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PART I

The birth of astrophysics and other late-nineteenth-century trends

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1

The origins of astrophysics

A.J. MEADOWS

The rise of astrophysics in the nineteenth century represented a major turning point in the development of astronomy. In terms of the balance of present-day research, it proved to be the vital step forward. Prior to the growth of astrophysics, by far the major effort in astronomy was devoted to studies of where bodies were, and of how they moved. Now the emphasis has reversed: most of our current research effort is concerned with the physical properties of celestial bodies.

Astrophysics and spectroscopy

Physical studies of celestial objects can be carried out in a variety of ways; but the crucial factor in the early development of astrophysics was the study of spectra. The reason is simple – spectroscopy provided more information on physical and chemical properties than any other method. Interest in laboratory spectroscopy began to grow in the first half of the nineteenth century, as part of the general development of chemical techniques. Flame spectra provided a useful tool in some of the detailed studies of elements and simple compounds that characterized the rise of modern chemistry.

Astronomical spectroscopy can be seen, in part, as a later off-shoot of these initial attempts at chemical analysis via spectra. But the link was not entirely straightforward for it was mediated initially by the strong nineteenth-century interest in the nature of colour. An interplay between studies of colour, spectra and astronomy can be found in the work of several scientists in the first half of the nineteenth century. Fraunhofer is an obvious example. Less well-recognized, perhaps, are the similar interests of British scientists such as D. Brewster (1781–1868) and John Herschel (1792–1871) or, later in the century, of the Leipzig astronomer J.K.F. Zöllner (1834–82).

Brewster and Herschel both worked on all three topics for several decades. Brewster first became involved in these areas via an attempt to show that Newton's ideas on the prismatic spectrum were incorrect; whereas Herschel originally concerned himself with experiments on colour filters and their properties. These differing interests led both men to studies of flame spectra and also to the study of the solar spectrum – the latter, because the Sun provided much the brightest laboratory light source then available. At first, study of the Fraunhofer lines in the solar spectrum was regarded as ancillary to the use of sunlight as a source of different colours (an emphasis similar to that of Fraunhofer). But it was quite rapidly recognized that the spectral lines themselves were important, since they might provide a way of improving chemical analysis. From the 1820s onwards, this emphasis on analysis led to two types of investigation. The first attempted to understand the spectral changes that occured when different substances were subjected to a range of conditions in the laboratory. The second tried to reconcile observations of laboratory spectra with those of the solar spectrum.

It was assumed from early on in the study of laboratory spectra that the spectrum observed was in some sense characteristic of the substance producing it. The problem was discovering the exact link. Spectra of the same substance could soon be produced in more than one way – for example, by flame or by spark. Differences between the spectra produced by different methods suggested that even pure substances might not be characterized by a unique spectrum. This was also suggested by the apparently ubiquitous appearance of the Fraunhofer D line (subsequently shown to be double), which was observed regardless of the substance under examination. Part of this difficulty in interpreting spectra related to a lack of

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understanding of the theoretical basis, and we return to it later. Part stemmed from the fact that chemistry itself was still in a stage of rapid development. Thus, the widespread distribution of sodium – and so of the D lines – was shown in the later 1850s to be due to trace contamination by salt. This explanation resulted from the chemists' continuing attempts to isolate 'pure' substances. By about 1860 chemists were in general agreement that spectra could be used to characterize chemical substances uniquely, though detailed interpretation of spectral differences remained difficult.

The problem of comparing laboratory spectra with the solar spectrum hinged on the obvious difference that the former were in emission, whereas the latter was in absorption. Could the two types of spectrum be equated? Brewster's interest in coloured vapours led him quite early to an examination of the spectrum of nitrous oxide (a brownish-red gas). He found that sunlight, when passed through the gas, showed absorption bands. Brewster's explanation of his results – he thought the nitrous oxide spectrum explained the solar lines – was totally inadequate. But his experiment did point to the existence of a link between emission and absorption. The next step – identifying the same line in emission and absorption – was taken by J.B.L. Foucault (1819–68) in Paris in the middle of the nineteenth century. What he did was to test the supposed coincidence between the solar D line and the prominent yellow emission line observed in laboratory spectra:

As this double line recalled, by its form and situation, the line D of the solar spectrum, I wished to try if it corresponded to it, and in default of instruments for measuring the angles, I had recourse to a particular process.

