Steps toward the Hertzsprung–Russell Diagram

In the late nineteenth century, astronomers seeking to classify stars by their spectra using then-current concepts of stellar evolution found a temperature–luminosity plot that revolutionized the subject.

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Every student of stellar astronomy encounters the fundamental relationship expressed by the Hertzsprung–Russell Diagram. One cannot effectively discuss stars—how they are born, live and die, how they are distributed in space and how our Sun fits amongst them—without using this relationship as a fundamental tool of communication.

The Diagram, now almost seventy years old, is today seen in many forms. Basically it is a plot of stellar energy output against stellar surface temperature (see figure 1). The majority of stars plotted occupy a well-defined diagonal band, with a secondary grouping along the top. The observation, first made unambiguously by Ejnar Hertzsprung in 1905 and then by Henry Norris Russell in 1910, was that fainter stars are, on the average, redder than bright ones—except for those prominent stars grouped at the top of the diagram. Astronomers were on the verge of discovering this relationship for quite some time, effectively from the early 1890's. What kept this discovery from being realized and exploited earlier? We will see that the observations necessary to identify stars of similar spectral type, but of vastly differing luminosities—today identified as "giants" and "dwarfs"—were not available until after the turn of the century. As I shall show, 19th-century astronomers were unable to detect the existence of giants and dwarfs among stars of the same spectral type, which led them seriously astray.

But to say that astronomers needed only to produce adequate data before the diagram was possible is an oversimplification. In fact neither Hertzsprung nor Russell looked directly for the relationship. Each came to it from independent directions, and with different interests. But both required very much the same data base—the brightnesses and spectra of stars—and so both had to turn to a single critically important source: Harvard College Observatory and E.C. Pickering.[1]

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The meaning of stellar spectra

The origins of the Hertzsprung–Russell Diagram have one common theme: the understanding of the meaning of the different spectra seen amongst the stars. Since the 1860's and the time of Gustav Kirchhoff, astronomers engaged in spectral classification, including Angelo Secchi, Hermann Carl Vogel, J. Norman Lockyer and William Huggins, all held to the same basic observation that of all the stars examined (which by the 1880's had amounted to several thousands) only a few basic types were to be found, though variants existed. Astronomers then as now were fascinated by the variants—stars that had variable spectra or stars with bright-line spectra. But on the whole, the meaning of the variation of spectra among the few normal groups was the primary question. Throughout the late 19th century the possibility that composition differences were the cause was a persistent theme but the pervading uniformitarian philosophy of Nature, and the fact that the stars did arrange themselves into so few fundamentally different groups, were strong arguments for some other explanation. Secchi in the 1860's and 70's, and Lockyer after him, worked hard to establish temperature as the primary variable causing changes in spectral type. To most, however, the simple correlation of spectrum with stellar color was somehow at the base of the differences seen in spectra.

But there was a problem with this apparently simple picture. The trouble was that at the time, in what was a highly empirical subject, this problem was itself far from being empirical. Very few astronomers of the late 19th century could approach the question of the meaning of stellar spectra without being influenced by the idea that stars were mechanisms that radiated energy from a finite store and hence experienced a continual process of aging. This process became known as the "evolution" of a star, terminology inspired by the Darwinian revolution but in its usage somewhat misleading. And since astronomers had concluded that all sources of energy—chemical, electrical or meteoritic—were inadequate or impossible, only the process of the cooling of an incandescent sphere undergoing continual gravitational contraction, thereby converting mechanical energy into heat, was thought possible.

