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THE DISCOVERY OF THE COMPANION OF SIRIUS AND ITS AFTERMATH

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Introduction

It is part of modern astronomical lore that the white dwarf companion to Sirius was first theoretically predicted by F. W. Bessel in 1844 and then accidentally discovered by A. G. Clark in 1862. In the years leading up to 1862, Bessel's unseen companions of both Sirius and Procyon represented key unresolved astrometric and gravitational problems. Thus, when the companion of Sirius was finally observed the event was hailed as a major discovery. Indeed, Clark, although he had not been trained as an astronomer, received the 1862 astronomy prize of the Lalande Foundation in recognition of his discovery.

The many subsequent breakthroughs, in both observational astronomy and theoretical astrophysics, that flowed from Clark's discovery of the white dwarf companion of Sirius, have borne out the importance of the first observation of Sirius B, as the companion is now known. These Sirius-related milestones include the slow realization (1910–15)[1] that the stars consisted not simply of 'giants' and 'dwarfs', but also included an entirely new class of very small, very faint stars, the white dwarfs; the first (albeit flawed) measurement of a gravitational redshift (1924–25);[2] and the ultimate explanation of white dwarfs in terms of degenerate matter and the Chandrasekhar limiting mass (1926–35).[3] In this paper we provide an account of the discovery of Sirius B, and of how the news was received in Europe, including a discussion of the previously unknown involvement of Urbain J. J. Le Verrier.

State of Knowledge Prior to 1862

In 1844 Friedrich Wilhelm Bessel, the director of the Königsberg Observatory, found perturbations in the proper motions of the stars Sirius (α CMa) and Procyon (α CMn).[4] In the case of Sirius, Bessel measured only the relative changes in Right Ascension (RA) with respect to the mean proper motions of three other fundamental stars, but made no attempt to measure changes in declination because of the difficulty of establishing accurate declinations free of atmospheric refraction for a star lying as far south as Sirius ($\delta \sim -16^{\circ}$). The perturbations in RA were small (~3′), but well in excess of his expected uncertainties; moreover, they seemed to show a periodicity, which he estimated at 50 years. Bessel attributed the anomalous motions of Sirius and Procyon to the gravitational effects of unseen companions. He justified this conclusion with his now famous remark: "But light is no real property of mass. The existence of numberless visible stars can prove nothing against the existence of

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numberless invisible ones." He concluded his paper with the prophetic remark that the continued study of the motions of Sirius and Procyon may "provide important information concerning the physical constitution of the universe".

Bessel's study of the motions of Sirius was continued by Christian August Friedrich Peters (1806–80), who eventually succeeded Bessel as director at Königsberg in 1849. In his 1851 habilitation thesis,[5] Peters systematically extended Bessel's original analysis of the motions of both Sirius and Procyon. Peters was able to be much more specific about the nature of the companions of both stars that Bessel had discovered. For Sirius, Peters found that the companion had a period of 50.093 years, moved in a highly eccentric orbit, and had most recently passed near Sirius in 1841. More importantly, he produced an ephemeris for the RA motions of Sirius for the years 1755 through 1870. Peters's work nevertheless was still just one dimensional, considering only relative RA displacements.

The obvious next step was to include the corresponding perturbations in declination. This analysis was independently undertaken in 1861–62 by two relatively young astronomers: Thomas Henry Safford (1836–1901) at the Harvard College Observatory, and Arthur Auwers (1838–1915) at Königsberg. In the autumn of 1861 Safford sent a lengthy description of his results[6] to the University of Michigan publication, *Brünnow's astronomical notices*, where it appeared on 20 December 1861. He also sent an abbreviated report[7] to the *Monthly notices of the Royal Astronomical Society*. Auwers, who was well along with his own calculations, became aware of Safford's published work and sent a brief summary of his own results to *Monthly notices*,[8] and the papers of Safford and Auwers appeared side-by-side in the March 1862 issue. Thus, just as the discovery of Sirius B was unfolding, the chief remaining astrometric problem of the two-dimensional (RA and dec) reflex motion of Sirius had been resolved.

The Discovery

Alvan Clark and his two sons, Alvan Graham Clark and George Bassett Clark (Figure 1), had formed a small firm, Alvan Clark & Sons,[9] in 1851 to manufacture refracting telescopes. In 1860 the firm obtained a contract from the University of Mississippi in Oxford, Mississippi, to build the world's largest refractor (Figure 2), with an $18\frac{1}{2}$-inch objective lens.[10] By January of 1862 the figuring of the doublet lens was well advanced. It was the Clarks' practice to field-test their lenses for both resolution and colour correction on actual stars. For this purpose lens cells were mounted on crane-like structures in the yard of their workshop.