I caused an image of the Sun, formed by a converging lens, to fall on the arc itself, which allowed me to observe at the same time the electric and the solar spectrum superposed; I convinced myself in this way that the double bright line of the arc coincides exactly with the double dark line of the solar spectrum.

But Foucault's experiment went beyond the establishment of coincidence: it also hinted at the way in which absorption and emission lines were interrelated. For he continues:

This process of investigation furnished me matter for some unexpected observations. It proved to me, in the first instance, the extreme transparency of the arc, which occasions only a faint shadow in the solar light. It showed me that this arc placed in the path of a beam of solar light, absorbs the rays D, so that the above-mentioned line D of the solar light is considerably strengthened when the two spectra are exactly superposed. When, on the contrary, they jut out one beyond the other, the line D appears darker than usual in the solar light, and stands out bright in the electric spectrum which allows one easily to judge of their perfect coincidence. Thus the arc presents us with a medium which emits the rays D on its own account, and which at the same time absorbs them when they come from another quarter.

Foucault's observation, published in *L'Institut* on 7 February 1849, can be seen as the real beginning of a comparison between solar and laboratory spectra. Yet it was not properly followed up for another ten years. There was no single reason for this delay, but one problem is worth mentioning – the continuing element of doubt whether, or not, the Fraunhofer lines were formed on the Sun. In the early 1830s Brewster showed that some Fraunhofer lines darkened as the Sun approached the horizon, obviously suggesting that the terrestrial atmosphere was involved in their production. The remaining lines might be of solar origin, but, in the mid-1830s, even this was questioned. J.D. Forbes argued that absorption lines seen at the edge of the solar disc should be darker than the corresponding lines at the centre of the disc, because the slant height through the atmosphere would be greater towards the limb. Observations of the limb spectrum at an annular eclipse in 1836 showed no such difference, thus casting some doubt on a solar origin for the lines. Alternative explanations – for example, that the Fraunhofer lines were due to interference effects within the optical system – could not be entirely ruled out (though it is probably fair to say that the explanation in terms of interference phenomena is more interesting for its analogy with early criticisms of Galileo's telescopic observations than for its wide acceptance).

Despite such uncertainties, most scientists interested in Fraunhofer lines were not only prepared to believe that they were formed on the Sun, but, by the 1850s, were beginning to link the results of

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laboratory spectroscopy to the formation of the solar spectrum. Perhaps the most extended discussion during this decade was provided by A.J. Ångström, but the trend is well reflected in a short reminiscence by G.G. Stokes (1819–1903).

As well as I recollect what passed between Thomson [i.e. Lord Kelvin] and myself about the lines was something of this nature. I mentioned to him the repetition by Miller of Cambridge of Fraunhofer's observation of the coincidence of the dark line D of the solar spectrum with the bright line D of certain artificial flames, for example a spirit lamp with a salted wick. Miller had used such an extended spectrum that the 2 lines of D were seen widely apart, with 6 intermediate lines, and had made the observation with the greatest care, and had found the most perfect coincidence. Thomson remarked that such a coincidence could not be fortuitous, and asked me how I accounted for it. I used the mechanical illustration of vibrating strings which I recently published in the Phil[osophical] Mag[azine] *in connection with Foucault's experiment. Knowing that the bright D line was specially characteristic of soda, and knowing too what an almost infinitesimal amount suffices to give the bright line, I always, I think, connected it with soda. I told Thomson I believed there was vapour of sodium in the Sun's atmosphere.*[1]

Kirchhoff

Although speculations concerning the nature of the solar spectrum were common by the 1850s, one fundamental requirement for its proper discussion still remain unfulfilled. An explanation of the production of spectra required a basic physical understanding of the relationship between absorption and emission. This was first provided by G.R. Kirchhoff (1824–87), working with his Heidelberg colleague, R.W.E. Bunsen (1811–99). Bunsen's development of his well-known burner, with its non-luminous flame, was an important step forward in the method of producing spectra. However, Bunsen intended to use the flame in conjunction with colour filters: it was Kirchhoff who suggested the use of a prism. Between them, they managed to evolve the basic instrumental requirements for a proper spectroscopic analysis.