The cooling process was thought to be directly visible through the spectral differences seen among stars. Thus when astronomers set about examining stars for their spectra, and began looking for an appropriate system for their classification, just about all the systems devised began with blue stars. Blue stars were apparently the hottest, and had the simplest spectra. These stars were also most closely associated with gaseous nebulae in space, and had spectra quite similar to nebulae (exhibiting dark-line spectra with the same groupings and sequences found in parts of the bright-line nebular spectrum). The process of contraction of blue stars from nebulae was supposed to continue to the yellow stars (solar type), and finally, in the general cooling process, to the red stars and then to extinction. This order from blue to red was followed by all the major and popular classifications, with but a few exceptions, which we shall

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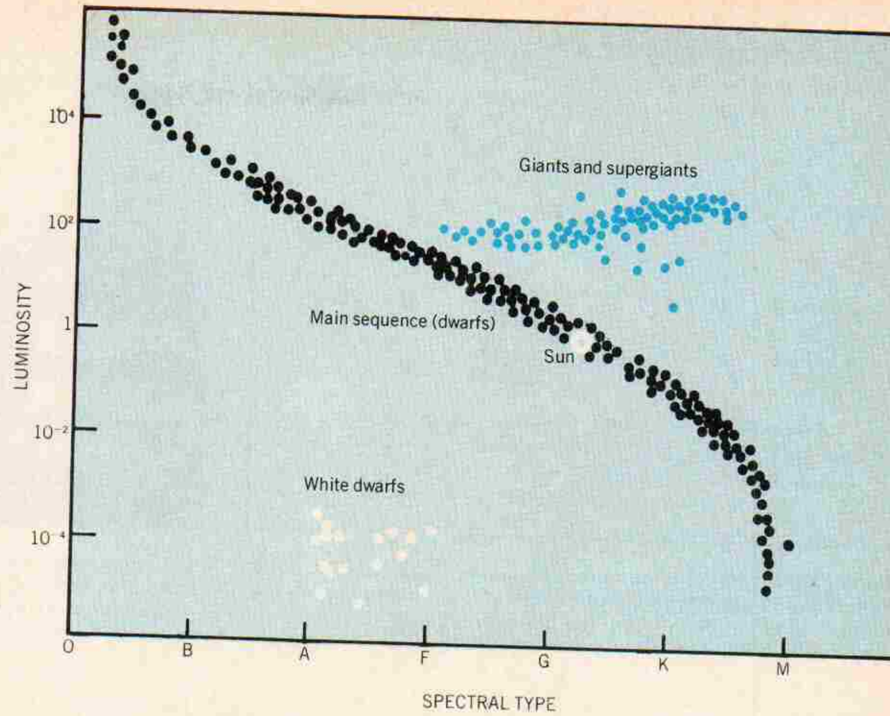


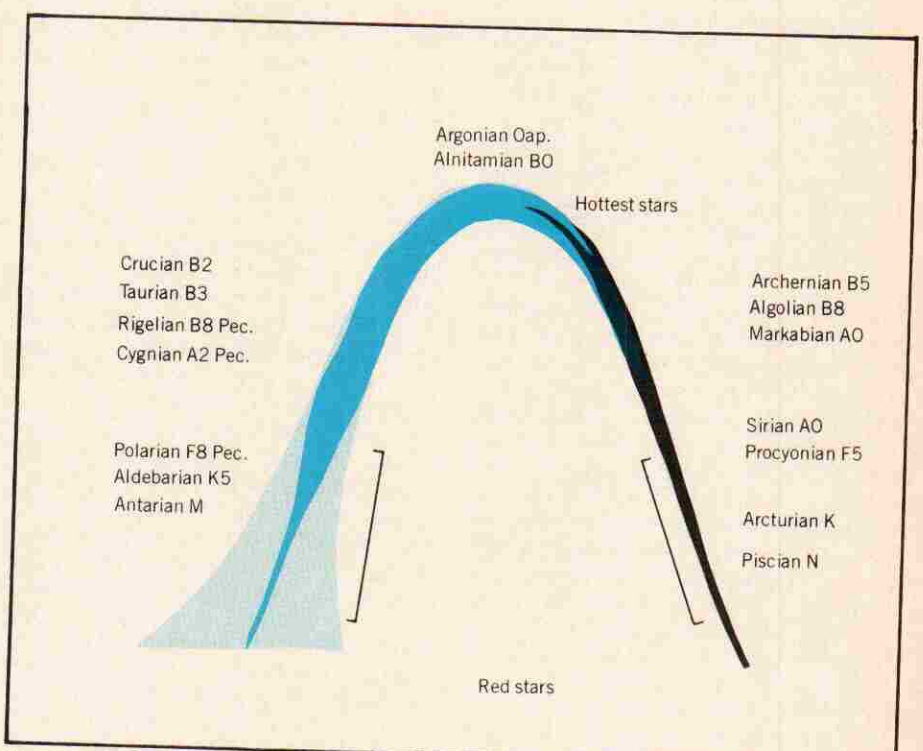
The Hertzsprung–Russell Diagram with the observed stellar spectral classes on the Harvard System plotted against stellar luminosity, or total energy output (Sun = 1). There is a well-defined relationship between a star's surface temperature and its energy output. But, as can be seen from the diagram, each of the redder stars may have one of at least two possible luminosities for its spectral class. The failure to recognize this feature led 19th-century astronomers astray in their attempts to search out empirical relationships among the various parameters that describe the physical characteristics of stars. Figure 1

