feature article

Simon Newcomb, America's first great astronomer

William E. Carter and Merri Sue Carter

In the late 19th century, Newcomb determined the scale of the solar system with an accuracy unrivaled until decades after his death.

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In 1854, at age 19, Simon Newcomb stood outside the gates of the US Naval Observatory in Washington, DC, longing to go inside to see the telescopes and perhaps even meet one of the astronomers. But he had no idea how he might be received; he was not a US citizen and the only knowledge of astronomy that he could claim was what he had been able to glean on his own from a few aged books. He simply could not risk the humiliation of being turned away, he decided, and left without so much as making an inquiry.[1]

Seven years later, in the fall of 1861, Newcomb returned to the Naval Observatory to take up duties as a professor of mathematics. Canadian by birth, he still was not a US citizen, but his commission as a naval staff officer was signed by President Abraham Lincoln. And during the intervening years, Newcomb had spent countless hours studying math and astronomy on his own; worked as a "computer" at the Nautical Almanac Office in Cambridge, Massachusetts; graduated summa cum laude from Harvard University's Lawrence Scientific School; and made an arduous 4000-kilometer round trip from Cambridge to the wilds of central Canada as a member of an American scientific team organized to observe a total eclipse of the Sun.[2]

It was not that Newcomb had set out to earn a position at the Naval Observatory after his aborted visit. He considered Cambridge the intellectual center of the nation and would have much preferred an appointment at Harvard, or perhaps even one as a mathematician at the Nautical Almanac Office; but neither was in the offing. A professorship at the Naval Observatory gained him a secure and respected position in the scientific community, with sufficient income to marry and start a family. And with the nation in the early days of a civil war, there was much to be said for working at an agency essential to the war effort.

A century after his death, it is difficult to imagine how Newcomb might have found a position better matched with his extraordinary talents and ambitions. Washington, DC, may not have been the intellectual center of the nation, but it was the center of power, where the right connections could yield support for scientific research far beyond the means of most academic institutions.

Only months after his return to Washington, Newcomb was fortunate enough to cross paths with Civil War hero General James Abram Garfield. After Garfield won election to the House of Representatives in 1863, he dropped by the Naval Observatory to renew his acquaintance with the young scientist. Newcomb was delighted to find that this "man of classic culture, refined tastes, and unsurpassed eloquence"[1] was truly interested in assisting the advance of science in America. With such a powerful friend in Congress, Newcomb soon found himself selected to lead the highly visible and costly

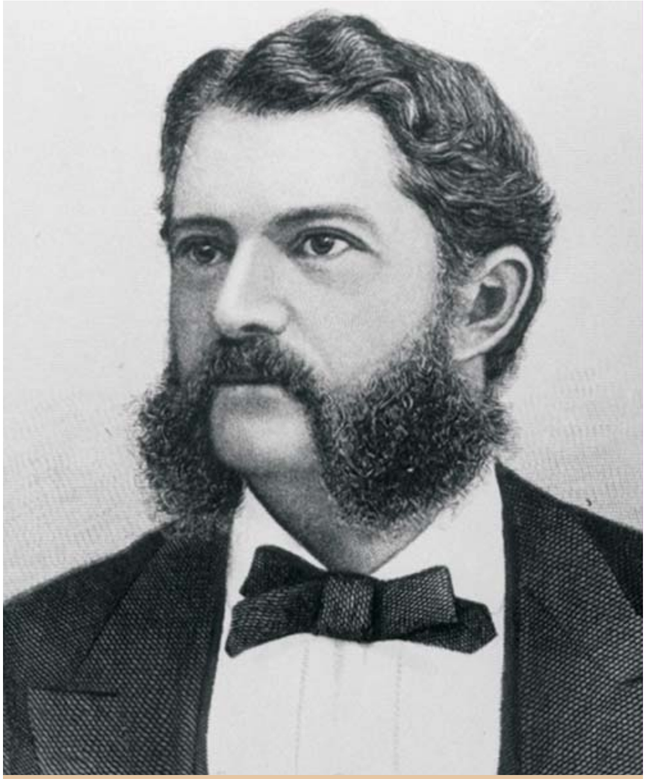

Figure 1. Simon Newcomb circa 1871, the year he was appointed secretary of the American Transit-of-Venus Commission. He was born in Wallace, Nova Scotia, Canada, on 12 March 1835, to John Burton Newcomb, an itinerant grade-school teacher, and Emily Prince, daughter of a New Brunswick magistrate. (Courtesy of the US Naval Observatory.)

