From the Editor

Urbain Le Verrier's prediction of the existence of the planet Neptune, based on the perturbations of Uranus, was a spectacular vindication of Newtonian dynamics. But when Le Verrier turned his attentions to the errant ways of the innermost planet, Mercury, the outcome was rather different. His prediction of an unknown body between Mercury and the Sun was not borne out by observation, despite concerted searches by astronomers at successive total eclipses. This unexpected failure was, ironically, the first step in the overthrow of Newtonian dynamics that had initially served Le Verrier so well, and ultimately led to Albert Einstein's General Theory of Relativity. November 2015 marked the centennial of Einstein's solution of the anomalous motion of Mercury. As our tribute to the centenary, this issue of *The Antiquarian Astronomer* opens with a paper from Bill Sheehan and Tony Misch tracing the history of the problem with Mercury's orbit and the exciting, if ultimately unfulfilled, hopes that its solution might lead to the discovery of an intra-Mercurial planet.

Starting on page 13, SHA member Paul Haley offers us the second part of his history of the career of David Gill, providing new insights into his collaboration with Ernest Mouchez of Paris Observatory on the international Carte du Ciel project. Joe LaCour, an instrument maker, and SHA founder-member David Sellers describe how they reconstructed the first screw micrometer for astronomical use from contemporary accounts. Louise Devoy and Agathe Daronnat of the Royal Observatory Greenwich introduce us to a hitherto unknown lunar observer of last century, and tell us about their efforts to preserve his recently discovered drawings of lunar craters.

As ever, the Editor is pleased to receive ideas for future contributions from members and non-members alike.

Ian Ridpath

About the Society for the History of Astronomy

The Society for the History of Astronomy (SHA) was formed in June 2002 with three main aims:

- To provide a forum for those with an interest in the history of astronomy and related subjects;
- To promote the history of astronomy by academics, educators, amateur astronomers, and local historians;
- To encourage research into the history of astronomy, especially research by amateurs, and to facilitate its collation, interpretation, preservation, publication, and dissemination.

To implement these aims, the Society organizes regular meetings and publishes its twice-yearly *SHA Bulletin* and an annual Journal, *The Antiquarian Astronomer*. These provide opportunities to publish research by members and others into any aspect of the history of astronomy and related subjects. Because most members are amateur astronomers and amateur historians, much of their research is likely to be outside the scope of professional journals.

Papers for *The Antiquarian Astronomer* should contain original research, new interpretation, insights of material in the public domain, or bring to a wider audience material of limited availability or that is available only in dispersed locations. Papers offered to *The Antiquarian Astronomer* should not have been previously published and are subject to external peer review. Back issues of *The Antiquarian Astronomer* appear on the SAO/NASA Astrophysics Data System (ADS) two years after publication; to access them, go to http://adsabs.harvard.edu/bib_abs.html and type our official abbreviation, antas, into the box marked Journal Name/Code.

The Society also publishes a Bulletin which usually appears twice per year. The scope of the Bulletin includes, but is not necessarily limited to: news and developments in the history of astronomy, meeting reports, articles, obituaries, book reviews, and members' letters. Articles for the Bulletin can be on any aspect of the history of astronomy and are usually up to 2000 words in length. They normally do not contain significant new research (such research should be published in *The Antiquarian Astronomer*) and are not peer reviewed. Contributions for the Observatory Scrapbook series are particularly welcome; these items consist of a brief description (typically 500 words or fewer) and an illustration of some historical observatory. It is prudent to discuss contributions for the *Bulletin*, particularly book reviews, with the Editor(s) in advance to avoid duplication. Addresses can be found on the inside back cover.

Timely information, particularly about forthcoming events, both SHA and other, is communicated to members via the quarterly eNews, which most members will receive by email.

A special centennial:
Mercury, Vulcan, and an early triumph for General Relativity

William Sheehan and Tony Misch

The discovery of the outer planet Neptune in 1846, based on the calculated position published by Urbain Jean Joseph Le Verrier, has been described as the zenith of Newtonian mechanics. However, when Le Verrier attempted to extend Newton's gravitational theory to the innermost planet, Mercury, he found a small unexplained discrepancy: an anomalous precession of the perihelion of Mercury, later calculated as 43″.0 per century. Applying the same assumption as had succeeded with Neptune, Le Verrier proposed the existence of an intra-Mercurial planet or a ring of debris. Yet observational searches for Vulcan were unsuccessful. The anomalous precession of the perihelion of Mercury was finally explained by Albert Einstein in 1915 in terms of the General Theory of Relativity, and provided one of the first confirmations of the theory's correctness.

1. A perihelion problem

Urbain Jean Joseph Le Verrier died of cancer of the liver on 1877 September 23, thirty-one years to the day after Johann Galle had first sighted the planet Neptune within a degree of the position that Le Verrier had calculated. He was by then the most celebrated astronomer in France, and quite possibly the world.[1]

Unsurpassed master of the abstruse empire of celestial mechanics, his almost superhuman calculations into the mutual perturbations of the planets had not only succeeded in extending the outer frontier of the Solar System but also revealed an unsolved mystery on the inner one. The unsolved mystery represented the only evident failure of Le Verrier's vast enterprise. As is often the case in science, the failure would prove more interesting, and more productive, than the successes.

The problem of the motions of Mercury, the innermost planet to the Sun and consequently the most difficult to observe, had dogged astronomers ever since the time of Ptolemy. The tables of the planet's motion were especially inaccurate when it came to predicting the planet's transits across the Sun. Those for the 1707 transit were a day in error; those of La Hire and Halley for the 1753 transit were wrong by many hours; while Lalande's tables for the 1786 event were early by 53 minutes, as a result of which all the astronomers in Paris except Delambre had abandoned their telescopes prematurely.

