Chapter 2
What Stellar Classification Tells Us

2.1 Secchi. The First Steps

When Bunsen and Kirchoff observed the stars spectroscopically, they opened up a new field of observation, and stellar spectroscopy soon became a routine. What the astronomers discovered was a bewildering variety of stellar spectra, to the point of confusion and disarray. There was an urgent need for some order, for once order is established, theories about the evolution of stars, as well as their energy source, can be conceived and checked against observation. It was stellar classification that revealed to astrophysicists where the elements are synthesized and how stars evolve. However, it was not an easy ride.

These were the days of Darwin, Kelvin, and the debate that opposed the theory of evolution and the church, while Galileo's exploits had not yet been forgotten. Yet the church needed the stars. As a matter of fact, the Vatican Observatory is one of the oldest in the world. A major problem with the Julian calendar arose around 1500 AD. The Julian calendar, introduced by Julius Caesar in about 46 BC, was not sufficiently accurate, and accumulated about 10 days of deviation from the solar year over 15 centuries of use.[1] Pope Gregory XIII appealed to the Jesuit mathematicians and astronomers of the Roman College to solve the problem and fix the calendar. Using the Vatican's Tower of the Winds, which housed the Meridian

[1] The Julian calendar was devised to reproduce the tropical year, the time it takes the Earth to go around the Sun, which is 365.242 190 419 days long. The Julian calendar is based on 365 days divided into 12 months plus a leap day added to February every fourth year (provided one wants the day and the hour to be of fixed duration). Hence, the average Julian year is 365.25 days long. The small difference between the actual length and the average accumulates, and there is a need to shorten the average Julian year. This is corrected by skipping a leap year every 400 years. The difference is now 0.00781 $\sim$ 0.01 day per year. In 400 years there are 100 leap days and if one is omitted, it reduces the difference by 0.01 leaving 0.002190 of a day to be corrected. Since the adoption of the Gregorian calendar varied from country to country, astronomers use the Julian day number. For example, 1 January 2006 is Julian day 2 453 750.

G. Shaviv, *The Life of Stars*, DOI 10.1007/978-3-642-02088-9_2,

Hall,[2] these astronomers were able to propose the required correction to the Pope and generate the modern Gregorian calendar (completed 1582). They essentially adopted the proposal by the Italian physician Aloyius Lillus (circa 1510–1578). This was the moment the Pope recognized the power of astronomical research, and from this time on the church began to support it.

In the middle of the nineteenth century, our story encounters the Jesuit[3] Father Angelo Secchi (1818–1878m), who in another sense can also be called the father of stellar classification. This ground-breaking contribution by a priest induced Pope Leo XIII to establish the Vatican Observatory (Specola Vaticana) in 1891.

So what did Father Secchi do to deserve this honor? What he noticed was that some stars have many absorption lines in their visible spectra, while others have relatively few. Between 1863 and 1867, Secchi carried out a remarkable study of the spectra of some 4 000 stars,[4] using a visual spectroscope[5] on the telescope of the Roman College Observatory. He then sorted the stars into five groups, based on the number of absorption lines he could detect by eye. The use of photography for spectroscopy had not yet been invented. With these limitations Secchi defined five different classes of stars (see Table 2.1). A close examination of the classification reveals that:

- the Type V stars are very different from all other types, as they show emission lines and not absorption lines,
- there are two classes of red stars.

No physical explanation was given for the different classes, and neither was there an explanation for the two classes of red stars. Yet, following his scientific instincts, Secchi felt that the two groups of stars were different. It would take 40 years to clarify this observation, and to understand that the stars have a range of temperatures that correspond to the various lines seen in the spectra.

As Secchi was a scientist and a priest, it is of interest to quote some of his writings. For example, in 1856, he wrote:

> *It is with sweet sentiment that man thinks of these worlds without number, where each star is a sun which, as minister of the divine bounty, distributes life and goodness to the other innumerable beings, blessed by the hand of the Omnipotent.*

Did he intend to imply that there might be life around other stars? In 1858, Secchi observed the planet Mars and saw thin lines crossing the surface. He was the one who coined the term 'canali' to describe them. In the same period, Giovanni Vir-

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[2] The Meridian Hall was a room with a hole in the wall and a straight line on the floor. When the Sun crossed the meridian, it lit the hole, which cast a beam of light on the floor. The time the Sun crossed the meridian, i.e., noon, was thus determined.

[3] The Jesuit order, which also specializes in scholarship, runs the Vatican Observatory.

[4] Secchi, P.A., Catalogo delle stelle di cui si e determinato lo spettro luminoso all', Osservatorio del Collegio romano, Parigi, Per Gauthier-Villars, 1867, 32 pages, Compt. Rend. **63**, 626 (1866).

[5] The spectroscope, or prism, was attached to a telescope. Since there were no means for recording the spectra, such as photography, Secchi made his observations by eye.

Table 2.1 Father Secchi's stellar classification of 1866

Class	Properties	Prototypes	Color
Type I	Strong hydrogen lines	Sirius, Vega	White–blue
Type II	Numerous metallic lines (Na, Ca, Fe), weak hydrogen lines	Sun, Capella, Arcturus	Yellow–orange
Type III	Bands of lines which get darker towards the blue (TiO_2), and metallic lines as in Type II above	Betelgeuse, Antares	Red
Type IV	Bands that shade in the other direction. Faint stars, few visible to naked eye		Deep red
Type V	Bright emission lines, either in conjunction with, or instead of, absorption lines		

ginio Schiaparelli (1835–1910m) published detailed maps of the surface of Mars.[6] Imagine a priest being inspired by a fantastic story about dying life on a neighboring planet.

2.2 Huggins and Lockyer. Scientific Astrophysical Spectroscopy

Two key figures in stellar classification were Huggins and Lockyer, working in England during the latter part of the 19th century. They can be characterized as astronomers who combined spectroscopic experiments in the laboratory with detailed examinations of a relatively small number of stars, the aim being to discover the composition and physical conditions of those stars, rather then to explore a large number of stars and classify them into groups. However, before the contribution of these great astronomers can be discussed and understood, we should mention that all the identifications were carried out by comparisons. There were several attempts to standardize observations, for example, by Kirchoff, who published a spatial scale and a list of lines, but the general state of spectroscopy was really something of a mess. In 1868, Angstrom[7] (1814–1874m) suggested an absolute scale of wavelengths with a unit length of 10^{-10} meters. Later this unit was called the angstrom.

William Huggins (1824–1910m) was an amateur astronomer who built a private observatory in 1856, and devoted his time to spectroscopy. After his marriage in 1875 to Margaret (1848–1915) they published jointly some of the earliest spectra of astronomical objects. In 1864, William Huggins succeeded in matching some of the dark Fraunhofer lines in the spectra of several stars with terrestrial substances,

[6] Schiaparelli, G.V., *La Planete Mars*. See also Schiaparelli, G.V., *The Distribution of Land and Water on Mars*, PASP **5**, No. 31, 169 (1893).

[7] Angstrom, A.J., *Recherches sur le spectre solaire: le spectre normal du soleil*, Uppsale, 1868, p. 1.

demonstrating that stars are made of the same earthborne elements, rather than some kind of exotic substance. Huggins and Miller[8] tried to find an explanation for the fact that different stars have different colors, rejecting all the explanations proposed by Sestini,[9] and suggesting that the difference in composition of the atmosphere gives rise to the different colors. Recall that these were the days when Kelvin's hypothesis about the cooling liquid Sun still prevailed. So the authors assumed that all stars had liquid interiors, which emitted the same light. The core was assumed to be covered by an atmosphere, whose composition determined which part of the light would be absorbed and which would go through unimpeded, thereby creating the color of the star.

Huggins and Miller concluded that the differences between the stars were very small, and yet that these small differences were sufficient to give rise to the variation in color. They went on to argue that:

> *We may infer that the stars, while differing the one from the other in the kinds of matter of which they consist, are all constructed upon the same plan as our Sun, and are composed of matter identical, at least in part, with material of our system.*

This seems to be the first scientifically checked conclusion that elemental composition might be uniform throughout the universe. They also claimed that at least some of the laws of physics prevailing on Earth were valid in the stars, but they did not provide a proof. They went on to hypothesize the existence of solar systems like ours around similar stars. Their conclusion about possible life on other planets was of course stretching their scientific logic and evidence a bit too far.[10]

A correct stellar classification should be carried out without any prejudice or theory of stellar evolution. Lockyer was apparently an adamant follower of Kelvin and Helmholtz, although no reference was made to them in any of his many papers on the subject. According to Lockyer:

> *New stars, whether seen in connection with nebula or not, are produced by the clash of meteor swarms, the bright lines seen being low temperature lines of elements, the spectra of which are most brilliant at a low stage of heat.*

Lockyer published this theory for the first time in 1877,[11] and tried to explain all phenomena on the basis of this theory. He was not generally successful in his attempts. Consider, for example, the phenomenon of nova. A nova is a star that erupts suddenly, increasing in brightness by a prodigious amount, whereafter the light decays over a period of several months. Such a phenomenon disturbed Lockyer, as it did not fit in with the theory. He made attempts to resolve it,[12] but to no avail, and the arguments did not convince his contemporaries.

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[8] Huggins, W., & Miller, W.A., Phil. Trans. Roy. Soc. London **154**, 423 (1864).

[9] Benedict Sestini (1816–1890) was a Jesuit astronomer and mathematician who published a *Catalogue of Star Colors*, Memoirs of the Roman College (1845–1847).

[10] Note that Huggins and Lockyer could identify the existence of the same elements on the Earth and on the stars, but could not determine the relative abundances. There was still no theory that predicted how spectral lines form in a stellar atmosphere.

