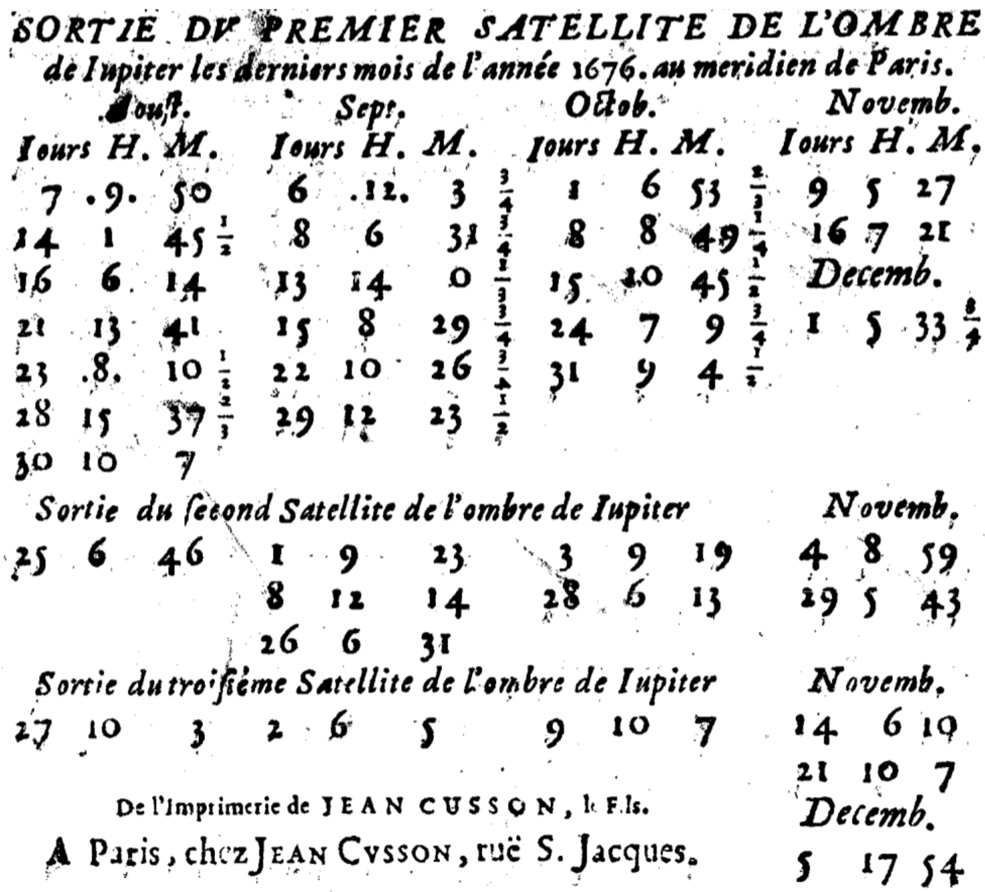
The first satellite orbits Jupiter at a distance of only six Jupiter radii and is eclipsed in every revolution, i.e. every 42.5 hours. The next two satellites have orbits of 9 and 15 Jupiter radii and periods that are the double and quadruple of the period of the first satellite. These satellites are also eclipsed in every revolution, but the duration of their eclipses vary more over the orbit of Jupiter due to their larger distances from the planet. Finally, the fourth satellite is at 26 Jupiter radii and with a period 9.5 times the one of the first satellite. Because of its larger orbit, it will sometimes (near Jovian solstice) pass above or below the shadow cone of Jupiter, and when it does enter the cone it will often be at a shallow angle, thus making the eclipses harder to predict. The second and third satellite suffer the same problem but to a lesser degree.

The time between consecutive eclipses varies throughout the 11.86 years it takes Jupiter to complete an orbit around the Sun. A satellite has to complete a full orbit from one eclipse to the next, but it also has to catch up with the shadow cone, which moves at 4.6 arc minutes per day. For the first, and fastest, satellite this catching up takes close to one minute. This would be of little concern except for the fact that Jupiter's orbit has an eccentricity of 0.048, which means that the angular velocity of Jupiter varies 10% up and down from the mean value during the 11.86 years. The first satellite therefore needs one minute, plus minus 10%, to catch up with the shadow. This smooth variation in the eclipse period is known as an 'inequality' and was well understood at the time. The new irregularity discovered in 1676 was therefore called the *second* inequality.

We can see that to make a good eclipse prediction, we need to know:

- The orbital period of the satellite;
- The present angular velocity of Jupiter in its orbit;
- The inclination of the shadow cone with the orbital plane of the satellite;
- A recent eclipse as a starting point.

This list ignores two effects. The more important one is the light travel time from Jupiter to the Earth, and the other is the variation in the eclipse period and in the inclination and eccentricity of the orbits due to gravitational interactions between the satellites. The first became clear in 1676, and the second remained speculative until the introduction of Newtonian mechanics and the work of Laplace. Finally, a prediction, to be useful in the seventeenth century, had to be presented in apparent solar time, rather than mean time, by including the equation of time. An example of such predictions is shown in Figure 1, which is from a short note by Cassini listing the eclipses for the autumn of 1676.[13] An analysis of these predictions shows that the eclipse period for Jupiter I used here is $42^h\ 28^m\ 36^s$.[14]



SORTIE DV PREMIER SATELLITE DE L'OMBRE de Iupiter les derniers mois de l'année 1676. au meridien de Paris.

Aoust.			Sept.			Octob.			Novemb.		
Iours	H.	M.	Iours	H.	M.	Iours	H.	M.	Iours	H.	M.
7	9	50	6	12	3 3/4	1	6	53 2/3	9	5	27
14	1	45 1/2	8	6	31 3/4	8	8	49 1/4	16	7	21
16	6	14	13	14	0 1/3	15	10	45 1/2	Decemb.		
21	13	41	15	8	29 3/4	24	7	9 3/4	1	5	33 3/4
23	8	10 1/2	22	10	26 3/4	31	9	4 1/2			
28	15	37 2/3	29	12	23 1/2						
30	10	7									
Sortie du second Satellite de l'ombre de Iupiter									Novemb.		
25	6	46	1	9	23	3	9	19	4	8	59
			8	12	14	28	6	13	29	5	43
			26	6	31						
Sortie du troisième Satellite de l'ombre de Iupiter									Novemb.		
27	10	3	2	6	5	9	10	7	14	6	19
									21	10	7
									Decemb.		
									5	17	54

De l'Imprimerie de JEAN CUSSON, le Fils.
A Paris, chez JEAN CVSSON, ruë S. Jacques.

