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CASSINI, RØMER AND THE VELOCITY OF LIGHT

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Abstract: The discovery of the finite nature of the velocity of light is usually attributed to Rømer. However, a text at the Paris Observatory confirms the minority opinion according to which Cassini was first to propose the 'successive motion' of light, while giving a rather correct order of magnitude for the duration of its propagation from the Sun to the Earth. We examine this question, and discuss why, in spite of the criticisms of Halley, Cassini abandoned this hypothesis while leaving Rømer free to publish it.

Keywords: velocity of light, satellites of Jupiter, longitude, Jean-Dominique Cassini, Jean Picard, Ole Rømer, Edmond Halley, James Bradley, Christiaan Huygens.

"The Danish astronomer Olaus Römer (1644-1710) discovered the velocity of propagation of light at the Paris Observatory in 1676." Inscription on the north frontage of the Paris Observatory.

1 INTRODUCTION

The discovery of the finite nature of the velocity of light has been abundantly commented on by many authors. The general opinion is that it is due to Ole (or Olaus) Rømer (Figure 1),[1] who published it on 7 December 1676 in the *Journal des Sçavans*. The paper by Rømer (1676), well-written and very clear, shows that the discovery was made while studying the motion of the first Galilean satellite of Jupiter, Io (Figure 2). There is, however, some doubt about this discovery, which we will now try to dissipate. Before this, let us examine why the satellites of Jupiter were so actively observed during the seventeenth century.

Figure 1: Ole Rømer, engraving by J.G. Wolffgang (1735). Rømer appears here in full glory. After his return to Denmark, around 1681, he became Mayor and head of the police of Copenhagen, and also head of the State Council of the Realm (Library of the Paris Observatory).

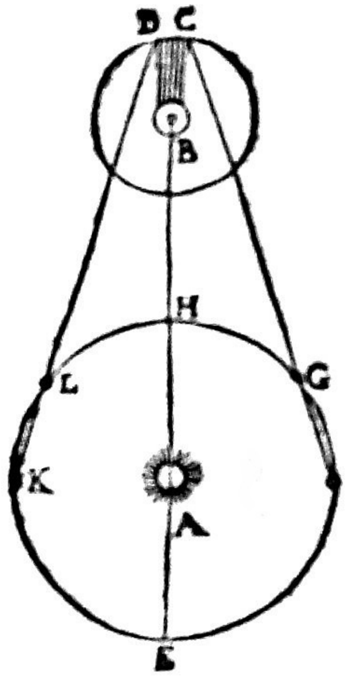

Figure 2: Rømer's drawing in his article of the *Journal des Sçavans.* The Sun is in A, Jupiter in B with its shadow cone, and the drawing is in the reference system Sun-Jupiter. Two positions of the Earth, L and K, are represented at the times of two emersions of the first satellite out of Jupiter's shadow; in D, the Earth moved away from Jupiter between these two observations, and the second one seems late because of the extra time required for the light to propagate. Conversely, immersions of the satellite in the shadow, in C, seem increasingly early when the Earth moves from a non-labelled point to G (Library of the Paris Observatory).

Immediately after he discovered the four main satellites of Jupiter, Galileo proposed that their motion could be used as a natural clock. In 1692 Jean-Dominique Cassini (Figure 3) wrote:

> It is not by curiosity alone that the most famous astronomers of the present century have observed with so much care the planet Jupiter; they mainly did it in order to obtain an exact knowledge of longitudes, on

which the perfection of geography and navigation depends. They estimated that one would have a fast and secure way to determine longitudes, if one could find in the sky some rapid phenomenon which could be observed at the same time from very distant points on the Earth. This being assumed, comparing with each other the times of observations done simultaneously in different locations distant from each other from the East to the West, it would be easy to know by how much one of these places is more to the East than the other; which indicates their difference in longitude. (Cassini, 1692: 1-2; our translation)

Figure 3: Jean-Dominique Cassini, by Lépold Durangel (1879), from an old engraving. The Paris Observatory is on the background, with one of the long refracting telescopes used by Cassini, placed here by mistake on the roof of the building (Library of the Paris Observatory).

The eclipses of the Jovian satellites thus allowed clocks in different locations to be synchronized. Measuring with clocks synchronized in this way the times of meridian transit of the Sun or of the same star at each location, one obtains by subtraction the difference of longitude of these places after small well-known corrections are made. Prior to this, lunar eclipses were used, but as Cassini (ibid.) noted, "… these eclipses are not frequent enough, and they are so difficult to observe that one has not found in this way the longitudes of many places." Improvements in instruments allowed easy observations of Jupiter's satellites, at the very time when Cassini (Figure 3) took over the leadership of the Paris Observatory (which was founded in 1667 by the French Academy of Sciences). Cassini (1692: 2-3; our translation) continues:

This only became possible in 1668, when Mr. Cassini published ephemerides from these satellites, and the method to calculate their eclipses. Since that time, one has performed at the Observatory a large number of observations, together with astronomers of the Academy sent especially by order of the King in all parts of the world, and with other astronomers with whom mail was exchanged; and by the means of these observations one found in the longitudes indicated on all maps a large quantity of errors which have been corrected for.