Le Verrier had made a preliminary attempt on the problem even before the wayward motion of Uranus had claimed his attention, publishing an initial paper, *Détermination nouvelle de l'orbite de Mercure et de ses perturbations*, in 1843. Here he expressed reservations about subduing the errant planet without first recasting the tables of the Sun's apparent motion (and, since the apparent motion of the Sun was a reflection of the Earth's motion, the motion of the Earth itself). A highlight of his subsequent book, *Théorie du Mouvement de Mercure*, published in 1845, was a prediction for the transit of 1845 May 8, which would be partially visible from France and entirely from North America.

1.1. *An unexplained displacement*

The most noteworthy observations of the 1845 transit of Mercury were made by Ormsby Macknight Mitchel, using the 11-inch (0.28-m) Merz equatorial of the Cincinnati Observatory. Mitchel reported that 'within *16 seconds* of the computed time, did the planet touch the solar disc, at the precise point at which theory had indicated the first contact would occur'.[2]

What seemed to Mitchel a miraculously accurate prediction so shattered Le Verrier's confidence in his tables that he immediately stopped their publication, even though they were being typeset by the Bureau des Longitudes.

Not yet ready to begin the wider investigations into the Sun's motion that he had mooted in 1843, and soon distracted by other problems – including the errant motion of Uranus, which would gain him immortality – he set Mercury aside for the time being. In fact, he would not return to it again until 1849.

Fig. 1: *Urbain Le Verrier (1811–77) still dominates French astronomy in the form of this statue that stands imperiously outside the entrance to Paris Observatory. (Météo-France)*

Then he would grapple with it for another ten years before finally publishing his definitive results.

Only in 1859, the year of Darwin's *Origin of Species* and Kirchhoff and Bunsen's three laws of spectroscopy, did Le Verrier let his reworked memoir on Mercury go to press. The result, in a word, was stunning. For even after taking everything into account, Mercury was, quite simply, not moving quite as it ought to do according to the Newtonian law of gravitation. A small discrepancy stubbornly and exasperatingly remained, due neither to observational errors nor to incorrect terms in the perturbation theory.

Le Verrier was confident enough to announce that the discrepancy was quite real. The perihelion of Mercury's elliptical orbit was precessing around the Sun at a rate slightly faster than predicted. In Le Verrier's own words: 'In a century Mercury's perihelion turns not merely 527″ as a result of the combined actions of the other planets, as [Newtonian] theory requires, but rather 527″ + 38″. There is, then, with the perihelion of Mercury, a progressive displacement reaching 38″ per century, and this is not explained.' [3]

1.2. *An intra-Mercurial mass?*

Following a line of reasoning similar to that which he had used to analyse the discordant motions of Uranus, leading to the discovery of Neptune,[4] Le Verrier invoked the existence of a small amount of additional mass inside the orbit of Mercury. It would have to be sufficient to account for the excess motion of the perihelion of Mercury, but not so great as to produce an effect on the planet's nodes or on the motions of Venus or the Earth. What could this unknown mass be?

If it were a planet at a mean distance from the Sun of, say, 0.17 au, to produce the observed effect on Mercury's perihelion it would have to be of similar mass to Mercury itself. But as Le Verrier realized, such a planet would outshine Mercury. He asked: 'How could a planet, extremely bright and always near the Sun, fail to have been recognized during a total eclipse? And would not such a planet pass in transit between the Sun and Earth, and thereby make its presence known?' [5]

It seemed so improbable that Le Verrier rejected the notion, at least for the time being. Instead he thought it more likely that the mass was in the form of a ring of small bodies between Mercury and the Sun – an inner asteroid belt, in other words.

Le Verrier published his conjecture on 1859 September 12 in a letter to his colleague Hervé Faye, the secretary of the Paris Academy of Sciences. In it, he urged astronomers to keep a close watch on the disk of the Sun and to scrutinize even the tiniest spot in the event it might prove to be not a sunspot at all but a planet in transit. Faye, for his part, suggested that the best time to look for such a planet might be during a total eclipse. The next favourable opportunity for European astronomers was less than a year away, on 1860 July 16, when the path of totality would cross Spain.

2. A bolt from the blue: Dr Lescarbault

Just before New Year's Day 1860, a doctor and amateur astronomer of Orgères-en-Beauce, Edmond Modeste Lescarbault, wrote to Le Verrier, claiming to have already observed just such a moving spot as Le Verrier had proposed. He had done so, he said, from his small private observatory the previous March 26.

It was never entirely clear why he had waited so long to communicate the observation, nor why he overcame his hesitation only after reading an article in *Cosmos*, a journal edited by the Abbé François Moigno, which summarized Le Verrier's calculations. But then Lescarbault was, as a contemporary described him, 'a bit of a dreamer'.

Lescarbault had been keeping an eye on the Sun in the hope of recording a small transiting planet ever since 1837.[6] On receiving the letter, a sceptical Le Verrier set out from Paris to the small village, and knocked imperiously at the doctor's door. Assured after his interview of the doctor's integrity and the soundness of his methods, Le Verrier returned to Paris convinced that the intra-Mercurial planet had been seen. He

Fig. 2 (left): *Edmond Modeste Lescarbault (1814–94), a French doctor and amateur astronomer, claimed to have observed the intra-Mercurial planet Vulcan in 1859. (Denis Canguilhem)*

Fig. 3 (above): *Lescarbault's observatory at his home in Orgères-en-Beauce, about 80 km southwest of Paris, from a contemporary picture postcard.*

calculated an orbit for it and even gave it a name, Vulcan.

Although Le Verrier was to remain a believer until the end of his life, Lescarbault's Vulcan was never seen again. What he might have seen remains a mystery.