[11] Lockyer, N.J., Nature **16**, 413 (1877).

[12] Lockyer, N.J., Phil. Trans. Roy. Soc. London **182**, 397 (1891).

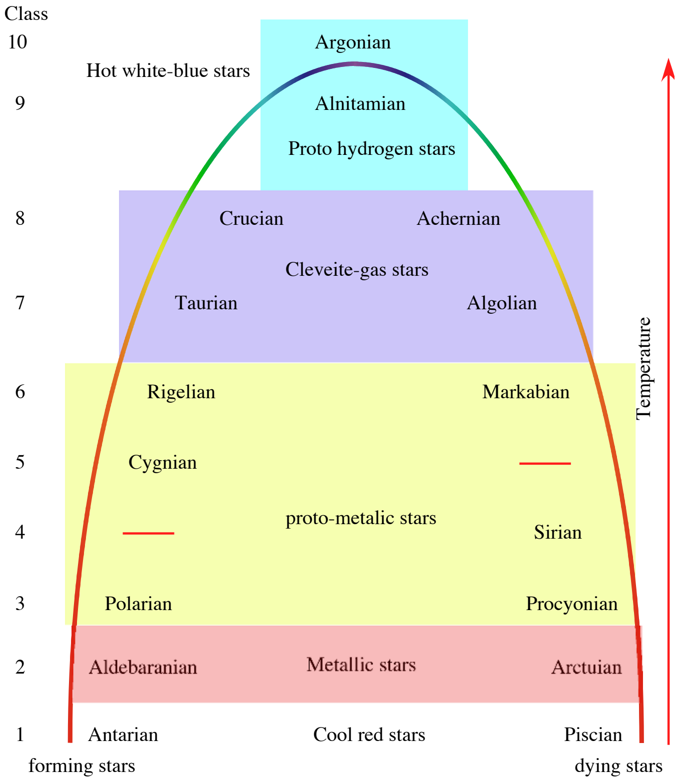

Fig. 2.1 Lockyer's chemical classification of stars (1899). Names refer to typical stars belonging to the relevant class. For example, Algolian implies a spectrum similar to the one found for Algol

Lockyer devised a stellar classification system around the idea that there are two sequences of stars: those that are heating up and those that are cooling down (see Fig. 2.1).[13] According to his meteoritic theory, the stars form cool on the left side of the diagram. They then heat up, and during the gradual heating process, they move through classes 1 to 10. When the stars reach a maximum temperature, they begin to cool off, dropping back down through the classes. As the temperature rises, the spectrum changes. At the beginning of a star's evolution, when its temperature is low, it is red, and appears to be made of metals. When the star reaches its maximum temperature, it exhibits mostly hydrogen, and when it cools down, it eventually disappears as a dead star. All stars experience the same evolution. Lockyer used the term 'proto' to indicate vapors (in contrast to liquids).

[13] Lockyer, N.J., Phil. Trans. **184**, 724 (1893), and a paper entitled *On the Chemical Classification of the Stars*, read before the Royal Society on 4 May 1899 [Proc. Roy. Soc. **65**, 186 (1899)].

But how did Lockyer decide which stars were increasing in temperature and which were decreasing? As a trained spectroscopist, Lockyer noticed the following: stars with the same color (and hence temperature) and consequently belonging to the same class, appeared to differ in the appearance of the hydrogen lines. Stars in the same spectral class could be divided into those with wide, medium, and narrow lines. Hence, Lockyer had to split the stars into two groups according to the shape of the hydrogen lines, and in this way he got two series of stars. Lockyer also noted that one series of stars showed bright lines (what we call emission lines today), while the other did not show such lines. How was he to interpret this situation? According to Lockyer, the stars formed by collisions of meteors. Most of the impacts would not be head-on, but grazing collisions (the meteors passing near one another and rubbing together). This type of collision would release gas, and it was this gas that was supposed to give rise to the bright spectral lines. This phenomenon helped Lockyer decide which of the two series corresponded to newly formed stars and which corresponded to cooling stars. In a way, these were Secchi's two types of stars, but in another form.

Clearly, Lockyer's scheme did not answer the question as to where the elements came from, or what their source might be. The question was never raised by Lockyer (or Huggins). The stars in this theory contain all the elements from the beginning, heat up, and then cool. As for the elements, they came with the birth of the star and were buried in the dying star. Nothing happened to those elements during the entire evolution of the star. Moreover, the problem of binary stars raised by Huggins and Miller was not addressed at all. A binary star system is a pair of stars which revolve around a mutual center of gravity. About 2/3 of all stars are binaries, so the phenomenon is rather widespread. Logic would say that the stars in a binary system were formed at the same time.[14] If so, the spectral class of the pair should be identical, whereas observations show that this is not the case in most binaries. Thus, instead of using the state of the observed binary stars as evidence against his picture, Lockyer argued that it was impossible for the two stars to have formed at the same time. And here lay an unresolved problem. Some twenty years were needed to solve the puzzle.

Helium, the second most abundant element in the universe was discovered in the Sun before it was found on Earth. Pierre-Jules César Janssen (1824–1907), a French astronomer, noticed a yellow line in the Sun's spectrum while studying a total solar eclipse in 1868.[15] Lockyer realized that this line, with a wavelength of 5 874.9 Å,

[14] If the stars were not formed at the same time, one star must capture the other. But the capturing of a star is very complicated, because the binary state means that the stars are bound together, and hence that their binding energy is negative, whereas two free stars would have positive energy. Consequently, for capture to take place, special mechanisms would be required to remove the positive initial energy and leave the system with negative energy. In summary, unless there is a third star around, or some kind of mechanism which dissipates the extra energy, it is difficult to work out a scenario for capture to take place.

[15] Janssen, M., Astronomical Register **7**, 107, 131 (1869). However, these reports on the eclipse do not contain a word about any new element. He discussed only the bright lines he saw from the protuberances on the surface of the Sun. The discovery was announced in Compt. Rend. **67**, 838 (1868).

could not be produced by any element known at that time. Since this yellow line was close to the famous sodium D lines, it was called the D_3 line.[16] Lockyer drafted in the well-known chemist Frankland (1825–1899)[17] to help with the identification of the mysterious line. The paper described how they mixed different gases but could not reproduce the D_3 line. Lockyer hypothesized, therefore, that a new element on the Sun was responsible for this mysterious yellow emission. The unknown element was named helium by Lockyer. Imagine, a single unidentified spectral line was observed and a new element discovered! Moreover, it would turn out to be the second most abundant element in the Universe. It is important to note that it was discovered during a solar eclipse, when the Sun was covered. As late as 1896, Lockyer[18] reached the conclusion that the D_3 line does not form as a part of the spectrum emerging from the solar corona.

Lockyer's biographers[19] claimed that the name helium was coined by Lockyer. Frankland, on the other hand, was more hesitant, as there were quite a number of claims concerning new elements. In later publications on the Sun, Lockyer used the name helium extensively, while in other publications,[20] he used the name cleveite (see later). Lockyer tried the same technique several more times,[21] but luck did not strike twice, and no new lines were discovered.

Lockyer's discovery of a new element was accepted with skepticism. Shuster, for example,[22] wrote:

> *If Mr. Lockyer is right we must look forward to finding some trace of helium, or calcium or hydrogen in the discharge taken from iron poles. When this is done, and not till then, will this theory be considered as proved.*

But one does not find traces of helium in such a discharge, and Lockyer's chemistry (not the evolutionary sequence of the stars) was right after all.

2.3 Is There a Universal Abundance?

In 1880, Plummer[23] suggested that there was an effective universal abundance of elements, pointing out that, out of 16 elements discovered in meteorites, 14 had

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[16] If you put a grain of salt in the flame of a gas range, you will see immediately bright yellow light. This is the famous sodium D line. The line is actually a double line, but cannot be seen as such with the naked eye. It gives rise to the yellow color of sodium lamps used to light streets.

[17] Frankland, E., & Lockyer, N., Proc. Roy. Soc. **17**, 288, 453 (1869); ibid. **18**, 79 (1869).

[18] Lockyer, J.N., Phil. Trans. Roy. Soc. London, Ser. A **187**, 551 (1896).

[19] Lockyer, T.M., & Lockyer, W.L., *Life and Work of Sir Norman Lockyer*, Macmillan, London 1928, p. 42.

[20] Lockyer, J.N.,Proc. Roy. Soc., London **61**, 148 (1897).

[21] For example, Lockyer,J.N., *On the Unknown Lines Observed in the Spectra of Certain Minerals*, Proc. Roy. Soc. London **60**, 133 (1896–1897).

[22] Shuster, A., *On the Chemical Constitution of the Stars. And Additional Remarks*, Proc. Roy. Soc. London **61**, 209 (1897).

[23] Plummer, J.I., Obs. **3**, 581 (1880).

been seen in the Sun, while the other two were trace elements. Consequently, either meteorites fall into the Sun and make it up, or the Sun ejects them in its frequent eruptions. This universality in the abundance of the elements was thus used to support Helmholtz's idea.

In 1882, Hildebrand used a spectroscope to examine the uranium mineral cleveite,[24] and discovered spectral lines of a mysterious unidentified gas, which was called cleveite gas after the mineral in which it was found. The hunt for helium on the Earth ended in 1895, when Ramsay conducted an experiment with cleveite. He exposed the cleveite to mineral acids and collected the gases thereby produced. He then sent a sample of these gases to two scientists, Lockyer and Sir William Crookes, who were able to identify the helium within them. Two Swedish chemists, Abraham Langlet[25] and Cleve, independently identified helium in cleveite at about the same time as Ramsay.

