On the Provability of Heliocentrism I. Ole Romer and the Finite Speed of Light

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I. Ole Rømer and the Finite Speed of Light

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Abstract. This paper describes observational support of heliocentrism during the late Renaissance. Initiated by Galileo's clues from telescopic sightings, the first indirect quantitative support for the heliocentric doctrine resulted from accurate eclipse timings of the satellites of Jupiter, made possible by breakthroughs in technology (telescope optics and the pendulum clock) and driven by the quest for longitude at sea and on land. The resulting discovery of Olaus Rømer that the velocity of light is finite, is an indirect argument supporting heliocentrism.

Preamble

E PUR SI MOVE: these are the words which Galileo Galilei is said to have uttered on the 22nd of June 1633, after abjuring the heliocentric doctrine. The origin of this legend is hard to trace, and many variants of the expression are found in the literature: *e pur si muove*[1], *eppure si muove, eppur si move, eppur si muove*, and so on. Berthold (1897) traces the first written version "eppur si move" to a publication in 1757 by Giuseppe Baretti (1719–1789).

But there appears to exist a painting by Bartolomeo Esteban Murillo (1617–1682) depicting Galileo in prison, with a wall ornamented with drawings of the Earth orbiting the Sun, Venus in phase, Saturn and its ring, and also the phrase *e pur si move*. Lagrange (1912) inspected this painting in the city of Roulers (Roeselare): the work is signed with the year 1643 or (1645?), and the frame carried a dedication to General Ottavio Piccolomini (1599–1656), who served Spain against the French in the Netherlands and was a defensor of the city of Ypres (Ieper), the last Spanish bastion in the Low Countries. This commander in the Spanish army was the brother of Ascanio Piccolomini, archbishop of Siena, who assumed custody of Galileo after his trial (Sobel 1999).

As Galileo was Pisan, and the Italian language – in particular the literary language – was basically a form of Tuscan, it was not unlikely that the words reportedly uttered may actually have been "*eppur si muove*". Galileo himself in his essays was a very good stylist and in any case the distance between his written language and his spoken was unlikely to be great (Lepschy 2006). The typographically incorrect "move" for the Italian "muove" is thus most probably an error introduced by the Spanish painter Murillo when he created the work commissioned by Piccolomini. But though the existence of this artwork is be-

[1] And yet it moves.

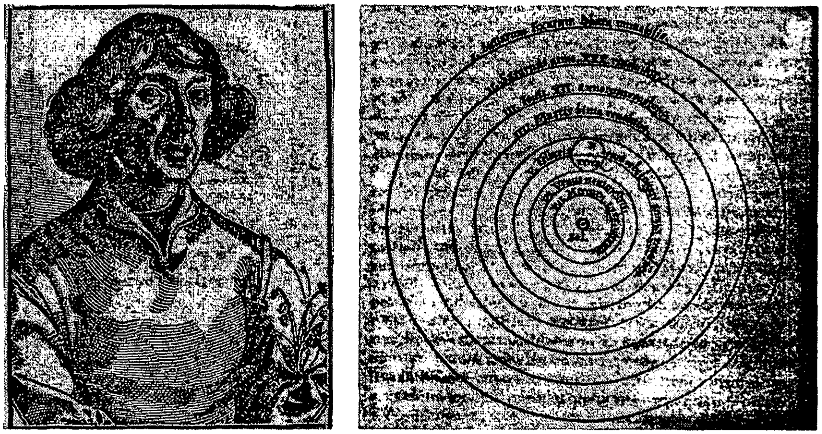


Figure 1. *Left:* Nicolaus Copernicus. *Right:* heliocentric worldview from *De Revolutionibus.* Images courtesy History of Science Collections, University of Oklahoma Libraries; copyright the Board of Regents of the University of Oklahoma.

yond doubt, Galileo's alleged uttering is most probably as much of a fiction as is the fable about the EUREKA of Archimedes.

1. Heliocentrism

Heliocentrism is the doctrine that accepts the Sun as center of the universe. Heliocentrism opposes geocentrism, which considers a motionless Earth as the absolute center of the the cosmos.

In 1543, Nicolaus Copernicus (Fig. 1) published his *De Revolutionibus Orbium Coelestium*, in which he revived a millenium-old idea[2] proposing a central Sun orbited by Mercury, Venus, the Earth–Moon system, Mars, Jupiter and Saturn. The outer region of this Sun-centered universe was populated with the so-called fixed stars. The geocentric (Aristotelian) model was unable to explain the unequal duration of the seasons, and had no simple mechanism for the observed loops in the planetary paths.[3] The heliocentric (Copernican) model, on the other hand, predicted the phenomenon of parallax: the apparent displacement of a star as measured from two points on the Earth's orbit (the so-called annual parallax), but Renaissance observational technology was insufficiently accurate to reveal any significant parallax effect. As such, being equally good in explaining the appearances of the heavens, both models had the benefit of doubt.

[2] Aristarchus of Samos ($\sim$ 300 B.C.) was the first to conceive a heliocentric worldview.

[3] Hence the introduction of epicycles and deferents for all celestial bodies except the Sun.

The heliocentric doctrine implies two aspects of motion which should, in one way or another, be observable: the annual revolution, and the diurnal rotation of the Earth.