The great French popularizer of astronomy Camille Flammarion, who was hostile to Le Verrier, explained the observation away as due to an error of the crudest kind. His explanation, however, placed the observation in the morning whereas Lescarbault had observed in the evening. Another astronomer hostile to Le Verrier, Emmanuel Liais, professed to have been observing the Sun from Brazil at the exact moment Lescarbault made his observation but had not seen anything out of the ordinary. Nothing is certain in this story.[7]

Perhaps this is fitting, since Vulcan belongs more in the realm of myth than of reality. It would, writes Richard Baum,

> launch astronomers on an extraordinary quest: the hunt for the planet of romance. A pursuit which, in its twists of circumstance, parallels the large body of stories about lost riches that mushroomed in the South-Western states of North America following the Spanish entrada; stories of searches for lost gold and silver mines and other treasure which have since become an integral part of regional folklore. Someone makes a discovery then loses it and is haunted for the rest of his or her life trying to find it. Such a strand folklorists classify a 'motif', defined as 'the smallest element in a story having the power to persist in tradition'. This is the nature of Lescarbault's legacy. It is an adventure, not for wealth or material gain, but in ideas – the intellectual equivalent of the myth-building process that stirs the imagination and causes the loquacious to fantasize and exaggerate, as did those who motivated the Conquistador Francisco Vasquez Coronado (1510–1554) with richly adorned accounts of the fabulous but mythical Seven Cities of Cibola.[8]

3. Vulcan's last stand

The 1860 eclipse in Spain came and went, with no Vulcan being seen.[9] Neither did it show up at subsequent eclipses, such as the Great Indian Eclipse of 1868 August 18 or the North American eclipse of 1869 August 7–8.

What might be termed 'Vulcan's Last Stand' came at the Great North American Eclipse of 1878 July 29, the last total eclipse of the Sun visible from the United States in the 19th century. The Moon's shadow cut a majestic swath across the vast western United States before passing into the Gulf of Mexico between Galveston and New Orleans.

The most sensational results were obtained by a University of Michigan astronomer named James Craig Watson. Born in Canada in 1838, Watson spent his first twelve years on a farm before his father moved the family to Ann Arbor, Michigan. There he worked in a small factory and studied to become, at the age of 15, a student at the University of Michigan in Ann Arbor.

Drawn to astronomy, he built a 4-inch refractor and devoted himself to mastering Laplace's *Mécanique céleste*. He soon gained a reputation as a rapid and reliable computer of comet and minor planet orbits. His amazing fluency in calculations allowed him for many years to supplement his income, and incur the envy of lesser-endowed astronomers, by moonlighting as an insurance actuary.

Watson became a full professor of astronomy at 21, and director of the observatory at 24. Within a matter of weeks he discovered an asteroid, Eurynome. The euphoria proved addictive, and henceforth the discovery of minor planets became his main passion.

Inevitably he became a competitor, and eventually a bitter rival, of Christian Heinrich Friedrich Peters of Hamilton College, then the leading American discoverer of minor planets. Both were sometimes difficult personalities. Watson was generous in his own circle, but did not seek out friends: 'for the ordinary forms of social intercourse he had not taste, and he held aloof from them, giving to his work hours that others spent in recreation'.[10]

Peters was a notorious curmudgeon with an unfortunate affinity for litigation. It is perhaps a comment on contemporary opinion that the biographical memoir of him for the National Academy of Sciences, usually submitted shortly after a member's death by a close colleague and often expressing considerable affection, remained unwritten for over a century, when co-author Sheehan finally removed it from the backlog.[11]

A clash between the two was inevitable. When it came, it came over Vulcan.

Fig. 4: *The total eclipse of 1878 on the front cover of the August 24 edition of Harper's Weekly, as seeen from the Rocky Mountains in Colorado. 'Vulcan managed to hide himself from our scrutiny,' reported the Harper's correspondent, St George Stanley.*

4. The Great 1878 Eclipse

Watson had long believed in Vulcan. He had corresponded with Le Verrier about it, and had observed the Sun's disk at times when Le Verrier had predicted transits of the planet, with negative results. The 1878 eclipse, due to last not quite three minutes, seemed to offer a better chance of success. Watson planned to sweep near the Sun, which would lie in Cancer at the time, with a 4-inch refractor borrowed from the Michigan State Normal School at Ypsilanti (now Eastern Michigan University).[12]

He took the train from Ann Arbor to Rawlins, Wyoming, a rough frontier town that would lie on the centreline of totality. It was bustling with astronomers, among them Simon Newcomb, recently appointed director of the U.S. Nautical Almanac office, who had searched for intra-Mercurial planets at the 1869 eclipse. Even Thomas Edison was there, along with one of his inventions, a pocket-sized device for measuring infrared radiation he called a *tasimeter*.

On the day of the eclipse, July 29, high winds in Rawlins persuaded Newcomb and Watson to try their luck at an isolated Union Pacific rail stop nearby called Separation, at an elevation of 6,901 feet. Even in its prime, it consisted of only a wooden water tower, a rail siding, and a few small wooden buildings where the station agent lived and worked, but there was accommodation for the astronomers. About three-quarters of a mile east of the station a semicircular sand dune, 15 feet high, furnished an admirable protection from the winds to the south and west. It was there that the planet-searchers set up their instruments.

Although Separation died not long after the eclipse, abandoned when the Union Pacific shifted its track south, co-author Sheehan found a few remains when he visited the site in 2006. It was still possible to make out the dune where Watson set up his telescope. Otherwise, the place is bleak and forlorn, surrounded by a rough alkali plain. It would be hard to imagine a more desolate scene.

4.1. *Sweeping for Vulcan*

Watson, who was never inclined to be modest about his abilities, had in advance of the eclipse committed to memory the positions of all the stars to seventh magnitude in a search zone centred on the Sun, 15° long by 1½° wide. In addition, because the telescope was not ideally suited to the task, he had to improvise.

Although mounted equatorially, it was not furnished with setting circles. He made up for the deficiency by placing upon the axes circles covered with white cardboard over which he mounted a pointer with a knife edge, intending to mark with a pencil the position of any suspicious object.

Even before totality, Watson had begun sweeping east and west of the Sun with an eyepiece magnifying 45 times. When totality began, he placed the Sun in the middle of the field and began moving the telescope slowly and uniformly. He retraced his path, then moved the telescope one field to the south and began sweeping again.

He encountered δ Cancri and other known stars. He then re-centred on the Sun and swept in the same manner to the west. As he did so, between the Sun and θ Cancri he came across, as he recalled, 'a ruddy star whose magnitude I estimated to be 4½. It was fully a magnitude brighter than θ Cancri, which I saw at the same time, and it did not exhibit any elongation, such as might be expected if it were a comet'. (He later contradicted this statement, claiming that even at 45× it had a perceptible disk.) He marked its position on his circles and recorded the chronometer time before resuming his sweep.