identify later in the course of this article.

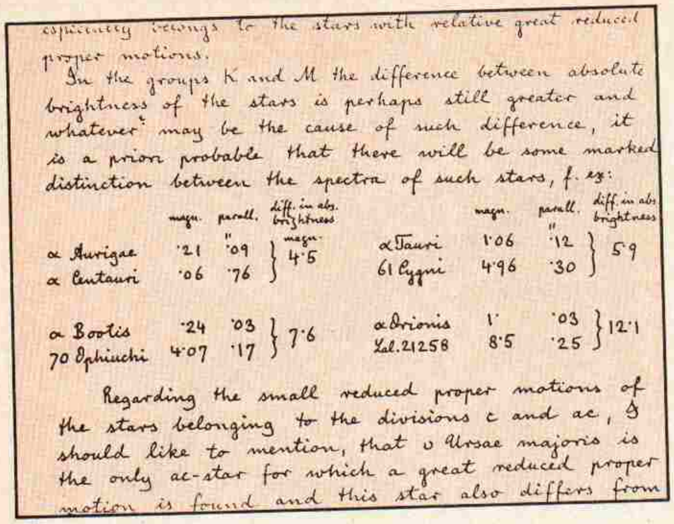
As spectra became better identified, and especially when larger telescopic apertures allowed for an increase in the dispersive powers of the attached spectroscopes, many peculiarities in individual spectra became apparent. One of the most important of these was the early recognition by Secchi of two distinct types of spectra among red stars. In these two red classes, banded structure that appeared in the same positions exhibited different structure. Secchi thought that the differences were enough to warrant a separate class, which he tacked on to his system as a fourth class. Thus his first class were the blue stars, his second were the solar type yellows, and his third and fourth were the reds. Vogel, however, believed that this separation was too great. In his system of classification, which he developed from 1874 through 1895, he retained only the three major classes, very much as defined by Secchi, but used subdivisions for what he considered to be secondary spectral distinctions. Vogel based his classification system directly on stellar evolution, and felt that the two classes of red stars were explained by minor variations in composition. Lockyer, however, advocated Secchi's original separation. He believed that Secchi's first red class, class III, exhibited bright lines and hence made them closer in evolutionary stage to nebulae than were the blue stars. Secchi's class IV stars, in Lockyer's minority view, were furthest removed from nebulae, and hence occupied the classic evolutionary place of red stars.

Lockyer favored Secchi's system because he was one of the very few who did not follow the popular concept of evolution. In Lockyer's view stars passed through the temperature sequence twice, ascending in temperature from a cold nebular state and then, after attaining a maximum temperature as a blue star, cooling to extinction through the normal color and spectral progression. Even though there was much in Lockyer's scheme that can be seen at subtler levels in the evolutionary schemes of the majority of astronomers of the time—those represented best by Vogel and Huggins—Lockyer's zeal in connecting his temperature arch (see figure 2) with his belief that nebulae were swarms of meteors in collision, and that all stars on his ascending branch were condensing meteoric swarms, kept his views quite unpopular throughout the latter half of the 19th century.[2]

