The green line: a chapter in the history of auroral physics

Helge Kragh examines the steps forward and false alarms on the way to understanding the green line, a key stage in the development of auroral physics.

Spectroscopy changed the course of auroral research, providing for the first time a method to gain information of the chemical composition of the aurora borealis. However, the aurora refused for a long time to reveal its secrets. First observed by Anders Ångström in 1868, the brilliant green line of wavelength 5577 Å came to be seen as the holy grail of auroral spectroscopy. Fifty years later, its nature was still an enigma. The solution of the problem in the 1920s, a breakthrough in auroral physics, was due to the Canadian physicists John McLennan and Gordon Shrum, who identified the line as coming from oxygen. Their celebrated discovery can only be understood in the perspective of the contemporary work of the Norwegian physicist Lars Vegard, who vigorously advocated an alternative explanation of the green line in terms of excitations of frozen nitrogen dust particles. The story of the riddle of the green line is an important part of the history of auroral physics.

The polar aurora became a topic of science during the Age of Enlightenment, when natural philosophers such as Edmond Halley in England and Jean Jacques d'Ortous de Mairan in France pioneered the field. However, it was not until the second half of the 19th century that auroral research took off, both observationally and theoretically. The new field of research was thoroughly interdisciplinary, cultivated by a mixture of astronomers, physicists, meteorologists and chemists – and, not to forget, amateurs. The favoured view was that the aurora was caused by some kind of solar electrical action, a view that gained momentum with the discovery of cathode rays and their interpretation as streams of electrons. By the turn of the century Kristian Birkeland in Norway suggested his influential theory based on solar electrons which formed the basis of most later theories.

In order to understand the aurora as a physical phenomenon it was necessary also to explain how the spectacular colours arose in the upper atmosphere. This turned out to be a frustratingly difficult problem. For one thing, there was no theory of how electrically excited atoms emitted light; for another, the nature of the atmospheric substances responsible for the light was uncertain and a matter of much discussion. Lacking theory, the only way to understand the auroral spectrum was to compare its lines with spectra produced in the laboratory. This approach had in general worked well in astrophysics, but for half a century it failed to yield an answer to the nature of the main components of the auroral layer.

Fifty years of confusion

The holy grail of the aurora was a bright greenish line first observed by the Swedish spectroscopist Anders Jonas Ångström (1868). The wavelength reported by Ångström, 5567 Å, was redetermined by numerous later scientists, eventually to stabilize as $\lambda = 5577$ Å. Interferometric measurements made in 1923 gave the more precise value $\lambda = 5577.350 \pm 0.001$ Å (Babcock 1923). For the next few decades the nature of the line, often referred to just as the auroral line, remained a puzzle. The general line of attack was to make experiments with gases in discharge tubes at varying temperature and pressure, and compare the spectra with those obtained from aurorae. Among those who studied the problem in this way was John Rand Capron (1879), an English businessman and respected amateur scientist. His many experiments did not lead to an identification of either the green line or the other less conspicuous auroral lines. Although other researchers were no more successful, there was no shortage of hypotheses of the origin of the green line. With varying degrees of seriousness, during the period 1870–1910 the line was suggested to be due to:

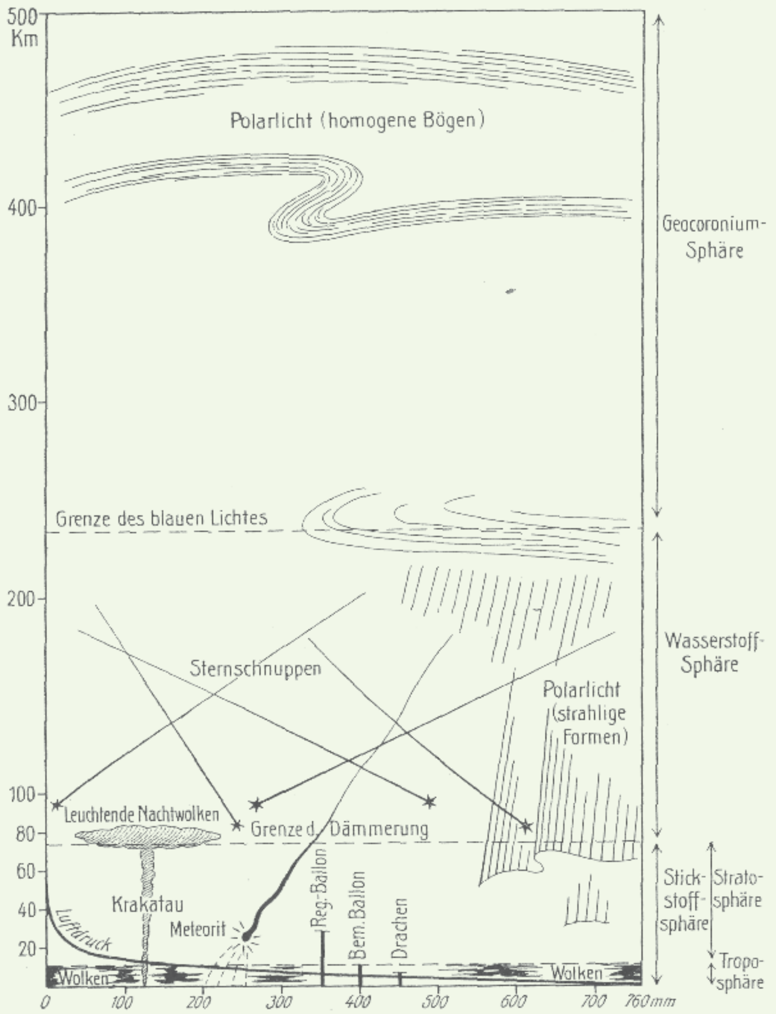
- nitrogen
- oxygen
- krypton
- meteoritic iron or manganese dust
- a fluorescent form of argon
- an unknown auroral element.

"Hypothetical elements such as coronium and nebulium, suggested on the basis of unidentified spectral lines, held considerable credibility."

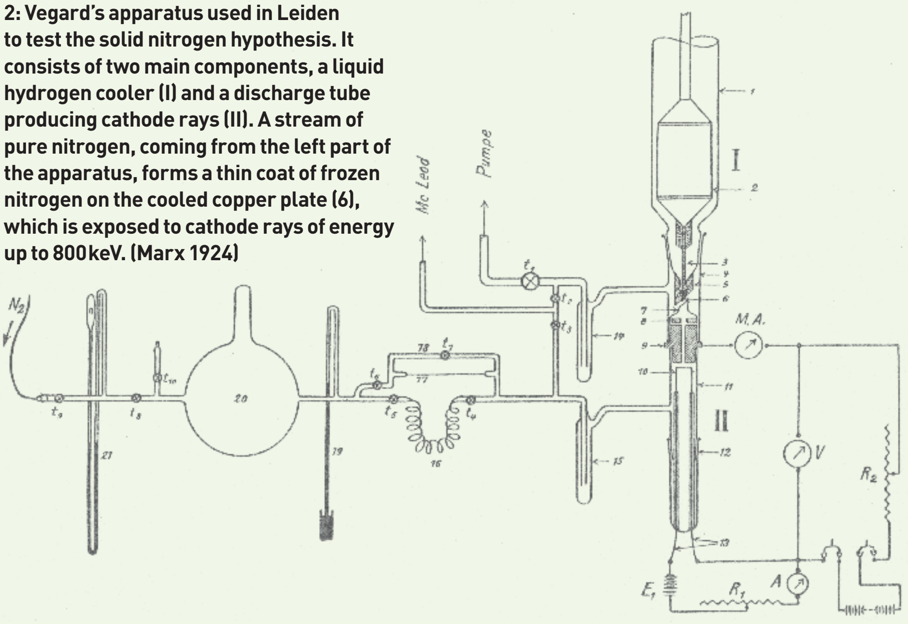
As an illustration of the unsettled state of affairs, consider the opinions of two scientists from the early 20th century. Julius Scheiner, a German astrophysicist, concluded in 1907 that "the auroral spectrum is absolutely identical with the cathode spectrum of nitrogen." In the same year the English meteorologist Marshall Watts (1907) stated with no less confidence: "There seems now little doubt that the chief line of the aurora ... must be assigned to krypton." However, their optimistic views were unfounded. The German expert in spectroscopy, Heinrich Kayser (1910), came closer to the mark when he commented: "We know nothing at all about the chemical origin of the lines of the polar light."

