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Physics in Perspective

Pioneering Women in the Spectral Classification of Stars

E. Dorrit Hoffleit*

Spectra reveal more about the constitution of stars than can be ascertained by any other means. About 1867 Angelo Secchi classified stellar spectra into five distinct categories. No significant improvements in his system could be made until the advent of dry-plate photography. Then both Henry Draper in New York and Edward C. Pickering at Harvard began taking hundreds of spectrum plates. After Draper's death in 1882, his widow endowed The Henry Draper Memorial at Harvard for the analysis of stellar spectra. Pickering then employed mainly women to help him devise a more detailed system of classification than Secchi's. Ultimately, the most appreciated lady became the one who dutifully carried out the routine work of classifying exactly as she was told, while another slowly made independent new discoveries that Pickering would not accept even after other astronomers proved them to be highly significant.

Key words: Stellar spectra; HD system; MK system; stellar magnitude; Annie J. Cannon; Henry Draper; Anna Palmer Draper; Williamina Payton Fleming; Ejnar Hertzsprung; Antonia C. DeP. P. Maury; Edward C. Pickering.

Introduction: Historical Background

> I am thoroughly in favor of employing women as measurers and computers and I think their services might well be extended to other departments. Not only are women available at smaller salaries than are men, but for routine work they have important advantages. Men are more likely to grow impatient after the novelty of the work has worn off and would be harder to retain for that reason.
>
> Frank Schlesinger to George Ellery Hale, July 13, 1901[1]

We learn about the temperatures, composition, and intrinsic luminosities of stars largely through the analysis of their spectra. Prior to such astrophysical interpretations, stellar spectra were classified into numerous successive categories simply in order of increasing complexity according to their appearance. Women played major roles in this work.

Before the advent of photography, progress in stellar spectroscopy was slow, though significant, starting with Joseph Fraunhofer's study of the solar spectrum in 1815, in which he counted some 600 lines and carefully measured the relative

* E. Dorrit Hoffleit, age 95, received her Ph.D. degree at Radcliffe College in 1938, was Director of the Nantucket Maria Mitchell Observatory from 1957 to 1978, and is Senior Research Associate, Retired, in the Department of Astronomy at Yale University.

positions of the 324 most conspicuous ones. The elements responsible for producing these lines were first identified by Gustav Kirchhoff and Robert Bunsen in 1859. Angelo Secchi (1818–1878) in 1863 was the first to attempt to classify stellar spectra, recording such details as he could observe visually with a 24-centimeter refractor equipped with an objective prism. With this and other equipment he observed the spectra of some 4000 stars and classified 500 of them into five categories. Relatively little progress followed until the advent of dry-plate photography. Then both Edward C. Pickering, Director of Harvard College Observatory, and Henry Draper made great strides in the accumulation of photographs of stellar spectra.

Henry Draper (1837–1882) was a pioneer in stellar spectroscopy and in 1872 was the first to obtain a photographic spectrum of a star (Vega) showing four spectral lines. Ultimately, Draper (Fig. 1) succeeded in obtaining 78 excellent photographs of stellar spectra. Resigning his post as physiologist at the University of the City of New York, he hoped to devote full time to the analysis of these spectra. This was not to be. Soon after his untimely death, Pickering offered to help his widow, Anna Palmer Draper (Fig. 2), in any way he could to complete the analysis of her husband's spectra. She had been his devoted assistant in his astronomical work and now hoped to have his work continue, perhaps by establishing an observatory in New York as a memorial to her husband, with herself as head. When she found herself incapable of carrying out her plans, she turned to Pickering (Fig. 3), who desperately needed funds for doing exactly the type of work she had in mind. Starting in 1886 she began subsidizing a Henry Draper Memorial at Harvard. Pickering's *Annual Report* for the year ending January 1887 indicates that by the end of 1886 the spectra of over 5400 stars brighter than 6^{th} magnitude, and about 2400 fainter stars, had already been classified on plates taken with an 8-inch Voigtlander telescope equipped with an objective prism yielding spectra about one centimeter long. On the 80 square degree plates (Fig. 4), an average of nearly 40 stars per plate could be classified. Much of the work of identifying the stars, classifying their spectra, and determining their photographic magnitudes became women's work at Harvard. Before Mrs. Draper's bequest, just six women had been employed at Harvard College Observatory, including Williamina Fleming. By the end of Pickering's career in 1919, a total of 47 women had been employed at some time at the observatory, many of whom contributed to the work of the Henry Draper Memorial. The most significant were Williamina Fleming, Antonia Maury, and Annie J. Cannon.

Williamina Payton Fleming (1857–1911)

Fleming was born Williamina Paton Stevens in Dundee, Scotland, in 1857. Her father, a skilled craftsman who ran a carving and guilding business, had been experimenting with photography and was the first to introduce the new Daguerreotype process to Dundee residents. He died when Williamina was only seven. On her mother's side she was descended from the first Viscount of Dundee, John Graham of Claverhouse (1648–1689), from whom she is reputed to have inherited traits of

Fig. 1. Henry Draper (1837–1882). *Source*: *Annals of Harvard College Observatory* **92** (1918), frontispiece.

energy, perseverance, and loyalty which tended to breed both stern leadership and staunch friendship. She was educated in public schools and at age 14 became a pupil-teacher. In 1877 she married James Orr Fleming and soon the couple came to America, to Boston, Massachusetts. Early in 1879, after she became pregnant, her husband deserted her. She needed to support herself, and the only job she could find was as a domestic in the household of Edward C. Pickering, the Director of Harvard College Observatory. When her child was due she returned temporarily to Scotland. Appreciative of Pickering's help, she named her son Edward Pickering Fleming.

Fig. 2. Mrs. Anna Palmer Draper (1839–1914), founder of the Henry Draper Memorial at Harvard College Observatory in 1886. *Source*: *Annals of Harvard College Observatory* **93** (1919), frontispiece.

As Fleming (Fig. 5) had been a teacher in Scotland before her marriage, Pickering was aware that she was qualified for more scholarly work than housekeeping. Her first work other than clerical involved determination of photographic magnitudes of stars.* Eventually, in 1899, she was made Curator of the Photographic Plates, the first Harvard Corporation appointment accorded a woman, and the only one until the 1950s. She meticulously examined all of the plates for quality as soon as they were taken or delivered from Harvard's southern station in Arequipa, Peru, and then had them properly filed.

* Magnitudes of stars are assigned on a scale such that a difference of 5 magnitudes corresponds to a factor of 100 in brightness, or each interval of one magnitude represents a ratio of 2.512, with larger magnitudes corresponding to fainter stars. Apparent magnitudes correspond to how bright a star looks to the observer, while absolute magnitude is defined as how bright the star would look if it were at a distance of 10 parsecs. Parsecs are distances corresponding to the reciprocal of the parallax; a star with a parallax of $0''.100$ would be at a distance of 10 parsecs. 1 parsec = 3.26 light years or 19.16×10^{12} miles.

Fig. 3. Edward C. Pickering (1846–1919), Director of Harvard College Observatory, 1877–1919, at age 45 in 1891. *Source*: Solon I. Bailey, "Edward Charles Pickering, 1846–1919," *The Astrophysical Journal* **50** (1919), facing p. 236.

For helping him classify the spectra obtained at Harvard, Pickering first engaged Nettie Farrar to assist him, but within a year of Mrs. Draper's support Farrar planned to leave to get married. She therefore was first asked to educate Mrs. Fleming to take over. Earlier, on another project, it is reputed that Pickering had become annoyed with the unsatisfactory work of a young male employee, bruskly stating he thought his housekeeper could do a better job. Indeed, Fleming did.