This paper focuses on two fundamental support arguments for the annual revolution: the observed appearances of the the celestial bodies of the solar system, and the consequence of accurate eclipse timings of the first satellite of Jupiter. A subsequent paper deals with the arguments supporting the diurnal motion of the Earth, culminating with the famous demonstrations with Foucault's pendulum.

2. Visual Evidence Supporting Heliocentrism

The year 1609 witnessed a significant technological breakthrough: the invention of the *spyglass* or telescope. In early 1610, Galileo Galilei (1546–1642) used his personal telescope to look at celestial objects, and discovered several unanticipated characteristics: the huge number of fixed stars, the uneven surface of the Moon, the appearance of sunspots, and the phases of Venus. The latter observation yielded an immediate element of support for the heliocentric model, as a geocentric configuration could never produce such an aspect. The non-ideal or "defective" surfaces of the Sun and Moon, on the other hand, were a direct blow at the Aristotelian geocentric doctrine.

On 7 January 1610, Galileo noticed three little stars near Jupiter, appearing exactly on a straight line. The next day, the three stars appeared to the west of Jupiter, and they were not only closer to each other, but they were also separated by equal intervals in distance. His observational alertness was quite remarkable, as can be seen from his journal of observations. He continued observing till March 2, 1610, and then rushed his manuscript in print as the *Sidereus Nuncius*[4], in which he noted all observed configurations of Jupiter's four satellites. He concludes:

> *"We have moreover an excellent and splendid argument for taking away the scruples of those who, while tolerating with equanimity the revolution of the planets around the Sun in the Copernican system, are so disturbed by the attendance of one Moon around the Earth while the two together complete the annual orb around the Sun that they conclude that this constitution of the universe must be overthrown as impossible. For here we have only one planet revolving around another while both run through a great circle around the Sun: but our vision offers us four stars wandering around Jupiter like the Moon around the Earth while all together with Jupiter traverse a great circle around the Sun in the space of 12 years."*[5]

In other words, his discovery is a visual though indirect argument by analogy: the objection that the Earth cannot revolve around the Sun while dragging the Moon all the way along, is countered by the example of Jupiter doing the

[4]Dedicated to Cosimo II, Grand Duke of Tuscany, see frontispiece in Fig. 1.

[5]Translation by van Helden (1989).

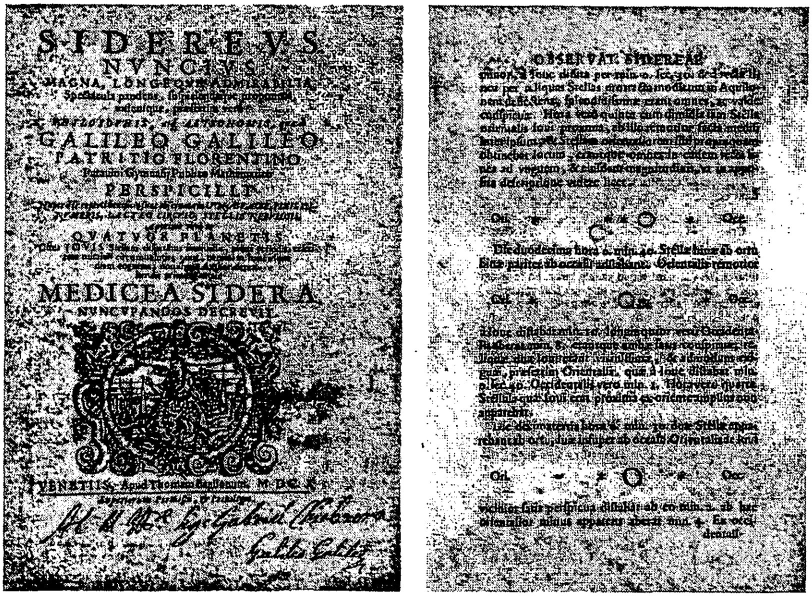


Figure 2. *Left:* Frontispiece of *Sidereus Nuncius* (1610). *Right:* sample page with three configurations of the Jovian satellites. Copy dedicated to Gabriello Chiabrera (1552–1638), an italian poet of the Medici court. Images courtesy History of Science Collections, University of Oklahoma Libraries; copyright the Board of Regents of the University of Oklahoma.

same thing with not one but with four moons of its own. Galileo also advanced Copernicanism in his *Letters on sunspots* published three years later.

Quite soon this new world view is introduced in maps and charts, see Fig. 3. But celestial maps were not the only artistic expressions of heliocentrism. One most interesting example of heliocentric-oriented artwork can be seen in the Prague palace of Albrecht von Wallenstein (1583–1634), built between 1623 and 1630. The Astrological Corridor shows allegories of the planets, featuring Jupiter and its four satellites (Fig. 4), Venus "in phase" and Saturn in its strange appearance – with appendages shrunk to little disks, as depicted in Galileo's first *Letter on sunspots* to Mark Welser in 1612 – and as it was observable during the construction of the palace.[6] Note that Ottavio Piccolomini, mentioned in the Preamble, had served under General Wallenstein and also supported the conspiracy that led to Wallenstein's deposition.[7] There may thus very well be a direct link between the new-worldview frescoes in the Wallenstein Palace and the Murillo painting created a decade later for Piccolomini.

[6]See Hadravová & Hadrava (2004) for a detailed description of the decoration of the palace.

[7]See *Wallensteins Tod*, a drama created by Johann von Schiller in 1800–1801.