How come helium was discovered during an eclipse and not in any previous observations of the Sun? During an eclipse, the Moon covers the Sun, but not the corona of the Sun. The apparent diameter of the Moon is just equal to the apparent diameter of the Sun as viewed from the Earth (sometimes a bit less and sometimes a bit more depending on how close the Earth is to the Moon during the eclipse). The temperature of the surface of the Sun is about 5 800 K, while the temperature of the corona is 2 000 000 K. The tenuous corona is a million times less bright than the dense Sun, so it can only be observed during an eclipse.[26] At the relatively low temperature of the Sun's surface, helium lines are not excited (owing to the properties of helium), and hence no helium is seen on the Sun in regular observations. At the surface temperatures of the hottest stars, about 30 000 K, many helium lines appear. At the high temperature of the corona, most of the helium lines are no longer seen (the temperature already being too high), except for the strong D_3 yellow line. It is a pure coincidence that the temperature of the corona leaves one line of helium, while no lines of helium are seen in the solar photosphere.

2.4 Harvard and Potsdam

Before the turn of the 19th century, the centers for stellar classification research moved to Potsdam and Harvard, and the leading figures were Herman Carl Vogel (1841–1907m), who was the director of the Potsdam Observatory from 1882 until his death in 1907, and Edward Charles Pickering (1846–1919m), who was the director of the Harvard College Observatory from 1877 until his death. Pickering and Vogel independently discovered the first spectroscopic binary stars. The irony

[24] Named after Per Teodor Cleve (1840–1905), who was a Swedish chemist and geologist.

[25] Langlet, A., Fresenius J. Anal. Chem. **36**, 79 (1897).

[26] According to Stefan's law, the hot corona should have been $(2 \times 10^6/5\,800)^4$ times brighter than the Sun, because it is so much hotter. But the corona is far from being a black body, because it is so tenuous. One can observe stars through the corona, as was done in an experiment to verify the general theory of relativity.

was that Pickering discovered lines of ionized helium (helium atoms which have lost one electron) in the hot star Zeta Puppis in 1896,[27] and identified it incorrectly as a special form of hydrogen. Later these lines were found in other hot emission line stars and Wolf–Rayet stars.[28] Pickering was convinced that the lines were due to hydrogen under unknown temperature and pressure conditions.[29] Lockyer, who also misidentified the lines, called the spectrum of ionized helium proto-hydrogen (see his stellar classification scheme).

With two influential and charismatic leaders, no wonder stellar classification became such a competitive arena between the old and the new worlds. The Harvard College Observatory was founded in 1839 and was one of the first observatories in the New World. The Potsdam observatory, not far from Berlin, was established in 1874 and quickly became one of the most important centers for astrophysical research. A notable event occurred at the Potsdam observatory in 1881, when Michelson attempted his first reliable experiment to detect the Earth's motion with respect to the ether, in the cellar under the eastern dome. His persistent lack of success in detecting any motion in this and later experiments in America led eventually to the overthrow of the ether theory by Einstein, and set the scene for the special theory of relativity.

2.5 Vogel. The Helium Stars

The first catalogue of stellar spectra was published by Vogel in 1874.[30] The catalogue also contained a classification of spectra. The latter was based on the same mysterious element discovered by Lockyer in the Sun, the element that the physicists and chemists refused to recognize for many years.

In 1895, Vogel upgraded his classification of stellar spectra.[31] In this year, Ramsay confirmed that cleveite gas was indeed helium. Ramsay identified the strong D_3 line Lockyer had seen. Shortly afterwards, Runge and Paschen[32] provided a complete list of spectral lines for cleveite gas, and this allowed a secure identification of the stellar gas with the terrestrial gas.

Vogel himself explained that:

[27] Pickering, E.C., ApJ. **4**, 369 (1896). The Brackett line of ionized helium, which has a series limit at 364.4 nm, is called the Pickering line, and is observed in helium stars. This line is seen in O type stars.

[28] Wolf–Rayet stars are hot stars with a high rate of mass loss, and surface temperatures in the range 25 000–50 000 K. The mass loss is essentially due to a strong fast-moving wind that blows continuously out from the star.

[29] The irony is that what were then called the 'additional hydrogen lines' or the Pickering series could be fitted to the Balmer formula, provided half integral quantum numbers were allowed.

[30] Vogel, H.C., A.N. **84**, 113 (1874).

[31] Vogel, H.C., Ap. J. **2**, 333 (1895).

[32] Runge, C. & Paschen, F., Ap. J. **3**, 4 (1896). This paper is a reissue of Sitz. d. K. Akad. d. W. Berlin, July 1895, pp. 639, 759.

> *A rational system of classification is conceivable only on the basis that the different spectra of the stars are indications of different stages of development. In my opinion, it is to be regretted that, in the comprehensive spectroscopic Durchmusterung [survey] of stars [...] to faint stars, which Pickering has undertaken [...], the stars are classified without reference to any general considerations but are merely divided into sixteen classes.*

In other words, Vogel wanted a theory-biased classification, and criticized Pickering for avoiding such a scheme. Vogel complained that his original scheme, suggested over twenty years earlier,[33] had been 'proved' by observations, though it was not clear how a classification can be proven right or wrong. And of course, Vogel maintained that his scheme showed continuous transition between the classes. As stars with bright lines were supposed to be the first stage of development à la Vogel (and Lockyer), they had to belong to the first class. Vogel's spectral classification contained only three classes: white stars, yellow stars, and red stars,[34] and not ten as in Lockyer's classification.

In a meeting of the Berlin Academy on 8 February 1894,[35] Vogel reported on the peculiar double spectrum of β Lyrae and suggested that the motion of the spectral lines might be caused by the motion of two or more bodies. This meant then that there were at least two stars revolving around their center of gravity. So Vogel inferred that *the two stars should have the same composition but differ with respect to density and state of incandescence*. In this way, Vogel reached the correct conclusion that the different conditions on the two stars give rise to two different spectra, in spite of the fact that their composition is the same. While Vogel stressed in his papers that his classification supported the theory of the evolution of stars, his papers never specified exactly what theory of stellar evolution that might be.

2.6 The Henry Draper Project

One of the problems of stellar spectroscopy at the time was that all observations were carried out by eye. There were no technical means to register observations. The breakthrough came in 1872 when Henry Draper (1837–1882m) made the first photograph of a stellar spectrum. The honor of being the first star to have its spectrum photographed went to Vega. This trait ran in the family, because his father John William Draper, made the first photograph of the Moon in 1840, on what were known at the time as Daguerre plates (named after the inventor), while his niece Antonia Maury shocked the establishment with her work on stellar classification (see Sect. 2.7).

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[33] Vogel, H.C., A.N. No. 2000, **84**, 113 (1874).

[34] The original classification which appeared in A.N. No. 2000, contained no explanation of the theory of stellar development that Vogel claimed his classification agreed with. I could not find any such theoretical explanation in Vogel's later papers. I can only guess that the combined influence of Helmholtz, Kelvin, and Lockyer was sufficiently strong to affect Vogel's perception of stellar evolution from hot to cold stars.

[35] Vogel, H.C., Sitzugsberichte der k. Akad. zu Berlin, 1895, p. 947.

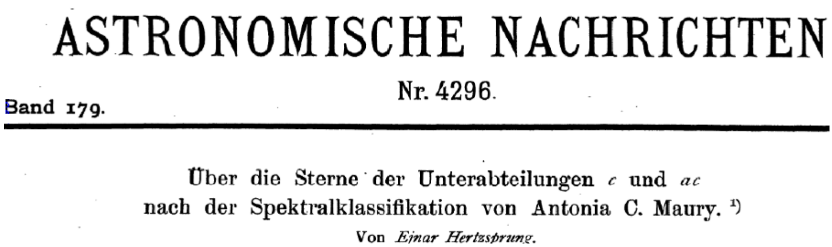
There were still problems with the kind of film used, and efforts were required to increase its sensitivity. However, this was a huge step forward. Draper was also among those to carry out spectral classification of stars, and his original scheme is an expansion on Secchi's four-class classification. Draper used capital letters (A,B,C,...,P) running alphabetically, followed by numerical subcategories (A1, A2,...). It should be mentioned that Draper was a physician who practised medicine, and was even the dean of the medical faculty of the New York City University, where he was a professor of physiology and chemistry. The astronomical community, however, appreciated his work as an amateur. After his death, his wife established the Henry Draper Memorial Fund at Harvard Observatory, supporting the extensive work on the Henry Draper catalogue of stellar spectra. Today astronomers joke by asking for the 'telephone number' of an object, when they need the Draper catalogue number, e.g., HD 12389, so deeply rooted this catalogue has become in astronomers' night life!

2.7 Oh Be A Fine Girl Kiss Me

Edward Charles Pickering was a leading physicist and astronomer who, having come from a prominent New England family, attained a full professorship at MIT at the age of 22, before moving on to Harvard in 1877 to become the director of the Harvard College Observatory at the age of 30. Pickering, quite justifiably, decided to classify a large number of stars without reference to any theory of evolution of the stars. But the job was colossal and well beyond the power of a single man. So Pickering hired assistants, all female, who became known as Pickering's women, to help him with this work. The most prominent names are Willimina Flemming (1857–1911m) (who was a teacher, converted due to circumstances to Pickering's housemaid), Annie J. Cannon (1863–1941m), Antonia Maury (1866–1952m), and Henrietta Swan Leavitt (1868–1921m), who excelled in their work and rose to eminence for the admirable work they did. Rumor had it that the reason for hiring women was the low salary they were paid at the time, about half to a third that of men. What Pickering could not guess, however, was the standard of excellence that would be achieved by these women.