Pickering with Fleming's assistance devised the system of stellar spectral classification that is basically still adopted to this day (Fig. 6). The most prevalent system available in 1885 was that of Father Angelo Secchi (1818–1878), finalized in 1878. For each of his five types, Secchi assigned standard stars as shown in Table 1. Pickering found this system much too coarse even for his small dispersion spectra, so he and Mrs. Fleming arranged the spectra in seventeen groups in order of increasing complexity in appearance, assigning successive letters of the alphabet to the groups, from A through M (except that J was omitted because it was not always distinguishable from I), and assigning N through Q to less numerous stars that would not fit into the regular sequence. For the first Draper Catalogue (DC),

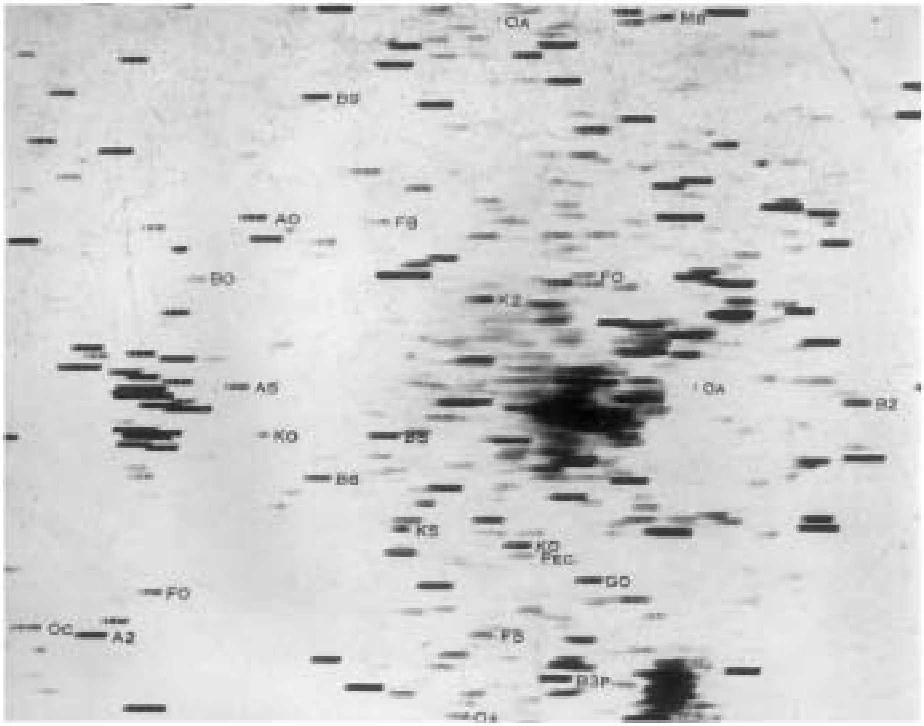

Fig. 4. A typical Harvard objective prism plate, taken at Harvard's southern station in Arequipa, Peru, on May 13, 1893, with the 8-inch Bache telescope covering 8 × 10 degrees in the sky. Field of η Carinae, exposure time 140 minutes. *Source*: *Annals of Harvard College Observatory* **99** (1924), frontispiece.

published by Pickering in 1890, Fleming classified 10,498 stars brighter than 8th photographic magnitude, based on 28,266 spectra on 633 plates. The spectra ranged slightly longer than the span from the hydrogen Hβ line at 4861 A to the calcium K line at 3933 A (Fig. 7).* Although all of the categories from A through Q were represented, except that no star of Type N was bright enough to be included, Pickering already was aware that not all of his classes were valid, some having been based on poor-quality spectra.

Table 1 shows the types assigned by Pickering and Fleming to Secchi's standards, as well as the types assigned in later Harvard publications (HA50, HD), and in the current version (1996) of the *Bright Star Catalogue* (BSC5). Within their natural uncertainties the agreements are good. With the passage of time better and better spectra became available, frequently necessitating more complex spectral classes. The final two columns of Table 1 give the total number of stars Secchi had classified in each of his five types, and the range of their classes in the first Draper

* 1 A (Ångström) = 10^{-10} meter. Visible light ranges from about 3900 A to 7600 A. The photographic stellar spectra used for setting up the classification system ranged from a little short of the hydrogen Hε line at 3970 A to slightly beyond the hydrogen Hβ line at 4861 A.

Fig. 5. Williamina Paton Fleming (1857–1911). *Source*: Cannon, "Williamina Paton Fleming" (ref. 7), facing p. 314.

Catalogue (DC). At first, in 1868, Secchi had utilized just four Types I–IV for classifying stars. In 1878 he added a fifth Type V, ostensibly for stars showing prominent emission features, obviously exclusive of long-period variables, Type III, which also show emission lines, as Fleming noted. Secchi had cited only two stars for Type V, γ Cas and β Lyrae, both now classified as Be (B-type stars showing

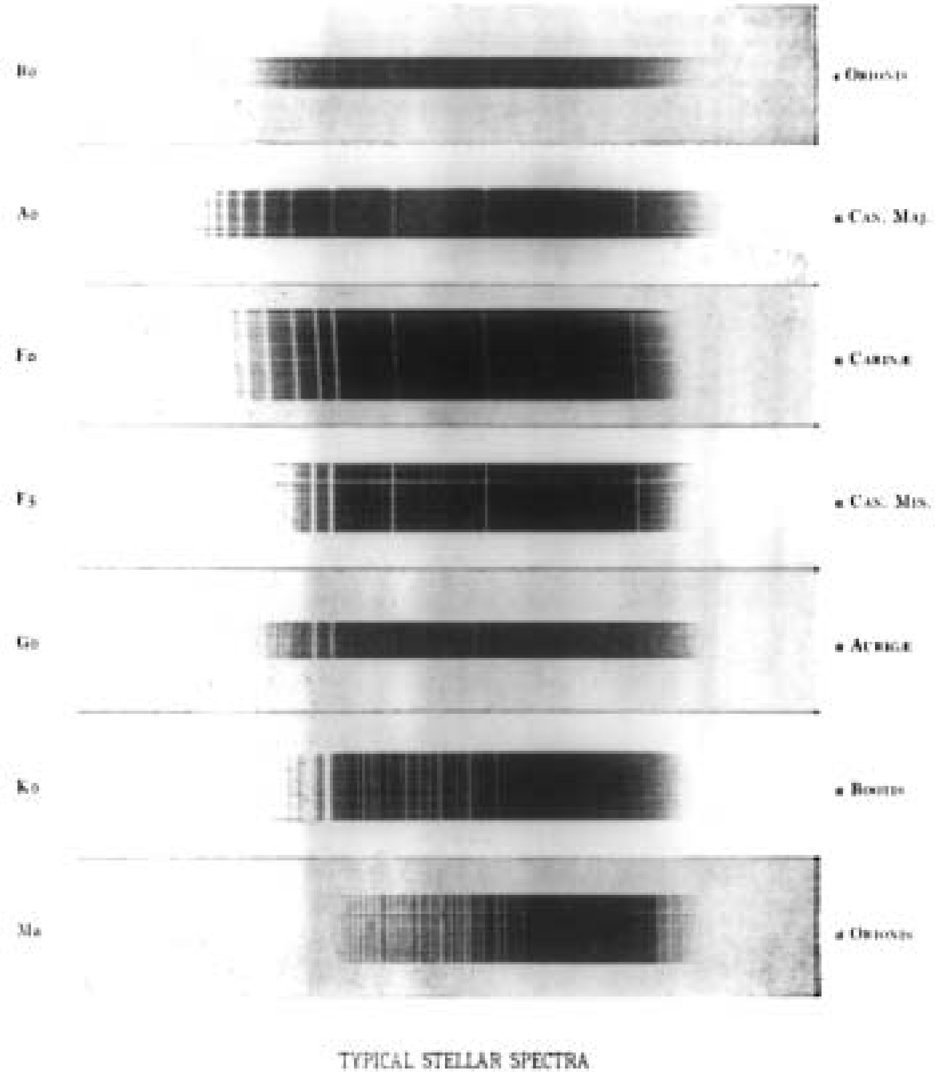

Fig. 6. Typical Harvard spectra taken with the 11-inch Draper telescope. *Source*: *Annals of Harvard College Observatory* **91** (1918), frontispiece.

emission lines). Pickering believed that Type V should embrace stars with more spectacular emission features, so he and Fleming did not include γ Cas and β Lyrae among their Type V but instead included stars subsequently classified as emission O types and Wolf–Rayet stars, a type first discovered in 1867 by Charles Wolf (1827–1918) and Georges Rayet (1839–1906). These stars are characterized by strong emission features of hydrogen and helium, but not of metals. Most stars show only absorption features, dark lines or bands crossing the colorful continuum, while emission features are lines or bands brighter than the continuum.

