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AUGUSTE COMTE'S BLUNDER: AN ACCOUNT OF THE FIRST CENTURY OF STELLAR SPECTROSCOPY AND HOW IT TOOK ONE HUNDRED YEARS TO PROVE THAT COMTE WAS WRONG!

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Abstract: In 1835 the French philosopher Auguste Comte predicted that we would never know anything about the chemical composition of stars. This paper gives a broad overview of the development of stellar spectroscopy, especially from about 1860. Developments in stellar spectroscopy segregated quite clearly into three main fields of endeavour: spectral classification, radial velocities and spectral analysis. This paper concentrates mainly on spectral analysis, or how stellar spectroscopy one hundred years after Comte showed that quantitative information on the composition of stars was possible. The journey was quite arduous, as it required numerous developments in theoretical physics and in laboratory spectroscopy, which in turn allowed stellar spectral analysis successfully to be undertaken by the mid-twentieth century.

The key developments in physics that first had to be understood were in quantum and atomic theory, ionization theory, the concept of the Planck function, local thermodynamic equilibrium, the first stellar model atmospheres, line formation theory, turbulence, collisional broadening of spectral lines and the theory of radiative transfer and of the curve of growth. The close links between stellar spectroscopy and theoretical physics will be emphasized. In addition laboratory physics, to measure line wavelengths and oscillator strengths, was also an essential precursor to quantitative data on the chemical composition of stars.

Comte may have been an influential philosopher of science in his time. Perhaps his one small transgression was not to have read the works of Joseph Fraunhofer, which in the early nineteenth century already contained the first small clues that Comte's assertion might be wrong.

Keywords: Auguste Comte, spectroscopy, stellar composition, stellar abundances, Gustav Kirchhoff, Robert Bunsen, stellar evolution, curve of growth, radiative transfer.

1 INTRODUCTION

The French philosopher, Auguste Comte (Figure 1), in his *Cours de Philosophie Positive* in 1835 wrote in relation to the stars (all translations by the author):

Figure 1: Auguste Comte, 1798–1857.

> We understand the possibility of determining their shapes, their distances, their sizes and their movements; whereas we would never know how to study by any means their chemical composition, or their mineralogical structure, and, even more so, the nature of any organized beings that might live on their surface (Comte, 1835).

And further on:

> I persist in the opinion that every notion of the true mean temperatures of the stars will necessarily always be concealed from us.

This passage from Comte has been much quoted in the astronomical literature, especially by astronomers happy to ridicule Comte for his apparently misguided prophecy, yet ignorant of his enlightened epistemology concerning scientific method.

Nevertheless, Comte did make a mistake, and this paper analyses both why he got his prophecy wrong, and why it took essentially a century after Comte before quantitative data on stellar chemical composition became available.

The first astronomer seriously to study stellar spectra was Joseph Fraunhofer (Figure 2), who in 1814 and 1823 studied the line spectra of the Sun and of a few bright stars (Fraunhofer, 1817; 1823). In these papers, Fraunhofer labelled the most prominent lines in the solar spectrum with letters of the Roman alphabet (see Figure 1 in Pasachoff and Suer, 2010: 120), he measured some solar line wavelengths using an objective grating, and he showed that the spectra of Betelgeuse, Sirius and Venus differ among themselves, even though some lines (such as D, b) were common to all sources.

Evidently Comte had not read these seminal papers of Fraunhofer, which (in hindsight) already contained the first small clues that Comte's assertion might be wrong.

2 KIRCHHOFF AND BUNSEN, PIONEERS IN SOLAR SPECTRAL ANALYSIS

Following Fraunhofer's pioneering investigations in the early nineteenth century, many workers explored the spectra of sparks and flames in the laboratory, notable among them being William Henry Fox Talbot (1800–1877) and John Herschel (1792–1871). Their work culminated in the research by Gustav Kirchhoff (Figure 3) and Robert Bunsen (1811–1899) in Heidelberg, who in 1860 published a study of the emission line spectra of many chemical elements (Kirchhoff and Bunsen, 1860). Already, in 1859, Kirchhoff had deduced the presence of sodium in the Sun from the coincidence of the D lines in absorption with the bright lines observed in the laboratory, an observation made earlier by Léon Foucault (1819–1868) in 1849 (Foucault, 1849). Kirchhoff and Bunsen (1860) surmised that the way was now open for the qualitative analysis of the Sun and stars.

Kirchhoff then embarked on a large project to draw a detailed map of the solar spectrum showing hundreds of absorption lines (Figure 4). He used the map to deduce the presence of Fe, Ca, Mg, Na, Ni and Cr in the outer layers of the Sun, and the possible presence of Co, Ba, Cu and Zn (Kirchhoff, 1861; 1863). Less than three decades after Comte made his assertion, it was already shown to be incorrect, at least for the Sun. But the results for the solar spectrum were no more than qualitative and there was no theoretical understanding of how the absorption lines were formed.

3 THE REBIRTH OF STELLAR SPECTROSCOPY IN THE 1860s

It is at first surprising that nearly four decades after the pioneering work of Fraunhofer, suddenly at least five astronomers made observations of the visual spectra of the stars in the early 1860s. On the other hand, Kirchhoff and Bunsen had done the groundwork to make this next step—the application of spectroscopy to stars, in the same way as Kirchhoff had done for the Sun—a natural one to undertake.

The first person to embark on observing stellar spectra in the 1860s was Giovanni Donati (1826–1873) in Florence. He used a single prism spectroscope on his 41-cm refractor (Figure 5) and he described the spectra of 15 bright stars (Donati, 1862). But by far the most productive observers were William Huggins (1824–1910) in London (assisted at first by William Miller (1817–1870)) and Angelo Secchi (1818–1878) in Rome. Lewis Rutherfurd (1816–1892) in New York also undertook stellar spectroscopy from this time. All these observers commenced their work in late 1862. At the same time, the British Astronomer Royal, George Biddell Airy (1801–1892), initiated a spectroscopy programme at Greenwich.

Lewis Rutherfurd (1863) was the first astronomer to attempt to classify stellar spectra. He recognized three main classes. He was also the first after Donati to publish his results. His classification was soon eclipsed by that of Secchi, who initially defined two classes (Secchi, 1863), which were later extended to three classes (Secchi, 1866) and then four (Secchi, 1868). His classes were

Figure 2: Joseph Fraunhofer, 1787–1826.

I: white or blue stars, with spectra similar to Sirius;
II: solar-type spectra;
III: red stars with bands, such as α Orionis;
IV: carbon stars.

Figure 3: Gustav Kirchhoff, 1824–1887 (courtesy: Smithsonian Institution).