Annie J. Cannon studied physics and astronomy and was hired by Pickering in 1896. In spite of her ardent and important work, it was only in 1938, two years after her retirement, that she got a regular Harvard appointment as William C. Bond Astronomer. The American Astronomical Society established the Annie J. Cannon Award in Astronomy in 1934, while Annie was still alive. The Cannon Award is distributed annually to a woman resident of North America, who is within five years of receipt of a Ph.D., for distinguished contributions to astronomy or for similar contributions in related sciences, which have an immediate application to astronomy.

Antonia Caetana de Palva Pereira Maury was the granddaughter of J.W. Draper and the niece of Henry Draper. Due to disagreements with Pickering about her proposed changes in the classification and their meaning, she left the Harvard College



ASTRONOMISCHE NACHRICHTEN

Band 179. Nr. 4296.

Über die Sterne der Unterabteilungen *c* und *ac*
nach der Spektralklassifikation von Antonia C. Maury. [1]

Von *Ejnar Hertzsprung.*

Fig. 2.2 Hertzsprung's paper, explaining the importance of Maury's unique classification

Observatory to teach in New York. However, in a seminal paper in which he actually discovered what is known today as the Hertzsprung–Russell diagram,[36] Hertzsprung referred to Maury's classification, and gave it a fundamental meaning. The title of the paper contains Maury's name. Maury returned to HCO when Harlow Shapley became the director in 1920, and remained active for many years. In 1943 she was awarded the Annie J. Cannon Award in Astronomy by the American Astronomical Society.

The original Henry Draper Catalogue classification system runs alphabetically, but the Harvard group decided to change the classification to OBAFGKM, so that, out of 22 classes, only 7 were left. The ensuing difficulties in remembering this strange combination gave rise to many mnemonics, the most famous being: Oh Be A Fine Girl Kiss Me.[37]

The anecdote about how the alphabetical order changed to become a famous acronym in astrophysics is blended with many stories that are not always faithful to the events. We prefer to follow the author's own account, that is, the version due to Cannon.[38] To begin with, the letters A to Q were assigned to stellar spectra. This classification was purely empirical, based wholly on external appearances, without any intention of expressing differences of temperature, stages of evolution, or any other physical parameter. The first classification of 10 351 stars was carried out by Mrs Flemming.[39] Miss Antonia C. Maury[40] then discovered small peculiarities in the classification, and made detailed studies of wavelengths and line intensities. As a result, she formed 22 groups of spectra, using Roman numerals instead of letters. Differences in the width of the lines were designated by *a, b*, and *c* to express medium, wide and narrow lines. It is this extra classification that was the center of the

[36] Hertzsprung, A., Uber die Sterne der Unterabteilungen c und ac nach der Spektralklassifikation von Antonia C. Maury, AN 4296, **179**, 373 (1909).

[37] The new order B,A,F,G,K,M appears already in the paper: Pickering, E.C., Ap. J. **6**, 349 (1897), and it is stated that it *indicates divisions in a continuous sequence*, but without mention of a temperature or any other continuous parameter. Pickering, E.C., Ap. J. **7**, 139 (1898).

[38] Cannon, A.J., The Henry Draper Memorial, J. Roy. Astr. Soc. Canada **9**, 203 (1915).

[39] Volume XXVII Part I Harvard Annals.

[40] Annals of the Harvard College Observatory **28**, 1 (1897).

Table 2.2 The Henry Draper Catalogue stellar classification. (The temperatures do not appear in the original catalogue)

Class	Color	Spectral features	T [K]
O	Blue	Strong lines of ionized helium, ionized metals, weak hydrogen lines	40 000
B	Blue	Neutral helium lines, hydrogen lines stronger	25 000
A	White	Strong hydrogen lines, ionized calcium	9 500
F	White	Strong ionized calcium lines, neutral metals	7 200
G	Yellow	Numerous strong ionized calcium lines, strong neutral metal lines	5 800
K	Orange	Numerous strong lines of neutral metals	4 900
M	Red	Numerous strong lines of neutral metals, strong molecular bands	3 600

controversy between Maury and Pickering, and which resulted in Antonia Maury leaving the HCO.

Recall that Secchi had also observed differences in the width of the lines, and decided to separate them, while Lockyer had based his entire theory on these small differences. So it was not a new phenomenon. And yet it did not have any explanation. At the same time, Pickering had qualms about the extra *a*, *b*, and *c*. In 1897, Miss Cannon undertook the classification of the bright southern stars.[41] Cannon noticed that the appearance of some of the letters, such as C, D, and E, were not confirmed by later and better photographs. Similarly, class H was found to be identical with class K when better spectra were obtained. Consequently, these letters were dropped from the sequence. In 1891, Pickering wrote: *The principal question now outstanding is to determine what substance or substances cause the characteristic lines in the spectra of stars of the Orion type.* The Orion stars are a group of very bright stars found in the Orion constellation. The reason for Pickering's problems were the lines of the mysterious cleveite gas seen in these stars, the very lines used by Vogel for his classification.

Before Ramsay identified the cleviete gas as helium (1895), Vogel[42] identified the lines of terrestrial helium with those of the Orion stars, and called them cleveite gas stars. After the identification by Ramsay and the acceptance of helium as a genuine element, the preponderance of such stars in the Orion constellation and the detection of helium in these stars led to them be called helium stars. As it had been clearly demonstrated by the Harvard classification that these spectra precede the spectrum of Sirius (as could be inferred from the hydrogen lines), the letter B, which was

[41] Harvard Annals, Vol. 38 part II.

[42] Vogel, H.C., *On the Occurrence in Stellar Spectra of the Lines of Cleveite Gas, and on the Classification of Stars of the First Spectral Type*, Ap. J. **2**, 333 (1895).

assigned to the Orion stars, clearly had to be placed before the letter A (which is the spectrum of Sirius), or otherwise all the stars previously labeled A and B had to be swapped. Since several thousand stars had already been classified and published, a change in the order of the letters was the only practical course. The remaining original classes were B, A, F, G, K, and M, and they represented the sequence of gradual changes in line properties from one class to another, as far as it was then established.

Further classifications of helium stars discovered that the letter B could not stand for all of them, with their varied line intensities and differences in the number of lines present in their spectra. Cannon therefore decided to divide each class into 10 subclasses, like B1, B2, etc. Again, even this fine division could not overcome the problem of the variations in the widths of the lines, so the groups *a*, *b*, and *c* remained. With the fine division, Cannon found that, even by dividing class O into 10 subclasses, she could find a connection between classes O and B. To put it simply, Cannon found stars (for example 29 Canis Majoris) with a spectra that was just between O and B0. So once again the natural order of the alphabet had to be broken, and O was then placed before B in the stellar sequence. This is how, in Cannon's own words: *The sequence O,B,A,F,G,K,M formed a continuous sequence*. Note that 'continuous' meant that the change in the line ratio and strength was continuous, while the term 'temperature' was not mentioned.[43]

However, even this major step forward, classifying the stars by a physical quantity, turned out to be insufficient to describe the wealth of phenomena exhibited by the stars. Additional sorting was therefore invented, into the so-called luminosity classes. The fundamental underlying question was: can the stars be described by a single physical variable, say the temperature of the surface, or are further physical parameters needed to describe the star in a unique way? It seemed that Maury's classification pointed in that direction. The scientific instincts of Cannon and Maury, leading to the final classification sequence, laid the ground for Hertzsprung's and Russell's discoveries.

2.8 Anjar Hertzsprung. First Correlations

Anjar Hertzsprung (1873–1967m) was a Danish astronomer who trained as a chemical engineer, and was an expert in photochemistry. This may explain why his great discovery was first published in Zeitschrift fur Wissenschaftlishe Photographie and not in a known astronomical journal. After gaining experience as a chemist, he became an independent astronomer, and in 1902 was invited to Göttingen to work with Karl Schwarzschild, and later followed Schwarzschild to Potsdam in 1909, where he became the director after Vogel's death. It was during these years that he carried out the work that brought him fame, in the form of the Hertszprung–Russell diagram, which has since become the single most important tool in understanding the theory

[43] Annals of the Astronomical Observatory of Harvard College, Vol. 91, The Henry draper Catalogue, by A.J. Cannon and E.C. Pickering, 1918.

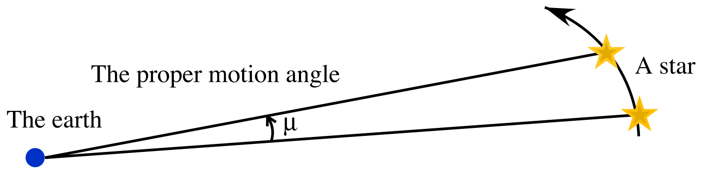


Fig. 2.3 The proper motion μ of a star is the angle the star appears to move through in one year

of stellar evolution. Hertzsprung published about 200 papers, all as sole author. The bulk of the papers were published in observatory publications like Astronomische Nachrichten, which was at that time the bulletin of the Potsdam observatory, or BAN of Leiden, and not in traditional refereed journals. As a rule, his papers were seldom more than three pages long.

In the first paper, Hertzsprung[44] discussed the implications of the spectral classification. He first noticed the refinements to the classification introduced by Miss Maury. As Hertzsprung mentions, Maury guessed that the stars belonging to her classes *a* and *b*, in contrast to class *c*, form a *collateral series of evolution, that is to say, not all stars have the same spectral development*, and he set out to determine whether this was true. It was not the first time that such a possibility had been mentioned. The fundamental and crucial question Hertzsprung posed, and tried to answer, was this: if we brought all stars to the same distance, would we see differences between stars of the same spectral class? The observed stars are at different distances. We observe the bright stars at large distances and the fainter ones only when they are at smaller distances. Does this fact change our perception of the classification? To answer this question, Hertzsprung had to find the distances to the stars. He did so by using their proper motion.