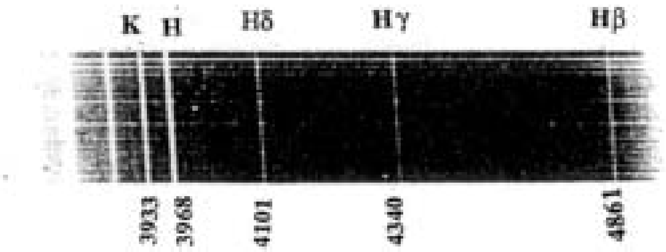

Fig. 7. Spectrum of Procyon, Class F5, showing the wavelengths of the hydrogen lines Hβ, γ, and δ, and of the calcium H and K lines. Enlargement of detail of Fig. 6.

Pickering listed 33 bright-line stars belonging to his Type V, of which he had discovered three visually with the Harvard 15-inch refractor, while 19 were found on objective prism plates, mainly by Mrs. Fleming. Only 8 of the 33 are naked-eye stars, but all are still too faint, or are below or too close to Secchi's horizon for him to have been able to observe their spectra. Thus he could not have been able to discover any of Pickering's Type V stars.

The southern Boyden Station of Harvard College Observatory at Arequipa, Peru, was established in 1890. Both the northern station in Cambridge and the southern station were then equipped with 8-inch telescopes with two objective prisms, giving spectra of about 0.2 or 0.7 centimeters long (Fig. 4). With these spectra, Fleming undertook the classification of stars in seven open clusters. She still used most of the types included in the Draper Catalogue, namely, A, B, E, F, G, H, K, M, N, and Q, but Pickering, in the discussion of the results, lumped E with G and H with K, indicating that the differences depended on brightness rather than composition. Table 2 lists the seven clusters examined and the distributions of the final spectral classes. In all but two of the clusters the most prevalent type is A; in

Table 1. Secchi standard spectral types. The table shows the stars that Secchi assigned as standards to each of his Types I–V in 1878, and the types assigned to them by Pickering and Fleming in the first Draper Catalogue (DC, HA27) of 1890, as well as the types assigned to them in later Harvard publications (HA50 of 1908, HD of 1924) and the *Bright Star Catalogue* (BSC5) of 1996. The second-to-last column gives the total number of stars that Secchi classified in each of his Types I–V in 1878, the second star of Type V being β Lyrae (B8IIpe). Secchi's Type V was broadly defined simply as spectra showing emission lines. The last column gives the ranges of Secchi's classes in the first Draper Catalogue (DC) of 1890. Pickering rejected the two stars in Secchi's Type V (γ Cas and β Lyrae) and instead proposed as Type V stars more conspicuously emission objects, currently called O types, Wolf-Rayet stars, and planetary nebulae.

Secchi Type	Secchi Standard	DC Standard	HA50 Standard	HD Standard	BSC5 Standard	Secchi Total	DC Range
	1878	1890	1908	1918–1924	1996	1878	1890
I	Vega	A	A	A0	A0Va	168	A–D
II	Arcturus	K	K	K0	K1.5IIIFe-0.5	154	E–L
III	α Her	M	Mb	Mb	M1.5Ib-II	25	M
IV	Y CVn		N	N	C5.5J	17	N
V	γ Cas	Q	Bp	B0p	B0IVnpe(shell)	2	G, Q

Table 2. Fleming's classification of stars in seven open clusters into their spectral classes, giving the number of stars in each of the eight spectral classes. In five of the seven clusters, type A is the most prevalent spectral class; in two type F is the most prevalent; these types are now called Pleiades and Hyades, respectively. She reported finding type-B stars only in cluster IC 2602 (the Carina cluster).

Cluster	A	B	F	G	K	M	N	Q
Pleiades	**59**	0	14	9	9	0	0	0
Praesepe	28	0	**41**	9	11	1	0	0
IC 2602	**49**	6	2	1	6	0	0	0
NGC 3532	**190**	0	2	6	6	0	0	0
Coma	18	0	**42**	9	36	2	0	0
NGC 6405	**68**	0	4	4	13	2	0	0
NGC 6475	**269**	0	34	10	31	0	1	1

Praesepe and Coma it is F. Only in the Carina cluster (IC 2602), in the center of Fig. 4, did Fleming report finding B-type stars. This is the first time – in 1897– that open clusters of stars could be separated into two major categories, those in which either A-type or F-type stars predominated, now called Pleiades or Hyades types, respectively.

In 1867 Secchi discovered that his Type III spectrum of the long-period variable, Mira (period about 11 months) showed hydrogen emission lines. Apparently unaware of this, Pickering in 1886 made the same discovery photographically. That same year Mrs. Fleming found that U Orionis (which John I. Gore had discovered the previous year but assumed to be a nova) also has an M-type spectrum showing hydrogen emission lines. Hence, when she discovered in 1890 that R Caeli showed a similar spectrum, she surmised that a Mira-type variable could be identified as such from the observation of a single spectrum, which expedited the discovery of Mira-type variables as compared to the usual photographic discoveries, which were made by the time-consuming process of intercomparing many chart plates. Of course, she substantiated her claim by verifying her spectroscopic discoveries by checking them against numerous direct chart plates. From her discovery of Nova Norma in 1893, she again decided that the spectrum was so different from other stars that a nova, too, could be identified as such by a single spectrum. In all she discovered 10 novae and over 300 variable stars.

Fleming's work was not limited to spectral classification and checking on the variability of stars with intriguing spectra. She accomplished valuable photometric work as well. For the 222 variables she had discovered before 1907, she selected sequences of comparison stars for which she determined the magnitudes. Then she began estimating magnitudes for all of the 107 variable stars with known amplitudes over two magnitudes, which enabled her to ascertain the periods of variation of many of them.

Mrs. Fleming noted many stars either simply as *peculiar*, or having uncertain types. It was finally suggested that some of them might well be considered an additional Type VI, and Pickering listed 51, assigning them to a new Type R, all but two of which were discovered at Harvard.

A paper published soon after her death in 1911, "Stars Having Peculiar Spectra,"[2] gives tables of 13 categories of stars. Table 3 gives the name and number of stars in each category, as well as the number actually discovered by Fleming herself, amounting to about a third of all. The final category XIII includes 29 stars without comments on the type of peculiarity. These have been compared with the classes given for them in Nancy Houk's reclassifications of HD stars[3] and in the La Plata catalogue of stellar spectra,[4] which also uses the Morgan-Keenan (MK) system for the zones for which Houk's reclassifications of HD stars are not yet completed. Twelve of the 29 stars have now been classified S, a category not yet defined in 1912. The *General Catalogue of Variable Stars* (four volumes published in Moscow, 1985–1990) indicates that 17 of the 29 stars with spectra considered peculiar by Fleming are variable.

In what Pickering describes as her last paper,[5] Fleming gave spectra and photographic magnitudes for over 1400 stars in 48 Harvard Standard Regions. Her work preceded the publication of standard sequences for each of the 48 regions, which incorporated some of her work but was carried out by a fairly large crew, including Annie J. Cannon. The Harvard Standard Regions still provide provisional comparison stars for the determination of magnitudes of any newly discovered object.

While scrutinizing all of the Harvard photographic plates as soon as they were acquired, Fleming found what is presumably the first spectrum ever photographed of a meteor, on a plate taken at Harvard's southern station in Arequipa, Peru, on June 18, 1897, and a second spectrum, taken with the 24-inch

Table 3. Fleming's final groups of peculiar stars. Fleming discovered one-third of these stars. She did not comment on the type of peculiarity for the 29 stars in her final category XIII. Twelve of these stars are now classified S, and 17 of the 29 are variable stars.