Figure 1. Predictions published by Cassini for the reappearances (emersions) of the Jovian satellites in the last months of 1676. The table uses astronomical dating and apparent solar time for Paris counting from noon. Image credit: gallica.bnf.fr / Bibliothèque nationale de France.

Kristensen & Pedersen compare these predictions with modern calculations by Lieske. Figure 2 shows in graphical form the results from their Table 4.[15] The values are plotted against the distance between the Earth and Jupiter, conveniently expressed as light travel time in minutes. Because light propagation is taken into account by Lieske but not by Cassini, the values for each satellite are expected to fall on a line of slope -1 like the dashed line in the figure. For the first satellite (small, filled circles) the two first points are the ones from the beginning of August, which are based on actual observations. The remaining points are extrapolated from these starting values and agree remarkably well – to about half a minute – with the line. The last but one point is for 16 November, where the difference to Lieske has increased by 10 minutes since August. We will return to this value below. While the predictions for the first satellite have a good precision this is clearly not the case for the other two, where the predictions have errors much larger than the effect of light delay.

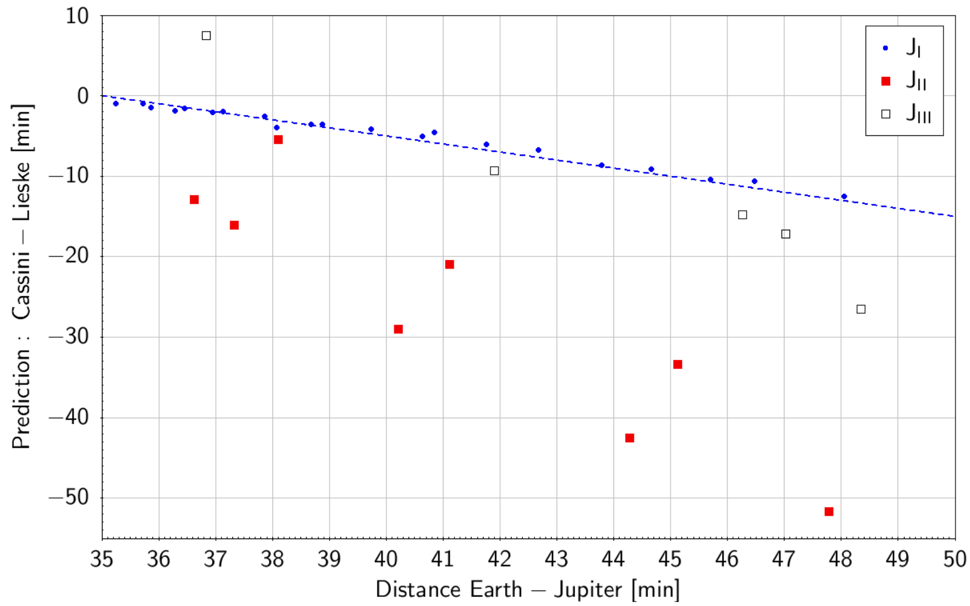


Figure 2. Comparison of the predicted emersions for the three first satellites of Jupiter by Cassini with modern predictions by Lieske during the autumn of 1676. The values are calculated by Kristensen and Pedersen.[16]

There are, as already mentioned, several reasons why the eclipses of the satellites are hard to predict accurately. A satellite may cross the shadow cone centrally where the shadow is widest but, depending on where Jupiter is in its orbit, it may also cross the shadow at some distance above or below the centre. There the shadow is narrower and the satellite will enter the shadow later and leave it sooner. This effect may reach four minutes for the first satellite, but as much as 12 and 45 minutes for the next two, and a couple of hours for the last satellite, if it crosses the shadow at all. It is clearly mandatory for the predictions to work reliably, that the orientations of the orbits of the satellites are well established. As a further complication they vary due to the interactions between the satellites, but that was not known at the time.

Observations of eclipses are also far from trivial. When a satellite is eclipsed it first enters the penumbra and then immerses itself into the umbra. There is therefore an interval of several minutes where the light from the satellite gradually fades, and it depends on the observing conditions, the eyesight of observers and the characteristics of their telescopes at which point they deem that the satellite is gone. Entering the umbra takes four minutes for the first and second satellite, eight to fourteen minutes for the third and more – often much more – than ten minutes for the last. The penumbra is of less concern, but adds one or more minutes to the fading. The reappearance after the eclipse is of course equally poorly defined. It seems, all in all, that the third and fourth satellites are not nearly as suited as universal clocks as the inner two.

Rømer’s contributions

In the late summer of 1671 Jean Picard (1620-1682) arrived in Copenhagen on a mission for the Academy. His task was to determine the geographical position, in particular the longitude, of the island of Hven where Tycho Brahe (1546-1601) had had his observatory almost a century earlier. The idea was to observe eclipses of Jovian satellites simultaneously from Paris and from Hven. The mission was very successful in several ways. The longitude was determined to better than one minute, which was fully sufficient; Picard also became acquainted with Ole Rømer, who had been assisting with the observations; and Picard got permission to bring Tycho’s observations with him back to Paris to have them printed. The publication of these observations had been prepared for several years and Rømer had been one of the young collaborators on the project, which however was cancelled. Picard could therefore return to Paris in spring 1672 with a completed mission and with Tycho’s manuscripts. He also brought Rømer to supervise the printing.

In Paris, the printing of Tycho’s observations was also soon cancelled, but Rømer stayed as a very active member of the observatory staff until 1681, when he returned to Copenhagen to become Professor of Astronomy. In November 1676 he famously announced to the Academy, that he had found a new irregularity in the eclipses of the first satellite of Jupiter, and interpreted it as the result of a finite velocity of light which needed 22 minutes to cross the diameter of the Earth’ orbit.

Rømer had been studying the eclipse period for the first satellite, i.e. the time between consecutive immersions and the time between consecutive emersions. He was not doing comparisons to a set of predictions but looking at fundamental properties of the data itself. Surprisingly, when the period is determined from immersions you always get a lower value than when it is determined from emersions. Immersions are only observable from the Earth when Jupiter is west of the Sun and emersions only when Jupiter is to the east. We cannot know how long it took for him to realise the connection to the Earth approaching – this is when we can observe immersions – and receding – this is when we can observe emersions – from Jupiter, but with the idea of a finite light velocity all pieces fell into place.

