Shuckburgh, "Description", 102. From a comparison of observations made with Ramsden's "Palermo" and "Armagh" circles, John Pond calculated that these instruments showed an error of about 1″; see, J. Pond, "... Description of an astronomical circle", *Philosophical transactions*, xcvi (1806), 420–54, pp. 421–2.

Edward Troughton. Pond, "Description", claimed that by cancelling out errors with opposite microscopes, the errors of his "Westbury Circle" could be reduced to 0″·25. Edward Troughton's Greenwich Circle of 1812 carried six microscopes capable of measuring down to 0″·1; see Derek Howse, *Greenwich Observatory*, iii (London, 1975), 27.

William Simms. The Great Transit Circle built for the Greenwich Observatory in 1850 could read to 0″·06, by means of six cross-checking microscopes capable of isolating scale errors; see Howse, *Greenwich Observatory*, iii, 44. The consistency of the transit's errors is indicated in G. B. Airy's *Astronomical Observations at the Royal Observatory, 1852* (London, 1854), Appendix II, 17–19.

Some years ago, an angular accuracy graph was compiled by H. Mineur, and included in H. T. Pledge, *Science since 1500* (London, 1939), 291. Mineur did not cite his sources, although he named the astronomers who attained the specific peaks in his graph. Because it is likely that Mineur and myself used the same sources for the overlapping parts of our respective graphs, there is a close similarity between them. It must be stressed, however, that the graph in this paper is drawn quite independently of Mineur's, and from the sources cited herein.

REFERENCES

1. Allan Chapman, *Dividing the circle* (Amersham, in press).
2. Of course, no one is claiming that Newton's work on the lunar theory was initiated by Flamsteed, although the important point remains that Newton required reliable observational 'fixes' if his theory was to be taken seriously as a true representation of nature. In 1690, the only instrument in Europe capable of providing such fixes to the requisite degree of accuracy, moreover, was the mural arc in the Royal Observatory.
3. Many references to the work of Gascoigne are extant; see Chapman, *Dividing the circle*. For primary sources, see William Derham, "Extracts from Mr Gascoigne's and Mr Crabtree's letters, proving Mr Gascoigne to have been the inventor of the telescopick sights of mathematical instruments, and not the French", *Philosophical transactions*, xxx (1717), 603–10.
4. Robert Hooke, *Some animadversions on the first part of Hevelius, his 'Machina Coelestis'* (London, 1674), 7.

JHA, xiv (1983)

NOTES

ROEMER'S SPEED OF LIGHT

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The first determination of the speed of light is a celebrated chapter in the history of science; it is also one that has been misinterpreted frequently. It is the aim of this note to eliminate some of the confusion.

During the early part of his career as an astronomer, before coming to Paris in 1669, Giovanni Domenico Cassini (1625–1712) spent considerable effort on an investigation of the motions of the satellites of Jupiter. This work culminated in his *Ephemerides Bononienses Mediceorum siderum* (Bologna, 1668), the first reasonably accurate tables of the motions of the satellites. These tables would make Roemer's discovery about the speed of light possible. In Paris Cassini and his staff continued observing Jupiter's satellites, and in 1693 he was able to publish even more accurate tables. One member of the staff of the Royal Observatory making these observations was Ole Roemer (1644–1710), brought back from Denmark by Jean Picard in 1671.

In 1675 Cassini found an inequality in the motion of Jupiter's innermost moon (now called Io) which was strongly correlated with the distance between Jupiter and the Earth. Cassini initially hypothesized that this inequality was due to a finite speed of light, but he then rejected this notion.[1] Roemer adopted Cassini's stepchild, and predicted in September 1676 that the eclipse of Io that was to occur on 9 November of that year would take place 10 minutes later than the time that would be predicted if the "equation of light" was ignored. His paper delivered to the Académie royale des Sciences on 22 November was summarized in the issue of 7 December 1676 of the *Journal des Sçavans*, and a translation of this summary was printed in the *Philosophical transactions* of 25 June 1677 (O.S.).[2] In this manner Roemer's hypothesis came to the attention of the learned world at large.