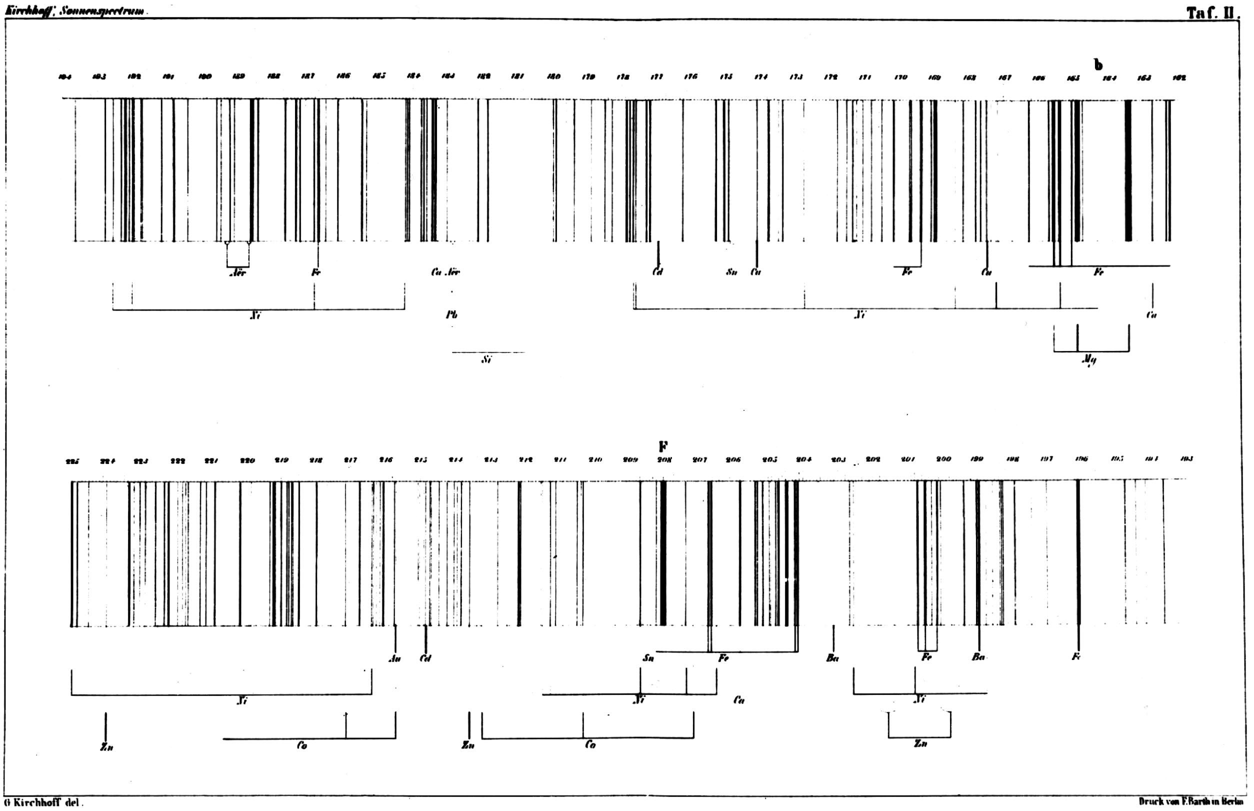

Figure 4: Part of Kirchhoff's drawing of the solar spectrum (after Kirchhoff, 1863).

The work of Huggins and Miller (1864a) focussed on line identifications in stellar spectra, using a two-prism spectroscope on the 8-inch refractor at Huggins' private observatory at Tulse Hill (see Becker, 2010). By 1864 they published descriptions of the spectra of some 50 stars, and compared the observed line positions with those recorded from laboratory sources. This work in qualitative spectral analysis thus continued the observations of Kirchhoff and Bunsen for the Sun, but now applied to the stars. For Aldeberan, 70 line positions were recorded and the presence of the elements sodium, magnesium, hydrogen, calcium, iron, bismuth, thallium, antimony and mercury in this star was reported, though evidently the last four of these were based on incorrect line identifications.

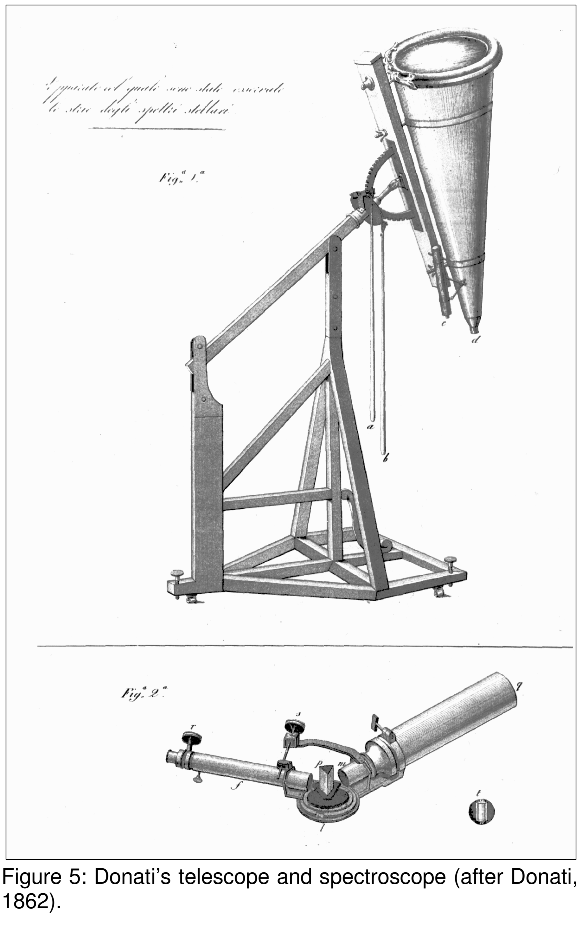

Figure 5: Donati's telescope and spectroscope (after Donati, 1862).

In 1864 Huggins and Miller (1864b) also turned their attention to the nebulae, and showed that objects such as the Great Nebula in Orion had an emission-line spectrum, quite dissimilar to the spectra of the stars. They suggested that these nebulae must consist of great clouds of hot nebulous gas which would never be resolvable into stars.

As for Airy, he directed the programme of observations carried out by members of his staff at Greenwich. Initially drawings of some stellar spectra were published (Airy, 1863). Later this developed into a programme that attempted visually to measure Doppler shifts, but without any significant success.

4 THREE BRANCHES OF STELLAR SPECTROSCOPY

From the 1860s and for almost the next century, research into stellar spectroscopy was rather clearly demarcated into three separate branches, namely spectral classification, stellar radial velocity determinations and spectral analysis. All three branches benefitted enormously from the introduction of the dry emulsion photographic plates into astronomy. The first successful experiments in stellar spectrum photography were by Henry Draper (1837–1882) at his Hastings-on-Hudson observatory in New York (Draper, 1879) in 1872, followed by William Huggins (1877) in 1876. In both cases, ultraviolet-transmitting spectrographs (quartz or Iceland Spar optics) and reflecting telescopes with silvered mirrors were used.

Stellar classification using objective prism spectrography advanced greatly with the work of Edward C. Pickering (1846–1919) at Harvard College Observatory from 1885. His initial trials were with an 8-inch astrograph known as the Bache telescope, which was equipped with a 13-degree objective prism. Huge classification programmes were undertaken at Harvard for the next 40 years, culminating in the *Henry Draper Catalogue* and its extension.

As for radial-velocity work, this became one of the most popular branches of the new astrophysics by the turn of the century. The early pioneers included Hermann Carl Vogel (1841–1907), the Director of the newly-established Potsdam Astrophysical Observatory, working with Julius Scheiner (1858–1913). From 1888 they perfected the techniques of photographic spectroscopy to determine Doppler shifts, by comparing the position of the Hγ absorption line in the spectra of the stars with the same line seen in emission from a hydrogen-filled Geissler discharge tube, which was mounted in the telescope. The plates were subsequently measured in a travelling microscope. A classical paper presenting the results for 51 stars followed in 1892 (Vogel, 1892). A light-weight two-prism slit spectrograph was used on the 30-cm Schröder refractor.

