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Neptune: From Grand Discovery to a World Revealed

Essays on the 200th Anniversary of the Birth of John Couch Adams

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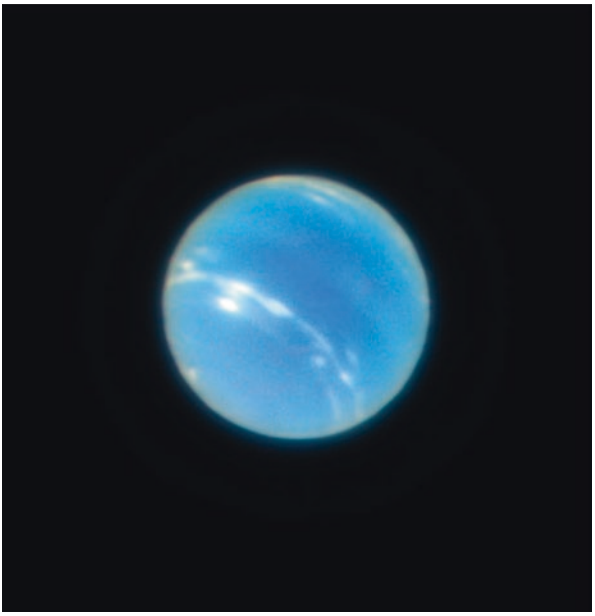
ISSN 2509-310X ISSN 2509-3118 (electronic)
Historical & Cultural Astronomy
ISBN 978-3-030-54217-7 ISBN 978-3-030-54218-4 (eBook)
https://doi.org/10.1007/978-3-030-54218-4

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland



Frontispiece. This image, obtained on June 18, 2018, during commissioning of the narrow field mode of the MUSE (Multi Unit Spectroscopic Explorer) spectrograph on the European Southern Observatory's Very Large Telescope (VLT) array, located high in the Atacama Desert of Chile, is one of the best ever taken from the earth (Credit: MUSE Consortium and ESO)

"Let us all praise famous men."

In memory of our colleagues, friends, and three great students of Neptune, whose influence and contributions we here gratefully acknowledge:

Richard Baum (1930–2016)

Bradford A. Smith (1931–2018)

Craig B. Waff (1946–2012)

♆

Foreword

The first sighting of the planet Neptune, by Johann Gottfried Galle and Heinrich Louis d'Arrest at the Berlin Observatory on September 23, 1846, was the culmination of one of the great international quests in scientific history. An Englishman and a Frenchman had independently calculated the position of the Uranus-disturbing planet, while a German clinched the achievement by giving Neptune—as it would later be christened—its "first light" of visual recognition. Then, American mathematicians were central in computing its orbit from historical sightings. The discovery seemed to provide a resounding proof for the forensic power of Newtonian gravitation, in so far as Newton's theory was needed to predict the position of a hitherto unknown body, by means of the gravitational behavior of a known one.

But as Dr. William Sheehan so clearly points out, the whole Neptune discovery saga right back to the I840s has been the focus for all manner of controversy. Controversies included Anglo-French exchanges, apparently a hero and villain polarization of the various personalities involved, along with a trail of conspiracy theories. And needless to say, twentieth-century popular science writers have had a field day with it, for—in the "right hands"—Adams's and Le Verrier's calculations and their consequences can be crafted into a fine thumping tale, replete with missed clues and opportunities, mutual jealousies, and dark dealings!

I personally have had a fascination with the whole affair since my youthful reading of Morton Grosser's *The Discovery of Neptune* (1962), which for years was the definitive book on the subject. But then, more recent scholars recognized that the only credible way forward was to return *ad fontes*, to the primary sources. In particular, these included the vast archive of Sir George Biddell Airy, the Astronomer Royal, now classified under "RGO 6," including his daily "Journal." Once stored at the Royal Observatory archive at Herstmonceux Castle, Kent, they now reside in the Cambridge University Library, along with parallel documents now preserved in Cambridge, Paris, Berlin, and elsewhere.

And from this scholarly approach, a much more balanced interpretation began to emerge, especially after the missing "RGO 6 Neptune file" was brought back from Chile to where somehow it had wandered, to provide a resounding refutation of the myth that the guilty Airy had destroyed it.

William Sheehan; his fellow editors Trudy E. Bell, Carolyn Kennett, and Robert W. Smith; and their six additional contributors have resolved to follow a true path through the surviving scholarly literature pertaining to the Neptune discovery, to give a modern, balanced evaluation of the whole affair.

Each contributor approaches from a particular perspective and places the discovery of Neptune within a precise historical context. The English, French, German, and American contributions are carefully discussed, along with the scientific and other motives displayed by the individual astronomers.