Roemer concluded that light takes 22 minutes to traverse the Earth's annual orbit. The importance of this conclusion, attacked by Cassini but supported by Christiaan Huygens,[3] was that it demonstrated that light is not instantaneously propagated, as both Aristotle and René Descartes had maintained. The exact numbers of Roemer's demonstration were of little importance. Now, however, three centuries later, when the finite speed of light has become an accepted fact in science, Roemer's contribution is seen not as a demonstration of the finite speed of propagation, but rather as the first measurement of this finite speed. The numbers have, therefore become important, and here the troubles begin.

Although there are numerous instances of ahistorical interpretations of Roemer's result, I shall deal only with one recent example, Zdeněk Kopal's biography of Roemer in the *Dictionary of scientific biography*. Kopal writes:[4]

> [Roemer] was . . . able to report to the Academy that the speed of light was such as to take twenty-two minutes for light to cross the full diameter of the annual orbit of the Earth; in other terms, that the light from the Sun would reach Earth in eleven minutes (a time interval now measured to be about eight minutes and twenty seconds). The speed of light was thus established scientifically for the first time, with a value of about 140,000 miles per second—a reasonable first approximation to the currently accepted value of 186,282 miles per second.

Besides the complete absence of any appreciation of the fact that in Roemer's day the importance of his demonstration lay in the speed of propagation being finite, we also note that Kopal divided the *modern distance* to the Sun by *Roemer's time*:

$$\frac{93{,}000{,}000 \text{ miles}}{11 \times 60 \text{ sec.}} = 140{,}909 \text{ miles/sec.}$$

Kopal could have concluded, quite correctly, that Roemer's 11 minutes was "a reasonable first approximation to the currently accepted value" of about 8 min. 20 sec. Before he could draw the same conclusion about the speed of light measured by Roemer, however, he needed to know Roemer's solar distance.

In a recent article on this subject, S. Débarbat has drawn our attention to a more justified calculation made by Bernard le Bovier de Fontenelle, Perpetual

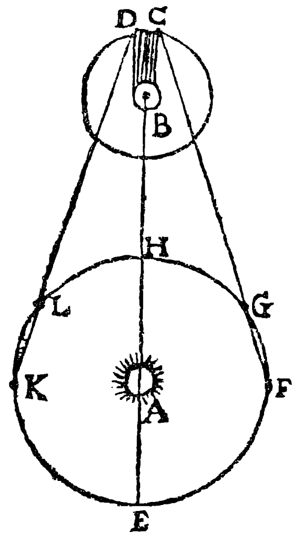

FIG. 1.

Secretary of the Académie royale des Sciences in his *Histoire de l'Académie* published in 1733. Fontenelle used a solar distance of about 22,000 Earth radii (corresponding to a solar parallax of 9″·5), determined by Cassini as a result of the observations of Mars in France and Cayenne in 1672, and a radius of the Earth of 1500 *lieus*, or leagues and he calculated that Roemer had measured the speed of light to be 48,203 leagues per second. Débarbat converts this to modern measures by using the figure of 2282 *toises* (fathoms) per league published by Cassini's son Jacques (1677–1756) in 1718, and a length of 1·95 m for the *toise* used at the Paris Observatory. She concludes that Roemer's speed of light was about 215,000 km/sec., or about 134,000 miles per second, not very far from Kopal's value.[5]

Fontenelle and Débarbat assumed that Roemer, who had participated in the parallax measurements in 1672, agreed with Cassini's conclusion, a solar parallax of 9″·5, conveniently close to the modern value. This assumption is, however, unwarranted. Cassini did not publish his value for the Sun's parallax until 1684.[6] In 1673 John Flamsteed had, however, published his solar parallax of 10″, corresponding to a distance of about 21,000 Earth radii,[7] and Cassini had replied that his own result agreed closely with Flamsteed's.[8] It is thus not unreasonable to assume that Roemer knew that Cassini took the Sun's parallax to be 9″·5, corresponding to a distance of about 22,000 Earth radii. But did he agree with Cassini and Flamsteed on this score? He did not, and the evidence can be found right in his paper in the *Journal des Sçavans*.