From a modern point of view the proposals of new elements appear suspect, even illegimate, but in the late 19th century it made good sense. Hypothetical elements such as coronium and nebulium, suggested on the basis of unidentified spectral lines, held considerable credibility, and in 1895 helium, until then just another hypothesis, was discovered in terrestrial sources and thereby turned into a real element (Kragh 2009). Interestingly, the first scientist to propose the existence of a particular auroral element was the American philosopher and polymath Charles S Peirce, who in about 1870 had taken up spectroscopic and photometric studies at Harvard College Observatory. On 15 April 1869 he measured the spectrum of an aurora seen that evening, and the same year he suggested in an anonymous review that the green line might be due to "a very light elastic gas" with atomic weight less than hydrogen's (Peirce 1984). Although the hypothesis of a sub-hydrogenic element was unorthodox, it did not contradict either the periodic table or other established knowledge from physics and chemistry. Peirce's daring hypothesis attracted almost no attention, but several years later it was independently revived by Alfred Wegener, of continental drift fame.

At about the same time as Wegener prepared his classical work on the drifting continents, he published a major work on the thermodynamics of the atmosphere (Wegener 1911). In this and other works from 1910–12 he proposed a new picture of the upper atmosphere in which it consisted of a mixture of hydrogen and a new "geocoronium" gas, supposed to be lighter than hydrogen. As indicated by the name, he thought it might be a terrestrial variant of the solar coronium. Wegener suggested that the green auroral line was due to geocoronium, supposed to be the predominant element at heights greater than 220 km. His hypothesis was well known, but failed to win recognition. Not only was it conspicuously *ad hoc* but also, after Bohr's



1: Wegener's picture of the atmosphere, including the high-altitude geocoronium sphere. (Wegener 1911 p7)



2: Vegard's apparatus used in Leiden to test the solid nitrogen hypothesis. It consists of two main components, a liquid hydrogen cooler (I) and a discharge tube producing cathode rays (II). A stream of pure nitrogen, coming from the left part of the apparatus, forms a thin coat of frozen nitrogen on the cooled copper plate (6), which is exposed to cathode rays of energy up to 800 keV. (Marx 1924)

atomic theory of 1913, ideas of sub-hydrogenic elements ceased to be taken seriously.

Vegard's nitrogen hypothesis

The first photograph of an auroral spectrum dates from 1898, and by the 1910s the art of auroral spectrophotography had advanced greatly. Progress was to a large extent due to two of Norway's experts in the physics of the aurora, Carl Størmer and Lars Vegard. A former assistant of Birkeland, since 1912 Vegard had specialized in auroral spectroscopy, an area in which he was probably the leading authority in the interwar period (Egeland *et al.* 2008). He was aware of Wegener's geocoronium hypothesis, but dismissed it at the expense of the less heterodox view that the green line was caused by photoelectrically excited nitrogen atoms in an unusual state not known from the lower atmosphere. Vegard also dismissed the hypothesis, preferred by Sydney Chapman and others, that the upper part of the atmosphere was composed largely of helium. In about 1923 he concluded that at heights greater than 100 km the atmosphere consisted of an electrified layer of nitrogen in the form of frozen dust particles (Vegard 1923). Arguing that his favourite hypothesis agreed with all known astronomical and meteorological phenomena, Vegard was particularly intrigued by its connection to the auroral spectrum. If he could reproduce the lines of the aurora from solid nitrogen he would have killed two birds with one stone: he would have solved the old problem of the chemical composition of the auroral borealis and also have confirmed the new picture of an electrified upper atmosphere.