Yet, what long puzzled me is why John Couch Adams did not announce his 1845 Neptune calculations to the world in *The Times* newspaper, as he had done on October 15, 1844, with his calculations pertaining to de Vico's comet. For this would have secured the unequivocal priority and prestige for the young fellow of St. John's College, Cambridge. Yet for some reason, he never did so.

Nor was it clear why Adams never took his computed planet position to the superbly equipped, self-funded, and independent community of British "Grand Amateur" astronomers, several of whom owned telescopes of much greater power and size than those in the Cambridge University and Greenwich observatories and who had no public or academic duties to occupy their time. Such gentlemen constituted most of the Fellowship of the RAS and of the Royal Society, and Adams must either have met many of them personally or read their journal publications.

The first Englishman to sight Neptune, on September 30, 1846, working from data which had reached England from the Continent, was John Russell Hind, employed director of the privately owned South Villa, Regent's Park, Observatory. Then, reading about the Berlin discovery, William Lassell, FRAS and FRS (1849), the Liverpool Grand Amateur, awaited the next clear night, so that he could direct his mighty 24-inch-aperture, 24-foot-focal-length equatorial reflector to the correct place in the sky. Lassell's notebooks in the RAS Library suggest that on the night of October 2–3, 1846, he saw the planet immediately, its disk shape making it instantly recognizable. Then, upon what was probably the next good night, October 10, 1846, Lassell not only immediately found Neptune shining brightly but also saw its large satellite, subsequently christened Triton, along with what he (incorrectly) believed to be a ring encircling the new planet.

Likewise, Lord Rosse, an astronomical friend of Lassell's, with his newly operational 72-inch-aperture "Leviathan," would have seen Neptune at first glance had he been asked to look for it. So why did Adams never tap into this extensive, and wholly accessible, astronomical resource of serious and superbly equipped British "Grand Amateur" astronomers? This book reexamines these and other questions.

Bill Sheehan and his colleagues have forged a clear path through almost two centuries of Neptunian history. That history extends from first puzzlement regarding Uranus's orbital behavior through the brilliant analyses of mathematicians, the controversy surrounding the discovery, and the subsequent myths and conspiracy theories. This book achieves an impartial scholarly appraisal of one of astronomy's greatest sagas.

Allan Chapman
President of the Society for the History of Astronomy
London, UK

Introduction: A Century and a Half of Discovery and Controversy

The major planet Neptune, outermost ice giant of the outer Solar System, was telescopically discovered by Johann Gottfried Galle and Heinrich Louis d'Arrest at the Berlin Observatory in September 1846, as a direct consequence of the calculations of the French mathematical astronomer Urbain Jean Joseph Le Verrier predicting where to point the telescope. The find—which instantly expanded the size of the known Solar System by half again—was immediately hailed as one of the most remarkable in nineteenth-century astronomy and indeed in all the sciences. Why was it deemed so important?

Thirteen years before, one of the great polymaths of the nineteenth century, William Whewell, had argued that (1833: xiii)

> Astronomy is not only the queen of the sciences, but, in a stricter sense of the term, the only perfect science; —the only branch of human knowledge in which particulars are completely subjugated to generals, effects to causes … and we have in this case an example of a science in that elevated state of flourishing maturity, in which all that remains is to determine with the extreme of accuracy the consequences of its rules by the profoundest combinations of mathematics, the magnitude of its data by the minutest scrupulousness of observation; in which, further, its claims are so fully acknowledged, that the public wealth of every nation pretending to civilization, the most consummate productions of labour and skill, and the loftiest and most powerful intellects which appear among men, are gladly and emulously assigned to the task of adding to its completeness.

And what more spectacular demonstration could there have been of "the most consummate productions of labour and skill" than the prediction of the existence of, and subsequent discovery of, a major planet? Here was a stunning example of the abilities of the "loftiest and most powerful intellects which appear among men" brilliantly adding to astronomy's "completeness."

Neptune's discovery had thereby strengthened the belief among astronomers as well as "men of science" (to use the nineteenth-century term for scientists) of the truth of the established order in the workings of the cosmos. That order was set on the foundations of Newton's law of universal gravitation, for it was calculations exploiting that law that had disclosed Neptune. When Charles Darwin came to pen the final sentence of his *On the Origin of Species by Means of Natural Selection*…, published in 1859, his momentous account of the working of laws in the natural world, it was no accident he argued (1859: 490), "whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and wonderful have been, and are being evolved."

