Sir George Gabriel Stokes, Bart. (1819-1903) – his impact on science and scientists

PAUL RANFORD FCA SFHEA MSC BA(HONS)

"The pages of the 'Proceedings' and 'Transactions' abound with grateful recognitions of help … rendered [by Stokes], and in many cases his suggestions or comments form not the least valuable part of memoirs which appear under the names of others." [1]

Introduction

This paper focuses on the history, rather than the mathematical physics, of Sir George Gabriel Stokes at the Royal Society.

The epigraph above, an extract from Stokes's obituary notice written by Lord Rayleigh, implies that the impact of Stokes on C19th science might be best characterised not by his mathematical physics work (as the historiography generally has it), but by the assistance he provided to other scientists in their endeavour to further scientific knowledge.

We might reasonably assume that a quotation from an obituary notice exaggerates by inclining to the hagiographic rather than providing a more considered reflection. The selection of evidence presented here however confirms that Lord Rayleigh was nothing less than honest and precise in his language. The key understanding required is the measure of Stokes's authority over scientists in addition to his selfless willingness to assist them. He became one of the two Secretaries of the Royal Society in 1854, only seven years after Royal Society reforms had placed the emphasis of the Society (and its criteria for Fellowship) on scientific achievement and excellence rather than on patronage or privilege. [2(p362),3(pp216-7),4(p104)] Stokes embraced this notion with an apparent natural (or, at least, undisputed) talent for recognising scientific excellence, and with serious intent and stamina to improve substandard work presented to him. While he remained the junior of the two secretaries (by only one year) until the retirement of William Sharpey in 1871, he took sole responsibility[i] from 1854 for the so-called "internal scientific work" of the Society.[5(p323-4),6(p98)] This mainly involved reading papers submitted for publication in the *Proceedings* or *Transactions of the Royal Society* and corresponding at length with authors in order to suggest – and sometimes enforce – improvement before allowing the work to be considered for publication.

Stokes's original researches – his experimental and theoretical work – influenced Victorian science in ways that are undeniably profound. He formulated a theory to explain the phenomenon of fluorescence (he coined the word), allowing the then newly discovered technique of spectroscopy to be extended into the ultraviolet part

---

[i] Sir Michael Foster (2nd longest serving Secretary of the Royal Society (from 1881-1903)) recalled this in his appreciation of Stokes published in Larmor (6). In private to Huxley, Foster's views on Stokes as President of the Royal Society were rather less than appreciative, although this offers no reason to doubt the factual basis of the elements included above.

of the spectrum.[7,ii] The Navier-Stokes equations are regularly applied today in any investigation involving fluid flows,[iii] and it is for these that he is best known. His most influential work, however, is his far broader, longer-lasting and far less well-documented impact on Victorian science and on extensions of scientific knowledge generally throughout and after his long tenure as joint-Secretary and then President of the Royal Society, a total period of 36 years (1854-90). It was during this era that seminal advances were made in the understanding of the physical sciences, including electrical and magnetic phenomena, the essential concepts underpinning the new science of thermodynamics, the kinetic theory of gases and (towards the end of Stokes's life), the beginnings of investigations into atomic structure.

For much of this long period Stokes acted as the Editor of the Royal Society's two main scientific publications, *Philosophical Transactions of the Royal Society* ("*Phil. Trans.*") and *Proceedings of the Royal Society* ("*Proceedings*"). He maintained and forged new peer review practices, chose appropriate referees for each paper (assuming much of the work himself),[8] arbitrated between the differing views of referees and author in lengthy official communications between them (and in lengthier unofficial correspondence with the author) and ultimately (with very few exceptions over his tenure) judged the scientific and technical merits of papers to standards he defined and upheld.

By "technical merit", Stokes meant underpinned by rigorous mathematics, preferably based on fundamental and well-established Newtonian laws. Stokes's mathematics was the product of the "Cambridge school", the mathematical Tripos in which pure algebraic skills were forged and tested under gruelling examination conditions.[9] Stokes graduated in 1841 as "Senior Wrangler" – first in the mathematical order of merit for the academic year – and also as "First Smith's Prizeman". The Smith's Prize was an examination of different character involving the application of mathematics to problems of natural philosophy, in which students were expected to show insights not required in the Tripos[10] and success in both examinations resulted in the reward of Stokes's immediate election to Fellowship of Pembroke College,[iv] where he remained for 66 years[v]. Stokes's mathematical techniques and experimental outlook later influenced generations of British scientists, including James Clerk Maxwell, J.J. Thomson and Lord Rayleigh, to all of whom he acted as mentor, mathematical tutor and examiner. Many of the physicists of the Victorian era conversed in the language of wrangler-level mathematics, and at the centre of them

---

[ii] The simplicity of the experiments Stokes's undertook to reach his profound conclusions was typical. See also Larmor (6), p19: "… if you gave Stokes the Sun there was no experiment he could not do for two-pence", although the source of this quotation is not provided by Larmor. Several of Stokes's contemporaries expressed similar views.

[iii] From gas pipes to glacial flows and large-scale atmospheric perturbations.

[iv] Larmor (6), p7.

[v] Stokes's Fellowship of Pembroke college was not unbroken – from 1857 he was forced to resign on his marriage, but after the rules changed in 1862 he was readmitted to Fellowship.

all Stokes, Lucasian professor for over 50 years, was the master. To those scientists not so well equipped to deal with mathematical theory, Stokes selflessly provided the assistance required to underpin theory. This paper provides examples of both categories.

The primary sources from which the historical impact of Stokes on his contemporaries may be best appraised are, for the most part, held in Cambridge University Library ("CUL").[11] There are a variety of difficulties in accessing these documents. First, there are approximately 68,000 separate pages (equivalent to 25-30,000 individual documents, significantly larger than the Darwin collection), mostly comprising letters <u>from</u> his correspondents rather than Stokes's own words. Secondly, they are accessible only via reels of microfiche as the original documents are regarded as too fragile or precious for direct examination by researchers, and this adds considerable amounts of time (and some mechanical manipulation) to the effort of accessing any specific item. Examining documents via the projecting lens and screen of the microfiche reader, however good the original photographic record, adds its own complications to the task, especially as, thirdly, the handwriting of Victorian scientists (not least that of Stokes himself) generally offers no compromise to the eye of the interested historian.

While it seems likely that these inconveniences compound to frustrate historians, the lack of scholarly focus on Stokes[12] should not be so glibly explained. This brief paper also begins consideration of the broader question on why Stokes seems neglected in the historiography compared to many of his peers. The discipline of the history of science itself, the paths of its development since 1945, may have some significant bearing on this question and I will offer below some preliminary comments on how and why this might be so.

My research programme comprises the examination of specific contributions made by Stokes to the work of other scientists, tracing original submissions through refereeing reports from Stokes or other referees (relevant where Stokes has used his authority to amend or dismiss a suggestion) and correspondence between referees, authors and Stokes through to eventual publication in a Royal Society journal. The extent to which Stokes has influenced the published version of the relevant submission are assessed and compared to the historical credit afforded him. The measure of such influence is generally found to be far the greater of the two. I examine here only three case studies of the many available, two of which relate to eminent physicists of the Victorian era with extensive published biographical histories in which Stokes's part, given the evidence below, seems curiously understated.