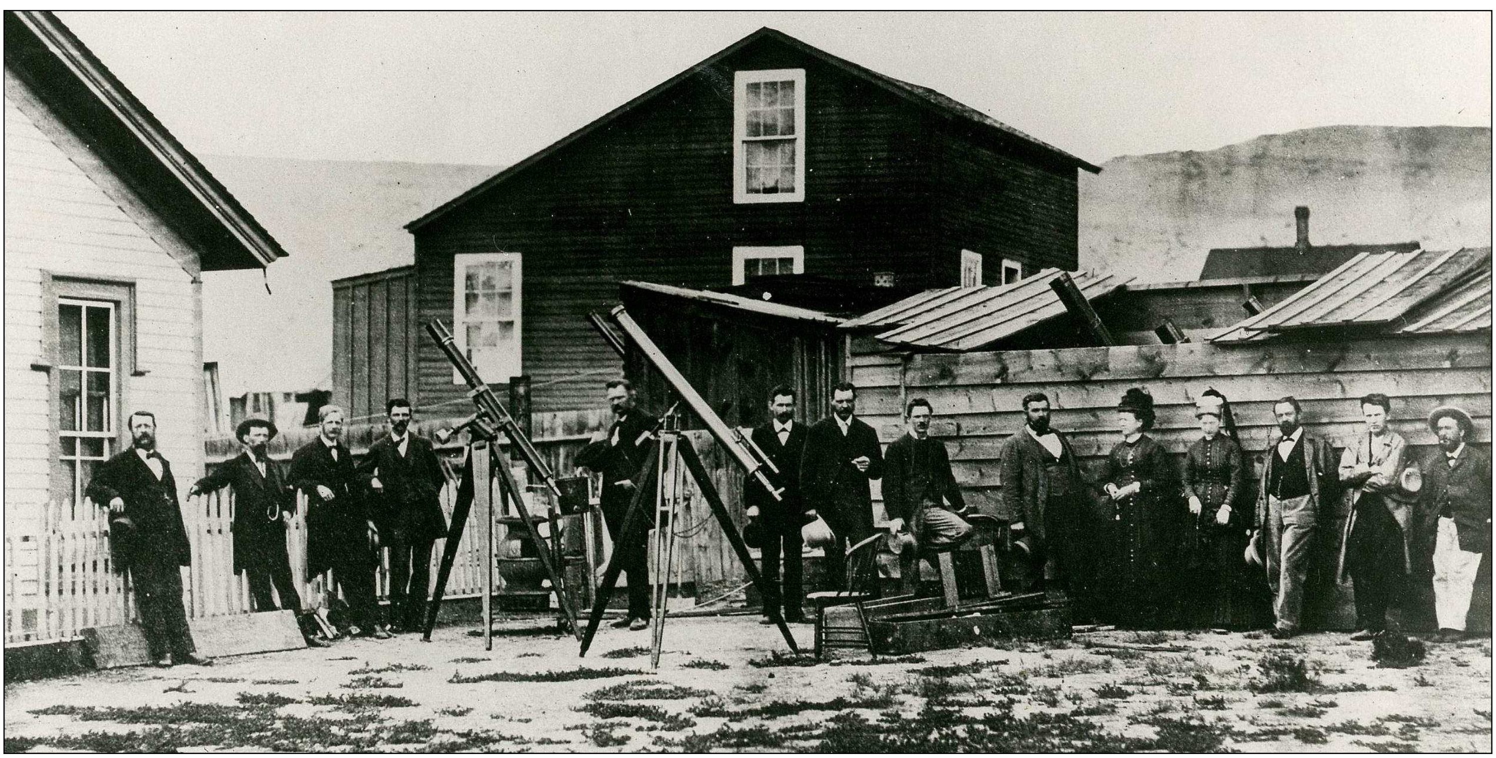
Several degrees west of the Sun he encountered another, even brighter star, 'also ruddy in appearance', and marked its position on the circles. Seized with excitement, he ran over to Newcomb, 'in hopes that he might … get a place of the strange star which I had first observed', but Newcomb was occupied in reading off his setting circles the position of a star he had in the field and could not be disturbed.

The object Newcomb was intent on measuring with such diligence was north of the Sun, and proved to be an ordinary star, whereas Watson's two strange objects were both south of the Sun. He later conceded that, while one might be a known star, the other was certainly a stranger. Newcomb could not help reflecting afterwards, 'It is of course now a matter of great regret that I did not let my own object go and point on Professor Watson's.' By the time Watson returned to his telescope, totality was over.

Against the suddenly brightened sky, Watson was unable to recover his second object, and therefore could not say for sure whether it was a known star (ζ Cancri) or not. Of the first ruddy star, he was sure: it was not a known star, and he had the record of the paper circles, carefully inspected by Newcomb and Lockyer *in situ*, to prove it.

There was nothing more to do but await the results of observers elsewhere along the eclipse track. In the end, the only seeming confirmation of Watson's supposed planet came from Lewis Swift, a well-known

Fig. 5: *Astronomers gathered at Rawlins, Wyoming, for the total solar eclipse of 1878 July 29. James C. Watson of the University of Michigan is the bearded figure sixth from right. Watson's observations of two unidentified stars near the eclipsed Sun cemented his belief in an intra-Mercurial planet. Thomas Edison stands with arms folded second from right. (Carbondale County Museum, Rawlins, Wyoming)*



