Over 200 years passed between the first announcement that light travels at a finite velocity and the publishing of Einstein's special theory of relativity, which entrenched this speed as a fundamental constant of the physical laws that govern our universe. This paper will focus on specific scientists and their efforts to determine the speed of light during this time period. The investigations of the contributing figures will revolve around describing their experiments, evaluating the relative accuracy of their methods, and their determinations' respective physical or astronomical significances. In general the paper will follow the trend of increased accuracy in speed of light determinations; however, the physical and astronomical significance of each experiment is not so progressively ordered.

Increasingly more accurate astronomical values of the speed of light pushed astronomical precision to new heights. Corrections to the speed of light improved planetary and stellar tables, providing astronomers with the ability to investigate phenomena which had previously been difficult to isolate because of the conflation of effects. The advent of terrestrial determinations of the speed of light allowed astronomers to improve accuracy of different constants while still offering similar potential to confirm or negate theory.

Perhaps with the sole exclusion of length, all measurement is theory mediated, and as such, we must look to science to supply a robust theoretical basis from which we can convert observations into measurements. Scientific theory provides a framework within which we can interpret data and by which we may achieve indirect measures. More direct measures of the same quantity provide an opportunity to evaluate the assumptions present in prior measurements. In turn the determined quantities stemming from these more or less theory mediated measurements may predict new theory or falsify previous constructs.

This paper will investigate the contributions of scientists who determined the speed of light in both astronomical and terrestrial units. The issue of theory mediation will be assessed in divergent historical and experimental contexts, as will be the implications for physics of these determinations. Nevertheless, a special focus will be paid to the interaction between theory and measurement in an attempt to indentify the errors in these determinations.

The early history of the speed of light was relegated to more metaphysical discussions, although we shall see that even here theory and experiment played an integral role. The debate between proponents of light's instantaneous transit and finite transmission would eventually find itself amenable to scientific testing. As such this uncertainty surrounding light's propagation would reform itself into a problem of measurement, well suited for the realm of experimental physics according to the suggestions of Galileo Galilee and René Descartes. Although neither could claim success in settling the philosophical question regarding light's nature, the scientific inquiry which their experimental suggestions inspired would set in motion centuries of work confirming and correcting the finite speed of light.

This process would begin in the late 1670s when Ole Rømer introduced the first observational evidence for the finite speed of light, as well as the first astronomical determination of its velocity. While his work was neither conclusive proof that light was transmitted at a finite velocity, nor a particularly accurate estimation of this hypothetical velocity, it adequately described a theory that could then be independently confirmed by subsequent experimentation. This confirmation and correction would come at the end of the 1720s as James Bradley proposed his theory of the aberration of light. Bradley's theory would set a high bar for astronomical accuracy while at the same time creating additional ties between the speed of light and astronomy and physics. From here the thesis will move on to cover the work of Hippolyte Fizeau and Leon Foucault and their respective terrestrial determinations of the speed of light as well as their famous work "dispelling" the corpuscular theory of light. Building off of Galileo's overly simplistic suggestion, the Frenchmen would make the first direct measures of the speed of light. This shift to terrestrial determinations would allow for the much needed corrections of less accurate astronomical constants and while at the same time freeing astronomers to search for evidence of discordances between physical theory and observation. Soon after, James Clerk Maxwell's new equations of electromagnetism would utilize experiments in electromagnetism and his contemporaries' more accurate terrestrial determinations of the speed of light to assert that light is simply a kind of electromagnetic wave. The late 1870s and early 1880s would see yet another massive leap forward in the determined accuracy of the speed of light following the completion of Albert A. Michelson and Simon Newcomb's rotating mirror experiments. By the use of these more accurate measures of the speed of light, Newcomb would set about standardizing the related astronomical constants, a task which would facilitate his creation of the most accurate orbital tables yet devised.

Before scientists argued about the measure of the speed of light, however, the argument was much more base and metaphysical: does light traverse distances instantaneously or over time? Outside of Empedocles of Acragas, it seems much of the ancient Greek world was convinced that light's velocity was infinite. Aristotle sharply rebuked Empedocles and his supporters for their controversial views, insisting light traveled instantaneously. Even so, this question of whether light was transmitted instantaneously or over time was not of primary importance to the Greeks, who were still unable to decide whether light and vision emanate from the eye of the observer or from the object under observation. This secondary quandary provides an interesting opportunity to begin assessing the most basic effects of theory mediation. Heron of Alexandria provided a proof of the instantaneous transmission of light based on the theory that vision emanated from the eye. If we subscribe to this theory of vision, when we face up towards the night sky with our eyes closed, then upon opening them there should be a noticeable delay in our perception of the stars due to the time it would take our vision to reach such distant objects. Thus lacking any evidence of such a delay, Heron was obligated to conclude that the speed of light is infinite. Heron's theory of vision allowed him to provide evidence for the instantaneous transmission of light. While this is certainly an extreme example, it does emphasize the reliance on theory to make even qualitative assessments of physical properties.

While the major Islamic scholars of the medieval age were proponents of the view that light was propagated over time and not at an instant, many of the most celebrated Western natural philosophers who came after them reverted back to the idea that the speed of light was infinite. During this pre-Newtonian time period, optically inclined figures such as Johann Kepler would lean on his own metaphysics to support his hypothesis that light travelled instantaneously. Beginning with the assumption that light was immaterial, Kepler followed Aristotelian lines, insisting that that which could not experience resistance to motion would necessarily travel at an infinite velocity.

Galileo Galilei

During this same time period, the first experiments which were not steeped in metaphysics (or woefully misguided ideas about vision) would be suggested. Undoubtedly the most famous of these remains Galileo's lantern experiment suggested in his book *Two New Sciences*, a refreshing departure not only from the prevailing views of the time, but also Galileo's own metaphysical explanation (based on his belief in an ultimate indivisible subsection of matter) for the infinite speed of light in *The Assayer*.[1] In *Two New Sciences*, the character Salviati suggests an experiment whereby,

> "…two men each take one light, inside a dark lantern or other covering, which each could conceal and reveal by interposing his hand, directing this toward the vision of the other. Facing each other at a distance of a few braccia, they could practice revealing and concealing the light from each other's view, so that when either man saw a light from the other, he would at once uncover his own."[2]

After this proposed trial phase, Salviati proposed that the men could run this experiment at distances in excess of eight or ten miles at night, possibly with the aid of a telescope to identify the light. If a notable delay was perceived by an experimenter between uncovering his own lantern observing the light from the other experimenter's lantern, one could surmise that this was due to light's time of travel between the experimenters, and thus that its speed is finite. Even this simple experiment would require secure optical theories to account for the use of telescopes. Ignoring this, the experiment would only be practical if the time of transmission of light between the experimenters was sufficiently large so that the experimenters could identify a delay. Drawing the conclusion that light possesses an infinite velocity from this experiment necessitates a prior theory limiting the possible velocity of light such that it was amenable to the experimental set up. The experiment was eventually performed by the Florentine Academy at a distance of one mile, although at such a short distance no sensible delay was observed, and further no reliable conclusion could be drawn regarding the finite or infinite nature of light's transmission.

René Descartes

Slightly later during this same era we encounter the work of Descartes, a man whose influence in optics was so profound that his characterization that his theories on light would affect the dismissal of the corpuscular theory of light two centuries after his death. Descartes commitment to the instantaneous transmission of light would contribute to the divided reception of the first evidence that light has a finite speed, observed and presented to the *Academie Royale des Sciences* by this paper's first major figure Ole Rømer. Descartes' loyalty to the instantaneous transmission of light hinges upon its incorporation into his metaphysical doctrine. To Descartes light was merely a pressure caused by the motion of incandescent bodies within his so-called "subtle matter." This "subtle matter" permeated all other matter and was itself incompressible. Thus the implication of such a pressure build-up within incompressible matter implied light would propagate instantly across any distance.[3]

Nevertheless, Descartes' reasoning was not all based on a vain attempt to preserve his metaphysics. Outside of the analogies, such as his comparison of light to sound, that Descartes provided in *Dioptrique* and *Le Monde*, he related an account of a syzygy involving the moon, earth and sun, aligned in this order. This account illustrated that if the speed of light were indeed finite and if it took around one hour to travel from the Earth to the moon, observers on Earth would be able to detect a very obvious two hour delay between the point of collinearity and the total lunar eclipse. With observations of such events contradicting this hypothetical, observers noted the full lunar eclipse at approximately the same time as the collinearity, and Descartes took his example as proof of the infinite velocity of light. This example is damning evidence against anything other than an exceptionally quick speed of light; it shows that any theory incorporating a "slow" speed of light would contradict prior observations. Christiaan Huygens would later calculate that if the light time from the Earth to the moon was ten seconds or less, no such delay in the lunar eclipse would be sensible by an Earth-bound observer. Despite the problems with Descartes' example, the Cartesian cosmology, of which the infinite speed of light was an integral part, remained popular, especially on the continent. Thus the obstinacy which Rømer would encounter in 1676 should come as no surprise. In a letter to Beeckman, Descartes regarded the instantaneous velocity of light as "so certain that if, by some impossibility, it were found guilty of being erroneous, I should be ready to acknowledge to you immediately that I know nothing in philosophy."[4]

Ole Rømer

Ole Rømer was born in 1644 in Aarhus Denmark, beginning his studies at the University of Copenhagen in 1662 under the tutelage of Rasmus Bartholin. It would be Bartholin's work preparing the observations of Tycho Brahe for publication that would provide the opportunity for Rømer to establish himself in the scientific community of late 17^{th} century Europe. To understand why this concurrence of events afforded such a crucial opportunity to the young Dane, the scientific atmosphere of the late 17^{th} century must be considered. Among the first tasks of the newly founded, Paris based *Academie*

Royale des Sciences was the creation of more accurate maps. Determinations of longitude had been made possible by two earlier 17th century discoveries, the pendulum clock invented by Huygens in 1657 and the discovery of the satellites of Jupiter by Galileo in 1610. Noting their regularity, Galileo recommended that their motion be exploited to describe a natural clock. The eclipses of the satellites of Jupiter provide a regular astronomical phenomenon which can be simultaneously observed in both a place of known and one of unknown longitude from which the difference in local times can be judged. Knowing the difference in local times allows the observer to determine the difference in longitude by appealing to the Earth's rate of rotation per day. Cassini's first tables of these satellites published in 1668 set reasonably accurate rules regarding the frequency of the eclipses of the four known satellites, thus removing the final barrier to applying the above mentioned method of simultaneous observation to the determination of unknown longitudes. Practical matters aside, astronomers on the continent soon realized that this new method also provided a method to make more precise corrections for the errors inherent in observations made at different longitudes.

Unsurprisingly, longitudinal corrections to the expansive observations of Tycho Brahe, mostly undertaken at his observatory at Uraniborg on the then-Danish island of Hven, became a priority at the *Academie*. In July of 1671 Picard was officially dispatched from Paris to complete the necessary observations.[5] In late August that same year Picard would arrive in Copenhagen to confer with Bartholin, at the same time meeting Rømer, who by this time had taken up editing Tycho's manuscript. By September Picard, Bartholin and Rømer had made their way to Uraniborg to record observations of the eclipses of the satellites of Jupiter (which were at the same time being observed by

Cassini in Paris). Impressed with Rømer's talents, Picard brought him back to Paris along with their observations and an original manuscript of Tycho's observations, later noting the value of his return company to French science.[6]

After moving into his accommodations in the newly constructed observatory in Paris, Rømer made numerous astronomical observations in Paris and across France both independently and in his role as an assistant to Picard and Cassini. Additionally, Rømer established a reputation as a man of great mechanical genius, creating planispheres, better micrometers (which were almost immediately adopted) and deriving the most efficient shape for gears.[7] His mechanical skill notwithstanding, Rømer's name is not included in this investigation for his inventions, but for being the first to determine a value for the speed of light.

It may be of interest to readers that there is some controversy over who first suggested a speed of light correction to account for the noted second inequality in the satellites of Jupiter. Du Hamel attributes the initial announcement of this explanation of the second inequality to an August 1676 announcement of Cassini's wherein he describes a 10 to 11 minute transit time for light to pass from the Sun to Earth.[8] A 1707 *Academie* history agrees on Cassini's priority while disputing the date, suggesting "M. Cassini proposed this idea in a writing published in August 1674"[9] The strangely early date here is likely due to the author's misreading of Du Hamel. Yet another source, an early 1700s manuscript collation, also dates Cassini's pronouncement on August 22nd 1676, just months before Rømer's address.[10] Regardless, Cassini's dedication to this idea was far from resolute. It would be strange to attribute such a discovery to a man who would soon become its most outspoken opponent. Perhaps the idea did originate with Cassini, only to be passed on to his assistant Rømer, but Cassini's total abandonment of this concept strips him of any recognition on its account.

Accordingly our concern shifts to September 1676 and Ole Rømer's prediction that the November 9th eclipse of the first satellite of Jupiter would be 10 minutes late. Following the confirmation of this delay by the *Observatoire Royal*, Rømer presented a paper to the *Academie* on November 21st outlining his new equation accounting for this delay in terms of the speed of light. In his paper Rømer described the systematic variation in the first Jovian satellite's period of revolution, wherein observations of immersions (recorded as the Earth was approaching Jupiter) gave shorter periods of revolution than observations of emersions (recorded as the Earth withdrew from Jupiter). The occasions for recording immersions and emersions are naturally limited by the Earth's positioning relative to Jupiter. As the Earth approaches Jupiter our view is such that the shadow cast by the Sun shining on Jupiter is displaced in its wake, meaning that satellites appear to be consumed by this blackness before they pass behind the planet. Similarly, as the Earth recedes from Jupiter, its shadow appears in its path, thus making it appear as if the satellites simply appear out of this blackness some distance from Jupiter. Rømer's proposed equation of light, which was to explain the systematic changes in the satellites' orbital periods, was such that light would require 22 minutes to traverse the diameter of the Earth's orbit.

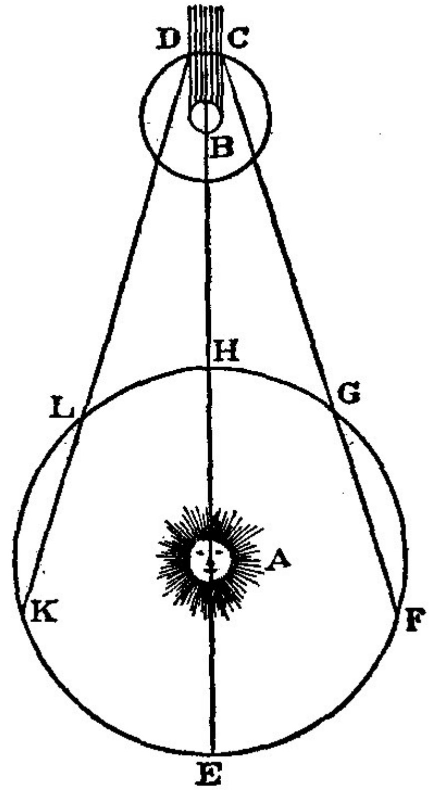


FIG. 70.

How then did Rømer arrive at the conclusion that a finite speed of light was to blame for the difficulties in predicting the eclipses of the Jovian satellites? A manuscript folio written by Rømer found in 1913 clarifies his path to discovery. This document contains a list of the eclipses of the Jovian satellites between 1668 and 1677, 67 of which were of the first satellite. Out of these 67, 51 are explicitly listed as immersions or emersions, while the rest are either incomplete or represent a transit of the satellite across the face of Jupiter.[11] Rømer claimed to have made over 70 observations of the first satellite since 1668 while in the company of Picard, carefully separating them into nine periods, grouped according to whether they were emersions or immersions.

Period	I	Earth	receding from	Jupiter	Mar. 1671—May 1671	Emersions
»	II	»	approaching	»	Oct. 1671—Feb. 1672	Immersions
»	III	»	receding from	»	Mar. 1672—June 1672	Emersions
»	IV	»	approaching	»	Nov. 1672—Mar. 1673	Immersions
»	V	»	receding from	»	Apr. 1673—Aug. 1673	Emersions
»	VI	»	receding from	»	July 1675—Oct. 1675	Emersions
»	VII	»	approaching	»	May 1676—June 1676	Immersions
»	VIII	»	receding from	»	Aug. 1676—Nov. 1676	Emersions
»	IX	»	approaching	»	June 1677—July 1677	Immersions [12]

In her 1915 analysis of this rediscovered manuscript, Dr. Kirstine Meyer utilizes the aforementioned 51 relevant observations to compute mean periods of revolution for the first satellite during each of Rømer's nine periods.