Group	Name	Number	Fleming	Percent
I	Novae	28	10	36
II	Gaseous Nebulae	151	59	39
III	Type V Spectrum	108	91	84
IV	H Lines Bright	92	69	75
V	SB Class	47	2	4
VI	Algol Variables	134	4	3
VII	β Lyrae Class	13	1	8
VIII	Short-Period Variables	168	3	2
IX	Long-Period Variables	629	192	31
X	Class N	267	63	24
XI	Class R	61	58	95
XII	Oe5	26	0	0
XIII	Peculiar	29	21	72
Total		1753	573	33

Bruce telescope on May 18, 1909. Whereas the first showed six lines, five of which Pickering attributed to hydrogen, Fleming reported the second spectrum as showing 23 bright lines or bands. These two spectra were not fully analyzed until 1932, when Peter Millman, for his Harvard Ph.D. thesis, made the first extensive analysis of all of the first nine meteor spectra photographed anywhere. He concluded that none of the lines in any of the meteor spectra were due to hydrogen; that all of the lines in Fleming's first spectrum were due to iron; and that Fleming's second spectrum showed 53 lines, most of which he attributed to iron, a few to chromium, magnesium, and silicon.

An excellent obituary of Mrs. Fleming was given by British astronomer Herbert H. Turner, outlining her heritage as a descendant of the Scottish "Fighting Grahams." He concluded:

> As an astronomer Mrs. Fleming was somewhat exceptional in being a woman; and in putting her work along side of that of others, it would be unjust not to remember that she left her heavy daily labours at the observatory to undertake on her return home those household cares of which a man usually expects to be relieved. She was fully equal to the double task, as those who have had the good fortune to be her guests can testify.[6]

It was indeed fortunate for both Pickering and Fleming that he employed her at the observatory. As she had been an excellent domestic, Pickering's spouse must have missed her. She was also expert at fancy needlework and could dress dolls in typical Scottish garb. Harvard football games delighted her, especially the Harvard–Yale game. Moreover, while she was still a maid at the observatory residence, Pickering had thought of asking her to teach the observatory staff the Highland polka! Cannon, in an obituary of Fleming, wrote, "Her bright face, her attractive manner, and her cheery greeting with its charming Scotch accent, will long be remembered by even the most casual visitors to the Harvard College Observatory."[7] One wonders what possessed Mr. Fleming to abandon so gifted, versatile, and sociable a lady.

In 1893 Fleming had published an article, "A Field for Women's Work in Astronomy," concluding,

> While we cannot maintain that in everything woman is man's equal, yet in many things her patience, perseverance and method make her his superior. Therefore, let us hope that in astronomy, which now affords a large field for woman's work and skill, she may, as has been the case in several other sciences, at least prove herself his equal.[8]

Alas, superior women would not always be properly credited with superior achievements.

Before the completion of the first Draper Catalogue, Pickering had already inaugurated further investigations utilizing larger telescopes with objective prisms yielding higher dispersion to improve the system of stellar spectral classification. He employed Antonia Maury in 1888 to reclassify the northern stars more precisely than was possible for the earlier results, and Annie J. Cannon in 1896, the southern.

Antonia C. DeP. P. Maury (1866–1952)

Antonia Maury (Fig. 8) was probably the most intellectually gifted of the three Harvard ladies who were pioneers in stellar spectral classification. I had the good fortune to become her friend in her later years, and found her knowledgeable in almost any topic that came up in conversation: literature, art, conservation of natural resources, and many more besides astronomy.

Fig. 8. Antonia C. DeP. P. Maury (1866–1952). Photograph by William Henry, probably September 1920. *Credit*: Harvard Observatory Archives.

Antonia was the daughter of Mytton and Virginia Draper Maury. Her father was an Episcopalian priest and Editor of *Maury's Geographical Series* (1875–1895). Her mother, the sister of Henry Draper, was the daughter of John William Draper (1811–1882), who was the first, in 1840, to obtain a photograph of the Moon by the newly perfected Daguerreotype process; and in 1843, the first photograph of the spectrum of the sun. As a small child Antonia helped her uncle Henry with his chemical experiments. Her father taught her Latin and at age 9 she was reading Virgil in the original Latin. Later she entered Vassar College where she was one of the last students of Maria Mitchell (1818–1889), America's first woman astronomer. In 1887 she graduated from Vassar with honors in astronomy, physics, and philosophy. The following year she was happy to be employed at Harvard under the Memorial to her beloved uncle.

Pickering employed her to examine the Harvard plates taken with the 11-inch refractor, which had belonged originally to Henry Draper and which his widow first loaned, then donated to Harvard College Observatory. It was equipped with four objective prisms that could be used singly or in combination, yielding spectra from 2 to 8 centimeters long between the hydrogen Hβ and Hε lines. Maury was expected to classify the spectra according to the Pickering–Fleming system, improving upon that system in accordance with the long-dispersion spectra, which showed more detail than those used by Fleming. Instead of simply accepting and improving upon that system, however, Maury meticulously set up her own independent system, separating the spectra into 22 groups and assigning them Roman numerals, and subdivisions *a*, *b*, and *c* to indicate whether the spectral lines were relatively wide (normal), hazy, or exceptionally sharp. On comparing her own with the Pickering–Fleming system, she ascertained that Fleming's class B should precede, not follow A, and that absorption class O should precede B. To this Pickering acquiesced. Fig. 9 shows how well her types I-XX are correlated with modern determinations. (This does not include the rare emission O-type spectra.)

Maury's final catalogue, published in 1897, contained 681 stars north of declination $-30°$. Her notes indicated all observable details; her sharp eyes overlooked nothing. Only her notes indicated which spectra showed emission features. Unfortunately, she did not add the letter *e* to the spectral class assigned to those stars. She indicated which of her groups corresponded to Secchi's four types, and which to Type V as defined by Pickering (not Secchi). Her group XXII included four stars, all Pickering Type V Wolf–Rayet stars. The standard star was the variable EZ CMa; the other three were all in Cygnus. All four are classified Ob or Oc by Miss Cannon in the Henry Draper Catalogue (generally referred to as the HD) and subsequently WN5 or WN6. Besides lines of hydrogen and helium, the Wolf–Rayet spectra are characterized by strong emission bands due to either carbon or nitrogen.

Maury recorded 18 stars as having composite spectra. All but one are still recorded in modern catalogues as being composite. The exceptional one, τ UMa, is now classified Am, called a metallic-line star whose spectrum has features of both A and F types. Occasionally such stars had been mistaken for binary stars. In the HD catalogue, Miss Cannon classified several stars, including τ UMa, as probable binaries, actually assigning two HD numbers on the assumption that one component is type A, the other F or G; for example, ξ Cep, for which Cannon assigned

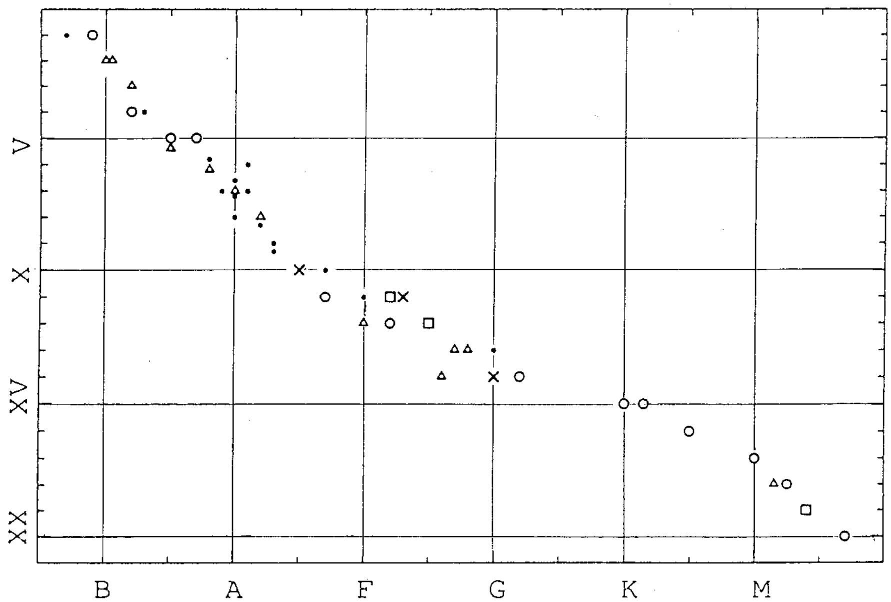

Fig. 9. Maury's spectral classes compared with modern MK classes. Dots, luminosity class V, crosses IV, circles III, squares II, and triangles I. Plot by the author.

classes A3 and G, is now classified as a single star of class A3m, the *m* standing for metallic lines.