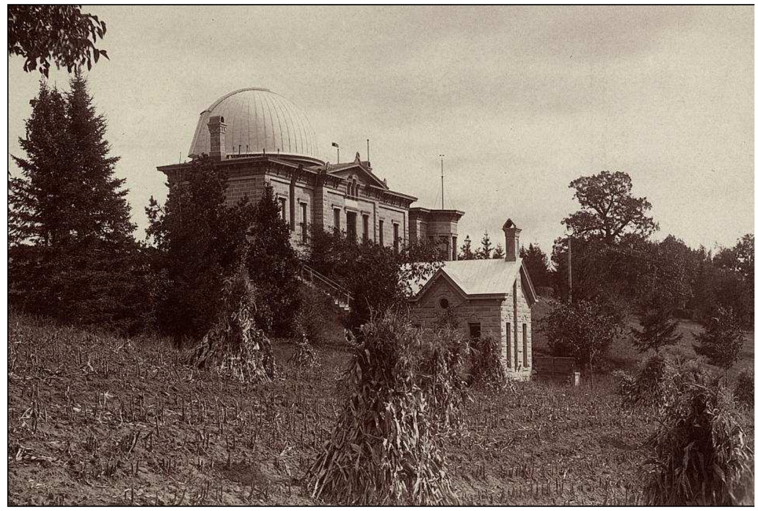


Fig. 6 (left): *James C. Watson (1838–80) became director of the University of Wisconsin's Washburn Observatory in 1879. There he built a subterranean telescope to search for Vulcan without the need for an eclipse, but died before it could be completed.*

Fig. 7 (above): *Watson's Vulcan telescope was housed in the small building downslope from the main observatory. (Department of Astronomy, University of Wisconsin–Madison)*

discoverer of comets from Rochester, New York, who observed the eclipse from Denver. He offered a tantalizing report of two stars of about 5th magnitude, about eight minutes of arc apart. Although one was identified as θ Cancri, the other was unknown. Swift added: 'I have no doubt that the unknown star is an intra-Mercurial planet'.

Watson was disposed to claim this observation as decisive. 'I do not know whether he obtained anything more than an estimate of the position,' he wrote to Lockyer, 'but the place in which it is reported that he saw the planet agrees with my observation. This corroboration is peculiarly fortunate, considering the negative results of other observers.'

4.2. *A profusion of errors*

Unfortunately, closer scrutiny introduced doubts. Watson discovered several errors leading to corrections in the positions of the stars that he had observed. By late August, these revisions had led him to announce that the second object, which he had supposed to be ζ Cancri, could not be that star after all. Instead, it too must also be an intra-Mercurial planet.

Meanwhile, Swift published additional information about his observations, which introduced further difficulties. After making the necessary revisions, his positions were found to be incompatible with Watson's. Instead of one planet or even two, it now seemed that Watson and Swift had between them observed four – or, more likely, none. Stock in Vulcan was plummeting.

Peters had been following developments closely and was ready to strike. He published a devastating paper, 'Some critical remarks on so-called intra-Mercurial planet observations', in *Astronomische Nachrichten*.[13] This paper has been described by Joseph Ashbrook as 'a strange blend of sharp insight and utter tactlessness'.[14]

Peters's main point was that Watson had overestimated the accuracy of his paper-circle method for measuring the positions of stars. The lack of a telescope with proper setting circles, Peters declared, had been Watson's downfall. 'The marking was done in the dim light of the total eclipse, or with lamplight,' he said. 'Either the slightest touch would bend the pointer, the flexible brass wire, a little to the side, or a parallax of some amount was unavoidable. The marking had to be done expeditiously and with a certain hurry.' Under the circumstances, errors were inevitable, and Peters concluded that Watson had observed θ and ζ Cancri, 'nothing else'.

Peters's arguments prevailed, and a few years later the great Irish historian of astronomy, Agnes M. Clerke, issued her verdict: 'The most feasible explanation of the puzzle seems to be that Watson and Swift merely saw each the same stars in Cancer: haste and excitement doing the rest'.[15]

Occasionally someone muses that perhaps Watson's observation was too easily given up, and that he might really have seen something – a Sun-grazing comet, for instance, a suggestion that began with Lewis Swift.[16] But the circumstances of the observation seem too doubtful for such proposals to be entertained for long. Peters's critique has stood the test of time far better than Watson's claims to have seen Vulcan.

4.3. *Watson's obsession*

Watson, at least, remained defiant. He had been recruited from Ann Arbor to Madison to take charge of the University of Wisconsin's new Washburn Observatory. Equipped with a 15.6-inch Clark refractor, the observatory was erected on a lovely site near Lake Mendota.

When Watson arrived in the summer of 1879, the observatory was far from complete, and the new director set to work designing and superintending the construction of new buildings and apparatus. Yet one thing never left him. 'No stress of other work or other interests,' writes his biographer George C. Comstock, 'could displace Vulcan from his mind.' It had become his great obsession, and in pursuit of it he devoted the last year of his life to building one of the strangest observatories in astronomical history. It was to be constructed on the south slope of the hill of the Washburn Observatory, with the purpose of observing the intra-Mercurial planet in broad daylight, without the need for an eclipse. Comstock recounts:

> At the foot of [the] hill was dug a deep cellar with a tube extending from it through the soil, parallel to the earth's axis and terminating in a masonry pier at the top of the hill. A telescope was to be so mounted in the cellar as to point up through the tube to a heliostat mounted at its upper end, by which rays of light coming from the sun or other celestial body might be directed into the telescope. The tube, fifty-six feet in length, was to serve as a long dew-cap and enable the observer to sweep close up to the sun's limb without being blinded by the stray light surrounding it. So confident was Watson of the success of this device, and that by its aid Vulcan could be refound, that he did not hesitate to undertake its construction at an expense to himself of several thousand dollars.[17]

Watson died of pneumonia during the winter of 1880, before the observatory was completed. It was taken up by his successor, Edward Singleton Holden, whom Peters warned: 'One thing I would beg you most earnestly: do not sit in that subterranean hole, to watch until Vulcan passes. Not that I apprehend you might discover him … but it might deadly ruin your health, and you better fill up the hole, though perhaps objection might be made by the Madison people, with whom Watson seems to have appeared as the greatest human in the world.'[18]

Holden felt obliged to ignore Peters and eventually complete the observatory, but it was a complete failure. No stars were seen through it at any time. It was abandoned for scientific purposes, although it long remained a landmark on campus before finally being torn down in 1946; no trace of it remains today.