To test the hypothesis Vegard went to Leiden to do experiments at Heike Kamerlingh Onnes's famous low-temperature laboratory, at the time the most advanced laboratory of its kind. He spent the first half of 1924 in Leiden, doing experiments with thin layers of frozen nitrogen exposed to high-voltage cathode rays. As early as 16 January he noticed that the nitrogen emitted a brilliant greenish light that looked very similar to the one he knew so well from the aurora borealis (Vegard 1924a). What he found in this and subsequent experiments was actually a band with three maxima very close to the green auroral line, and in addition he got bands corresponding to some of the other lines in the spectrum of the aurora. Although he did not succeed in reproducing the sharp green line of wavelength 5577 Å, he argued that it was a limiting case of the observed band and would appear if only the crystalline nitrogen particles could be made small enough. Later in the spring of 1924, he was confident that he had solved the riddle of the green line. As he reported to *Nature*, "the typical auroral spectrum is emitted from solid nitrogen, and thus my hypothesis with regard to the constitution of the upper atmosphere has been confirmed" (Vegard 1924b). His experiments, made with both liquid hydrogen and helium, indicated that the aurora-like spectrum only appeared at temperatures below 35 K, from which he concluded that the auroral region of the atmosphere must be correspondingly cold.

Vegard announced his discovery widely, in journal articles, review papers, and at scientific conferences. It was received with interest, but also with caution. In England the young Oxford physicist Robert d'Escourt Atkinson, assisted by his professor Frederick A Lindemann and the meteorologist Gordon Dobson, had no faith at all in Vegard's claim, which he criticized mercilessly (Atkinson 1924). According to the view of the upper atmosphere advocated by Lindemann and Dobson, it consisted mainly of helium and was much warmer than allowed by Vegard's theory. The difference was substantial: according to Vegard, the temperature at about 100 km could at most be 35 K, whereas Lindemann and Dobson argued for a temperature of approximately 300 K.

Other objections came from Toronto, where the physics professor John C McLennan had recently established a cryogenic laboratory, the first facility after the Leiden laboratory to produce liquid helium. McLennan, a fellow of the Royal Society since 1915, was Canada's most distinguished physicist and an expert in radioactivity and spectroscopy (Langton 1939). Contrary to Vegard, he had no previous experience with auroral research. Unconvinced of Vegard's discovery claim, McLennan and his research student Gordon Shrum performed in 1924 a series of experiments of essentially the same kind as those Vegard made in Leiden. Although the two Canadians found the same nitrogen band as the Norwegian physicist, they failed to confirm his main claim concerning the 5577 line (McLennan and Shrum 1924). Apparently satisfied with having refuted Vegard's hypothesis, McLennan and Shrum refrained at the time from offering an alternative solution to the riddle of the principal auroral line. The alternative came the following year.