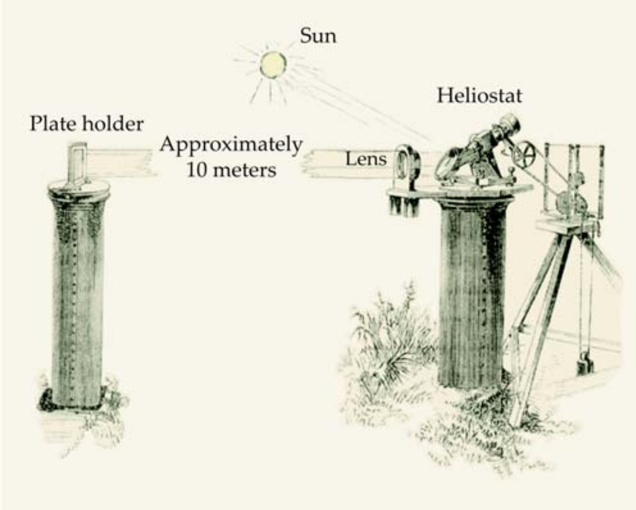

Figure 2. The camera designed by Simon Newcomb to photograph the 1874 and 1882 transits of Venus across the Sun. A heliostat tracked the Sun and reflected its light through a fixed telescope, where the image was focused onto a glass photographic plate. Another glass plate, ruled with a grid of lines and a thin vertical wire attached to a plumb bob, immediately in front of the focal plane, created lines on the Sun's image, as pictured in figure 3. The lines were used to determine the position of Venus relative to the center of the Sun rather than to its poorly defined edge. Hundreds of such photographic images could be made as the planet crossed the face of the Sun. (Courtesy of the US Naval Observatory.)

American transit-of-Venus program and in charge of purchasing the largest-aperture refracting telescope in the world for the Naval Observatory.

By the close of the century, Newcomb was arguably the most renowned astronomer in the world. European scientific institutions and societies showered him with their highest honors, including the 1890 Copley Medal, awarded by the Royal Society of London. Fellow Americans celebrated his achievements with honorary degrees, and in awarding him the first Catherine Wolfe Bruce Gold Medal in 1898, the Astronomical Society of the Pacific proclaimed in its citation that he had "done more than any other American since [Benjamin] Franklin to make American science respected and honored throughout the entire world."

A complete account of Newcomb's many achievements in astronomy, mathematics, physics, and economics is beyond the scope of this article. Indeed, the collection of his works held in the Library of Congress contains more than 46 000 items. We focus on Newcomb's contributions to one of the central astronomical issues of his time: accurately determining the astronomical unit, the distance from Earth to the Sun. Newcomb did everything he could to ensure the success of massive American campaigns to better determine the astronomical unit by observing the transits of Venus in 1874 and 1882. Yet he also set out independently on a different path to reach the same goal. Ultimately, he succeeded in deriving a more accurate value sooner, at a tiny fraction of the cost, and without leaving Washington.[3]

The transits of Venus

Among the books Newcomb worked his way through was Isaac Newton's *Philosophiae naturalis principia mathematica*, more commonly known as the *Principia*. He was greatly impressed by Newton's development of the equations of motion for bodies in the solar system (see the box below), but he was disappointed, as others before him had been, to find that values of the universal gravitational constant G and the mass M of the Sun—or at least their product, GM—were needed to explicitly calculate the semimajor axis of Earth's orbit, or that of any of the other planets. The Sun was still a mystery, and until the physics of its interior was better understood, there was little hope of accurately estimating its mass.

In his 1663 book *Optica Promota*, Scottish mathematician and astronomer James Gregory suggested that one should be able to accurately determine the distance from Earth to the Sun by comparing observations, taken from widely spaced stations of known latitude and longitude, of Venus moving directly between the two bodies. Those transits of Venus are rare on the scale of the human life span. They occur in pairs, one transit separated from the other by eight years, but the pairs themselves are separated by more than a century. In 1716 Edmond Halley submitted to the Royal Society of

The last of the great masters

Simon Newcomb never doubted the fundamental correctness of Newtonian physics and assumed that any apparent anomalies in the observed motions of the planets and moons in the solar system could be explained by imperfect accounting of gravitational interactions among them. Until, that is, he revisited the issue of the anomalous precession of Mercury's orbit, discovered by the French astronomer Urbain Le Verrier in 1855. Using the best observations he could obtain, in 1882 Newcomb found the discrepancy in the precession to be 43 seconds per century, even larger than the 38 seconds per century found by Le Verrier.