This was obviously of prime importance, so that Bernard le Bouyer de Fontenelle (1657–1757) was able to write:

Were there no other use of astronomy than that drawn from Jupiter's satellites, it would justify well enough these huge calculations, these diligent and scrupulous observations, this large ensemble of instruments built with so much care; [and] this superb building [the Paris Observatory] raised for our science. (Fontenelle, 1740: 3; our translation).

In another text, Cassini (1693a) gives an historical account of the attempts to use Jupiter's satellites for longitude determination. One can find there the names of Galileo, Peiresc and Kepler, as well as lesser-known astronomers. Cassini claimed that it was possible to reach an accuracy of 15 seconds in the determination of the time of immersion or emersion of a satellite. A study by Suzanne Débarbat (1978) shows that this figure is somewhat optimistic: differences between the observers could reach half a minute, even for the eclipses of Io. But the accuracy of the observations of Jupiter's satellites was sufficient to show the irregularities in their motions, some of which were well understood and taken into account in the ephemerides, while others were not. It is in this context of systematic research that the discovery of the finite nature of the velocity of light occurred.[2]

2 THE DISCOVERY

Amidst the numerous texts which describe and comment on the discovery of the finite velocity of light, the poorly-known one by Urbain J.-J. Le Verrier (1811–1877), written in 1862 on the occasion of the first accurate measurement of this velocity by Léon Foucault (1819–1868), appears to us of particular interest. Le Verrier (1862) reminds us that the astronomer Jean Picard (1620–1682) was sent to Denmark in 1671 to measure the longitude difference between the old observatory of Tycho Brahe and the Paris Observatory, and that he was helped by a young man named Rømer, who "… showed such great abilities for astronomical works that Picard took him back to France where he became one of the most active members of the Observatory."

A letter from Cassini to Picard dated 3 October 1671 provides further information:

M. Carcani will see that M. Colbert [the Prime Minister of France] knows how strongly you insist on the reward due to M^r^. Bartholin for his work on the observations of Tycho, and will take care that the money is sent to him, as well as the fee due to the young man you recommand and who worked with you at Uranibourg, so that he can come to Paris. He will certainly do this rapidly so that no time is lost. (Cassini, 1671; our translation).

Erasmus Bartholin (1625–1698) was a famous physicist and astronomer from Copenhagen, and the young man was obviously Rømer. Colbert granted them 2,000 livres, as reported in another letter from Cassini to Picard dated 10 October. But let us continue with Le Verrier's text:

> This is Rœmer'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 ... When one considers the origins of a discovery, it is rare not to find some obscurity ... Should we ask ourselves if Rœmer is the sole author of the discovery of the velocity of light, in agreement with the only tradition of our time? (Le Verrier, 1862; our translation).

3 THE ROLE AND THE RESERVATIONS OF CASSINI

As remarked by Le Verrier (ibid.), the history of the discovery of the finite velocity of light is not entirely clear. Let us examine the chronology, which is of importance as in the case of many discoveries.

The minutes of the *Académie Royale des Sciences* are incomplete for the year of the discovery, between 18 July and 14 November 1676. The missing content can however be reconstructed, thanks to indirect sources that cite or copy it. Jean-Baptiste Du Hamel (1624–1706), Secretary of the Academy from its creation to 1697, reproduces in 1698 in his *Histoire de l'Académie* in Latin a text that he considers important and little known (Du Hamel, 1698: 143-146). Here is an English translation of what he wrote, based on a somewhat later manuscript that was translated into French:

> The different configurations of Jupiter's satellites being of great importance for Astronomy and Geography, Mr Cassini found it adequate to warn astronomers on 22 August by means of a public announcement about the way they will appear during the next year, in order to determine accurately their motions.
>
> But because one cannot find copies of this report anymore and since it is very short, we thought it opportune to reproduce it here. Selected observations of Jupiter's satellites made by the Academy during the past five years have displayed a new inequality common to all of these satellites, and which is of such importance that it could cause the prediction of their eclipses to be in error by up to a quarter of an hour. For example, the emersion of the first satellite on 16 November occurs about 10 minutes later than according to the calculation based on emersions observed immediately after the opposition of Jupiter. (Du Hamel, s.d.).