On the night of Friday 31 January, Alvan Graham Clark and his father accidentally observed a small faint companion near Sirius during a colour test of the lens.[11] It is unlikely that either father or son fully appreciated the significance of the companion, since they never recorded its discovery and it is almost certain that neither was aware at the time of Bessel's prediction. All the personal accounts of the discovery stem from recollections given many years later. Nevertheless, Alvan Clark was a keen double star observer and in the habit of reporting his discovery of new doubles in

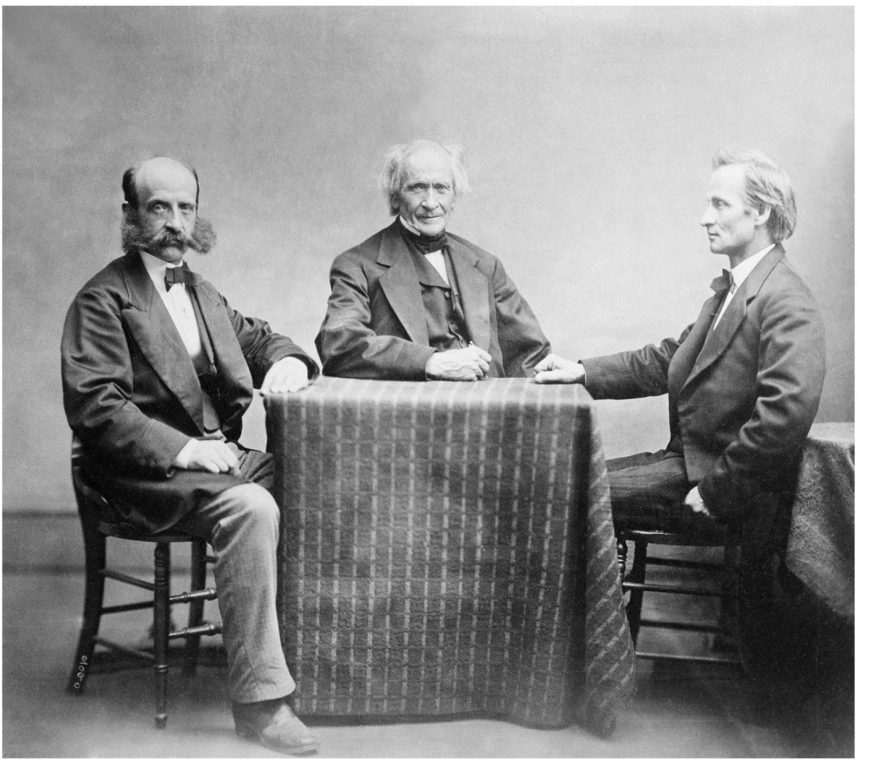

FIG. 1. Alvan Clark and his sons. Left to right: George Bassett Clark, Alvan Clark, and Alvan Graham Clark. Courtesy of the Mary Lea Shane Archives of the Lick Observatory.

the local press and to professional astronomers.

Up to this point, all that has been said about the discovery can be obtained from the often obscure published literature of the period. To determine what happened immediately following the discovery it is necessary to consult the observing records at the Harvard College Observatory and the personal papers of George Phillips Bond, the Observatory director.

On Saturday, 1 February, the log book of the 15-inch 'Great Refractor' records no observations but it does contain a simple entry in Bond's hand, "A. Clark jr. reports the discovery of a companion of Sirius last evening with the $18\frac{1}{2}$ in. object glass. Following in AR at 10″ dist." Evidently, Alvan Graham had sent a brief message to Bond relating the discovery. Bond, as we will see, was clearly aware of the potential importance of the faint companion. He took every opportunity the following week to confirm the sighting, but was thwarted by the weather and the seeing. At last, on the evening of 7 February, he was successful:

FIG. 2. The original wooden tube of the Clark's $18\frac{1}{2}$- inch while it was in use by the Chicago Astronomical Society. Courtesy of the Adler Planetarium.

> After scrutinizing the neighborhood of Sirius on every clear night of the week since Feb. 1 without obtaining a single opportunity of quiet definition a sight of [the] companion was attained this evening during an interval of about 5^m when the vision was tolerably good. For an hour before and after it was impossible to catch a glimpse of it.[12]

Next to the entry is a tiny sketch representing what he observed through the eyepiece. It consists of an arrow pointing to the left, indicating west, together with a large dot and a much smaller dot to the right. He quickly used the micrometer to measure the position angle and separation of the companion.