The discovery of Neptune, then, as important as it was, was so for reasons that are not always easy for us to grasp from our early twenty-first-century vantage point. Now Newton's universal gravitation, which seemed unassailable then, has been replaced by Einstein's general relativity, and the detection of additional bodies belonging to the outer Solar System (Kuiper belt objects, KBOs) and even of entire systems of planets (exoplanets) orbiting distant stars has become commonplace.

It is also hard to recall the international rivalries that caused the discovery to be immediately engulfed in controversies, at first mainly involving fierce disputes about priority. These disputes subsided once a carefully crafted compromise had been negotiated allowing the Frenchman Le Verrier and the hitherto unknown English mathematician John Couch Adams to be regarded as mathematical co-discoverers of the planet.

The compromise seemed to hold for over a century, with a consensus version of the story widely accepted and reinforced by works published during the centennial year of the discovery (1946). But then, in the 1960s, vital papers went missing. The so-called Neptune file meticulously assembled and kept by the Astronomer Royal George Biddell Airy had been "misplaced" by a highly distinguished stellar astronomer and occasional historian of astronomy, Olin Eggen, who had been referring to it while writing biographies of Airy and James Challis. Though suspicion that he was the one who had absconded with the file was general, he repeatedly denied it, and even the authorities at Cambridge and the Royal Greenwich Observatory were careful not to lay any finger of blame, for fear that exposure of the fact might lead to the file's destruction. Only after he died in 1998 did one of his graduate students discover it in his flat in Chile. After a more than 30 years' absence, it was carefully packed up and returned from Chile to England under the personal care of the librarian of the Cambridge University Library, Adam Perkins. Thirty years is a long time, and in the meantime, researchers who had wished to consult the file had not only been inconvenienced, they had found ample room to exercise their suspicions and imaginations. The main question was this: Did members of the British scientific establishment, in fact, rewrite the history and *steal* Neptune from the French? Without the original documents, and in a post-Watergate world, it did not seem impossible. History, like nature, abhors a vacuum, and a number of authors with somewhat paranoid and conspiracy-favoring tendencies sensed a scandal and exercised rather remarkable ingenuity in working out and promoting sensationalistic revisionist theories. Without the ability to refer to missing documents, it was difficult to refute them.

Had they been right, this might well have been turned from one of the great triumphs of nineteenth-century science to a complete dismantling of the reputations of "eminent Victorians" Airy and Challis who, whatever their shortcomings, had always seemed to value in the highest degree traits of hard work, conscientiousness, and moral probity. But they were not right. The file's recovery put paid to their theories. A close study of the original documents filled in a few minor elisions but frankly offered very little that was genuinely new. Instead, the remarkable accuracy of the transcript published by the scrupulous and obsessive Airy himself soon after the discovery was confirmed. The file, which had always seemed an unimpeachable source of dates and detail, once again could be referred to with confidence, given secure anchoring to studies of the search for and discovery of Neptune that would otherwise have been completely at sea. The British, though they might have tried to spin things in a favorable way to help ensure that their countryman, Adams, got some share of the credit, did not *steal* Neptune from the French and then try to cover up their crime. There was no conspiracy. The conspiracy theories need not concern us further here: they have now been thoroughly debunked (Hutchins, 2008: 91–95). Having laid aside these imaginary controversies, we can now turn our attention to the real controversies which remain.

For the story, though remaining one of the most celebrated and oft-retold in the history of astronomy, is also one of the most complicated. It has a captivating theme—the mathematical discovery of a planet that had never yet been seen through the telescope. As with any such story, this one has multiple strands. The original documentation of the nineteenth century (including Airy's "Neptune file") provides the bedrock evidence, but that documentation is extraordinarily vast. And although that documentation—especially Airy's account to the Royal Astronomical Society (RAS) which was derived from the file—may be regarded as "eyewitness" in some sense, here, as everywhere else, what is seen depends on the viewpoint of the beholder. Does one look at such documentation with a microscope or a fish-eye lens? What is the appropriate eyepiece with which to detect Neptune in the telescope?

There were major negotiations even at the time of the discovery (beginning, not least, with Airy) to allocate "priority" and to establish a synoptic view of what had actually taken place. The international controversy that embroiled British and French astronomers—tentatively resolved by a carefully brokered consensus to share credit between the two co-predictors, Adams and Le Verrier—may not seem as interesting today as it did once. But—as with the controversy in our own time about Pluto's planetary status—it generated enormous contemporary interest, some of it doubtless of the tabloid variety, at the time. And anyone who is interested in how social and cultural contexts give shape to science will recognize the importance of uncovering some of the layers, as archaeologists or geologists painstakingly uncover the strata that hold clues as to the meaning of the past.