Finally – the green line revealed

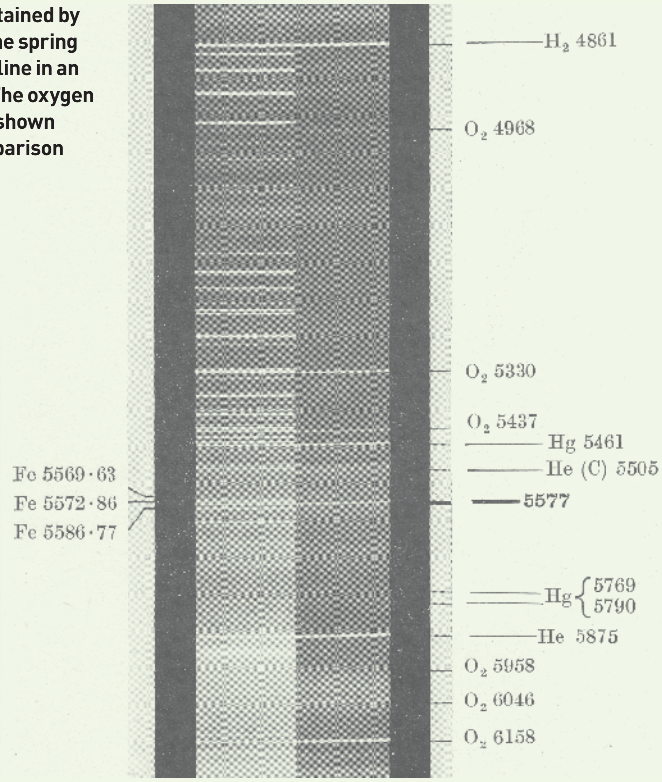
McLennan and Shrum were not merely convinced that the green line was not due to nitrogen, they also shared the belief of Chapman and others that the auroral region consisted mainly of helium. They consequently reasoned that the line probably originated in helium in some unusual state not known on Earth. Experiments to confirm the helium hypothesis were carried out in Toronto by Shrum, who after many failed attempts succeeded in obtaining the green line in an experiment of late February 1925. Alas, he was unable to reproduce the result! Then, after two weeks of increasing frustration the line did turn up again, according to Shrum's recollection in this way (Shrum 1986):

> *"I thought I was going to have a nervous breakdown. At last I was so desperate that I tried a most unscientific approach. I decided that I would get up at the same hour of the morning as I had on the great day, have the same breakfast, go over to the university at the same hour, put on the equipment in the same way, and look in the tube at exactly the same time. I did all that, looked in, and the line was there."*

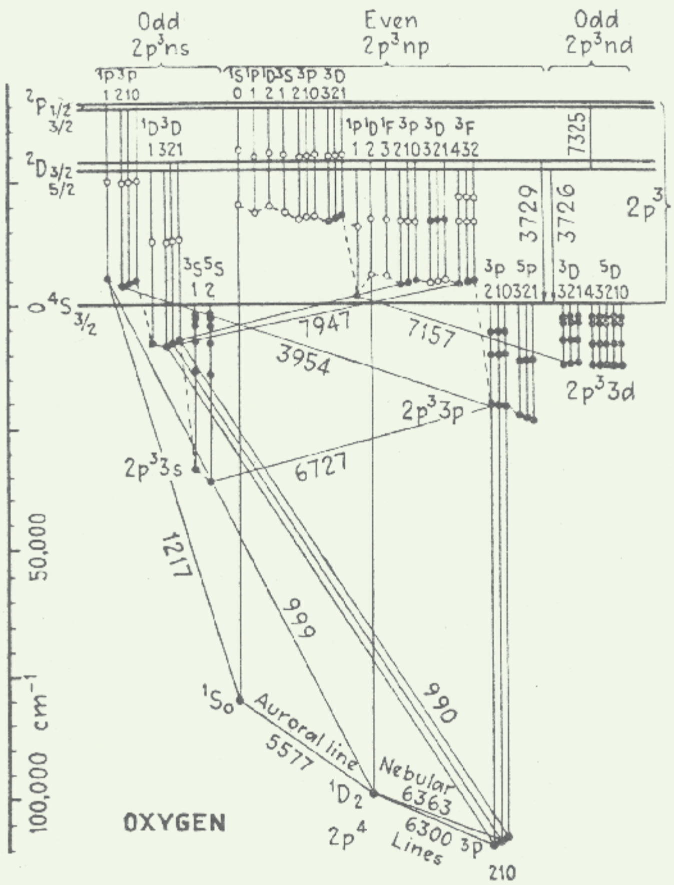
What had happened was that on the "great day" he had not purified the gas properly and therefore worked with helium contaminated with oxygen and nitrogen. Having realized this, he quickly changed to helium–oxygen mixtures and now had no difficulty obtaining the green line. Only at this stage did McLennan enter the experiments.