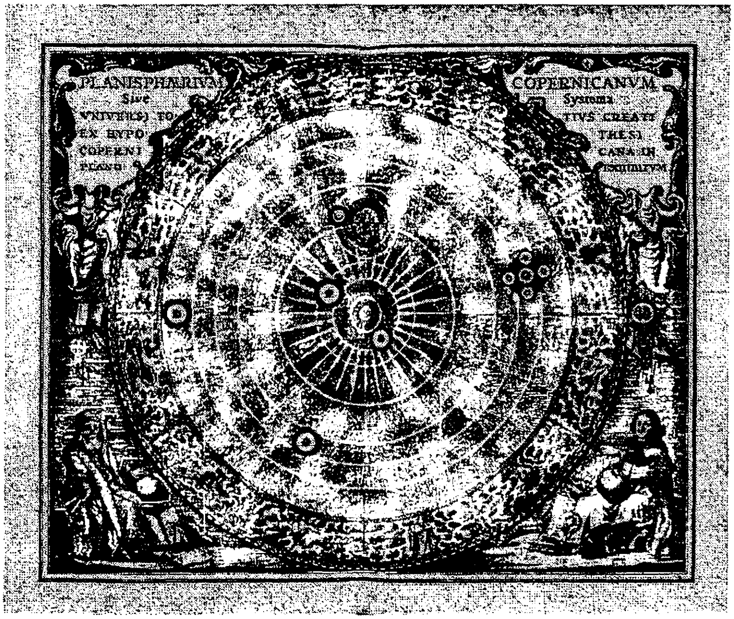


Figure 3. *Planisphaerium Copernicanum*, or the system of the entire universe according to the hypothesis of Copernicus. The man in the bottom-left corner may be Aristarchus of Samos, the person on the right undoubtedly is Copernicus. Source: Cellarius (1660) *Harmonia Macrocosmica*, with kind permission of TASCHEN GmbH (`www.taschen.com`).

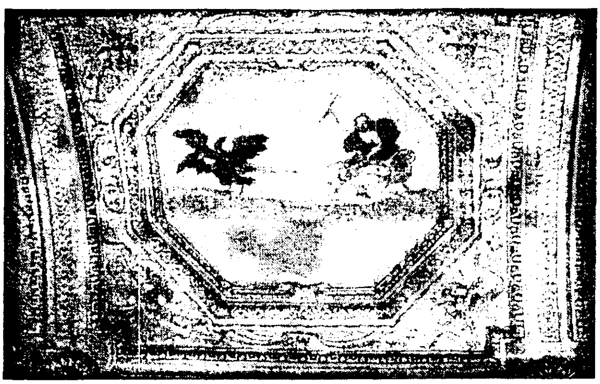


Figure 4. Fresco in the Prague Wallenstein palace illustrating Jupiter and its four satellites. Photo courtesy Petr Hadrava.

Another most interesting case, though of a later date, can be found in the baroque *Klementinum*, one of the most notable Prague historical buildings,

Figure 5. Section of a ceiling in the Czech National Library Manuscripts and Early Printed Books Department located in the Prague Klementinum, featuring numerous stars surrounded by orbiting planets and comets.

which served as an astronomical observatory since the arrival of the Jesuits in 1556. Figure 5 shows part of the ceiling of the New Mathematical Hall in the Czech National Library located in the Klementinum. The painting, by an anonymous artist, features numerous stars circled by orbiting planets – even comets in interstellar orbits, reminiscent of René Descartes' universe and Giordano Bruno's *On the Infinite Universe and Worlds* (1584). It should be noted that some heliocentric theses were generally accepted at Prague University, and that there had been established a spirit of free scientific research during the 1576–1612 period of reign of Rudolf II in Prague leading to a very tolerant attitude towards heliocentrism (see Šima 2006).

3. An Unanticipated Breakthrough

Galileo was quickly able to determine approximate orbital periods for Jupiter's satellites (see Drake 1979 for an account of Galileo's analysis in 1610–1611, and also van Helden 1996). His subsequent calculations indicated that on 18 March 1612 he should have seen a satellite, and he for the first time realised that an eclipse of a satellite of Jupiter by the shadow cone behind the planet had occurred. It was then realized that the system of satellites provided a celestial clockwork visible for many observers around the world. All one had to do was to observe the instantaneous disappearance or reappearance of a satellite, and compare the local time with the predicted local time of the same event in a place with known longitude. The time difference would then immediately yield the unknown longitude of the remote place. One severe obstacle was the lack of accurate clocks indispensable for the timing of celestial events. A breakthrough occurred on Christmas day 1656, when Christiaan Huygens (1629–1695) carried out the first successful experiment with a pendulum clock. He described his findings in 1673 in his *Horologium Oscillatorium*.

The accurate determination of longitude was not only a matter of life and death at sea,[8] but it was also of crucial importance on land: accurate longitudes meant accurate maps, a matter of the highest commercial, political and military importance. This utilitarian element was very visibly present in the establishment of learned societies in the 17th century. Figure 6 illustrates the creation of the French Académie des Sciences and the foundation of the Observatoire de Paris (under the auspices of Louis XIV) in 1667. In the same vein, the Royal Observatory at Greenwich was founded by Charles II in 1675 "in order to finding out of the longitude of places for perfecting navigation and astronomy" (Laurie & Waters 1963).