Period I	1d.	18h.	28m.	47s.	Emersions
» II	1	18	28	18	Immersions
» III	1	18	28	35	Emersions
» IV	1	18	28	27	Immersions
» V	1	18	28	46	Emersions
» VI	1	18	28	48	Emersions
» VII	1	18	28	20	Immersions
» VIII	1	18	28	47	Emersions
» IX	1	18	28	30	Immersions [13]

This table corroborates Rømer's statements to the *Academie* and those contained in his correspondences to Huygens that the mean period is less when calculated according to periods of immersions than when calculated using emersions. As was mentioned above, the observation of immersions and emersions is based on the relative position of the Earth to Jupiter, or simply whether it is approaching Jupiter or moving away from it. From this it was unproblematic for Rømer to deduce that a change in distance between the planets was responsible for the apparent changes in the period of the first satellite. Seeking an explanation as to why such a change in distance would affect the satellite's period, Rømer surmised (or borrowed from Cassini) that a change in distance between Jupiter and Earth would cause a change in the time light originating at the satellites would require to reach Earth, making it appear as if these eclipses were occurring irregularly. Cassini would object to this explanation, remaining unconvinced by the available observations. Huygens, intrigued by what he had heard of Rømer's theory, initiated a correspondence with Rømer. In a response to Huygens, Rømer rejects seven other hypotheses which he states would not account for the delay. Here he eliminates Jupiter's irregular orbit and that of the Earth, the equation of time, the configuration of the remaining three satellites relative to the first, the position of the Sun relative to the interior satellite, a shift in latitude, and the effect of Jupiter's atmosphere on the interior satellite.[14] Rømer is quick to do away with these six, reminding Huygens that none of these hypotheses account for the systematic fluctuations in the delay according to the relative position of the Earth and Jupiter. The seventh hypothesis relates difficulties in pronouncing definite times of eclipses when the Earth is at certain orientations with respect to Jupiter because of uncertainties as to the umbra and penumbra of Jupiter's shadow.[15] At the very least this seventh hypothesis does reference the Earth's orientation with respect to Jupiter. Nevertheless, the systematic variance which would result from such a cause cannot fully account for the observed relationship between the delays of the eclipses and Earth's and Jupiter's relative positions. That none of these seven phenomena could appropriately describe the delays in question lent Rømer's equation of light some credibility; it stood as the lone simple explanation for the irregularity. Huygens was utterly convinced.

The calculations required to determine the speed of light from these eclipse observations are strikingly simple. Two observations of eclipses recorded in solar time, both either immersions or emersions, are treated with the equation of time, which converts both into mean time. The equation of time corrects for the non-uniformities in the Sun's daily motion relative to the stars: the obliquity of the ecliptic, and the eccentricity of the Earth's orbit around the Sun. With both eclipse observations in mean time, we can subtract to get the total change in time between the two. We see from Rømer's manuscript that he obtained mean values for the periods of the first satellite, comprised of both the periods of immersions and those of emersions during a year.[16] Utilizing the yearly mean orbital time of the first satellite, he solved for the expected time period by multiplying his calculated mean time by the number of eclipses that occurred during the observed time period. Taking the difference of the expected and observed time periods gives us the delay for a set of emersions, or if it was an immersion how much earlier the eclipse appeared. Finally we divide this delay or hastening figure by the change in distance between the Earth and Jupiter (measured in mean Earth Sun distance) during this observed time period to determine the time light takes to traverse the mean radius of the Earth's orbit.

As was mentioned above, Cassini vehemently objected, not to the fact of the delay or its relation to the relative positions of the Earth and Jupiter, but to Rømer's explanation and speed of light equation. Cassini was perturbed by the equation's decreasing accuracy in dealing with the three other Jovian satellites. This was an understandably cautious view for the much experienced scientist. Although Rømer's equation of light agreed with observations of the first satellite, it was somewhat inconsistent in dealing with the irregularities present in the other three satellites and, as suggested by Cassini's nephew Maraldi I, with the relatively large eccentricity of Jupiter's orbit (compared to that of the interior planets), which should have a noticeable effect on the observed delay. Having not personally observed this second effect due to

Jupiter eccentricity, Cassini more steadfastly clung to his position, choosing to reject Rømer's theory entirely to his death in 1712.

In his 1677 response to Huygens, Rømer had already listed four obstructions to describing the inequalities of the outer three satellites with his new equation of light. The first three are as follows: the emersions and immersions of these three are much more infrequent, their emersions and immersions from Jupiter's shadow are less abrupt and thus the timings of these eclipses is less accurate, and further irregularities in the inclinations and nodes of their orbits could produce discrepancies of multiple minutes for eclipses which are manifest in the obliquity of Jupiter's shadow. His fourth explanation of why his explanation of light is difficult to extract from three exterior satellites reads more like an excuse.[17] Here Rømer admits that these exterior satellites exhibit irregularities either due to the eccentricity of their orbits or to other unknown causes. The discrepancies produced by these unattributed irregularities are said to be two to three times greater than those produced by his equation of light.[18] Rømer's point is well taken; it is difficult to separate a smaller systematic movement from a larger mysterious motion. To Cassini the fit of Rømer's equation of light to the first satellite was not enough to overcome its inability to explain away the totality of the motion in the exterior satellites. Consequently, it is unsurprising that both Cassini and Rømer were unwilling to apply the equation of light to the outer three satellites.

Judging by the new tables for Jupiter's satellites published by Cassini in 1682, however, his objection based on the three exterior satellites may also be rooted in his grossly inflated estimation of the irregularities of these outer three satellites. Halley thoroughly covers Cassini's bizarre interpretation in his 1694 adaptation and criticism of Cassini's new tables for Jupiter's satellites:

> "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 Rømer's Hypothesis entirely... 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 Rømer's Demonstration; wherefore he has rejected it as ill founded. But there is good cause to believe that his motive thereto, has thought not proper to discover."[19]

In this way, not only did Cassini give an inexplicably small value for the second inequality present in the first satellite, 14′ 10″ of time, he insisted upon altering this correction such that it was proportional to the increases in the mean orbital period for the outer three satellites. As for why Cassini would do this, we only have to look back to the letter from Rømer to Huygens, wherein Rømer explains that irregularities in the outer satellites may be two to three times larger than that of the first. Additionally, Cassini does not make a serious attempt to explain the irregularities, relating them to the relative positions of the Earth and Jupiter, and is therefore not entitled to explain the occult nature of his table's proportions. Although as Halley notes, "…it be hard to imagine how the Earth's Position in respect of Jupiter should any way affect the Motion of the Satellites."[20] Nevertheless, in seeking to establish the same proportion in the second inequality as in the mean periods of the satellites, Cassini's delay predictions for the outer satellites remain much too large. Halley shows this to be particularly true in the case of the third and fourth satellites. Had Cassini's proportion proven accurate, Rømer's equation of light would naturally have to be rejected, as it predicts effectively the same value for the light time delay for each of the four satellites. Halley goes on to calculate the speed of light from the third and fourth satellites in hope of showing that, despite both Rømer and Cassini's misgivings regarding the applicability of the equation of light to these outer satellites, speed of light values of an appropriate and consistent magnitude could be obtained.

Allowing then that Halley has sufficiently answered Cassini's major critiques of Rømer's equation of light, why ultimately is Rømer's figure of 22 minutes for light to cross the diameter of the Earth's orbit so inaccurate as compared to modern determinations of the speed of light? As was previously mentioned in relation to the outer satellites, timing the moment of an eclipse is an extremely subjective matter. The slower satellites will incur more subjective error in this sense; however, even the inner most satellite still orbits Jupiter in over 1 day and 18 hours, leaving ample opportunity for mistiming the exact moment of eclipse. As such, small errors in timing the interior satellites have a greater effect on the calculated speed of light than similar errors in the outer satellites. The point here is that none of the satellites are exempt from errors in the timings of their respective eclipses.

Additionally, Halley's criticism extends past Cassini's strange proportion as he laments that the accuracy of the tables is sapped by Cassini's choice not to include the eccentricity of Jupiter's orbit, an omission which Maraldi had previously excused. Rømer does not appear to have corrected for the effects of Jupiter's eccentricity, although he was aware of it: "[the first satellite's] revolutions were advanced or retarded according as Jupiter did approach to or recede from the Sun."[21] It should be noted that Rømer's time of 22 minutes for light to travel the diameter of the Earth's orbit was obtained using the observations made during the years 1671, 1672 and 1673. This was due not only to the disproportionate amount of observations taken during these three years, but also because of the relatively regular movement of Jupiter in its orbit around the sun during this time, a result of the aphelion passage of Jupiter in 1672. Nevertheless, the poor state of theories of Jupiter's orbit (a result of the complicated interaction between the planet and Saturn) affected Rømer's determination of the distance between Jupiter and Earth even during these three relatively calm years. Even so, corrections for errors in this distance based on modern determinations do not yield a more accurate speed of light when applied to Rømer's calculations during this three year time period; in fact they bring it in even better agreement with his stated 22 minute mean value. Modern corrections of distance do yield more accurate results when used in place of Rømer's figures for years after 1673. In particular, Rømer's famous announcement of a 10 minute delay for the November 9th 1676 emersion no longer yields his 11 minutes, but a more sensible figure just under 9 minutes. Without a suitable theory of Jupiter's motion, Rømer utilized distances according to the much simpler 1671-1673 period long after they were applicable, causing him to underestimate the distance between the two planets. Likely some error is also accounted for by the timing instruments Rømer used to record the times of observation. While Huygens' pendulums were very accurate over the course of a day, some minor inaccuracies may still have originated from the imperfect standardization of the measurement of time.

A comparison of the mean periods of revolution which Rømer used with modern values shows what is a significant source of error for Rømer, but again not one which will allow us to immediately grant Rømer a better figure for his speed of light. In fact, using the modern mean period for the first satellite, the expected time for the January 12^{th} 1672 eclipse is 51 minutes and 18 seconds earlier than Rømer would have predicted. The actual time of immersion based on Rømer's observations is now later than the expected time, completely contrary to his hypothesis. Thus it is clear that there is some effect or effects which caused Rømer to overestimate the time between eclipses. Rømer mentions the unequal revolutions of the "*primum mobile",* which would later be explained by the aberration of light, but this phenomenon cannot come close to explaining the large discrepancy.[22] The effect of Saturn on Jupiter's orbit undoubtedly affords a perturbation in the orbits of his satellites themselves, while the ringed planet also acts to displace Jupiter's equator. As a result, Jupiter's bulging equator is constantly changing its position relative to the satellites, thereby altering their motion. This mutual interaction between the two planets would not be fully accounted for until Laplace, leaving Rømer with little chance of anticipating its effects on his equation of light.

Two more effects which do seem particularly relevant are those of the refraction of light by the Earth's atmosphere, and the necessary observation of these eclipses predominantly during daylight hours. Refraction of sunlight by our atmosphere depends upon Jupiter's declination, so that when it is observed low in the sky the effect can be rather large. Turbulent air could cause particularly confounding non-homogenous refraction effects. That Rømer was forced to observe an overwhelming majority of these eclipses during the daytime certainly contributed a level of difficulty to ascertaining the exact moment of occultation.[23] It seems that the requirement that some observations occur during the daylight and others during the night might be an occasion for discrepancies in the recorded time between eclipses to arise. Finally, Rømer was correct in pointing out that neither the eccentricity, nor the configuration of the satellites relative to one another, a Laplace resonance effect, could be the source of delay. Nonetheless, these factors would have been major sources of error present in Rømer's calculation. The resonance effect is a particularly significant source of error in the periods of the four satellites. This effect causes the nodes of the orbit to drift, and renders triple conjunction of the interior satellites impossible.[24] As such, it seems as though the majority of error in Rømer's equation of light is due to the resonance effects, the effects of Saturn upon Jupiter, and the inexactness of observation afforded by certain astronomical phenomena and the unfortunate timing of many eclipses.

Calculating the speed of light from the satellites of Jupiter during Rømer's time was a highly inaccurate endeavor. Even Halley who determined a value (8.5 minutes) very close to the modern value for light time from the Earth to Sun during his criticism of Cassini's tables arrived at this value purely coincidentally.[25] In deriving this light time from the fourth satellite he cited the change in distance between the Earth and Jupiter during the time between the September 24th and December 17th eclipses of this satellite of "more than the Radius of its own Orb."[26] The radius here referring to the diameter of the Earth's orbit, Halley's value is too large by the true mean radius (in the modern sense) of the Earth's orbit. Halley also recognizes that the initial September 24th observation, having occurred during the morning "might well hinder the seeing of this smallest and slowest *Satellite*, till such time as a good part thereof was emerged."[27]

Although the first edition of Newton's *Principia* quotes a value of 10 minutes for light to travel from the Sun to Earth, the Scholium to Proposition 96 of Book 1 in the third edition boldly states "the fact that light is propagated successively [i.e., in time and not instantaneously] and comes from the sun to the earth in about seven or eight minutes is now established by means of the phenomena of the satellites of Jupiter, confirmed by the observations of various astronomers."[28] The mean orbital periods of the Jovian satellites followed in step, also becoming closer to modern figures by the publishing of the *Principia*'s third edition.

The Import

This first determination of the speed of light was in and of itself not enough to conclusively show that light was transmitted at a finite speed. Without an established theory of Jupiter's orbit, or a way to deduce the same equation of light from each of the four Jovian satellites, Rømer could only truly show that an irregularity in the first satellite of Jupiter was related to the Earth's distance from the planet. That the equation of light was a fitting explanation was beside the point, for the irregularity was not connected to any theories of optics nor was there any optical theory that had predicted a speed of light value of this magnitude. At the same time we might also say that Cassini was overly cautious. Rømer had noted that the eccentricity of Jupiter, its distance from the Sun, also affected the delays in the eclipses, as was predicted by his hypothesis regarding the effects of light time delay. Had Laplace's theory of the Jupiter and Saturn interaction and his explanation of the resonance effects of the Jovian satellites come earlier, perhaps enough of the remaining perturbations in the outer satellites could be explained that Rømer's equation would have received a more welcoming reception in mainland Europe. If unrelated theories managed to explain the irregularities of the satellites so that Rømer's equation of light was able to fully account for the remaining discrepancies, the equation of light could draw support from the gravitational theory whose irregularities it justified.

Nevertheless, even with such evidence, Rømer's explanation of the delays in the Jovian satellites was too isolated from established theory to conclusively settle whether light was transmitted instantaneously or over time. As it stood, Rømer's equation of light was neither a sufficient explanation of the irregularities in the eclipses of the Jovian satellites, nor a necessary consequence of the delays' connection to the relative positions of the Earth and Jupiter.

Although Rømer's discovery was received with much hesitation by those at the *Academie*, and even Huygens admitted it was still unproven, it was almost unanimously accepted among the British scientific community at the time. The usefulness to astronomy of Rømer's equation of light was entirely relegated to making corrections to astronomical positions and tables describing motion, especially the eclipses of the Jovian satellites. In a letter between Huygens and La Hire in May 1690, it is intimated that Flamsteed was making good use of Rømer's still controversial equation of light.[29] Indeed Flamsteed's 1725 tables, *Historia Coelestis Britanica*, utilizes the equation of light particularly, although not exclusively in matters dealing with the satellites of Jupiter. Despite its limited scope of applicability, the equation of light did instill confidence in other astronomers that the cosmic laboratory might be used to determine the speed of light.

Rømer never translated his astronomical measures of the speed of light into terrestrial values, most likely due to his understanding of the error left unaccounted for by his method as well as the abysmal values for solar parallax being used in the late 1600s. In his *Treatise on Light*, Huygens (spurred on by his wave theory of light and its need for a speed of light value) estimated the diameter of Earth's orbit around the sun to be 24,000

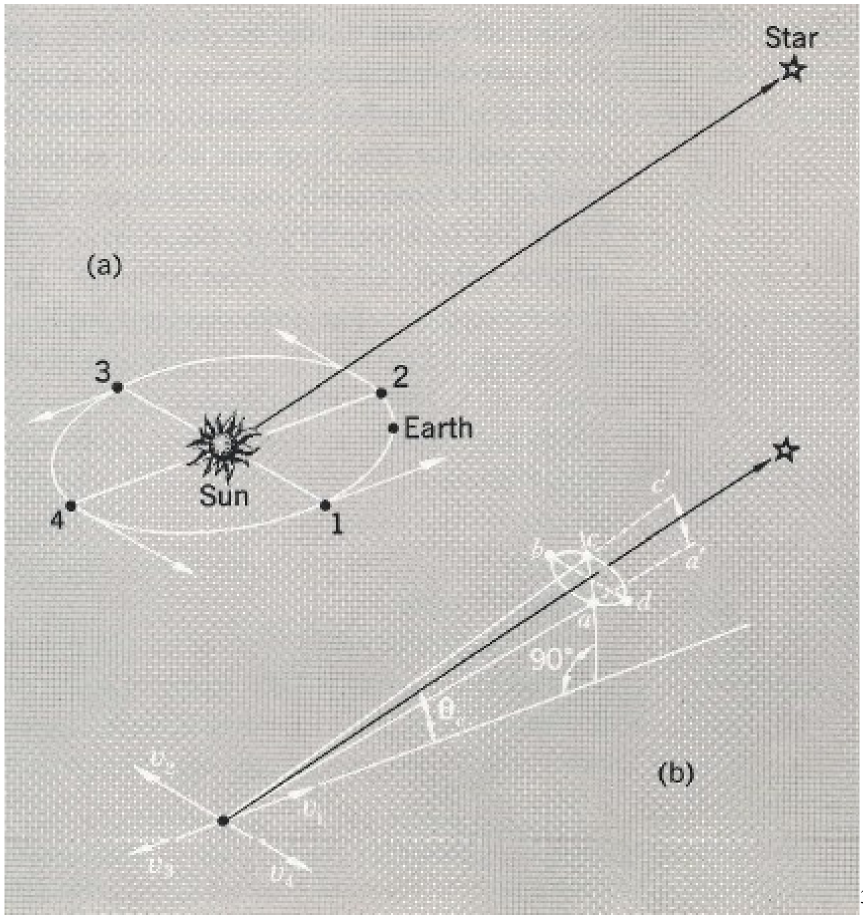
Earth diameters. For the sake of argument Huygens uses a value of 22,000 Earth diameters for this distance (about 1,000 Earth diameters less than the modern figure), combining this number with Rømer's inflated figure of 22 minutes for light to cross the diameter of the Earth's orbit to determine the terrestrial speed of light, 212,000km/s.[30] The error in Huygen's calculated terrestrial speed of light is almost entirely a result of Rømer's inaccurate equation of light.