In their full report on the discovery, communicated to the Royal Society on 15 June 1925, McLennan and Shrum argued from their laboratory experiments that the lower auroral atmosphere consisted of helium with about 5% oxygen gas. They realized at that time that the

3: Part of the spectrum obtained by McLennan and Shrum in the spring of 1925, showing the 5577 line in an oxygen–helium mixture. The oxygen lines are at the right side, shown together with an iron comparison spectrum.



4: Energy levels and transitions in atomic oxygen, as known in 1934, including the auroral line and two nebular lines. (White 1934)



green line did not come from helium, as initially believed, but from the oxygen component. Subsequent experiments made in Toronto confirmed that helium merely acted as an agent of enhancement and that the auroral line could be produced even in pure oxygen. The match between the auroral wavelength and the oxygen line found in the laboratory was convincing (table 1).

Experimental identification was one thing, theoretical explanation quite another. Fortunately, by the fall of 1925 the new quantum mechanics of Heisenberg and others had arrived on the physics scene, resulting in a much improved understanding of atomic spectra. By applying the quantum theory of spectra, in 1926–28 McLennan (1928) and his assistants argued that the green line was a result of "forbidden" transitions between metastable states of oxygen. The first basically correct explanation, that the line is due to a direct transition from a $^1S_0$ state to a $^1D_2$ state (with the notation of the time), was proposed slightly later by the German physicist Ludwig Sommer (1928) and corroborated by Rudolf Frerichs (1930) and others. This was not the first time that the relatively long-lived metastable states were used to understand a celestial spectral line. In 1927 the US physicist Ira Bowen explained the equally puzzling nebulium lines 5007 and 4960 along the same line of theoretical reasoning (Bowen 1927, Hirsh 1979). There is a great deal of similarity, both historically and as regards the physical mechanisms, between the cases of the auroral lines, the nebulium lines and the coronium lines.

The reproduction and explanation of the green line was a breakthrough in auroral physics and the high point in McLennan's career. In 1927 he received the gold medal from the Royal Society and in 1934, shortly before his death, he was even nominated for a Nobel Prize. Shrum's very important part in the discovery was and still is rarely recognized. Yet it should be pointed out that the key discovery of the green line in the early spring of 1925 was almost completely due to Shrum, whereas McLennan played only a secondary role. And what about Vegard? Committed to his ambitious theory of a global layer of frozen nitrogen dust, the Norwegian physicist refused for several years to accept the McLennan–Shrum explanation of the green line. Only in the 1930s did he admit that his own theory was wrong and that of the Toronto physicists correct (Vegard 1938).

Sometimes episodes in the history of science are better understood by what happened much later. Many years after the works of Vegard, McLennan and Shrum in 1924, it was realized that they must all have worked with nitrogen contaminated with small amounts of oxygen. According to present knowledge, the structure of the nitrogen band near the 5577 line is caused by a complex energy transfer from nitrogen molecules to produce metastable $^1S_0$ oxygen atoms

Table 1: The green auroral line, 1868–1934

author	year	wavelength (Å)	evidence
A J Ångström	1868	5567	aurora
H C Vogel	1871	5572±1	aurora
C Runge	1898	5571.0	aurora
J Sykora	1900	5570±3	aurora
J Westman	1904	5572.6	aurora
L Vegard	1913	5576.9	aurora
M Slipher	1919	5578.05	night sky
L Vegard	1923	5577.6	aurora
H D Babcock	1923	5577.350±0.001	night sky; interferometry
L Vegard	1924	5578.6	laboratory; nitrogen
J McLennan, G Shrum	1925	5577.35±0.15	laboratory; oxygen
J McLennan, J McLeod	1927	5577.341±0.004	laboratory; oxygen; interferometry
G Cario	1927	5577.348±0.005	laboratory; oxygen
L Vegard, L Harang	1934	5577.3445±0.0027	aurora; interferometry

(Henriksen and Egeland 1988). Had Vegard's frozen nitrogen been pure, he would not have observed the band. Since McLennan and Shrum found the same band in their low-temperature experiments, they too must have worked with impure nitrogen.