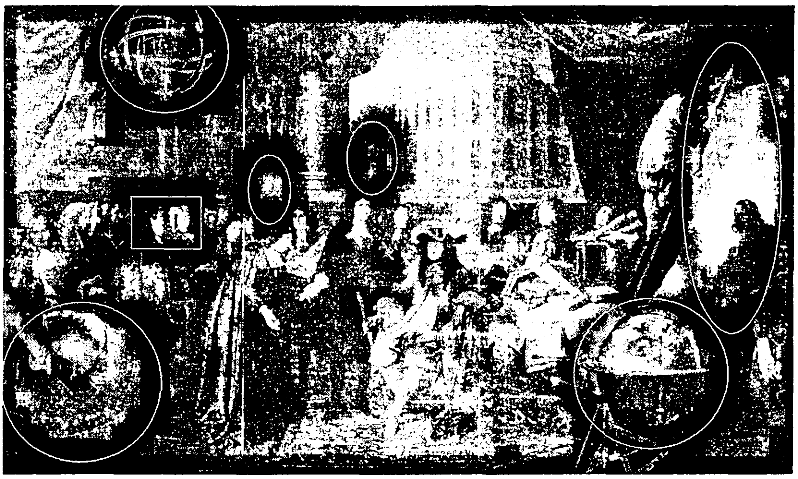


Figure 6. Establishment of the Académie des Sciences and foundation of the Observatoire de Paris by Louis XIV in 1667. The person seated at the table is Louis XIX. The ovals indicate the tools of the scientists: a terrestrial and a celestial globe, a clock, the telescope, a quadrant, and a wall map of part of France. The rectangular square in the middle indicates the Observatoire's most eminent scientists of the time: Giovani Domenico Cassini (left) and Christiaan Huygens (according to Verduin 2004). Painted by Henri Testelin (1616–1695), Musée National du Château et des Trianons, Versailles.

One of the pioneering mapmakers was the French astronomer Abbé Jean Picard (1620–1682) who worked with Giovanni Domenico Cassini (1625–1712), a professor at the University of Bologna and one of the first members of the *Académie Royale des Sciences*. In 1669 Cassini moves to Paris where he observes

[8]Sailors used to derive their positional longitude by the crude method of dead reckoning based on their measured speed in knots.

under the auspices of the *Académie*. The very first official scientific expedition ever organised was led by Jean Picard, and was an enterprise entirely dedicated to the determination of the difference of longitude between Paris and Tycho Brahe's Uraniborg Observatory on the island of Hven in the Øresund. In his *Voyage d'Uranibourg*, Picard states that

> *"Il ny a rien de plus commode & de plus précis pour la découverte des Longitudes sur terre, que les Observations du premier Satellite de Jupiter ...*"[9].

The Jovian satellites, so to speak, became a clock to read universal time – that is, Paris time.

One of Picard's able team members was the young Dane Ole Rømer (1644–1710, see Fig. 7). Their measurements of 25 October 1671 and 4 January 1672 yielded longitude differences of 42′20″ and 42′09″, respectively. The difference between those figures is only 11″, or about two kilometer. The longitude difference between both places based on modern measurements differs by two arcminutes only (of the order of 20 km). When Picard returned to Paris after the conclusion of his expedition, he was followed by Ole Rømer. Rømer had tried

Figure 7. Portrait of Ole Rømer. Courtesy Ole Henningsen, Rundetårn Museum Copenhagen.

[9]There is nothing more versatile and more precise for the determination of longitude on land, than the observations of the first satellite of Jupiter (Ouvrages de Mathematique de M. Picard, 1731, p. 95).

to measure parallaxes of fixed stars by intensive observation and by reducing observational errors through technically innovative instrumentation. As such, he intensively contributed to the solution of several technical and scientific issues, and introduced many new ideas to the instruments of his time.[10] He had a keen eye for instrumental accuracy, and he worked on the quantification of ambient temperature effects on instrumental errors. To do this properly, he even had to define a temperature scale himself, and thus laid the foundations of the Fahrenheit scale (see Cohen 1948).

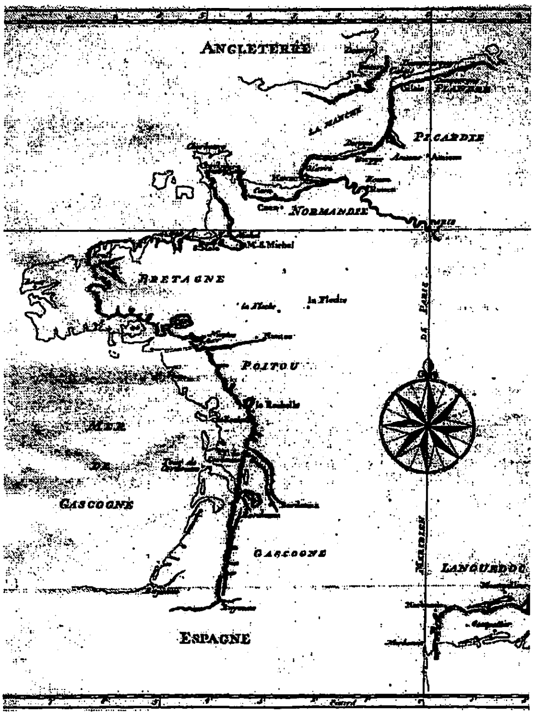


Figure 8. Part of the map of France reproduced from the *Ouvrages de Mathematique de M. Picard* (Gosse & Neaulme, La Haye 1731). The corrected coast line is the thick line. The upper right corner of the map specifies: CARTE DE FRANCE *Corrigée par Ordre du Roy sur les Observations de Mss. de l'Academie des Sciences.* Note that zero longitude is still indicated by the meridian of Paris. Source: library of the Argelander-Institut für Astronomie of Bonn University.