From the theoretical side, Lockyer's model for stellar evolution was anticipated by the studies of J. Homer Lane of Washington, D.C. and of August Ritter of Potsdam who, between 1870 and 1883,



Norman Lockyer's "Temperature Arch," which first appeared in the late 1880's. Lockyer's elaborate classification system is represented by generic archetypes. Within the arch we have bracketed the region where a significant number of stars examined for parallax (and hence for luminosity) by Russell and Hinks were also included on Lockyer's later lists. Clearly these stars, while exhibiting similar temperatures, must differ greatly in other characteristics. Figure 2



especially belongs to the stars with relative great reduced proper motions.

In the groups K and M the difference between absolute brightness of the stars is perhaps still greater and whatever may be the cause of such difference, it is a priori probable that there will be some marked distinction between the spectra of such stars, f. ex:

	magn.	parall.	diff. in abs. brightness		magn.	parall.	diff. in abs. brightness
α Aurigae	·21	·09″	4·5 magn.	α Tauri	1·06	·12″	5·9
α Centauri	·06	·76		61 Cygni	4·96	·30	
α Bootis	·24	·03	7·6	α Orionis	1·	·03	12·1
70 Ophiuchi	4·07	·17		Lal. 21258	8·5	·25	

Regarding the small reduced proper motions of the stars belonging to the divisions c and ac, I should like to mention, that υ Ursae majoris is the only ac-star for which a great reduced proper motion is found and this star also differs from

Part of a letter from Hertzsprung to Pickering dated 15 March 1906. Here Hertzsprung shows that in the redder classes, the two sequences of stars (Antonia Maury's spectral classifications "c" and "non-c," proposed in 1897) differed by greater amounts in absolute magnitude.

The listing reads left to right in columns. Reproduction from the E. C. Pickering Collection, Harvard University Archives. The photograph of Hertzsprung on the right is reproduced by courtesy of Dorrit Hoffleit, Yale University Observatory. Figure 3

discussed the behavior of contracting gas spheres in convective equilibrium. Their independent findings showed that such bodies, beginning their lives as perfect gases, first heated upon contraction and began a cooling process only when densities within their interiors reached levels that caused them to deviate from the perfect-gas laws.[3] These works began to be noticed generally by astronomers in the 1890's and caused considerable consternation in those, especially Huggins, who wished to reconcile them with the observed sequence of spectra.

Aside from difficulties reconciling theoretical arguments with observation, the observations themselves left much to be desired. Lockyer's belief in the presence of bright lines in some red stars was symptomatic of the great difficulty of interpreting visual stellar spectra. In the 1880's photography began to rectify the situation, but even then, astronomers found that the highly limited sensitivity and poor reproducibility of photographic emulsions kept the new technique from causing an overnight sensation. It was also painfully evident that most of the prevalent classification schemes could well be fortuitous, and fraught with selection effects. The persistence of these crucial limitations in technique and completeness was in keeping with the status of the rest of the astronomical data base. Systems for determining the brightness of stars were far from standardized, and very few stars had reliable trigonometric parallaxes to determine their distances.

Such was the situation in stellar astronomy when Pickering, then a young physicist at MIT, accepted a post as the new director of Harvard College Observatory in 1877. In the 1880's Pickering began to organize two large projects with generous support from the family of Henry Draper and others, to improve the situation. He established an objective-prism survey of the spectra of stars visible from Cambridge and Arequipa, Peru, and developed an accurate and consistent scheme for the determination of the apparent brightnesses of stars.

The use of objective prisms, thin prisms placed in front of the objective lenses of telescopes, was not new to Pickering. Both Joseph Fraunhofer and Secchi had used this efficient means of securing spectra. But Pickering attached these prisms to wide-field photographic astrographs, and thereby was able to secure spectra of hundreds of stars in one exposure. These exposed plates yielded the spectral classes of thousands of stars through direct eye examination in the rooms of the Harvard College Observatory, a comparatively mild environment compared with the cramped and often frigid confines of the telescope dome.