The final case study relates to a less well-known, scientist – in fact a chemist, so outside Stokes's generally recognised sphere of expertise – but on whom Stokes's impact was nonetheless formative in terms of his published *oeuvre*. This case demonstrates the extraordinary lengths to which Stokes would go to support, guide and occasionally direct in ways that were not always ultimately fruitful nor (it might be inferred) wholly appreciated. The completeness of the historical record of this correspondence, which is as far as I know unexamined from this perspective, provides insight into the vicarious means (and the extraordinary investment of time and effort) by which Stokes sought to extend scientific knowledge, even sometimes in a minor way, through his work with other scientists.

Case study 1 – William Thomson (Lord Kelvin) FRS (1824-1907)[vi]

Of all Stokes's several cordial relationships with other scientists, undoubtedly the most significant was his friendship with Thomson/Kelvin evidenced by the warm correspondence between them over 55 years. This was transcribed and published with explanatory notes by David Wilson in 1990,[13] and provides a treasure trove of opportunity for historical analysis of scientific developments over the Victorian era. There was no contemporary scientific issue that was not, or could not be, discussed between them. The letters from Thomson/Kelvin are full of ideas, false starts, crossed purposes, requests for information or for confirmation of points of view, and above all, mathematical physics. Stokes's responses are (with minor exceptions) more sober, reflective, cautious, and (occasionally) calling Thomson/Kelvin to order. And, if anything, even more mathematical physics. Together they form an extraordinary resource to which many biographers have eagerly referred selectively, but no attempt has yet been made to set the correspondence in context as a background to the scientific developments of the day. It will be argued here, based on a few examples only, that the extent to which Stokes contributed to Thomson/Kelvin's many accomplishments is not yet fully appreciated. Further study will undoubtedly produce additional supportive evidence in due course.

Thomson was the younger man by 5 years. He had graduated as 2nd Wrangler and 1st Smith's Prize winner in 1845 – Stokes had graduated in 1841. They had similar backgrounds – Irish-born, schooled in Britain (Stokes in Bristol, Thomson at the University of Glasgow, where his father was Professor of Mathematics) and then through the Cambridge Mathematical Tripos, both being tutored by "wrangler maker" William Hopkins (1793-1866). Wilson believed that they "certainly met by early 1845" to discuss Thomson's Smith's Prize examination.[13(preface, p.xli)] In mid-1846, Stokes was one of the many contributors of testimonials supporting the appointment of Thomson to the Chair of Natural Philosophy at Glasgow University, a position to which Thomson was elected on 11th September 1846 (at the early age of 22).[14(p113)]

[vi] References to William Thomson (Lord Kelvin) in the remainder of this paper will be labelled "Thomson" (in the period prior to his ennoblement in 1892), "Kelvin" (subsequently), and "Thomson/Kelvin" if appropriate within the general context.

Thomson/Kelvin is well known for his technological achievements, mainly the submarine cables allowing communication over vast distances, including between Ireland and the Newfoundland (and thus, with other cables already in place, between other outposts in an expanding telegraphic network including London to New York).[15(p161-2)] His first paper on relevant theory (dated 3rd March 1855) published in *Proceedings* was unequivocal concerning the contribution of Stokes from the outset:

“The following investigation was commenced in consequence of a letter received by the author from Prof. Stokes, dated Oct. 16, 1854.”[16]

The letter in question[vii] – apparently the first between Stokes and Thomson for some months – concerned a paper by Michael Faraday examining the time taken for electrical conduction to pass through some tens of miles of submerged insulated copper wire in comparison to similar wire that was not submerged.[17] In his letter Stokes theorised the reasons for the relative “considerable magnitude of the time concerned” in conduction through a submerged wire and asked if Thomson knew of any other reasons for the phenomenon.

Thomson responded with great enthusiasm, writing two long letters of mathematical physics that treated electrical flows as analogous to heat flows and thus allowing for leakage of electrical force as “radiation losses”.[13(ref.115)] Stokes’s own immediate response no longer exists in the CUL archives, having presumably been removed for printing in the Stokes’s published Mathematical and Physical Papers where an extract thus survives.[18(vol4:p61-62)] His complex mathematical analysis leads him to state: “Your [Thomson’s] conclusion as to the American wire follows from the differential equation itself which you have obtained.” He then reached additional conclusions on how the physical structure of the cable (as functions of electrical capacity, resistance and length) would impact on the time taken for electrical signals to pass along the cable. All of Stokes’s mathematical analysis became grist for Thomson’s arguments and practical designs.

I am not concerned here with the complex mathematical and scientific nature of the ensuing extended conversation between Stokes and Thomson. This has been discussed by Smith and Wise in their detailed biography of Lord Kelvin.[14(commencing p.448)] and I have little to add to their history here, apart from noting that their observations of Thomson’s misunderstanding of some details of Stokes’s questions and his immediate reformulation of the issue of principle that attracted him – in this case the “practicability of sending distinct signals along such a length as the 2000 or 3000 miles of wire that would be required for America”[viii] – are characteristic of Thomson/Kelvin’s occasionally arbitrary responses to Stokes (or presumably

---

[vii] The letter to which reference is made here is published in Wilson (13), ref.114.
[viii] Thomson to Stokes, 30th October 1854 in Wilson (13), ref.116.

anybody else) when lost in enthusiasm for the scientific matter at hand. (I also note here, parenthetically, that Smith and Wise's otherwise commendable biography tends to treat Stokes as a passive interlocutor provided to allow for necessary exposition on the thoughts of the protagonist – e.g. "In a letter to Stokes, Kelvin explained … [some matter of scientific significance]". Smith and Wise are far from alone amongst biographers in such treatment of Stokes, as my continuing researches are revealing.) It is the personal response of Stokes to this correspondence that is more interesting, at least for my purposes. For on 1st December 1854 Thomson requested some clandestine activity:

"I should be much obliged if you would not mention to any one [sic] what I wrote to you regarding the remedy for the anticipated difficulty in telegraphic communication to America, at present, as Rankine has suggested that I should join with him in applying for a patent for a way of putting it in practice…"[ix]

This seems bold enough, but Thomson requested yet more to enable him to write out the relevant theory:

"As I did not preserve any memoranda of what I wrote to you, I would be greatly obliged by your letting me have my letters until I get a copy of them made…"[x]

Many in Stokes's shoes would have responded sourly to Thomson's stated intention to profit from ideas that were demonstrably founded upon (or at least benefiting from) Stokes's own contributions. But Stokes was not so easily upset[xi] nor apparently motivated by the opportunity for monetary return,[19] and by return of post he provided the letters as requested together with more mathematical physics relating to the behaviour of electrically charged objects in a submarine environment.[xii] Over the next few months the conversation continued to extend the mathematical theory, although some of Stokes's contributions appear to be missing from the CUL archives.[xiii] But soon, at least, Thomson released Stokes from his (one-sided) obligations:

"There is not the slightest occasion now for any secrecy as to any of the letters I have been writing to you on this subject."

[ix] The Scottish engineer and physicist William John Macquorn Rankine (1820-72), together with Thomson/Kelvin one of the original contributors to the science of thermodynamics.
[x] Thomson to Stokes, 1st December 1854 in Wilson (13), ref.119.
[xi] Wood (19,p79) described Stokes as "not interested in material things and somewhat unworldly".
[xii] Stokes to Thomson, 2nd December 1854 in Wilson (13), ref.120.
[xiii] Thomson refers to some Stokes's letters from around this period that are not published in Wilson (13).