James Bradley

James Bradley was born at Sherbourn in Glocestershire either in 1692 or 1693, the third son of William Bradley and Jane Pound. The young Bradley attended Oxford for both his B.A. and M.A., but it would be under the caring tutelage of his maternal uncle the Rev. James Pound that his remarkable abilities would be developed. Pound was already a revered astronomer by the time of their union, and during his time with Bradley he undoubtedly communicated his passion for observation as well as his years of experience. And so James Bradley would come to maturity with a profound respect for precise observation, as well as the skills and experience necessary to undertake them, so generously passed down to him by his uncle.

James Bradley is best remembered for discovering the aberration of light in 1728 and the publishing of his discovery of nutation 20 years later. The practical importance of the aberration of light is often overlooked; the way in which Bradley deduced the speed of light from aberration would remain the preferred method for deriving this constant for nearly 120 years. That, however, raises the further question of how the aberration of light yielded such an accurate value for the speed of light. As such, part of this chapter will be devoted to discussing the role of the discovery of nutation in securing the accuracy of Bradley's speed of light value.

Bradley accounted for the apparent oscillatory deviations in predicted stellar position that would come to be known as the aberration of light by proposing that the phenomenon is solely governed by the ratio of the speed of light to the transverse speed of the Earth (the component of this speed perpendicular to the real path of light from the celestial object in question). Bradley's measurements of the deviations of stars from their predicted paths, collected between the end of 1725 and 1728, allowed him to create a theory which accounted for the majority of the observed motions with a regular yearly cause. Contained within this explanation was a method to retrieve a value for the speed of light based upon maximum observed deviations, a consequence of including the speed of light as a fundamental constant within the formula describing yearly aberration. The figure below describes the effects of the stellar aberration relative to the Earth's movement around the Sun. Although (b) depicts the effects of the aberration of light to both the declination and right ascension of the star, Bradley's observations were limited to the oscillation in declination.



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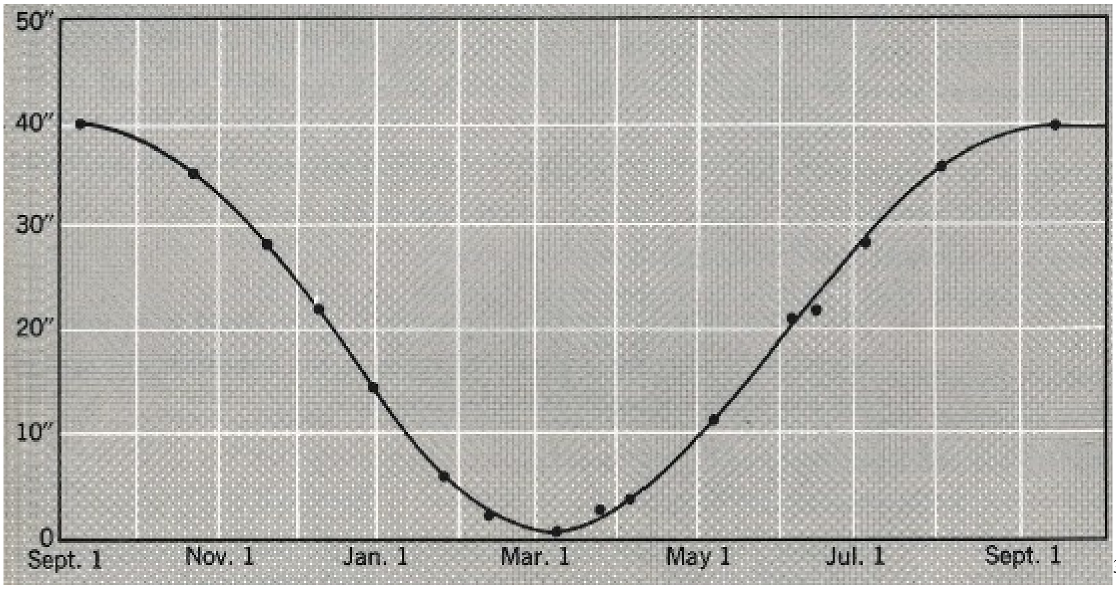
Bradley's technique for determining the speed of light thus depended on the accuracy of his observations as well as on his ability to isolate the stellar motion due to the aberration of light from any other effects like the precession of the equinox or other unforeseen phenomena which might have been affecting his observed values for maximum deviation. The level of accuracy Bradley would achieve, his consistency in method, his relentless testing of instruments, was unmatched during his lifetime. Any fears regarding his competency as an astronomer will hopefully be assuaged below.[32] The bulk of this chapter will concern itself with examining Bradley's capacity for successfully individuating the causes and extents of particular contributions to the total apparent stellar motions, despite the messy overlapping of multiple explained and at the time unexplained phenomena. The supreme accuracy of the value for the speed of light he determined from just one of these apparent motions will be revealed by delving into the methodology behind his research into stellar deviations, which extended from 1725 until the delivery of his theory of nutation to the Royal Society in January of 1748. It will be shown that Bradley's pursuit of a complete theory of nutation was necessary to preserve the accuracy of his theory of aberration and consequently his deduced speed of light value.

The phenomenon now known as aberration of light was first stumbled on by chance as Bradley, working under Samuel Molyneux at Kew, noticed a peculiar wobble in γ Draconis while attempting to replicate Robert Hooke's alleged discovery of annual stellar parallax, a slight apparent motion of the stars due to the Earth's motion around the Sun.[33] In late 1725 and early 1726, Molyneux had employed Bradley in a project to determine the veracity of Hooke's claims, using a Huygens telescope with a focal length of 24 feet 3 inches built by George Graham, with an accuracy of nearly half an arc second. In regards to the observed wobble, γ Draconis was seen to oscillate in declination, first southerly and then northerly about its expected position, pausing for a period of months before changing direction and completing one full cycle in a year's time. Bradley was quick to realize that this motion could not be due to annual stellar parallax, and thus that any claims to the discovery of parallax by Hooke, Flamsteed, Picard or otherwise were undoubtedly false. Bradley was nevertheless intrigued by this unforeseen phenomenon and undertook a second year of investigation on his own beginning in mid 1727 in Wansted, utilizing a much smaller but comparably accurate

Graham-built instrument. The recorded oscillation in stellar position observed during 1727 and 1728 is pictured below.



[34]

The only "historical" account which explains Bradley's key epiphany, the inspiration that prompted him to incorporate the speed of light in a ratio with the speed of the Earth around the Sun, is the possibly apocryphal tale of his pleasure cruise on the Thames.[35] Whether this story is a factual description of events is entirely inconsequential for the purposes of this paper. What is of consequence is Bradley's theory, which has the motion of the Earth in its orbit displacing the apparent location of a star in the direction of the Earth's progress, by an amount determined by the ratio between the component of the Earth's velocity perpendicular to the line to the star and the speed of light.

With a theory of the speed of light's role in the deviant motions, Bradley's collection of observations at Wansted allowed him to settle on a mean value for the yearly maximum displacement due to the aberration of light of 40″ ½, between his observed maxima common to different stars of approximately 40″ and 41″.[36] These maxima represent the difference between the approximately 20″ northerly and 20″ southerly deviations from the stars' expected paths. One full cycle of oscillation between these positions was observed in Bradley's year at Wanstead.[37] Bradley insisted that the true value could deviate at most less than a single second from his mean value due to the "near agreement which [he] met with among [his] observations".[38] This bold claim of agreement is supported by the analyses of seven stars in his monograph on the aberration of light, beginning of course with his favorite exemplar, γ Draconis. All of the stars therein he concluded to have maximum displacements of either 40″ or 41″. At this point Bradley declares that since other stars he has observed displace similarly, with maxima of approximately 40″ or 41″, the observations of the seven stars he has provided are enough to settle on these specific maximum values. The additional unstated reasoning for his confidence to this high level of accuracy is the consistent and demanding tests he performed on the telescopes he worked with, all of which established that both of the zenith sectors he used during the entirety of the relevant observations were accurate to better than 1″. Bradley, however, did note other apparent motions, separating them from his work on aberration, as of yet unsure if they were due to an underestimated value for the precession of the equinox or other new phenomena. His isolation of the source these discrepancies will be discussed below.

Utilizing his theory of aberration of light and an assumed transverse component of the speed of Earth (in astronomical units), the mean value of stellar deviation and the bounds on its accuracy provided a value for the speed of light and bounds on that value's accuracy. Bradley gives his speed of light value, calculated using the mean maximum displacement, in terms of the mean Earth-Sun distance, specifically 8′ 13″ for light to traverse this expanse.[39] The nearly 1″ maximum of possible error in his stellar observations translates to his stated 10″ bound on his speed of light time, while the second smaller bound he reports, a 5″ discrepancy in the time from Sun to Earth, is merely the ½″ difference between his mean value and the two observed maxima of displacement. The level of accuracy claimed here is astonishing; Bradley's assertion that he is within one or two percent of the true speed of light is remarkably daring.[40]

Bradley's confidence in the accuracy of his own determination of the speed of light does appear at first glance to be slightly premature. Without an explanation for all the motion he observed, his ability to truly separate only or all of that motion which is due to the aberration of light is open to question. The vagaries involved in assigning causes to motions which overlap one another and whose magnitudes encroach on the reliable accuracy of one's instruments cannot be ignored. Within his paper on aberration Bradley informs his contemporaries that he had "deduced the real annual alteration of declination of each star from the observations themselves; and [he] the rather choose to depend upon them in this article, because all which [he has] yet made concur to prove that the stars near the equinoctial colure change their declination at this time 1″ ½ or 2″ in a year more than they would do if the precession was only 50″, as is now generally supposed."[41] By doing so Bradley did not presuppose the value for precession, merely that "the alteration from this cause is proportional to the time, and regular through all parts of the year."[42] Bradley did not rely on the assumed value of the precession of the equinox to separate it from the oscillatory effects of the aberration of light; it was enough that its motion be of a divergent type across the period of a year. Bradley would also notice northerly changes in "those [stars] that are near the solstitial colure, which on the contrary have altered their declination less than they ought, if the precession was 50″."[43]

Both of these minor contradictory motions were detached from the aberration of light as they would appear similar to the motion due to precession in that they were apparently “regular through all parts of the year.”

These contradictory motions would later be attributed to the nutation of the Earth’s axis, a phenomenon describing oscillatory North and South 9″ departures from predicted stellar position over an 18 year period, corresponding to the Saros cycle of lunar eclipses. Although nutation does exhibit an acceleration in its motion much like aberration, the very small yearly movement combined with such a long period makes the phenomenon look regular, as if it is just a part of the total yearly precession. Bradley independently separated all of this “regular” motion from the effects of aberration, noting that some stars indicated it was in excess of the traditional value for precession, 50″, while others showed the opposite. While he was unsure whether these residual motions should be partly incorporated into precession, he was aware that both contradictory motions could not be incorporated because precession acts equally on all stars.

It seems difficult to isolate any stellar motions without making presumptuous claims about particular effects. By assuming that precession is regular throughout the year, a point he would later go on to defend despite its fairly solid standing within astronomy at the time, and that the aberration of light was entirely libratory, an assumption built into his theory (otherwise the orientation of the ecliptic would have to shift), Bradley could easily separate the oscillatory motion of aberration from the apparently regular combination of precession and nutation. The precise values for precession and the contradictory motions could be obtained by simple subtraction, taking the difference between the position of a star at the beginning and end of a full year. The change in position due to the aberration of light would be canceled out over one year, leaving only the motion due to the precession of the equinox and any other apparently secular (over that time period) effects. Performing this calculation for each star would yield the equal but opposite discrepancies relative to the traditional precession value for stars in the equinoctial colure and those in the solstitial colure, a difference which would later be attributed to nutation.

Initially doubting that the extra phenomenon was from a single cause, and at times skeptical of its authenticity altogether, Bradley was content simply to account for the remaining phenomena by removing them from his figures for maximum displacement due to the aberration of light. He had not yet settled on nutation as the single cause of the opposite deviations, hinting at this time that they may at least in part be due to an under or overestimated precession value. This possibility seemed more acceptable because of the limited time of observation during the mid 1720s, as compared to the 18 year period of nutation. The important point here is that the deviations were separated from his calculated values of the apparent displacement due to the aberration of light. This anticipatory move ultimately preserved the accuracy of his speed of light determinations, despite leaving wholly unexplained motions that would require their own account if the speed of light values were to be unquestionably trusted.

If Bradley could fully describe these deviations without altering his theory of the aberration of light or leaving unexplained motions of a comparable order of magnitude, then his speed of light determination could survive unaltered; if, however, these deviations showed that the effects of one or more phenomena even partially infringed upon by the motion attributed to the aberration of light, Bradley's speed of light value would be undermined by an unresolved source of motion, and his bounds would be misplaced around an incorrect mean value, thereby disproving his claims of accuracy and demolishing the tight bounds with which he so proudly constrained the value.

By 1732 Bradley was already fairly confident that he had identified the cause of the deviant motion. A thorough analysis of his observations up until 1732 would describe a motion as if "the north pole of the equator seeming to have approached the stars, which come to the meridian with the Sun, about the vernal equinox and the winter solstice; and to have receded from those which come to the meridian with the Sun about the autumnal equinox and the summer solstice."[44] Bradley was well aware that at the start of his period of observations, 1727, the moon's ascending node was near the beginning of Aries, indicating a maximum latitude relative to the equatorial plane. The combination of these circumstances led him to propose that the observed effects were caused by "the moon's action upon the equatorial parts of the Earth."[45] He reasoned that the nearly stationary position of the plane of the ecliptic relative to Earth's equator meant that the effects of precession due to the Sun would likely be regular each year, thereby justifying his claim of regular precession from his work on the aberration of light. By contrast the moon's tendency to vary up to ten degrees in latitude relative to the equator would cause a variation year to year based on its relative position, reflected in his observations of the mysterious residual motion.

A 1737 correspondence with Maupertuis, subsequent to the Frenchman's polar expedition, reveals Bradley's level of confidence in his theory. The letter indicates that Bradley was certain he had ascertained the general motion due to the phenomenon as well as isolated its cause through his observation of a half period of the phenomenon.[46]

Although Bradley conceived of nutation as affecting a libratory motion on the Earth's axis and thus also on the apparent position of the stars, having witnessed only half of the period of this phenomena he was still unwilling to base the accuracy of predicted values of nutation, deviations due to the aberration of light, and ultimately his calculated value and bounds for the speed of light upon such conjecture. He expresses this uncertainty in his eventual publication, stating he "was unable to judge, from only nine years of observations, whether the axis would entirely recover the same position that it had in the year 1727."[47] With the accuracy of his prior work inextricably linked to his theory of nutation, Bradley could not accept just guessing as to whether the phenomenon was entirely libratory or not. Therefore, with the goal of confirming his supposition and preserving the accuracy of prior discoveries, Bradley would continue his regimen of observation until he could determine the extent of nutation's total motion.

A second letter to Maupertuis a year later in October 1738 describes Bradley's progress on this issue: "whether they will entirely recover their original situation by the end of the period of eighteen years, I cannot yet determine from the observations of these two last years only. There seems, indeed, from my latest observations, some reason to suppose that they will not; but the difference between the hypothesis and observations scarce amounting at present to more than a single second, I cannot pretend to say whether that is owing to anything besides the uncertainty of the observations themselves, and therefore must refer the decision of this point to future experience."[48] And so in 1738 Bradley had a very good reason to continue his observations: his records suggested that the motion was not entirely libratory, contradictory to his hypothesis.

Seemingly contrary to the point Bradley raised in this letter to Maupertuis, η Ursae Majoris and γ Draconis, the only stars Bradley presented in his final publication on nutation that were observed in 1736, 1737, and 1738, differed in their implications regarding a fully libratory motion. A comparison of Bradley's calculated effects of nutation from 1727-1729 and 1736-1738 (each the beginning of a 9 year half of the total period) for η Ursae Majoris showed that the star had moved 0.6″ more during the beginning of the second half of the cycle than during the first.[49] This observation seems to match the sentiment expressed in Bradley's second letter to Maupertuis, a discrepancy of nearly a second suggesting non-libratory motion. A similar comparison for γ Draconis reveals a perfect agreement within these same two time periods, offering nothing but support for the initial hypothesis and its prediction of an entirely restoring motion.[50] While the 1738 observation for η Ursae Majoris was made on June 29th, it would not be until September 13th that same year that Bradley would record a place for γ Draconis. Considering that the second letter to Maupertuis was dated October 28th, 1738, it is likely Bradley had not yet calculated the effects of nutation for γ Draconis. There is an argument to be made that Bradley's language in this 1738 letter to Maupertuis implies a completion of the analysis of the year's observations, suggesting the inclusion of the September observations of γ Draconis. This argument is contradicted by the tables printed in the presentation to the Royal Society that show four more stars observed in December of that same year. Alternatively, it is possible, although unlikely, that Bradley made errors during his initial calculations for the effects of nutation regarding the position of γ Draconis, eventually correcting them before communicating his discovery to the Royal Society.