Struggling to explain his findings, Newcomb suggested that there might be a disk of fine matter in the inner regions of the solar system with sufficient mass to disturb the orbit of Mercury. He was even willing to consider the possibility that gravitational attraction did not decrease with exactly the square of the distance between bodies. A small increase in the exponent would explain the observations. But Newcomb continued to consider the anomalous precession of Mercury's orbit an unsolved problem for future astronomers to deal with.[8]

The problem was settled in 1915 when Albert Einstein announced his theory of general relativity. The distortion of spacetime caused by the Sun's gravitational field changed the expected precession of Mercury's orbit to almost exactly that found by Newcomb. Einstein was, of course, pleased by the close agreement between Newcomb's findings and his theory of general relativity. Years later, in response to an inquiry from Newcomb's eldest daughter Anita Newcomb McGee, Einstein wrote that Newcomb's life work was "of monumental importance to astronomy" and that he was "the last of the great masters who . . . calculated with painstaking care the motions in the solar system."[9]

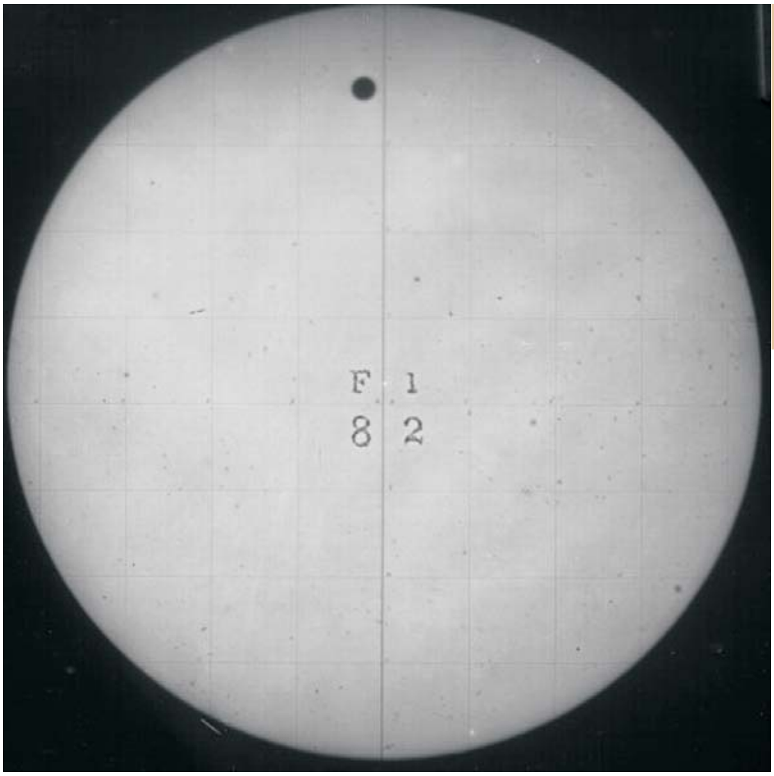

Figure 3. This photographic plate, which captures Venus near the midpoint of its 1882 transit across the Sun, is one of very few such plates that still exist. Thousands were originally taken by American teams during the 1874 and 1882 transits. (Courtesy of the US Naval Observatory.)

London a proposal containing a detailed plan for collecting transit observations, even though he knew that he was unlikely to live to see the next pair of transits in 1761 and 1769. Halley died in 1742, but much of the observing program he proposed was carried out.

Newcomb had reason to assume that he would live to see the 1874 and 1882 transits of Venus and that he would likely participate in any observing campaigns mounted by the US. His first decade at the Naval Observatory flew by. On the personal side of his life, he became a US citizen, married, rejoiced at the births of three daughters, and mourned the death of a newborn son. On the professional side, he initiated observations for a new fundamental bright-star catalog, completed a study of the orbits of Neptune and Uranus, and traveled to Iowa to observe a solar eclipse. In 1869 he was elected a member of the National Academy of Sciences, and in 1870 he made his first trans-Atlantic trip to Europe to observe a solar eclipse and meet the leading astronomers of the UK, France, Germany, and Russia.