If one had doubts about the correctness of the transcription he gives next, another document which proves that Du Hamel is entirely reliable. Joseph Nicolas Delisle (1688–1768) and his collaborators collated before 1738 the minutes of the Academy (including the now missing ones) when preparing an ambitious, but never written, book on the history of astronomy. Their collation, which is literal, can be found in a manuscript register (Figure 4) conserved in the Library of the Paris Observatory (Anonymous 1, s.d.). Here is our translation of their text:

> Inequality of Jupiter's satellites, by M. Cassini. 22 August 1676
>
> The selected observations of the satellites of Jupiter decided by the Academy five years ago yielded a new prostapheresis [irregularity of motion],[3] the same for all the satellites, which is so important that it could give an error up to a quarter of an hour in the prediction of the eclipses; thus, for example, the next emersion of the first satellite on 16 November will occur about 10 minutes later than predicted by the calculation, which usually derives from the emersions which occurred immediately after the opposition of Jupiter and the Sun in the months of July or August.
>
> *This irregularity is related to a variation in the visible diameter of Jupiter, or to the distance of Jupiter from the Earth, and it seems to come from the fact that light arrives from the satellites with a delay such that it takes ten or eleven minutes [to cross] a distance equal to the half-diameter of the annual orbit.* [our italics].
>
> But the difficulty with this element would make the calculation very intricate if one could not find at the same time a method to build tables in which the true times of the eclipses of any satellite are obtained only from its mean motion and from a single prostapheric table, without help from other tables.
>
> This table will contain the inequality of the days or the true motion of the Sun [i.e. the inequality due to the eccentricity of the Earth's orbit], the eccentric motion of Jupiter [i.e. the inequality due to the eccentricity of the orbit of Jupiter] and this new, not previously detected, inequality. This sort of table will surpass all those in use until now thanks to its shortness, to the ease of its use and to the extent of the data.

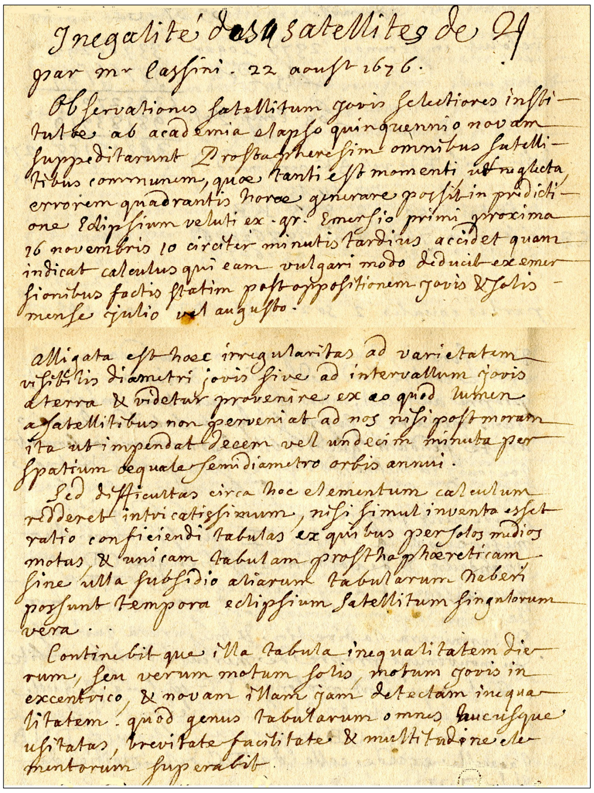
Inegalité des satellites de ♃
par mr Cassini. 22 aoust 1676.
Observationes satellitum Jovis selectiores institutae ab academia elapso quinquennio novam suppeditarunt Prostaphaeresim omnibus satellitibus communem, quae tanti est momenti ut neglecta errorem quadrantis horae generare possit in praedictione Eclipsium veluti ex. gr. Emersio primi proxima 16 novembris 10 circiter minutis tardius accidet quam indicat calculus qui eam vulgari modo deducit ex emersionibus factis statim post oppositionem Jovis & Solis mense julio vel augusto.
alligata est haec irregularitas ad varietatem visibilis diametri jovis sive ad intervallum jovis a terra & videtur provenire ex eo quod lumen a satellitibus non perveniat ad nos nisi post moram ita ut impendat decem vel undecim minuta per spatium aequale semidiametro orbis annui.
Sed difficultas circa hoc elementum calculum redderet intricatissimum, nisi simul inventa esset ratio conficiendi tabulas ex quibus per solos medios motus & unicam tabulam prosthaphaereticam sine ulla subsidio aliarum tabularum haberi possunt tempora eclipsium satellitum singulorum vera.
Continebit que illa tabula inequalitatem dierum, seu verum motum solis, motum jovis in excentrico, & novam illam jam detectam inequalitatem. quod genus tabularum omnes hucusque usitatas, brevitate facilitate & multitudine elementorum superabit.