5 EARLY PROGRESS IN SPECTRAL ANALYSIS

Whereas spectral classification and radial-velocity determinations were both well established as important branches of stellar astrophysics by the turn of the century, the same cannot be said of spectral analysis. William Huggins had by 1864 shown that some of the common elements, whose spectra he observed in the laboratory, were also present in the stars and in gaseous nebulae. By 1867 the French astronomers Charles Wolf (1827–1918) and Georges Rayet (1839–1906) had discovered the emission line stars named after them (Wolf and Rayet, 1867), but the identification of the bright bands eluded them. Henry Draper and William Huggins had extended the observed spectra of bright stars into the near ultraviolet using photography, and they recorded the series limit of the Balmer lines. The element helium[1] was first found by J. Norman Lockyer (1836–1920) in the solar chromosphere in 1868, and by 1895 both Lockyer (1895) and Vogel (1895) had recorded this element in the spectra of blue stars of Vogel's class Ib (essentially B stars on the MK system). As early as 1868 Secchi had correctly identified carbon in his class IV stars, and other observers, including T.H.E.C. Espin (1858–1934), N.C. Dunér (1834–1914), C.F. Pechüle (1843–1914) and N. von Konkoly (1842–1916), greatly extended the number of these objects known. However, not all claims of element identifications in stellar spectra were reliable: thus Henry Draper (1877) photographed the ultraviolet solar spectrum and claimed to find oxygen lines in emission, a result soon discredited by Lockyer (1878).

This era in spectral analysis of the late nineteenth century was summed up by William Huggins in 1909, when he described his own early researches:

> One important object of this original spectroscopic investigation of the light of the stars and other celestial bodies, namely to discover whether the same chemical elements as those of our Earth are present throughout the universe, was most satisfactorily settled in the affirmative … A common chemistry, it was shown, exists throughout the universe. (Huggins and Huggins, 1909: 49).

In spite of these successes by Huggins and others, real progress in spectral analysis was stalled for about half a century from the rebirth of stellar spectroscopy in the 1860s. Ultimately the goal was to be able to interpret the lines observed in stellar spectra, including line strengths and even line profiles, so as to obtain quantitative information on the chemical composition and other physical parameters of stars. But progress required the theory of line formation, knowledge of stellar atmospheres, ionization theory, atomic theory, oscillator strengths and the ability to measure equivalent widths from high resolution spectra. To achieve all this and go on to make quantitative analyses of element abundances in stars took 100 years from Comte, and occurred about 75 years after Huggins' early work.

6 SOME NECESSARY DEVELOPMENTS IN THEORETICAL, LABORATORY AND INSTRUMENTAL PHYSICS

In hindsight, it is clear that developments had to occur in three separate areas before the deadlock that was holding up progress in spectral analysis could be resolved. These three areas were in theoretical physics, especially in atomic theory; in laboratory physics to measure such quantities as element wavelengths and oscillator strengths; and finally in astronomical instrumentation technology (see Stanley, 2010). The two big developments in the first few decades of the twentieth century were in high-resolution coudé spectrographs, especially those using blazed diffraction gratings and Schmidt cameras, and the recording microdensitometer, which converted a photographic plate of a stellar spectrum into a strip-chart record amenable for direct measurement of the lines.

Table 1 lists some of the essential developments within each of these three categories.

7 LOCKYER'S METEORITIC HYPOTHESIS

In 1887 Lockyer (1887; 1890) devised his so-called meteoritic hypothesis, in which star formation was presumed to occur from colliding streams of interstellar meteorites. The youngest stars were cool (such as Antares), but coalescence and contraction led to hotter stars such as Sirius or Vega. The next stage was the cooling of the stars after they reach a maximum temperature to the final stage of cool carbon stars, such as 19 Piscium (Figure 6).

Lockyer claimed to be able to distinguish between the ascending temperature branch and the descending branch spectroscopically, using selected lines he described as enhanced. The enhanced lines appeared stronger in the ascending branch of stars we now recognize as supergiants, and he theorized that they arose from the dissociation of elements into 'proto-elements' at high temperature and luminosity. In practice they are lines of ionized species which are stronger in stars of low gravity.

Table 1: Essential developments in physical theory, laboratory physics and astronomical instrumentation as precursors to progress in stellar spectral analysis.

Physical Theory	Laboratory physics	Instrumentation
Excitation theory (Boltzmann, 1871)	He I spectrum studied in lab (Ramsay, 1895)	Photographic dry plates in spectroscopy (Huggins, 1877; Draper, 1879)
Discovery of the electron (Thomson, 1897)	Line identifications: for the Sun: Rowland (1895-1897); Moore, Minnaert and Houtgast (1965); for stars: many workers, including Dunham (1929), Hacker (1935), and Davis (1939; 1947).	Blazed gratings (Wood, 1910; Adams and Dunham, 1938)
Planck's theory of black body radiation (Planck, 1900)	Study of atomic energy levels in the laboratory (Bowen, 1928)	Microdensitometer (Moll, 1920)
Radiative transfer (Schwarzschild, 1906)	Oscillator strengths (R. and A. King, 1935; Meggers, et al, 1961; Corliss and Bozman, 1962; Bashkin and Meinel, 1964)	Coudé spectrograph (Hamy, 1924; Adams, 1941; Dunham, 1934)
Line broadening theory (Voigt, 1912; Weisskopf, 1932; Lindholm, 1942)	Calibration of standard lamps for star colours (Kienle, et al., 1938)	Schmidt cameras (Schmidt, 1932; Dunham, 1934)
Ionization theory (Saha, 1920)		
Concept of LTE (Fowler and Milne, 1923)		
Model atmospheres (Eddington, 1926—grey atmosphere; McCrea, 1931; Strömgren, 1940)		
Curve of growth (Minnaert and Mulders, 1930; Schütz, 1930)		
H^- ion (Wildt, 1939)		

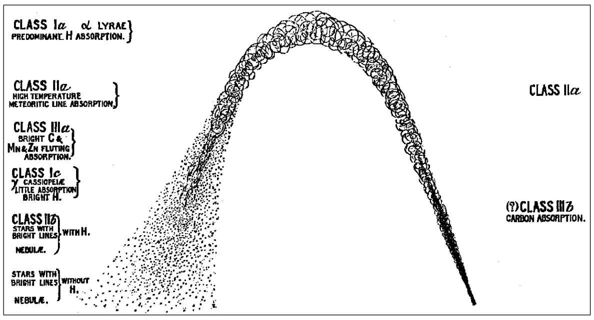

Figure 6: Lockyer's temperature curve for stellar spectral evolution (after Lockyer, 1887: 144).