The patent mentioned by Thomson was in place.[xiv] It was the first of twelve patents on the electric telegraph taken out by Thomson/Kelvin (occasionally in association with others – although never Stokes) over the next 40 years.[20]

Thomson/Kelvin never ceased to attempt to mine the valuable resource he had in Stokes. Almost forty years after their correspondence began, he reported that "I always consult my great authority, Stokes, whenever I get a chance"[21(p.168)]. He was always eager to work more closely with Stokes, even from the very beginning. When the Chair of Mathematics at Glasgow University became vacant in January 1849 on the death of Thomson's father, Thomson urged Stokes to apply for the position. From Stokes's perspective this was an attractive proposition which he considered most carefully, but ultimately decided that he could not in good conscience undertake Glasgow's "religious test" – the requirement to worship within the Presbyterian denomination of the Protestant faith (Church of Scotland), rather than that of the Episcopalian denomination of the Anglican Church.[14(p.48),15(p.88-91)] This was devastating news to Thomson – he declared his "state of agitation" concerning the decision (an unusual display of emotion in their chain of correspondence) – and brought all of his considerable powers of persuasion to bear over the next fortnight, taking the view that conformity to the polity of the Church of Scotland "would be in no way inconvenient, or repugnant to your feelings".[xv] It seems clear that Thomson was less scrupulous on religious matters, regarding the tests as no more than a necessary formality.[xvi] Stokes admitted to being "…staggered in my purpose by your powerfully written letter"[xvii] but in the end Thomson had to admit defeat. On such grounds were major scientific decisions made.

A second opportunity arose in October 1859 on the death of John Pringle Nichol (1804-1859), professor of Astronomy at Glasgow. Thomson again urged Stokes to apply for the position. While noting the importance to science to get Stokes "out of London & Cambridge, those great Juggernauts under which so much potential energy for original investigation is crushed", Thomson was not being wholly altruistic: "…I feel it an immense advantage to myself to have you so near".[xviii] The religious tests were no longer an issue – they had been discontinued in 1853. But by this time Stokes was well established as Lucasian Professor and at the Royal Society; it seems that the position was not attractive enough to pursue.

Thomson/Kelvin become one of the foremost scientists of the era. Other scientists looked to him for approbation. Knighted in 1866, ennobled as a baron in 1892, he gained fame and fortune from his technological achievements. Stokes, for his

---

[xiv] British patent no.2547 was filed by Thomson, William J. Macquorn Rankine and James Thomson (William's brother) in December 1854.
[xv] Thomson to Stokes, 12th February 1849 in Wilson (13), ref.35.
[xvi] Thomson signed the 39 Articles of Religion of the Anglican Church on graduation from Cambridge.
[xvii] Stokes to Thomson, 16th February 1849 in Wilson (13), ref.37.
[xviii] Thomson to Stokes, 6th October 1859 in Wilson (13), ref.176.

contributions to this and other of Thomson/Kelvin's projects, gained neither. Kelvin's oration at Stokes's funeral in 1903 was filled with his admiration of Stokes, and of his contribution to science. It ended with a most poignant tribute which illustrates the extent to which he acknowledged his debt to his old friend and confidant:

"For sixty years of my own life, from 1843 to 1903, I looked up to Stokes as my teacher, guide, and friend. His death was for me truly a bereavement."[xix]

Case study 2 – Sir William Crookes FRS (1832-1919)

In his well-researched and highly readable biography of Crookes, W.H. Brock names Stokes as "one of Crookes' many 'invisible' helpers…"[22(p.11)] although, as I will argue here, there is ample evidence to show that Stokes was in fact the main and most significant influence on Crookes' scientific work. Crookes himself thought so when providing his record of correspondence[xx] with Stokes to Larmor:

"…if what I owe to Stokes is deducted from my work there will be precious little left I can claim for my own!"[xxi]

The evidence below shows that this should not necessarily be regarded as a wholly exaggerated claim. In the same letter to Larmor, Crookes explained his longstanding practice of sending Stokes's letters (the handwriting of which he had difficulty making out) to his own printing office, for his head printer "could decipher almost anything", and thus made his own private printed copies. (This possibly reveals as much about Crookes' wealth as it does the value he placed on Stokes's words.)

The debt owed by Crookes to Stokes is perhaps greater than that of any scientist other than that of Thomson/Kelvin. The significance to science of their collaborative relationship is supported by the 100+ of their letters published in Larmor's *Memoir*, together with more than 200 others held in the Stokes collection at CUL. The extent of Stokes's labours on behalf of Crookes is not easy to characterise in general terms. Stokes was involved – as always – with details throughout. These included checking mathematics, suggesting the design of experiments and apparatus (it seems that Crookes' glassblower was remarkably adept), taking responsibility for the final version of theory underpinning experimental results and submitting Crookes' papers to a sympathetic and competent referee, the first choice usually being James Clerk Maxwell.[23(p300)] Harrison (1988) reduces the role of Crookes to that of a mere coordinator of the work of Stokes and a paid assistant (and of the funds provided as Government grants),[24(p115-116)] but this is surely trivialising Crookes' extraordinary

---

[xix] Kelvin in Larmor (6), p318
[xx] Crookes provided many of his printed versions of Stokes's letters to Larmor, who published over 100 examples in the Memoir (6).
[xxi] Crookes in Larmor (6), p362.

technical ability and experimental insights into new fields of investigation discussed below. Besides, Crookes regularly offered generous appreciation of Stokes's collaboration, even if this might be (as I argue here) not wholly acknowledged by historians of science.

The collaboration began slowly. In 1852, Stokes helped to explain anomalies in Crookes' photographs of polarised light through crystal.[18(Vol 4:p30-37)] From 1856 to 1869, correspondence comprises minor notes on lines in the solar spectrum as revealed by Crookes' photographs, and Stokes's corrections to the precision of Crookes' calculations of the atomic weight of Thallium (of which Crookes was the discoverer).[26(p.160)] The resulting paper on Thallium was read at the Royal Society on 19th February 1863 and Crookes' Fellowship of the Royal Society followed on 4th June of the same year.

By the late 1860s Crookes had become enthused by the then fashionable entertainment of spiritualism.[xxii] Convinced that this had a scientific basis that could be studied, he submitted a paper to the Royal Society in June 1871 that was rejected by Stokes. Furthermore, the two secretaries of the Royal Society (Stokes and William Sharpey[xxiii]) refused to attend related experiments. On the suggestion that the Royal Society should examine the phenomenon, Stokes wrote:

"I have heard too much of the tricks of Spiritualists to make me willing to give my time to such a committee myself."[25(p.32)]

Stokes's stated issues with studies of spiritualism included lack of experimental rigour and concerns about charlatans. Brock (2016) inferred that Stokes was protecting the reputation of the Royal Society[22(p.144),xxiv] , while Wilson[5(p.326)] suggested that the basis of spiritualism – the belief that spirits of the dead might be capable of communication with the living – conflicted with Stokes's heterodox religious conviction that the human spirit remained in an unconscious state until resurrection of the saved.[xxv] All of these views seem equally plausible, and probably all operated to some degree.

The correspondence on spiritualism, later set out at length and from a distinctly biased perspective by Crookes[25], brought a coolness to his relationship with Stokes.

[xxii] Spiritualism as discussed here is the supposed communication with the spirits of the dead, an idea that flourished in the English-speaking world during the late C19th.

[xxiii] In 1871 Sharpey remained nominally the senior of the two, although he retired in that year to be succeeded by T.H.Huxley.

[xxiv] It seems that Stokes certainly took very seriously the requirement to uphold the reputation of the Royal Society – see his daughter Isabella's account, Larmor (6), p37.

[xxv] Stokes's views on the doctrine of eternal damnation (which he argued was contrary to Scripture) were set out in his collection of letters to James Marchant, published as *Conditional Immortality – A Help to Sceptics* in 1897.