Nevertheless, this inconsistency suggesting non-libratory motion would not sit well with his work on both aberration and the speed of light, and he certainly would be inclined to observe a balancing out of this motion. While confirmation of his hypothesis would be a primary concern, there were other possibilities for continued study. Just as he had seen hints at a secondary phenomenon, nutation, while looking into the aberration of light, this irregularity could also suggest that there was another hidden phenomenon lurking behind and offsetting the effects of nutation. If this motion had been accidentally incorporated into the aberration of light, his speed of light value would be less accurate and his bounds inappropriate. Regardless, if no other regular phenomenon could be found to explain away the discrepancy, Bradley would find issue presenting a theory which implied an entirely libratory motion that was directly contradicted by his own observations. Without a complete explanation of the motions observed, the possibility of other phenomena with effects on this order of magnitude would continue to cast doubt on the accuracy of his speed of light values and the aberration of light, not to mention nutation. Either an infringing tertiary phenomena or entirely unexplained stellar motion would taint his speed of light values as determined from his theory of the aberration of light.

As such, Bradley, concerned specifically with the discrepancies in the motion of η Ursae Majoris and either without the relevant figures for γ Draconis, or utilizing incorrect results from the star, was under the impression that what he later identified as nutation might not be entirely libratory and that the accuracy of his prior work was in jeopardy. Consequently, the phenomenon later named nutation would certainly require further study. As for how this inconsistency would find its way out of Bradley's work, the so-called strange years, 1740 and 1741, would show unexpectedly small results for the effects of nutation, helping to bring both halves of the cycle into better agreement and eventually confirming Bradley's initial supposition of a fully libratory effect.

During the course of his work on nutation, Bradley was troubled by a complex question: are all the motions which are of such an order of magnitude that they may significantly interfere with the value of the speed of light determined from the aberration of light fully explained and properly separated from the observations which determine the speed of light's value? To answer such a question Bradley would need to account for all of the unaccounted for motion that he observed when analyzing the aberration of light. Finding an adequate explanation, nutation, was of little help, until it could be shown to be libratory, thus implying no other contravening effects of magnitude exceeding the precision of his observations. The surprisingly long period of observation, a full 20 years devoted to nutation, was merely the only way Bradley could confirm that nutation was truly libratory and guarantee the accuracy of both his theory of aberration and his speed of light value.

The Import

Considering that Bradley's work with his theory of the aberration of light was only the second method to obtain a speed of light value, the obvious question is how it compared with Ole Rømer's determination of the speed of light from the eclipses of the satellites of Jupiter, the first accepted determination of the finite speed of light. While Rømer's initial speed of light figure is 11 minutes for light to pass from the Sun to the Earth, more than a third larger than Bradley's, those who repeated Rømer's observations would return a value around 7 minutes according to Bradley.[51] As was previously discussed, Rømer's experiment contained numerous subjective qualities such as when to mark the beginning and ending of satellite ingresses and egresses, and what theory of Jupiter's orbit to use, as well as being plagued by ignorance of effects not yet discovered. With these sources of error in mind, the discrepancy between Rømer's successors' and Bradley's times should not be surprising.

Bradley's formula for the aberration of light, which includes a value for the speed of light, secured Rømer's claim of non-instantaneous transmission of light. The significance behind two unrelated methods yielding strikingly similar values for the speed of light was not lost on Bradley: "These different methods of finding the velocity of light thus agreeing in the result, we may reasonably conclude, not only that these phænomena are owing to the causes to which they have been ascribed; but also, that light is propagated (in the same medium) with the same velocity after it hath been reflected as before."[52] And so there was a confirmation of a finite speed of light, made possible by the disjointedness in approach of two determinations, and their eventual near agreement for the value of the speed. The divergent methodologies of Rømer and Bradley would also allow for testing of Bradley's speed of light measure through Rømer's technique. If it could be shown that Bradley's value of 8′ 13″ for the Sun to Earth transit of light complies with Rømer's explanation of the unexpected timings of the ingresses and egresses of Jupiter's satellites, then the accuracy of Bradley's value would have a pertinent secondary confirmation.

The second point Bradley makes, regarding the speeds of reflected and non-reflected light, is somewhat more subtle. The line of reasoning here is supported by the assumption that the fixed stars and our Sun are similar objects emitting light at similar velocities, a relatively uncontroversial theory among most astronomers by the 18^{th} century. It was further supported by Bradley's determination that the magnitude of stars had no effect on aberration and thus affected no change on the determined speed of light. Therefore, given the similarity between the values determined by Rømer's successors and Bradley, reflected light and non-reflected light travel with the same velocity (again only within similar mediums). This was once more a consequence of the divergent methodologies; Rømer obtained a measurement of the speed of light from the reflected image of the satellites of Jupiter, while Bradley received his value directly from calculations related to emitted light from the fixed stars. As such, the similarity of these values was interpreted as indicating that there was no apparent change in the speed of light after reflecting off a body. A comparison of Rømer's initial value of 11 minutes for light to pass from the Sun to Earth with Bradley's calculated value of 8 minutes 13 seconds would seem to indicate exactly the opposite, that light slowed down as a result of reflection; however, as mentioned earlier, those who repeated Rømer's experiments utilizing Jupiter's satellites would return a value around 7 minutes. This meant the only objection to Bradley's logic would have to incorporate the unseemly idea that reflection accelerates light.

Bradley's choice of units avoided the inaccuracies inherent in translating to Earth-bound units. The contentious horizontal solar parallax values of this time would render any such conversion questionable. Nevertheless, his discovery of the aberration of light would pave the wave for future terrestrial determinations of the speed of light to utilize his constant of aberration (or a more accurate determination of it) to calculate more accurate values of solar parallax than could be determined by observation.

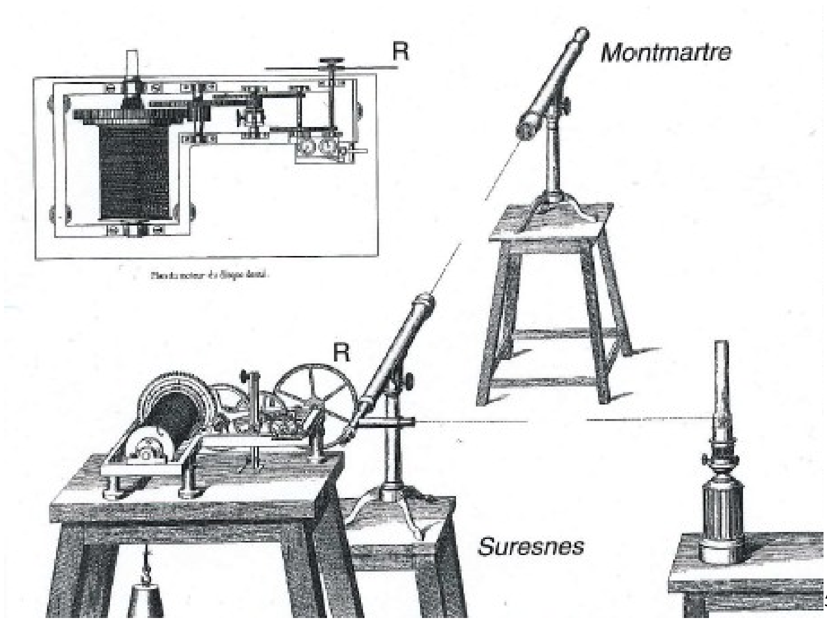
The extremely precise value for the speed of light would also allow astronomic corrections for light time-delay to become increasingly more exact, as well as supporting the predictive accuracy of Bradley's own theory of aberration. These consequences could also be used to refute the remaining anti-Copernicans. Bradley's theory of the aberration of light relies upon a mobile Earth and thus a Copernican cosmology. Allowing that a lack of apparent annual stellar parallax is not a sufficient objection to Copernicanism, due to the likely scenario that the stars may be over 400,000 times further from the Earth than the Sun and thus would show no observable parallax, the primary objection to Copernicanism would rest on a theory of instantaneous transmission of light.[53] The agreement of Rømer's refined experiment and Bradley's determinations together with the astronomically verified power of Bradley's more accurate value for the speed of light could therefore be brought to bear on those still unwilling to give up a static Earth by pointing to a direct refutation of the instantaneous transmission of light.

Fizeau and Foucault

The early 19th century saw the near simultaneous invention of two distinct methods of the determination of the terrestrial velocity of light. Hippolyte Fizeau's toothed wheel was the first to be applied to this purpose in 1849, and while Charles Wheatstone's rotating mirror was initially employed to determine the velocity of electricity, Leon Foucault would finally utilize the apparatus to determine the absolute speed of light in 1862. Fizeau and Foucault were close friends around the time of Fizeau's initial experiment; Foucault's praise for Fizeau's work illustrated the high regard in which he held his colleague. In the interim between Fizeau and Foucault's determinations of the speed of light, however, there was a falling out between the scientists as they competed to be the first to perform Arago's crucial experiment regarding whether light moved faster in air than in water. The result of this comparison of mediums was to settle the controversy surrounding the two main competing theories of light, the corpuscular and wave theories. The corpuscular theory predicting that light was accelerated in denser mediums and the wave theory insisting the opposite, Arago's experiment was promoted as a sort of *experimentum crucis*. Despite the success of both Fizeau and Foucault's experiments, the two were unable to rekindle their friendship, something Foucault regretted until his premature death in 1868.[54] Nevertheless, it was Foucault who was first to report his conclusion to the *Academie Royale des Sciences* in the summer of 1850, a full 7 weeks before Fizeau. Fizeau seemed to insinuate that this delay was a result of his waiting for Arago's permission to begin his experiment, unlike Foucault who merely informed Arago of his intentions. Although Fizeau encountered other setbacks while recreating Arago's experiment, his perception of Foucault's ungentlemanly approach is likely to have caused the rift between the two that so pained Foucault during his later years.

Hippolyte Fizeau

Fizeau's 1849 determination of the speed of light by use of his invention of the toothed wheel apparatus was the first terrestrial determination of the speed of light. The method was of his own design and the apparatus was built by Froment to Fizeau's specifications. The experiment is often described as a spiritual successor to the shuttered lamp experiment proposed by Galileo, essentially replacing the second observer with a mirror and adding a mechanical system to indirectly measure the time light spends in transit. Fizeau's apparatus consisted of two telescopes, a Drumond lamp and the famous rotating toothed wheel. Within the eyepiece of the first telescope was a piece of transparent glass fixed at a 45° angle so as to send a ray of light from the Drumond lamp out of the first telescope and to the second while still allowing for observation. The second telescope, located some distance away, was fitted with a small reflector in its focus so as to reflect any light coming from the first back towards it, doubling the distance that light travels within the apparatus. Passing into the body of the first telescope was the toothed wheel such that the beam of light had to pass between its 720 equally spaced helicoidal teeth both when passing out of the first telescope and upon its return.[55] Naturally then if a tooth was set in the path of the eyepiece no light could be observed. The rotation of the toothed wheel, driven by weights, would send out flashes of light, interspersed according to the rate of transfer of teeth into the focus, the time between flashes being in proportion to the rate of rotation. Similarly, with the wheel in motion the flashes of return rays coming from the second telescope would not be visible to the observer if a tooth had passed into the focus.



[56]

Fizeau conducted his experiment between a house at Suresne and the hill Montmartre. From the first telescope at Suresne and the second staring back into the first from Montmartre there was about 8,633m between them.[57] During his inquiry, Fizeau found that different rates of rotation generated different patterns of light flashes visible to the observer. At a speed of 12.6 revolutions per second the returning flashes of light became completely obscured, having been masked by the tooth adjacent to the gap from which they exited. At twice this speed of rotation the returning light rays were again made visible, apparently passing through the next gap between teeth. At three times this speed the returning light was hidden once more, this time by the second tooth from the exit gap, continuing in this pattern with multiples of the original 12.6 revolutions per second.[58] Unfortunately, Fizeau does not make clear his instrument for measuring the rate of rotation of the toothed wheel, referring to it simply as a “meter.”[59]

Having made the observations with his apparatus, Fizeau was thus capable of determining the velocity of light in air. Knowing the spacing between the gears and the speed of rotation Fizeau could calculate the time needed for a point on the circle’s circumference to “traverse a very small angular space, 1/1000 of the circumference for example.”[60] Fizeau goes on to explain that “When the number of revolutions is very large, this time is generally very short; for ten and one hundred turns a second, it is only 1/10000 and 1/100000 of a second.”[61] As such, Fizeau could calculate the time needed for the wheel to turn so that the next gap shifted into the focus. At around 25.2 revolutions per second, the first speed at which the light was visible again after having been obscured, the calculated time would also represent the transit time of light back and forth between the two telescopes, the light crossing twice the distance between them before its return. At that speed the returning light has just again become visible, meaning it is passing back through the next gap along the wheel. Light then must have passed from the first telescope to the second and back in the time required for the wheel to spin such that this next gap was in the focus. After Fizeau established the time of transit for light across twice the distance between the telescopes, it became a simple matter to then determine the velocity of light in air.

Fizeau’s calculated mean speed of light from his 28 observations was reported as “70,948 leagues [per second] of 25 to the degree.”[62] A league of 25 degrees being equivalent to 4,444.44m the modern expression of Fizeau’s calculated speed would be just over 315,320km/s.

A discussion of sources of error in Fizeau’s determination is somewhat beside the point. Fizeau was not particularly concerned with producing a value of supreme precision; rather, his experiment was purely a demonstration of the possibility of terrestrial measurements of the speed of light. Additionally, Fizeau’s two page discussion of his experiment does not leave much room to include the necessary details by which one could perform an appropriate evaluation of his work. Nevertheless, it may still be of some worth to discuss with some generality the points at which error was introduced into his speed of light value so that the reader may become better aware of future attempts to mitigate these errors. It must be noted that Fizeau's measurement of the distance between his telescopes is given only to the meter, although changes of a tenth of a meter only effect nearly a 5km/s difference in the calculated speed of light in air. Nevertheless, Fizeau does not give an account of his measuring the distance between the telescopes, but it would be of no great surprise to learn that his determinations erred in upwards of half a meter, especially when considering the hilly landscape over which the experiment took place. Similarly, Fizeau does not go into any depth in describing workings of his "meter" and how it measured the rate of rotation of his toothed wheel, although it seems likely that this figure was theoretically determined through its relation to the weight used to set the wheel in motion. It is only fair to expect some error in measuring a speed by this method as the descent of the weight and the resistance of the apparatus are both subject to non-uniformities, and invoke non-trivial measurements of weight and resistance themselves. These conjectures aside, Fizeau expresses his rate of rotation with only one trailing decimal. Although the final determination is an average of 28 trials, an unrecorded hundredth of rotation per second would alter speed of light determinations by over 120km/s.

Fizeau and Foucault and the Fizeau-Foucault Apparatus

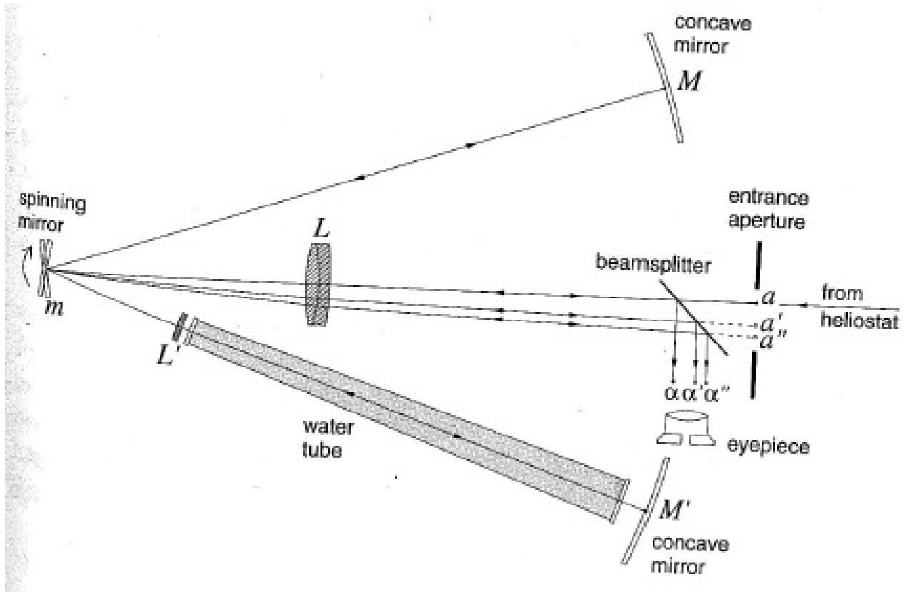
Following Fizeau's demonstration of a terrestrial measure of the speed of light, Fizeau and Foucault turned their attention to the experiment suggested by Francois Arago in 1838. Arago had in part borrowed the ideas behind his experiment from Charles Wheatstone, who after completing his determination of the duration of the electric spark utilizing his rotating mirror, drew attention to the applicability of his apparatus to determining a velocity of light and to comparing the velocities of light in water and in air.[63] Although Arago's failing health and his difficulties with the experiment's arrangement prevented him from undertaking this experiment, he had taken steps to show its feasibility in deciding between the corpuscular and wave theories of light. Taking up Arago's experiment, Fizeau and Foucault were committed "To complete the downfall of this poor theory of emission" so that they might "give it the fatal blow, it was only a matter of performing [Arago's] famous experiment."[64] Ultimately, both men would arrive at nearly identical constructions, and considering that they both lacked the intent to make accurate determinations of the value of the speed of light in air and water during these trials, the slight differences between the two experiments are of little concern.[65] [66]

Critically both Fizeau and Foucault undertook a major modification of Arago's experiment that would allow them to the judge the difference in the time of transmission of light through air and through water. Arago's plan had originally called for a near instantaneous flash of light to be sent simultaneously through both the air and water to impact the swiftly revolving mirror from which the relative deviations between the images of the rays could be observed.[67] In this way Arago imagined that the flash of light passing through water would arrive at the mirror later than the flash passing through air, thus creating an image on a different section of the mirror. It was clear to both Fizeau and

Foucault that a comparison could not be made during a short enough time so that the light from the water leg of the experiment was not sent to the mirror at each point in its rotation. As such, Fizeau suggested that a spherical fixed mirror be used to return a deflection from the rotating mirror back along its own path to impact the rotating mirror once again after which the deflection would be observed.[68] This method allowed for the use of a continuous beam which would produce something like Arago's flashes only when the mirror was aligned in a definite position, limiting the orientation which would return an image to towards the eyepiece. Although technically flashes were to be observed, each flash was emitted once per revolution of the rotating mirror, such that at velocities above 30 revolutions per second the observed deflection would appear as a continuous image. Fizeau and Foucault would split ways to independently carry out Arago's experiment immediately following Fizeau's breakthrough modification.