The configuration of Jupiter at its quadratures was shown by Roemer in Figure 1, where A is the Sun, B Jupiter, C Io, and $EFGHLK$ the orbit of the Earth. At the quadratures, when the Earth is at G or L, the change in distance between the Earth and Jupiter is due virtually entirely to the Earth's motion alone. Roemer argued that since Io's period is about $42\frac{1}{2}$ hours, and since in that time-period the distance between Jupiter and the Earth changed by at least 210 Earth diameters at the quadratures, if light took one second to travel one Earth diameter then at one quadrature Io's period would be measured $3\frac{1}{2}$

minutes longer and at the other quadrature 3½ minutes shorter than it is in reality. Such a systematic difference from one quadrature to the next—a total of 7 minutes—had never been measured, and therefore it took light much less than a second to travel one Earth diameter.[9]

But how did Roemer know that in 42½ hours the Earth travelled "at least 210 Diameters of the Earth"? Obviously he had calculated it from a solar distance, and we can reverse the calculation. If the Earth travels at least 210 terrestrial diameters in 42½ hours, it must travel

$$\frac{210}{42\frac{1}{2}} \times 24 \times 365\tfrac{1}{4}$$

or 43,314 terrestrial diameters in a year, and this is the circumference of its orbit. From this it follows that the radius of the orbit, the solar distance, is at least $43{,}314/2\pi$, or 6894 terrestrial diameters, or, more conveniently, 13,787 terrestrial radii. The angle subtended by the Earth's radius as measured from the Sun, the horizontal solar parallax, was therefore at most $\sin^{-1} 1/13{,}787 = 14''{\cdot}96$, according to Roemer. Obviously he had started from the assumption that the Sun's parallax was at most 15″. This was an earlier value held by Jeremiah Horrocks, Gottfried Wendelin, and Thomas Streete.[10] Roemer, who had participated in the measurements that led to Cassini's solar parallax of 9″·5, apparently did not think much of the measurements or Cassini's conclusion.

In the same article the diameter of the Earth was given as about 3000 *lieus* (that is, 26·2 *lieus* per degree), surely meant to be only a very approximate figure. When Roemer wrote the article, the best information on lengths was in Picard's *Mesure de la Terre* of 1671. Picard gave the length of a *lieu* of which there were 25 in one degree as about 2282 *toises*, or $2282 \times 6 = 13{,}692$ Paris feet, and he gave the ratio of the Paris foot to the London foot as 1440:1350.[11] From this it follows that if Roemer used this value he made the length of a *lieu*

$$\frac{13{,}692 \times 1440 \times 360}{1350 \times 5280} = 2{\cdot}77 \text{ English miles.}$$

Therefore the diameter of the Earth was, very roughly, $3000 \times 2{\cdot}77$ miles, or about 8300 miles. Picard's more accurate direct measurement of 57,060 *toises* per degree[12] leads to a diameter of about 7900 miles. With Roemer's solar distance of at least 13,787 Earth radii, the first figure yields a solar distance of at least 57,000,000 miles and the second at least 55,000,000 miles. Since Roemer claimed that it took light 22 minutes to traverse the diameter of the Earth's orbit, we can say that in his own terms this meant that he had measured the speed of light to be *at least* about 85,000 miles per second, or about 135,000 km/sec.

REFERENCES

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2. "Demonstration tovchant le mouvement de la lumière trouvé par M. Römer de l'Académie royale des Sciences", *Journal des Sçavans*, 7 December 1676, 233–6 (reprinted in Cohen, *op. cit.*, 373–6, and Taton, *op. cit.*, 151–4). "A Demonstration concerning the Motion of *Light*, communicated from *Paris*, in the *Journal des Sçavans*, and here made English", *Philosophical transactions*, xii (1677), 893–4 (reprinted in Cohen, *op. cit.*, 377–8).
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