In the autumn of 1859 Kirchhoff and Bunsen effectively repeated and extended Foucault's work, though apparently neither was aware of

1.1. R.W.E. Bunsen, G.R. Kirchhoff and H.E. Roscoe in Heidelberg, 1862.

Foucault's experiments. (One of the problems of early astrophysics was that key results often appeared in publications not regularly scanned by others in the field.) In November 1859, Bunsen reported to the English chemist, H.E. Roscoe:

At the moment I am occupied by an investigation with Kirchhoff which does not allow us to sleep. Kirchhoff has made a totally unexpected discovery, inasmuch as he has found out the cause for the dark lines in the solar spectrum and can produce these lines artificially intensified both in the solar spectrum and in the continuous spectrum of a flame, their position being identical with that of Fraunhofer's lines. Hence the path is opened for the determination of the chemical composition of the Sun and the fixed stars with the same certainty that we can detect chloride of strontium, etc., by our ordinary reagents.[2]

Over the next two years, Kirchhoff established the basic principles of spectrum analysis. His results can be summarized as follows: (1) Incandescent solids or liquids typically give continuous spectra in the visible region, while gases give lines or bands (the positions of which depend on the gas

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examined). (2) When a source of continuous spectrum, such as the Sun, is viewed through a cool gas the wavelengths at which absorption occurs correspond to those at which emission occurs when the gas is heated.

These basic principles led Kirchhoff on to two immediate conclusions concerning the Sun. The first concerned its chemical composition, as derived from a comparison of solar and laboratory spectra.

Iron is remarkable on account of the number of the lines which it causes in the solar spectrum; magnesium is interesting because it produces the group of Fraunhofer's lines which are most readily seen in the Sun's spectrum, namely, the group in the green, consisting of three very intense lines to which Fraunhofer gave the name b. *Less striking, but still quite distinctly visible, are the dark solar lines coincident with the bright lines of chromium and nickel. The occurrence of* these *substances in the Sun may therefore be regarded as certain. Many metals, however, appear to be absent; for although silver, copper, zinc, aluminium, cobalt and antimony possess very characteristic spectra, still these do not coincide with any (or at least with any distinct) dark lines of the solar spectrum.*[3]

Kirchhoff's second deduction concerned the nature of the Sun. He postulated that the Sun consisted of an incandescent liquid core (he thought, at first, that it might have a solid crust) surrounded by an extensive gaseous envelope (which he identified with the corona). This model was soon replaced by astronomers with one that better fitted their observations. Nevertheless, it is important as the first model of the Sun based on the new physics (and chemistry) of the nineteenth century. The changes it introduced become evident from a comparison with the solar model previously accepted. Though not solely due to William Herschel, this model was often attributed to him in nineteenth-century writings. It supposed that the Sun possessed a cool, solid core surrounded by luminous cloud layers. Brewster, in his *More Worlds than One*, a popular work on life in the universe, indicated that this picture was still acceptable in the 1850s.

... we approach the question of the habitability of the Sun, with the certain knowledge that the Sun is not a red-hot globe, but that its nucleus is a solid opaque mass receiving very little light and heat from its luminous atmosphere.

After Kirchhoff, the assessment of what solar models were scientifically acceptable changed radically.

Solar eclipses

Kirchhoff's model emphasized the important role played by the solar atmosphere, thereby increasing interest in its properties. Since the atmosphere could only be observed at eclipses, the attention of astronomers was concentrated on these.