Arago's experiment will thus be described in the manner in which it was carried out by Foucault, for it was he who achieved priority in determining whether denser mediums accelerated or retarded light. Sunlight focused by a heliostat would form an image of an interspaced platinum wire. The image of this reticule was then passed through an angled beamsplitter and then a lens on its way to a rotating mirror, the lens serving to mitigate the diffraction which naturally occurs when light passes through water. Angled away from the path the original ray describes on route to the rotating mirror were two concave mirrors, one on each side of this path. These fixed mirrors were both 4m from the rotating mirror with their foci directed at the original image made on the mirror. Along one of these two diverted paths was placed a 3m tube of water through which light would pass on its way back and forth between the rotating and fixed mirrors.

The other path leading to the second fixed mirror was left open so that the light would only pass through air. Foucault's apparatus is pictured below



[69]

While the mirror was rotating a flash of the image of the wire would be sent down the air path and the water path once per rotation when the rotating mirror was appropriately situated for each path. After being reflected by the fixed mirrors of their respective paths, the images would again be reflected by the rotating mirror. Had the mirror not been rotating, but merely set to send the light down either the water or air path, the image would return back through the lens, correcting for the diffraction effects of the water, reflect off the beamsplitter into the micrometer eyepiece, setting the zero point. This zero point was also visible when the rotating mirror, whether it be in motion or not, was oriented perpendicular to the initial path of the ray. Considering then that because the mirror was rotating at a very high rate, it would describe some angular distance during the time it took for light to make its way to and back from the fixed mirror at the end of either path, and the faster the rate of rotation the greater the angular distance that could be described.

The rotation of the mirror during this interval necessarily created a displacement between the original path of light coming from the heliostat and the return path of the final image equal to twice the angle swept out by the rotating mirror. The deflection being equal to double of the angle swept out by the mirror is merely a consequence of the law of reflection. The more time the ray spent in transit between the rotating mirror and the fixed mirror and back, the more time that was allotted for the rotating mirror to spin and increase the deflection of the final image in the eyepiece. As such, the path which was shown to produce the greatest deflection was associated with a slower velocity of light, a consequence of that path's medium.

As the speed of light was known to be particularly high, both the angle described by the rotating mirror and the angle twice its size seen in the eyepiece would necessarily be particularly small. Increasing the deflection of the final image was a priority, so as to allow for an accurate determination of the difference between the velocities of light in water and air. The distance between the fixed mirrors and rotating mirror was limited due to the impracticality of observing a ray through any significant length of water due to excessive diffraction. This left increasing the rate of rotation of the mirror as the only viable option to increase deflection. Increasing the speed of the mirror while still preserving the clarity and stability of the final image was wrought with practical difficulties. Foucault was forced to abandon his intricate geared system which drove the rotating mirror after it was shown to be self-destructive and imprecise at high velocities. As a result, Foucault employed a 24-bladed steam turbine to drive his mirror and achieve some precision in setting its speed.[70] Subsequently, a long process of dynamically balancing the rotating mirror so that it spun around a principal axis was undertaken to insure smooth rotation and to avoid any lateral forces or vibrations in the bearings. Adjustments in this balancing process were made by gauging the increase or decrease in the violence of the system. The mirror was also made double sided, to double the quantity of light passing to the fixed mirrors on each rotation, providing a more distinct final image. Finally, a system of continuously feeding oil lubricant to the apparatus was devised to overcome some of that residual irregularity in the mirror's rotation.[71]

A screen with a narrow slit was introduced to the concave mirror of the air path so that the reticule image of the water path would not be obscured by the strong light surrounding the reticule image of the air path upon observation.[72] With this modification in place, Foucault finally observed successive and simultaneous images of the air path and water path reticules on April 27th 1850, finding them to be unequally displaced at the same rate of rotation.[73] As he had expected, the displacement of the water path image was further right than that of the air path. At speeds between 600 and 800 revolutions per second, deviations were at most 0.3mm.[74] Foucault would also note that the ratio of the displacements of the water and air paths was approximately equal to the ratios of the indexes of refraction of water and air. Due to the inaccurate estimation of the rate of rotation of the mirror by means of the comparison of the pitch of the noise coming from the bearings to a tuning fork, no accurate determinations of the speed of light in water or in air could be derived. Nevertheless, Foucault had established that light moves faster in air than in water, a confirmation which for many seemed to signal the ascendancy of the wave theory and the death of the corpuscular theory of light. Foucault presented his findings to the *Academie* on May 6th 1850, along with a suggestion of how to modify the experiment to obtain absolute measurements of the speed of light.[75] Fizeau, hampered by bad weather, did not announce his own similar confirmation until June 17.[76]

Leon Foucault

In 1861 Le Verrier supplied funds for Foucault to undertake a new terrestrial determination of the speed of light in hopes of finding a larger and thus according to Le Verrier, more accurate value for solar parallax. Le Verrier's work on the mutual gravitational effects between planets had led him to conclude that the values of solar parallax deduced from observation and those computed by use of Fizeau's 1849 determination of the speed of light were too small.

The method and apparatus used in Foucault's 1862 determination would again make use of Wheatstone's rotating mirror and a single fixed concave mirror in an arrangement similar to Foucault's 1850 experiment. The relevant improvements to the original setup were as follows: (1) an extension of the distance between the rotating and fixed mirrors to a length of approximately 20m, (2) a change in the device which drove the rotating mirror, and finally (3) a wholly disparate method of measuring the speed of rotation.[77] The increase in distance would affect a proportional increase in the time of transit of light by five times, thus also increasing the deflection from the rotating mirror by a factor of five. The non-uniformities in the steam turbine were mitigated by the switch to a turbine powered by pressurized air from an organ bellows built by the organ builder Cavaille-Coll.[78] This system would allow Foucault to stabilize the speed of his rotating mirror with much greater confidence. Abandoning the tuning fork method used in 1850, Foucault would utilize stroboscopic effects created by a spinning toothed wheel paired with a clock device to measure the rate of rotation of mirror.[79] With the clock used to identify the timing of flashes of light, the stroboscopic effects would cause the rotating mirror to appear to move non-continuously, allowing Foucault to accurately judge the rate of rotation of the mirror. Foucault claimed that a speed of approximately 400 revolutions per second could be preserved for several minutes with errors of only 1 part in 10,000.[80]

Despite Foucault's modifications he found his determinations of the velocity of light were far more discordant than was suggested by his apparatus. He would eventually isolate inaccuracies in the micrometer as the principal cause of this discordance and decided upon a strange alteration to compensate for the resultant errors. Keeping the inaccurate micrometer in use, Foucault placed it, as well as the beamsplitter, heliostat and toothed wheel upon a movable base. The distance of this system from the rotating mirror was set so that the displacement of the reticule image was always 0.7mm.[81] The general layout of the experiment is pictured below, where R is the rotating mirror, S is the heliostat, L is the lens and M is the fixed concave mirror. The eyepiece and beamsplitter as well as the moving carriage are not pictured.

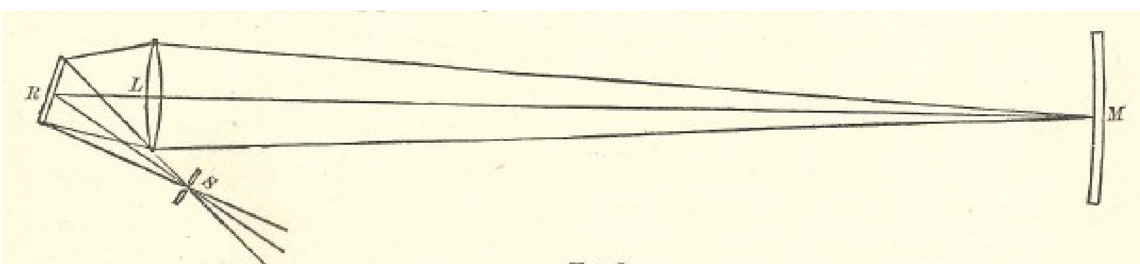


Fig 2.

After completing a trial, Foucault would calculate the speed of light utilizing *l*, the distance between the rotating mirror and the fixed mirror, *n*, the rate of rotation of the mirror, *r*, the distance between the rotating mirror and the final image at the micrometer, and d, the deflection of the reticule as measured by the micrometer. As such, the velocity of light in air was found to be:[83]

This equation is merely a clever transformation of a simple rate equation. As the light must pass over the distance between the mirrors twice, the distance travelled is to be $2l$. The time of passage being too quick to measure directly, it was defined by distance between the micrometer eyepiece and the rotating mirror, the deflection always remaining constant.

Half of the tangent of the angular displacement of the image, $d/2r$, is equated to the angular movement of the rotating mirror during that same time by the law of reflection. When this term is divided by $2\pi \times n$, or the total angular displacement of the mirror in one second in radians, the result is the fraction of a second required for the rotating mirror to sweep half the measured displacement, or put more simply the light time.

Through his use of this formula and an average of his 20 results for velocity, Foucault arrived at a value of 298,000km/s for the velocity of light with an underestimated probable error of 500km/s.[84] The solar parallax value derived by Foucault from his speed of light determination, 8.86″ confirmed Le Verrier's suspicion that the prior values were too small.[85]

Of the sources of error leading to Foucault's undervalued velocity of light, some are described in Fizeau's manuscripts, such as the eccentricity of the rotating mirror's surface, complex refraction effects due to vortices formed by mirror spinning through the air, contortions of the face of the mirror due to centrifugal forces, and finally the unwanted convergence of the faces of the beamsplitter.[86] Foucault having set the deflection as a constant, put his confidence in the exactness of his measures of distance and of his measure of the rate of rotation of the mirror. In actuality Foucault did record deflection values above and below 0.7mm for all of his trials except for the last four. Considering Foucault's aforementioned admission regarding the micrometer's accuracy, these 16 measures are to be treated with much skepticism. Equally unlikely is the perfect alignment of the last four measures of deflection, which are claimed to coincide exactly with 0.7mm. The most significant source of error is nonetheless Foucault's inaccurate estimation of the rotating mirror's rate. Foucault's acceptance of 400 revolutions per second as the rate of revolution across all of his trials is in complete contradiction to his own method. If the rate remains constant but the distance of the moving setup changes, preserving a constant deflection of 0.7mm would necessarily become impossible, implying that his estimation of accuracy for this measure was overstated.

The Import

The reaction within the physics community to the successful completion of Arago's experiment, that it supposedly signaled the death of the corpuscular theory of light, was wholly unjustified. Although the experiment did confirm that light travelled slower in denser mediums, a phenomenon fully expected by the wave theory of light, the superimposition of unessential hypotheses onto the corpuscular theory of light resulted in its premature elimination. Following from Descartes the component of the velocity of a light ray parallel to the surface of the water was supposedly conserved in a manner analogous to the law of reflection when the ray "refracted" into the water. Corpuscular theory explained this phenomenon as due to a lack of force on the particles of light in that direction.[87] Combining this conservation hypothesis with the observation that upon penetrating the water, the refraction angle is smaller than the incident angle, it is necessarily implied through simple geometry that the speed of light has been increased. Appeals were also made to the transmission of sound which had been observed to increase in speed when propagating through denser mediums, drawing on Descartes' conception of light as an immaterial pressure wave. Nevertheless, these conceptions of refraction and of light itself were fundamentally flawed. The tangential velocity is not conserved, nor is light a pressure wave. After removing these assumptions we see that Arago's experiment can form no judgment regarding the superiority of the corpuscular or wave theories of light. Both theories are compatible with the fact established by Arago's experiment, that light moves slower in denser mediums.

The primary importance of Fizeau and Foucault's work defining absolute values for the speed of light was its relevance to solar parallax. Although Fizeau's determination was merely intended to show the possibility of terrestrial measures of the speed of light, Foucault's determination was undertaken with the clear intention to discover a larger value of solar parallax. The value of solar parallax is a representation of the Sun's apparent displacement according to an Earth based observer, caused by the heliocentric orbit of the Earth. This displacement is necessarily proportional to the mean Earth-Sun distance, which is the measure coveted by astronomers. The method of calculating solar parallax will be discussed in greater detail in the next chapter. Despite Foucault's underestimated mean value of the speed of light his calculated value of solar parallax was still too high as a result of inaccuracies in the other constants which make up the formula to calculate solar parallax from the speed of light. Nevertheless, Foucault's smaller value of solar parallax would allow for a notable increase in the accuracy of orbital tables.

James Clerk Maxwell

By 1862 James Clerk Maxwell had already calculated the speed of propagation of an electromagnetic field. Later he would note his calculated velocity was commensurate with the values of the speed of light determined earlier in the century, leading him to assume that light is an electromagnetic wave. In fact commensurable values in units of velocity had been obtained as early as 1855 by Wilhelm Eduard Weber and Rudolf Kohlrausch through their Leyden jar experiments measuring electrostatic and magnetic forces.[88] Maxwell's 1864 publication *A Dynamical Theory of the Electromagnetic Field* critically makes use of his correction to Ampere's circuital law, first developed by Maxwell in his 1861 work *On Physical Lines of Force*. Adding to Ampere's assertion that a magnetic field could be generated by an electrical current, Maxwell showed that a magnetic field might also be generated by changing electric fields. This correction allowed Maxwell to derive a wave equation from the equations of magnetic force and those of electromotive force. The wave consists exclusively of magnetic disturbances where the direction of magnetization was in the plane of the wave or else it would not be propagated as a wave at all. It is described as similar to the transverse nature of any disturbance in light to the direction of its propagation.[89]

Maxwell cites Weber and Kohlrausch's constant value in velocity units, which is shown to be equal to the velocity of the plane wave in air. This equality is proven by the deriving the same equation for the velocity of the plane wave as an earlier formula linking the electric elasticity in a particular medium to the number of electrostatic units in one electromagnetic unit. Although the value cited is in meters per second, Weber and Kohlrausch's constant value was inferred from measurements of electric and magnetic forces. This constant was determined by measuring the electromotive force of a charged condenser of known capacity and then measuring the discharge of the condenser with a galvanometer to record the quantity of electricity.[90] It was Maxwell who first realized the similarity of this electromagnetically determined velocity value of 310,740km/s to the earlier speed of light measures of Fizeau, which he lists as 314,858km/s, and more recently Foucault, 298,000km/s.[91] Maxwell also lists an astronomically deduced value of light stemming from the combination of the constant of aberration and solar parallax that is more strikingly similar, 308,000km/s, to the electromagnetic determination.[92]

The Import

The commensurable values of velocity deduced from these experiments appeared to show that light was just another form of electromagnetic wave. Maxwell would remark, "The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws."[93] Establishing light as an electromagnetic wave would provide perhaps the ultimate justification of the Huygens wave theory of light. Most importantly however, the speed of light had taken on new significance outside of astronomical corrections. The speed of light was shown to be a governing constant of electromagnetism and the field of optics instantly became a subsection of electromagnetism. Not only would this discovery expand the field of electromagnetism, but it would open the door for different increasingly accurate kinds of electromagnetic determinations of the speed of light which might then be used in astronomy.