Major reassessments of the discovery of Neptune occurred for the centennial in 1946 and sesquicentennial in 1996 (though, in the latter case, these were somewhat marred by the missing file and the resulting conspiracy theories). There was a brief revival of interest again in 2011, when the bicentennial of Le Verrier's birth was celebrated and the first Neptunian "year" since the discovery was observed.

We have now (in 2019) just celebrated the bicentennial of Adams's birth, and so the timing seems right for another reassessment. In addition to being able to refer again to the original Airy file, which is now in the care of the Royal Greenwich Observatory archives at the Cambridge University Library, many other documents, not available to previous researchers, have been recovered and put in some semblance of order. Significantly, these have included not only British accounts—which, because of Airy's central role and to a lesser but still significant extent that of John Herschel and a few others, had always been rather overrepresented—but also those of French and German astronomers. Here for the Neptune story, we trace origins, the shoulders stood upon, and then move forward.

The result has been the introduction of a trove of fresh documentation. In addition, thanks to the efforts of scholars in several countries, many of whom are contributors to the present volume, we now have a much broader perspective from which to view the discovery of Neptune than ever before and a better understanding of what the Neptune story tells us about the practices of science in the mid-nineteenth century.

It is also fair to say that the methodology of historians of science has advanced greatly since 1846 or even 1946. In particular, rather than merely chronicling the past, historians of science have become much more adept at understanding the processes by which scientific knowledge is shaped. Instead of focusing only on individual "heroes," historians have come to realize the importance of the way that a specific scientific problem like the errant motion of Uranus, which led to the discovery of Neptune, brings together a group of individuals in an interactive network. (An early example of this kind of research is found in Susan Faye Cannon's paper "Scientists and Broad Churchmen: An Early Victorian Intellectual Network" [Cannon, 1964] which provides a model for Robert W. Smith's Chap. 7 here. [Also see Smith, 1989.])

The cultures of specific scientific institutions, conditioned by social conditions and the purposes for which they were established, must be considered. The important British institutions were Cambridge University (where Adams did his calculations), Cambridge University Observatory (which had largely been set moving in a positive direction by Airy but where his successor, James Challis, was overwhelmed with responsibilities before undertaking the first telescopic search), and the Royal Observatory, Greenwich (where—as stressed by Professor Allan Chapman [Chapman, 1988]—the public service aspect of time-keeping and supporting navigation precluded a purely speculative research purpose such as searching for a planet). The Paris Observatory and the Bureau of Longitudes were the corresponding centers in France. And in Germany, which was at the time not even a unified country, the Berlin Observatory played the key role of actually detecting the planet in the heavens.

Since the network of individuals involved in the calculation and eventual discovery was indeed international and the correspondence remarkably extensive and rapid in those days of letter-writing (and post-1815 peace in Europe), there are many threads of communication across the entire European community of scholars inviting reconstruction. Fortunately, the documentation available is extensive enough to allow "fine-grained" analyses of events, personalities, and contingent developments. Cannon (ibid.: 30), thinking of the middle of the nineteenth century in general, remarked, "we possess the most complete documentation, for selected individuals, not only that ever has existed but that ever will exist."

As a characterization of the middle of the nineteenth century, this still seems true. On the basis of this extensive documentation, a number of exhaustive studies have appeared, including Martin J. S. Rudwick's *The Great Devonian Controversy* (Rudwick, 1985) and James A. Secord's *Victorian Sensation* (Secord, 2003). Perhaps with the exception of the publication of the *Vestiges of the Natural History of Creation*, no other scientific event was more vigorously discussed during the first part of the nineteenth century, in Britain at any rate, than the discovery of Neptune.

But the discussion was not only British nor even only British and French. The Germans played a much more significant role than has previously been recognized; they were not merely opportunists who happened to have a close prediction and a good map. And Americans were also involved, as the discovery happened just as American astronomy, hitherto woefully lagging behind European achievements, began to come into its own as a first-rank power of astronomical research.

We are only too keenly aware of the truth of the old adage *Ars longa, vita brevis*. The amount of material available to Neptunian scholars is both a blessing and a curse. Such rich materials allow the construction of an almost Dickensian canvas, with an array of characters fully the equal of any found in a Victorian novel. History here challenges narrative skill to the utmost and demands something of the art of the novelist, rather than tacking backward from the known ending of the story, as conspiracy theorists and Whiggish historians do.