The main solar features visible at a total eclipse – the chromosphere, corona and prominences – were all noted before the 1860s. Interest in eclipse studies was stimulated by F. Baily's observations of bright 'beads' of light round the limb of the Moon at the 1836 eclipse. This led to more extensive observations at the next European eclipse in 1842, and consequent agreement on the existence of both prominences and the corona. The chromosphere was clearly distinguished at the 1851 eclipse. The physical nature of these features remained at first uncertain, but the advent of astronomical spectroscopy offered the possibility of a solution. A series of total eclipses at the end of the 1860s and in the early 1870s allowed repeated attacks on the problem using the newly-developed astrophysical techniques.

The first major advance occurred at the 1868 eclipse, which was watched from India and Malaya by several European astronomers. Spectroscopic observations of the prominences at this eclipse showed the presence of bright lines, so demonstrating that prominences were gaseous. P.J.C. Janssen (1824–1907), one of the observers, was sufficiently impressed by the brightness of the lines that he decided to scan the solar limb out of eclipse to see if the lines could still be seen. He was immediately successful; observations on succeeding days further showed that prominences could undergo rapid changes in size and shape with time. Meanwhile, others had already considered the possibility of observing prominences out of eclipse. Initially, the instrumentation available was insufficiently powerful, but in 1868 Norman Lockyer (1836–1920), using new equipment, managed to detect the spectra of prominences out of eclipse

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1.2. The French mint struck this medal to commemorate the discovery by Jules Janssen and Norman Lockyer of the method of observing prominences out of eclipse.

almost simultaneously with Janssen. Since prominences were frequently thought of as jets from near the region of the solar surface, these spectroscopic results were taken as confirmation of the Sun's basically gaseous nature.

It soon became apparent that the red-coloured region seen round the limb of the Sun at eclipses also produced a bright-line spectrum that could be detected out of eclipse. Indeed, Father Angelo Secchi (1818–78) soon showed that hydrogen in emission could be traced all the way round the solar limb. As a result of these observations, the need to study prominences and the chromosphere at eclipses became much less pressing. Eclipse spectroscopy thenceforth concentrated on other problems, especially those relating to the corona and to the flash spectrum.

Because the corona was so faint, progress in its spectroscopic observation proved to be slow. The most important advance in the early years was the confirmation that it produced an emission-line spectrum. At the 1869 eclipse, visible in North America, the American astronomers C.A. Young (1834–1908) and W. Harkness independently confirmed the presence of a bright coronal line in the green region of the spectrum.

These advances in chromospheric and coronal spectroscopy raised a further query, this time concerning the absorption spectrum. Kirchhoff's ideas implied that the part of the solar atmosphere producing the Fraunhofer spectrum should, when seen at the limb, show an identical spectrum in emission. Observations of the chromospheric and coronal spectra clearly demonstrated that neither of these was the required reversal of the Fraunhofer spectrum. Where, then, was it produced? This question finally received an answer at the 1870 eclipse. Young had looked for the reversed spectrum at the previous eclipse, but had failed to find it. This time, using a tangential rather than radial slit, he was successful. He observed the brief appearance of a set of emission lines – apparently at complementary wavelengths to the normal absorption spectrum. The short duration indicated that the part of the solar atmosphere producing the lines must be of small vertical extent. Young's observation therefore not only confirmed the accuracy of Kirchhoff's original prediction, but also pinned down the region of the solar atmosphere that produced the Fraunhofer lines. This 'reversing layer', as it was called, occupied the region just above the supposed photospheric cloud layer.