Michelson and Newcomb

Throughout the late 19th century Albert A. Michelson and Simon Newcomb would both make increasingly more accurate terrestrial determinations of the speed of light based upon the rotating mirror method made famous by Leon Foucault. Both Michelson and Newcomb worked in varying capacities for the United States Navy. Michelson returned from a special appointment to the Naval Academy to become a physics and chemistry instructor there beginning in 1875 and Newcomb took advantage of staff vacancies in the Naval Observatory (resulting from the outbreak of the American Civil War) to obtain employment as an astronomer and professor of mathematics in 1861. In 1878 Michelson began preliminary measurements of the speed of light utilizing a modified construction of Foucault's apparatus, sparking the interest of Newcomb who by then had already begun planning to undertake his own measurement. Once Michelson's trials had finished in 1879, Newcomb brought him to Washington DC where Michelson assisted Newcomb, by this time the director of the Nautical Almanac Office, until Michelson accepted a position at the Case Institute. This collaboration forged a lifelong friendship and mutual respect between the two scientists.

Albert A. Michelson

Michelson notes that by 1877 a modification of Foucault's setup had suggested itself to him.[94] He implies this modification takes its inspiration from the principal objection of Marie Cornu to Foucault's method of the determination of the speed of light. Nevertheless, this objection was undoubtedly made manifest to any keen experimenter and physicist. Cornu's objection concerned the magnitude of the deflection by which Foucault measured the speed of light, arguing that it was too small to allow for suitably accurate measurement. Michelson's modifications would thus be aimed at increasing the magnitude of this deflection so that more accurate measurements could be made. Larger deflections would naturally make the inherent uncertainties of measurement a smaller proportion of the measured value. As such, a relatively inexpensive revolving mirror capable of a mere 128 turns per second was installed at the laboratory of the Naval Academy in 1878.[95] Using a distance of 500ft between the rotating mirror and the fixed reflector, Michelson obtained deflections around twenty times those described by Foucault. From these informal trials Michelson derived a mean value for the speed of light, 300,140km/s $\pm$ 480km/s.[96]

A private donation of $2,000 afforded Michelson the opportunity to acquire new more precise instruments, although he would forgo the purchase of these new components until further testing indicated what would be the ideal setup to achieve a large, clear and stable deflection.[97] Michelson's preliminary tests had shown that even at 500ft between the rotating and fixed mirrors the limited amount of light entering the eyepiece made for an imprecise image due to irregularities in the atmosphere. During tests along the north sea-wall of the Academy at a distance of 2,000ft, Michelson would find an optimal distance between the illuminated slit and rotating mirror and the rate of revolution for the rotating mirror, 250 revolutions per second, needed to achieve a clear deflection of approximately 100mm.[98] Additionally, these trials suggested that a larger lens and rotating mirror should be used. After the procurement of the specific instruments suggested to him during the course of his observations, Michelson finally began to collect data to be used in his determination of the speed of light on June 5th 1879.[99]

Ultimately the arrangement of Michelson's apparatus would remain very similar to that of Foucault. Where Michelson diverged was in his use of a fixed plane mirror instead of Foucault's array of five fixed concave reflectors, the actual image being of an illuminated slit and not a reticule, and his repurposing of the lens which sat between the rotating mirror and the fixed mirror.[100] The image of a reticule diffuses more quickly across a distance than an illuminated slit. Foucault placed the lens as near as possible to the rotating mirror simply to form a distinct image of the reticule at the distant fixed concave mirror, meaning that light would only return from the fixed mirror when the rotating mirror swept the initial image of the slit across the face of the fixed reflector. This presents a serious practical problem when attempting to increase the deflection of the return image by increasing the distance between the rotating mirror and the fixed mirror because an increase in this distance will necessitate an increase in the size of the mirror so as to return a similar proportion of the light. Thus, according to Foucault's arrangement, the dimensions of a mirror required to achieve the magnitudes of deflection that Michelson was striving for were prohibitively unreasonable. Michelson would overcome this difficulty, making possible trials over much longer distances than Foucault, by placing a lens of large focal length further from the rotating mirror, taking care that the image of the slit remained at the fixed mirror. The repurposing of the lens also makes the concavity of the fixed mirror redundant. The lens keeps the light in the same line it described emanating from the rotating mirror (on its return), thereby performing the role of Foucault's concave mirror by appropriately refocusing the light on its return to the rotating mirror. In this way, the experiment is viable over a longer distance as more light is preserved by the setup, specifically any light which refracts through the lens will form an image on the surface of the fixed plane mirror. A simple schematic detailing Michelson's apparatus is pictured below. S represents the illuminated slit, R is the rotating mirror, L is the lens and M is the fixed plane mirror.

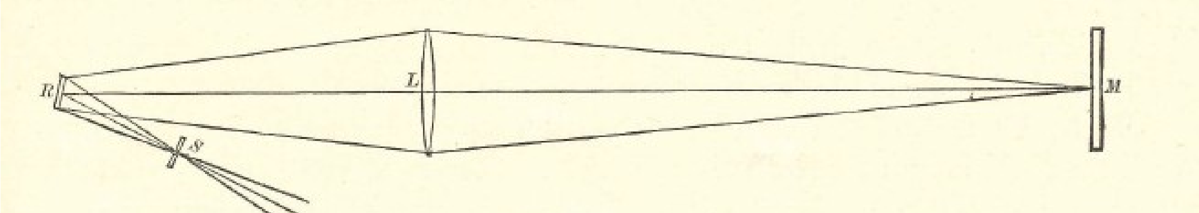


FIG. 1.

Michelson did encounter some conflict in maximizing the displacement of the return image. This displacement is measured as the tangent of the arc subtended by it. Maximizing this measurement hinges on increasing the distance between the rotating and fixed mirrors, increasing the difference between the focal length of parallel light rays and the focal length for rays at the fixed mirror, and of course increasing the speed of the rotating mirror.[102] Increasing this distance means the light will require a longer time in transit to return to the rotating mirror, allowing the mirror to describe a greater angular distance and to create a greater displacement of the return ray. Increasing the speed of rotation of the mirror will produce a similar effect; the mirror will simply be able to describe this greater angular distance in less time. The increase in the difference between the focal length of parallel rays and that for rays at the fixed mirror produces a brighter and more exact image. As the distance between the mirrors increases, however, the difference in the focal length of parallel rays at the lens and the focal length for rays at the fixed mirror decreases. Michelson's solution was twofold; he used a lens of extreme focal length and placed the rotating mirror within the principal focus of the lens, increasing this difference in focal lengths.[103] Nevertheless, there was a limit to the amount that the displacement could be increased by moving the lens closer to the rotating mirror. The quantity of light diminishes as the rotating mirror nears the lens.

Michelson's attempt to maximize the deflection determined the setup for his experiment. The placement of the lens, the distance between the rotating and fixed mirrors, and the high speeds of the mirror were all consequences of a need for greater accuracy in determining the speed of light.

A heliostat reflected sunlight through a slit that created an image on the revolving mirror. From here this image was reflected and passed out of the temporary frame building which housed all of this the apparatus, out along the north sea-wall of the Naval Academy first to the lens and then the distant fixed mirror.[104] In the short time light spends in transit from the rotating mirror to the fixed mirror and back, the rotating mirror covers a certain angular distance. As a result the returning image of the slit is deflected in the direction of rotation through twice this same angular distance swept out by the mirror. A movable micrometer eyepiece records the position of the bisection of the slit, which is bolted to the same frame as the eyepiece, and is moved to record the position of the deflected return image, while an electric tuning fork is used to obtain the revolutions per second of the rotating mirror.[105] That this deflection is twice the angular distance described by the mirror is a trivial consequence of the law of reflection.

Calculating the speed of light from the obtained deflections and recorded revolutions per second is made more complicated by necessary conversions to suitable units and the inclination of the plane of rotation of the mirror (so as not to immediately return direct reflections of light from the slit back into the eyepiece, but above or below it). Michelson does account for these factors; however, for the purposes of this investigation they are not of primary importance. Therefore, where V is the velocity of light, D is twice the distance between the revolving and fixed mirrors, n is the number of revolutions per second and φ'' is the angle of deflection in seconds of arc:[106]

Here 2,592,000″ is simply twice the angular value of one complete rotation, 360°, in arc seconds. Multiplying by two here serves to halve the value of deflection in the denominator, making it equal to the angular distance traversed by the rotating mirror during the trial according to the law of reflection. As such, we see that the formula is a very simple expression of velocity where the distance the light travels, D, is divided by time, expressed here as the fraction of the angular distance covered by the mirror measured by the deflection.

Michelson's published (unweighted) mean value for the velocity of light in air determined over the course of his 1879 trials is listed as 299,944km/s with an average difference from the mean of approximately 51km/s and a probable error of ±5km/s.[107]

The accuracy of Michelson's determination of the velocity of light is contingent on (1) the stability and uniformity of his apparatus and (2) the accuracy of his measurements of deflection, the rate of rotation per second, and distance. As regards the distance between the mirrors, measured five times by a weighted tape, Michelson and Professor Rogers of Cambridge were confident that, because of their precision in measurement, the "total error due to D would be at most .00004."[108] Measuring the speed of rotation by use of Michelson's electric tuning fork is more complicated. It is unlikely that there is any serious error in the standard tuning fork used to calibrate the electric one. Equally unlikely is any significant error resulting from the interaction between the forks during calibration. The standard fork was kept and independently rated at the Stevens Institute, as well as being tested against two other forks. All testing showed that any interaction between the forks was entirely undetectable. Nevertheless, it seems there is room for error in noting the exact time that the image of the mirror reflected from the fork came to rest, an event signaling a convergence of the fork's frequency with the mirror's rotational speed. Although Michelson attempted to eliminate this source of error by measuring the speed of the mirror sometimes during its acceleration and other times during its deceleration, such a treatment cannot guarantee proper nullification of this error.[109] The determination of the moment that the image stabilizes is still up to the discretion of the observer and measuring this to achieve accuracy to the hundredths of revolutions per second seems wishful at best. In fact, it was known to Michelson that the electric fork could alter its vibrations up to two hundredths per second.[110]

Michelson's measurement of the deflection of the light ray is particularly accurate in its method; however, there are some issues with Michelson's initial consideration. The value of one turn of the screw that moves the micrometer eyepiece was determined for each part of the screw in terms of the standard meter; any noticeable error would have to originate from irregularities in the standard meter.[111] Professor Rogers of Cambridge would later make an independent confirmation of the reliability of this copy of the standard meter.[112] Distortion of the mirror due to its rapid revolutions would produce either multiple images (which were not observed), or a distortion of the image that would not affect the measurement of the deflection.

Michelson does err in his consideration of the function tan (), as he misrepresents the distance between the front face of the rotating mirror and the crosshair of the micrometer as a base of the considered triangle as opposed to its hypotenuse.[113] Soon after in his report, Michelson suggests a temperature correction for φ, resulting in an increase in 12km/s in his determination of the speed of light.[114] In a subsequent investigation urged by Newcomb, however, Michelson finds this correction to be inappropriate and removes it.[115] The combination of these two improper corrections yields a speed of light figure which is 34km/s higher than the value that Michelson's data implies.

After removing the 34km/s error and multiplying the resulting mean velocity of light in air by the index of refraction of air, thereby reducing it to a vacuum, Michelson's value for the speed of light stands at 299,910 $\pm$ 50km/s.[116]

Simon Newcomb

Simon Newcomb's publication on his determination of the velocity of light during the years 1880 to 1882 illustrates his keen awareness of the history of this measurement, and his willingness to learn from and improve on the work of those who came before him. Newcomb traced the development of terrestrial determinations of the speed of light from Galileo's initial proposal of shuttered lanterns, to its natural successor in Fizeau's toothed wheel.[117] By the time he received word of Michelson's preliminary trials in 1878, Newcomb's own plan to investigate the velocity of light had already rapidly advanced. In fact, many of the modifications to Foucault's setup that Newcomb would implement during his 1880s trials were conceived of more than a decade prior in 1867 as a direct response of Newcomb to Foucault's work. In March of 1879 Newcomb received $5,000 in funding from the Department of the Navy for the task of making a new determination of light's velocity.[118] Despite lacking an account of the precision with which Michelson was concurrently conducting his own experiments, Newcomb was impressed by Michelson's ability. Newcomb accordingly extended an invitation for Michelson to join him in Washington DC. Although Michelson left early for the Case Institute in September 1880, Newcomb would continue his trials until 1882, ultimately returning what was recognized as the most accurate value for the speed of light at that time.[119]

So then what modifications did Newcomb make so that his experiment far exceeded the accuracy of those of Michelson and Foucault? Newcomb was well aware of the need to increase the deflection in Foucault's setup; however, his creativity in negating sources of error and imprecision is what truly sets his experiment apart from any of his predecessors. The general arrangement of Newcomb's apparatus is mostly familiar: a focused light source emits parallel rays towards a rotating mirror from which they are reflected to a distant fixed mirror and then back again to the rotating mirror. In the time the light spends moving to and from the fixed mirror the quickly rotating mirror would have described some angular distance, thereby displacing the returning ray by twice that angular distance covered by the mirror.

Similar to Michelson the year before him, Newcomb looked to expand the distance between the rotating and stationary mirror so as to increase the resulting deflection. A lens was still needed to manage the light ray either between the illuminated slit and the rotating mirror or between the two mirrors. Placing the lens between the slit and the mirror would be counterproductive to the goal of achieving large deflections, as anything but very small deflections would create a major source of uncertainty as they passed through different parts of the lens.[120] Certainly placing the lens between the mirrors creates alternate sources of error. As the lens' focal length is increased so as to increase the amount of light transmitted, it compounds the errors due to atmospheric vibrations over the distance. Newcomb was forced to mitigate the atmospheric errors exacerbated by the lens by limiting his observations to times of "fine atmospheric definition."[121] Nevertheless, the most damaging error resulting from placing the lens between the mirrors was that an image of the lens would be returned with the image of the slit, illuminating the field of view and complicating observations. To counteract this unwanted illumination Newcomb used one telescope to send the image and another in the same vertical plane to receive the return image (their relative positions were interchangeable).[122] Telescopes had become necessary to resolve the image of the slit due to Newcomb's very ambitious expansion of the distance between the mirrors to around 3 to 4km. This bifurcation of the observation process is perhaps the most important modification of Foucault's experiment, heralding new possibilities for experimental accuracy. The zero point from which displacements were measured was eliminated, allowing for observations to occur on the first mirror no matter its direction of revolution. Inherent in measuring the displacement from a zero point is an uncertainty stemming from the different character of the two images. Henceforth, Newcomb calculated the velocity of light based on the difference between the displacements of two trials at differing mirror velocities (high positive and negative velocities).[123]

The fixed mirror was made concave as in Foucault's experiment, permitting the experimenters to focus the return ray back along a specified but distinct path. In doing so

Newcomb insured less ambient light would enter the receiving telescope. The rotating mirror was a polished steel rectangular prism, which, although not as aerodynamic as the circular mirrors of Foucault and Michelson at high velocity, provided more horizontal space to accept incoming and outgoing light rays on different parts of the surface. More surface area on the rotating mirror had become required due to Newcomb's efforts to darken the field of the receiving telescope and permit the observation of fainter images.[124] The greater warping effects upon this wider rectangular shape at high speed made the heavier, but more structurally rigid, choice of a prism a practical solution. The prism would also send more light through the apparatus (by the addition of reflective surfaces) as well as lessening the disturbance of the air surrounding the mirror and the potentially confounding effect of the air vortices.

Without a zero point to reference, Newcomb's experiment took on a very unfamiliar method. The coupled sending and receiving telescopes were secured in place along an arc with its focus at the revolving mirror. The position of the telescopes along the arc was precisely recorded with the aid of two microscopes.[125] Light rays emitted from the sending telescope would then be transmitted to the revolving mirror and then out of a small hole in the structure housing this mirror. The rotating mirror and accompanying structure was first located at Fort Myer, moving then to the central post of the United States Army signal service at Fort Whipple. Having passed out of this structure the ray would then be reflected back by the concave fixed mirror. This fixed mirror was first located on the grounds of the Naval Observatory; however, as Newcomb's trials progressed and a larger distance was deemed amenable, it was moved to a point near the base of the northwest corner of the Washington Monument.[126]

Returning then through a separate hole in that first structure, the light ray would again be reflected by the rotating mirror, although by a different point on its surface, finally passing into the receiving telescope. Nevertheless, the micrometer in the receiving telescope was not adjusted to capture the position of return image. Instead the observer played with the velocity of the rotating mirror until the return image appeared stationary between the parallel preset wires. The observer indicated the time during which the image was trapped between the wires with a telegraph key which when depressed would interrupt the recording of the speed of the mirror by the specially modified chronograph.[127] An approximate weight indicating the clarity and stability of the image observed, on a scale of 0-5, was included for each trial.[128] After additional measurements to insure the telescopes had not moved, both were reset elsewhere along the arc, the mirror was set to run in the opposite direction, and the rest of the process was subsequently repeated. Once both of these trials had been completed, Newcomb would have enough data for one determination of the speed of light.