[10]He differed in opinion from those "accomodating instruments to the [observatory] buildings rather than the buildings to the instruments" (see See 1903).

4. Eclipse Predictions

In 1668, Giovanni Domenico Cassini published his *Ephemerides Bononienses Mediceorum Siderum*, a set of Tables predicting times of eclipse events of Jupiter's satellites (Fig. 9). The power of the method is obvious from the map of France which was corrected by the astronomers on order of the king in 1671 (Fig. 8), and legend says that Louis XIV remarked that he lost more territory to the *Académiciens* than to the English. More accurate ephemerides followed, like Flamsteed's 1684 catalogue of apparent times of ingress and immersion into the Jupiter shadow cone.

The method had its drawbacks too: not only was it impossible to handle long-focus telescopes on the deck of a rolling ship, observations on *terra firma* were severely hampered by the annually recurring observing windows which are quite narrow. Figure 10 shows the evolution of the distance from Jupiter to the Earth and to the Sun over almost one Jupiter-year.[11] The optimal observing conditions occur around the minimum times of the full curve, i.e. when Jupiter is closest to the Earth, near opposition.


EPHEMERIDES
BONONIENSES
MEDICEORVM
SYDERVM
EX HYPOTHESIBVS, ET TABVLIS
IO. DOMINICI CASSINI
AD EMINENTISSIMVM PRINCIPEM
IACOBVM
S.R.E. CARDINALEM
ROSPIGLIOSVM.
BONONIAE, M.DC.LXVIII

Nouemb. 1668.
Configurationes Mediceorum.
Hora 10. P.M.

Figure 9. *Left:* Frontispiece of *Ephemerides Bononienses Mediceorum Siderum*, dedicated to Cardinal Giulio Rospigliosi, the future Pope Clemens IX. *Right:* sample page with predicted configurations of the Jovian satellites for the second half of November 1668. Eclipses are indicated, with two satellites eclipsed on November 30 (*tertius in facie* and *Primus post* ♃). Source: The Bologna Astronomical Archives.

[11] Calculations from the day of this lecture (October 19, 2006) till the bicentenary anniversary of the foundation of the University of Ghent (October 9, 2017).

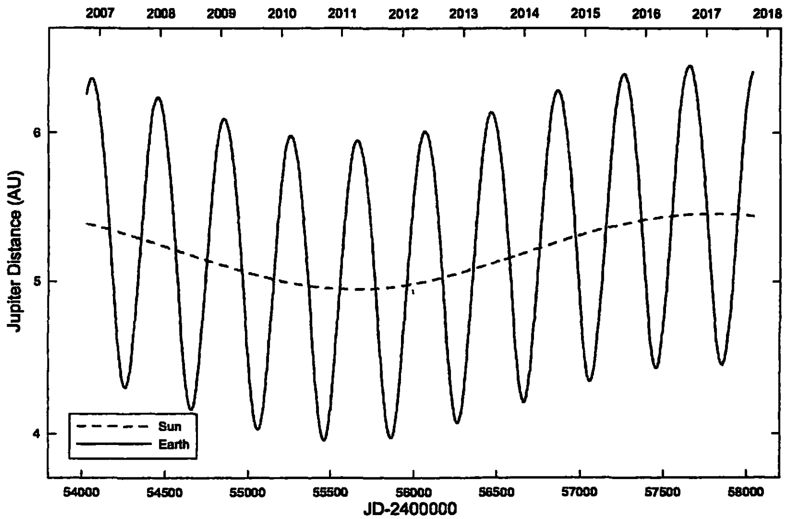


Figure 10. Evolution of the distance from Jupiter to the Earth (full line) and to the Sun (dashed line) over almost one Jupiter-year. The eccentricity of the Jupiter orbit ($e = 0.048$) causes a range in distance to the Sun of 75 million km. The distance from Jupiter to Earth varies from about 600 to far over 900 million km with a period of almost 400 days $\sim$ 13 months. The distances are given in Astronomical Units (1 AU = 149,597,870.691 km), the time units are days (lower axis) and years (top). Ephemeris calculations based on the NASA Jet Propulsion Laboratory Horizons Systems.

In a paper entitled "Eclipses of Jupiter satellites during the last months of 1676" in the *Journal des Sçavans*[12] of 31 August 1676, Cassini publishes eclipse timings

> "*...pour la détermination exacte des Longitudes des lieux oú elles seront observées ...& on verra la difference des Longitudes entre Paris et les lieux de leurs observations.*"[13]