As busy as his day-to-day duties kept him, Newcomb still found time to think about the rapidly approaching 1874 transit of Venus. He knew that European nations would mount special programs to observe the event. If Congress could be persuaded to fund an American program, Newcomb wanted to do everything he could to ensure results that were at least equal in quality to, if not better than, the Europeans'.

The traditional method of observing a transit was to record the precise times that the edges of the planet and the Sun appeared to come into contact—twice as the planet moved onto the face of the Sun and twice as it moved off of it.[4] The relative motion between Venus and the Sun, as seen from Earth, is slow. Typically, it takes about 20 minutes between the first and second contacts and 20 minutes between the third and fourth contacts, which happen several hours later. Newcomb knew that different observers at the same location often disagreed on the exact time of each contact. The disparities were large enough to cause Captain James Cook to record his concern about the accuracy of observations collected by members of his expedition in Papeete, Tahiti, in 1769. Estimates of the astronomical unit derived by different researchers using observations of the 1769 transit varied by as much as 5%—roughly 7.5 million kilometers.

One problem in observing transits by eye was that there was no way for observers to practice. Four planet–Sun contacts that occur once, or at most twice, in a lifetime hardly provide opportunities to develop skill. But there was an even more fundamental problem: The Sun has no fixed, sharply defined edge. Each observer had to draw an edge in his own mind's eye. Newcomb concluded that the only hope of collecting observations of the upcoming transits that would yield an estimate of the astronomical unit to better than about 1%, about 1.5 million kilometers, was to use the emerging technology of photography.

Newcomb was appointed secretary of the American Transit-of-Venus Commission in 1871 (figure 1). His duties included preparing programmatic and budget information for submission to Congress. Garfield, chairman of the House Appropriations Committee, invited Newcomb to his private residence to discuss the enterprise over dinner. There would be no contentious hearings with politicians grilling scientists over every dollar requested. Garfield himself would steer the budget requests through Congress, with Newcomb providing any needed information as the process played out. Over the life of the eight-year program, the special appropriations alone, not including general funding, totaled $375 000, over $7 million in 2009 dollars.

Based on advice from experts with experience photographing the Sun, Newcomb designed a new and unique camera consisting of a heliostat, long-focal-length telescope, and photographic plate assembly[5] (see figures 2 and 3). While the cameras were being built, he prepared detailed instructions to ensure that the observations collected by the American teams would be of the highest possible accuracy.

Determining longitude at remote sites remained a challenge. Even the best clocks available might drift seconds during the weeks it would take observing teams to travel to the more distant sites. Telegraphic time comparisons were inconvenient at best and often unreliable or impossible, especially when they relied on transoceanic cables, which suffered frequent failures. By observing lunar occultations when known stars move behind the edge of the Moon, observers could accurately determine longitude using a clock that remained stable for periods of time as short as a few hours. Newcomb was distressed to find that the best available lunar tables differed