Figure 4: The manuscript of the text of Cassini of 22 August 1676. It is written on two pages, joined together here. It is very probably from the hand of Delisle (Library of the Paris Observatory).

The discovery of this manuscript—where the mentioned date is beyond any question because the excerpts of the Minutes of the Academy were copied in chronological order—solves definitively a date problem raised by the version of Du Hamel. In effect, the page setting of his book could raise a doubt about the date of the discovery to which it related.[4] On his side, Pedersen (1978) supposes that Du Hamel's memory was failing when he reproduced this text at the age of 75, and that his citation concerns Rømer rather than Cassini. The manuscript collation negates this hypothesis. The first written account of the discovery is thus undeniably by Cassini.

It is not known if the 16 November emersion for which a delay was predicted with respect to ephemerides was actually observed or not. However, another one had been observed on 9 November, with a delay of 10 minutes (Anonymous 2, 1676).

After the Minutes of the Academy are resumed, one reads for 21 November 1676:

> Römer read to the Company an account where he shows that the motion of light is not instantaneous, which he demonstrated by the inequalities in the immersions and emersions of the first satellite of Jupiter. He will confer with Messieurs Cassini and Picard in order to insert this report in the first Journal. (Our translation).

The mentioned account is from an article to be submitted to the *Journal des Sçavans*, which was published on 7 December 1676, as we have seen. However, Cassini soon raised objections about the hypothesis of the "… successive propagation of light …", and he attempted to raise other possibilities to explain an inequality that he did not clearly find in the eclipses of the other satellites:

> Saturday 28 November, the Company being assembled ... 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 Mons^{r} Römer will answer.
>
> [The following Saturday, 5 December] Mons^{r} Cassini read his observations on the inequalities of the motions of the satellites of Jupiter. (Minutes of the Academy of Sciences, 1676; our translation).

The objections of Cassini can be found in a later text (Cassini, 1693a: 391; our translation):

> [After correcting for the known inequalities] … there remain other inequalities in the motions of Jupiter's satellites, that differ from each other. When constructing my first tables, the motion of the fourth satellite looked to me more equal than those of all the others, and the first satellite seemed to approach the equality of the fourth. I noticed that in the second and the third there were more important inequalities, and I confessed that in the ephemerides I used some empirical equations which I derived from the observations [see later], whose causes I could not yet discover. Monsieur Romer explained very ingeniously one of these inequalities that he observed for several years in the first satellite by the successive motion of light, which needs more time to come from Jupiter to the Earth when it is more distant than when it is closer; but he did not examine if this hypothesis would suit the other satellites, which would require the same time inequality.

Cassini (1693b: 47; our translation) also writes:

> The Academy did indeed notice in the series of these observations that the time for a considerable number of immersions of the same satellite is appreciably shorter than for the same number of emersions, something which can be accounted for by the hypothesis of the successive motion of light: but this was not enough to convince the Academy that the motion of the light is indeed successive, because one cannot be certain that this time inequality is not produced by the eccentricity of the [orbit of the] satellite, or by irregularities in its motion, or by some other cause not yet understood, that might become clear in the future.

Thus Cassini abandoned the hypothesis of the finite velocity of light, because of irregularities in the motion of Jupiter's satellites that he could not understand. However, he had the intuitive feeling that some of them could result from the interaction between the satellites (but did he know of Newton's *Principia*?).[5]

Rømer's idea was accepted with enthusiasm by Christiaan Huygens (1629–1695), who had temporarily left Paris for the Netherlands in June 1676 and discovered them through the excellent English translation (by Halley?) of the *Journal des Sçavans* paper, which was published on 25 July 1677 in the *Philosophical Transactions of the Royal Society* (Rømer, 1677). Actually, Huygens needed a finite velocity for light in order to account for reflection and refraction in his undulatory theory (Costabel, 1978; Verdet, 1978), and he was very pleased with Rømer's theory.[6] In his *Traité de la Lumière* of 1690, which was written in 1678 (after he returned to France) and was shown to his colleagues at the Royal Academy of Science, in particular the "… famous Messieurs, Cassini, Romer and De la Hire …", Huygens reproduces the demonstration of Rømer, "… waiting for him to give every element for its confirmation." (Huygens, 1690: 467). Then he calculates the velocity of light from Cassini's and Rømer's data, and finds it

> … more than 600,000 times larger than that of sound, which is not at all the same thing as being instantaneous, since there is the same difference as between something finite and something infinite … (Huygens, 1690: 469).