The proper motion of a star is its apparent velocity across the sky expressed as the angle crossed per year (see Fig. 2.3). When the star is very far away, the proper motion is usually a very small angle and cannot be measured. If the star is close, one can expect a high proper motion. The so called 'fixed' stars are not really fixed in the galaxy. They move with speeds of tens of kilometers per second. But as the distances are so large, the constellations appear to us as fixed. Furthermore, with this approach, only the component of the velocity perpendicular to the line of sight is measured, and not the true velocity in space. One can measure the velocity of a star towards or away from the Earth by means of the Doppler effect, provided the velocity is large enough. In any case, Hertszprung had at his disposal only the transverse component of the velocity in the form of proper motion.

Altogether, Hertzsprung had 308 stars with good data. In analyzing the data he discovered that, while the stars of class A all have about the same brightness, the stars of classes G and M each split into two groups, one very bright and one faint. Hertzsprung did not represent the data graphically, but presented it in the form of a table. He hypothesized that the bright red stars form a second collateral evolu-

[44] Hertzsprung, A., Zeitschrift fur Wissenschaftlishe Photographie **3**, 429 (1905); ibid. **5**, 89 (1907).

Fig. 2.4 The Pleiades open star cluster. This cluster is about 425 light years away. Credit NASA

tionary sequence, and gave two lists of stars that form the two parallel sequences of evolution. According to his hypothesis, one sequence has sharp lines, while the other does not.[45] The idea was reminiscent of Lockyer's theory, yet Lockyer was not mentioned in this paper. Hertzsprung ended his paper by stating that: *This result confirms Maury's assumption that the c stars are something unique*. Indeed, this was a colossal discovery. This was the giant branch of stars.

One should point out that two years after Hertzsprung left Göttingen, Hans Rosenberg published the diagram for the Pleiades cluster[46] (it was sent for publication June, 1910) the way we are used to seeing it today, that is, with the log luminosity depicted on the *y* axis and spectral type along the *x* axis (see Fig. 2.5). The figure included 41 stars altogether, but only the main series, the liquid cooling stars, were clearly visible. Only 5 stars with spectral type later than A5 were seen. Most of the stars were B class. Rosenberg was the first to draw a diagram of a cluster of stars. The advantage was that, in a stellar cluster, all stars are at the same distance from us, and hence there is no problem of distance determination. We know today that the stars in a cluster of stars were formed at the same time from the same initial cloud of gas, and hence have the same age and composition. This unique property makes the stellar cluster the ideal object for such investigations. Unfortunately, however, Rosenberg's contribution has hardly been recognized.[47]

[45] Hertzsprung's first series was referred to as the main series, because it contained the liquid cooling stars. Eddington would later change the name to 'main sequence'.

[46] Rosenberg, H., A.N. **186**, 71 (1911).

[47] Rosenberg notes that the idea of observing a star cluster was due to Schwarzschild. He also mentions the special classification by Miss Maury.

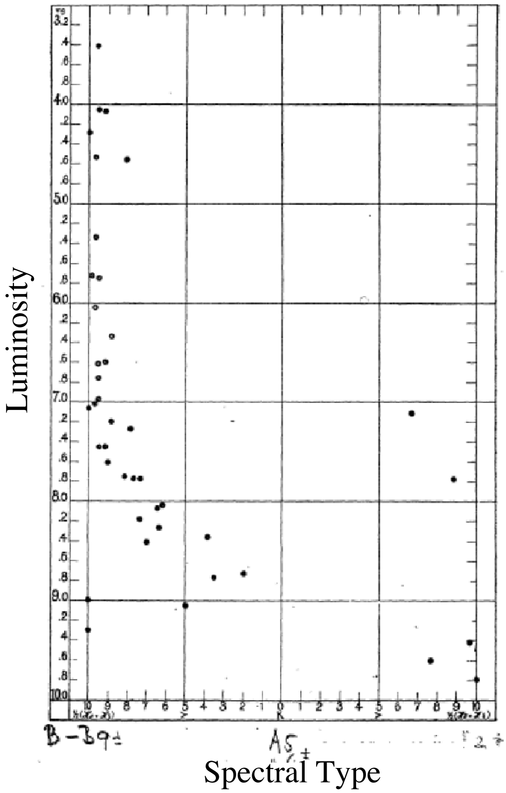


Fig. 2.5 The Rosenberg (1911) diagram for the Pleiades star cluster. The ordinate is the absolute magnitude, i.e., the logarithm of the brightness divided by some standard brightness

While Hertzsprung corresponded with Pickering, communicating all his results, Pickering seems to have chosen to ignore Hertzsprung. But when Karl Schwarzschild visited Harvard for a conference in 1910, he advertised Hertszprung's results and nobody, including Russell and Pickering, could ignore them any longer.

At the same time, Hertzsprung[48] was working on the Hyades star cluster. The Hyades is a relatively small group of stars located at a distance of about 150 light-years from us, which is considered a short distance in the galaxy. The unique feature of a star cluster is that all the stars are to a very good approximation at the same location in space, and hence at the same distance from the Earth. Consequently, the problem of bringing all the stars to the same distance in order to compare their brightness does not exist, and one can compare the stars directly. Hertzsprung did not calculate the temperature of the stars although he had the data for doing it, but instead calculated the wavelength at which the stellar light intensity was maximal

[48] Hertzsprung, A., Potsdam Publ. No **63**, 26 (1911).

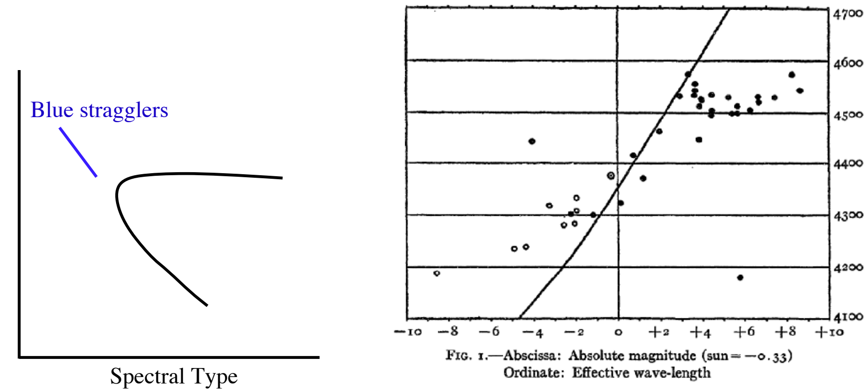


Fig. 2.6 *Left*: The blue stragglers discovered by Hertzsprung are the blue continuation of the main series towards the bluer stars. Hence the name blue. The word 'straggler' implies that these stars somehow wandered to this location in the diagram. *Right*: The first HR diagram produced by Hertszprung. The diagram is of the Hyades star cluster. The effective wavelength is related to the surface temperature

from the measured colors of the stars. In this way he plotted a diagram in which the abscissa represented the brightness of the star, increasing from right to left, and the ordinate represented the temperature, increasing from top to bottom. So strange were the coordinates and the diagram that astronomers did not recognize it, let alone understand and appreciate it. So when Russell drew the diagram in 1914 in the form we know it today, it was called the Russell diagram. Nevertheless, several years later astronomers realized that Hertzsprung had indeed drawn what we call to day the Hertzsprung–Russell diagram, or the HR diagram for short, and the name of Hertzsprung was added to the title.

Hertzsprung's findings were nothing but a vindication of Lockyer's evolutionary theory, although he refrained in his papers from expressing such ideas. However, in 1925 he discovered a phenomenon which he claimed did not agree with Lockyer's hypothesis, nor with any other hypothesis advanced at the time. Hertzsprung found that the diagram of the Hyades contained a group of stars that were situated at the continuation of the main group of stars, but with a gap between them and the rest of the stars (see Fig. 2.6). There appeared to be no continuity between this group of stars and the rest. Today these stars are called the 'blue stragglers', stars that somehow wandered to this location, and their true nature is still a mystery.

Hertzsprung probably suspected that the concentration of the stars along the horseshoe might not be the evolutionary track of the stars, as Lockyer had hypothesized, but the location of stars with different masses. This may sound a small difference, or even purely semantic, but it had major implications. So he decided to check the mass dependence of the diagram. In 1915,[49] he used the 60-inch telescope on Mount Wilson to observe another star cluster. Once again the plots were in strange units, but

[49] Hertzsprung, E., Ap. J. **101**, 1 (1915).

when presented in terms of our present day system, we discover that he managed to check the effect of the mass, only to find out that he could not discern such an effect. The constancy of the brightness for absolute magnitudes +3 to +8 remained (see Fig. 2.6). Hence, it did not appear to be a mass effect. Hertzsprung's explanation for brightnesses above +3 (due to the unique astronomical notation, this actually means fainter stars!), which corresponds to a temperature of 3 400 K for a black body the size of the Sun, was that relatively dark solid matter forms on the surface of the star, blocking the light. This was, of course, completely wrong, and there was not a shred of evidence to point in this direction. If the dark matter absorbed the light, it would soon heat up, rather than stay cool.

2.9 The 1910 Referendum: Science by Popular Vote?

Any classification of continuous properties by a small number of classes poses a problem: when is the change sufficient to warrant a new class? There were therefore astronomers who classified the stars into 3 or 4 classes, and those who preferred to use a larger number of classes. Next surfaced the problem of what principles should guide the classification: should it express a priori some assumed evolution of stars, or should it be independent of any theory? The use of different classifications duly gave rise to problems and confusion, and by 1904 some two dozen stellar classifications had appeared in the literature. In 1904, Frost[50] asked:

> *Is it not time that a beginning be made by the organization of an international committee to consider the question of a new classification of stellar spectra, representative of the observable facts of the first decade of the twentieth century?*

Eventually, it was agreed by leading spectroscopists to try to resolve the classification question in the 1910 meeting of the International Solar Union meeting in Pasadena. As summarized by F. Schlesinger,[51] the leading contenders were:

- The Draper Classification developed by Harvard,
- Miss Maury's classification, which also originated in Harvard, and
- Vogel's classification devised in Potsdam.