But a thaw was not long delayed. Crookes developed the “radiometer” – a simple device comprising a delicate balance with vanes allowed to spin freely inside an evacuated vessel – to test a new force that Crookes felt might have some bearing on his spiritual researches.[22(p.163)] The phenomena demonstrated by this device implied that beams of visible light possessed a momentum that could drive a “light mill”. Crookes demonstrated the radiometer to the Royal Society in April 1875.[22(p.173)] His assertion on the momentum of light was eventually disproved by new papers[xxvi] and demonstrations read to the Royal Society in March 1876 by Stokes himself, with Crookes in attendance.[22(p.225)] These overwhelmingly confirmed that it was residual air in the radiometer that caused the windmill effect, not the direct action of light. Despite this apparent setback, Stokes was there to emphasise that Crookes had discovered something truly new to science:

“… the action is none the less [sic] a perfectly new one… its theoretical explanation is not an application of well-ascertained laws, but the following out of a certain speculation[xxvii] as to the ultimate constitution of matter and the nature of heat; and your discovery, from the thorough novelty of the action, cannot but exercise an important influence on the progress of our knowledge.”[26,xxviii]

Crookes continued to experiment with ever more highly exhausted vacuums, testing with improved apparatus Maxwell’s counter-intuitive theoretical discovery that the viscosity of a gas is independent of its pressure.[27,xxix] Crookes appeared to feel somewhat out of his depth on theory – a draft of his 1881 paper “On the Viscosity of Gases at High Exhaustions” was sent to Stokes on Christmas Eve 1880 with some trepidation:

“I am rather nervous as to the results of your scrutiny. I have indulged somewhat in theory towards the end, but I think not to a greater extent than the facts warrant.”[xxx]

Help was, as always, at hand. Stokes offered to add notes of his own to discuss Crookes’ results, and to add mathematical theory and observations to relate those results to Maxwell’s theory. Crookes accepted the offer with alacrity on 3rd January 1881: “I felt this all along but I did not like to suggest it to you knowing how much your time is occupied.” Stokes’s notes appeared as an appendix to Crookes’ paper in *Phil. Trans*.[28]

[xxvi] Independently provided by Osborne Reynolds and Arthur Schuster
[xxvii] The “certain speculation” here is the kinetic theory of gases, which Crookes’ experimental results tended to confirm.
[xxviii] Stokes to Crookes, 18th April 1876 in Larmor (26), p373.
[xxix] Maxwell notes the experimental observation (p54) and then supplies the mathematical theory (concluding on p83). He communicated this theoretical result to Stokes much earlier, on 30th May 1859 (see Larmor (26), p10 and also Stokes’s Papers (11), ref. M410).
[xxx] Crookes to Stokes 24th December 1880 in Larmor (26), p441.

Crookes' experiments with the radiometer led him to investigations of electrical discharges in glass vessels in which Crookes had attained yet higher levels of exhaustion than realised elsewhere. New phenomena including cathode rays thus produced impressed even Stokes:

"Crookes has really opened out quite a new field of research in these recent experiments of his."[xxxi]

In this new research, Crookes and Stokes proceeded together. The nature of cathode rays was then unknown, and Stokes suggested differentiating experiments to decide whether the rays were particulate or electromagnetic in nature.[18(Vol. 5, p262),29,xxxii] Together Stokes and Crookes carried the argument amongst British scientists that the cathode rays were negatively charged particles, while German physicists were convinced otherwise.[5(p326),xxxiii] Stokes set out the principal arguments, and descriptions of the experiments undertaken (mainly designed by him), in unusual settings – first, his Annual Address as President of the Victoria Institute on 15th July 1896[30,xxxiv] and then in his Wilde Lecture[xxxv] 10 days later.[29(esp.p49-53)] In both, he extended his talk to speculate on the cause and nature of Röntgen Rays (x-rays), discovered inadvertently only a few months earlier during work that duplicated Crookes' own experiments with cathode rays. But by this time, at the age of 77, Stokes's limitations in theoretical physics were becoming apparent – his explanations of x-rays were rooted in his belief that light phenomena could only be explained as "vibrations in the ether" rather than in Maxwell's electrodynamics. He and Crookes were however correct, at least in terms that would be understood at the time, concerning the nature of cathode rays. On 31st March 1897 Stokes wrote to Crookes that the "Kathodenstrahlen" (the German term for cathode rays) are "not rays at all, but streams of molecules".[xxxvi] Thirty days later at the Royal Institution, J.J. Thomson announced his discovery of what is now called the electron.

This case study on William Crookes concludes with some more general observations on his continuing correspondence with Stokes, which lasted until December 1901, by which time Stokes was 82 years old and little more than a year from the end of his life. Crookes never ceased to rely on Stokes's mathematical assistance (e.g. a new

---

[xxxi] Stokes to his father-in-law Thomas Romney Robinson, 6th April 1979 in Larmor (6) p355
[xxxii] These experiments included a "light windmill … [caused] to spin rapidly under the action of the rays", and the bending of a "very thin film of blown glass" as the rays fell upon it, as well as deflection under electrostatic and magnetic forces.
[xxxiii] See also Stokes's letters to Crookes, detailing the German attitudes (Larmor (26), pp474-476)
[xxxiv] Lord Kelvin was present at this meeting and gave the response to the Presidential Address. The objectives of the Victoria Institute, and the circumstances of Stokes's role as its President, are explained by Stuart Mathieson in [REFERENCE TO STUART'S PAPER IN THIS EDITION]
[xxxv] The prestigious Wilde Lectures (and associated Gold Medal) were founded by Dr Henry Wilde FRS in 1895, and awarded annually by the Manchester Literary and Philosophical Society to the originator of a significant literary, scientific or philosophical work.
[xxxvi] Stokes to Crookes, 31st March 1897 in Larmor (26), p476.

and more accurate formula for interpolating lines in spectral analysis in mid-1895), experimental advice with a large spectrograph (over ten letters exchanged from November 1896 to March 1897) and some occasional plain speaking:

"It would be useless to try your experiment for the object for which you designed it. Bessel has already proved [the question at hand] with an accuracy incomparably superior to anything you could do in your way."[xxxvii,xxxviii]

To the end, Stokes was checking Crookes' sums – which clearly needed checking:

"…I found however some numerical errors or errors of copying, whichever it may be. I think there may be errors of both kinds. The first is pretty clearly a mis-copy; the second looks like an arithmetical error. I think it would be well to check your additions and subtractions."[xxxix]

With that, and a few more letters on radioactivity and spectra of rare earths under electrical stress, the correspondence petered out. Overall, Crookes' extravagant assertion that "precious little" of his own work would be left over if what was owed to Stokes was deducted does now seem something of an exaggeration. Crookes supplied extraordinary technical ability and an indefatigable approach in applying it, especially in improving apparatus for producing and measuring vacuums at micro-atmosphere levels and better. His experimental insights led to new fields of investigation, particularly on cathode rays (if not on testing the claims of spiritualist fraudsters). Stokes, for his part, provided experimental suggestions, mathematical and theoretical underpinning of results, support with publication and in the awarding of grant funding, and steadfast advice to help avoid gross error. Both made significant input into their collaborative effort and, based on the evidence above, I suggest that the resulting extensions in scientific knowledge were beyond the potential achievement of either acting alone.