Although Lockyer's ideas on stellar evolution never gained wide acceptance, his insights into the 'enhanced' lines predated the more rigorous ideas of ionization, based on the physics of an equilibrium reaction of Meghnad Saha (Figure 7). His ideas were also a forerunner to the sharp-lined c-stars defined by Antonia Maury (1864–1952) at Harvard (Maury and Pickering, 1897), which Ejnar Hertzsprung (1873–1967) showed to be stars of high luminosity (1909). Luminosity effects in stellar spectra were exploited by Walter S. Adams (1874–1956) and Arnold Kohlschütter (1883–1969) (but without reference to the work of Hertzsprung or Lockyer) to obtain spectroscopic parallaxes (Adams and Kohlschütter, 1914).

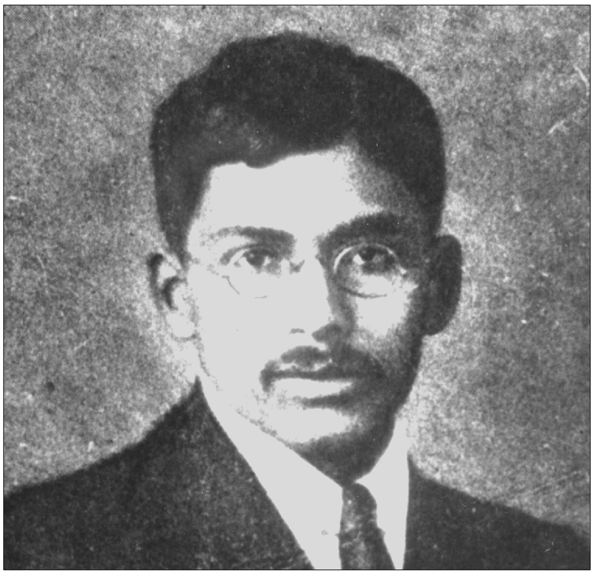

Figure 7: Meghnad Saha, 1894–1956 (after Sen, 1954).

8 THE STELLAR TEMPERATURE SCALE AND SAHA'S IONIZATION THEORY

The first attempts to measure stellar temperatures came from the visual spectrophotometry of Johannes Wilsing (1856–1943) and Julius Scheiner at Potsdam (1909). They used five filter pass-bands to compare the brightness of stars with the energy distribution of a standard lamp, which was in turn calibrated using a black-body source. Hans Rosenberg (1879–1940) in Tübingen developed the technique of photographic spectrophotometry for comparing stellar energy distributions to those of black bodies (1914). A sequence of stellar temperatures thus resulted which placed stars in their correct order and showed a good correlation with spectral type, but the temperatures showed large systematic errors, because of the departures of the energy distributions of real stars from Planckian black-body curves.

Saha's (1920) ionization theory, when applied to the Harvard sequence of spectral types using the marginal appearance of different lines in stellar spectra, also gave a temperature sequence (Saha, 1921). The theory was developed further by Ralph H. Fowler (1889–1944) and E. Arthur Milne (1896–1950) (1923), explicitly taking into account the combined effects of ionization and excitation to deduce a more reliable temperature scale, and they also made the first determinations of electron pressures in stellar atmospheres. The electron pressures also clearly showed the difference between dwarfs and giants (Fowler and Milne, 1924; Milne, 1928). Thus, in the interval of less than a quarter of a century, the early work of Lockyer on enhanced lines and of Maury on c-type stellar spectra received a satisfactory explanation through Saha's ionization theory.

9 CECILIA PAYNE AND STELLAR CHEMICAL COMPOSITION

Ionization theory was the basis for a major study by Cecilia Payne (Figure 8) in her 1925 Ph.D. thesis at Harvard on stellar atmospheric element abundances using Harvard objective prism spectrograms. The results were published as a Harvard monograph titled *Stellar Atmospheres* (Payne, 1925), which was based on her thesis. According to Otto Struve, this was the most brilliant Ph.D. thesis yet written in astronomy (see Struve and Zebergs, 1962: 220).

In this work, Payne obtained ionization temperatures from the marginal appearance of selected spectral lines. In addition, she demonstrated low pressures for the Maury c-type stars (supergiants), as had been done earlier by Fowler and Milne. Her greatest achievement was to estimate the relative logarithmic abundances for 18 elements in the atmospheres of the stars studied. She demonstrated a general uniformity of chemical composition for stars of different spectral type, and also she demonstrated the preponderance of the light elements H and He. This latter result she herself doubted, possibly on the advice of Russell who reviewed her work (see DeVorkin, 2010).

Given the still rudimentary state of the understanding of atmospheric theory and the physics of line formation in the 1920s, it is remarkable that Payne made such striking progress in her interpretation of the Harvard spectra. The results nevertheless had much uncertainty, in part because the hydrogen abundance came from highly saturated Balmer lines, and not from the continuous opacity.

10 RUSSELL AND ADAMS AND STELLAR COMPOSITION

In the 1890s Henry Rowland (1848–1901) at Johns Hopkins University produced his much-used *Preliminary Table of Solar Spectrum Wavelengths* (Rowland, 1895-1897). In this catalogue of solar lines he gave wavelengths and identifications as well as so-called Rowland 'intensities' (R) on an arbitrary scale and based on visual estimates.

Russell, Adams and Charlotte E. Moore (1898–1990) calibrated the Rowland intensity scale in terms of the relative number of atoms in the Sun's reversing layer, using lines in the same atomic multiplet (with the same L and S quantum numbers in upper and lower states) (Russell, Adams and Moore, 1928). For example, a change in Rowland intensity from $R = -3$ to 40 implied $\Delta\log N \approx +6$. This calibration required invoking the new quantum mechanics of atomic structure, as developed by Ernest Rutherford (1871–1937) in 1911, Niels Bohr (1885–1962) in 1913, Arnold Sommerfeld (1868–1951) in 1919 and Erwin Schrödinger (1887–1961) in 1926.

Russell and Adams next used the calibration of the Rowland scale to analyse spectra of seven stars: α Ori, α Sco, α Boö, α Cyg, α Per, α CMi and α CMa. Spectral types ranged from A to M, and the first five evolved away from the main sequence. They studied 14 atoms or ions and obtained the relative abundances of line absorbers in reversing layers. The analysis was based on the reversing layer model of Arthur Schuster (1851–1934) (Schuster, 1902, 1905) and Karl Schwarzschild (1873–1916) (Schwarzschild, 1914), in which the line absorbers were concentrated in a thin layer above the photosphere. Large differences were found from star to star; thus the supergiants (α Ori, α Sco) had 100 times as much absorbing vapour in the reversing layer as the Sun, whereas Sirius had 100 times less. The electron pressures were 10^{-8} of the solar value for the supergiants but 200 times solar for the A-dwarf, Sirius, as deduced by the application of Saha's equation to elements that appeared in two ionization states (i.e. Fe, Sc and Ti).

This work represented the first analysis of stellar spectra using the stronger saturated lines. Cecilia Payne had relied entirely on the weakest lines of marginal appearance. Nevertheless, the analysis was limited to comparing the handful of lines within any given multiplet, so its scope was still quite restricted.