By the early 1870s the main areas of astrophysical attack on the problems presented by the solar atmosphere had been determined. The following decades were almost fully occupied in pursuing the insights, and sorting out the confusions, that arose during this initial period of

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eclipse observation. Two examples, relating to the chemical composition of the atmosphere, illustrate this point. Janssen and Lockyer had both noted a bright yellow line in prominence spectra near, though not identical with, the D line. It proved impossible to find an equivalent line in any laboratory source, and Lockyer boldly speculated that a new element – helium – was needed to explain it. From the beginning this explanation met with opposition – even from Lockyer's collaborator, E. Frankland. The debate continued until nearly the end of the century, when helium was finally detected in the laboratory. The green coronal line, which has been mentioned above, had an even more chequered history than the helium line. It was initially identified with a known iron line, an identification that caused increasing difficulty. Atmospheres were expected to show some segregation of their constituents, with the lightest molecules congregating to a greater extent near the top. The lightest known element was hydrogen, but the green line could certainly be traced to distances further from the Sun than any hydrogen line. How could the heavy element, iron, extend further into space than hydrogen? It was later shown that the line had been misidentified, but the basic question still remained – what element could it be? The solution of the problem was not found until the 1940s, when it was shown that this coronal line, and others, were produced by known, but highly ionized elements. Meanwhile, nineteenth-century astrophysicists attributed the lines to a new element – 'coronium' which, like helium, had not yet been detected on Earth.

Progress in the initial development of astrophysics

Early astronomical spectroscopy concentrated on the Sun, in part because it was the brightest object available. But another factor lay behind this special interest in the Sun – the discovery of solar–terrestrial relations. S.H. Schwabe in Germany had begun systematic observations of sunspots in 1826. By 1843, he was able to announce that the number of spots visible seemed to undergo a cyclical variation with period of about ten years. The conclusion attracted little attention until it was quoted by Humboldt in his book *Kosmos*. This appeared in 1851, at just the time that J.v. Lamont in Germany and E. Sabine in England were analysing the results of several years' geomagnetic observations (the former for two German stations; the latter for four, widely distributed, colonial stations). Both found that geomagnetic variations occurred with a period of about ten years. It was a small step from this to the conclusion that some link existed between changes on the Sun and on the Earth.

Attention was thus drawn to the physical properties of the Sun, and more especially to the nature of solar activity. As John Herschel wrote to Faraday on 10 November 1852: "If all this be not premature we stand on the verge of a vast cosmical discovery such as nothing hitherto imagined can compare with." Many astronomers were consequently stimulated to observe sunspots in the 1850s and 1860s. During the latter decade, the interest in solar–terrestrial relations mixed with the new solar spectroscopy in the development of astrophysics.

An excellent example of this mixture of factors in the development of astrophysics is provided by Secchi's career. Initially attracted by Joseph Henry's photometric observations of sunspots in the 1840s, the Vatican astronomer moved on to a more general interest in the Sun during the 1850s and then to spectroscopic studies of the Sun and stars in the 1860s. The connection between the growth of his interest in solar physics and in terrestrial magnetism was noted with distaste in his obituary in *Proceedings of the Royal Society of Edinburgh*:

> *Secchi, though an excellent observer and a man of great power, was of a discursive turn of mind. He had little power of concentration, and appears to have tired of the monotony of astronomical observations, and to have turned his attention to the more popular studies of terrestrial magnetism and solar physics.*

In view of this emphasis, it is hardly surprising that the first major attempt to provide a comprehensive explanation of the new solar observations – by H. Faye – started from recent studies of sunspots. Although the details of Faye's model soon came to be queried (and were abandoned to some extent even by their author), his general approach indicated the framework for most later discussions of solar physics. Two points, in particular, were widely accepted and were, in fact, also proposed by John Herschel and Secchi. First,