We do not know when this study was carried out, but summer 1676 is a good bet. If it were much earlier, he would only have had two series of immersions and would probably have had less confidence in the result. The third series of immersions ended by mid June, when Jupiter was near opposition to the Sun, and its shadow therefore not visible from the Earth. As reconstructed by Kristensen & Pedersen[17] the eclipse periods from the four series of emersions are: $42^h 28^m 44^s$, $42^h 28^m 37^s$, $42^h 28^m 47^s$, $42^h 28^m 50^s$; and from the three series of immersions: $42^h 28^m 17^s$, $42^h 28^m 12^s$, $42^h 28^m 21^s$. The difference may seem small, but it accumulates over many revolutions, so it is very significant.

The meeting of the Academy 21 November 1676

The minutes of the meeting of the Academy on Saturday 21 November states:

> Mr Rømer has read a paper to the Academy, where he shows that the motion of light is not instantaneous, which he has demonstrated from the inequality of the immersions and emersions of the first satellite. He will confer with Messrs Cassini and Picard about publishing this paper in the next issue of the journal.[18]

The famous paper by Rømer appeared soon after, viz. in *Le Journal des Sçavans* for 7 December 1676. The paper is held in the third person, and is published in French. It must therefore be a translation of an original text by Rømer in Latin, and it was probably translated by the secretary of the Academy, J.-B. Du Hamel (1624-1706). It is rather short, only three small pages, and some paragraphs may well have been abridged. The paper appeared half a year later in an English translation in *Philosophical Transactions*.[19]

Rømer explains that he has found a way, from observations of the first satellite, to show that the velocity of light is finite and that it needs 22 minutes to cross the diameter of the Earth orbit. He finds this from the accumulated delay in a series of emersions as compared to the accumulated advance of a series of immersions.

> The necessity of this new Equation of the retardment of Light, is established by all the observations that have been made at the *R. Academy,* and in the *Observatory,* for the space of eight years, and it hath been lately confirmed by the Emersion of the first Satellit observed at *Paris* the 9*th* of *November* last at 5 a Clock, 35′ 45″ at Night, 10 minutes later than it was to be expected, by deducing it from those that had been observed in the Month of *August*, when the *Earth* was much nearer to *Jupiter*: Which M. *Romer* had predicted to the said Academy from the beginning of *September*.[20]

The final paragraph of the paper briefly discusses if other effects than the finite velocity of light could give rise to the observed inequality, but discards them all.

The statement that the delay due to the propagation of light is seen in all observations from the last eight years must refer to the eclipses of the first satellite. In the compilation of observations by Kristensen & Pedersen[21] the bulk of observations is from 1671-1676 with only two observations before 1671, one in 1668 and one in 1669, but these two are separated 13 months, i.e. one synodic period of Jupiter, so they may have served as a determination of the eclipse period. The observational material for the second and third satellite was rather meagre, and hardly existing for the fourth satellite.

The observation on 9 November at $5^h 35' 45''$ by Rømer was in fact only 9 minutes later than the prediction of Cassini ($5^h 27'$), but he must surely have known of the observation by Picard[22] at $5^h 37' 49''$. Taken together they come very close to the predicted 10 minutes delay and taken individually they are still both consistent with the prediction. What is more puzzling is the mention of a prediction by Rømer towards the Academy "from" the beginning of September, why so vague? The French text says "… ce que Mr Römer avoit predit à l'Academie dés le commencement de Septembre", so no specific date is mentioned. The point of the text is clearly to stress that the prediction was made long ago, and in fact already since the beginning of September. The precise date is not relevant in this context. The important point is that Rømer's prediction was far more accurate than the traditional one.

The text does not specify who found the new irregularity, but it is very explicit that is was Rømer who found the velocity of light, and that Rømer predicted a 10 minutes delay.

A confusing point is how to reconcile the 22 minutes for crossing two AU and the 10 minutes delay. From the observations on 7 and 14 of August to mid November the distance between Jupiter and Earth increased by 1.23 AU (9 November) or 1.32 AU (16 November), suggesting delays around 14 minutes. The most obvious interpretation is that Rømer made his own prediction independently of Cassini, but starting from the same observations in August. He must then have used a smaller eclipse period – shorter by 5-6 seconds – than Cassini, but in his talk compared his own result with the one published by Cassini (Figure 1) and then derived a difference of 10 minutes. Possibly from the same data, Isaac Newton (1642-1726) derived a value of seven minutes[23] for 1 AU. He may have used the increase in distance from the beginning of August to mid November of 1.41 AU and the delay of "10 minutes" to obtain that value.

The meetings on 28 November and 5 December

The following weeks the velocity of light was again on the agenda and Cassini raised objections to Rømer's idea. On 28 November the minutes read:

> … the immersions and emersions of the first satellite of Jupiter were again discussed, and the fact that the sum of immersions is shorter than the time of emersions, and it was considered relevant that Mr Cassini gives in writing the reasons he proposed, and Mr Römer will answer.[24]

On the following week, 5 December:

> Mr Cassini read his observations on the inequalities of the motions of the satellites of Jupiter.

These are the first pieces of evidence we have, that Cassini was unconvinced about the velocity of light and the discussion must have been very tense since Cassini was asked to provide his arguments in writing. The precise contents of Cassini's objections are not mentioned, but can be inferred from Rømer's correspondence with Huygens and from Cassini's tables from 1693, where he persists in his rejection of the finite light velocity.

The Huygens – Rømer correspondence

Christiaan Huygens was a member of the Academy from its foundation in 1666 and until 1681. He had left Paris in June 1676, at a time when the fighting in his native country during the Franco-Dutch War seemed to have died down, and was therefore unaware of the discussions about the velocity of light[25] until he read Rømer's – rather short – paper in *Philosophical Transactions* from July 1677. During the following months, he and Rømer exchanged several letters, which allowed Rømer to present more details on his discovery. We have used the edition of Rømer's correspondence by Friedrichsen and Tortzen[26] and follow their numbering (3), .., (11) of the letters. Huygens to Rømer: 16 September (3); 11 November (6); 18 November (7); and at least one lost letter. Rømer to Huygens: 30 September (4); 1 November (5); 3 December (8); 11 December (9); 30 December (10); 19 February (11).

In the letters they not only discuss the discovery itself, but also its implications. They discuss lunar eclipses and Descartes' use of them to prove light propagation to be instantaneous (5, 7, 8); they discuss the double refraction of light in Iceland spar (8); and Rømer suggests how a kind of aberration of light due to the circular motion of the ether could be observed (10). We will here focus on the letters directly related to the discussion between Rømer and Cassini (3, 4, 6, 8, 9, 11).

The correspondence opens with Huygens congratulatory letter (3) after reading Rømer's paper. He urges Rømer to publish the observations and other relevant material, and is eager to learn the opinions of Cassini and Picard, and how Cassini will adapt his theory to this new discovery.