11 SOME INSTRUMENTAL DEVELOPMENTS: BLAZED GRATINGS, COUDÉ SPECTROGRAPHS AND MICRODENSITOMETERS

Important instrumental developments in the 1920s and 1930s permitted major advances in the ability to record the spectra of bright stars in great detail, with resolving powers of several times 10^4 and reciprocal dispersions in the range of about 2 to 8 Å/mm. The key developments were the construction of large stable coudé spectrographs, especially those with large format blazed-plane diffraction gratings and Schmidt camera optics (Schmidt, 1932), and the technology of producing a graphical strip chart record of a photographic spectrum, especially one with the non-linear photographic response taken into account so as to produce a record calibrated in intensity.

Figure 8: Cecilia Payne (later -Gaposchkin), 1900–1979 (AIP Emilio Segre Visual Archives, *Physics Today* Collection).

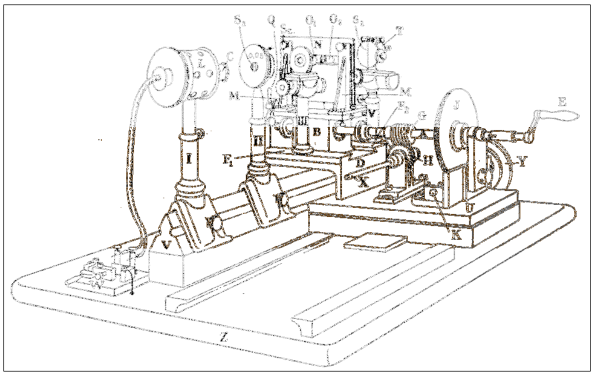

Figure 9: The first registering microdensitometer by W.J.H. Moll (after Moll, 1920).

The first coudé spectrograph was developed by Maurice Loewy (1833–1907) in 1907 at the Paris Observatory (see Hamy, 1924). But it was Walter Adams (1911; 1941) at Mt Wilson who built spectrographs with high resolving power and dispersion, first for the 60-inch telescope and later for the 100-inch. Together with Theodore Dunham, Jr (1897–1984) (1934; 1956), the key developments he introduced were the use of Wood blazed gratings instead of prisms and of Schmidt cameras instead of refracting systems that suffered from chromatic aberration.

The recording microdensitometer, developed by W.J.H. Moll (1876–1947) in 1920 at Utrecht (Figure 9), became the essential tool for producing graphical tracings from the photographic plates. A machine of this type was used by Marcel Minnaert (Figure 10) et al. to produce the *Utrecht Photometric Atlas of the Solar Spectrum* (1940), and many other instruments based on a similar principle were subsequently developed elsewhere, including by Robley C. Williams (1908–1995) and W. Albert Hiltner (1914–1991) (Williams and Hiltner, 1940) at Michigan, where they produced a *Photometric Atlas of Stellar Spectra* (Hiltner and Williams, 1946). Such graphical tracings allowed the direct measurement of spectral lines so as to obtain their strengths or equivalent widths, instead of mere visual estimates of their strength as recorded hitherto by Rowland and others.

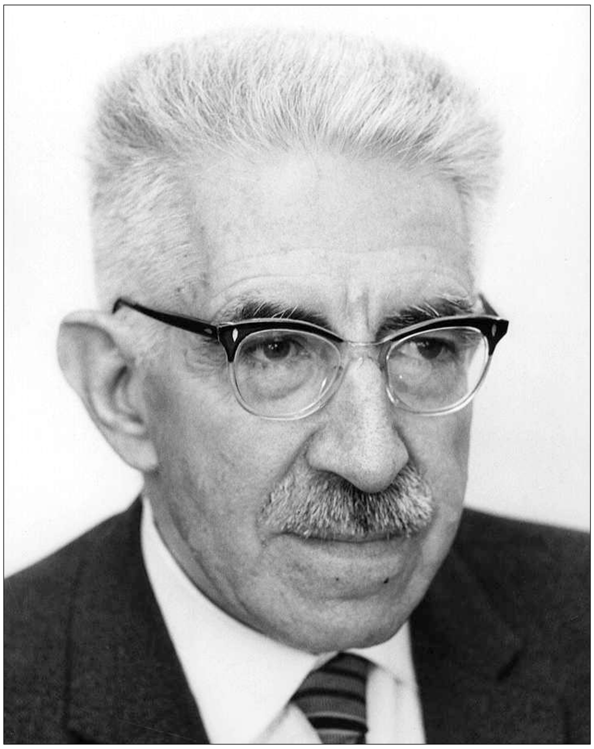

Figure 10: Marcel Minnaert, 1893–1970 (University of Utrecht).

12 UNSÖLD AND RUSSELL ON THE COMPOSITION OF THE SUN

By the late 1920s the way was open for a more detailed analysis of the solar spectrum, based on the Schuster-Schwarzschild reversing layer model, Russell's calibration of the Rowland scale and the comparison of lines within a multiplet using quantum theory. In 1928, Albrecht Unsöld (1905–1995; Figure 11) in Kiel (Germany) made a new analysis of a solar atmosphere in radiative equilibrium and showed that the electron pressure, P_e, was about 10^{-6} atmospheres; he also deduced the relative reversing layer abundances of the elements Na, Al, Ca, Sr and Ba (Ünsold, 1928).

Also in 1928, Charles E. St John (1857–1935) and colleagues (St John, et al., 1928) at Mt Wilson produced a revision of Rowland's great catalogue, but still with the line strengths recorded on Rowland's arbitrary scale. This was, however, the basis for Russell's new solar spectrum analysis in 1929. He derived the relative abundances for 56 elements and 6 diatomic molecules. The very high abundance of hydrogen, first suggested by Payne, was now confirmed. Russell also discovered a peak in the abundance of iron in a plot of logarithmic abundance against atomic number. The iron peak had $\log N_H/N_{Fe} = 4.3$. The irony is that Russell had discouraged Payne from publishing the high hydrogen abundance that she had found for stars in her doctoral thesis (see DeVorkin, 2010), and he suggested that she state that her result for hydrogen was "… almost certainly not real …"; now, just four years later, he proposed the same finding, and concluded that his results for the Sun were in reasonable accord with Payne's for giant stars.

13 SCHÜTZ AND MINNAERT AND THE CURVE OF GROWTH

In the 1920s, it was possible to compare the relative numbers of absorbers causing different lines in the same multiplet, but at this stage there was no way of comparing lines in different multiplets nor was there any knowledge of oscillator strengths, that would permit line opacities to be deduced. The next key step in the theory was the construction of the curve of growth, which linked the logarithm of line strengths (or equivalent widths) to the logarithm of the number density of absorbing atoms in a gas, such as in the reversing layer. This step was first taken theoretically by Wilhelm Schütz (1900–1972) in Munich (1930), and then followed up by Marcel Minnaert and his students in Utrecht, when they constructed an empirical curve of growth for the Sun based on equivalent width measurements instead of the old Rowland line intensity scale (Minnaert and Mulders, 1930). For lines in each multiplet, Minnaert found that a small segment of the curve was plotted; by shifting these segments horizontally, he in effect calibrated the relative strengths of the lines in different multiplets to produce a single curve of growth for the Sun.

The square root dependence of the strongest line strengths on abundance was demonstrated at this time, and the less sensitive dependence ($W \propto N^{0.31}$) of the intermediate strength saturated lines was also found. Unsöld, Otto Struve (1897–1963) and Christian T. Elvey (1899–1970), the latter two at Yerkes Observatory, applied the new theory to interstellar lines (Unsöld, et al, 1930), and Antonie Pannekoek (1873–1960) in Amsterdam applied the curve of growth to α Cyg, in order to study the damping constant for the strongest lines in this supergiant star (Pannekoek, 1931).