Pickering felt that the detail Maury recorded for each star was a waste of time; he was anxious to present Mrs. Draper with results as quickly as possible. His disapproval of Maury's independence and slow progress affected her emotionally. Her father, moreover, made matters even more uncomfortable by writing Pickering ostensibly on her behalf. She left intermittently, but when Pickering threatened to turn her work over to another, she did come back to finish the work she was doing in honor of the uncle she greatly admired. The elegant Mrs. Draper already disliked her niece-in-law who dressed carelessly and did the work as she herself thought best, instead of dutifully, and without questioning, following the direction of her superior (namely, to adopt the Pickering–Fleming system and apply it more precisely to her better spectra). Mrs. Draper actually encouraged Pickering to dismiss her. Finally the catalogue was finished in 1897.

Except for Maury's discovery of how different series of lines progressively faded and others increased in intensity from one standard to the next, one wonders how long it would have taken Pickering to realize the need for rearranging the sequence of his lettered classes. He also disapproved of Maury's use of the *a*, *b*, and *c* divisions, considering them simply an indication of the quality of the photographic images, unrelated to intrinsic stellar characteristics. Pickering's opinions notwithstanding, these designations ultimately became recognized as the first spectroscopic indications of luminosity differences among stars of the same HD class that depend primarily on their temperatures.

For nearly a decade Maury's system was practically forgotten. Then in 1905 and 1907 Danish astronomer Ejnar Hertzsprung (1873–1967) published his discovery, based on an analysis of apparent changes in position, called proper motions, that stars of the same color must come in two groups of widely differing intrinsic luminosities. Hertzsprung (Fig. 10) reasoned that if this were really so, there should be some differences in their spectra. He found nothing relevant in the published Harvard classes given by Pickering and Fleming in 1890 or by Cannon in 1901. But when he consulted Maury's catalogue, he found that the stars to which she had assigned the *c*-characteristic were indeed the stars of highest intrinsic luminosities. We call them giants and supergiants, the others dwarfs, but Hertzsprung described them as analogous to the whales among the fishes. He wrote Pickering a glowing appreciation of Maury's work, calling it "the most important advancement in stellar classification since the trials of [Hermann] Vogel [(1841–1907)] and Secchi." Hertzsprung also deplored that Pickering in his *Harvard Revised Photometry* of 1908 failed to include the *c*-designation in the spectral classes provided by Miss Cannon. He wrote, "To neglect the *c*-properties in classifying stellar spectra, I think, is nearly the same thing as if the zoologist, who has detected the deciding differences between a whale and a fish, would continue classifying them together."[9]

Fig. 10. Ejnar Hertzsprung (1873–1967). Photograph taken in Leiden, probably about 1937 when he received the Bruce Gold Medal of the Astronomical Society of the Pacific. From a copy in the Department of Astronomy, Yale University.

Pickering replied that the spectra Miss Maury had studied were not of sufficiently good quality to make the very distinctions Hertzsprung had proven significant! Hertzsprung did not accept Pickering's verdict, pointing out that all of Maury's stars with the *c*-designation were stars of negligible proper motion and therefore must be more highly luminous than others of the same color class and apparent magnitude. If two stars appear to be of the same magnitude but one is more distant than the other, then the more distant must be intrinsically the more luminous.

In Miss Cannon's classifications of the southern spectra in 1901, she did call attention in her Remark 40 to stars whose spectra showed sharp lines, but here it would be ambiguous whether the sharpness related simply to the quality of the photograph or to the star itself. As most Harvard objective prism plates showed more than one star, it would have been easy to check whether the lines of the other stars on the same plate all had sharp lines merely representing plate quality, or if not, demonstrating that the star with Maury's *c*-characteristic was indeed special. Both Maury and later Cannon noted in their Remarks that an ionized strontium line was exceptionally strong in some stars, but not in others of the same general class. These stars, too, Hertzsprung found to be high-luminosity stars. He remarked in 1910 at the International Solar Union that, "I imagine for the future a spectral classification in two coordinates, the one giving the normal color index and the other the normal brightness corresponding to the spectrum observed."[10] Such a system was initiated at the Yerkes Observatory in 1940, and became known as the MK system in honor of its principal authors, William W. Morgan (1906–1994) and Philip C. Keenan (1908–2000). The Henry Draper Memorial classes are being replaced progressively by the modern MK, but are still lacking for nearly half of those classified by Annie J. Cannon. If only Pickering had appreciated Maury's conclusions and accepted and acted upon Hertzsprung's remarks, a two-dimensional system could have evolved at Harvard over 30 years before the currently preferred MK system.

With Pickering's impatience and disapproval of Miss Maury's work, it is small wonder that she was an unhappy person at Harvard. She has been described in print by someone, who could not have known her personally, as "a dour and talented astronomer whose physical insights and boredom with drudgery did not well fit her for the routine work of spectral classification."[11] I strongly disagree with the implications of this verdict. The word "dour" is not a synonym for "unhappy." She spent more time than anyone carefully, and with keen interest, ferreting out all of the details discernable in the spectra, pondering what their significance might be, assuming they had a bearing on stellar evolution. She was not bored with her work, just frustrated by the obvious disapproval of her efforts. She might well have become bored later if she had been required to apply an already accepted system to thousands upon thousands of stars (as Annie Cannon was glad to do), with no time allowed for applying the results to astrophysical or galactic-structure problems. Cecilia Payne-Gaposchkin (1900–1979), whom I rate as the ablest of 20th-century astrophysicists, understood Maury's predicament well, attributing Maury's slowness to her inquisitive mind, pondering what it all meant astrophysically. Payne-Gaposchkin concluded that Pickering chose his staff to work, not to think.

In 1889 Pickering discovered the first spectroscopic binary recognized as such, τ UMa (Mizar), by noticing that the calcium K line in its spectrum was sometimes double, at other times single.* As the two component stars revolve around one another, one would appear to be approaching, the other receding from the observer, hence the spectral lines of one would be shifted periodically toward the blue, those of the other toward the red end of the spectrum. Later the same year, Maury discovered the second spectroscopic binary, β Aurigae. Many photographs then were taken of the spectra of these two binary stars, which Maury measured and used to compute their orbital periods. This work was appreciated. From England, John Herschel (1837–1921), son of Sir John F. W. Herschel (1792–1871) and grandson of Sir William Herschel (1738–1822), wrote Pickering in 1890 "to convey to Miss Maury my congratulations on having connected her name with one of the most notable advances in physical astronomy ever made."[12] In 1898 she published an updated paper on β Aurigae,[13] based on 200 spectra, yielding a period of 3.984 days as compared to the current value of 3.9600 days. Agnes Clerke quoted a parallax of $0''.06$ for β Aurigae.[14] On the basis of its parallax,** William Huggins (1824–1910) found that the separation of the two components of β Aurigae would be only $0''.005$. Clerke concluded that one would need a telescope of 80 feet in aperture to be able to resolve the components visually! In 1920 Maury published a paper on the orbits of μ^1Scorpii and V Puppis (both eclipsing as well as spectroscopic binaries).[15] Spectroscopic binaries had become Miss Maury's prime interest.

In her catalogue Maury added a capital C, indicating composite spectra, to the classes of 20 stars. A catalogue of spectroscopic binaries with determined orbits that was compiled in 1989 by A.H. Batten and colleagues at the Dominion Astrophysical Observatory in Victoria, British Columbia, Canada, includes 15 of Maury's stars with composite spectra as well as β Aur and ζ UMa, which had been discovered by the doubling of their spectral lines rather than by noting differences between the spectra of their two components.