Rømer confirms (4) that he is planning a detailed publication [never happened] about his discovery, but he has trouble sorting out his many observations and computations. He also tells, that he and Picard are busy with levelling at Versailles.

Rømer explains that he and Picard agree, whereas Cassini has doubts about the conclusions because the inequality due to the light does not give a satisfactory explanation to the phenomena for the other satellites. Rømer gives four main reasons why the three outer satellites are unsuited for testing the velocity of light: the immersions and emersions are less frequent; the timings are less precise because of the slower motion and more oblique incidence with the shadow; the orientations of their orbits are not as well known, and this can result in deviations of several minutes for an oblique incidence; these satellites have known irregularities that make the observations deviate two to three times more from Cassini's theory than what is suggested by the new inequality. He adds that this is particularly clear for the third and fourth satellite, but also dismisses the second satellite, because it displays large deviations in both longitude and latitude. Both Cassini and Rømer noticed "a few days ago",[27] that after the emersions of the first and second satellites, the second was below the first while it according to Cassini's theory should have been above. This came as a surprise to Cassini, who assumed all satellites to lie in the same plane.[28]

Rømer has checked more than 70 observations of the first satellite since 1668, and identified nine useful time series. Five are series of emersions between 1671 and 1676, and the four remaining are series of immersions between 1671 and 1677. Throughout those six years, the period of emersions is always longer than the average period, while the period of immersions is shorter.

For the determination of "the famous 22 minutes", he primarily used observations from 1671, 1672 and 1673, partly because more observations were made, and partly because Jupiter was in its aphelion in 1672 and therefore had a constant motion and distance from the Sun.

Rømer emphasizes that his main errand is to understand the nature of the propagation of light, and that he therefore has checked if the irregularity in the eclipses could come from somewhere else. He mentions seven possible causes that he can all exclude. The six first are evident because they are not in phase with the relative motion of Earth and Jupiter. They include relative configurations of the satellites, Sun, Moon, Jupiter's atmosphere, motion in latitude. The seventh argument is the important one, viz. that also irregularities in the orbit of the first satellite can be excluded. He has namely found the same acceleration and retardation when timing the transit of the satellite across the face of Jupiter, and also for the transit of its shadow.

In addition, Rømer is observing "Cassini's spot" on Jupiter, which has recently reappeared after being invisible for three years. He hopes to get more observations in December, and that they will give a conclusive answer. Huygens agrees (6) to Rømer's arguments, but is sceptical when it comes to using the spot because of its slow angular motion as seen from the Earth. Rømer argues (8), that the spot can be used, as its transit of the centre of Jupiter can be timed to about 2 minutes. In December, Rømer got (9) more observations including the transit of the shadow of the first satellite and timings of the spot. Both show the expected delay as compared to September, while the separation of Jupiter and the Earth has increased about 1.25 half-diameters of the annual orbit.

Cassini finally suggested (11), that the orbital period of the first satellite varies with a periodicity of 13 months [Jupiter oppositions occur every 13 months, so this is also the period where emersions and immersions repeat], thereby removing the need for a velocity of light. Rømer finds this idea rather artificial and his text is a bit sarcastic. It is not known if this last letter was actually sent.

Cassini's idea of a 13 months variation in the orbital period, that would have to be in phase with the relative motions of the Earth and Jupiter, was completely arbitrary, and it was perfectly logical that Rømer and others rejected it. Curiously, however, the orbital period is not constant but has a 16 months variation caused by the gravitational interactions with the other satellites. This is much less important than the light time, but it is the main reason Rømer found a travel time of 22 minutes for the Earth orbit diameter, rather than the correct value of 17 minutes. This point is discussed further in the Appendix.

Cassini's contributions

The primary contributions from Cassini are two papers published in 1676, the minutes of a meeting of the Academy in August 1676, and the tables he published in 1693.

Cassini's paper 17 August 1676

In 1676, Cassini called for an observing campaign of the eclipses of the Jovian satellites. In a one page paper, published Monday 17 August,[29] he gives the predictions for the rest of the year. A section of that page is shown in Figure 1. He is very satisfied with these predictions and explains that the table has been updated according to recent observations and recommends its use for longitude determination. The eclipses will be observed at the Paris Observatory, weather permitting, and the results published for comparison with other observations. He asks to receive all such observations. The three last predictions for the first satellite are for 9 and 16 November and for 1 December.[30] We may add that for these predictions the elevation of Jupiter in Paris was 17º, 5º, and 11º, respectively, so the one on 9 November was the more promising and actually the only one that was observed.

Cassini gives no hint of doubt as to the quality of the predictions, and there is no mention of any other purpose than longitude determination in this short text. There is also no mention of a new inequality and no mention of the velocity of light.

The recent observations he refers to must be the emersions of the first satellite observed on the 7 and 14 of August, which are the first observations made after the opposition of Jupiter on 9 July, and which closely match the predictions in the table (Figure 1).

The publication by Cassini on 17 August is pointed out by Débarbat,[31] but generally overlooked by other authors. It is, however, important for a better understanding of the events.

Cassini's paper, 5 October 1676

Around the same time, in the 25 September/5 October issue of *Philosophical Transactions*, which was published bi-monthly, appears over three pages "An Extract of a Letter written by Signor Cassini to the Author of the Journal des Scavans … about the Configurations .. of the Satellites of Jupiter, for the years 1676, and 1677, for the verification of their Hypotheses".[32] There he explains that, according to his theory, the satellite orbits will form a straight line in March 1677 passing through the centre of Jupiter [i.e. the Earth will cross the plane of the orbits]. Observations made before and after this event will determine the precise orientation of the orbits with respect to the orbital plane of Jupiter. This is essential for eclipse prediction, and will overthrow the theories of Galileo, Marius, and Hodierna.[33]

The letter is not a call for observing eclipses, but to observe the configuration of the satellites. It contains many details of the conflicting ideas about the orientation of their orbits, but mentions no other purpose with the campaign than to settle this important question and mentions neither a new irregularity nor the velocity of light.

The meeting of the Academy 22 August

On Saturday 22 August 1676, the same week as the publication of his new predictions, Cassini addressed the Academy. The minutes have disappeared, but two copies survive. One by J.-B. Du Hamel,[34] who was the secretary of the Academy, and a later by J.N. Delisle (1688-1768).[35] There are only minor deviations between the two versions.