In the formula that follows T represents time required for light to traverse twice the distance between the rotating and fixed mirrors, or as Newcomb puts it "the time in which the mirror, turning with an indicated speed, will move through half the arc indicated by the measures."[129] The symbol Δ'' stands for the difference between the angular readings of the telescopes' positions along the arc during the two trials, as taken by the microscopes (in seconds of arc). h is the factor to reduce chronometer seconds to mean solar seconds, a factor which changed during each of the three years of the experiment. v represents the algebraic difference between the number of revolutions of the mirror during one chronometer second in each trial. As in Michelson's report, 2,592,000″ is simply twice the number of arc seconds in one complete revolution. Similarly the doubling is again due to the need to halve Δ″ so as to translate the observed difference in angular readings to the difference between the angular distances described by the rotating mirror, according to the law of reflection. As such, the formula becomes:[130]

If we introduce a term D corresponding to twice the distance between the two mirrors so that we can solve for the velocity of light in air (*V)* we are left with:

In this form it is clear how similar Newcomb and Michelson's methods really are. Ignoring the addition of the term *h* in Newcomb's formula due to his choice of a chronometer, the only difference in their calculations is that Newcomb's does not contain a zero point and thus must utilize the differences in angular positions and rates of revolution from two trials.

Newcomb's calculated mean velocities for light in air differ appreciably between the three seasons of trials. The mean value in 1880 was 299,615km/s, in 1881 it was 299,682km/s and in 1882 it was 299,766km/s.[131] As Newcomb improved on the apparatus and method between the seasons, he regarded the value determined in 1882 as the most reliable. Regardless, Newcomb would provide a weighted mean of all three years (heavily favoring 1882) and return a speed of 299,728km/s for light in air.[132]

As Newcomb configured his experiment, the accuracy of his determination of the speed of light will be contingent on the precision with which he observed these variables. Newcomb is quick to make clear, "The differences of these results far exceed the probable errors arising from the accidental differences between the separate daily means."[133] Comparing the least and greatest obtained velocities for light for each of the three years of his trials, 1880-1882, there is a range of over 400km/s.[134] Even during 1882, the year in which Newcomb was confident that he had accounted for most if not all constant error, the range between the least and greatest velocities exceeds 100km/s a factor of ten larger than the limit of probable error due to separate measures.[135] What then are the possible sources of systematic discrepancies in his determination?

Newcomb provides a list of four hypotheses upon which the experiment is based, "which may possibly need modification":[136]

I. That the motion of the revolving mirror is uniform in running.
II. That the figure of the mirror remains invariable.
III. That the angle of reflection is always equal to the angle of incidence.
IV. That the changes in the direction of the ray thus reflected are correctly measured by the angular motion of the receiving telescope around the axis of the revolving mirror.

As regards the first of these hypotheses, Newcomb is aware that because of the system of air-blasts and fan blades which regulates the rate of the rotating mirror, the pressure on and thus the revolution of the mirror is necessarily non-constant. Nevertheless, he derives what is essentially a gross maximum account of the possible error due to this simplification, insisting it could not exceed an inconsequential 4km/s.[137]

That the second of these hypotheses is in error is made less persuasive by Newcomb's choice of a steel prism instead of a plane mirror and the attachment of this mirror on both its top and bottom to the fan wheels which set it in motion. While observations before 1881 appeared to have shown some effects of torsional vibration (images from different faces of the prism separated in the direction of motion) corrections to the orientation of the sending and receiving telescopes negated this effect going forward.[138] The lack of any apparent systematic variance in the observations of 1882 seems to corroborate Newcomb's account. In combining the data from his three years of observation some error was introduced as the pivots of the revolving mirror were reground between each of the three series, likely changing the torsional vibration.[139] Regardless, changing torsional vibration during the rotation of the mirror would not affect the reliability of the law of reflection.

Although Newcomb may have mitigated the torsional vibration in the system by 1882, he undertook an intricate study to determine the observable effects of a fault with hypothesis four. Newcomb noted that three sides of his prism were slightly convex and thus a 12km/s correction was added to the final speed of light determination.

By 1882 Newcomb claimed to have accounted for any significant sources of systematic error. Nevertheless, his mean value for the velocity of light in 1882 was larger than that determined in 1881, which similarly was larger than that determined in 1880. Of these three years it is the mean of his determinations in 1881 which is closest to the modern value. As a result of the lower values in 1880 and 1881, the weighted mean of all three years is very near the modern value. The first season of trials beginning in 1880 having been conducted over a distance nearly 1000m shorter (2000m shorter as the distance is covered twice by the ray), it is apparent in Newcomb's tables that this setup either could not or was not asked to achieve the larger differences in deflection recorded in the years following.[140] Additionally, there are more uncertainties noted in the observations due to unclear images, untimely disassemblies of the apparatus, problems with the microscopes, as well as issues with the regulation of the mirror's speed.[141] As such, it is not surprising that this low series from 1880 is the most divergent from the modern value.

Still, why are Newcomb's 1881 values appreciably closer to the modern value for the speed of light despite his insistence that the 1882 trials were of greater reliability? It does not stem from difference in *h* values during the two years. Although it is tempting to pin this on the change in chronometers, the 1881 chronometer kept very good sidereal time while the 1882 mean time chronometer lost approximately 1.2s per day; however, this correction actually increases the velocity of light in 1881 relative to 1882, contrary to the phenomenon requiring explanation.[142] It seems that this oddity may not be a true experimental problem at all. If we investigate the dates in 1882 which Newcomb incorporates into his calculation for the mean time of transit, there are a limited few which drag down the mean time for light to cross twice the distance. Despite Newcomb's low weighting of the observations on July 31st and August 9th 1882, both combined to steer the mean time of passage away from the mode.[143] Although their influence only affected the mean value by 0.0005 millionths of a second, the difference between Newcomb's mean time and the modern time for light to cross this distance is only about .0039 millionths of a second. These two sets of observations also happen to be the first recorded instances of Newcomb's associate J.H.L. Holcombe acting as the experiment's observer.[144] Newcomb also notes the particularly poor conditions afforded on the 31st of July, resulting in the serious discordances between trials on that day and giving more reason as to why it should not have been included. If the trials from these two days are removed from the mean, Newcomb's mean values for time and thus the velocity of light are equally distributed on either side of the modern values. That the mean value for the velocity of light for all three years is closer than that of 1882 is the result of a coincidence wherein errors during the experiments in 1881 and 1882 happened to yield values greater and less then the currently accepted speed. Nevertheless, even by eliminating the “bad trials”, the supposedly more reliable 1882 data still expresses a mean velocity of light which is too high.

The record of the distance between the rotating mirror and the fixed mirror, be it at the Observatory station or the station at the Washington Monument, is perhaps the least likely source of any significant constant error. The accuracy achieved by the triangulations of these distances was shown to be in error by less than 5cm.[145] Determinations of the position of the telescopes along their arc were also made very accurately, using two cross-checking microscopes on either side. Considering that the rotating mirror and telescopes were sheltered from direct sunlight, temperature changes were very mild, shielding the integrity of these measurements of angular position along the metal arc.

To calculate the speed of light in a vacuum from the determined speed of light in air the index of refraction for air (at the appropriate temperature and pressure) is applied to achieve the reduction to a vacuum. At this time Newcomb was already aware of a second experiment by Michelson that appeared to show that the index of refraction of a medium is not sufficient to reduce the speed of light calculated in that medium to its speed in a vacuum. Although Michelson’s experiment seemed to show that the given index of refraction of carbon disulphide was too small, Newcomb considered any proposed correction to the index of refraction of air to be insignificant and unworthy of the effort.[146] [147] Using the unadjusted value for the index of refraction of air, Newcomb adds 82km/s to his 1882 value for the speed of light (in addition to the 12km/s for the curvature of the prism), determining that light travels 299,860 ± 30km/s in a vacuum. [148]

What then is the source of Newcomb's error in determining the velocity of light in 1882? It seems most likely that mistakes in determining the rate of rotation of the mirror in one second were the major contributors. The mirror was geared so that every 28th revolution of the mirror was recorded on a sheet by the chronometer in addition to its record of mean seconds.[149] In Appendix II of Newcomb's report he readily admits that, although the measurements to determine the rate of revolution were made to the hundredths, "it may be assumed that the mean accidental error of the measurements is several hundredths, possibly five or more."[150] If we look into a trial generating a value around Newcomb's mean velocity for light, an adjustment of approximately 6 hundredths of a revolution combined over one positive and another negative trial yields the modern value for the speed of light. Thus, errors of this order of magnitude are enough to create the disparity between Newcomb's values for the velocity of light and the modern value. Additionally, the limit on the error here helps to explain why the 1881 and 1882 determinations are distributed so evenly about the modern value.

Michelson and Newcomb's values for the speed of light, 299,910 ± 50km/s and 299,860 ± 30km/s respectively, are nearly identical. The difference between the two is just slightly more than the probable error incurred by observation in Newcomb's experiment and just within that of Michelson's trials. As it happens Michelson's value for the speed of light is less than 118km/s higher than the modern value, while Newcomb's value is approximately 62km/s greater; the difference for both is only slightly more than twice their respective bounds. Newcomb's omission of a zero point ultimately did not set his experiment much apart from Michelson's, as the latter measured his zero directly from the illuminated slit itself. Perhaps Michelson should be commended for getting almost equally accurate results over a shorter distance.

The Import

What then was the point of all this effort and expenditure? Certainly Fizeau, Foucault, and Cornu had previously generated speed of light values that were still satisfactory for most physicists' purposes. Michelson may have simply been fascinated with the problem of measuring the speed of light; however, for Newcomb this experiment was a necessary component serving his ambition to "devote all the force which he could spare to the work of deriving improved values of the fundamental elements and embodying them in new tables of the celestial motions."[151] The speed of light was merely one constant among many that Newcomb would seek out through experimental and observational means. The codependence of these constants upon one another was described in detail in Newcomb's *The Elements of the Four Inner Planets and the Fundamental Constants of Astronomy*. As regards the speed of light in a vacuum, a more accurate terrestrial value paired with the best available figure for the constant of aberration yields a correspondingly accurate value for solar parallax. As the magnitude of solar parallax is naturally fixed by the size of the Earth's orbit, and thus knowing one allows the astronomer to calculate the other. The formula relating the aberration constant, the speed of light and solar parallax is as follows: where κ is the constant of aberration, V is the speed of light, n is the Earth's mean motion, and e is the eccentricity of Earth's orbit, then the mean distance between the Earth and the Sun is equal to:

With a known value of the radius of the Earth the mean distance can be translated into the angular measure known as solar parallax. Newcomb investigated this relation between the constants from both directions, using the constant of aberration and the speed of light to determine solar parallax, but also using a measured value for solar parallax and the speed of light to calculate a value for the aberration constant. Nevertheless, the preferred orientation is towards improving solar parallax; its measured values were known to err appreciably, and its fundamental role in determining so many astronomical relations renders its precision invaluable. Newcomb would ultimately make use of Nyren's value of the constant of aberration, 20.492″, to obtain a value for solar parallax of 8.794″.[152] This value of solar parallax agrees exactly with the modern value within the level of accuracy to which it was given.

Newcomb was interested in creating the most accurate orbital tables possible, and as all astronomical measurements were determined in astronomical units, or the mean Earth-Sun distance, a more accurate value of solar parallax would describe more accurate orbits. This is particularly true for those three other inner planets which track orbits only a fraction of the mean Earth-Sun distance from the Sun or in the case of Mars fractionally further from the Sun than this mean distance. As the astronomer is not in the Earth's center, but set somewhere on the surface, the apparent position of the celestial object is displaced in the same direction as the Earth's center relative to the observer, an error that can be corrected with terrestrial units provided solar parallax. For these planets and small errors in solar parallax can equate to gross misrepresentations of their orbital distances because they constitute a greater proportion of that planet's distance from the Sun.

Therefore, the more precision that is applied to determining the speed of light, the more accurately the orbits of the (particularly interior) planets can be described.

The use of solar parallax is not limited to the determination of planetary orbits. Within his *Elements* Newcomb describes solar parallax's relation to the parallactic inequality of the Moon, and its use with Kepler's third law to obtain the mass of the Earth. With the mass of the Earth, the necessary ratio between Earth's mass and that of the Moon will supply the lunar mass. A combination of the Moon and Earth's masses and the solar parallax gives Newcomb the mass of the Sun. Thus the increase in accuracy of the determination of the speed of light has wide ranging implications for astronomy. Not only were planetary and lunar orbital distances calculated to a higher accuracy, but the solar, lunar, and terrestrial masses were made more precise as well.

The exactness which Michelson and Newcomb brought to their determinations of the speed of light was exported to the related constants and astronomical measures. The probable error in the speed of light set approximate boundaries on the variability of other constants, giving at least an account of the extent of the precision of the resultant orbits and masses. By increasing the general standard of precision in these astronomical measurements, more support is given to the theories guiding them. Bradley's theory of aberration, and Newtonian gravitation itself were bolstered by the general increase in accuracy at least partly owed to Michelson and Newcomb's speed of light determinations. Still this increase in accuracy was not just a method of supporting existing theory, but also an attempt to discover new irregularities within existing theory and to better understand existing irregularities. The anomalous precession of the perihelion of Mercury had already been discovered by Le Verrier in 1859, estimated then to be around 38″ per century. As such, Newcomb was understandably interested in detecting more deviations from Newtonian theory, in addition to correcting the magnitude of this precession. His more accurate value of solar parallax yielded a more precise figure for the mass of the Earth that then factored into calculating the Newtonian effects on Mercury.[153] This theoretic procession could then be subtracted from the observed value, eventually yielding the more accurate 43.37″ per century. Both the corrections to Mercury's precession and the search for additional discrepancies in Newtonian theory were made possible by the general increase in astronomical accuracy afforded by his experiments and observations. The interlocking nature of the physical constants sets a limit on the possible error present in any one figure, as any error would need to be expressed in the other constants as well, thus setting a standard of accuracy that observations must achieve so as to confirm theory. Michelson's and Newcomb's more accurate values for the speed of light indirectly contributed to a revolutionary shift in astronomical accuracy, helping set the values for other constants with such accuracy that the world over (other than France) would recognize that all ephemerides should be based on Newcomb's work.

On Measuring the Speed of Light

What sits at the core of this paper is a tale illustrating how modern science has achieved ever increasing accuracy in determining the speed of light. The technical aspects of this process have been covered, experiments have been described and their precision and error investigated. But what of the process of measurement itself, what is it to measure a quantity which cannot be directly observed, and what was the relevance of these measurements to astronomy and physics?

Returning to the beginning of this investigation, Ole Rømer introduced the speed of light as a hypothetical explanation for an apparent relation linking the distance between Jupiter and the Earth and the observed delay of the Jovian satellites. An astronomical quantity of questionable accuracy was derived by Rømer to represent this hypothetical relation; however, the simplification and explanation of the relation detailing the satellites' delays could hold no weight in establishing whether or not light travelled at a finite speed. Initially, the function of Rømer's equation of light was entirely limited to astronomical corrections for light time, most specifically corrections to tables of the eclipses of the Jovian satellites.

Although Rømer is celebrated for this discovery, Cassini's reluctance to accept the hypothesis of light's finite transmission was well founded. The relation connecting the Earth's distance from Jupiter and the delays in the eclipses of the satellites of that planet is entirely independent of Rømer's explanation for the cause of such a peculiar correlation. Even if Rømer had also given a complete account of how Jupiter's distance from the Sun affected the observed delays, he could hold no claim to having established that the speed of light is finite. Indeed Rømer could only account for the irregularity in the orbit of the innermost satellite, and with physics still very much in its infancy, merely hint at possible explanations for the residual perturbations in those other three. It is only in retrospect that we may say Rømer was the first to determine the speed of light, knowing now that his explanation of the observed phenomena was correct (albeit highly inaccurate).

Rømer's explanation for the equation of light was entirely isolated from the rest of physics at the time. His explanation was not an essential consequence of the apparent relation between the locations of the two planets' and the delay in the Jovian satellites. What then makes James Bradley's discovery of the aberration of light worthy of confirming that light travels at a finite speed?

Bradley's theory of the aberration of light employed an entirely disparate method to determine a similar astronomical value for the speed of light to Rømer's. The theory of the aberration of light was arrived at through careful observation of the systematic variance in the motion of the stars caused by the Earth's yearly orbit around the Sun. After two years of observations, the phenomenon could be isolated from the confusion of stellar motions by its relation to the Earth's position, more specifically to its velocity. Bradley's mathematical formulation of the observed stellar oscillations actually included the hypothetical speed of light in relation to the velocity of the Earth.

The general agreement on a value for the speed of light between approaches which are so unlike one another is beyond coincidence. Although the values differ from one another by around a third of the modern value they are of the same order of magnitude. The convergence of these values around a speed which was so much larger than any other previously determined lent great credence to hypothesis that light was transmitted at a finite speed. Bradley's formula accounted for the apparent displacement of stellar position, incorporating a value for the speed of light, one which ultimately would be determined from the observed value of stellar aberration it supposedly governed. Thus, that light travelled at finite speed was an essential element of Bradley's theory; however, so was that the Earth was in motion around the Sun. Confirmation of heliocentrism would not come until 1838 when Bessel first measured stellar parallax. As such, we must say that Bradley's theory confirmed the speed of light insofar as it determined a very similar value to that of Rømer, contingent on the assumption that the Earth was in orbit around the Sun.

Bessel's observation of stellar parallax itself would have been indistinguishable from the amalgam of stellar movement without the prior discoveries of the aberration of light and later that of nutation. Additionally, nutation itself only became apparent after Bradley observed yearly deviations of around one arc second from the pattern he had established for the aberration of light.