Bond next observed the companion on the night of Monday, 10 February. On the

18th Bond was invited to the Clarks's workshop in Cambridgeport for an evening of viewing through the new $18\frac{1}{2}$ inch 'object glass', and with it he could easily perceive the new companion of Sirius. Bond's account of the visit[13] contains his professional opinion of the new lens, including its superior colour correction.

Boston 1862

On Wednesday, 12 February, Bond wrote two papers describing his observations and attributing the initial discovery to Alvan Graham Clark. The first paper[14] was sent to the *American journal of science* and the second[15] to *Astronomische Nachrichten*. The two papers are a study in contrast. In the very brief *Astronomische Nachrichten* paper Bond merely reports "the interesting discovery of a companion" made by Clark and gives his own measurements of 10 February. There is no explicit mention that this may be Bessel's unseen companion. To his domestic audience in the *American journal of science*, Bond is much more expansive and speculative. After giving his measurements of 10 February and crediting Clark, Bond states: "It remains to be seen whether this will prove to be the hitherto invisible body disturbing the motions of Sirius, the existence of which has long been surmised from the investigations of Bessel and Peters upon the irregularities of its proper motion in right ascension." He then mentions the recent work of his assistant Truman Safford on the declination motion of Sirius and states that "For the present we know only that the direction of the companion from the primary accords perfectly with theory". Bond concludes with the following statement: "Its faintness would lead us to attribute to it a much smaller mass than would suffice to account for the motions of Sirius, unless we suppose it to be an opaque body or only feebly self-luminous." Bond's observations were followed by those of the amateur astronomer and early spectroscopist, Lewis Morris Rutherfurd, in New York City on 8 March.

Europe 1862

It is not exactly clear when Bond's manuscript reached *Astronomische Nachrichten*, but packet steamers of the period typically took 10 to 14 days to cross the Atlantic. Thus, the first week of March is a likely date of arrival of the paper at Altona Observatory. As will be seen, this date has significance. The recipient of the paper was C. A. F. Peters, who assumed the editorship of *Astronomische Nachrichten* in 1854. Given Peters's prior work on Sirius, he was certainly in an ideal position to judge how well Bond's measurements corresponded to any possible companion. Peters published Bond's paper, without comment, several weeks later in the 28 March issue of *Astronomische Nachrichten*. The only indication of Peters's initial reaction to the discovery is to be found in the News of the Week section of the 28 March edition of Abbé Moigno's *Cosmos*, where there is a brief one-sentence statement,[17] that "Mr. Peters writes us that he does not accept the identity of the companion that has just been discovered, with the one that is calculated". As we will see, the origin of this statement appears to have been a personal letter from Peters to Abbé

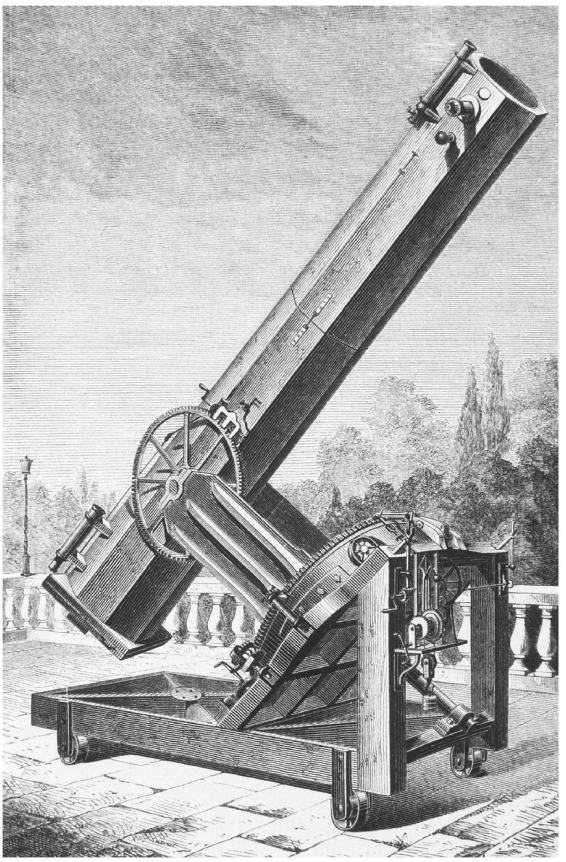

FIG. 3. Foucault's 80-cm telescope on the terrace of the Paris Observatory, where it was originally used. Courtesy of William Tobin.