But tempting as it is, when presented with such inexhaustible resources, to take shortcuts, we have resisted that temptation. In particular, we have resolved to abstain from glib character analyses, facile attribution of motive or blame, and all species of retrospective analyses in general. Rather, we have attempted, as far as humanly possible, to remain faithful to what the scientists themselves thought they were up to at the time. We haven't avoided what might be referred to as "reverse prediction" entirely, but as a rule, it's a clumsy device—rather like the appearance of Time between the third and fourth acts of Shakespeare's *The Winter's Tale*—and we have tried to avoid it. We have striven always to represent the perspectives of the individuals involved as they themselves experienced them and of course provided the international point of view needed given the universal (or at least trans-European) significance of Neptune's discovery. To some extent, no doubt, we have failed or fallen short. But at least it is useful to state clearly our aspirations.

A few comments regarding intended audience: Determining this is a struggle for any single author, and the difficulties are multiplied in a multiauthored work. The discovery of Neptune is at once one of the best-known and most attractive subjects in the history of astronomy—thus one which has always had wide popular appeal—but it is also one in which the predictions depended upon highly technical mathematical methods (classical perturbation theory). Thus, we have had to find a compromise between appealing to a broader general audience on the one hand and to a highly sophisticated, scholarly, but potentially small one on the other. We have tried our best to strike the right balance. In general, however, we have thought it better to err on the side of the more general reader—for instance, in Chap. 1, which provides an overview of topics in celestial mechanics which are needed as background to understanding the later chapters. Our success is for the reader to decide.

In outline, the contents of the book are as follows.

Foreword—Allan Chapman

Introduction: A Century and a Half of Discovery and Controversy—William Sheehan

Chapter 1. Preliminaries to the Neptune Discovery: Newtonian Gravitational Theory—William Sheehan

Since the discovery of Neptune represents a high point in the history of celestial mechanics, Isaac Newton's theory of gravitation is in a real sense a major "hero" of this story. We present some of the backgrounds involving Newton and his contemporaries and explore the way that, in the century after Newton published his *Principia* in 1687, Newtonian gravitational theory—largely through elaboration into the complex methods of perturbations achieved by a series of brilliant mostly French successors—came to acquire its tremendous prestige.

Chapter 2. Planetary Discoveries Before Neptune: From William Herschel to the "Celestial Police"—William Sheehan and Clifford J. Cunningham

By the end of the eighteenth century, the Solar System was, at least by present standards, a rather simple affair. The outermost planet was still, as it had been in antiquity, Saturn. The planets, their moons, and a few periodic comets like Neptune that moved in very eccentric orbits round the Sun could be fairly represented as moving according to clockwork. Then in 1781, William Herschel discovered a new planet, Uranus, and at a single stroke doubled the scale of the known Solar System. Guided by a strange but seemingly valid "recipe," the Titius-Bode law that gave the relative distances of the planets and to which Uranus was quickly accommodated, astronomers began to search for additional planets in the place of a missing number between Mars and Jupiter. Their search bore fruit with the discovery of the first four "minor planets." Meanwhile, celestial mechanicians rather confidently set out to calculate Uranus's orbit. By the early 1800s, Uranus was known to be veering off course. Astronomers gradually became aware of a "crisis" in gravitational theory that would be resolved only by the discovery of a more remote planet whose existence could be disclosed only by its disturbances on Uranus. By the early 1820s, elite mathematicians across Europe were aware of the challenge.

Chapter 3. John Couch Adams: From Cornwall to Cambridge—Brian Sheen and Carolyn Kennett

Of the several mathematicians aware of or attempting to skirmish with the problem of Uranus, only two, unknown to each other, made serious attempts to attack it. They were John Couch Adams and Urbain Jean Joseph Le Verrier. One did so as a matter of private research; one was set upon it. By 1845, Le Verrier had already made his mark in research in his professional post at the Paris Observatory and thereby gained the support of his director, François Arago, who set him full-time on the Uranus problem. Adams, who in contrast to Le Verrier has not yet been the subject of a scholarly biography, grew up in somewhat impecunious circumstances in Cornwall; but he was nurtured, encouraged, and supported by a loving family so that, while quiet by nature and inconspicuous because he was poor and diligent rather than a social set rowdy as a Cambridge undergraduate, he was self-assured and ambitious for his mathematics which he saw as a path to helping his hard-pressed family. Thus, he possessed assurance and ambition which allowed him to flourish in the very demanding academic milieu at Cambridge and to tackle one of the most challenging and complex problems in astronomy as described in Chap. 4. This chapter's explanation of Adams's pre-Cambridge years is thus essential to a full understanding of him and his subsequent achievements.