5. Vulcan in eclipse

The total solar eclipse of 1883 found Holden at the head of an American party on tiny Caroline Island in the South Pacific, where he devoted the precious minutes of totality to his own intra-Mercurial search, sweeping the sky in the region of the Sun with a 6-inch (15¼-cm) Clark refractor. Seeing no interloper he concluded: 'It is my opinion, therefore, that at future eclipses it will not be necessary to devote a telescope and observer to the further prosecution of this search, and I must regard the fact of the non-existence of Vulcan as definitely settled.'[19]

Five years later, in 1888, Holden assumed the directorship of University of California's Lick Observatory, on Mt Hamilton near San Jose, then the premier institution of its kind. Serendipitously, on New Year's Day 1889 – the first day of Lick's first full year of operation – a total eclipse crossed California only 150 miles (240 km) north of the observatory.

Holden dispatched an eclipse party from the observatory to nearby Bartlett Springs and published a pamphlet of observing guidelines for the general public. He organized local photographers to take pictures of the event, inviting them to contribute their results for analysis to Lick. After the eclipse, the group banded together to form the Astronomical Society of the Pacific, with Holden as the first president.

Holden included no provisions for looking for Vulcan in Lick's official programme of observations, but the elusive planet briefly galvanized interest on Mount Hamilton when a member of the public, James Howard of the Pacific Coast Steamship Company in San Francisco, reported the presence of specks, apparently all in the same position, on three negatives he submitted to the observatory. After careful examination by Holden and his colleagues E. E. Barnard and James Keeler they were declared 'accidental'.[20]

During his tenure as Lick director, Holden organized four further eclipse expeditions: in late 1889 to French Guiana; to Chile in 1893; to Japan in 1896; and to India in 1898. Holden left Lick under a personal and political cloud the month before the India eclipse party sailed out from San Francisco, and his successor, James Keeler, died tragically young in 1900.

5.1. *An eclipse camera*

Keeler's successor, W. W. Campbell, who would remain at Lick's helm for the next 30 years, was if anything even more skeptical of the existence of an intra-Mercurial planet than Holden had been. Nevertheless, he left no stone unturned, and sent with the well-equipped party to the 1901 eclipse in Sumatra a new, four-barrelled, wide-field camera, designed and built expressly to search for intra-Mercurial planets. The camera consisted of four tubes, rigidly attached to one another in two parallel pairs, offset by 20 degrees – an arrangement that, with two repointings during the long eclipse, covered a 6° × 36° area along the ecliptic, centred on the Sun. The camera performed flawlessly but clouds compromised the results.

The next chance came in 1905, when the Moon's shadow touched three continents. Relying on the generous hand of California banker and Lick patron William Crocker, Campbell formulated the ambitious plan of sending out *three* well-equipped Lick parties, positioned at strategic points along the entire path of the eclipse. One would observe near the eclipse's beginning in Labrador, another would encounter it in Spain, and the last would see it off in Egypt.

Additional observing stations required additional instruments. The original intra-Mercurial camera was copied and now existed in triplicate. Observations made with identical equipment at different times during the eclipse (totality at Egypt would occur two and a half hours later than at Labrador) increased the chances of success, and offered an added attraction – should an unknown planet be recorded at successive sites, an immediate, if approximate, orbit determination would follow. Not that such a result was expected. Campbell emphasized, however, that a 'negative result would be scarcely less valuable, though certainly less interesting ... and the intra-Mercurial question would cease to be a pressing eclipse problem'.[21]

Once again, however, the results were again equivocal: thick clouds in Labrador, thin clouds in Spain, and Saharan dust in Egypt interfered with the observations. The official report read: 'it is not believed that the photographs will add anything to the results obtained at the Sumatra eclipse'.[22]

5.2. *Drawing a blank*

In 1908 on Flint Island, only 150 miles (240 km) from Caroline Island where a quarter of a century earlier Holden had declared the intra-Mercurial problem settled, the Lick cameras finally accomplished what they had been built to do. Operated by Lick astronomer Charles Dillon Perrine, who had also used one of the cameras at the 1901 and 1905 eclipses, they recorded 300 stars down to a limiting magnitude of 9.0. All were identified with known stars. Campbell now affirmed: 'In my opinion, Dr. Perrine's work at the three eclipses of 1901, 1905, and 1908, brings the observational side of the famous intra-Mercurial planet problem definitely to a close.'[23]

That may have been so, but the theoretical problem – the anomalous advance of the perihelion of Mercury – remained as far from explanation as ever.

The American doyen of celestial mechanics, Simon Newcomb, had in 1882 repeated Le Verrier's calculations of the transits of Mercury, and confirmed that the anomalous advance was genuine, although he corrected the value from Le Verrier's 38″ per century to 43″ per century. His result would prove to be definitive.[24]

A brief hope of a reconciliation between negative observational results and theory was chased by U.S. Naval Observatory astronomer Asaph Hall, famed as the discoverer of the satellites of Mars. In 1894 Hall published a paper in which he tried tinkering with the inverse square law of gravitation. Instead of the exponent being exactly 2, he proposed it be amended to 2.00000016.[25] Almost at once, however, it was realized that this led to unacceptable consequences in the motion of the Moon.

Two years later, the German astronomer Hugo von Seeliger invoked ellipsoidal concentrations of small particles around the Sun, possibly related to the tenuous zodiacal light. It satisfied Newcomb that the Newtonian law of gravitation could be salvaged, but it was little more than an effort to whisk the problem under the carpet.

In the end, the astronomers would never solve the problem. The solution came instead from radical new ideas in physics.

Fig. 7: *Lick Observatory eclipse instruments set up on Flint Island, South Pacific, in 1908. Two of the four-barreled cameras first used for the 1905 expeditions can be seen in the background. Lick's director W. W. Campbell felt that the negative result from Flint put the Vulcan question to rest. (Lick Observatory)*

6. Einstein triumphant

After 1908, two of the intra-Mercurial cameras were dismantled, while the third was refashioned into the Einstein camera, with its tubes realigned to photograph a square area around the Sun. It was so-called because it was designed to test Einstein's prediction of how the propagation of light is influenced by a gravitational field.[26] In 1907 he concluded that a light ray passing the Sun should suffer a deflection of 0″.85.