14 THE CONTINUOUS OPACITY PROBLEM AND THE ELUSIVE H^- ION DISCOVERED BY WILDT

The issue of the hydrogen-content of stars was crucial to understanding the source of continuous opacity in stellar atmospheres, which in turn was necessary to construct solar and stellar models and to interpret line strengths in the spectra of the Sun and stars. In 1934 Unsöld, believing the main solar opacity came from the photo-ionization of metals, rejected the H^--rich atmospheres found by Payne and Russell. He instead proposed a solar model in which the hydrogen-to-metals ratio was about 14:1. Unfortunately this gave a poor fit to the overall solar energy distribution, which was shown by G.F.W. Mulders (1936) to require an opacity source roughly constant with wavelength.

No opacity source was known in the mid-1930s which fulfilled these requirements, and this proved to be a major obstacle to any further progress in understanding the strengths of spectral lines. A breakthrough came in 1939, when Rupert Wildt (1905–1976) at Princeton proposed the H^- ion as the likely source of the missing opacity and that this ion was stable at solar temperatures. The existence of the ion with two bound electrons had been known for about a decade, but it had never hitherto been proposed as a source of opacity in the Sun and other late-type stars. With an ionization energy of just 0.74 eV and only one stable bound state, this was an ideal species for absorbing photons over a wide range in wavelength with $\lambda < 1.6$ μm, provided the high hydrogen abundance proposed by Payne and Russell was correct. Beyond that wavelength limit in the infrared, the H^- ion was still useful through free-free absorptions. S. Chandrasekhar (1910–1995) in 1944 calculated the photo-ionization cross-section of H^- as a function of wavelength, and the results gave a good fit to the missing opacity source for the solar photosphere. Moreover, they also explained the small Balmer discontinuity for solar-type stars, as H^- dominated over neutral atomic H opacity.

The H^- ion caused a complete revolution in our understanding of the spectra of late-type stars (types F5 to K). Unsöld's influential book, *Physik der Sternatmosphären*, which first appeared in 1938 just before the discovery of the H^- ion, had to be completely rewritten for its second edition of 1955 to take both H^- and the high hydrogen abundance into account.

15 THE FIRST MODEL ATMOSPHERES BY McCREA AND STRÖMGREN

In 1931 the problem of the continuous opacity in the solar photosphere was highlighted by William McCrea (1904–1999) when he was the first to calculate non-grey models for stellar atmospheres based upon atomic hydrogen photo-ionization and also free electron scattering as the sole opacity sources (Figure 12). The highly wavelength-dependent opacity of hydrogen atoms gave an extremely poor fit for the Sun's energy distribution, but the theoretical results were reasonable fits for the observed energy distributions of A- and B-type stars. In fact, grey atmospheres at 6000 K gave a much better agreement for the Sun than any of McCrea's models based on atomic hydrogen opacity.

Figure 11: Albrecht Unsöld, 1905–1995.

This situation changed immediately after Wildt's discovery of the H^- opacity. In 1940 Bengt Strömgren (1908–1987) calculated a solar model atmosphere based on the H^- opacity (Strömgren, 1940). His analysis

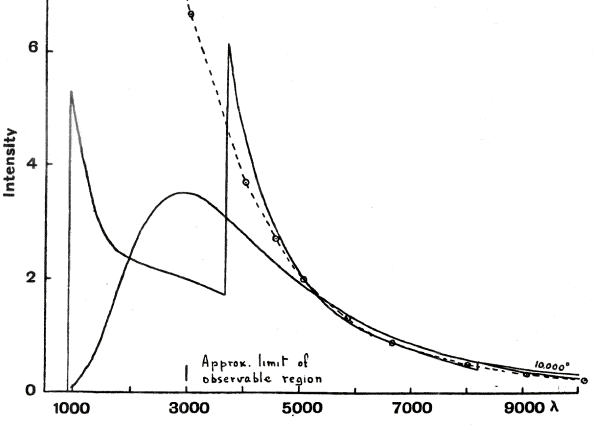

Figure 12: The first model atmosphere fluxes calculated by W.H. McCrea. The results for a pure hydrogen atmosphere at 10000 K are compared with black-body curves at 10000 K and 15000 K (after McCrea, 1931).

of the solar spectrum used $T_{\mathrm{eff}} = 5740$ K, log $g = 4.44$ (cgs units) and a hydrogen-to-metals ratio ranging from 1000 to 16,000. Strömgren showed that the equivalent width of a weak line was proportional to the ratio of the line opacity to the continuous opacity, and hence to the ratio of the number density of metallic absorbers to hydrogen (given that the continuous opacity was dominated by hydrogen in one form or another). For the first time absolute solar curves of growth could be calculated, which allowed the conversion of equivalent widths into metal-to-hydrogen ratios.

In 1944 Strömgren 'computed' a grid of models for A5 to G0 stars using H and H^{-} for the opacity. These gave the first reliable flux gradients and Balmer jumps for the Sun and also for the later A- and F-type stars.

16 UNDERSTANDING THE VOIGT PROFILE AND MICROTURBULENCE

The Voigt profile for the line opacity function had been introduced by the German physicist Woldemar Voigt (1850–1919) as a convolution of Doppler and Lorentz profiles (Voigt, 1912). The Doppler component came from the thermal distribution of particle velocities in a gas, while the Lorentz component was shown to be the opacity function for a damped harmonic wave train as would be found by radiative damping. The Voigt function was therefore a hybrid profile for the line opacity that could be applied in the case of line absorptions in stellar atmospheres. It was this profile that enabled Schütz (1930) to calculate a theoretical curve of growth for spectral lines.

The Voigt profile for the line opacity function was applied by Struve and Elvey (1934) at Yerkes, when they analysed the spectra of six stars, including the supergiants 17 Lep, ε Aur and α Per. The line strengths depended on the Doppler velocity, but they found that much higher Doppler velocities for the supergiants were needed than predicted by thermal Doppler broadening alone. Thus they introduced the concept of turbulence to provide an additional Doppler broadening on a scale that was small compared to the photon mean free path (since described as microturbulence). High microturbulent velocities were found for the supergiants (e.g. 20 km/s for ε Aur). This has become a standard technique in stellar spectral analysis since that time; whatever the exact cause of microturbulence, it is generally required to explain the Doppler broadening of all stars, even of dwarfs, where microturbulent velocities of around 1 km/s are commonplace.

17 THE UTRECHT SOLAR ATLAS AND SOLAR CURVES OF GROWTH BY ALLEN AND WRIGHT

In 1940 Marcel Minnaert and his colleagues G.F.W. Mulders and Jacob Houtgast in Utrecht completed their major work, the *Photometric Atlas of the Solar Spectrum, from λ3612 to λ8771 …* (Minnaert et al., 1940). The photographic plates had been recorded at Mt Wilson in 1936 by Mulders, with a resolving power of 1.5×10^5, and they were traced on the Moll microdensitometer at Utrecht, which Houtgast had modified to give direct intensity recordings. The atlas had a huge influence on solar and stellar high resolution spectroscopy after World War II. The second revision of Rowland's tables was produced by Moore, Minnaert and Houtgast in 1965. This volume for the first time recorded the equivalent widths of some 24,000 solar lines, 73% of them with identifications.