Moigno written prior to 14 March.

Clark's discovery was first confirmed in Europe on 20 March at the Paris Observatory, by Jean Chacornac using Léon Foucault's recently completed 80-cm glass reflector (see Figure 3). Chacornac's results, including a second observation on the 25th, were published[18] in *Astronomische Nachrichten* a week after the appearance of Bond's paper. Chacornac, whose measurements agree very well with those of Bond, makes no mention of Clark's discovery or of Bond's paper. Chacornac did, however, add one significant piece of information: the companion was ten thousand times fainter than Sirius. Chacornac's paper in the 3 April edition of *Astronomische Nachrichten* was followed by an editorial comment by Peters,[19] that "… it is thus certainly possible that at last Bessel's companion is found", thus reversing the doubts

he had earlier communicated to Abbé Moigno. By the end of March, news of the Clarks's discovery appeared in the pages of *Cosmos*, the *Memoirs* of the French Academy of Sciences, *Monthly notices of the Royal Astronomical Society*, and even in the popular press. William Lassell on Malta learned of the discovery from *Galignani's messenger*,[20] a popular English language 'gentleman's magazine' published in Paris. Lassell observed the companion on 11 April with his 48-inch reflector and published the results in the 28 April issue of *Astronomische Nachrichten*. Lassel's observations,[21] which were the last reported for the year 1862, caused some consternation, since Lassell placed the companion 5 arc seconds closer to Sirius than the separations measured by the other observers.

Le Verrier 1862

In 1879 the American double star observer Sherwood Burnham[22] wondered why the companion had not been found earlier, since "The suspected companion had been looked for by many observers without success … [but] once discovered, it was readily seen and even measured with the same instruments with which it had been vainly looked for before". That it was not seen at the time of Bessel's discovery is understandable, since Sirius B passed through periapse in 1844 and would have been unobservable in the glare of Sirius. However, by 1848, once the companion emerged beyond about 4 arc seconds from Sirius, it could potentially have been detected. Certainly by 1851, when the separation had grown to 5.1 arc seconds and after Peters's ephemeris, there was at least an indication of which side of Sirius the companion could be expected to lie. From Burnham's remarks it is safe to assume that observers had looked, but few, if any, published reports of their negative results. Knowing where to look and what to look for was clearly paramount. As for Procyon, detection of its companion presented a much greater observational challenge than of that of Sirius. Its white dwarf companion was finally detected by Schaeberle in 1896 using the Lick 36-inch.[23]

Le Verrier, whose main area of expertise was solar system dynamics, was also seriously interested in the gravitational paradox represented by the unseen companions of Sirius and Procyon, and he actively and personally pursued at least one pre-discovery search for the companion of Sirius. Le Verrier had established his reputation with the theoretical prediction of the location of the planet Neptune in 1846, thus explaining the anomalous motions of Uranus. In 1859 his investigations of the motions of Mercury had led him to the discovery of the anomalous perihelion advance of the innermost planet. Le Verrier's proposed solution of that paradox was the hypothetical inner Mercurial planet that came to be known as 'Vulcan'. Indeed, at the very time of the discovery of Sirius in 1862, Le Verrier was deeply involved in issuing predictions of possible opportunities for transit and solar eclipse sightings of Vulcan.

Le Verrier's career has been associated almost exclusively with the mathematical study of the motions of bodies (real and imagined) within the solar system. His lack of interest in the physical nature of the planets is well attested to by Camille Flammarion

(1842–1925), who worked under Le Verrier early in his career. Flammarion once remarked that he doubted that Le Verrier had ever even taken the trouble to view his greatest discovery, the planet Neptune, through a telescope.[24] Likewise, Le Verrier showed little evident interest in the stars, except perhaps as fiducial points for the accurate measurement of planetary positions. Nevertheless, when Le Verrier was appointed to the directorship of the Paris Observatory (then the Imperial Observatory) in 1854, one of his tasks was to upgrade the instrumentation. Perhaps his most important achievement in this regard was to hire the remarkably inventive and versatile physicist, Léon Foucault (1819–68) in 1855.