The Lick team was early in making an effort to test this prediction. They shipped the Vulcan camera to Kiev for the eclipse of August 1914 with an expedition led by Heber D. Curtis, but thick clouds nullified the attempt. In the meantime World War I had broken out, disrupting Curtis's return and long-delaying the return of the instruments to California.

Along with his attempt to calculate the bending of light near the Sun, Einstein had also been pondering the problem of the perihelion of Mercury. He wrote to his close friend Conrad Habicht on 1907 December 24, 'At this time I am busy with considerations on relativity theory in connection with the law of gravitation… I hope to clear up the so-far unexplained secular changes of the perihelion of Mercury… [but] so far it does not seem to work.'[27]

Years of struggle lay between hope and fulfilment. Finally, in November 1915, Einstein arrived at the equations that determined how matter curves spacetime. He could now speak lyrically of the 'magic' of his new theory.[28] On November 17 he wrote to his friend Michele Besso: 'Perihelion motions explained quantitatively…you will be astonished.' In fact, his solution for the value of the precession per revolution gave 43″ per century, exactly the value Simon Newcomb had obtained in 1882.

A biographer of Einstein, Abraham Pais, suggests that this discovery was 'by far the strongest emotional experience in Einstein's scientific life, perhaps in all his life. Nature had spoken to him. He had to be right'. Einstein himself recalled that as soon as he saw that his calculations agreed with the astronomical observations, 'for a few days, I was beside myself with joyous excitement'. He later recounted that his discovery had given him heart palpitations, and had the feeling that something actually snapped in him.[29]

In the same paper of 1915 Einstein also announced that the bending of light was twice as large as he had found in 1911: 1″.7 instead of 0″.85. These two results were the first observational proofs of General Relativity. The first brought the curtain down on the curious enigma that was Vulcan, while the second would lead to the repurposing of the intra-Mercurial camera (and similar instruments) to search for the bending of light near the Sun at future eclipses.

Indeed, the Lick team used the Einstein camera at the eclipse of 1918 June but failed to achieve conclusive results. Finally and triumphantly, at the eclipse of 1919 May 29, when the darkened Sun stood in the midst of the Hyades, British teams sent to Sobral (led by Andrew Crommelin from the Greenwich Observatory) and to Principe Island off the coast of Spanish Guinea led by Arthur Eddington succeeded in confirming Einstein's prediction. At the Royal Society, where Newton's portrait hung in the meeting hall, the president hailed relativity as perhaps the most momentous product of human thought.

As the results of the measures were made public, newspapers around the world trumpeted the news. According to *The Times* of London (1919 November 7): 'REVOLUTION IN SCIENCE/NEW THEORY OF THE UNIVERSE/NEWTONIAN IDEAS OVERTHROWN', while *The New York Times* announced (1919 November 9): 'LIGHTS ALL ASKEW IN THE HEAVENS/Men of Science More or Less Agog Over Results of Eclipse Observations/EINSTEIN THEORY TRIUMPHS'.

7. A scientific postscript

Einstein's November 1915 calculation essentially solved the anomalous precession of Mercury. The General Relativity prediction of 42″.98 per century has been confirmed to within the limits of observational error.

In addition, General Relativity predicts smaller precessions of Venus and the Earth of 8″.62 and 3″.84 per century, which have also been confirmed by observation; while, 50 years after Einstein solved the Mercury problem, radio astronomers Russell A. Hulse and Joseph H. Taylor discussed the case of the binary pulsar PSR 1913+16, in which a pair of massive stars orbit one another in an elliptical orbit with a minimum separation equal to the Sun's radius. They found the perihelion advances strictly in accordance with Einstein's theory at 4°.23 per year,[30] a discovery that won them the Nobel Prize for physics in 1993.

In yet another triumph for General Relativity, Jacques Laskar and Mickael Gastineau at the Paris Observatory have included relativistic effects in numerical solutions of the evolution of the Solar System. They find that there is some probability over the next few billion years of a change in the eccentricity of Mercury's orbit that would be capable of either allowing collisions of Mercury with Venus and the Sun, or of Mercury, Mars, or Venus with the Earth.[31] Without including the effects of General Relativity, none of these calculations would be valid.

Although Vulcan is now only a ghost, and the reported sightings no more than illusions conjured by the combination of heightened expectation and wishful thinking, the region it supposedly inhabited is still of interest to astronomers. The so-called vulcanoid zone between 0.07 and 0.21 au from the Sun is dynamically stable. Astronomers have postulated the existence of a primordial vulcanoid population there, of which some remnant might have survived depletion from the combined effects of collisional erosion and subsequent radiative transport out of the zone. Debris from a large impact on Mercury relatively late in its evolution, stripping away much of its crust and mantle, would likely have ended up in the vulcanoid zone and might still remain there.

Even so, increasingly sensitive surveys have been no more successful in finding such bodies than the efforts with the old Lick Observatory intra-Mercurial camera. The most thorough search so far, with NASA's STEREO Heliospheric Imager, identified no vulcanoids larger than 5.7 km in diameter.[32] Nor were occasional observations of the outer vulcanoid zone by the MESSENGER probe while in orbit around Mercury successful. The search for an intra-Mercurial body continues to lead to a null result.

Yet hope springs eternal. Vulcan does not exist, and never did; but perhaps someday, as a faint and shadowy semblance of the vaunted planet of Le Verrier, a vulcanoid could be discovered, and gain immortality as a postscript in the story of Le Verrier's failed prediction and Einstein's great discovery.