Soon after the publication of the Utrecht atlas, Kenneth Wright (1911–2002) at the Dominion Astrophysical Observatory used the atlas to measure the equivalent widths of about 700 lines in the solar spectrum (Wright, 1944). He constructed one of the first solar curves of growth for Fe I and Ti I, using oscillator strengths from the measurements of Robert B. King (1908–1995) and Arthur S. King (1876–1956) (1935; 1938). It was one of the best curves of growth produced at that time, and enabled Wright to measure an excitation temperature of $T_{\mathrm{ex}}(\odot) = 4900 \pm 125$ K and a solar microturbulent velocity of $\xi = 0.9$ km/s from Fe I lines.

Wright's construction of the solar curve of growth superseded an earlier curve by Clabon W. Allen (1904–1987) in 1934. Allen had measured solar centre-of-disk equivalent widths from the solar spectrograph at Mt Stromlo in Australia and he constructed parts of the curve of growth for several elements, using the theoretical relative intensities of lines within a multiplet (Allen, 1934).

18 FOUR BASIC PREREQUISITES FOR STELLAR ABUNDANCE ANALYSIS

By the late 1940s, four basic requirements for good quantitative abundance analyses in the Sun and stars were now evident. First, good quality effective temperatures for stellar photospheres were essential. The great sensitivity of line strengths to a star's effective temperature emphasized the importance of a reliable temperature as a precursor to any abundance analysis. Thus a random error of ±100 K in a star's estimated effective temperature can produce an abundance error in (Fe/H) of about 50% by number.

The ability to measure good quality equivalent widths from calibrated intensity recordings generated from photographic spectrograms was the next essential requirement. Not only was the Utrecht *Photometric Atlas* highly influential, but also the atlas produced by Hiltner and Williams (1946) at Michigan for eight bright stars was another important step forward.

Thirdly, line lists for standard stars were very important so that as many lines as possible could be reliably identified. Several major spectral catalogues were produced. The *Second Revision of Rowland's Preliminary Table* by Moore, Minnaert and Houtgast (1965) provided the necessary data for the Sun. But other observers catalogued the lines in the spectra of stars of other spectral types. These included Dunham (1929) for the F5 supergiant, α Per; Struve and Dunham (1933) for the B0 dwarf, τ Sco; W.W. Morgan (1906–1994) for 13 A-type stars (1935); Sidney G. Hacker (1908–1983) for the K2 giant, Arcturus with 3883 lines (1935); John W. Swensson for Procyon (F5IV) with a catalogue of 3600 lines (1946); and Dorothy Davis (1913–1999) for Antares (M1Ib) (1939) and for β Peg (M2II-III) (Davis, 1947), the latter star having 10,000 lines in the catalogue.

A compendium that summarized much of the laboratory data on the spectral lines of the different elements was Charlotte Moore's (1933) *Multiplet Table of Astrophysical Interest*, with editions in 1935 and, after revision, in 1945. This became a standard reference for line identifications when analysing new stellar spectra (see Rubin, 2010).

Finally, an urgent need for oscillator strengths was evident from the late 1940s, once the essential techniques for quantitative element abundance determinations had been worked out by many people over the preceding two decades. More than anything, the glaring lack of reliable oscillator strengths was a major obstacle to rapid progress. Robert and Arthur King (1935) at Mt Wilson began an extensive programme of oscillator strength determinations using an electric furnace. But an even larger programme was initiated by William Meggers (1888–1966) et al. (1961) at the US National Bureau of Standards in the 1930s. After some 25 years about 39,000 lines of 70 elements had been measured. Charles Corliss (1919–2002) and William R. Bozman calibrated some 25,000 of these line measurements so as to obtain absolute oscillator strengths (Corliss and Bozman, 1962). These are just a few of the many programmes directed at improving the data on oscillator strengths in the literature. For ionized lines, the work of Stanley Bashkin (1923–2007) and Aden B. Meinel (b. 1922) using the technique of beam foil spectroscopy was also notable (Bashkin and Meinel, 1964).

19 A PIONEERING CURVE OF GROWTH ANALYSIS OF R CrB BY LOUIS BERMAN IN 1935

A pioneering curve of growth analysis of a hot carbon star, R CrB (spectral type cF7p), by Louis Berman (1903–1997) in 1935 is especially remarkable, both because it was an especially early exposition of the curve of growth technique for a star other than the Sun, and also because Berman analysed a very peculiar star with highly non-solar abundances.

Berman's data mainly came from Lick prismatic spectra, and he obtained equivalent widths for over 600 lines after producing microdensitometer tracings. He obtained an excitation temperature of 5300 K from the Fe I curve of growth, and then used this to deduce abundances of 24 elements, expressed as column densities in the reversing layer. His results showed that the star contains 69% carbon and 27% hydrogen (by the number of atoms, for those elements studied).

20 FOUR PIONEERS OF STELLAR ABUNDANCE ANALYSIS IN THE 1940s

By the 1940s the long process of preparing the ground for abundance analyses of stellar photospheres had been completed and the way was now open for all the theory, laboratory data and instrumentation to come together for the first analyses that could give a full picture of the chemical composition of stars. The four astronomers who made the early progress were Albrecht Unsöld, Jesse Greenstein (1909–2002), Lawrence W. Aller (1913–2003) and Kenneth O. Wright.

Unsöld developed the coarse analysis method analysis or 'Grobanalyse' in which the structure of the photosphere was ignored and replaced by mean values of temperature and pressure. He analysed just one star, the B0 dwarf τ Sco (Unsöld, 1942). He used spectra from the newly-commissioned coudé spectrograph on the McDonald Observatory 82-inch telescope.

Although this was the only star Unsöld analysed, he was the pioneer in understanding the theory of line formation in stellar atmospheres, and hence his work was tremendously influential and set the standard for others to follow. The τ Sco analysis was the first curve of growth analysis of any star except for Berman's work on R CrB and Allen's work on the Sun. Abundances for nine light elements (H, He, C, N, O, Ne, Mg, Al, Si) were obtained and these were found to be solar, in agreement with the results of Russell (1929) and Strömgren (1940) for the Sun. As Strömgren had explicitly included the H$^-$ in the Sun's continuous opacity, this agreement with a solar composition for τ Sco indirectly supported the role of H$^-$ for the main source of solar opacity, as Unsöld explicitly noted.

At Caltech, Jesse Greenstein developed the idea of the differential abundance analysis. This technique obtained the composition of a star relative to a standard star, and in Greenstein's (1942) case, the analysis was of Canopus (F0Ib) relative to the Sun (Figure 13). The differential technique meant that oscillator strengths for each line were not required, and this therefore avoided one of the major uncertainties that plagued absolute abundance work for any star.