Case study 3 – Arthur Smithells FRS (1860-1939)

The third case study explored here purposefully involves a lesser (although still well-respected) light in the scientific community. Arthur Smithells was a chemist (i.e. not a natural Stokes's correspondent) and at over 40 years younger, not of Stokes's generation either. Born in Lancashire, his education was mainly undertaken in Scotland. He attended Glasgow University for two years, attending some lectures delivered by Stokes's friend Sir William Thomson. Acquiring a passion for science and chemistry in particular, he enrolled at Owens College in Manchester,[xl] becoming

---

[xxxvii] Stokes to Crookes, 9th February 1898 in Larmor (26), p469.
[xxxviii] In this letter, Stokes provides what is undoubtedly the actual cause of an anomalous experimental result observed by Crookes, who had jumped to an erroneous conclusion.
[xxxix] Stokes to Crookes, 22 February 1898 in Larmor (26), p471.
[xl] Subsequently Victoria University of Manchester, then Manchester University.

a pupil of Henry E. Roscoe FRS. After gaining some teaching experience at Manchester High School for Girls, and after post-graduate work in Germany (including some months spent in the laboratory of Robert Bunsen), he was appointed Assistant-Lecturer in Chemistry at Owens College, then to the Chair of Chemistry at Yorkshire College in Leeds[xli] at the early age of 25.[31]

In early 1892 Smithells (together with a co-author Harry Ingle) published an article "On the Structure of Luminous Flames" in the *Journal of the Chemical Society*[32], a subject which had already drawn the attention of Stokes.[33] Smithells took the opportunity of writing directly to Stokes, commencing a very lively correspondence over the next six years. The collection of their correspondence held in Cambridge is helpful to historians in several ways. From about 1879 Stokes had been using a typewriter and keeping carbon copies of many of his letters, thus solving two problems in one. Smithell's handwriting, contrary to most in the archive, is a neat cursive script. Thus, there is a full and relatively accessible record of their discussion, and from this some idea of the relentless tide of scientific logic and suggestions of experiments that Stokes offered to all-comers on a daily (occasionally twice or even thrice-daily) basis can be gained.

The collection[xlii] listed in Wilson's catalogue[11] comprises 275 letters, 96 written by Smithells and 179 by Stokes. Analysis by numbers of pages simply highlights the imbalance – 179 pages by Smithells, 394 by Stokes. Given that Stokes's work was typewritten, the number of words on each page would lead to even greater disproportion, but by now the point is established. Stokes himself admitted the disparity in a March 1894 postscript: "I am afraid I have been rather pestering you with too many letters", to which Smithells responded with good grace: "Please do not suppose that your letters however numerous can ever be otherwise that [sic] a source of intense gratification to me. I prize your interest and advice as a real privilege."[xliii,xliv]

My purpose here is, again, not to examine the scientific content of the Stokes-Smithells correspondence, which has already been considered in some depth by Robert DeKosky.[34] I intend instead to examine the impact of Stokes on Smithells' published work, and the extent to which he has gained (or failed to gain) associated historical credit.

[xli] Later, with the active help of Smithells, the University of Leeds.

[xlii] There is evidence in the archive that some items may be missing – e.g. a letter from Stokes dated 11th April 1894 which thanks Smithells "for your letter of yesterday" that is not in the collection. I am proceeding here as though the collection is complete enough to support my general conclusions.

[xliii] Stokes to Smithells 8th March 1894 – Stokes's Papers[11], S300.

[xliv] Much later, in a letter to Joseph Larmor after Stokes's death, Smithells offered a clue about the pressure of responding to Stokes – "I found it difficult to keep up my end of the correspondence" (Larmor (6), p265)

In December 1893 Stokes read a draft paper written by Smithells (with much assistance from Stokes) on “The Luminosity of Gases”. Stokes’s reply (which included his usual raft of suggested amendments) demonstrates that, even in this late stage of his career (aged 74) and after he had retired from the Council of the Royal Society in 1892[xlv], he retained some authority in the world of scientific publishing: “I have read this paper, and I should like to see it published in the Philosophical Magazine” in which it did indeed appear (together with Stokes’s amendments) in two parts soon afterwards.[xlvi] Smithells’ gratitude to Stokes was unequivocally stated in the 2nd part of his paper: “I have to express my grateful acknowledgements to Sir G.G. Stokes, Bart., for the interest he has taken… and for his valuable and ever ready counsel”.

After publication, the Stokes-Smithells correspondence entered a quieter period. A request from Smithells (in December 1894) to proofread the 2nd part of his paper[xlvii] (published in January 1895) was followed by a brief flurry (April-September 1895), mainly concerning a paper by Professor Vivian B. Lewes[35] that contradicted Smithells’ theories on the combustion of hydrocarbon flames. Lewes’s conclusions were quickly refuted privately by Smithells and Stokes to their own satisfaction, and Smithells suggested (on 29th April 1895) compiling the objections together for publication. This suggestion could barely have been stated with more deference:

“I feel diffident however about appropriating so much that is due to your suggestion and guidance. I am tempted to suggest a joint paper yet I feel you might not care for that, and the very suggestion seems to me unpardonably bold”.[xlviii]

Stokes, excusing himself on the grounds of “illness of a relative”, dealt with this suggestion politely but clearly: “I think you had best write your paper independently”[xlix] and Smithells duly produced a draft of “a paper which I propose to send to the Chemical Society”.[l] After incorporating Stokes’s amendments, Smithells’ objections to Lewes’s theory were read at the Chemical Society on 7th November 1895.[36,li] With a final couple of letters from Stokes suggesting new experiments (which Smithells undertook) to quantify the temperature of a candle flame, after

---

[xlv] From his daughter Isabella’s memoir in Larmor (6), p37.
[xlvi] Part I in Lond Edinb Dubl Phil Mag. 1894;37:245-259, Part II in 1895;39:122-133.
[xlvii] Stokes obliged (on 14th December 1894), and did “not see anything that needs alteration”, although he suggested the term “sprayer” be coined to substitute for “spray” when referring to “the instrument designed to produce a spray” (Stokes’s emphasis, and an indication of the level of detail into which Stokes was inclined to probe in his scientific proofreading.) Smithells accepted Stokes’s recommendation.
[xlviii] Smithells to Stokes, 29th April 1895 (Stokes’s papers (11), S976).
[xlix] Stokes to Smithells, 11 May 1895 (Stokes’s papers (11), S978).
[l] Smithells to Stokes, 18th July 1895 (Stokes’s papers (11), S981).
[li] Professor Lewes’s lengthy response appeared in: Lewes VB. The acetylene theory of luminosity. Trans Chem Soc. 1896; Vol 69:226-243).

September 1895 there followed a 2-year hiatus. In December 1897 however, communication recommenced at even higher levels of activity (see Figure 1):