The text is short and consists of four paragraphs. Cassini explains that a new inequality for the satellites of Jupiter has been found, which is the same for all the satellites, "*omnibus satellitibus communem*", and which may lead to an error of up to a quarter of an hour in the predictions. For the upcoming emersion of the first satellite on 16 November it means a delay by 10 minutes as compared to the predictions made in the usual way, "*vulgari modo deducit*", from the emersions immediately after the opposition of Jupiter. Here Delisle's copy adds that the opposition took place in July or August, while Du Hamel leaves this point open. Cassini further explains that the new irregularity is related to variations in the visual diameter of Jupiter or the distance between Earth and Jupiter, and that it seems to be caused by a delay in the arrival of the light, which needs 10-11 minutes for a half-diameter of the orbit of the Earth. In the last two paragraphs Cassini discusses the impact this new irregularity has on his predictions and if suitable tables can be established. He is thinking of combining the first and second inequality in the same table and also of including the equation of time.

There are several interesting points in this announcement: the new irregularity, the hypothesis of the velocity of light, the numerical value for the velocity, the revised prediction for 16 November, and the discussion of a practical way to improve the tables of predictions. This is the first mentioning of all these points. The main topics for Cassini are clearly the new inequality and how to deal with it in practice. The question of the velocity of light is secondary. Du Hamel, which must have been present on the 22 August, briefly introduces Cassini's communication saying that Cassini wanted to give a warning about the quality of the predictions, so Du Hamel does not see this as the announcement of an epoch-making discovery.

The text is rather unclear when it comes to deciding to which degree Cassini is reporting his own work. It is however very likely that the last two paragraphs – on the practical consequences – are indeed his own contribution. They appear as the main issue and they deal with his favourite research area. The first paragraph, however, has several signs of not being his own. He says the observations show the same inequality for all the satellites, but this is inaccurate – to say the least – and a clear sign that he is explaining the work of someone else and that a few details have escaped him. Later he rejects the velocity of light precisely because the new inequality is only seen in one of the satellites. Another inconsistency is the 10 minutes delay building up from August to November. As mentioned earlier, the distance between Earth and Jupiter increased 1.32 AU until 16

November. If one AU takes 10-11 minutes, 1.32 AU would need 14 minutes rather than 10. This means that he is not simply adding the light delay to the predictions he published earlier the same week. This is certainly hard to understand, unless he is in reality quoting the results of someone else. What really occupies his mind is how to amend his system of predicting eclipses to the new situation.

The dating of the meeting has given rise to confusion. Du Hamel joins 1675 and 1676 in his exposition from 1698 and even says the meeting on Saturday the 21 November 1676, where the minutes are still preserved, was held around 22 November (*"Circa diem 22 Novembris …"*). There are, however, strong arguments from the way Delisle's material is organized, that the correct date is 1676.[36] An additional, strong argument for 1676 is that observations immediately after the opposition of Jupiter and the Sun in "July or August" are mentioned in Deslisle's version. In 1676 the opposition took place on 9 July and emersions were observed on 7 and 14 August, so 1676 fits the bill contrary to 1674 and 1675, where the opposition happened on 3 May and 5 June, respectively. Also the prediction for 16 November makes good sense for 1676, where this was the last but second of the eclipses visible from Paris, while the 16 November eclipses in 1674 and 1675 were not observable. We can therefore consider the dating settled.

Cassini 1693

In 1693, Cassini published a new set of tables for the satellites. In his discussion of the inequalities he says that: "… Romer explained very ingeniously one of these inequalities that he observed for several years in the first satellite by the successive motion of light, …", and continues: "… but he did not examine if this hypothesis would suit the other satellites, which would require the same time inequality."[37]

This is written many years after the events, but Cassini clearly gives Rømer the full credit for both the discovery of the inequality and for the idea that it was due to a finite velocity of light. Cassini still rejects the velocity of light and repeats his old argument that this is only seen in one of the four satellites. It has sometimes been suggested[38] that Cassini was dishonest in this text because he did not want to admit that he himself had introduced the velocity-of-light explanation and wished to blame it all on Rømer. There is, however, the simpler interpretation, viz. that Cassini was fair and honest and explained things the way he saw them. In any case, he also gives Rømer credit for finding the inequality, and that can hardly be explained away with Cassini wanting to rid himself of something.

Another accusation against Cassini is the idea that he faked his 17 August predictions, in order to make his announcement on 22 August appear more convincing.[39] This is again very speculative and it is hard to see how Cassini would gain credibility by publishing faked predictions.

The two hypotheses

The question, we set out to answer, is who discovered the new inequality of motion and the velocity of light. Was it 'Cassini first' with Rømer merely 'adopting Cassini's stepchild' or was it 'Rømer first' with Cassini borrowing Rømer's rightful child for a short moment? Who is the bad guy?

The presentation by Cassini on 22 August 1676 and the one by Rømer only three months later are clearly important. They both mention a new irregularity and its interpretation, both mention a value for the velocity of light, and both mention a predicted delay for a mid November emersion. The key question is if Cassini presented his own ideas, or if he – at least partly – spoke on behalf of his team.

Did Rømer adopt a stepchild?

Let us look at the implications of a 'Cassini first' hypothesis. In this case, Cassini finishes his new predictions soon after the 14 August 1676 observation and has them published (17 August), but suddenly switches his attention to the older observations. To his dismay he finds a new inequality, ascribes it to the velocity of light, makes the computations to derive a value for the velocity, repeats all his predictions from scratch with a new eclipse period and hurries to inform the Academy that same week (22 August). For unclear reasons, he is even presumptuous enough to say the inequality was found in all the satellites. He also gives the revised prediction for November and a plan for how predictions can be improved in the future. This is all very impressive, but let us for the argument agree that it is not entirely impossible. Rømer must have been involved, because when Cassini suddenly regrets it all, he lets Rømer take over the idea. Now Rømer has the incredible nerve to present the whole thing to the Academy as his own discovery only three months after Cassini's presentation in August to the very same Academy. He gives the same inequality, the same interpretation, the same velocity, and the same prediction for November, which he even explains that he himself presented to the Academy as early as the beginning of September. He does not stop there, but goes on to explain in detail to Huygens how he derived the 22 minutes for the light time of the Earth orbit diameter. Years later Cassini adds to the misconduct by saying this was all Rømer's idea.

Sorry, but this makes no sense. Someone would have noticed. Rømer was no swindler, and neither was Cassini. Better and more consistent proofs are needed to substantiate such allegations. When asked explicitly by Huygens about Cassini's view, Rømer could easily have explained that Cassini had an idea but then got second thoughts for a number of very good reasons, but there is no hint of this in the letters. There is also no reason why Cassini in 1693 should pretend that the whole thing was Rømer's idea, unless that was actually the case. He could easily have explained his refusal of the velocity of light without being dishonest, by simply explaining what actually happened or at least rephrasing a few sentences. There is no shame in getting an idea, testing it, and then giving it up because it did not work as expected.