Le Verrier had asked Foucault to investigate the feasibility of building the world's largest refracting telescope, and in 1855 flint and crown glass blanks with a diameter of 29-inches (74-cm) were acquired by the observatory. Foucault, however, became more intrigued by the obvious advantages of reflecting telescopes[25] made possible by the recently developed processes for chemically silvering glass mirrors. Over the next six years he worked to overcome the practical problems associated with the fabrication and testing of such telescopes, producing successively larger glass reflectors, up to diameters of 40-cm. He managed to convince Le Verrier that an 80-cm (31.5-inch) reflecting telescope was possible. The new instrument, which was nearing completion in the winter of 1861, would prove much superior to the old metal reflectors that had dominated large aperture instruments since the days of William Herschel. Foucault's telescope saw first light at the Paris Observatory on 17 January 1862. One of the chief observers using the new telescope was Jean Chacornac, who kept a set of log books[26] of observations he made with the 80-cm and other instruments during the early 1860s.

The level of Le Verrier's interest in the theoretical and observational problem posed by the unseen companions of Sirius and Procyon can be gauged from the contents of contemporary reports. In his 1855 *Rapport sur l'Observatoire Impérial de Paris*,[27] Le Verrier provides a summary of the work of Bessel on the proper motion of Sirius, readily endorses the idea of a gravitationally bound companion, and states that this companion might, with improved telescopes, been observed one day. A confirmation of this position and a further revealing comment are contained in the 28 March 1862 edition of Abbé Moigno's *Cosmos*, which reports news of the discovery of Sirius B. There, Le Verrier is quoted as saying that he had not hesitated in adopting Bessel's interpretation of the presence of an unseen companion and that, had he been in possession of a telescope of sufficient strength, he would have long searched for the dark star.[28]

The availability of the new 80-cm telescope reawakened Le Verrier`s interest in an unseen companion.[29] Indeed, among the first objects viewed with the new telescope was Sirius. Chacornac's log book for Monday, 27 January, contains the following somewhat enigmatic entry:

> Examine Sirius with the No. 2, 3 and 4. The No. 2 and 3 are equipped with a bar. L.V. says he sees a companion left, 5 or 6″ away. I see nothing but short rays, a star below 11th magnitude is the only one visible.[30]

Thus, Chacornac searched for the companion of Sirius just four days prior to its discovery by Clark. Chacornac saw nothing, other than some faint field stars. The intriguing piece of information is that Le Verrier ('L.V.') appears to have examined the star himself in the telescope and that he perceived something 5 or 6 arc seconds away. At that time, the companion was actually at a separation of 9.6 arc seconds and at a position angle of 85º (almost due east) of Sirius. Therefore, it is highly unlikely Le Verrier actually detected the companion, which was missed by the experienced observer Chacornac. Nevertheless, it demonstrates Le Verrier's keen interest in locating the dark companion and clearly implies that Le Verrier was present at the telescope that evening.

There are no further entries in the log books that correspond to observations of Sirius until 14 March:

> March 14. According to the ... of M. Peters, Bond has seen in the glass of 18 inches of M. Clark the satellite of Sirius 10″ away. Of this star — I just looked for it with the 80 and nothing can be seen. However, bars are placed in the eye-pieces and with the help of β Orionis whose companion is 9″ away I find that the bars, although thick, are still thinner than this distance and the rays of the star with the No. 5 are not a quarter of the diameter of the bar. Consequently, the companion should be well below and visible. However nothing, nothing is visible. Foucault attests this. The weather is passable. Vaporous from $7h\frac{1}{2}$ to $8h\frac{1}{4}$. Eyepiece No. 3, 4 and 5.[31]

The sense of this entry is that news of Clark's discovery and Bond's confirmation arrived in Paris on, or just before, 14 March. Le Verrier presumably passed on this news to Chacornac when he instructed the latter to return to the telescope to verify the discovery. Le Verrier learned of the discovery from Abbé Moigno, to whom C. A. F. Peters had presumably written soon after he received Bond's paper in early March. That Moigno then immediately contacted Le Verrier is apparent in the pages of *Cosmos* of 28 March from Moigno's use of the editorial 'we':

> As soon as the announcement of the memorable discovery of Mr Clark, in Cambridge (United States), reached us, we transmitted it to M. Le Verrier, begging him to point Foucault's magnificent instrument at Sirius so that, in the event of success, it would thus nobly prove itself. M. Le Verrier put himself to work with almost all his assistants; himself, Mr Chacornac, Mr Foucault, and others, looked attentively, and continuously for several days, but without noticing anything.…[32]

Further unsuccessful observations in the search of the companion occurred on the 18 and 19 March. Finally, on the evening of 20 March, Chacornac was successful:

> 1862 20 March. Single observation of the companion of Sirius 11 43 AP 215°6 [this refers to raw unreduced measurements of the separation and position angle respectively; the reduced measurements published by Chacornac are 11.43°,

> 85.3°, respectively].… Sirius appears with rays so short that I immediately see the companion. The night is not clear. It is dusk and it is nevertheless easily visible. Later, darkness comes, the image gets fuzzier and it becomes more difficult to distinguish — it must be 5 or 6 mag or even more.[33]

However, when Le Verrier was informed of Chacornac's detection of the companion he was initially reluctant to publish until Chacornac reconfirmed the observation, as Chacornac's log attests.