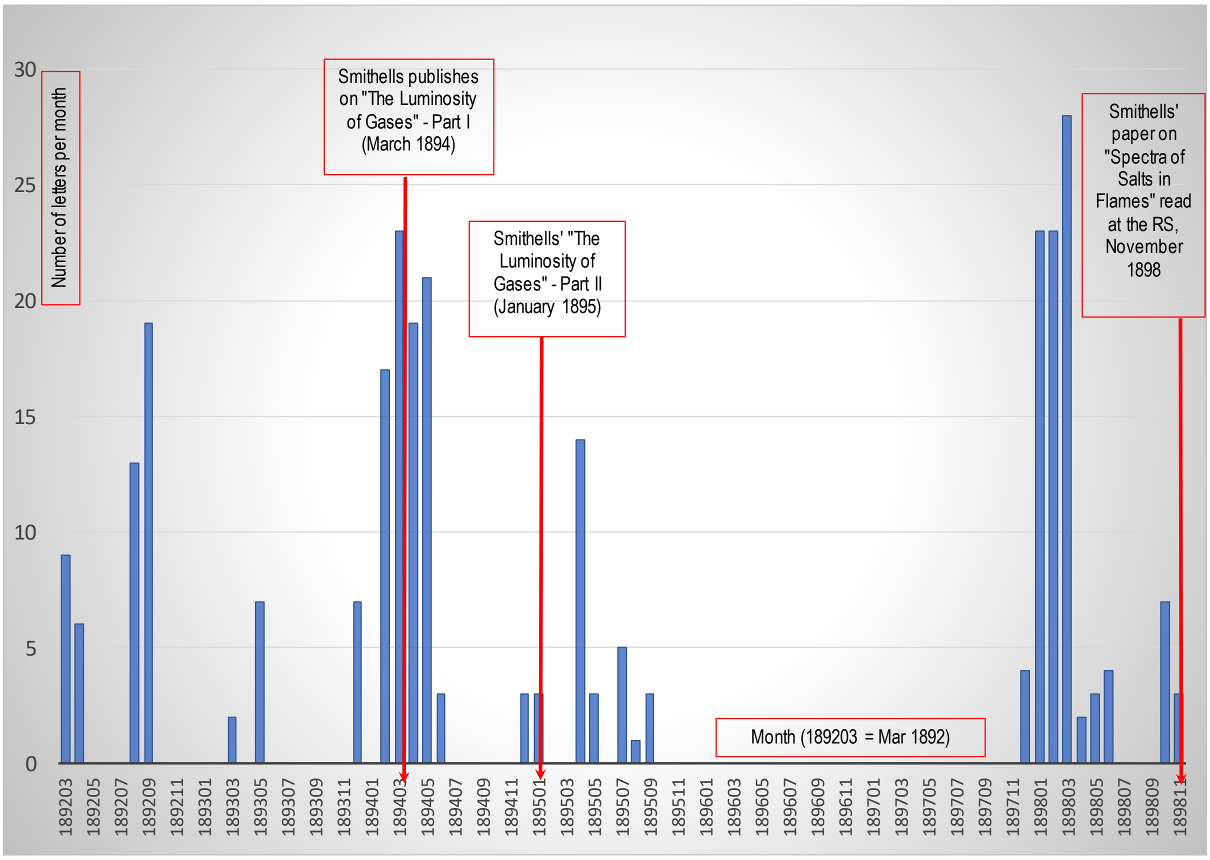

Figure 1 - Stokes-Smithells Correspondence in the CUL collection, by month, from March 1892 to November 1898 (275 letters in total), together with the dates of publication of Smithells' papers

The revitalised exchange of letters began with a 6-page effort from Smithells, which began:

"It is some time since I last troubled you with my problems and perplexities. Since then I have been continuously at work on themes relating to flames and hope to publish soon a paper containing results of experiments on the electrical conductivity of flames containing vaporised salts".[lii,liii]

[lii] Smithells to Stokes, 20th December 1897 (Stokes's papers[11], S990).
[liii] The paper mentioned here must be an early version of Smithell's paper published in Phil.Trans. in early 1899, discussed below.

Stokes was once again immediately receptive, and over the next three months over 70 letters were exchanged – as usual, the greater proportion (over 60% in number, far greater in words) from Stokes. These letters provide, in their rapid to-and-fro, clear evidence of Stokes's keen interest and input into Smithells' work at this time – chasing down and reading papers, providing points of view, questioning assumptions, suggesting experiments and helping with the interpretation of the results in a continuous cycle that led to yet further suggestions.

On January 22nd 1898 Smithells sent Stokes a draft of a new paper on carbon spectra that had been the main subject of their original correspondence:

"I am afraid you will find it tedious and not very satisfactory, but it represents a resumé of evidence… Please do not suppose that I am asking you to criticise the paper. I can hardly expect that as it is so long, but if you will be good enough to put some mark against what you think is bad I should be much obliged."[liv,lv]

By this time, Smithells knew what to expect from his audience. Despite a death in his close family,[lvi] Stokes provided ten pages of typescript of closely argued queries and suggested designs for additional experiments, followed by further short letters dated 28th and 30th asking Smithells to proceed no further with his paper until another more substantial letter, then being worked up, had been received. In the meantime, Stokes had been carrying out his own experiments (together with the Cambridge chemist Professor G.D. Liveing) to confirm Smithell's conclusions and he reported on these activities on 31st January.[lvii] In response (on 1st February 1898) after immediately accepting all of Stokes's suggested changes in detail, Smithells asked Stokes for advice on where this paper might be published.

"As to your paper" responded Stokes in a handwritten note on 4th February 1898, "I should be happy to present it to the Royal Society",[lviii] an offer that Smithells accepted "gladly, and feel it a great honour".[lix] Stokes, in turn, provided specific instructions on rigour of argument, required referencing, and the requirement for a short abstract (to be immediately published in *Proceedings*) that, altogether, would not look out of place for submissions to today's academic literature (including the

---

[liv] Smithells to Stokes, 22nd January 1898 (Stokes's papers (11), S1011).
[lv] Smithells mentions "a very able student of mine H.A. Wilson now working with Professor J.J. Thomson in the Cavendish Laboratory [who] helped me with the experiments…". Wilson will appear again below as one of the co-authors of the Smithells' paper published in Phil. Trans. in early 1899
[lvi] Stokes's stepmother-in-law, Mrs Robinson – the widow of the Armagh astronomer Thomas Romney Robinson – died in Stokes's house on Sunday 23rd January 1895. Stokes apologised for keeping Smithells' paper "for too long" in his reply dated Tuesday 25th.
[lvii] Stokes to Smithells, 31st January 1898 (Stokes's papers (11), S1016).
[lviii] Stokes to Smithells, 4th February 1898 (Stokes's papers (11), S1020).
[lix] Smithells to Stokes, 9th February 1898 (Stokes's papers (11), S1025).

Phil. Trans.).[lx,lxi] By the end of February, Stokes was suggesting that the finalised paper should be sent to him for communicating to the Royal Society, as:

"When a person has a subject at his fingers' end, as you have this, in expounding it one is apt, from excessive familiarity, to leave out some important link in the chain of evidence, which one who is less familiar notices. Hence it would be as well that I should look over it before communicating it, and write to you if I notice any omission of the kind."[lxii],[lxiii]

Smithells' acceptance of this "as a very great honour" was returned almost immediately.[lxiv] But doubts about details meant that Smithells continued to tinker with his paper (with Stokes's ready willingness to engage almost daily). By the end of May Stokes was beginning to agitate for submission, because "there are only 2 more meetings … before the summer recess", and "I think the argument is quite in a state to fit the paper for presentation…".[lxv] Smithells continued to prevaricate, submitting a draft but requesting a delay in publication until the autumn to hammer down a particular experimental difficulty.[lxvi] Giving Stokes additional time however served no useful purpose – having expressed "no particular object to presenting the paper before the vacation" on 31st May 1898, by the next day he had "just one point on which I am disposed to take a different view from you…" and by 10th June this had expanded to a 5-page letter of further observations and suggestions.[lxvii] Smithells, under pressure with College administration and fraught with doubts about the rigour of his work, was forced to delay once more. His response, for the first time, contains a touch of iciness – "Let me now thank you sincerely for your valuable criticism"[lxviii] – and the correspondence fell silent until early October, when Stokes again urged submission, reminding Smithells that the paper needed a "chance of getting known before the discussion of the claims of the candidates for the [Royal Society] fellowship comes on".[lxix]

At this point Smithells appears to have become exhausted by experimental difficulties and Stokes's apparently endless capacity, when given a very short time to ponder, for spotting and reporting on minute holes in an argument. Besides, his candidature for Fellowship of the RS was being pursued (presumably unknown to