Did Cassini show Rømer's child?

Let us now turn to the alternative idea, that it was 'Rømer first'. In this case Cassini works on his new predictions in July and August and makes his publications, while Rømer is digging into the older observations, finds the new inequality, realises the implications for the light propagation, and works out the velocity. When he learns about the new predictions by Cassini he re-computes some of the last eclipses using his own – short – eclipse period and includes the light delay. He then goes to tell Cassini about the discovery. Rømer was cautious and would want to work things out in detail before involving others, and he explains in 1676 how he some years earlier had been afraid of being accused of taking someone else's ideas when he constructed a new and very reliable micrometer.[40] Cassini must have been convinced that Rømer was on to something and hurries to inform the Academy. Cassini's main point is to warn about deficiencies in his recent predictions and how to improve them by new tables. It is therefore natural that this is presented by him, and that the light propagation is included. Given that Cassini's very recent predictions have turned out to be compromised, it leaves a better impression in the Academy that Cassini himself gives this message, rather than it is given by a young collaborator. Cassini may well in the presentation have made clear that the light velocity part was due to Rømer, and when Rømer in November refers to the prediction he made to the Academy "from the beginning of September", it may well refer to either the 22 August meeting or one soon after. It is hard to imagine that no one asked for more details when Cassini told about something as important as the velocity of light. In November Rømer no longer remembers the exact date, which is not interesting in itself, and uses the vague term "since the beginning of September".

Cassini says in August, that the new inequality is seen in all four satellites, but this was a misunderstanding. When he later realises that he got it wrong he is clearly disappointed and reacts strongly. From that point he persistently refuses the light propagation and remains immune to the additional evidence provided by Rømer.

In the letters to Huygens, Rømer leaves no doubt that it is all his own work and shows enthusiasm and a wish to crosscheck his idea, make new tests and eliminate any remaining doubts. This is a dedication fully consistent with someone defending his own new discovery.

Conclusions

The idea, that Cassini's presented his own discoveries on the 22 August 1676 is in severe contradiction with all primary sources, and is in fact hardly consistent with the minutes of that very meeting. It requires the publications and letters by Rømer, as well as Cassini's later publication, to be dishonest. It also requires the Academy to have allowed Rømer to claim ownership to a discovery it knew belonged to Cassini.

The other view, that the discovery was by Rømer, leads to no such contradictions and does not require any bad guy. It only requires that Cassini in his 22 August presentation was concerned with his own predictions and merely mentioned Rømer's discovery in order to analyse its consequences for his own work. This makes perfect sense in the context of Cassini's published predictions from earlier the same week.

We therefore conclude that the discovery of a new inequality in the motions of Jupiter's first satellite and the discovery of the velocity of light were both due to Rømer. Cassini was attracted to Rømer's discovery for a short period and analysed its implications but turned against it when he realised it was only observed in one satellite. Had it been his own discovery, he would have known that!

Annex

In order to illustrate the first and second inequalities of the eclipses and in order to understand why Rømer found a low value for the velocity of light of only 1 AU/11 minutes rather than the expected 1 AU/8.32 minutes, we look at a very simple model, our basic model, for the eclipse period, T:

$$T = \tau + \frac{|\vec{\boldsymbol{r}}_s \times \vec{\boldsymbol{v}}_s|}{2\,\pi\,r_s^2}\,\tau^2 + \frac{\vec{\boldsymbol{r}}_e \cdot \vec{\boldsymbol{v}}_e}{r_e\,c}\,\tau\,,$$

where τ is the orbital period of the satellite, $\vec{\boldsymbol{r}}_s$ and $\vec{\boldsymbol{v}}_s$ the position and velocity vectors of Jupiter relative to the Sun, $\vec{\boldsymbol{r}}_e$ and $\vec{\boldsymbol{v}}_e$ the position and velocity relative to Earth, and c the velocity of light. We include three terms: the orbital period $\tau = 42^h\ 27^m\ 33.5^s$; the first inequality, representing the time the satellite needs to catch up with the moving shadow of Jupiter; and the second inequality, which is the increase in light time delay during one satellite orbit.

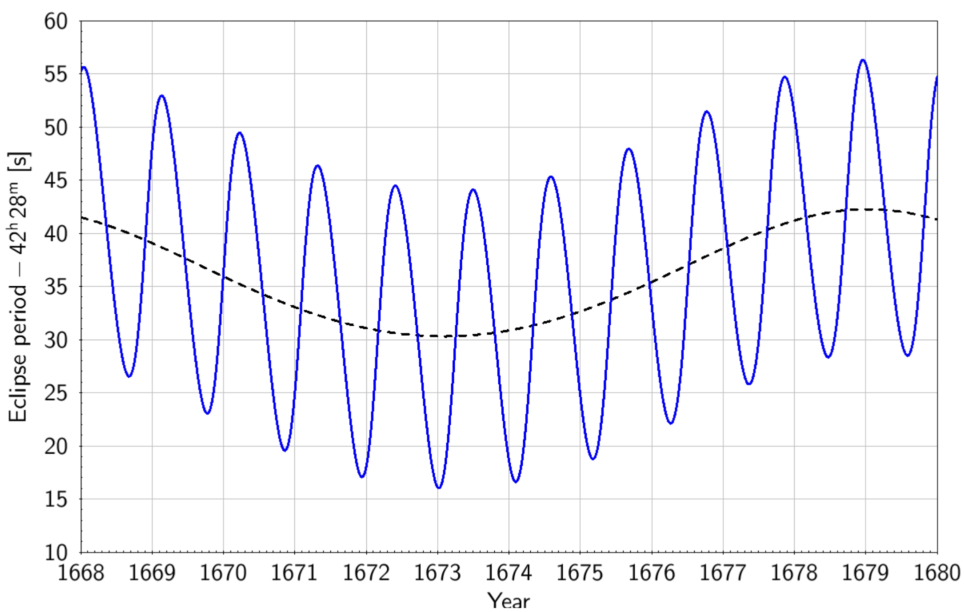


Figure 3. The eclipse period predicted from our basic model for the years 1668-1680. The dashed line shows the prediction when ignoring the light time delay. Values are based on the DE405 ephemeris from JPL.

Figure 3 illustrates the variation of the eclipse period during a 12 years orbit of Jupiter around the Sun. The dashed line shows the variation that follows from the changes in Jupiter's angular speed in its orbit around the Sun, an effect that is easily computed from Kepler's laws of planetary motion and which was well known at the time. The more wiggly pattern comes from the varying light time delay as the Earth approaches (points below the dashed line) or recedes (points above the dashed line) from Jupiter and is shown here using the modern value for the velocity of light.