Schlesinger mentioned the classification systems of Lockyer and McClean as used in important research projects, but not as leading classifications.

A series of five questions was composed and sent to leading spectroscopists. These were:

1. It will be noticed that, at the meeting reported above, there seemed to be a practically unanimous opinion that the Draper Classification is the most useful that has thus far been proposed. Do you concur with this opinion? If not, what system do you prefer?

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[50] Frost, E.B., Ap. J. **20**, 342 (1904).

[51] Schlesinger, F., Ap. J. **33**, 260 (1911). Schlesinger was the secretary of the Classification of Stellar Spectra of the International Union for Cooperation in Solar Research.

2. In any case, what objections to the Draper Classification have come to your notice and what modifications do you suggest?
3. Do you think it would be wise for this committee to recommend at this time or in the near future any system of classification for universal adoption? If not, what additional observations or other work do you deem necessary before such recommendations should be made? Would you be willing to take part in this work?
4. Do you think it is desirable to include in the classification some symbol that would indicate the width of the lines, as was done by Miss Maury in Annals of the Harvard Observatory, Vol. 28?
5. What other criteria for classification would you suggest?

Present day pollsters will tell you right away that questionnaires are formulated in a biased way. This one was no exception. You can find all the replies in the above report by Schlesinger. It is interesting to note that half of the committee were Americans, and eight were Germans, while later, Alfred Fowler, a former student of Lockyer, was added. Lockyer was not on the committee and Vogel had passed away three years earlier.[52] The structure of the committee may be interpreted as an American bias, but it may also be viewed as the rise to dominance of the new world in the field of spectroscopy.

The respondents were unanimously in favor of the Draper Classification, suggesting a few changes here and there, none of which were accepted. In a few cases the idea of mixing stellar evolution into the classification scheme was suggested, and again (correctly) rejected. Some of the comments by the respondents are interesting. Cannon noted that the Draper Classification is based only on wavelengths between 388.9 and 492.2 nm, which is less than the visible range, and in this way many of the stars showing many lines at longer wavelengths were not properly classified. Hertzsprung mentioned the Maury sub-classification as valuable. He also suggested adding a new dimension to the classification, namely, the brightness of the star. As will be seen, this was exactly what he did. The astronomers (and theoreticians) accepted the additional classification only much later. Sometimes it takes the scientific community a long time to accept new ideas. Maury, such a superb observer, preferred a system based on (speculative) evolutionary concepts (something that should not be done), while Russell was strongly against feeding any theoretical conside-

[52] The people asked and reported by Schlesinger were: Adams, W.S., Mount Wilson, USA, Albrecht, S., Cordova, Argentina, Campbell, W.W., Lick Observatory, USA, Cannon, A.J., Harvard College Observatory, USA, Cortie, A.L., Stonyhurst, England, Curtis, H.D., Lick Observatory, USA, Curtis, R.H., Ann Arbor, USA, Ludendorff, H., and Eberhard, G., Potsdam, Germany, Flemming, W.P., Harvard College Observatory, USA, Frost, E.B., Yerkes Observatory, USA, Hamy, M., Paris, France, Hartmann, J., Gottingen, Germany, Hertzsprung, E., Potsdam, Germany, Hough, S.S., Cape of Good Hope, South Africa, Kustner, F., Bonn, Germany, Lord, H.C., Emerson McMillin Observatory, USA, Lunt, J., Cape of Good Hope, South Africa, Maury, A.C., Hastings-on-Hudson, N.Y., USA, Parkhurst, J.A., Yerkes Observatory, USA, Pickering, E.C., Harvard College Observatory, USA, Plaskett, J.S., Ottawa, Canada, Russell, H.N., Princeton University Observatory, USA, Scheiner, J., Potsdam, Germany, Schlesinger, F., Allegheny Observatory, USA, Schwarzschild, K., Potsdam, Germany, Sidgreaves, W., Stonyhurst College, England, Slipher, V.M., Lowel Observatory, USA, Wilsing, J., Potsdam, Germany.

rations into the classification. Moreover, Russell claimed that the bizarre choice of letters prevented anyone from thinking of the classification as based on a theory of evolution.

In reply to questions (4) and (5), Cannon asserted that, although the peculiar spectra fitting Maury's spectral types *c* and *ac* were rare, they should be investigated. No recommendation for special classification was given, however. Flemming's replies resembled Cannon's. Maury's reply to the fourth question is interesting. She relied on Hertzsprung's papers,[53] and recounted that these stars *led him to the conclusion that [they were] bodies at great distance and of super-normal light energy*. There was thus a mutual dependence on each other's research results. She then mentioned a list of stars prepared by Cannon, which she classified as *c*. These stars showed enhanced silicon lines and formed collateral series, and as Cannon noted, the series ended towards Secchi's Type III. This was an indirect statement that Maury's observation was correct.

Maury did not answer question (5) explicitly. In fact, most respondents ignored question (5), while some even preferred pictures. Some suggested using chemical elements as a means of classification instead. It is surprising that Hertzsprung made no reply at all to the question, and did not mention Maury's classification, even though her classification was the starting point for his discovery! Pickering provided a short reply to (4), and none to (5). Russell just suggested replacing Maury's *a*, *b*, and *c* for the width of the lines by Greek letters. There was not a word about the importance of this additional classification. Schlesinger, the secretary of the committee, wrote: *I regard this matter of specifying the width of lines as being of minor importance as compared with other questions that the committee is considering.*

Schwarzschild admitted that the Draper classification was the best, although he was against a recommendation by the committee to adopt it as the unique system for all purposes. His scientific instincts induced him to draw attention to Maury's classification and Hertzsprung's results, and he raised the possibility that there might be more than two variables that determine the spectra (and structure) of stars. Schwarzschild speculated that there might be different abundances in different stars, and that this might show up in the spectra. Slipher, a leading astronomer, simply replied that: *It is important to investigate the width of the line issue*. No more than that. It is clear from the replies that some of the respondents were confused by Maury's *a*, *b*, and *c* classes. The tacit question was: do they run in parallel with the regular classification or not? Russell cited Hertzsprung when he discussed the effect of the brightness on the classification.

We have gone to great lengths here to report the views of this group of leading astronomers, because it is surprising to say the least how such a critical point as the meaning of Maury's classification was not properly appreciated by so many accomplished scientists, even after Hertzsprung had demonstrated its great importance. The doorway to understanding stellar evolution was standing ajar, and few if any saw and appreciated the fact.

[53] AN **179**, 373 (1909); Zeit. fur Wissenschaftliche Photographie **3**, 429 (1905); and **5**, 86 (1907).

Russell asked that the use of ‘early’ and ‘late’, terms now so frequently used in describing spectra, be discontinued in favor of ‘white’ and ‘red’. For many years astronomers called the spectral classes A and B ‘early type’ meaning that these were the first stars, while the spectral types K and M were called ‘late type’, meaning that these were the old stars. It is unclear when the qualifiers ‘early’ and ‘late’ were invented and started to hint, quite incorrectly, at a supposed evolution of stars.

We stress that even in 1912 Pickering still believed that the spectral line he discovered in 1896 in the spectra of Zeta Puppis was hydrogen, even after Alfred Fowler,[54] Lockyer’s student, had shown that these lines could be produced in a laboratory by a mixture of hydrogen and helium.

It was only in 1922 that the Draper classification, which was generally accepted by the International Solar Union in 1910, was finally adopted by the recently formed International Astronomical Union.[55]

2.10 Warning Signs

In 1910, while working on a completely different problem, the systematic motions of stars, Jakob Halm (1866–1944) from the Royal Observatory in the Cape of Good Hope discovered[56] a connection between the velocity of stars and their location in the HR diagram. His first question concerned the motion of the Sun with respect to the stars in the galaxy. The Sun is not fixed in space, but moves with a speed of 24.7 km/s with respect to the stars in the galaxy. Halm realized that, when one has a group of stars with different masses in the galaxy, the average speed is inversely proportional to the square root of the mass of the star, i.e., $v \propto 1/\sqrt{M}$.

Consider a collection of particles with different masses, and assume the particles are in equilibrium. This means that the particles exchange energy between them as they collide with one another. The thermodynamic principle in this case tells us that the energies of the particles will be the same, but not the velocities or the momenta. As a consequence, when one has a mixture of gases in the atmosphere, one has molecules of different masses that behave exactly like the stars in the galaxy, moving in such a way that the kinetic energy (the mass times the velocity squared) is constant. Hence, the average speed of the molecule/star is inversely proportional to the square root of the mass. Numerically, the atomic weight of a hydrogen molecule is 2, while that of oxygen 32. Accordingly, the hydrogen molecule has an average

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[54] Fowler, A., MNRAS **73**, 62 (1912).

[55] The International Astronomical Union (IAU) was founded in 1919. Its mission is to promote and safeguard the science of astronomy in all its aspects through international cooperation. Its individual members are professional astronomers all over the World, at the Ph.D. level or beyond, and active in professional research and education in astronomy. However, the IAU also maintains friendly relations with organizations that include amateur astronomers in their membership. National Members are generally those with a significant level of professional astronomy. The IAU is composed of 8 993 Individual Members and 62 National Members worldwide (according to statistics in February 2006).

[56] Halm, J. MNRAS **71**, 610 (1911).