In modern units, he found 230,000 km/s. Note that Huygens was the first scientist to give a numerical value for this velocity (Wróblewski, 1985); neither Cassini nor Rømer had attempted this, probably because they considered that the velocity was inconceivably large. There is in the *Histoire de l'Académie Royale des Sciences* for 1676 (on page 215) a figure for the velocity of light of "… 48,203 *lieues communes* of France [per second] …",[7] but one should realize that this text was only printed in 1733. The context suggests that it was written by Fontenelle some time after 1707.

4 WHY DID CASSINI PERSIST WITH HIS OPINION?

Cassini had doubts about the explanation of some astronomical phenomena several years before 1676. His certainties began to be shaken as early as 1671, on the matter of an apparent displacement of Polaris with respect to the North Celestial Pole, which he discovered.[8] This displacement was real, but neither Cassini nor Picard nor Jean Richer (1630–1696), who also observed it, could understand the cause, which was aberration. What is important for us here is that, probably for the first time in his career, Cassini was in doubt: would it ever be possible to do better than Tycho Brahe, who reached an accuracy of the order of one minute of arc in his observations?

This position of doubt was also his when he discussed the delays in the eclipses of Jupiter's satellites. His carefulness explains why he proposed several hypotheses on the same footing: either the delays were due to the finite velocity of light, or they came from other causes, like a variation in the diameter of Jupiter. The possibility of such a variation looks absurd to us, but in Cassini's time it was not, since nothing was known about the physical nature of the planets. Cassini himself discovered variable spots on Jupiter, and he thought that he saw dark zones on the satellites which made their apparent diameter variable.[9]

Cassini's doubts about the hypothesis of the finite velocity of light are those of an experienced scientist: as claimed by Fontenelle (1707: 79), "… an hypothesis must account for everything." Giacomo Filippo Maraldi I (1665–1729), Cassini's nephew who also worked at the Paris Observatory, writes: "In order for an hypothesis to be accepted, it is not enough that it agrees with some observations, it must also be consistent with the other phenomena." (Maraldi, 1707: 32). If one was unable to find the expected delays or advances in the eclipses of the other satellites of Jupiter, masked by irregularities that could only be seen without understanding them, one had to abandon their explication in terms of the successive motion of light. Maraldi also considered rightly that the eccentricity of the orbit of Jupiter, which is rather large, should affect by several minutes the delays or advances of the eclipses if they were due to the finite velocity of light, but he claimed in 1707 (ibid.) that he had not seen this effect (which however was found later!). Backed up by this new argument, Cassini stuck to his position until the end of his life. Conversely, Rømer threw himself without hesitation into promoting the hypothesis of the finite velocity of light. One should remember that his article was published with the agreement of Cassini and Picard, who let him take sole responsibility for this.

Rømer never made public a refutation of Cassini's arguments against the successive motion of light. However, this can be found in a letter in Latin that he wrote to Huygens on 30 September 1677, where (at Huygens' request) he provided details of the discovery (Huygens, 1888-1950, t. 8: 32-35). From this letter, it seems that Picard shared Cassini's doubts. Rømer gives four reasons which, according to him, explain why the advances or delays due to the finite velocity of light cannot be seen clearly in the three external Galilean satellites: their immersions and emersions are less frequent than for the first satellite; their motions are slower so that the timing of these events is less accurate; the uncertainties in the inclinations and nodes of their orbits might also give errors of several minutes for eclipses occurring obliquely in the shadow; and finally:

> It is certain that these satellites exhibit irregularities that are not yet determined, either due to eccentricity [of their orbits] or to some other cause, which produce discrepancies between observations and the theories of D. Cassini of time intervals two or three times larger than the one we are looking for and determine from the first satellite. (Huygens, ibid.; our translation).

This is not really an explanation, since Rømer, like Cassini and Picard, did not understand the reason for these discrepancies. Yet in another part of the letter, Rømer demonstrates in a most convincing way that no other cause than the finite velocity of light can account for the delays or advances in the eclipses of the first satellite.

In spite of Cassini's views, the idea of the finite velocity of light made its way into France and elsewhere. If Maraldi I did not take the velocity of light into account in his tables, the Swedish astronomer Pehr Wilhelm Wargentin (1717–1783) did in his *Tabulae pro calculandis eclipsibus satellitum Jovis*. Calculated in 1741, these were the best Jovian satellite tables available at the time (Wargentin, 1746). These tables, and to a lesser extent those of Giovanni Domenico Maraldi (1709–1788, a nephew of Maraldi I), were used by Jean-Sylvain Bailly (see Condorcet, 1763), Joseph-Louis Lagrange (1766) and Pierre-Simon Laplace (1788) in support of their theory of the motion of Jupiter's satellites.