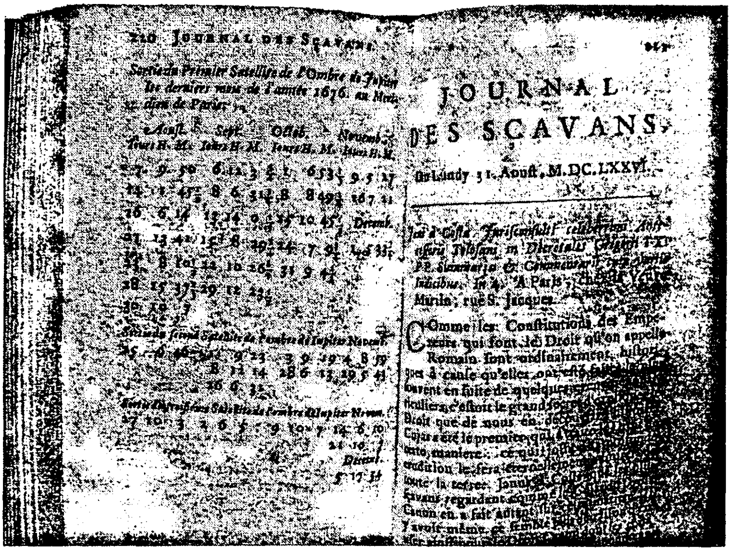
Figure 11 shows page 220 of this publication with the tabular material. Of particular interest is the prediction of an emersion on November 16 at 7 h 21 m local Paris time[14]. But in a subsequent meeting of the Académie in September 1676, Rømer announces that the November 16 emersion will be 10 minutes late:

[12]The *Journal* was founded in 1665, and published regular papers, but also reports of sessions of the Académie des Sciences.

[13]...for the exact determination of the longitudes of the places where they will be observed ...& one will see the difference of the longitudes between between Paris and their places of observation.

[14]Reckoned from the moment of sunset.

"... une émersion du premier satellite qui devoit arriver le 16 novembre suivant, arriveroit 10′ *plus tard quelle neût dû arriver par le calcul ordinaire"*[15]


JOURNAL DES SCAVANS.

JOURNAL DES SÇAVANS.

Du Lundy 31. Aoust, M.DC.LXXVI.

Figure 11. Cassini's predictions for the emersion of Jupiter's first satellite published in the *Journal des Sçavans* of August 31, 1676 (Collection Vienna University Observatory Library).

Figure 12 is a reproduction from part of a microfilm document from the Paris Observatory Archives showing Picard's handwriting:

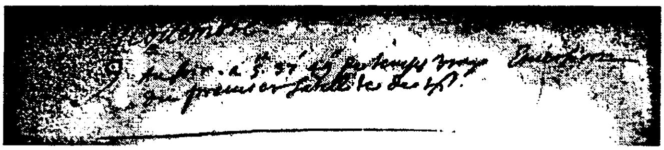


Figure 12. Picard's observing log for 1676, November 9. Source: Archives Observatoire de Paris.

"1676 Novembre. 9 Au soir. a $5^{H}37'49''$ *de temps vray Emersion du premier satellite de Jupiter."*[16]

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[15] An emersion of the first satellite which should arrive on 16 November next, will arrive 10 minutes later than it would through ordinary calculation.

[16] November 9 in the evening at $9^{H}36'49''$ real time emersion of the first satellite of Jupiter.

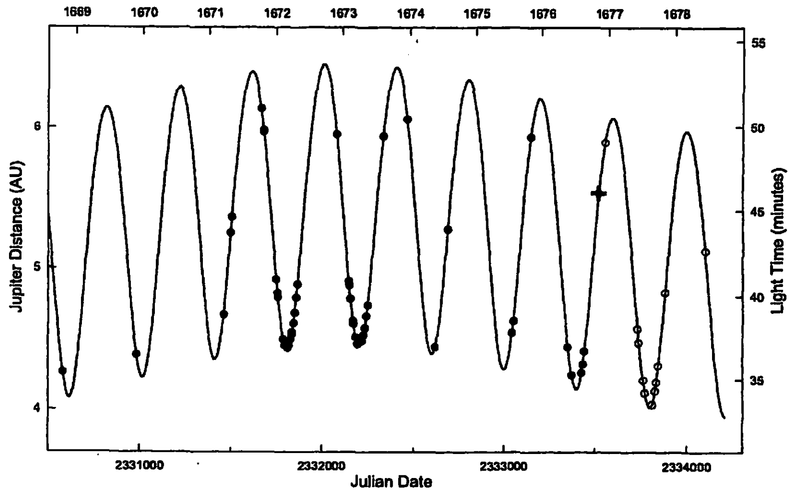

Figure 13. Distance from Jupiter to the Earth from 1668 till 1679. The • symbols represent most of the eclipse timings available to Rømer (timings listed by Cohen 1942), + refers to Picard's observation of 1676, and o indicate observations collected later. Same units as in Fig. 10. The axis on the right gives the light time in minutes. Ephemeris calculations based on the NASA Jet Propulsion Laboratory Horizons Systems.

Thus, following Picard's observation, the satellite emerges about 10 minutes later than predicted by Cassini two months earlier. How, then, did Rømer arrive at his bold prediction? Figure 13 shows the distribution of eclipse timings available to Rømer prior to his announcement in the Academy.