Table 2.3 The connection between average velocity and spectral type according to Halm in 1911

Spectral type	Average speed [km/yr]	Number of stars
B-B9	6.0	64
A-A5	11.2	18
F-F8	14.5	17
G-G5	12.6	26
K-K5	15.4	55
M	19.3	6

speed $\sqrt{32/2} = 4$ times greater than the average speed of the oxygen molecule. So Halm found that stars belonging to different spectral classes have different average speeds (see Table 2.3) and masses.

Halm went on to compare the brightness of stars, and found that the Orion type stars were on the average 2.29 times brighter than stars of class A, while stars of class A-K were 5.25 times fainter than stars of class A. Halm reached the very important conclusion that: *The intrinsic brightness and mass are in direct relationship*. This landmark conclusion, which could have drastically shortened the path to the meaning of the Hertzsprung–Russell diagram, was overlooked by everyone in the astrophysics community, save Eddington.

2.11 Henry Norris Russell

Henri Norris Russell (1877–1957m) was the leading American astrophysicist of his day, and an expert in spectroscopy. He was known to physicists through the Russell–Saunder coupling in atomic physics (showing how to calculate the properties of a collection of electrons) and to astrophysicists through the Hertzsprung–Russell diagram. He was deeply interested in stellar evolution and many of his scientific papers dwelt on related problems. Three of the leading American astrophysicists were Russell's doctoral students; Harlow Shapley (1885–1972m), Donald Menzel (1901–1976m) and Lyman Spitzer (1914–1997).[57]

In 1913, Russell addressed the meeting of the Royal Astronomical Society[58] and described the ongoing and still unpublished research in Princeton, explaining how he found his diagram. He took the brightness (luminosity) of each star and plotted it as a function of Pickering's and Miss Cannon's spectral determinations (see Fig.2.7). In this way he discovered that the stars populated certain restricted regions in the plane of brightness versus spectral type. A star of a given spectral class cannot have an arbitrary brightness, and its brightness is actually fixed by the spectral type.

[57] The Spitzer Space Infra Red Telescope carries the largest infrared telescope in space and is one of NASA's Great Observatories.

[58] Russell, H.N., The Observatory **36**, 324. Also, Nature **93**, 227 (1914).

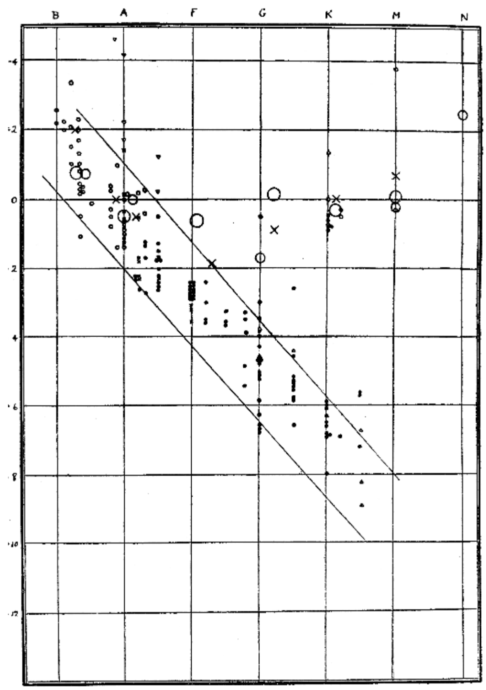

Fig. 2.7 The first spectral class–luminosity diagram drawn by Russell in 1913

Russell found that all faint stars were very red and all blue stars were very bright, but that not all red stars were faint. He noted that the red stars classified as M class stars could be divided into very bright red stars and faint red stars. However, there were no faint blue stars. The phenomenon of two groups of stars was also exhibited in other spectral classes, but as the color became bluer, the difference in brightness decreased, until the two groups merged at class B. Russell's description is drawn schematically in Fig. 2.8. After showing the diagram for stars whose distance had been measured, and whose intrinsic brightness could thus be calculated, Russell repeated Hertzsprung's trick of observing stellar clusters, four in number, for which there was no need to bring all stars to the same distance and for which the brightness comparison could therefore be carried out without any additional correction or calculation.

DeVorkin[59] claims that Russell learnt about Hertzsprung's discoveries from Schwarzschild during a meeting in Harvard in August 1910. A year later Russell wrote to Pickering suggesting follow-up of Hertzsprung's work. Although Russell could already have produced his diagram in 1910, according to the historian DeVor-

[59] DeVorkin, D.H., *The Origins of the Hertzsprung–Russell Diagram.* In: *In Memory of Henry Norris Russell*, Davis-Philip, DeVorkin (Eds.), Dudley Observatory Report 13, Proceedings of IAU Symposium 80 (1977).

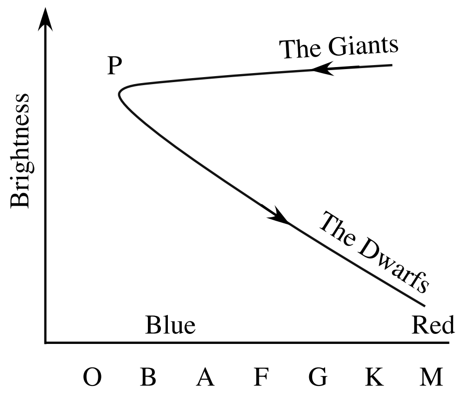

Fig. 2.8 The schematic diagram drawn by Russell in 1913 during the talk given at the Royal Astronomical Society, London. The stellar evolution is marked with *arrows*

kin, he did not do so because he was worried about the meaning of the great luminosity differences between the giants and the dwarfs, a terminology, so it appears, that Russell himself invented. As a matter of fact, Hertzsprung wrote to Pickering as early as 15 March 1906, describing his recent discoveries based on Maury's findings. There is no evidence that Pickering transferred this information to anyone, including Russell. It appears that Pickering was not happy with these findings, and did not attribute any significance to them.

In 1933, Russell[60] credited Hertzsprung as the inventor of the term 'giant'. However, the first time I have found Hertzsprung using this term was in the obituary he wrote on K. Schwarzschild in 1917.[61] It seems likely that the terms 'dwarf' and 'giant' were in fact invented by Russell in 1907, when he lectured in Princeton. Russell used this terminology in his address before the Royal Astronomical Society in 1913, and already at that point attributed its invention to Hertzsprung.

So how did Russell explain the two groups of red stars? Could it be that the brighter stars were more massive? In those days it was impossible to determine the mass of a single star. But the masses of binary stars could be determined by observing their orbits, and using Newton's and Kepler's laws for the motion of objects around their mutual center of gravity. In this way Russell could find the masses of several stars and show that the brighter stars are not always more massive than the faint ones, thus confusing the issue.

It was in his 1913 lecture that Russell used the terms 'giant' and 'dwarf' in public for the first time, to describe the branch of bright stars and the branch of fainter stars. 'Giant' meant extremely bright, while 'dwarf' meant faint. The original terms did not relate to the physical dimensions. Russell concluded that the differences in brightness were not due to differences in mass, but rather to differences in mean

[60] Russell, H.N., JRASC **27**, 375 (1933).

[61] Hertzsprung, A., *Karl Schwarzschild*, Ap. J. **45**, 285 (1917).

density, so that the bright stars had a much larger radius and hence volume, and were therefore brighter for this reason. It is not very convincing logic. The luminosity may be fixed, and as the star expands and increases it radiating area, the radiation per unit area can go down, so that the total luminosity and energy production in the star do not change. As it turned out, Russell guessed correctly, but for the wrong reasons.

Finally, Russell explained how the new findings did not support the then-accepted theory of evolution of the stars, but instead supported Lockyer's theory. The gaseous stars contract, releasing gravitational energy and heating up. The stars move up along Lockyer's left-hand series, as marked by the arrow, which corresponded to Russell's newly discovered giant branch, until they reach such high compression that they liquify. This happens close to the top of the curve (point P in Fig. 2.8). From this point on, the stars cool off and descend along the second series (which according to Russell is the location where most stars are observed). This sounded like a victory for stellar evolution à la Kelvin and Lockyer.

2.12 The Discussion on the Diagram

A year after the lecture in London, Russell sent his results to be published in Nature, the journal Lockyer edited. However, Eddington, who listened to Russell's lecture in London, had already published his criticism,[62] even before the official publication. The conventional hypothesis at the time was that the young stars are those of classes B and A, and for this reason they were called early type. The old stars, according to the conventional hypothesis, were the M stars, and for this reason they were called late type. Eddington based his criticism of the Russell hypothesis on the observational findings that dwarf M stars, which according to Russell (Lockyer and Kelvin) were the oldest of all stars, have on the average spatial velocities exceeding those of the giants. The adopted evolutionary hypothesis would have it that the stars were born with high speed and decelerated with time. It made no physical sense to assume that the stars moved faster as time went by, which was the implication of Russell's evolution theory. Eddington started his career in 1906 as chief assistant to the Astronomer Royal, and his main duty was work on stellar motions. This explains his direct knowledge of stellar velocities.

Russell admitted[63] that the objections to the *conventional picture that the stars of class B are effectively the youngest and those of class M the oldest are so serious that it appears surprising to the writer that this hypothesis is not oftener called in question.* Russell then presented three possibilities:

- The process of star formation has ended. No more new stars are formed.
- Stars undergo the initial contraction very fast, whence it cannot be observed.
- Contracting stars exist and we see them. If this is true, then the giant stars are those undergoing contraction.

[62] Eddington, A.S., The Observatory **36**, 467 (1913).

[63] The Observatory **37**, 165 (1914).

Russell then contended that the first two possibilities appeared to him less probable, and consequently he did not discuss them any further. He explained that, according to the Ritter–Lane theory,[64] the more massive the gaseous star is, the higher is the temperature it will reach before starting to turn back. Thus the stars of class B should be the most massive of all stars. Indeed, Ludendorff[65] investigated the masses of binary stars and found that the average mass of class B stars was 4.27 times the solar mass, while the average mass of a star in classes A and F was 1.4 times the solar mass.