Pickering's projects were made possible by the enthusiastic and untiring assistance of a corps of women, headed by Wilhaminia P. Fleming. By 1890, he and Mrs Fleming brought out the first *Henry Draper Catalogue of Stellar Spectra* containing some 10 000 stars.

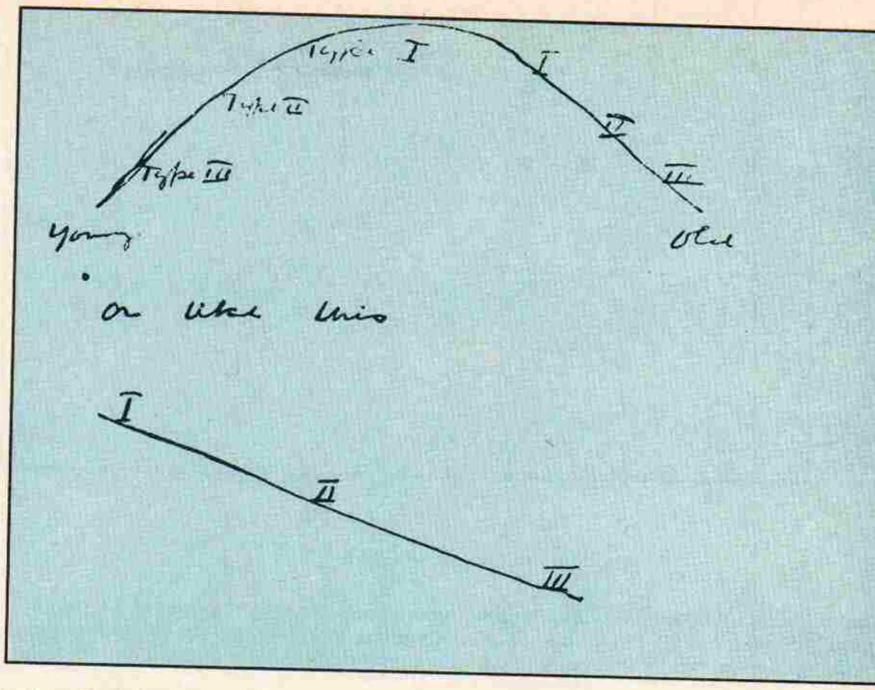
Pickering devised a simple alphabetic scheme of classification based upon the visibility of the hydrogen lines. Class A showed hydrogen lines strongest, and the series ranged on to O, P and Q. Refinements followed with more and better spectra. By 1898 he and a new assistant, Annie J. Cannon, who worked with Fleming, decided that the order must be reversed to O,B,A,F,G,K,M, primarily because O and B stars had similar helium spectra and both were closely associated in space with nebulae. This was a most important reversal in the classification system (which appeared in 1901) for it demonstrates the influence of evolution upon the Harvard classifiers. The fact that the Harvard classification has since turned out to be a highly accurate temperature classification appears therefore to be fortuitous. It has, however, remained standard to this day.

But Pickering had long realized that the average quality of each of the tens of thousands of stars his team had been classifying was at best rough. Stellar spectra were far more complicated than the single objective prism could reveal, and therefore warranted closer attention along the lines advocated by the pioneers Huggins and Vogel. Pickering therefore designed, as a corollary project, an examination of a few bright stars under higher dispersion. Antonia Maury, Henry Draper's niece and one of the few women at that time actually trained in astronomy and physics, was delegated the task, and through the 1890's from a small but high quality sample of stellar spectra she devised an extremely sophisticated system of classification.

In 1897 Maury proposed her new system of classification. It had 22 numerical groups and identified differences within many of these groups in terms of relative line strengths and line widths. In brief, she detected two primary subdivisions: stars with normal spectra (hydrogen lines broad) designated a and b; and stars with especially sharp hydrogen lines and with metallic lines somewhat enhanced, designated c and ac. She later identified these two subdivisions as "c" and "non-c" in character. Maury noted that the existence of the subdivisions within several of her numerical groups suggested the existence of "parallel courses of development." Her provocative words were not heeded at the time. Indeed, her work remained unnoticed until Hertzsprung decided to find out if the two subdivisions she had detected represented anything uniquely interesting in the physical properties of the stars themselves.