5 HALLEY'S CRITICISMS

The English astronomer Edmond Halley (1656–1742) is well known for having shown that the comet to which his name has been given reappears regularly every 76 years or so. Halley (Figure 5) knew Cassini very well, and visited him at the Paris Observatory during the first months of 1681.[10] Halley was thus very aware of the work carried out at the Observatory on the satellites of Jupiter. In 1694, he published an adaptation for London of Cassini's new ephemerides for Jupiter's satellites (Halley, 1694). He acknowledged that they were rather exact, but he made important criticisms.

Figure 5: Edmond Halley (after Wikipedia Commons).

Halley's text of is very interesting. He adopts as 'most ingenious' Rømer's hypothesis, acknowledges Cassini's opposition, then gives details about the way the latter constructed his new tables. Maraldi I explained why Cassini did not take the eccentricity of Jupiter's orbit into account, "… which would occasion a much greater difference than the Inequality of Jupiter and the Earth's Motion, both of which are accounted in these Tables with great Skill and Address." Cassini introduced an inequality in the orbital motion of the first satellite, assuming that the eclipses occurred 14m 10s earlier when Jupiter was in opposition that when it was in conjunction (we do not understand why Cassini choose this value, which is too small); which corresponds to an inequality of 2º in the orbital longitude of the satellite as seen from Jupiter. Halley (ibid.) continues:

But what is most strange, he affirms that the same Inequality of two Degrees in the Motion, is likewise found in the other Satellites, requiring a much greater time, as above two Hours in the fourth Satellite: which if it appeared by Observation, would overthrow Monsieur Romer's Hypothesis entirely ... [so] Monsieur Cassini has, by his *Praecepta Calculis* ... supposed that the Minutes thereof to be increased in the same proportion; as instead of 14′. 10″. in the First, to be 28′. 27″. in the Second, 57′. 22″. in the Third, and no less than 2h. 14′. 7″. in the Fourth; whereas if this second Inequality did proceed from the successive propagation of Light, this Æquation ought to be the same in all of them, which Monsieur Cassini says was wanting to be shown, to perfect Monsieur Romer's Demonstration; wherefore he has rejected it as ill founded. But there is good cause to believe that his motive thereto, is that he has thought not proper to discover.[11]

From the letter of Rømer to Huygens cited above, we can understand why Cassini used this 'most strange' trick when building the ephemerides for the external satellites: he had observed for them inequalities "… two or three times larger …" than for Io.

Halley then attempted to confirm the hypothesis of the finite velocity of light. Analysing various observations, some of which were made by Cassini, he showed that the inequalities for the third and the fourth satellites are much smaller than considered by Cassini, and were compatible with the idea of the successive propagation of light. Halley finally noted that Cassini's tables, printed in Paris by the Royal Printing Office, were full of mistakes "… which yet ought not in the least to be attributed to the Excellent Author, but rather to the Negligence of those employed by him."

Therefore, in spite of his admiration and respect for Cassini, Halley did not hesitate to strongly criticize his stubbornness in rejecting the idea of the finite velocity of light, and also the strange recipes he used to build the tables of the second, third and fourth satellites of Jupiter—which were fortunately much less observed than the first satellite.

6 CONCLUDING REMARKS

A text by Fontenelle (1707), the successor of Du Hamel as the Secretary of the Academy, summarizes the facts quite correctly, and we now see that there is no reason to contest it as has been done by several commentators (including Le Verrier):

The observations of Jupiter's satellites made by the Academy from 1670 to 1675 lead to the discovery in their motion of an inequality not previously known ... M. Cassini and M. Roëmer, then a member of the Academy, after scrutinizing this anomaly, found that it depended of the distance of Jupiter from the Earth … They called it the second inequality ... A very ingenious conjecture on the cause of this inequality first came to the mind of the two astronomers. They imagined that the motion of light was not instantaneous as all previous philosophers believed, but that it took some time to spread ... M. Cassini proposed this idea in a writing published in August 1674 [actually 1676, for Fontenelle was fooled by the page setting of Du Hamel's book and made a further careless mistake], to announce to astronomers the second inequality he had discovered in the satellites of Jupiter. To gain their confidence, he predicted that this inequality would cause a delay of 10 minutes, with respect to the calculations, for an emersion of the first satellite due for the following 16 November.

But M. de Cassini did not remain convinced for long that the successive propagation of light produced this second inequlity, while conversely M. Roëmer stuck to this hypothesis, and maintained it with such strength and subtlety that it became his own, and that a large number of skilled philosophers took it from him.