> March 21. M. LeV does not want to believe in the sighting of the satellite and does not want to publish the observation in his bulletin. I nevertheless strongly believe that the observation is serious and affirm it. I have really seen and observed it.[34]

Le Verrier reconsidered, and announced Chacornac's success at the 24 March meeting of the French Academy of Sciences. The very same evening, Chacornac tried, but failed, to detect the companion he had previously seen: "Seen Sirius at the meridian. Companion invisible, undulating image" noted Chacornac that night.[35] However, he was again successful on the 25th and, on the next day, Chacornac wrote a brief paper[36] describing his measurements of the 20th and 25th, which he submitted to *Astronomische Nachrichten*.

Le Verrier did not concentrate solely on Sirius. On 24 March Chacornac also wrote of an unsuccessful observation of Procyon, which Le Verrier had told him also had an unseen companion.

> March 24 … Seen Procyon following the advice of M. L.V. who says that this star has a motion in declination comparable to that of Sirius in AR. Under all angles nothing but a small star 50″ away — seen the goat (Capricorn). Nice image fairly stable. In the configuration of this star a companion is visible at the same place where I believed I saw one to Sirius on the 20th. The resemblance is striking. Could the companion be only an illusion? The counterpart of the opposing ray?[37]

Throughout Chacornac's successful and unsuccessful attempts to observe the companion of Sirius, there is frequent mention of the hazy ("vaporeux") conditions, what we would describe today as poor seeing. Le Verrier was keenly aware of the problems that Paris posed for the type of observations that would benefit most from such a large instrument.

The Fallout

Le Verrier, who predicted the location of Neptune and hypothesized the existence of Vulcan, had missed the opportunity to resolve the last of the three major gravitational anomalies of the mid-nineteenth century — the discovery of Bessel's dark star. Two significant results flowed from this failure. The first was that Alvan Graham Clark was awarded the Lalande Prize for the year 1862 by the French Academy of

Sciences.[38] The award recognized both the discovery of the companion as the outstanding astronomical achievement of 1862, and the accomplishment of successfully producing the $18\frac{1}{2}$-inch refractor. Le Verrier's role in this award, if any, is difficult to ascertain. He was not a member of the Lalande Prize committee, which included five members of the astronomy section,[39] but it is not inconceivable that he may have had a hand at promoting Clark for the prize.

A second and more tangible result was that Foucault's revolutionary 80-cm telescope was relocated from Paris to Marseille in 1864. A primary reason for this development was the view of Le Verrier that, due to the atmospheric conditions, Paris was not a suitable location for a major telescope. Abbé Moigno gives an interesting contemporary account of Le Verrier's state of mind and his determination to move the telescope out of Paris.[40] Moigno also clearly expresses the hope that Le Verrier would change his mind. However, from Chacornac's log books it is also clear that Le Verrier had already initiated steps to relocate the Foucault's telescope to Marseille.

> 9 March 1862 at 11:30 Le Verrier informs me that he has just come back from supper with the Emperor [Napoleon III]. There were only seven guests at an intimate gathering and that he spoke to the Emperor about an outstation in Marseille. That the Emperor received this proposal very favourably. And lastly, that at the Senate he found the Prefect of Marseille, M. de Maupas who is greatly taken by this plan. He will look after finding us an open site and persuading the City of Marseille to do the utmost for us: saying that one would turn over the Canebière [a famous street in Marseille] in order to have a branch of the Paris Observatory in Marseille. In compensation, the city would take over the old observatory which would disappear from the skyline.[41]

On the next day Chacornac wrote: "And now Toulon makes a claim for the outstation and offers more land than Marseille." Chacornac, however, remained unconvinced about the wisdom of establishing a branch observatory and ended his entry with the rhetorical question: "What will be the result of all of these castles [in the air]? ? ?"[42] Nevertheless, Le Verrier's failure to discover the companion of Sirius can still be viewed as an event that helped galvanize him in his determination to make the move.[43] Le Verrier used the failure and his considerable bureaucratic influence successfully to lobby the French ministry of works to help ensure the move.