5. Rømer's Hypothesis

Rømer put immediately forward his explanation for the retardation of the eclipse timings: he assumes that light traveled at finite speed, a bold idea that was in contradiction with the opinions of Descartes (and Aristotle). On 22 September 1676 he presented his conclusions on the propagation of light before the Académie des Sciences, and on 7 December 1676 he publishes his paper *Demonstration touchant le mouvement de la lumière* (Fig. 14). As he describes:

> *"Et parce qu'en 42 heures & demy, que le Satellite employe à peu prés à faire chaque revolution, la distance entre la Terre & Jupiter dans l'un & l'autre Quadrature varie tout au moins de 210 diametres de la Terre, il s'ensuit que si pour la valeur de chaque diametre de la Terre, il faloit une seconde de temps, la lumiere employeroit $3\frac{1}{2}$ min. pour chacun des intervalles GF, KL, ce qui causeroit une difference de prés d'un demy quart d'heure entre deux revolutions du premier Satellite, dont l'une auroit esté observée en FG, & l'autre en KL, au lieu qu'on n'y remarque aucune difference sensible."*

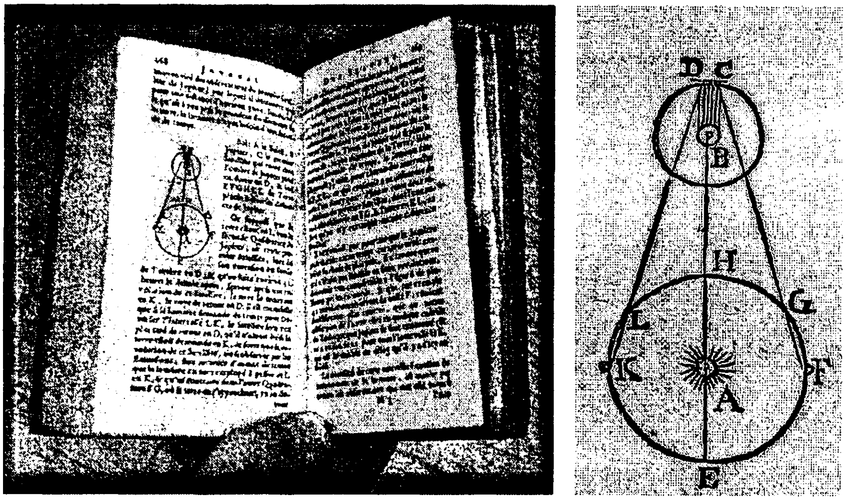

Figure 14. *Left:* Rømer's paper in the *Journal des Sçavans* of 7 December 1676. *Right:* detailed view of Rømer's explanatory diagram. Source: Vienna University Observatory Library.

Rømer knew that during one orbital period of the satellite (~ 42.5 hours) the Earth–Jupiter distance changes by at least 210 Earth diameters, and he thus conjectures: *if for the account of every diameter of the Earth there were required a second of time,*[17] *the light would take* $3\frac{1}{2}$ *minutes for each of the intervals GF, KL, which would cause a difference of nearly 'a half quarter of an hour' between subsequent revolutions of the first satellite at both quadratures. Differentiating between the observations at quadrature, a difference of 7 minutes was never measured and hence light needed less than one second to traverse one Earth diameter.* The intervals between successive eclipses are very uniform near opposition (point E in the diagram of Fig. 14 corresponding to the minima of the curve in Fig. 13), because the distance Jupiter–Earth is fairly constant during this phase. Most of the discrepancy occurs during the times when the distance between Jupiter and the Earth is changing most rapidly, which is when the Earth–Sun axis is nearly perpendicular to the Jupiter–Sun axis (F, halfway the oscillation and shortly before Picard's observation of 1676). At position F, the Earth is moving almost directly toward Jupiter, and at K it is moving almost directly away from Jupiter: at quadratures the change in distance Earth–Jupiter is almost entirely due to the Earth's orbital motion. Rømer estimated that light takes about 22 minutes to cross the Earth's orbit, an estimate that was subsequently corrected by Edmund Halley (1656–1742) to 8.5 minutes for the average distance Earth–Sun.[18] Rømer labeled his hypothesis *doctrina de Mora Luminis*, widely known now as the light-time effect in astronomy. The right-hand axis in Fig. 13 indicates light time in minutes.

[17] In fact, only 4% of the speed of light.

[18] See Débarbat (1978).

6. Cassini's Objection

But the observations collected in Paris revealed that only the calculated predictions for the *first* Iovian satellite Io could be adequately used: the question simply was why do the three other Galilean satellites not show the same time inequality that Rømer noticed for the first? Cassini thus accepted the time retardation as a principle, but could not agree with the numerical value since different satellites presented different results. The reason for the discrepancies lies in the fact that the motions of the three other satellites are affected by complicated mutual perturbations, see an aspect of this effect in Fig. 15

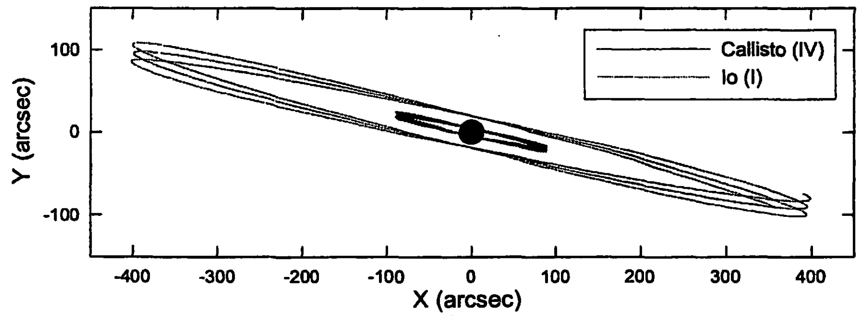

Figure 15. Orbits of satellites Io and Callisto over several days in October 2006. Note that Callisto does not even undergo eclipses at that moment as the planet's angular diameter is near its minimum, though eclipses occur when Jupiter nears opposition (angular diameter near 50″). Axis units are arcseconds. Ephemeris calculations based on the NASA Jet Propulsion Laboratory Horizons Systems.