This basic model is essentially the one used by Rømer, and it is of some interest to see how realistic it is. Figure 4 shows the eclipse period according to a modern ephemeris[41] for the satellites.

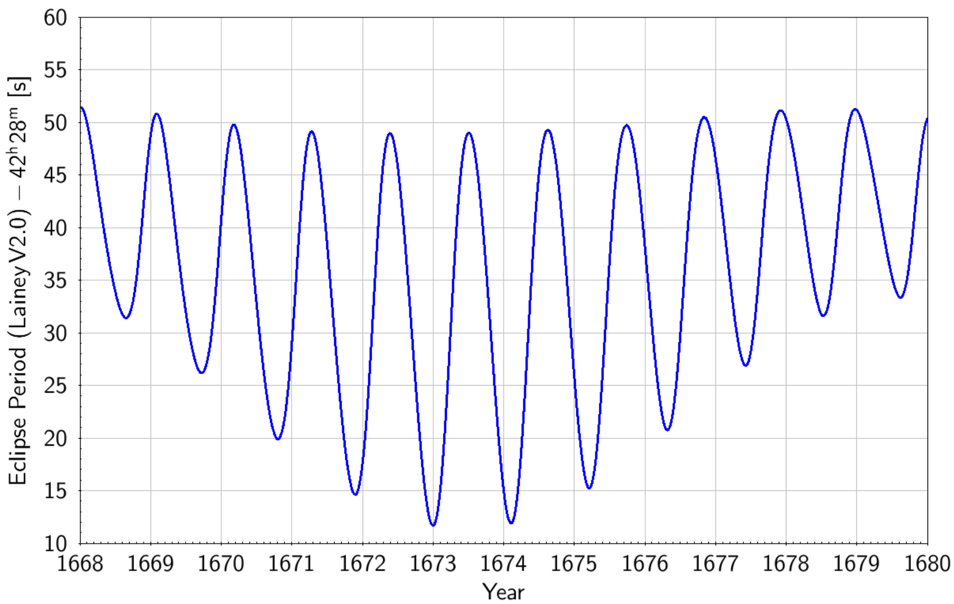


Figure 4. The eclipse period for the first satellite according to a modern ephemeris, Lainey V2.0, during the same period as illustrated in Figure 3.

Comparing Figures 3 and 4, we notice that our basic model captures the essential part of the variations in the eclipse period, but that the actual period has a significant, slow variation and that it had its largest yearly amplitude in 1673-1674, i.e. around the time of the observations used by Rømer. This gives a clue as to why Rømer found such a long light delay.

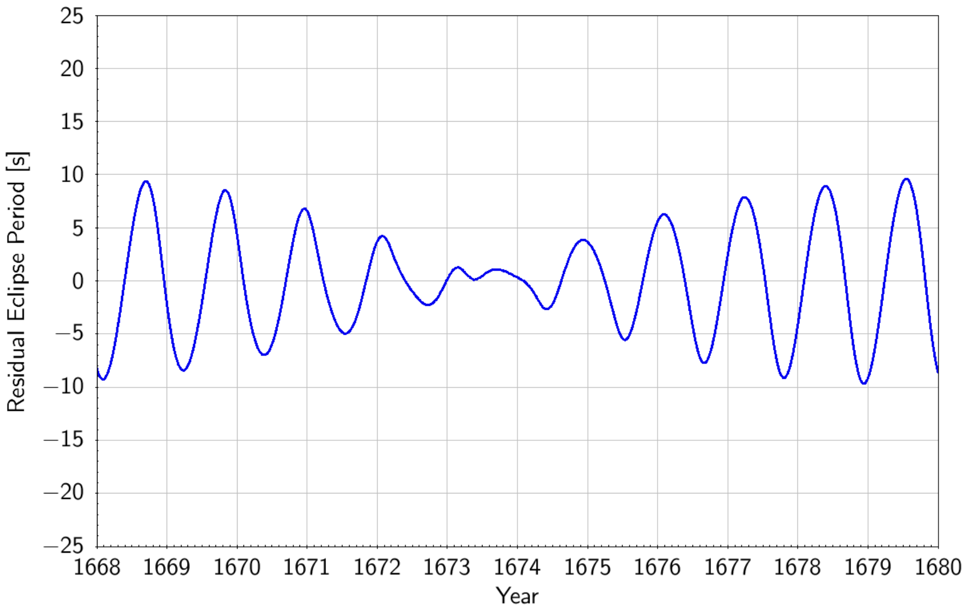


Figure 5. The difference between the actual eclipse period, Figure 4, and the basic model, Figure 3, when the basic model is scaled to a light time of 11 minutes/AU.

In order to understand this better, we scale the model shown in Figure 3 to a light delay of 11 minutes/AU and subtract it from the modern computations shown in Figure 4. This gives us a prediction of the observational residuals Rømer must have found after fitting his model as shown in Figure 5. It is clear, that Rømer must have given a high weight to observations from 1673, where the residuals are very small when we assume the same light delay he obtained.

The term missing in our model is a 16 months variation, the apsidal precession, in the orientation of the orbit of the first satellite caused by the interactions with the other satellites and leading to a variation of the eclipse period with a 5^s amplitude. The *ad hoc* claim by Cassini, that the eclipse period had a 13 months variation, therefore had something to it. His even more arbitrary claim, that this variation was in phase with the relative motion of Earth and Jupiter, also comes close the truth in the years around 1673. The much more solid claim by Rømer, that the observed variations could be explained by light delay, accounts, however, for the major part of the discrepancies.

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Note on contributor

Claus Fabricius started his career in astrometry at the University of Copenhagen working at the Carlsberg Automatic Meridian Circle before moving to space astrometry, first in the Tycho experiment of the European Space Agency's HIPPARCOS mission and now in the Data Processing and Analysis Consortium of the European Space Agency's *Gaia* mission. In spare hours, he is preparing, with colleagues, a publication on Rømer's instruments and his Triduum observations from 1706.