Conclusions

Auroral spectroscopy as a field of science changed drastically over the 60 years considered here. During the early period it was a visual and simple science that appealed to amateurs and required neither theoretical knowledge nor advanced instruments. After about 1915, the study of the auroral spectrum turned into a scientific subdiscipline based on complex spectrophotometric equipment. Moreover, it became increasingly a laboratory science. The hunt for the green line did not take place in the skies, but in the advanced cryogenic laboratories in Leiden and Toronto. Whereas theoretical physics had been irrelevant in the pre-World War I era, in the 1920s quantum theory became an important part of auroral physics. Only by means of the new quantum theory of spectra was it possible to understand the origin of the lines appearing in the aurora. However, whereas quantum theory was crucial to Bowen's identification of nebulium, in the case of the green line it only entered *post hoc*. The work in 1924–25, resulting in the discovery of the green oxygen line, was laboratory science with little input of theory.

Historians and sociologists of science speak of the "Matthew effect" as an expression of the inordinate amount of credit that is often assigned to highly reputed scientists at the expense of their collaborators or students. (Matthew 25, 29: "To all those who have, more will be given, and they will have an abundance; but from those who have nothing, even what they have will be taken away.") The discovery of the green line in Toronto, principally made by Shrum but generally credited to McLennan, provides a clear-cut example. ●

Helge Kragh, Dept of Science Studies, University of Aarhus, Denmark.

References

Ångström A J 1868 *Recherches sur le Spectre Solaire* (Schultz, Uppsala).
Atkinson R d'E 1924 *Proc. Roy. Soc.* **106** 429–440.
Babcock H D 1923 *Ap. J.* **57** 209–215.
Bowen I S 1927 *Nature* **120** 473.
Capron J R 1879 *Auroræ: Their Characters and Spectra* (Spon, London).
Egeland A *et al.* 2008 *Lars Vegard* (Bokbyen, Oslo).
Frerichs R 1930 *Phys. Rev.* **36** 398–410.
Henriksen K and A Egeland 1988 *Eos* **69** 721–725.
Hirsh R F 1979 *Isis* **70** 197–212.
Kayser H 1910 *Handbuch der Spectroscopie* vol. **5** (Hirzel, Leipzig).
Kragh H 2009 *Ann. Sci.* **66** 157–182.
Langton H H 1939 *Sir John Cunningham McLennan* (Un. Toronto Press, Toronto).
Marx E ed. 1924 *Handbuch der Radiologie* vol. **6** (Akademische Verlagsanstalt, Leipzig) 585.
McLennan J C 1928 *Proc. Roy. Soc.* **120** 327–357.
McLennan J C and G Shrum 1924 *Proc. Roy. Soc.* **106** 138–149.
McLennan J C and G Shrum 1925 *Proc. Roy. Soc.* **108** 501–512.
Peirce C S 1984 *Writings of Charles S Peirce* vol. **2** (Indiana Un. Press, Bloomington) 287.
Shrum G 1986 *An Autobiography* (Un. British Columbia Press, Vancouver) 46.
Sommer L 1928 *Zeits. Phys.* **51** 451–470.
Vegard L 1923 *Phil. Mag.* **46** 577–604.
Vegard L 1924a *Comptes Rendus* **179** 151–153.
Vegard L 1924b *Nature* **113** 716–717.
Vegard L 1938 *Naturwissenschaften* **26** 639–644.
Watts W M 1907 *Month. Weather Rev.* **35** 405–412.
Wegener A 1911 *Thermodynamik der Atmosphäre* (Leipzig, Barth).
White E 1934 *Introduction to Atomic Spectra* (McGraw-Hill, New York) 266.