Another star that especially intrigued Miss Maury was β Lyrae. Variability of its spectrum had been discovered by Mrs. Fleming in 1891, and Maury again made a careful study of its changes. For many years, at her request, more spectrograms were taken with the 11-inch Draper telescope. Her analyses culminated with an extensive article in 1933.[16] Well documented as her paper was, her conclusions were not always accepted. Frederick J. M. Stratton (1881–1960) appreciated her difficulties, stating in 1934 that, "Miss Maury herself would be the first to admit that much remains to be done on this star, but the labour and love that she has so long devoted to β Lyrae will be of the greatest service to those who carry on her

* A spectroscopic binary is a star that appears single to the naked eye or in direct photography but is revealed to be a double star by periodically showing double lines in its spectrum. If one of the stars is approaching the observer the wavelengths of its spectral lines are displaced toward the violet, if receding toward the red. In the case of a binary whose relative orbit is not nearly perpendicular to the line of sight, as one star appears to be approaching, the other appears to be receding from the Earth; hence the lines appear double.

** The parallax of a star is the angle subtended at the star by the radius of the Earth's orbit. It is determined from measurements of the change in the apparent position of the star in the sky as seen from the Earth about six months apart.

work to later stages."[17] Thereafter she paid occasional visits to Harvard to check on newer plates. Payne-Gaposchkin notes that Maury liked to quote Henrietta Leavitt (1868–1921), who had remarked about β Lyrae, "We shall never understand it until we find a net and fetch the thing down!"[18]

Under Harlow Shapley's later directorship of Harvard College Observatory, Miss Maury became happy, as he understood her and always encouraged independent thinking. Miss Maury's brother (who had assumed Draper as his last name) wrote Shapley thanking him for his understanding and encouraging his sister whom, he said, Pickering had not appreciated. Cecilia Payne-Gaposchkin has said of Miss Maury that she had a flair for picking the most difficult problems to pursue. Late in life Maury marveled at what had been learned about the vast universe, wistfully commenting, "But the human brain is greater yet because it can comprehend it all."[19] Today, a half century later, she would be amazed by all of the new discoveries that still defy universally convincing interpretations.

Annie Jump Cannon (1863–1941)

Annie Jump Cannon (Fig. 11) was born on December 11, 1863, in Dover, Delaware, the oldest of the three children of Wilson Lee and Mary Elizabeth Jump Cannon. By a previous marriage of her father, Annie also had one half brother and three half sisters. Mr. Cannon was a prosperous shipbuilder and merchant as well as a member of the Delaware Senate. It was a cultured and happy family. Her mother

Fig. 11. Annie J. Cannon (1863–1941). *Source*: *Annals of Harvard College Observatory* **112** (1949), frontispiece.

first taught Annie the constellations. In a makeshift observatory in their attic Annie recorded her observations by candlelight. After graduating from the Washington Conference Academy (high school), she entered Wellesley College where she studied astronomy under Professor Sarah F. Whiting, who instilled in her a desire to continue investigations of stellar spectra. However, after graduation from Wellesley in 1884, she returned to her home in Dover where she devoted much of her time to social activities and to music, being an excellent pianist. But when her mother, to whom she was especially devoted, died in 1893, Annie returned to Wellesley for a year of graduate work and as an assistant to Professor Whiting. She then attended Radcliffe College in 1895 until she was appointed an assistant under the Henry Draper Memorial in 1896.[20]

In his introduction to Annie J. Cannon's "Spectra of Bright Southern Stars" of 1901, E. C. Pickering stated, "In all three cases [Fleming, Maury, Cannon], it was deemed best that the observer should place together all stars having similar spectra and thus form an arbitrary classification [system] rather than be hampered by any preconceived theoretical ideas, or by the previous study of visual spectra by other astronomers."[21] This statement seems strikingly contradictory to his opposition to Maury's having done just that! Cannon did not devise an independent system but began in 1896 by dutifully accepting but refining the Pickering–Fleming system. She subdivided their classifications on the decimal system on the basis of her higher-dispersion spectra taken with the 13-inch Boyden refractor and up to three objective prisms, giving dispersions from the hydrogen $H\beta$ to $H\varepsilon$ lines ranging from 2.24 to 7.43 centimeters. She aimed for completeness of all stars south of declination $-30°$ and brighter than 5.00 photometric magnitude, but she added numerous fainter stars and, for comparison with Maury's classes, added many stars between declinations 0° and $-30°$, as well as a few northern stars.

Cannon gave very precise descriptions of the criteria she considered in assigning her classifications. She examined under magnification each spectrum to be classified by placing its spectrogram film next to standard spectra and then interpolating between them. Her finished catalogue of 1901 contained 1122 stars. She compared her classes with those determined for the same stars by Maury, showing clear correlations.

In later publications of 1912, Cannon contributed further spectral classes of bright stars lacking in her 1901 catalogue, of Maury stars reclassified on Cannon's system, and of double stars for which both components are of 7.5 magnitude or brighter. In 1913 Niels Bohr identified Pickering's so-called additional hydrogen lines, found originally in the spectrum of ζ Puppis, as arising from a singly ionized helium atom. This information was not yet available to Cannon, who assumed, as Pickering had, that they arose from the hydrogen atom and designated them as $H\beta'$ through $H\theta'$. In her 1912 publications, Cannon simplified her terminology by dropping the last letter of classes that fell between two standards, for instance, whereas previously she gave A3F, she now used only A3. At first she did not use a zero for stars equaling a standard; thus, for example, what previously had been classified K is now called K0, as recommended by Hertzsprung, reserving plain K for uncertain decimal divisions.

Upon completion of her catalogues of bright stars, Cannon began the classifications of stars to 9th photographic magnitude, using plates taken with the 8-inch Bache telescope in Arequipa and the 8-inch Draper telescope in Cambridge, giving spectra of either 0.2 or 0.7 centimeters between the hydrogen Hβ and Hε lines. This work, *The Henry Draper Catalogue* (HD), giving spectral classes for 225,300 stars, was published in Volumes 91–99 of the *Annals of Harvard College Observatory* between 1918 and 1924. This was the first, and it still remains the only catalogue of spectral types that is practically complete to 9th magnitude and covers the entire sky from pole to pole. Received by most astronomers at the time with much appreciation, a few experts nevertheless found fault because it does not distinguish between stars of high and low intrinsic luminosity, a distinction Danish astronomer Ejnar Hertzsprung had detected in 1905 in the classifications by Miss Maury. Later, in 1925–1936, in regions for which other astronomers requested spectral types, Cannon produced Volume 100 of the *Annals of Harvard College Observatory*, bringing her total number of classifications to 272,175. In this volume Cannon, for the first time, substituted decimal classifications for M-type stars, using M0, 1, 2, 3, 5, and 7 instead of Ma to Md.

Cannon frequently used part-time clerical assistance for recording her observations. On one occasion during the 1926–1927 college term, a Radcliffe student was recording for her when Harlow Shapley, Director of Harvard College Observatory, came in to request Cannon to do something she obviously did not want to do. Many years later the assistant (who had been a Radcliffe classmate of mine) reminisced, telling me that Cannon and Shapley one day argued hotly for some time when the usually charming Cannon suddenly turned off her hearing aid in order to hear no more! Shapley just had to leave. (Cannon had lost her hearing while a student at Wellesley in an unusually bitter winter.) My classmate could not recall the subject of Shapley's unfavorable request. I often wondered if he had not been trying to persuade her, in her future classifications for the HD Extension, to adopt Maury's *c*-characteristic and other remarks as part of her spectral classes, as Hertzsprung so urgently suggested. But Cannon adhered strictly to Pickering's opinions. In her mind Pickering could not have been wrong, even though experts Hertzsprung, Henry Norris Russell (1877–1957), Director of the Princeton Observatory, and Otto Struve (1897–1963), Director of the Yerkes Observatory, all agreed that the *c*-characteristic was a valid criterion for high luminosity and not merely an indication of superior-quality photographs.

Cannon did not live to complete her final volume of spectral classifications, which was published in 1949 by her devoted assistant, Margaret Walton Mayall (1902–1995), bringing the grand total of Henry Draper Memorial classifications to 359,083.