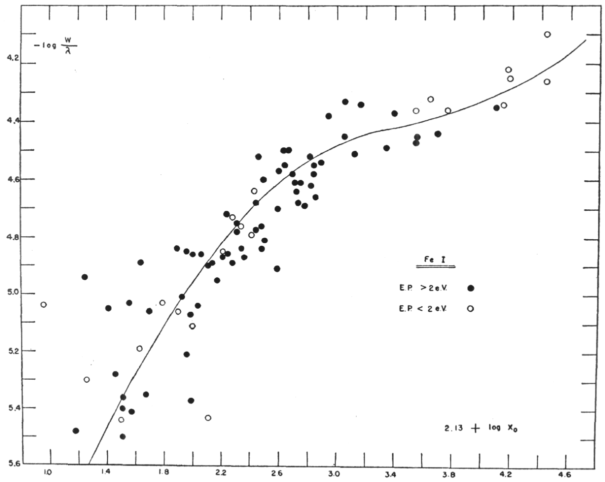

Figure 13: Greenstein's differential Fe I curve of growth for Canopus (after Greenstein, 1942: 186).

Although Greenstein's paper on Canopus did not take the analysis all the way to deducing differential element abundances, but only the degree of ionization, in 1948 he presented the results of the differential analysis of four further F-type stars (ρ Pup, θ UMa, Procyon and α Per), and also of the metallic-line star, τ UMa. Now the differential technique was developed to the logical conclusion of differential abundances (expressed as logarithmic values relative to the Sun (Greenstein, 1948).

Lawrence Aller was also developing spectral analysis techniques in the 1940s, and his main field of study was the A-type stars. His first paper in 1942 was on Sirius and γ Gem (Aller, 1942). This was a differential coarse analysis, similar to Greenstein's work on Canopus. He also analysed the O dwarf, 10 Lac (Aller, 1946) following the method of Unsöld for τ Sco. But his third paper, on γ Peg, introduced the method of fine analysis for a star, in which the temperature structure of the photosphere is taken into account (Aller, 1949). He used models whose temperature structure had been derived for grey opacities, following the procedure developed by Anne B. Underhill (1920–2003) in 1948. The absolute abundances of ten light elements (including C, N and O) were derived relative to hydrogen. The most abundant element of these three was oxygen, for which the fine analysis gave log (O/H) = –3.94.

The other notable spectral analysis pioneer of the 1940s was Kenneth Wright at the Dominion Astrophysical Observatory in Victoria, Canada. He analysed four stars: the F-type supergiants γ Cyg and α Per, the F-type dwarf Procyon, and the Sun. The observations came from the Cassegrain spectrograph on the DAO 72-inch reflector. The work was submitted for a Ph.D. thesis in 1940, but the full results were not published until 1947, being held up by the war. The initial work was an absolute coarse analysis based on the Schuster-Schwarzschild model. In 1946-1947, Wright (1948) reanalysed his data as differential analyses of three stars relative to the Sun. He derived logarithmic element-to-iron ratios relative to the Sun, but did not include hydrogen in the 21 elements surveyed.

Table 2: Some examples of stars with element abundance peculiarities from the mid-twentieth century.

^{12}C to ^{13}C ratio in evolved stars	McKellar (1947)
Discovery of weak lined stars	Roman (1950)
Analyses of halo stars with heavy element deficiencies	Schwarzschild & Schwarzschild (1950); Chamberlain and Aller (1951)
Technetium in red giant stars	Merrill (1952)
Rare earth abundances in Ap stars	Burbidge & Burbidge (1955)
Survey of lithium in stars	Bonsack (1959)
Abundance peculiarities in Am stars (high Fe-peak elements, low Ca, Sc)	van't Veer-Menneret (1963); Conti (1965)
^{3}He to ^{4}He ratio in 3 Cen A	Sargent and Jugaku (1961)
Holmium-rich star, HD101065	Przybylski (1963)
Barium stars	Warner (1965)

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Barium stars	Warner (1965)

Otto Struve (1950) summed up this very productive period in the 1940s when the foundations for spectral analysis were laid, roughly a century after Comte:

> Perhaps the most striking result … is the remarkable degree of uniformity that has been observed in the most widely different astronomical sources. The sun, the main sequence stars of type F and the He stars like tau Scorpii and even the O-type stars 10 Lacertae have all approximately the same composition … The first conclusion … is the establishment of a list of what we might call the normal abundances of the universe.

This statement is certainly reminiscent of that of Huggins (1909) when he described the early qualitative spectral analysis of the 1860s (see Section 5). In the intervening eight or nine decades, enormous advances in theoretical physics had been accomplished, as well as in instrumentation and laboratory physics. This had transformed spectral analysis from a descriptive science based on direct visual observation to a quantitative science based on photographic spectral recording and supported by the detailed physics of atomic quantum theory and of radiative transfer.

21 THE COSMIC ABUNDANCE DISTRIBUTION, BUT SOME STARS HAVE PECULIAR ABUNDANCES

The idea of a cosmic or normal abundance distribution of the elements to which Struve (1950) referred became the most notable achievement of stellar spectral analysis up until about 1950. But no sooner did a general principle appear to be emerging, than new data came to make the result seem less secure. Today we recognize many stars with unusual element abundances that do not follow the idea of a cosmic abundance distribution. Some of the most notable of these peculiar stars were found in the years of the mid-twentieth century. Table 2 lists some of the abundance peculiarities which were mainly discovered in the 1950s and 1960s.

22 BACK TO COMTE: SO WHY DID HE GET IT WRONG?

It is clear that Auguste Comte made a significant blunder in 1835, when he selected the chemical composition of stars as an example of knowledge we would never have. However, upon reflection, it seems like an excusable error. Evidently he believed the stars to be so far away (no observed parallax was published until 1838) that there appeared to be no possibility of ever going to the stars to carry out a chemical analysis or to measure their temperatures. Moreover, he did not conceive of making measurements at a distance using the message in the light.

Certainly Comte was not an astronomer, and perhaps he was just unlucky to pick an astronomical example to illustrate his argument in the *Philosophie Positive*, which was that "… every theory must be based upon observed facts … [and] facts cannot be observed without the guidance of some theories." So he was a pioneer of the scientific method based on empirical evidence.

Perhaps Comte's one small transgression was that evidently he was unaware of the papers of John Herschel, William Henry Fox Talbot and others on the spectral analysis of flames, and also of Fraunhofer on the spectra of the Sun and stars. In particular, Fraunhofer's papers contained the first small clues that just possibly Comte's assertion might be wrong.

23 NOTE

1. Although the D_3 line of helium at 5876 Å was observed by both Janssen (1869) and Lockyer

(1869) in the solar chromospheric spectrum, neither astronomer was at first convinced that this came from a new element. Lockyer suspected this, but did not publish this nor use the word 'helium' until after Ramsay's laboratory discovery of the gas in 1895. However, Lockyer and his colleague Frankland coined the word for their private use, as was confirmed later by Lockyer (1897). Lord Kelvin reported that Frankland and Lockyer had already proposed the name helium as early as 1871 when he wrote:

> Frankland and Lockyer find the yellow prominences to give a very decided bright line not far from D, but hitherto not identified with any terrestrial flame. It seems to indicate a new substance, which they propose to call Helium. (Thomson 1872).

A possible scenario is that Lockyer communicated this information to Lord Kelvin verbally, so it appeared in Kelvin's British Association Report for 1871. But they were reluctant to use the word in print until Ramsay had confirmed the D_3 line came from a new gas and popularized its name in 1895.

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