Notes

1. O. Römer, "Demonstration tovchant le mouvement de la lumiere trouvé par M. Römer de l'Academie Royale des Sciences", *Le Journal des Sçavans,* 7 December 1676, 233-6.
2. I.B. Cohen, "Roemer and the first determination of the velocity of light (1676)," *Isis*, xxxi (1940), 327-79. Descartes is discussed on pp. 333-7.
3. Cohen, *op. cit.* (Note 2). The year was actually 1676. Cohen has probably been misled by the way this meeting is mentioned by Du Hamel (Note 34).
4. A. Van Helden, "Roemer's Speed of Light", *Journal for the History of Astronomy*, xiv (1983), 137-41.
5. L. Bobis and J. Lequeux, "Cassini, Rømer and the velocity of light", *Journal of Astronomical History and Heritage*, xi (2008), 97-105.
6. A.V. Nielsen, *Ole Rømer: en Skildring af hans Liv og Gerning* (Aarhus, 1944), 74.
7. In special circumstances a full eclipse of one of the outer satellites can be observed, but in practice it is either the immersion or the emersion that we can see.
8. *Œuvres complètes de Christiaan Huygens*, xix, 256-7. We here quote the facsimile version inserted between these two pages.
9. "Observer le mouvement des 4 compagnons de Jupiter et en faire des tables."
10. "A l'aide de ces tables observer icy et en d'autres lieux du monde l'occultation de dits compagnons derriere ou devant le disque de Jupiter, pour trouuer par la la vraye longitude des dits lieux, et rectifier les cartes."
11. "Observer si la lumiere es communique des loin dans un instante." This point is included in the facsimile version.
12. J. Levy, "L'intérêt pratique des satellites de Jupiter", in *Roemer et la vitesse de la lumière*, ed. R. Taton (Paris, 1978), 129-35. Lévy mentions 300000 French livres by the king of Spain and 100000 livres by the States General of Holland.

13. J.-D. Cassini, “Eclipses des satellites de Iupiter dans les derniers mois de l’année 1676”, *Le Journal des Sçavans*, 17 August 1676, 192.
14. L.K. Kristensen and K.M. Pedersen, “Roemer, Jupiter’s Satellites and the Velocity of Light”, *Centaurus*, liv (2012), 4-38. Table 4.
15. Kristensen and Pedersen, *op. cit.* (Note 14). Their Table 4 contains two conspicuous typos, which we have corrected here, viz. the sign for the Cassini-Lieske values for 29 September and 1 October which is negative rather than positive.
16. Kristensen and Pedersen, *op. cit.* (Note 14) in their Table 4.
17. Kristensen and Pedersen, *op. cit.* (Note 14) in theirs Tables 6 and 7.
18. P. Friedrichsen and C.G. Tortzen, *Ole Rømer, Korrespondance og afhandlinger samt et udvalg af dokumenter* (København, 2001), 371.
19. O. Rømer, “A Demonstration concerning the Motion of Light, communicated from Paris, in the Journal des Scavans, and here made English”, *Philosophical Transactions*, xii (1677), 893-5. This is the 25 June/5 July 1677 issue.
20. Rømer, *op. cit.* (Note 19), 894.
21. Kristensen and Pedersen, *op. cit.* (Note 14), Table 5.
22. S. Débarbat, “La qualité des données d’observations traitées par Roemer”, in R. Taton (ed.), *Roemer et la vitesse de la lumière* (Paris, 1978), 143-57. Figure 5.
23. I. Newton, *Opticks* (London, 1704). On p. 2 it says: “… by an Argument taken from the Æquations 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.”
24. Bobis and Lequeux, *op. cit.* (Note 5), 100.
25. Kristensen and Pedersen, *op. cit.* (Note 14), 14.
26. Friedrichsen and Tortzen, *op. cit.* (Note 18), 167-94.
27. Rømer must be referring to the emersions of the two first satellites on 27 September, which took place less than half an hour apart.
28. This is a good approximation for Jupiter I, which has an orbit inclined only 0.04º, while the inclination for Jupiter II is 0.47º.
29. Cassini, *op. cit.* (Note 13).
30. Kristensen and Pedersen, *op. cit.* (Note 14), Table 4, point out that the last eclipse of Jupiter I is erroneously listed as 1 December. The correct date is 2 December.
31. S. Débarbat, “Rømer, lyset og dets hastighed”, in K. Tybjerg, J. Danneskiold-Samsøe and P. Friedrichsen (eds.) *Ole Rømer i kongens og videnskabens tjeneste* (Aarhus, 2011), 161-70.
32. J.-D. Cassini, “An Extract of a Letter Written by Signor Cassini to the Author of the Journal des Scavans, Containing Some Advertisements to Astronomers about the Configurations, by Him Given of the Satellites of Jupiter, for the Years 1676, and 1677, for the Verification of Their Hypotheses”, *Philosophical Transactions*, xi (1676), 681-3.
33. Simon Marius (1573-1624) published *Mundus Iovialis* in 1614, and Giovanni Battista Hodierna (1597-1660) published his *Ephemerides Medicœorum* in 1656.
34. J.-B. Du Hamel, *Regiæ scientiarum Academiæ Historia* (Paris, 1698), 145.
35. Bobis and Lequeux, *op. cit.* (Note 5) reproduce on p. 99 the copy ascribed to Delisle with an English translation.
36. Bobis and Lequeux, *op. cit.* (Note 5), 99.

37. J.-D. Cassini, “Les hypothèses et les tables des satellites de Jupiter réformées sur de nouvelles observations”, in *Recueil d’observations faites en plusieurs voyages par ordre de sa majestè* (Paris, 1693), 52. The paper is later reprinted in *Mémoires de l’academie royale des sciences*, viii (1730), 391. We here quote the translation by Bobis and Lequeux, *op. cit.* (Note 5), 100.
38. Kristensen and Pedersen, *op. cit.* (Note 14), write: “We agree with one of our anonymous referees that ‘one should be suspicious about the 1693 assertion of Cassini giving full credit to Roemer for the discovery. Cassini did not believe in the retardation of light, and he probably wanted that all the responsibility for this explanation was borne by Roemer …’.”
39. Kristensen and Pedersen, *op. cit.* (Note 14), write: “A more refined, conspicuous and convincing manner to present the new inequality can hardly be imagined. First faking the predictions and then foretelling the error.”
40. In 1672, having recently arrived in Paris, Rømer build a micrometer. His description, written around 1676, is quoted by Horrebow in *Basis Astronomiæ* (Hafnia, 1735) § 285: "… I did not know that others had tried to make something similar until my own instrument was finished. At that time it rather upset me who as a newcomer hoped to impress the Academy with my little invention – and especially Mr Picard … Without his knowledge I had my instrument made in order to be sure about its success before I showed it to himself. It might certainly appear as if I wanted to claim other persons’ results as my own, and I really feared this suspicion concerning me.”
41. The ephemeris V2 by V. Lainey is available on-line from Institut de Mécanique céleste et de calcul des éphémérides (IMCCE): *https://www.imcce.fr*