The common introduction to each of the nine volumes of *The Henry Draper Catalogue* (HD) describes the standard type for each of the classes P, O, Oe5, B, A, F, G, K, M, N, and R, but class S is described only in the last two of these volumes, in each of which just one star is classified S. These stars, characterized by features of zirconium oxide, are comparatively rare, and most of them had been classified previously simply as peculiar. Dorothy Davis (1913–1999)[22] in 1934 reclassified 21 variable and 11 non-variable stars as class S,[23] all but one of which are included in the HD; the exception, S Cyg, was fainter at maximum than the ostensible limit for the HD. The 31 included in the HD were classified by Cannon as follows:

Pec	K5p	Ma	Map	Mb	Mbp	Md	Np	Rp	S	Total
12	1	1	1	1	2	6	3	2	2	31

Thus, for 21 of the 31 stars some sort of peculiarity (p) had been noted by Cannon in the HD.

Cecilia Payne-Gaposchkin quoted Henry Norris Russell as saying that someone should ask Miss Cannon exactly how she classified the spectra. The descriptions she repeated in each of the HD volumes were derived from careful examination of large-dispersion spectra. Few of those details could be recognized on the very small-dispersion spectra of the much fainter stars that make up the bulk of the HD Catalogue. Payne-Gaposchkin's reply to Russell was that Cannon would not be able to tell exactly how she classified: "She was like a person with a phenomenal memory for faces. . . . She had amazing visual recall, but it was not based on reasoning . . . she simply recognized them."[24] Cannon no longer compared individual spectra with standards; she just looked at the spectra with a magnifying glass and classified them at the astonishing rate of about 300 stars an hour, or one every 12 seconds! She first numbered the stars to be classified on the plates. Then, while she examined their spectra, she dictated to an assistant the number and spectral class to be entered into a notebook. For the fainter stars, for which no lines were discernable, she relied on the distribution of light in the continuum.

At that time little was known about interstellar absorption of light. Blue light is scattered more than red light by the Earth's atmosphere, red light passing through almost unchanged. Similarly, for stars situated in the Milky Way, which contains huge amounts of interstellar gas and dust, one might expect Cannon's spectra of faint stars, especially those bluer B and A types on which no lines could be clearly seen, would be classified later,[25] or as though they were redder than modern classifications from better spectra.*

The spectral sequence, running from the blue O, B, and A types to K and M is obviously a color sequence that also proved to be a stellar-temperature sequence. While the sequence was established only on an empirical basis without appeal to physical theory, speculation became rife in attempting to relate the adopted sequence to stellar evolution. Miss Cannon in her first published catalogue commented on the adopted arrangement:

> The order of the development is not indicated, and the series might proceed from Class Mb to Class Oe, instead of from Class Oe to Class Mb. The latter seems more probable, perhaps owing to its agreement with Laplace's theory of stellar development.[26]

* The terms "early" and "late" are still used, without any implication as to stellar evolution, "early" corresponding to the beginning of the spectral sequence, "late" to the end of the empirically determined arrangement of the classes.

Pierre Simon Laplace (1749–1827), who had proposed his "Nebular Hypothesis" in 1796 in his *Exposition du Système du Monde*, did not show confidence in his theory, describing it as

> these conjectures on the formation of the stars and of the solar system, conjectures which I present with all the distrust which everything which is not a result of observation or of calculation ought to inspire.[27]

Indeed, Laplace's evolutionary theory, as well as several later ones by others, did not survive the development of modern astrophysics.

Nancy Houk and her assistants at the University of Michigan have been reclassifying the HD stars on the modern MK system. Their work has proceeded from the south pole at declination $-90°$ to declination $+4°$, but most of the northern hemisphere still remains to be classified. The MK types adhere to the published HD criteria for the temperature or color part of the classification but then add a second part, in conformity with Hertzsprung's early recommendation, with Roman numerals I through V, to represent the intrinsic luminosity or absolute magnitude part of the class,* supergiant to dwarf. Houk's spectra are of far better quality for the fainter stars than were Cannon's. Houk used nearly all ten divisions between the successive letters connoting the successive spectral classes. Cannon did not. For example, between classes G0 and K0 Cannon used only G5. Hence, assuming Houk's classes to be more precise, many of the relative errors in Cannon's classes merely represent coarser divisions rather than systematic errors depending on absorption effects.

Two regions in the Milky Way and two regions at high galactic latitudes (meaning far from the Milky Way) were examined for faint stars, 8^{th} magnitude or fainter, to test if Miss Cannon's classifications for faint relatively blue B and A-type stars were indeed affected by interstellar absorption more than the redder K and M-type stars. At high galactic latitudes there are very few B-type stars; and for most M-types Cannon did not use the decimal system of sub-classification. Hence, at high galactic latitudes A types, and only K types, were used. If Cannon had been classifying the faint stars by the distribution of light in spectra too faint to show any spectral lines, then stars in the Milky Way would be more seriously affected by interstellar absorption than similar stars at high galactic latitudes where one would expect interstellar absorption to be considerably less than in the Milky Way.

In Table 4 I have compared Houk's temperature components of her classes with Cannon's, giving the range of the differences and their averages for the four regions sampled, two in the Milky Way and two at high galactic latitudes. The average differences do indeed indicate that Cannon classified the bluer B-type Milky Way stars later than Houk's classifications, which are based upon plates clearly showing the line criteria. Thus, for stars in the Milky Way the bluer B-type stars were classified by Cannon an average of 4 or 5 divisions later than the more accurate modern MK classes,** while far from the Milky Way, at high galactic latitudes, there is negligible

* The absolute magnitude of a star is defined as the magnitude the star would have if it were at a standard distance of 10 parsecs. Parsecs are reciprocals of the parallax. Thus a parallax of 1″ of arc corresponds to a distance of 1 parsec, which is equivalent to 3.26 light years or 19.16×10^{12} miles.

** An average difference of $+4$, for example, indicates that Cannon classified stars 4 subclasses later than Houk; thus, Houk's class B0 Cannon would have called B4.

Table 4. Comparison between HD and MK temperature classes for stars of magnitude 8.0 and bright modern B-types compared with HD.

Region	MK Spectra		HD-Houk	
	Houk	**Range**	**Number**	**Average**
Milky Way				
Ser, Sct, Aql	B0 to B3	−1 to +6	26	+4
	K0 to K5	−2 to +4	28	+0.4
Scorpio	B0 to B3	−0.5 to +10	37	+5
	K0 to K5	−5 to +3.5	37	+0.1
High Galactic				
Cetus	A0 to A5	−3 to +4.5	25	−0.3
	K0 to K5	−5 to +4	25	−0.8
Sextans	A0 to A5	−3.5 to +2	25	−0.6
	K0 to K5	−5 to +5	25	+1.0
Bright (Naked-Eye) Stars				
	HD-BS			
RA 1–4 hours	B0 to B3	−3 to +4	43*	+0.1

* All but 8 in the *Milky Way*.

difference between the errors of the early A-type and late K-type stars. At high galactic latitudes there are hardly any B-type stars.

While this account indicates the deficiencies of Cannon's classifications of faint early-type stars, the apparent errors rarely exceed half a spectral class (for instance, from B0 to B5). In view of the poor quality of the spectra of the faint stars, the agreement with the later more definitive spectra is more impressive than are the actual errors. For some statistical studies, the HD values may still be useful.

The relative errors of Cannon's classifications of the early B-type stars (naked-eye stars brighter than 6.5 magnitude) in the *Bright Star Catalogue*,[28] as shown in the last section of Table 4, are negligible; the majority of these stars are in the direction of the Milky Way. These stars were all classified on the high-dispersion spectra such as Cannon used for setting up the standards for classification on the basis of spectral-line criteria. In the current version of the *Bright Star Catalogue*, MK classes are available from various sources for all but 6 percent of the 9110 stars.

Miss Cannon did more than her voluminous classifications of stellar spectra. She also had an intense interest in variable stars. Between 1897 and 1909 she made nearly 10,800 visual observations of variables with Harvard's 6-inch Post telescope. In 1897 W. M. Reed started a card-catalogue bibliography of variable stars that Miss Cannon took over in 1900 when it contained 15,000 references. She maintained it meticulously the rest of her life, and by 1940 it amounted to about a third of a million references. This is now housed at the American Association of Variable Star Observers. Cannon published two catalogues of variable stars, a provisional one in 1903 and another in 1907, as well as an extensive compilation, coauthored with Pickering in 1909, of observations of maxima and minima of long-period variables, some dating back to the 1500s. She herself discovered some 300 variables and 5 novae. Like her predecessor, Mrs. Fleming, Cannon found many of them by virtue of their spectra.