Indeed, it was worthy of inspiring some sort of passion in a high-spirited man. Why should light be able to cross space instantaneously, but not a piece of marble [i.e. a material object]? The motion of the most subtle body can only be faster than that of a heavier and more massive object, but it cannot be instantaneous either ... If one wishes that the motion of light be not a real change of place, an effective transport, but a simple pressure of some subtle matter, an undulation, sound is another one but it does not spread in an instant. Moreover, the 14 minutes that light takes to cross the diameter of the Earth's orbit, i.e. 66 millions of lieues, makes it pleasantly easy to perform calculations on this motion, to compare it to that of sound, to build upon it elevated and subtle speculations, and all this persuades in favour of the hypothesis. (Our translation).[12]

However, convinced by the arguments of Maraldi I published in the same volume, Fontenelle concluded that

… we must abandon, although perhaps with regret, the ingenious and attractive hypothesis of the successive propagation of light, or at least the only certain evidence that we thought we had for it, because a missed proof does not make a thing impossible. (ibid.).

As we have seen, the English astronomers were much less reluctant to adopt the hypothesis. In France, one would have to wait until 1728, the date of the discovery of aberration by James Bradley, to see scientists convinced that the propagation of light was not instantaneous. Bradley (1728) understood that

… [if] Light was propagated in an Instant, then there should be no Difference between the real and visible Place of an Object … [and that] if Light was propagated in Time, the apparent place of a fixt Object would not be the same when the Eye is at Rest, as when it is moving in any other Direction, than that of the Line passing through the Eye and Object; and that, when the Eye is moving in different Directions, the apparent place of the Object would be different …

This is aberration. Bradley realized that his discovery confirmed at the same time the finite velocity of light and the revolution of the Earth around the Sun (the first observational proof of the hypothesis of Copernicus). He admitted, however, that since no one had yet succeeded in observing the annual parallax of the stars, which also resulted from the revolution of the Earth,

… the Anti-Copernicians have still room to object against the Motion of the Earth; and they may have (if they please) a much greater Objection against the Hypothesis, by which I have endeavoured to solve the fore-mentioned Phænomena; by denying the progressive Motion of Light, as well as that of the Earth. But I do not apprehend, that either of these Postulates will be denied by the Generality of the Astronomers and Philosophers of the present Age. (ibid.).

But let us come back to our question: who discovered the finite velocity of light? If we take literally the text of 22 August 1676, then it was Cassini. This is also affirmed by Jean Étienne Montucla (1758: 579) who wrote:

One generally attributes to Roemer the merit of having found an explanation both likely and ingenious of this phenomenon. But this is mistaken; one can see in a writing by Cassini, published in August 1675 [actually 1676], that this astronomer was the first author.

However, perhaps Cassini wrote on behalf of his team, which included Picard, Rømer and perhaps even Richer and Philippe de La Hire (1640–1718). This becomes a most convincing hypothesis when one reads the minutes of the Academy and considers the working methods at the Paris Observatory: it may be that the discovery was collective, and was due to both Cassini and Rømer, as suggested by Fontenelle (we should remember that Cassini was still alive when Fontenelle was writing his 'history', and that they both attended Academy meetings every Saturday). In any case, Cassini cannot be dismissed for this discovery, as proposed by some commentators, and we must acknowledge his eminent contribution to the solution "… of one of the most beautiful problems in physics." (Cassini, 1693b: 46). He behaved like an open-minded scientist, who left to others the possibility of promoting ideas opposite to his own beliefs; but he also showed some stubbornness when refusing to adopt the idea of the finite velocity of light, in spite of Halley's demonstration—which he could hardly ignore.

Even if the discovery of aberration solved in a definitive way the problem of the velocity of light, the situation surrounding the ephemerides of Jupiter's satellites remained unsatisfactory until the time of Lagrange and Laplace, in spite of the efforts of Wargentin and of Maraldi II. Empirical terms were still introduced in order to account for the observations in the best possible way. The ephemerides remained in use for determining longitudes until the end of the eighteenth century, because they were precise enough in the short-term to give time, hence longitude, within a few minutes: this only required a single eclipse observation, without need for comparison with a simultaneous observation in Paris. But this was only possible on land; observations of Jupiter's satellites made at sea were impossible in practice because of the motions of the ships. In this case, the solution finally came with the construction of precise marine chronometers by John Harrison (1693–1776) in England between 1737 and 1773. Good marine chronometers were also built in France by clock-makers like Ferdinand Berthoud (1727–1807), Duroy and Jean-André Lepaute (1709–1789), and were tested ashore and at sea by astronomers. By 1800, longitude could be determined within a fraction of a degree on voyages of one or two months' duration.