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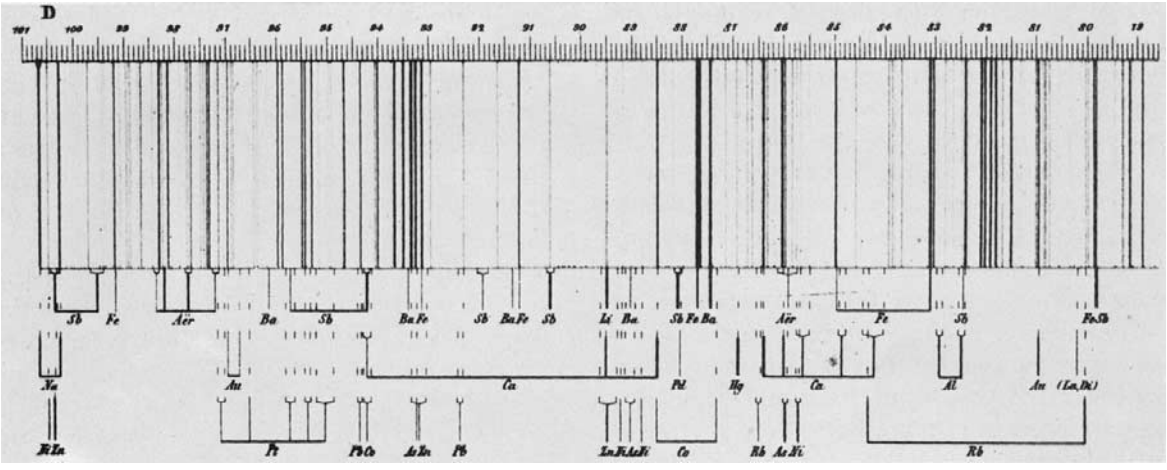

1.3. A section of the solar spectrum drawn by Kirchhoff and published in 1863 with the lines identified for such metals as antimony, iron, barium, lithium, sodium, gold, calcium, palladium, mercury, aluminium, lanthanum, and didymium (a mixture of neodymium and praseodymium, formerly thought to be an element).

the temperature increase from the surface inwards was sufficient to make the whole body of the Sun gaseous. Second, the photosphere represented a level in the Sun where refractory substances could condense out, forming a cloud layer. In establishing these propositions, a good deal of weight rested on the sunspot observations – visual, photographic and spectroscopic. For example, one important piece of evidence was the spectroscopic detection of increased absorption in sunspots by Lockyer and Secchi in the latter half of the 1860s.

It was an obvious extension of Kirchhoff's work on the total solar spectrum to examine the spectra of specific solar features, such as sunspots. Equally obviously, the sort of chemical and physical analysis that Kirchhoff had carried out on sunlight could also be applied to the light from stars and nebulae. One initial problem in all this work, which led to a number of false starts, was the difficulty of determining the precise wavelengths of lines in the spectra of celestial bodies.

Kirchhoff's original map of the solar spectrum suffered from a non-linear wavelength scale, owing to its prismatic dispersion. His arbitrary scale divisions were therefore not readily reproducible on instruments elsewhere. At the end of the 1860s Ångström published a new map of the solar spectrum, based on measurements with a grating, which gave a normal dispersion. His calibration, using a unit of one ten-millionth of a millimetre (one Ångström), soon displaced Kirchhoff's scale for the intercomparison of spectra.

The main requirement for astronomical spectra was not simply that they should be accurately calibrated, but also that they should be of the highest dispersion possible. The basic aim behind many astronomical measurements was the wish to determine chemical composition. This involved a comparison of the positions of lines from laboratory and astronomical sources. The higher the dispersion, the more readily any lack of coincidence could be detected. Unfortunately, the higher the dispersion, the fainter the resultant spectrum. All early measurements were visual; even with an object as bright as the Sun, Kirchhoff strained his eyes in drawing the spectrum. (His map of the solar spectrum was completed by one of his pupils.) For stars, the problem was obviously increased. Of the two astronomers most involved in stellar spectroscopy in the 1860s – Secchi and William Huggins (1824–1910) – the latter was more concerned, since he used the higher dispersions. In his earliest paper on stellar spectra, in *Philosophical Transactions* in 1864, Huggins pointed out:

The investigation of the nature of the fixed stars by a prismatic analysis of the light which comes to us from them, however, is surrounded by no ordinary difficulties. The light of the bright stars, even when concentrated by an object-glass or speculum, is found to become feeble when subjected to the large amount of

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dispersion which is necessary to give certainty and value to the comparison of the dark lines of the stellar spectra with the bright lines of terrestrial matter. Another difficulty, greater because it is in its effect upon observation more injurious, and is altogether beyond the control of the experimentalist, presents itself in the ever-changing want of homogeneity of the Earth's atmosphere through which the stellar light has to pass. This source of difficulty presses very heavily upon observers who have to work in a climate so unfavourable in this respect as our own. On any but the finest nights the numerous and closely approximated fine lines of the stellar spectra are seen so fitfully that no observations of value can be made.