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References and notes

1. The definitive biography on Le Verrier is: Lequeux, James, *Le Verrier – Savant magnifique et détesté* (Paris: EDP, 2009). This is available in English as *Le Verrier – Magnificent and Detestable Astronomer*, translated by Bernard Sheehan, edited and with an introduction by William Sheehan (New York: Springer, 2013).
2. Mitchel, Ormsby Macknight, *Orbs of Heaven* (London: G. Routledge & Co., 1857), p. 139.
3. Le Verrier, Urbain Jean Joseph, 'Lettre à M. Faye sur la théorie de Mercure et sur le mouvement du périhélie de cette planète', *Comptes rendus hebdomadiares des Séances de l'Académie des Sciences* (Paris: Mallet-Bachilier), 59 (1859), p. 381.
4. Hanson, Norwood Russell, 'Leverrier: the Zenith and Nadir of Newtonian Mechanics', *Isis* 53 (1962), p. 359.
5. Le Verrier, Urbain Jean Joseph, 'Théorie du mouvement de Mercure', *Annales de l'Observatoire Impérial de Paris* (*Mémoires*), V (1879), 1–195.
6. On Lescarbault, see Baum, Richard, and Sheehan, William, *In Search of Planet Vulcan: the ghost in Newton's clockwork universe* (New York: Plenum, 1997), 145–161, and Baum, Richard, 'The Lescarbault Legacy', *Patrick Moore's Yearbook of Astronomy 2013* (London: PanMacmillan, 2012), 179–220.
7. See Lequeux, *Le Verrier*, pp. 167–168. Out of curiosity, the authors investigated the possibility that the Sun might have been photographed on this date. The solar photography programme at Kew began in 1858, although it was not until 1862 that the photoheliograph was used on a daily basis. Thus it was at least possible that a photograph might have been taken on 1859 March 26. Lee MacDonald has kindly made a search, but although he finds that the Royal Greenwich Observatory archives at Cambridge contain a few Kew solar photographs, including some from 1859 August and September, it does not appear that any were taken on 1859 March 26.
8. Baum, 'The Lescarbault Legacy', 285–6.
9. For details, see Westfall, John, and Sheehan, William, *Celestial Shadows: eclipses, transits and occultations* (New York: Springer, 2015), 125–130.
10. Comstock, George C., 'James Craig Watson, 1838–1880', *Biographical Memoirs of the National Academy* (Washington, D.C.: National Academy of Sciences, 1895), Vol. 3, p. 54.
11. Sheehan, William, 'Christian Heinrich Friedrich Peters, September 13, 1813–July 18, 1890', *Biographical Memoirs of the National Academy of Sciences*, 76 (Washington, D.C.: National Academy of Sciences 1999), 289–312.
12. Watson's account of his observations are found in 'Reports on the Total Solar Eclipse of July 29, 1878 and January 11, 1880', *Astronomical and Meteorological Observations made at the United States Naval Observatory*, Part II, Appendix III (Washington, D.C.: 1880).
13. Peters, Christian Heinrich, 'Some critical remarks on so-called intra-mercurial planet observations', *Astronomische Nachrichten*, 94 (1879), 321–340.
14. Ashbrook, Joseph, 'The Adventures of C. H. F. Peters', *Astronomical Scrapbook* (Cambridge, Mass.: Sky Publishing Corp., 1984), p. 63.
15. Clerke, Agnes M., *A Popular History of Astronomy During the Nineteenth Century* (London: A. & C. Black, 4th ed., 1908), p. 250.
16. Swift, Lewis, 'Were They Comets?', *English Mechanic*, 58 (1898), p. 36.

17. Comstock, 'James Craig Watson', p. 52.

18. Peters, C.H.F., to E.S. Holden, 1881 February 17; Mary Lea Shane archives of the Lick Observatory

19. Holden, Edward Singleton, 'Report', in: *Report of the eclipse expedition to Caroline Island, May 1883*, II (Washington, D.C.: U.S. Government Printing Office for the National Academy of Sciences, 1884), p. 101.

20. Keeler, James Edward, 'Notes on the Negatives deposited at the Lick Observatory by members of the Pacific Coast Amateur Photographic Association' in *Reports on the Observations of the Total Eclipse of the Sun of January 1, 1889, published by the Lick Observatory* (Sacramento, California: Lick Observatory, 1889), p. 161.

21. Campbell, William Wallace, 'The Crocker Eclipse Expedition in 1905', *Astrophysical Journal*, 20 (1904), p. 235.

22. Campbell, William Wallace, and Perrine, Charles Dillon, 'The Lick Observatory–Crocker Eclipse Expedition to Spain', *Publications of the Astronomical Society of the Pacific*, 18 (1906), p. 24.

23. Campbell, William Wallace, 'The Crocker Eclipse Expedition of 1908 from the Lick Observatory, University of California', *Publications of the Astronomical Society of the Pacific*, 20 (1908), p. 79.

24. Newcomb, Simon, 'Discussion and Results of Observations on Transits of Mercury from 1677 to 1881', *Astronomical Papers of the American Ephemeris and Nautical Almanac*, 1 (1882), 367–487.

25. Hall, Asaph, 'A Suggestion in the Theory of Mercury', *Astronomical Journal*, 14 (1894), 49–51.

26. Einstein, Albert, *Annalen der Physik*, 35 (1911), p. 989.

27. Einstein, Albert; to Conrad Habicht, 1907 December 24; quoted in Pais, Abraham, '*Subtle is the Lord…': the science and the life of Albert Einstein* (Oxford and New York: Oxford University Press, 1982), p. 182.

28. Quoted in Pais, *'Subtle is the Lord …'*, p. 251.

29. Ibid., p. 253.

30. Hulse, R. A., and Taylor, J. H., 'Discovery of a Pulsar in a Binary System', *Astrophysical Journal*, 195 (1975), L51-L53. For this work, Hulse and Taylor were awarded the 1993 Nobel Prize in Physics.

31. Laskar, J., and Gastineau, M., 'Existence of collisional trajectories of Mercury, Mars and Venus with the Earth', *Nature*, 459 (2009), 817–819.

32. Steffl, A. J., Cunningham, N. J., Shinn, A. B., Durda, D. D., and Stern, S. A., 'A search for Vulcanoids with the STEREO Heliospheric Imager', *Icarus*, 223 (2013), 48–56.

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