Chapter 4. John Couch Adams: From a Senior Wrangler to the Quest for an Unknown Planet—William Sheehan

This chapter explains for the first time the onerous studies of an ambitious Maths Tripos undergraduate at Cambridge and the dominating duties and responsibilities required of him as a junior fellow and tutor, for which he was paid. These duties and responsibilities, which Adams took very seriously and prioritized above all else, constrained his personal research to vacations and inhibited the evolution of his relations and correspondence with senior astronomers such as Cambridge University Observatory astronomer James Challis and the Astronomer Royal George Biddell Airy. As early as 1841, while still an undergraduate at St. John's College at Cambridge, he became intrigued by the problem of Uranus's wayward motion, but only in 1843, when he completed his degree with high honors and was appointed a fellow at St. John's, did he take it up in earnest. Doing almost all the work during the vacations, he completed several calculations which gradually refined his solutions, until in October 1845, he had the solution later to become famous as it identified the position of the planet within two-and-a-half degrees of its discovery position. He then tried, without success, to meet the Astronomer Royal George Biddell Airy at the latter's residence at Greenwich and to present the results of his researches. The well-known stories of his near miss and subsequent failure to respond to Airy's "radius vector question" are reanalyzed here in terms of newly discovered documentation and challenge long-held stereotypes of Adams's relationships with Challis and Airy.

Chapter 5. Urbain Jean Joseph Le Verrier: Predictions Leading to Discovery—James Lequeux

This chapter, based on the magisterial biography of Le Verrier (Lequeux, 1990), outlines how the French mathematician—older and better established than Adams and with no knowledge of the latter's existence—set out on his own extensive calculations and arrived at a set of elements and a position for a planet beyond Uranus which he published in June 1846. It was this publication, coming into the hands of Airy, who immediately recognized its similarity to that Adams had dropped off at Greenwich the previous October, that led to a sudden acceleration of activity that included the organization of a search over that summer by Challis with Cambridge's large Northumberland refractor, the publication of a revised calculation and position by Le Verrier at the end of August, and events set in motion that would lead to the planet's discovery in Berlin.

Chapter 6. "That Star Is Not on the Map": The German Side of the Discovery—Davor Krajnović

The planet was discovered at the Berlin Observatory after a short search of the region of the sky indicated by Le Verrier, by Johann Galle and Heinrich d'Arrest on September 23, 1846. They had an advantage over Challis in that they were in possession of the latest and by chance the most relevant one of a set of Berlin star charts that had not yet been published to astronomers elsewhere. Of the multiple threads of the Neptune story, this one is in some ways the least known, and this chapter draws extensively on German primary and published sources to contextualize the discovery within the wider culture of German astronomy during this period.

Chapter 7. Clashing Interests: The Cambridge Network and International Controversies—Robert W. Smith

Immediately after the announcement of the discovery of the new planet in Berlin and while Airy was still vacationing on the Continent, a tremendous national and international furore erupted when several Cambridge alumni or university grandees—not including Adams and not all astronomers—immediately and without coordination claimed co-discovery for him, along with the right to name the planet. These claims, and the subsequent correspondence underlying them, are clear evidence of an informal "Cambridge network" of Cambridge University alumni, fiercely loyal to and like-minded by their social conditioning and common mathematical training and achievements, who saw this discovery as a particularly vital Cambridge interest and thereby an English one.

The activities of the Cambridge network, which significantly were launched only after Neptune had been recognized from Berlin, raise the whole question of what constitutes priority in discovery. The network's patronage and diverse interests, and eruption into rare and wide public visibility, brought to the fore the somewhat embarrassing question as to why other British astronomers, not associated with Cambridge, were not encouraged to join the search for the predicted new planet. Airy, as Astronomer Royal with an extensive array of correspondents both in Britain and the Continent, was in a unique position and took a complete grip in managing from a national point of view the disastrous situation of the discovery having been made in Berlin on the basis of a French mathematician's calculations. He largely succeeded in controlling the narrative and assuring that Adams received a negotiated share of the credit. This chapter, documented with much private correspondence revealing how astronomers and participants really felt about these most public events, thus provides the most complete explanation so far offered of the English claims on Neptune, within the contemporary context of social status, deference, Cambridge elitism, nationalism, and international attitudes to discovery and priority in this era of revolution in the sciences, so that the participants are understood within their own milieu.

Chapter 8. Neptune Examined: William Lassell, a Satellite, and Neptune's "Ring"—Robert W. Smith and (the late) Richard Baum

William Lassell was one of the greatest of the "Grand Amateurs," men of wealth and independence who built large telescopes and wielded them largely in pursuit of their own personal researches (in contrast to the national observatories whose duties and functions were more circumscribed). He was not a Cambridge man, but he was a close friend of several, especially Sir John Herschel, and was just deploying a new large telescope when the planet came to light in Berlin. Ambitious and wanting to burnish his own credentials, Lassell set out at Herschel's bidding to try to discover a satellite of Neptune, an important and useful challenge as if successful it would lead directly to calculation of the planet's mass. The latter was not only of interest in its own right but would provide a check on the calculations of Le Verrier and Adams. He succeeded within a week in discovering Triton, as Neptune's large satellite was later to become known. Nevertheless, this proof of Lassell's ability and instrument quality raises the question of why others apart from Challis were not primed to search. While attempting to confirm the existence of Triton, Lassell was vouchsafed impressions of something more—a possible ring of Neptune. As explained here, the latter has nothing to do with the planet's actual system of spidery rings and was eventually recognized to be nothing more than an illusion produced by spurious optical effects.