It was hoped from the start that both the problems noted by Huggins might be overcome by substituting the photographic plate for the human eye. Huggins attempted to photograph stellar spectra as early as 1863, but no results of value were obtained until the following decade. He was nevertheless able to establish two basic points about stellar spectra from visual observations. First, the same chemical elements could be detected in stars as were also found on the Sun and Earth. Second, the elements detected were not necessarily identical in different stars (for example, Huggins detected hydrogen in Aldebaran, but not Betelgeuse).

The difficulty of observing stellar spectra visually slowed down not only the chemical analysis of stars, but also the application of what was recognized to be a powerful new method for studying stellar motions. Christian Doppler had suggested in the 1840s that motion of a body in the line of sight could affect its colour. A few years later, A.-H.-L. Fizeau examined this possibility more rigorously, pointing out that the Fraunhofer lines might provide a delicate test of such motion. In 1868, both Huggins and Secchi tried to detect such a 'Doppler' shift in the spectrum of Sirius. Secchi's results were inconclusive, but Huggins, using better instrumentation, was able to claim he had found a definite red shift in the spectrum. Conclusive proof of Doppler effects in celestial spectra came, however, in 1871 from solar observations. H.C. Vogel, who was working at F.G. von Bülow's observatory near Kiel, then reported in *Astronomische Nachrichten*:

On 9 June, with the aid of a reversing spectroscope made available by Professor F. Zöllner which had been fitted on the large equatorial telescope, we succeeded in demonstrating the rotation of the Sun through the displacement of the spectral lines... From the observations, the velocity would seem to be rather greater than has up to now been deduced from the movements of the sunspots. However, in some respects these observations themselves have a considerable degree of uncertainty, whilst in other respects the determination of the wavelength of individual lines in the solar spectrum is not yet so exact for observations of the kind under consideration that one would be justified in drawing any more far-reaching conclusions. Only the conclusion, which is not unimportant for hypotheses about the nature of light, that the motion of a luminous point can lead to a change of wavelength for the light beams emitted from it, can be regarded as certain.

Of all early spectroscopic results, perhaps the most frequently cited single observation is Huggins's examination of a planetary nebula in Draco. The resultant detection of its emission spectrum necessarily implied, from Kirchhoff's arguments, that the nebula must be gaseous. Huggins initially identified the brightest nebular line as being due to nitrogen; but subsequent observations showed that, whereas the nitrogen line was double, the nebular line was single. In the 1880s, Lockyer pressed the claim of magnesium, rather than nitrogen, as the source of this line (his identification being linked to the meteoritic hypothesis of stellar evolution which he was then developing). Huggins disputed this, and wrote to J.E. Keeler at Lick Observatory asking him to use the better facilities there to resolve the question. Keeler's observations in 1890 showed that no known laboratory line satisfactorily explained the properties of the chief nebular line. By the end of the nineteenth century, it was therefore supposed that, just as the corona contained 'coronium', so the nebulae contained 'nebulium'.