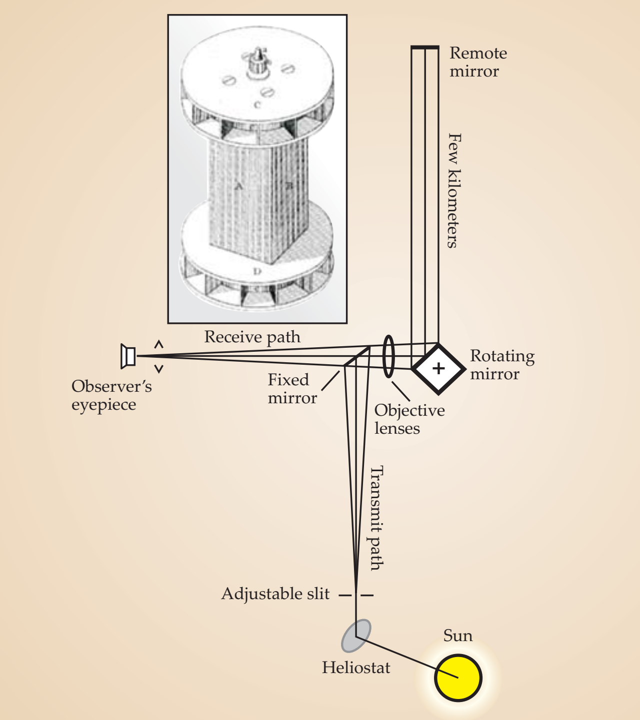

Figure 4. Measuring the velocity of light. In Simon Newcomb's experiment, a heliostat reflected sunlight onto an adjustable slit in the focal plane of a lens, which produced a bright collimated beam of light. The light reflected from a four-sided rotating mirror (inset), traveled to and from a remote mirror, and was then reflected to an observer's eyepiece. The angle between the transmit and receive paths, which were offset vertically to avoid glare in the eyepiece, was set so that the return image of the slit could be centered on cross hairs by finely adjusting the angular velocity of the rotating mirror. The rotation of the mirror during the light's travel to and from the remote reflector was divided by its angular velocity to obtain the light's roundtrip travel time. The rotating mirror rested on a diamond pivot and was driven—typically at 200–250 rotations per second—by a pair of air turbines, one above and the other below, which acted in concert to minimize twisting of the mirror. Each turbine had pairs of adjustable air jets that allowed the observer to spin the mirror in either direction and finely adjust its angular velocity.

significantly from recent observations, so he created special tables to be used by the transit-observing teams.

Newcomb did not join any of the teams sent out to observe the 1874 transit. Nor did he process the observations to estimate the astronomical unit—that task was turned over to William Harkness, another mathematics professor at the Naval Observatory. Newcomb did travel to South Africa to observe the transit of 1882, but that was more to meet David Gill, director of the Royal Observatory at the Cape of Good Hope, who shared Newcomb's interest in better finding the scale of the solar system. Newcomb may also have wanted to get away from Washington and clear his mind after Garfield's death.

Garfield was elected president in 1880. On 2 July 1881, he was shot by an assassin. Newcomb helped devise an air conditioning unit for the White House sickroom and arranged for Alexander Bell to build an induction balance to help the physicians search for the bullet lodged in the president's abdomen. Tragically, Garfield suffered for more than 10 weeks before dying of a massive abdominal infection. Newcomb was deeply saddened by the death of the "only truly honorable" politician he had ever known.

Velocity-of-light experiments

Beginning with his earliest thoughts about deriving the astronomical unit from observations of transits of Venus, Newcomb had strong doubts about the accuracy that could be achieved. He explored other approaches to solve the problem and fixed on a different method.

In 1725 the English astronomer James Bradley discovered that all the stars he observed appeared to move in small ellipses with an annual period and semimajor axis of about 20.5 arcseconds. He concluded that the apparent direction of starlight reaching Earth was altered by the velocity of Earth in its orbit, relative to the finite velocity of light. Bradley called that effect the aberration of light, and he used an approximate value for the velocity of Earth to estimate the velocity of light.

Newcomb proposed to invert the procedure by combining a more accurate value for the velocity of light with recently improved measurements of the aberration of light to better estimate the velocity of Earth along its orbit. Combining that velocity with the period of the orbit would yield the circumference and semimajor axis of the orbit.

Having neither the authority to drop his assigned duties at the Naval Observatory nor the necessary apparatus to conduct velocity-of-light experiments, Newcomb tried to spark interest in the physics community. Unfortunately, a decade passed and no one stepped up to take on the task. In 1877, when Newcomb became the superintendent of the Nautical Almanac Office, which had moved from Cambridge to Washington, DC, he immediately began pressing for funds to do the experiments himself.

Newcomb was surprised when he received a letter, dated 26 April 1878, from Albert Michelson, a young naval line officer assigned to teach physics at the US Naval Academy. Michelson noted that he had read about Newcomb's plans to better measure the velocity of light and went on to describe experiments he was already conducting (see the Reference Frame by Daniel Kleppner in PHYSICS TODAY, August 2007, page 8). Newcomb visited Michelson in Annapolis, Maryland, and was favorably impressed. When Congress finally approved Newcomb's request for funds of $5000, Michelson was reassigned to Washington to assist with the experiments.

During the summer of 1880, Newcomb and Michelson worked together to set up Newcomb's apparatus in a small, temporary observatory located high above the Potomac River on the grounds of Fort Whipple (renamed Fort Myer in 1881), not far from Arlington National Cemetery.[6] The experiments involved using the four-sided rotating mirror pictured in figure 4 to send pulses of light to a reflector located at the old Naval Observatory in Foggy Bottom or to a more distant reflector just a few meters from the northwest corner of the Washington Monument. The line lengths were accurately determined by the Coast and Geodetic Survey using a baseline established on Analostan Island (now Theodore Roosevelt Island), and triangulation. For a map of the arrangement, see figure 5.