Bradley's discovery makes clearer the problem of measurement in physics. As the speed of light was not at that time directly observable or measurable, theory was employed to allow astronomers to indirectly ascertain this quantity. In this way our measurements become inherently theory mediated, meaning their veracity relies upon certain other assumptions. In Bradley's case it is not merely an assumption that the Earth is moving; the value he calculates for the speed of light is relative to the value he had previously obtained for the "vertical" component of the Earth's velocity. Inaccuracies in measuring the velocity of the Earth would necessarily alter his determination of the speed of light, as would any future observations of aberration which differ from Bradley's results.

What then was the true crucial experiment that established as fact that light is not transmitted instantaneously? Perhaps it was when Bessel measured stellar parallax, eliminating the assumption of heliocentrism from Bradley's theory. Perhaps it was when Laplace worked out the Jupiter Saturn interaction and the resonance effects of the Jovian satellites such that the only remaining delay in the eclipses of the exterior satellites coincided with the revised accounts of the equation of light within the limits of observational accuracy, putting Newtonian gravity in a position to support the finite speed of light. More likely is that there are no crucial experiments in science. What occurs is the buildup of interlocking theories and in the case of this history the convergence of wholly disparate methods upon similar values for the speed of light. Discoveries are not built upon prior science; they are reinforced by, while simultaneously providing evidence for prior science.

During the time of Rømer and Bradley only astronomical determinations of the speed of light were made, its immense velocity seemingly limiting measurements to the cosmic laboratory. Terrestrial values for the speed of light could only be obtained by combining the astronomical value for the speed of light with observationally determined values for solar parallax. These conversions were made sparingly, as a terrestrial value provided no real benefit to physics, and with little hope for accuracy due to the difficulty in observing a precise value for solar parallax. Nevertheless, this three way relation between an astronomically defined speed of light, solar parallax and the terrestrial value for the speed of light would become increasingly relevant during the 18th century as terrestrial determinations of the speed of light were undertaken.

Operating on the understanding that the accepted value of solar parallax was too small, Fizeau and then later Foucault would make terrestrial determinations of the speed of light with their toothed wheel and rotating mirror apparatuses respectively. Naturally there was less prior theory involved in these terrestrial determinations, mostly simple optics, and thus the similar more directly obtained values offered yet more evidence for the theory that light moved at a finite speed and for all those theories which had been employed previously by Rømer and Bradley to arrive at their astronomical determinations of the speed of light. The speed of light, now a terrestrially determined value, along with better values for the constant of aberration afforded greater accuracy in calculating solar parallax. More accurate values of solar parallax were computed with Fizeau and Foucault's speeds; however, for Fizeau the importance lay merely with showing the possibility of terrestrial determinations, not with yielding a value of supreme accuracy.

Fizeau and Foucault are often better known for their reproductions of Arago's experiment to determine whether light moved faster in air or water. The rotating mirror apparatus used by both illustrated with much directness that light propagates faster in air than in water. Both men undertook their determinations with the intention of confronting and finally eliminating the corpuscular theory of light. With corpuscular theory adherents implying that light would travel faster in denser mediums, and supporters of Huygens' wave theory arguing for exactly the opposite scenario, Arago had designed the experiment performed by Fizeau and Foucault as an *experimentum crucis*. As such, most took Foucault and then later Fizeau's results that light travelled faster in air than it did in water as signaling the death of the corpuscular theory. While the experiment may have signaled a large drop in the corpuscular theory's popularity within the scientific community, it was far from a final proclamation on whether light was a wave or a particle. That light move faster in denser mediums was not an essential consequence of it being made up of particles; Arago's experiment had merely eliminated the corpuscular theory as it had been formed, showing certain background assumptions dating back to Descartes to be false, although having no significance as regards the constitution of light.

The advent of James Clerk Maxwell's work in electromagnetism would finally liberate the speed of light from its role as a simple astronomical correction, bestowing upon this value a newfound relevance in physics. In his 1864 article *A Dynamical Theory of the Electromagnetic Field*, Maxwell laid out his newly formed wave equation. Herein Maxwell worked out that the constant term, equal to the electrical permittivity of space multiplied by the magnetic permeability of space, is the inverse square of a velocity term. Numerical determinations made by his contemporaries showed this velocity to be nearly equal to those determined by Fizeau and Foucault. The striking similarity of these values for velocity led Maxwell to incorporate light into the class of electromagnetic phenomena. As Maxwell had yielded wave equations describing the propagation of electromagnetic disturbances of which light was now an example, the wave theory of light could enjoy greater credibility. As with Rømer and Bradley, the unexpected convergence of two values presented strong evidence for Maxwell's claim that light was an electromagnetic wave. Maxwell's merging of optical and electromagnetic phenomena placed new significance on the value of the speed of light. The speed of light henceforth would govern relations in electromagnetism in addition to its role in astronomy. Its speed in various mediums could be predicted through measurable electric and magnetic properties of that medium. The conceptions of light and electromagnetic waves were fundamentally united as a direct result of the agreement between accurate measures of the speed of light and the theoretical consequences of Maxwell's equations, a merger which would both provide opportunities for new methods of determining the value of the speed of light and increase the significance of making these ever more accurate determinations of the speed of light.

Michelson and Newcomb's rotating mirror experiments later in the 19th century would conclude in even more accurate, direct determinations of the speed of light. Newcomb's expressed goal in undertaking his experiment was to achieve greater accuracy in the speed of light so as to combine it with recent observations improving the accuracy of the constant of aberration, thereby arriving at a more precise value for solar parallax. Newcomb's more accurate value for solar parallax facilitated his calculation of more accurate interior planetary orbits and masses. These more precise masses made up part of his correction to Le Verrier's evaluation of the anomalous precession of the perihelion of Mercury, and helped Newcomb to evaluate other astronomical phenomena in search of similar deviations from Newtonian gravity. Thus, while the speed of light was once corroborated by filling in irregularities in Newtonian theory, an increase in its accuracy left the constant with an integral role in the search for faults in the most tested scientific theory ever. As the 19th century came to a close, the speed of light was no longer the hypothetical and imprecise astronomical correction conjured up 200 years prior; rather, it had become a highly accurate cornerstone of both electromagnetism and astronomy, and the unifying force in electromagnetism's embodiment of optics.

1 Galileo Galilei, *Two New Sciences*, trans. Stillman Drake (Toronto: Wall & Emerson, 2000), 50

2 Ibid.

3 Pierre Duhem, *The Aim and Structure of Physical Theory*, (Princeton: Princeton University Press, 1954), 33

4 Rene Descartes, Correspondence to Beeckman Aug. 22, 1634, in *Correspondences*, ed. P. Tannery and C. Adam, vol 1, Letter LVII, 307

5 Ole. Rømer and I. Bernard Cohen, *Roemer and the First Determination of the Velocity of Light (1676)*, < http://www.jstor.org/stable/225757> (University of Chicago Press, 1940), 340

6 Ibid., 341

7 Ibid., 343

8 Ibid., 344

9 Laurence Bobis and James Lequeux, *Cassini, Rømer and the Velocity of Light*, <https://docs.google.com/viewer?url=http%3A%2F%2Fwww.bibli.obspm.fr%2FBobis%2520and%2520Lequeux.pdf> (Journal of Astronomical History and Heritage, 11(2), 2008), 102

10 Ibid., 99

11 Ole. Rømer and I. Bernard Cohen, op.cit., 379

12 Ibid., 350

13 Ibid., 351

14 Ole Rømer, Correspondence to Huygens Sept. 30, 1677, in *Œuvres completes de Christiaan Huygens*, vol 8, Letter 2104, <http://books.google.com/ebooks/reader?id=Zjy_waNB5j8C&printsec=frontcover&output=reader&pg=GBS.PA32>, 52

15 Ibid.

16 Ole. Rømer and I. Bernard Cohen, op.cit., 351

17 Ole Rømer (1677), op.cit., 50f

18 Ibid.

19 Edmond Halley, *Monsieur Cassini His New and Exact Tables for the Eclipses of the First Satellite of Jupiter, Reduced to the Julian Stile, and Meridian of London*, < http://www.jstor.org/stable/102468> (Philosophical Transactions, vol 18, 1694), 239

20 Ibid.

21 Ole. Rømer and I. Bernard Cohen, op.cit., 378

22 Ibid.

23 Ibid., 379

24 Mary Somerville, *On the Connexion of the Physical Sciences*, ed. 5 (London: John Murray), 34-37

25 Halley, op.cit., 256

26 Ibid.

27 Ibid.

28 Isaac Newton, *Philosophiæ Naturalis Principia Mathematica*, trans. I Bernard Cohen and Anne Whitman (Berkeley: University of California Press, 1999), 625

29 Ole. Rømer and I. Bernard Cohen, op.cit., 354f

30 Christiaan Huygens, *Treatise on Light*, trans. Silvanus P. Thompson <http://www.gutenberg.org/files/14725/14725-h/14725-h.htm>, 9

31 A.P. French, *Special Relativity*, (New York: W.W. Norton & Company Inc., 1968), 41

32 If my efforts to prove Bradley's observational abilities are deemed insufficient, the reader should consult Book III Proposition 42 of Newton's *Principia*. Here Bradley's skill as an astronomer is on full display, his observations of the comet of 1723 deviating less than a single minute from Newton's calculated longitudes and latitudes.
Newton, op.cit., 936

33 R.T. Gunther, *Early Science in Oxford*, (vol. 8 Oxford 1923-45), 27-28

34 French, op.cit., 43

35 Thomas Thomson, *History of the Royal Society: from its institution to the end of the eighteenth century*, <http://books.google.com/books?id=nqjjR4Qt9IgC&ots=0_ShC-ZacL&dq=Thomson%E2%80%99s%20History%20of%20the%20Royal%20Society&pg=PR6#v=onepage&q&f=false> (Printed for R. Baldwin, 1812), 346

> At no point in my research have I encountered any reference by Bradley or his contemporaries, be it in publications, letters etc, to this cruise. It seems that Bradley's extensive work determining longitudes by the eclipses of Jupiter's moons is a more likely source of his epiphany regarding the speed of light.

36 James Bradley, "A Letter to Dr.Edmund Halley, Astronom. Reg. &c. giving an account of a new-discovered motion of the fixed stars", in *Miscellaneous works and Correspondence* <http://books.google.com/books?id=41M_AAAAcAAJ&pg=PA1#v=onepage&q&f=false> (Philosophical Transactions N°. 406 vol. 35, 1728), 12

37 The modern spelling of this east London suburb has become Wanstead.

38 Ibid., 12

39 Ibid.

40 Bradley's claim has proven to be true; his mean speed of light time from the Sun to Earth is less than 2% off from the modern value of approximately 8′ 20″.

41 Ibid., 10

42 Ibid.

43 Ibid.

44 James Bradley, "A Letter to the Rt. Hon. George Earl of Macclesfield, concerning an apparent motion observed in some of the fixed stars", in *Miscellaneous works and Correspondence* <http://books.google.com/books?id=41M_AAAAcAAJ&pg=PA17#v=onepage&q&f=false> (Philosophical Transactions N°. 485 vol. 45, 1748), 23

45 Ibid., 23

46 James Bradley, Correspondence to Mr. Maupertuis Oct. 27, 1737, in *Miscellaneous works and Correspondence* <http://books.google.com/books?id=41M_AAAAcAAJ&pg=PA391#v=onepage&q&f=false>, 409

47 Bradley (1748), op.cit., 25

48 Bradley (1738), op.cit., 411

49 Bradley (1748), op.cit., 31

50 Ibid., 36

51 James Bradley (1728), op.cit., 11

52 Ibid., 11

53 Ibid., 15

54 William Tobin, *The Life and Science of Léon Foucault: The Man who Proved the Earth Rotates*, (Cambridge University Press, 2003), 124

55 Hippolyte Fizeau, Comp. Rend. Acad. Sci. (Paris) 29 (1849), 90-92

56 Tobin, op.cit., 123

57 Fizeau, op.cit., 92

58 Ibid.

59 Ibid.

60 Ibid., 90

61 Ibid., 91

62 Ibid., 92

63 Simon Newcomb, "Measures of the Velocity of Light", in *Astronomical Papers Prepared for the Use of the American Ephemeris and Nautical Almanac*, vol 2, pt III, (Washington: U.S. Nautical Almanac Office, 1891), 117

64 Tobin, op.cit., 124

65 Henceforth both experimenters' apparatuses were referred to as the Fizeau-Foucault apparatus, another suggestion regarding the similarity of the two experiments.

66 Here I must admit to my inability to locate the Comptes Rendus containing Fizeau's short account of his experiment and its role in limiting this discussion.

67 Newcomb, op.cit., 117f

68 Tobin, op.cit., 124

69 Ibid., 125

70 Leon Foucault, "Pour Mesurer la Vitesse de la Lumiere", in *Recueil des travaux scientifiques de Léon Foucault*, <http://books.google.com/books?pg=PA180&vq=vitesse+de+la+lumi%C3%A8re&dq=Recueil+des+travaux+scientifiques+de+L%C3%A9on+Foucault+translation&id=yYIIAAAAMAAJ&ots=xBzj8rS52o#v=onepage&q=vitesse%20de%20la%20lumi%C3%A8re&f=false> (1850), 177

71 Foucault, op.cit., 178

72 Ibid., 207-211

73 Ibid.

74 Ibid.

75 Tobin, op.cit., 128f

76 Ibid., 129

77 Leon Foucault, “Determination Experimentale de la Vitesse de la Lumiere”, in *Recueil des travaux scientifiques de Léon Foucault*, <http://books.google.com/books?pg=PA180&vq=vitesse+de+la+lumi%C3%A8re&dq=Recueil+des+travaux+scientifiques+de+L%C3%A9on+Foucault+translation&id=yYIIAAAAMAAJ&ots=xBzj8rS52o#v=onepage&q=vitesse%20de%20la%20lumi%C3%A8re&f=false> (1862), 222-226

78 Ibid., 217-221

79 Ibid., 222-226

80 Ibid., 224

81 Ibid., 222-226

82 Albert A. Michelson, “Experimental Determination of the Velocity of Light”, in *Astronomical Papers Prepared for the Use of the American Ephemeris and Nautical Almanac*, vol 1, pt III, (Washington: U.S. Nautical Almanac Office, (1880), 117

83 Foucault (1862), op.cit., 223

84 Ibid.

85 Tobin, op.cit. 232

86 Ibid., 233

87 Ibid., 132

88 James C. Maxwell, *A Dynamical Theory of the Electromagnetic Field,* <http://docs.google.com/viewer?url=http://upload.wikimedia.org/wikipedia/commons/1/19/A_Dynamical_Theory_of_the_Electromagnetic_Field.pdf> (1864), 499

89 Ibid.

90 Ibid.

91 Ibid.

92 Ibid.

93 Ibid.

94 Michelson (1880), op.cit., 115

95 Ibid.

96 Ibid.

97 Ibid., 116

98 Ibid.

99 Ibid.

100 Ibid., 117

101 Ibid.

102 Ibid., 108

103 Ibid.

104 Ibid., 116

105 Ibid., 121

106 Ibid., 132

107 Ibid., 141

108 Ibid., 140

109 Ibid.

110 Ibid., 121

111 Ibid., 126f

112 Ibid., 127

113 Albert A. Michelson, "Supplementary Measures of the Velocities of White and Colored Light", in *Astronomical Papers Prepared for the Use of the American Ephemeris and Nautical Almanac*, vol 2, pt IV, (Washington: U.S. Nautical Almanac Office, 1891), 243

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115 Michelson (1891), op.cit., 243

116 Ibid., 244

117 Newcomb (1891), op.cit., 116

118 Ibid., 120

119 Ibid.

120 Ibid., 123

121 Ibid., 124

122 Ibid., 124f

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124 Ibid., 126

125 Ibid., 131

126 Ibid., 183

127 Ibid., 168f

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134 Ibid.

135 Ibid.

136 Ibid., 194-195

137 Ibid., 195

138 Ibid., 196

139 Ibid., 172-191

140 Ibid., 194

141 Ibid., 172-183

142 Ibid., 170

143 Ibid., 194

144 Ibid., 187

145 Ibid., 212

146 Michelson (1891), op.cit., 256

147 Newcomb (1891), op.cit., 201

148 Ibid., 201

149 Ibid., 127

150 Ibid., 215

151 Simon Newcomb, *The Elements of the Four Inner Planets and the Fundamental Constants of Astronomy*, <http://books.google.com/books?id=wCpLAAAAMAAJ&printsec=frontcover&dq=The+Elements+of+the+Four+Inner+Planets+and+the+Fundamental+Constants+of+Astronomy&source=bl&ots=DnaD1FVGOr&sig=_M5HLi_x-PunJXfAh0VhfATikYs&hl=en&ei=17G1TZzOJaLk0QG_99iDCA&sa=X&oi=book_result&ct=result&resnum=1&ved=0CBUQ6AEwAA#v=onepage&q&f=false> (1895), iii

152 Newcomb (1891), 203

153 Simon Newcomb, “Discussion and Results of Observations on Transits of Mercury, from 1677 to 1881”, in *Astronomical Papers Prepared for the Use of the American Ephemeris and Nautical Almanac*, vol 1, pt VI, (Washington: U.S. Nautical Almanac Office, 1882), 168-173