The discovery of the nebular emission lines is often seen as a vital turning point in the historical development of ideas concerning the physical nature of the nebulae. Although there is a good deal of truth in this, it must also be recognized that the application of spectroscopy to nebulae led to ambiguous results. Huggins's original observations showed that only a third of the nebulae observed had bright lines: the remainder possessed

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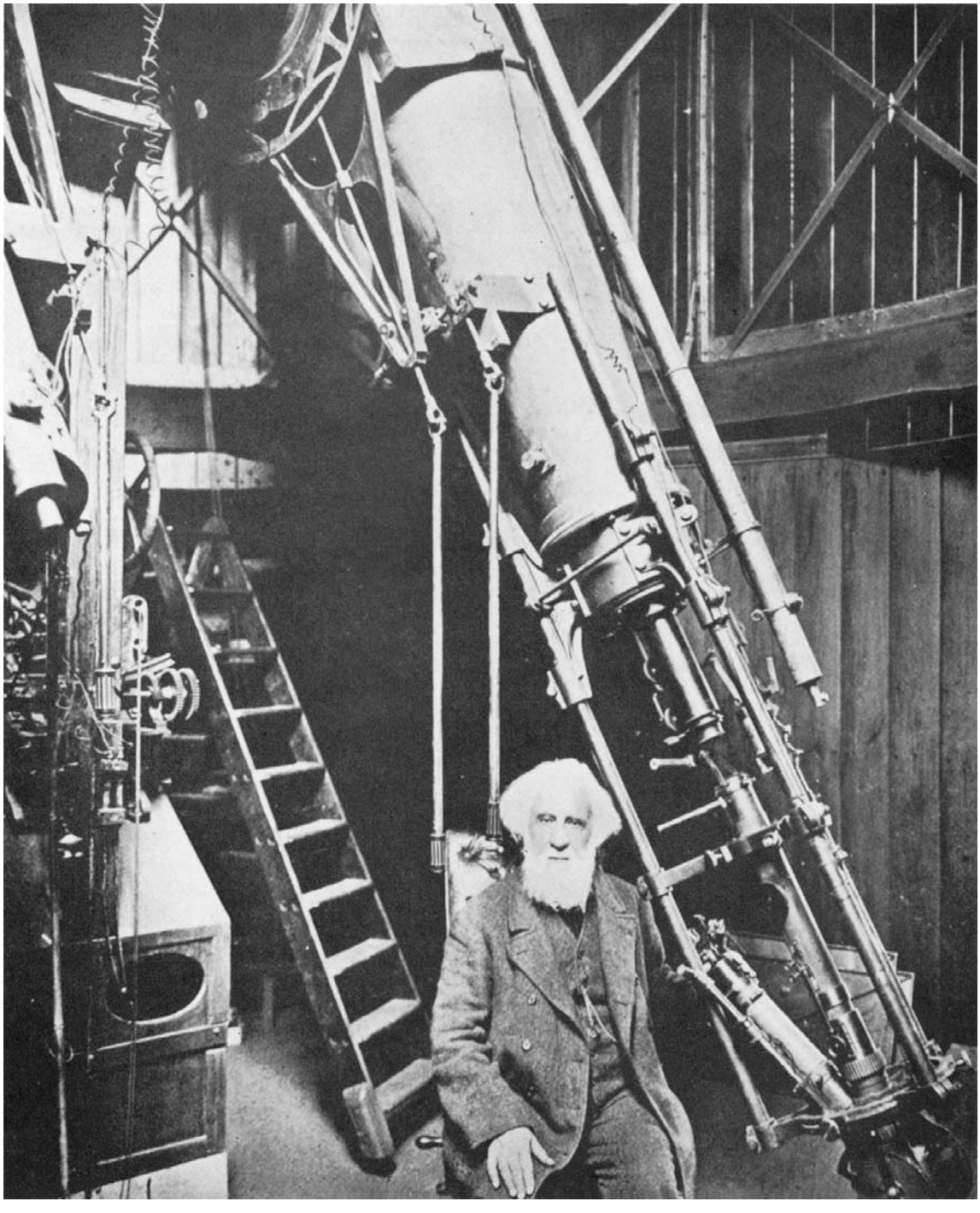

1.4. William Huggins in his observatory at Tulse Hill, 1890s. His spectroscope employed a 4-inch grating from Brashear, and was attached to a 15-inch Grubb refractor lent by the Royal Society.

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