How Newcomb managed to accurately measure time intervals of a few tens of microseconds—to within a fraction of a microsecond—requires some explanation. In the latter part of the 19th century, the combination of electrical contacts, or breaker points, and relays or solenoids qualified as leading-

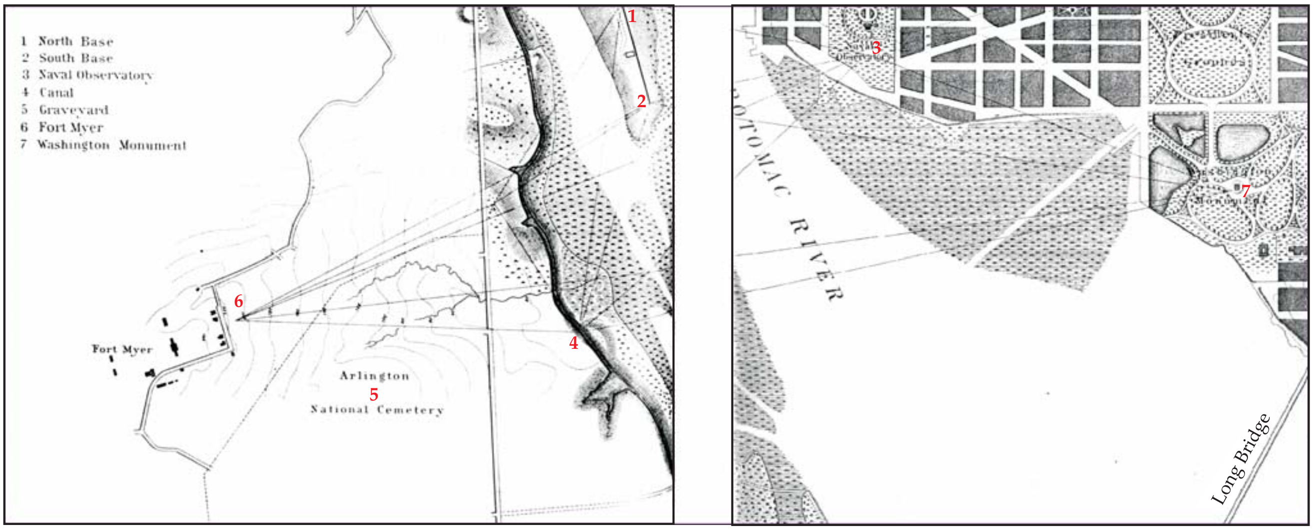

Figure 5. The locations of the temporary observatory and reflectors used by Simon Newcomb and Albert Michelson during velocity-of-light experiments in Washington, DC. The map also shows the triangulation network used by the Coast and Geodetic Survey to measure distances from the rotating mirror (illustrated in figure 4) at Fort Myer to the reflectors at the Naval Observatory (2550.95 meters) and the Washington Monument (3721.21 meters). The experiments were done before the marshlands along the Potomac River were filled and before the Jefferson and Lincoln memorials were built. (Courtesy of the US Naval Observatory.)

edge technology. It enabled reasonably fast, reliable, and automatic on–off switching of electrical devices before the development of vacuum tubes or transistors.

Newcomb used a mechanical clock that had points installed in its workings. The points were used to activate a solenoid in the pen assembly of a drum chronograph and produce tick marks at known times along the timeline drawn by the chronograph. Signals from points on the rotating mirror assembly were also connected to the chronograph, and the tick marks they produced were recorded on the same line. After completing a set of observations, Newcomb could determine the times of the tick marks created by the rotating mirror by measuring their locations relative to the known times of the clock tick marks. By averaging over many thousands of such events, Newcomb was able to determine the mean angular velocity of the rotating mirror and achieve the timing resolution needed for his velocity-of-light experiments.