---

[lx] Stokes to Smithells, 12th February 1898 (Stokes's papers (11), S1027).
[lxi] The Royal Society protocols and norms of scholarly etiquette and appropriate language and structure arose through the interactions between Stokes, referees and authors, and (as asserted in a forthcoming book (8)) were formalised only when Stokes relinquished formal supervisory roles.
[lxii] Stokes to Smithells, 26th February 1898 (Stokes's papers (11), S1039).
[lxiii] At this stage it seems unlikely that Stokes did not have this subject "at fingers' end".
[lxiv] Smithells to Stokes, 2nd March 1898 (Stokes's papers (11), S1040)
[lxv] Stokes to Smithells, 27th May 1989 (Stokes's papers (11), S1070)
[lxvi] Smithells to Stokes, 30th May 1989 (Stokes's papers (11), S1071)
[lxvii] Stokes to Smithells (Stokes's papers (11), S1072, S1073 & S1074)
[lxviii] Smithells to Stokes, 15th June 1898 (Stokes's papers (11), S1076)
[lxix] Stokes to Smithells, 8th October 1898 (Stokes's papers (11), S1077)

Stokes) in another direction: “With respect to your kindly interest in my election to the Royal Society, I may say I have in complete readiness a paper on the electrical conductivity of vaporised salts, which my former lecturer and dear friend Sir Henry Roscoe has kindly promised to communicate to the Royal Society.”[lxx] This is undoubtedly the paper mentioned above (see footnotes *liii* and *liii* above) in the letter which, ironically, revitalised the entire Stokes-Smithells’ correspondence in late 1897. The paper was read at the Royal Society in November 1898 and publication in *Phil. Trans*. followed early in the new year.[37]

It is interesting, and not a little poignant that, after all the extended correspondence and input from Stokes on suggested experiments and observations on the spectra of gold and copper compounds (acknowledged much later by Smithells in his letter to Larmor[lxxi]), Stokes is given no credit nor even mentioned in the paper published in *Phil. Trans.* in 1899. Perhaps Smithells had simply tired of it all and did not dare to have Stokes read it again. After a meeting at a Chemical Society dinner and handful of further letters on experimental methods and the spectrum of carbon compounds, the correspondence apparently ended with a letter from Stokes on 18th November 1898.[lxxii]

The belaboured paper on the spectra of carbon compounds was eventually published, apparently without further input from Stokes but this time containing generous acknowledgements to him, in the *Philosophical Magazine* in 1901[38] and Fellowship of the Royal Society was conferred on Smithells later that year.

Conclusion

The premise of this paper – that there is something wrong with the Stokes’s historiography – seems somewhat ambitious. Why would this be so, after 100 years of biographical study of many of Stokes’s contemporaries on whom (as I argue) Stokes had such impact? Nevertheless, the secondary sources are indisputably rather limited. Only one book in that 100 years has been devoted to Stokes[39], and that allocates only 11 pages (out of over 200) to his 50+ years as a central character in the Royal Society, the remainder focusing otherwise (for the main part) on his mathematical physics and offering very few specifics on his wide-ranging impact on science and scientists over that whole period. Other biographical sources do not exactly treat Stokes dismissively, but nor do they go much beyond acknowledging his assistance as a sounding-board off whom ideas are bounced without significant modification. The broad sweep of his involvement in theoretical speculation, on mathematical underpinning of argument, in the design of experiments to confirm or disprove a particular detail of theory – Stokes was generally relied upon as an expert

---

[lxx] Smithells to Stokes, 12th October 1898 (Stokes’s papers (11), S1078)
[lxxi] Smithells in Larmor(6,p265) – see also footnote *xliv* above.
[lxxii] Stokes’s papers (11), S1086

in construction of the novel *instantia crucis* – and, above all, insistence on rigorous scientific argument before allowing publication in a journal of the Royal Society, is seldom mentioned and has never (as far as I can ascertain) been explored in any depth.

The curious historian might ask why this is so. The examples set out here can only scratch the surface of the extent to which scientists, well known like Thomson/Kelvin or Crookes, or less familiar like Smithells, came to depend upon Stokes's counsel and encouragement to help publish their researches in significant scientific journals. The extraordinary volume of primary source material is, so far at least, much underutilised in historical analysis. Perhaps the related access and transcription issues described above would deter many diligent researchers from a broad investigation of Stokes, although biographers have certainly dipped into the detail relevant to their focus.

An additional factor might involve Stokes's own character. Notoriously taciturn in meetings, he freely admitted he was "naturally of rather a retiring character".[lxxiii] It appears from the evidence of the Thomson/Kelvin relationship, and the Smithells correspondence and elsewhere in the archive, that in seeking to extend the boundaries of natural knowledge Stokes sought no advantage either in financial profit or in enhancements to his scientific reputation. Yet it cannot be, as Harrison (1988) concluded, that Stokes was possessed of "guileless conduct in all worldly affairs".[24(p.92)] His long tenure in such a politically powerful position as Editor of the Royal Society's main scientific publications, in what must be regarded as a disputatious environment, points to an administrator of rare skill and temperament. His input was mostly appreciated, but (as the Smithells case above demonstrates), this was not always the case. It seems however, from other evidence, that the Smithells case may be regarded as the exception rather than the rule.

For the final component of my complex answer to the question of why Stokes's work at the Royal Society has not yet attracted the historical attention it might merit, I turn to the development of the discipline of the history of science itself since 1945. The extent to which the science – and thus scientists – has tended to dominate the history is discussed by my PhD supervisor, Professor Frank James, in his paper "Some significances of the two cultures debate".[40] Without restating the argument here, the resulting focus on the scientific content of the history rather than on its context and on the processes involving interplays between associated actors has led to a historical record that is not yet fully developed. A further historical spotlight on the supposed origins of so-called "modern" science in the 16th and 17th centuries led

---

[lxxiii] Stokes to Thomas Romney Robinson, 1st December 1877 in Larmor (6), p40. It appears from several of the tributes in the Larmor memoir that Stokes's supposed taciturnity was not evident on social occasions, see for example the appreciation by Professor G.D. Liveing, FRS in Larmor (6), p91-97, especially p92.

to a neglect (until the late 1970s) of the 19th century, and the treatments of several major scientists including Charles Darwin, Michael Faraday, James Clerk Maxwell and Thomson/Kelvin have, to one extent or another, been produced with the focus on scientific content rather than a contextualised examination that does not prioritise the science above other activities. The consequences include the historical underplaying of the impact of characters such as Stokes.[lxxiv]

On Stokes, at least, I conclude that his original (and undoubtedly formidable) physical and mathematical researches may not have been, as many historians currently have it, his main contribution to scientific knowledge. His impact on science, expressed through the efforts and publications of other scientists to an extent not yet fully recognised (despite being apparently well known amongst his contemporaries), was perhaps even more profound. Stokes was the hub of a significant correspondence network with which historians must eventually grapple in order to disentangle and thus identify his true influence.

Acknowledgements

I should like to acknowledge the assistance of my PhD supervisor at UCL, Prof. Frank A.J.L. James, who first suggested that G.G. Stokes would be a useful subject for study, who has provided valuable advice and wise counsel throughout, and who has shared with me a fascination in the story that continues to unfold. I thank Aileen Fyfe and her colleagues for sharing draft chapters of their forthcoming book manuscript [8]. Two anonymous reviewers have provided valuable commentary and suggestions that have improved my paper, and I am grateful to them.