But according to the theory, as the massive B stars cool, they should pass through classes A and F, and hence massive cold stars should be found in these classes as well. On the other hand, the most massive stars found in classes A and F were 2.19 solar masses, well below the average for class B. Russell went on to explain this fact by stating that it seemed that stars of class B lose more than 2/3 of their mass before cooling to classes A and F. This was not exactly what Kelvin and Lockyer had had in mind. Moreover, in this case, signs of mass outflow should have been observed in the spectra of the stars, but this was not the case.

As for the objection raised by Eddington (that the velocity of class B is lower than the velocity of classes K and M), Russell brought other pieces of data indicating that the brightest stars belonging to classes F and G have small velocities (and hence could be those stars that were on their way to becoming hot class B stars before starting to cool down). Nobody was convinced by the argument.

2.13 Summary for 1915

The Manchester meeting of the British Association, Section A, 9 September 1915 held a discussion about the spectral classification of stars and the order of stellar evolution.[66] The discussion is interesting because it provides a glimpse into the thinking of various scientists who participated in the discussion. Alfred Fowler (1868–1940m), a well-known spectroscopist, summarized the state of stellar classification. In Fig. 2.9, Fowler showed the relation between the stellar classifications, and he concluded by presenting the generally adopted theory, which was a variation of Lockyer's theory, and the two rival theories, the original Lockyer theory and Russell's new theory.

The generally accepted theory was based on the sequence from gaseous nebulas to red stars. About 99% of all stars, so estimated Fowler, were readily placed at some point on the series. In short, the right-hand column in Fig. 2.9 was interpreted as the evolution of stars. Stars were born in gases and died as red stars. The classification

[64] Note that Russell called the theory of stellar contraction the Ritter–Lane theory, rather than the Kelvin–Helmholtz theory.

[65] Ludendorff, H., *On the Masses of Spectroscopic Binary Stars*, A.N. **4520**, Band 189, 8 (1911).

[66] The Observatory **38**, 379 (Oct. 1915).

Secchi.	Draper.	Colour.	
—	P.		Nebulæ.
[V.]	O.		Wolf-Rayet.
[O.]	B.	White.	Helium stars.
I.	A.		Sirian.
I.-II.	F.		Procyonian.
II.	G. K.	Yellow.	Solar.
III.	M.	Red.	Antarian.
IV.	N.		Piscian (19 Piscium).

Fig. 2.9 Comparison between the classification schemes, according to Fowler in 1915

included the Wolf–Rayet phase as the second stage in the evolution.[67]. Stars form from a nebula, first become very hot stars like the Wolf–Rayet stars, and then cool down to die as red stars, confirming Kelvin and Helmholtz's hypothesis. The vertical column therefore represents stars with decreasing temperatures, from 10 000°C for the B stars to 3 000°C for the M stars. Actually, claimed Fowler, the best evidence to support this interpretation was Lockyer's laboratory work on how the spectra of various elements change with temperature. The conclusion was therefore that the temperature is the sole factor changing along the series. The chemical composition was identical in all stars.

While the majority of the scientific community supported this hypothesis, Fowler mentioned two who opposed it strongly: Lockyer and Russell. The difference between Lockyer and Russell was minute: Lockyer assumed that M stars were in the early phase of evolution and in the late phase of evolution, while Russell split the M stars into giants, which are young, and dwarfs, which are old. Thus Lockyer ignored the physical size of the stars.

In summary, there were two main hypotheses:

1. The Kelvin–Helmholtz hypothesis: There is a continuous progression from nebulas to red stars, in the order indicated by the Draper sequence, viz., O, B, A, F, G, K, M.
2. The Lockyer–Russell hypothesis: The history of the star begins with a cool nebulous mass, which first condenses into a red star of type M, continues through the yellow to the white stage with increasing temperature, and subsequently, with falling temperature, passes back through the yellow to the red stage, i.e., the order of the evolution, so far as it had been specified, was M, K, G, F, A, B, A, F, G, K, M.

Frank Dyson(1868–1939m) was the ninth Astronomer Royal, and is best known for directing the observations of the Sun and nearby stars in the famous 1919 solar

[67] Wolf–Rayet stars are hot stars with many spectral lines in emission, unlike most stars. Note that hot gases also produce emission lines. Hence, the 'normal' location for Wolf–Rayet stars, according to this classification, would have been between the nebulas and the hot B stars

eclipse.[68] These observations aimed to confirm general relativity. Dyson argued that the evolution was not monotonic in the temperature, but rather in the density. Stars evolved by increasing their density continuously, due to contraction. The contraction continued until a mean density of about 0.1 g/cm^3 was reached, at which point the gaseous star liquified under the enormous pressure and stopped behaving like a sphere of gas.

Father Cortie suggested that the Secchi classification went from simple to physically complex. Cortie therefore supposed that this physical complexity carried some physical meaning, which he hoped to preserve. But what about the nebulas? These were still undetermined, claimed Father Cortie.

Rutherford, who had heard Fowler, asserted that *astronomers may be proceeding too much on the assumption that the evolution proceeds only in one direction. [...] I see no reason why the evolution should always proceed in the direction of condensation.*

Lindemann argued that:

> *If the radioactive evidence for a great age of the Earth is to be trusted, there must be some other unknown source of heat in the Sun and stars. In this case, a revision of astronomical theories based upon Lane's and Ritter's work would be necessary.*

He then made the prediction:

> *If indeed gravitational energy is the sole energy source of stars, then there should be many 'dark stars', which are 'red dwarf stars', which continue to cool.*

Thirty five years later, Mestel essentially confirmed Lindemann's hypothesis.

Eddington, who was the first to react to Fowler's summary, claimed that no physicist would believe that the stars depended on a single parameter, and yet this appeared to be the case. He admitted that he was not an 'out-and-out' supporter of Russell's theory, because it played havoc with a great deal of what seemed orderly and intelligible. He mentioned the problem of the star velocities. As a matter of fact, right after Fowler's summary in The Observatory, there appeared an article entitled *The Relation between the Velocities of Stars and their Brightness* by Eddington,[69] in which he claimed that: *The feebly luminous stars move with much higher average speeds than the bright stars*. Eddington ended by suspecting that the cause for the difference between stars was the mass, so that the bright stars were more massive than the light ones. While the reason was obscure at the time, it posed a serious problem to all evolution theories presented up to then. As will be evident, Eddington had had the right hunch.

In 1917, Adams and Joy[70] carried out extensive research, in which they measured the luminosities and distances of 500 stars. It was the biggest effort so far, and they used the largest telescope in the world at the time, the 100 inch telescope on Mount Wilson, inaugurated in November 1917! The results of Adams and Joy provided complete approval of the giant dwarf branches of stars. But why was this approval so

[68] The expedition was led by Eddington, a fact that added significantly to Eddington's reputation.

[69] Eddington, A.S., Obs. **38**, 392 (1915).

[70] Adams, W.S., & Joy, A.H., Ap. J. **46**, 46 (1917).

important? The number of bright M stars in a given unit of space is very small. The bright M stars are rare. So in order to collect a large number of them and establish the result, one had to look far away. But distant stars hardly move, so one needs a big telescope to detect their motion in the sky.

Stars live for many years and we observe any particular star at a single moment in time. It is conceivable that the composition of stars might change in time, and in this way foul up the meaning of the classification, and with it our interpretation. This question interested Chapman,[71] who explored the way the different elements behave in the gravitational field of a gaseous star, if undisturbed for a long time.[72] Since metals are heavier than hydrogen, his calculations showed that (with time) the heavy element would sink and the light hydrogen would float, so that we should see only hydrogen on the surface of stars. And yet we see metals as well as hydrogen. Hence, concluded Chapman, there must be some agent which prevents the metals from sinking into the star. The explanation was the existence of convective motions, which continuously brought the heavy elements to the surface and prevented the star from settling into Chapman's equilibrium.

This result is extremely important, because it explains how it comes about that we see heavy elements on the surface of stars. If it were not for the convective currents, all stars would expose surfaces to us with only hydrogen in them, and we would not have known about the existence of other elements in stars, let alone been able to determine the relative cosmic abundance of the elements. Chapman treated the stars as gaseous. In this way he could actually carry out the calculation. He added a note in proof after hearing Jean's Bakerian lecture to the effect that his results were probably wrong for the dense dwarf stars, which are not gaseous. The question of mixing haunted the theory of stellar structure and evolution for many years, and continues to beleaguer the theory even today, as will become evident from recent observations of stellar explosions.

The Henry Draper spectral classification remained untouched for many years and continued to play a dominant role in the theory of stellar evolution. In 1935, Russell, Payne, and Menzel[73] reached the conclusion that the classification brought with it a host of problems, and that new principles and physical prerequisites were therefore needed. However, so much was invested in the Draper classification that it is actually impossible to replace it. In the words of the authors:

> *From its first days this system served only to place the spectra in convenient pigeonholes, from which those worthy of special study could be withdrawn, and redistributed with labels, such as Miss Maury's a, b, and c.*

They listed some 13 different problems. However, these changes had to wait.

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[71] Chapman, S., MNRAS **77**, 539 & 540 (1917).

[72] Chapman assumed a steady state, and did not calculate how long it would take for the steady state to be established. Further, he assumed the matter to consist of unionized atoms, an assumption which later turned out to be wrong. Finally, Chapman did not provide the time scale for the sinking of the heavy elements.

[73] Russell, H.N., Payne Gaposchkin, C.H., & Menzel, D.H., Ap. J. **81**, 107 (1935). The first in Princeton and the other two in Harvard, where the Draper system was devised.

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