Chapter 9. Neptune's Orbit: Reassessing Celestial Mechanics—William Sheehan and Kenneth Young

In the immediate aftermath of the discovery of Neptune, the calculation of its orbit was of the utmost importance. Several of the most important investigators were Americans, one of whom was Sears Cook Walker, whose orbit was, in a rather alarming degree, dissimilar to those predicted by Le Verrier and Adams. Walker's researches led another American, Benjamin Peirce, to question the validity of the European calculations altogether and to maintain that the discovery of Neptune had been a mere "happy accident." Adams attempted to refute Peirce's claims, and later, astronomers continued to press the same methods that had led to the spectacular discovery into service in the quest for additional planets. Le Verrier analyzed Mercury's anomalously precessing perihelion in terms of an inner planet, "Vulcan." Other astronomers, notably Percival Lowell, extended the purview of celestial mechanics into the outer Solar System and used Adams's and Le Verrier's methods to try to track down a planet beyond Neptune. It has only been since about 1990, with the advent of newer methods of doing celestial mechanics, that it has finally become possible to determine the limits of validity of the methods Le Verrier and Adams used. Their calculations were valid—but only within rather specific circumstances that were realized in the decades before and after Uranus's and Neptune's conjunctions in 1821 (Lai, Lam, and Young, 1990). Thus, though not exactly in the same sense argued by Peirce, the discovery of Neptune was indeed a "happy accident," and the approach that led to its discovery was a one-off that has never been repeated. Meanwhile, Vulcan has been shown to be nonexistent, and the anomalies of its motion satisfactorily accounted for by Albert Einstein's general theory of relativity. Hence, this chapter reassesses for the first time the methods of both Adams and Le Verrier and the unknown coincidences in celestial mechanics that allowed their successful calculations and also helps to explain how their discovery motivated the extraordinary efforts of elite astronomers to reprise this success in the decades that followed.

Chapter 10. Neptune Visited and the Outer Solar System Revolutionised, 1989–2019—William Sheehan

The discovery of Neptune marked the end of one quest—that of satisfactorily explaining, in terms of Newtonian gravitational theory, the wayward motions of Uranus—and the beginning of another, the quest to fill in the map and understand the nature of the contents of the outer Solar System whose icy precincts Neptune, as the outermost of the giant planets, bounds. Though the attempt to find planets beyond Neptune by analyzing remaining "residuals" in the motions of Uranus and Neptune would prove unsuccessful, Clyde Tombaugh, pursuing with dogged determination and thoroughness an empirical photographic survey of the sky in search of Percival Lowell's putative "Planet X," did manage to find a small "planet," Pluto, in 1930, which for a time was thought perhaps to answer to the description. We now know that Pluto is too tiny to have produced any significant disturbances in Uranus or Neptune; its discovery was indeed a "happy accident"—and, as is now known, Tombaugh had merely stumbled upon by far the brightest member of the Kuiper belt of icy objects that swarm beyond Neptune's orbit. Since 1990, the use of powerful new imaging technologies and gigantic telescopes has rapidly begun to fill in what had hitherto seemed nearly empty spaces with a plethora of icy debris known as Kuiper belt objects (KBOs). They represent a complicated bestiary, and their characteristics provide important clues to the history of how the Solar System came to acquire the structure it has. This brings us to an exciting frontier that has begun to be explored only in the last twenty-some years, in which giant planet migrations in the early Solar System played a role, and which tantalizingly hints at the existence of at least one more giant planet, far beyond Neptune. Neptune was a high point of the history of astronomy of the nineteenth century. If past is prologue, the future chapters of this story remaining to be told in the twenty-first century may well be more exciting than those that have already been told.

Flagstaff, AZ, USA William Sheehan

Acknowledgments

Allan Chapman of Wadham College, Oxford, has very generously written a foreword for the book. What Allan brought to the table long ago was his unique appreciation of Airy's personality, official role and responsibility, and *modus operandi*. In the aftermath of Neptune's discovery, Airy was scapegoated and has been derided by too many historians since (just as Challis has). For more than 30 years, Allan has quietly used every opportunity to emphasize a holistic understanding of the man beyond the Neptune affair which caricatured him and also his *very many* achievements. We hope that something of Allan's work in getting us to understand this history and its players, appreciate the science, and perceive stumbles by several of the principal actors as just the human errors we all make has informed what we have written here.