7. Rømer's Career

In 1681, summoned by Christian V, King of Denmark, Rømer became Royal Mathematician and Professor of Astronomy at the University of Copenhagen. From 1688 on, Rømer took many important administrative functions, such as waterworks engineer, chief tax assessor, chief of police, mayor of Copenhagen, senator and head of the State Council. Most unfortunately, almost none of Rømer's publications and data have survived, as all of the University of Copenhagen's Library books and archives were destroyed during the great fire of 20 October 1728 that destroyed most of the center of Copenhagen.

8. The Velocity of Light

Though many textbooks state that Rømer was the first to measure the velocity of light (see also Fig. 16), he did not explicitly give its value in distance units per second: his major conclusion was a purely qualitative one, i.e. that the speed of light is finite. But this conclusion was also conditional: the speed of light is

Figure 16. Olaus Rømer plaque at Paris Observatory.

finite *if and only if* the deductive reasoning is done in a heliocentric world.[19] In other words: *a geocentric model cannot support a finite velocity of light, nor can it explain the light-time effect.* Already Galileo was convinced of the finite character of the propagation of light, as expressed by Sagredo:[20]

> *"But of what kind and how great must we consider this speed of light to be? Is it instantaneous or momentary or does it like other motions require time? Can we not decide this by experiment?"*

But textbook inadequacies are not the only sources of erroneous information. Wróblewski (1985) points out that Rømer's work on the velocity of light has also been incorrectly described in many physics texts and books dealing with the history of science. Figure 17 illustrates the extent of this misinformation: though Rømer never gave any numerical value for the speed of light, dozens of authors quote a numerical value as his result. Amazingly, the outcome is bimodal: about half of the values hover around 220,000 km s^{-1}, the remaining ones are in the range 300,000–350,000 km s^{-1}. It should be understood that the velocity of light calculation is extremely sensitive to the value used for the Astronomical Unit, a quantity that was quite poorly known in Rømer's times. Hence the substantial number of underestimations. Values above the dashed line are physically unfounded and are simply the consequence of miscalculation or gross sloppyness. Or, as Koyré (1943) put it:

> *"... la traduction des oeuvres scientifiques appartenant à une époque autre que la nôtre comporte un risque supplémentaire, et assez grave: celui de substituer, involontairement, nos conceptions et nos habitudes de pensée à celles, toutes différentes, de l'auteur."*[21]

[19] Not only the geometric picture, but also because the tabulated eclipse times embed a correction for the so-called *prostaphaeresis*, the angle between Earth and Sun as seen from Jupiter.

[20] *Discorsi e dimostrazioni matematiche intorno à due nuove scienze*, 1638 translated by Henry Crew and Alfonso de Salvio.

[21] The involuntary substitution of *our* concepts and *our* habits of thought for those, completely different, of the author.

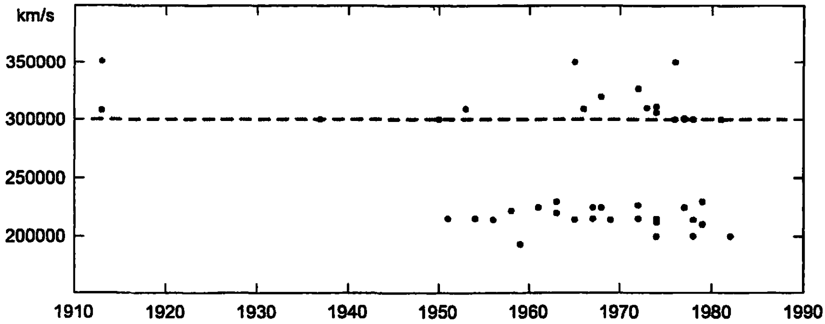

Figure 17. Numerical value for the speed of light quoted in history of science and physics texts and books as "derived by Rømer".

9. Conclusion

The story of Rømer's unexpected discovery is a textbook example of proper analysis of observational data: optimising observational precision in combination with increasingly accurate computational Tables, the procedure leads to the unexpected discovery of a fundamental physical concept. And as Montucla (1758) points out, long time-baseline and careful observations are a most necessary condition:

> *"Des observations continuées long-temps et avec soin, ont ordinairement l'avantage de faire apercevoir des phénomènes dont on n'avoit encore aucun soupçon; souvent même il arrive que ces observations conduisent à une découverte plus intéressante que celle dont on cherchoit à s'assurer par leur moyen.*[22]

Acknowledgments. I thank the Sarton Comité of the Universiteit Gent for bestowing upon me the Sarton Chair in the History of Science for the academic year 2006–2007.

I am indebted to Dr. Suzanne Débarbat for her help and advice in the consultation of the Archives of Paris Observatory, and to Dr. H. W. Duerbeck for help in retrieving archived documents. My work is supported by the Research Foundation Flanders (FWO).

[22] Observations over *long time intervals carried out with care*, normally have the advantage to make appear totally unexpected phenomena; it even occurs that these observations lead to a discovery that is more interesting than the one for which the observations were made for.

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