[lxxiv] To this list might be added the names of John Herschel, John Tyndall and George Biddell Airy

References

[1] Lord Rayleigh. Obituary notices of fellows deceased. Proc R Soc Lond. 1905; 75:199-216. Available from: http://doi.org/10.1098/rspl.1904.0163

[2] Turner, FM. The Victorian Conflict between Science and Religion: A Professional Dimension. Isis. 1978 Sep;61(3):356-376.

[3] Hall, MB, *All Scientists Now.* Cambridge: Cambridge University Press; 1984. 261 p.

[4] Barton, R. 'Men of Science': Language, Identity and Professionalisation in the Mid-Victorian Scientific Community. Hist.Sci. 2003;41(1):73-119.

[5] Wilson, DB. George Gabriel Stokes and Joshua King. In: Knox KC and Noakes R, editors. *From Newton to Hawking*. Cambridge: Cambridge University Press; 2003. p.295-342.

[6] Larmor J. *Memoir and Scientific Correspondence of the late Sir George Gabriel Stokes, Bart.* Vol 1, Cambridge, Cambridge University Press:1907. 475 p.

[7] James, FA. The conservation of energy, theories of absorption and resonating molecules, 1851-1854: G. G. Stokes, A. J. Ångström and W. Thomson. In: Notes and Records of the Royal Society of London. 1983; 38(1):79-107.

[8] Fyfe A, Moxham N, McDougall-Waters J, Røstvik C.M. Unpublished draft. *A History of Scientific Journals: Philosophical Transactions and Royal Society publishing*, 1665-2015. Pittsburgh: University of Pittsburgh Press.

[9] Warwick A. *Masters of theory: Cambridge and the rise of mathematical physics*. Chicago and London: University of Chicago Press; 2003. 572 p.

[10] Barrow-Green J. `A corrective to the spirit of too exclusively pure mathematics': Robert Smith (1689-1768) and his Prizes at Cambridge University. Ann Sci. 1999;56(3):271-316. Available from: https://doi.org/10.1080/000337999296418

[11] Stokes's papers, Cambridge University Library, Add. MS 7656 [reference numbers relate to Stokes's entries in Wilson DB, editor. *Catalogue of Stokes and Kelvin Collections*. 589 p. Cambridge: Cambridge University Library]

[12] Baldwin M. Tyndall and Stokes: Correspondence, Referee Reports and the Physical Sciences in Victorian Britain. In: Lightman B, Reidy M, editors. *The Age of Scientific Naturalism: Tyndall and His Contemporaries*. Pittsburgh: University of Pittsburgh Press; 2014. p171-186.

[13] Wilson DB, editor. *The correspondence between Sir George Gabriel Stokes and Sir William Thomson, Baron Kelvin of Largs. Cambridge*: Cambridge University Press; 1990. 783 p [Reference numbers are those assigned by Wilson in his sequential list.]

[14] Smith C, Wise N. *Energy and Empire*. Cambridge: Cambridge University Press;1989. 866 p.

[15] Lindley D. *Degrees Kelvin*. Washington DC: Joseph Henry Press;2004. 366 p.

[16] Thomson W. On the Theory of the Electric Telegraph. Proc R Soc Lond. 1856;7: 382-399 http://doi.org/10.1098/rspl.1854.0093

[17] Faraday M. On electric induction – associated cases of current and static effects. Lond Edinb Dubl Phil Mag. 1854;7(4):197-208.

[18] Stokes, Sir George G. *Mathematical and Physical Papers 1880-1905*. ["MPP"], 2nd edition. Originally Cambridge: Cambridge University Press, reprinted in 1966 and published in New York and London by Johnson Reprint Corporation. vols 1-3 (edited by Stokes, Sir George G), vols 4-5 (edited by Larmor J.)

[19] Wood A. Fifty-eight years of friendship: Kelvin and Stokes. In: Flood R, McCartney M, Whitaker A (editors). *Kelvin - Life, Labours and Legacy*. Oxford: Oxford University Press; 2008. p. 64-85.

[20] Trainer M. The patents of William Thomson (Lord Kelvin). World Pat Inf. 2004;26:311–317.

[21] Lord Kelvin. 1904 Lecture XIII [delivered in 1884] in *Baltimore Lectures on Molecular Dynamics and the Wave Theory of Light*, 703 p. London, C.J.Clay & Sons (CUP Warehouse)

[22] Brock WH. *William Crookes (1832-1919) and the Commercialization of Science*: London; Routledge: 2016 [first published in 2008 by Ashgate]

[23] Crookes in d'Albe F. *The Life of Sir William Crookes OM, FRS*: London; T Fisher Unwin Ltd: 1913

[24] Harrison AJ. Scientific Naturalists and the government of the Royal Society 1850-1900, (unpublished PhD Thesis. 1988: Open University; http://oro.open.ac.uk/57044/)

[25] Crookes, W. Researches in the Phenomena of Spiritualism, London: J. Burns; 1874. 112 p. [reprinted from the Quarterly Journal of Science, which Crookes edited at the time]

[26] Larmor J. *Memoir and Scientific Correspondence of the late Sir George Gabriel Stokes, Bart. Vol 2*. Cambridge; Cambridge University Press:1907. 507 p.

[27] Maxwell JC. On the Dynamical Theory of Gases. Phil. Trans. Vol. 157. 1866:49-88.

[28] Crookes W. On the Viscosity of Gases at High Exhaustions: (in Phil. Trans. Vol. 172, 1880:387-434.) [Stokes's notes on this paper follow as an Appendix 435-446.]
[29] Stokes, Sir George G. On the Nature of the Röntgen Rays [The Wilde Lecture]. Mem Proc Manch Lit Philos Soc. 1897;41; No. 15.
[30] Victoria Institute (1898). *Journal of the Transactions of the Victoria Institute, Vol. XXX*. London. pp13-25.
[31] Raper HS. Arthur Smithells, 1860-1939. 3. Obit. Not. Fell. R. Soc. 1940; 96-107. http://doi.org/10.1098/rsbm.1940.0009.
[32] Smithells A, Ingle H. The structure and chemistry of flames. J. Chem. Soc. 1892;61:204-216.
[33] Stokes, Sir George G. The interactions occurring in flames – A correspondence between Sir G.G. Stokes, Bart,. F.R.S., and Henry E. Armstrong. Proc Chem Soc. 1892; 8(106):22-27.
[34] DeKosky R. George Gabriel Stokes, Arthur Smithells and the Origin of Spectra in Flames. Ambix. 1980 27:2, 103-123, DOI: 10.1179/amb.1980.27.2.103.
[35] Lewes VB. The Cause of Luminosity in the Flames of Hydrocarbon Gases. Proc R Soc Lond. Vol. 57 (1894-1895). 1895:450-468.
[36] Smithells A. On flame temperatures and the acetylene theory of luminosity. J. Chem. Soc. 1896;67;1049-1063.
[37] Smithells A, Dawson HM, Wilson HA. The Electrical Conductivity and Luminosity of Flames containing Vaporised Salts. Phil. Trans. A. 1899; 193;89-128.
[38] Smithells, A. The Spectra of Carbon Compounds. Lond Edinb Dubl Phil Mag. 1901;6(1) Issue 4:476-503. (Acknowledgments of Stokes's input appear on pp478-479.)
[39] McCartney M, Whitaker A. and Wood A. *George Gabriel Stokes – Life Science and Faith*. Oxford: Oxford University Press;2019. 253 p.
[40] James, FA. Introduction: Some significances of the two cultures debate. Interdiscipl Sci Rev. 2016 Jun-Sep;41(2-3):107-117