Carolyn Kennett and Trudy E. Bell have been far more than editors and have gilded everything they touched. Carolyn contributed very many thoughtful editing suggestions and query resolutions, especially the vast painstaking work of standardizing the multiauthor text in order to achieve enjoyable flow for the great and complex narrative offered here. Trudy contributed her expertise regarding the role that Neptune played in the early years after its discovery in helping launch American astronomy onto the international stage. She sparked a friendly debate, which feeds significantly into Chap. 9. Our colleague, Roger Hutchins, has generously given of his limited time and unlimited expertise, reading and commenting on the manuscript several times. Bernard J. Sheehan helped produce the excellent translation into English of James Lequeux's biography of Le Verrier, which we have followed here. Guy Bertrand and Jacques Laskar at the Institut de mécanique céleste et de calcul des éphémérides (IMCCE) in Paris have shared research in progress and greatly enriched the discussion of the perturbation methods used by Le Verrier. We are grateful to H. M. Lai and C. C. Lam for allowing us to summarize and use figures from their 1990 paper with Kenneth Young, which marked a new era in understanding the limits of the calculations whereby Le Verrier and Adams predicted the position of Neptune. In the rapidly developing area of current research into the contents and evolutionary history of the outer Solar System, Dale P. Cruikshank of NASA Ames, Konstantin Batygin of Caltech (California Institute of Technology), and Greg Laughlin of Yale provided indispensable insights. They also generously shared researches in progress without which Chap. 10 could never have been written, as well as making accessible some very esoteric regions of higher mathematics. In addition, much help was provided in finding illustrations, as duly acknowledged in the credits. However, we are especially grateful to Lauren Amundson, archivist at Lowell Observatory, for her kind assistance.

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William Sheehan retired after 30 years in practice as a psychiatrist, earned his MD from the University of Minnesota (1987). He has written or coauthored more than 20 books about astronomy and history of science, including *In Search of Planet Vulcan* (with Richard Baum) (1997), the first full-length history of the quest for Le Verrier's intra-Mercurial planet, and *Discovering Pluto: Exploration at the Edge of the Solar System* (with Dale Cruikshank) (2018). He is a contributing editor for *Sky & Telescope*, has twice been Cox Memorial lecturer for the Society for the History of Astronomy, was a 2001 fellow of the John Simon Guggenheim Foundation, and was awarded the Gold Medal of the Oriental Astronomical Association (2004) for his work on Mars. He is a member of IAU's Working Group on Planetary System Nomenclature. Asteroid 16037 was named in his honor.

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Chapter 1
Preliminaries to the Neptune Discovery: Newtonian Gravitational Theory

William Sheehan

Abstract The discovery of Neptune stunned the 19th century world. It involved the mathematical prediction of the existence of a major planet never yet seen through a telescope, because of the way it seemed to be pulling on a known planet, Uranus, away from its predicted orbit. When an actual planet was discovered near the predicted position, it was famously hailed as the greatest triumph of Isaac Newton's theory of gravitation.

How did they do it? Largely by standing on the shoulders of giants—a dazzling succession of 18th century mathematicians, many of them French—who had to overcome many roadblocks in solving difficult problems, some of which had given Newton himself headaches. In so doing they developed celestial mechanics, the branch of mathematical astronomy that would later point the way to Neptune.

1.1 The Road to Neptune

One might set off from many different starting points to Neptune. Its discovery was perhaps inevitable, though the road taken was certainly not. Most accounts begin with William Herschel's (1738–1822) telescopic discovery of Uranus in March 1781. For the first time it became clear that a vast frontier of the outer Solar System, unsuspected by the ancients, who had circumscribed it within the orbit of Saturn, the outermost of the bright planets visible to the naked eye. The possibility of still other planets gradually came into the view of astronomers—though the view was not one of sight in the usual sense, but rather of something more akin to feeling. Some body (or bodies) was pulling on Uranus from beyond. The nature of the pull was formulated in terms of Isaac Newton's (1643–1727) theory of gravitation, and complicated formulae defined the pull in terms of the perturbations of each body in the Solar System acting on every other. These formulae were used by mathematicians

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W. Sheehan et al. (eds.), *Neptune: From Grand Discovery to a World Revealed*, Historical & Cultural Astronomy, https://doi.org/10.1007/978-3-030-54218-4_1