Conclusions

The events following Alvan Graham Clark's accidental discovery of the companion of Sirius represent an interesting case study of nineteenth-century scientific networking — as news of the discovery is followed from Clark, to Bond, to Peters, to Moigno, and finally to Le Verrier. It also highlights a previously unknown active interest of Urbain Le Verrier in an important problem of stellar astronomy, and it adds to our knowledge of the key role Le Verrier played in the development of French astronomical instrumentation.

Acknowledgements

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2. The suggestion of measuring the gravitational redshift of Sirius B was made by Arthur Eddington in a 1924 letter to W. S. Adams (Vibert A. Douglas, *The life of Arthur Stanley Eddington* (London, 1957), 75). Adams published his measurements in 1925 (W. S. Adams, "The relativity displacement of spectral lines in the companion of Sirius", *Proceedings of the National Academy of Sciences*, xi (1925), 382–7). Although long regarded as a third conformational test of General Relativity, it is now known that both Eddington's theoretical calculations of size of the redshift and Adams's measurement of it, were too low by a factor of four. (For a discussion of this issue see Norris Hetherington, "Sirius B and the gravitational redshift: An historical review", *Quarterly journal of the Royal Astronomical Society*, xxi (1980), 246–52).
3. Up until the late 1930s Sirius B was the only white dwarf for which a reliable mass was known. Eddington first called attention to the extreme density of Sirius B in 1924 (A. Eddington, "On the relation between the masses and luminosities of the stars", *Monthly notices of the Royal Astronomical Society*, lxxxvi (1924), 308–32, p. 322) and attributed the high density and small radius of the star to the complete ionization of the interior matter. He also noted such stars were thermodynamically problematic. The white dwarf problem was apparently resolved in 1926 when Ralph Fowler (R. H. Fowler, "On dense matter", *Monthly notices of the Royal Astronomical Society*, lxxxvii (1926), 114–22) published his equation of state for nonrelativistic degenerate matter. However, Chandrasekhar's 1930 relativistic equation of state, and the resulting Chandrasekhar limit, reopened the problem of the stability of white dwarfs' having masses above a certain limit. The relativistic equation of state and the limiting mass are at the origin of the dispute between Eddington and Chandrasekhar that came to a head in 1935 (see K. C. Wali, *Chandra: A biography of S. Chandrasekhar* (Chicago, 1991)).
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7. Truman Henry Safford, "On the proper motions of Sirius in declination", *Monthly notices of the Royal Astronomical Society*, xxii (1862), 144–7.
8. Arthur Auwers, "On the irregularities of the proper motion of Sirius", *Monthly notices of the Royal Astronomical Society*, xxii (1862), 147–50.
9. Deborah Jean Warner and Robert B. Arial, *Alvan Clark & Sons, artists in optics*, 2nd edn (Richmond, VA, 1995).
10. At the time the world's largest refractors were the two 15-inch telescopes constructed by the Metz & Mahler firm of Munich for the Pulkovo Observatory near St Petersburg, and the 'Great Refractor' at Harvard College Observatory. The American Civil War effectively ended the plans of the University of Mississippi for the 18½-inch. The completed telescope was acquired by the Chicago Astronomical Society in 1863. The lens is still in service at the Dearborn Observatory in Evanston, Illinois, while the original wooden telescope tube is on display at the Adler Planetarium in Chicago.
11. Simon Newcomb, "The story of a telescope", *Scribners monthly*, November 1873, 44–55, p. 47.
12. "Log book for 1862 (no. 199) of the 15-inch Equatorial", Harvard College Observatory.
13. "Log book for 1862" (ref. 12), 18 Feb. 1862.
14. George P. Bond, "On the companion of Sirius", *American journal of science*, xxxiii (1862), 286–7.
15. George P. Bond, "On the companion of Sirius", *Astronomische Nachrichten*, lvii (1862), cols 131–4. Bond published a second paper in the summer of 1862 including all of his observations of Sirius's companion, among them the initial 7 February confirmation observation. George P. Bond, "Letter to Editor", *Astronomische Nachrichten*, lviii (1862), cols 85–90.
16. Lewis Rutherfurd, "Companion to Sirius", *American journal of science*, xxxiv (1862), 294–5.
17. Abbé Moigno, *Cosmos*, 28 March 1862, 377: "*Le compagnon de Sirius*? M. Péters nous écrit qu'il n'accepte pas l'identité du compagnon qui vient d'être découvert, avec celui qu'il a calculé."
18. J. Chacornac, "Schreiben des Herrn Chacornac an den Herausgeber", *Astronomische Nachrichten*, lvii (1862), cols 175–6.
19. *Ibid*., col. 176: "… ist es darnach allerdings möglich, dass in dem letztern der Bessel'sche Begleiter aufgefunden ist."
20. *Galignani's Messenger*, 1–2 April 1862, 2.
21. W. Lassel, "Schreiben des Herrn W. Lassell an den Herausgeber", *Astronomische Nachrichten*, lvii (1862), cols 251–2.
22. Sherwood W. Burnham, "Double stars discovered by Mr. Alvan G. Clark", *American journal of science*, xvii (1879), 283–9.
23. J. M. Schaeberle, "Discovery of the companion to Procyon", *Publications of the Astronomical Society of the Pacific*, viii (1896), 314.
24. Camille Flammarion, *Popular astronomy: A general description of the heavens*, transl. by J. E. Gore (London, 1894), 466.
25. William Tobin, "Foucault's invention of the silvered-glass reflecting telescope and the history of his 80-cm reflector at the Observatoire de Marseille", *Vistas in astronomy*, xx (1987), 153–84.
26. Chacornac's log books for the period are bound together in a small volume (approximately 4 × 6 inches). Most of the entries, probably made at the telescope, are written in pencil in a difficult-to-read scrawl. Many words remain hard to decipher. Some annotations in ink are easier to read and appear to have been made by Chacornac later, in good lighting. The log books are held in the Bibliothèque de l'Observatoire de Paris, call number F14.
27. U.-J. Le Verrier, "Rapport sur l'Observatoire Impérial de Paris et projet d'organisation", *Annales de l'Observatoire Impérial de Paris*, i (1855), 1–68, p. 7. Here, the companion is described not as a star but as a large (but faint) planet in orbit around the Sirius sun.
28. Moigno, *op. cit.* (ref. 17), 391.
29. Moigno, *op. cit*. (ref. 17), 392.
30. Chacornac, *op. cit.* (ref. 26): "27 janvier 62. examine Sirius avec le No. 2, 3 et 4. Le No. 2 et 3 sont