7 NOTES

1. Rømer's name is also spelt Römer, Roemer, Rœmer and even Romer.
2. The observations used in the discovery are collected in a manuscript by Rømer which was written two years later.
3. Astronomers used to call *prostapheresis* (modern equivalent: equation of centre) the difference between the mean and the true position of the Sun, of a planet or of a satellite.
4. Du Hamel inserts the text in question in page 145 of his book, in a chapter entitled "De rebus Astronomicis anni 1675" (beginning on page 143). In the margin of page 144 we find the mention 'Ann. 1675', but at the end of the chapter, on page 146, it becomes 'Ann. 1675 & 76'. It is clear, when reading the chapter, that the text dated 22 August is from the same year as the publication by Rømer, i.e. 1676, but some commentators confused the dates: for example, Montucla (1758) attributes the text to August 1675 and Fontenelle (1707) to August 1674.
5. Indeed, Cassini writes in an unpublished project for an 'Abrégé d'Astronomie' preserved in the Library of the Paris Observatory:

   The observations show that aside from the known inequalities there are others which are larger in the second and the third satellite, and smaller in the first and the fourth. They clearly change their distances from Jupiter and anticipate or delay conjunctions and eclipses.

   Reason demands that there are three others similar to those of the Moon, and more difficult to disantangle, because one of them results from the equilibrium of all satellites together, which is continuously changing and produces effects on each satellite. Experience shows however that the sum of these inequalities is not large and that they do not prevent a prediction of the conjunctions and eclipses with approximately the same accuracy as for the predictions of those of the Sun and of the Moon. (Cassini, MS B4[2]; our translation).
6. On 14 October 1677 Huygens (*Oeuvres Complètes*, 1888-1950, t. 8: 36-37; our translation) wrote to Colbert, the Prime Minister of France:

   I have seen recently with much pleasure the beautiful invention [sic] of Mr. Romer, to demonstrate that light takes time to propagate, and even to measure this time; this is a very important discovery, worthy of a confirmation by the Royal Observatory. As to myself, this demonstration suits me more especially as, in what I am writing about Dioptics, I supposed the same thing about light, and demonstrated with it the properties of refraction, and recently those of the Iceland Cristal.
7. These 'lieues de 25 au degré' measure 4,444 metres, so the velocity of light is calculated as 214,000 km/s, a figure somewhat smaller than that derived by Huygens and much smaller than the current value of 299,792.458 km/s.
8. Here is what Cassini observed, as documented in letters to Picard, written in Italian, and preserved in the Library of the Paris Observatory (Ms B4[3]). On 24 October 1671, Cassini wrote:

   I already told you about the difference I found for the largest elevation of the Pole Star observed last fall, with respect to the present one ... I plan to set up a fixed telescope in order to see if this difference arises from the thing itself, or from the observation. (Our translation of the French translation Ms A4[2]).

   The "largest elevation" was the elevation of the Pole Star above the horizon at culmination. If it varied, this was because the Pole Star was getting closer or further from the North Celestial Pole. Picard wrote Cassini on 13 November 1671 that he had also seen this variation:

   I can say that, unless the observations I have made last summer during several following evenings are wrong, the Pole Star must presently be at a distance from the Pole of 2° 28′ 30″ instead of 2° 28′ 10″. Whatever it may be, I have not much difficulty to imagine that the axis of diurnal motion of the Earth, by changing its parallelism [sic], might experience some periodical agitation or libration. This would be enough to account for these kinds of anomalies. (Our translation).

Cassini asked more questions of himself, before writing to Picard on 14 January 1672:

I have found the largest elevation of the Pole Star similar to that last fall ... I examine if the differences ... could arise from the quality of the air, altered by the exhausts and the smoke from the city above which the visual rays propagate. [Note that Paris Observatory was located to the south of the city.] (Our translation).

He then writes Picard again on 11 February:

The confrontation of the observations of the distance of the Pole Star to the Pole, made by you, by M. Richer and by myself, shows that the difference of the instruments, or our estimate, or the difference in the quality of the air, or all these things together do not allow an exactness better than a quarter or a third of a minute of time [probably of a degree]. (Our translation).

9. Du Hamel (1698: 27) comments on Cassini's observations as follows:

There are some parts in the satellites that do not reflect light so that they are larger than they look. This is confirmed by the shadow of the fourth satellite [on the disk of Jupiter] because it sometimes looked more extended than the satellite itself. And because these kinds of spots do not always show up, and sometimes the satellites in the same situation with respect to Jupiter and the Sun do not always appear with the same magnitude, M[r] Cassini believes that one may conclude that they rotate around their axis or that they suffer some physical changes which cause sometimes their spots to appear then to disappear, as it happens on Jupiter. One might also conjecture that there is a kind of atmosphere around the first satellite, from the fact that Mr Cassini sometimes could not see its shadow on Jupiter when it was crossing its disk. (Our translation).

10. Indeed, it is Cassini who suggested to Halley that some comets should appear periodically (see Cook, 1998: 115).

11. This sentence is somewhat obscure, but there is little doubt that Halley accuses Cassini of insincerity.

12. Cassini indeed adopted 14m 10s for his new tables instead of the 20 to 22 minutes announced before. The actual value is 16m 28s.

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