Newcomb and Michelson worked closely for only a few months, but their brief collaboration proved to be a defining point in Michelson's life. After being granted a leave of absence from the navy to pursue graduate studies in Europe, Michelson resigned his commission in 1881 and accepted a position as a professor at the Case School of Applied Science in Cleveland, Ohio. Newcomb encouraged him to resume the velocity-of-light experiments—even helping to find funding and loaning him equipment. Ultimately, Newcomb and Michelson agreed to combine the values obtained from the Annapolis, Washington, and Cleveland experiments. The resulting mean was widely adopted and remained the accepted standard for more than four decades.[7]

Estimating the astronomical unit

When Newcomb returned from South Africa in 1883, he completed his analysis of the Washington velocity-of-light experiments and published a detailed report.[6] After reviewing the more recent published estimates of the aberration of light, he selected the value found by Swedish astronomer Magnus Nyren, whose observations were collected at the Pulkovo Observatory in Saint Petersburg, Russia. Combining his velocity-of-light and Nyren's aberration-of-light values, Newcomb estimated the astronomical unit to be 149.59 million kilometers, within 0.005% of the value used today.

Five years later, in October 1888, Harkness announced the initial results of his analysis of the transit observations; he estimated an astronomical unit of 148.572 million kilometers, too small by more than 1 million kilometers.[5] Although Harkness and his colleagues refined their calculations the following year, the accuracy of their new value still fell short of what Newcomb had achieved for a tiny fraction of the cost.

Political fall

As talented as Simon Newcomb was, much of his meteoric rise in the national and international scientific communities happened thanks to the support of powerful friends and mentors, including Joseph Henry (secretary of the Smithsonian Institution), Benjamin Peirce (superintendent of the Coast and Geodetic Survey), George Airy (astronomer royal of England), and especially James Garfield. By the end of 1881, Henry, Peirce, and Garfield were dead, and Airy was retired. Past slights, imagined or real, are not easily forgiven in the nation's capital, and Newcomb soon found his budget under attack.

Rather than devoting his time to political infighting, Newcomb decided to do the best science he could with the resources he was granted. With the approval of the secretary of the navy he took a position as a professor of mathematics and astronomy at the Johns Hopkins University in Baltimore, Maryland, and retained his position as superintendent of the Nautical Almanac Office. As a professor, Newcomb lectured, served on advisory committees for graduate students, wrote a calculus text, renewed his interest in economics, and served as editor of the *American Journal of Mathematics*.

In 1893 the Naval Observatory moved to new facilities in northwest Washington, DC, where it remains today; the next year the secretary of the navy issued a regulation making the Nautical Almanac Office a branch of the Naval Observatory. Newcomb bridled at the new bureaucratic structure, though, and continued to pursue his own agenda, often communicating directly with the secretary of the navy. Focusing on goals he had set for himself decades earlier, he worked tirelessly to derive a consistent set of astronomical constants and to compile a fundamental bright-star catalog using virtually all of the observations collected at the world's leading observatories since 1750.

In 1896, at the Paris Conference Internationale des Étoiles Fondamentales, representatives of the leading European nations approved, in principle, Newcomb's system—that is, his table of solar-system parameters (planetary masses, periods, and the astronomical unit) and star positions. Newcomb mandatorily retired from the navy the following year, but Congress appropriated funds for him to tie up any remaining loose ends of his work. His system became the international standard in 1901—except in the US. Old animosities, stoked by Newcomb's joining with other astronomers in pushing to place the Naval Observatory under the leadership of a well-qualified astronomer and perhaps even have it moved to another department of government, made him no longer welcome there. He certainly was not going to get the satisfaction of seeing his system used in the US Nautical Almanac. Not until 1912, well after his death, did Newcomb's system become the standard for the almanac.

Newcomb spent the last decade of his life working on what he saw as the ultimate challenge—accurately predicting the motions of the Moon. Lacking the funds to hire a team of computers, he was forced to forgo the novel approach he had formulated three decades earlier and follow a less computationally intense and proven method. In 1903 the Carnegie Institution of Washington began funding his work.

On 11 July 1909, just days after completing his lunar computations, Newcomb succumbed to the painful ravages of bladder cancer. Three days later President William Howard Taft, secretary of the navy George Meyer, and the ambassadors and ministers of several nations joined his family, scientific colleagues, and friends for a memorial service, followed by his burial with full military honors at Arlington National Cemetery. Appropriately, Newcomb's tomb is located high above the Potomac River along the same ridge where he erected a temporary observatory to perform the experiments that enabled him to determine the scale of the solar system better than anyone had before—indeed, better than anyone would for decades after his death.

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