garnis d'une barre. L.V. dit voir un compagnon à gauche à 5 ou 6″. Je ne vois rien que des rayons courts, une étoile au dessous de 11^{e} grandeur est seule visible." The bar mentioned here is part of a micrometer system that permits the measurement of angular distances and dimensions.

31. Chacornac, *op. cit.* (ref. 26), 14 March 1862.
32. Moigno, *op. cit.* (ref. 17), 392.
33. Chacornac, *op. cit.* (ref. 26), 20 March 1862.
34. Chacornac, *op. cit.* (ref. 26), 21 March 1862.
35. Chacornac, *op. cit.* (ref. 26), 24 March 1862.
36. Chacornac, *op. cit.* (ref. 18).
37. Chacornac, *op. cit.* (ref. 26), 24 March 1862.
38. "Prix d'Astronomie", *Compte rendu des séances de l'Académie des Sciences*, lv (1862), 936–7.
39. The members of the Lalande Foundation astronomy prize committee for 1862 were: Charles Delaunay, Joseph Liouville, Louis Mathieu, Ernest Laugier and Hervé Faye. It is unlikely that Delaunay was on very good terms with Le Verrier in 1862, following their earlier acrimonious debate on the secular variations in the mean motion of the Moon (see, e.g., *Compte rendu des séances de l'Académie des Sciences*, l (1860), 510–31). Furthermore, only Laugier and Faye could be considered observational astronomers.
40. Moigno, *op. cit.* (ref. 17), 392.
41. Chacornac, *op. cit.* (ref. 26), 9 March 1862.
42. Chacornac, *op. cit.* (ref. 26), 10 March 1862.
43. Le Verrier consistently defended the position, first outlined in 1862, that observations of faint objects and of objects that required a combination of a large telescope and a high magnification should be carried out under more favourable skies. In the course of the later debate (1867–68) on the wisdom of relocating the observatory in the Seine river valley, Le Verrier argued against such a move given that the observation of the most "delicate phenomena" had already been moved to Marseille (see, e.g., *Compte rendu des séances de l'Académie des Sciences*, lxv (1867), 1073–81; lxvi (1868), 21–29 and 68–76, p. 76).