Unlike Antonia Maury who was not appreciated at Harvard and therefore could not conceal an unhappy disposition, Annie Cannon had a pleasing, gracious personality and was liked by almost everyone she met. Williamina Fleming and Cannon at Harvard, as well as Frank Schlesinger's women assistants at Yale, fulfilled Schlesinger's expectations as expressed in his letter to George Ellery Hale (1868–1938) in 1901, as quoted at the head of this article, to which Harvard's Director Pickering fully subscribed. The successes of both male directors and their women employees were achieved because the women compiled, as instructed, massive catalogues whose value their male initiators realized but lacked the necessary time and patience to carry the work to completion themselves.

In 1885 when Pickering, Nettie Farrar, and Fleming were collaborating on establishing a classification system for stellar spectra, the number of women employed at Harvard College Observatory was six, all employed as "computers." The seven men that year all had professional titles. Until 1903 the number of men exceeded the number of women; thereafter more women than men were appointed (Fig. 12), indicating how well both Pickering and his successor Harlow Shapley (1885–1972), Director from 1921 to 1952, appreciated their services. Throughout Pickering's directorship (1877–1919), the majority of the women participated in work related to the Henry Draper Memorial.

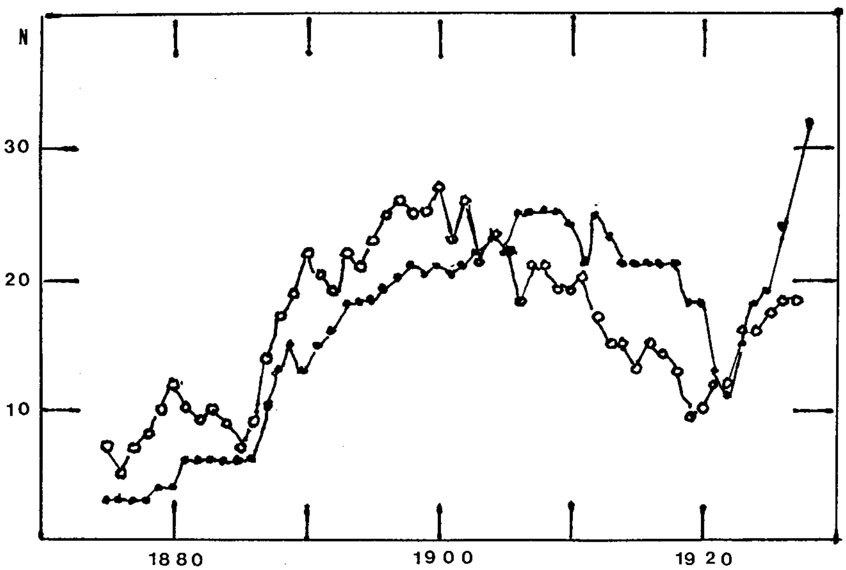

Fig. 12. Numbers of men (open circles) compared to numbers of women (dots) employed at Harvard College Observatory 1875–1927.

The Utility of Stellar Spectra

In 1914 Walter S. Adams (1876–1956) and Arnold Kohlschütter (1883–1969) at Mount Wilson Observatory published a paper that must have delighted Hertzsprung.[29] They found that numerous lines varied in intensity among spectra of the same HD spectral class and that the differences depended on the absolute magnitudes of the stars. Proper motions were available for all of the stars they studied, indicating (just as Hertzsprung had found for the differences between Maury's *c* and *a* characteristics) that the stars with strong variable lines had negligible proper motions compared to stars in which those lines were weak. They also had trigonometric parallaxes for 95 of the 162 stars they examined. After this success, Mount Wilson observers and those at the Dominion Astrophysical Observatory in Victoria, British Columbia, Canada, as well as numerous other astronomers, determined spectroscopic parallaxes by measuring relative intensities of lines that appeared to be dependent on the absolute magnitudes of the stars. Only in 1940 did Morgan and Keenan expedite the procedure by appending luminosity classes to the ordinary spectral classes. Subsequently, for the determination of space distributions of the various classes of stars, far better results could be obtained than were possible from the early classes that did not differentiate luminosity differences among stars of the same color or temperature.

From the two-dimensional MK type assigned to a stellar spectrum, one can tell what the composition of the stellar atmosphere is knowing to what atoms or molecules the spectral lines correspond. Physicists also have determined under what circumstances light from those elements can be radiated, and thereby one can determine the temperatures of the stellar atmospheres. Probably the most important use that can be made of the modern classifications is that they furnish data for determining stellar distances. This is very important, because the standard trigonometric means for determining parallaxes can be applied only to relatively nearby stars, whereas the so-call spectroscopic parallax method depends only on a sufficient amount of light to obtain a good spectrum. With ever improving techniques, spectra of increasingly fainter stars can be obtained, providing distances too great for trigonometric parallax determinations. Among the over 5800 stars for which trigonometric parallaxes are available in the most recent *General Catalogue of Trigonometric Stellar Parallaxes* (1995),[30] some 13 percent have errors greater than the sizes of the inferred parallaxes, making any inferred distances meaningless.

How are spectroscopic parallaxes determined? Astronomers make abundant use of a simple formula,

$$M = m + 5 + 5 \log \pi = m + 5 - 5 \log d,$$

where M is the absolute magnitude, m is the apparent observed magnitude, π is the parallax, and d is the distance in parsecs. From stars of a particular MK class for which accurate trigonometric parallaxes are available, the absolute magnitude M can be determined. One then assumes that these absolute magnitudes apply to other stars with the same spectral features for which trigonometric parallaxes are lacking, and one then uses the above formula in reverse to compute their parallaxes π and distances d.

Conclusions

Fleming and Cannon at Harvard fulfilled the expectations of the male directors that women could carry out large projects successfully for which they themselves did not have the time or patience to carry to conclusion. Maury's astrophysically more revealing classifications were unfortunately unappreciated, even discredited by Pickering, despite Hertzsprung's proof that they included valid criteria for stellar luminosity in addition to the Pickering–Fleming criteria that were correlated only with stellar temperature.

Miss Cannon's descriptions, repeated in every volume of the *Henry Draper Catalogue*, of the criteria she ostensibly used for her classifications of the HD stars could not possibly have been used for classifying the bulk of the faint stars of 8^{th} or 9^{th} magnitude. With small dispersion and limited light, no lines could be revealed in the majority of their spectra. She evidently classified simply on the basis of the distribution of the light in the spectral continuum, only the B and A types showing conspicuous light at the blue end of the spectrum, the K and M types predominating at the red.

A comparison of Cannon's spectra with the modern MK types assigned by Houk indicates systematic errors in the HD types that are dependent on interstellar absorption for stars in the Milky Way. At the time of Cannon's classifications, little was known about interstellar absorption, some astronomers actually believing (erroneously) that the observed reddening noted in the continuous spectra of some stars was an intrinsic property of the stars themselves.

Many honors were deservedly bestowed upon Cannon for her colossal systematic work of classification of stellar spectra, deficient as it has turned out to be because of Pickering's refusal to consider Hertzsprung's favorable evaluation of Maury's secondary criteria, which turned out to be correlated with stellar intrinsic luminosity. Ironically, the only honor awarded Maury (in 1943) was the Annie J. Cannon Prize,[31] founded by Miss Cannon in 1933, to be awarded by the American Astronomical Society to a woman who had rendered distinguished service to astronomy.

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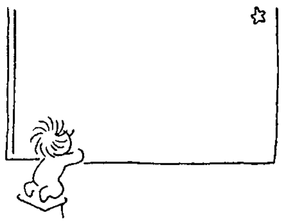
Department of Astronomy
Yale University
P.O. Box 208101
New Haven, CT 06520-8101 USA



HOW WE WONDER ?

A dialogue

- Twinkle, twinkle, little star,
h o w I wonder what you are.

Came an answer from afar:

- If you wonder sillily
I'll tell you willynillyly.
If you wonder nicely
I'll tell you what precisely.

Piet Hein