But Hertzsprung's work can only be

appreciated within its context, the statistical examination of the spatial distribution of spectra, which was a growing interest in astronomy since 1890.



In Russell's lecture notes dated 14 March 1907 the upper curve represents Lockyer's view, where Type I are blue stars, Type II, yellow, and Type III, the red stars. Russell's second curve represents the classical cooling line, and is strikingly similar to what one would expect from a main sequence. Russell commented on these two curves noting "... we cannot be sure at present though some things look as if the first hypothesis is correct ..." Reproduction from the Henry Norris Russell Papers, Princeton University Library.

Figure 4

Spatial distribution of spectra

Secchi and a few others had long realized that stars of his first class (blue stars) tended to be concentrated more towards the Milky Way plane than were stars of other classes. By 1890, this concentration had been noticed also for bright-line stars, but significant statistical studies began to appear only with the availability of the *Henry Draper Catalogue*. These studies had two major themes: The analysis of the structure of the sidereal system, and the nature of the stars themselves. Which were the most luminous stars, and which were the least? Which were the largest in radius and which were the smallest? Clearly, an analysis of the mean distances of the different spectral classes, when compared to their mean relative apparent brightnesses, would yield statistical information about their relative actual brightnesses and sizes (neglecting by necessity any differences due to relative emittance as a function of color or spectral class). It must be remembered that relative size implied relative age, because the only conceivable direction of evolution, on whatever scheme, was contraction. To astronomers of the turn of the century therefore, such studies could yield information about the evolutionary status of the different spectral classes.

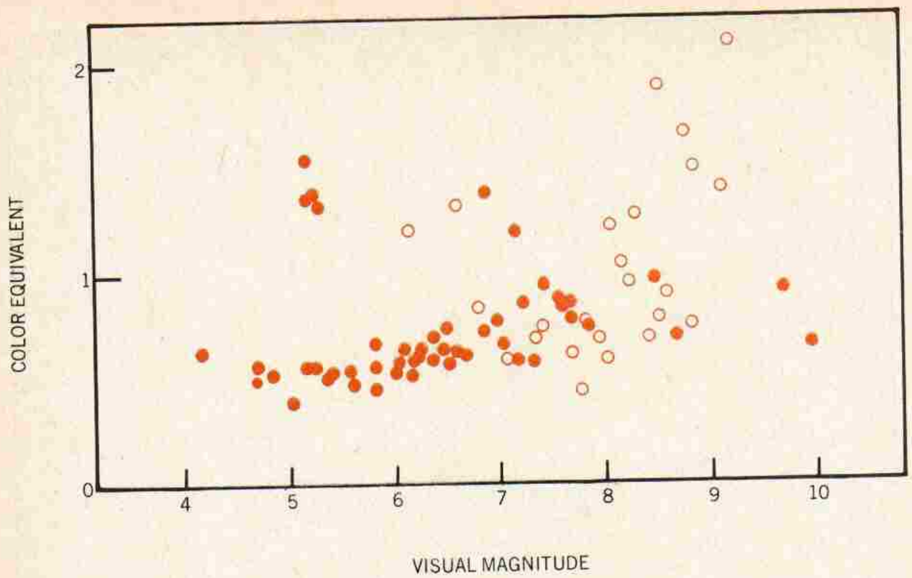
The first distribution studies were also the simplest, correlating spectral type with position on the celestial sphere. But later studies correlated apparent motions too, and when examined statistically, these yielded mean distances.

W.H.S. Monck, an Irishman about whom little is known, was one of the first, along with the legendary J.C. Kapteyn, to examine stars in this manner, correlating proper motions with spectra to determine mean distances and hence mean intrinsic brightnesses. When Monck sat down to the task of comparing the data at hand he found, in 1892, that proper motions increased with advancing (blue to red) spectral type, except that the reddest stars did not, as a group, have the largest motions; the yellow stars did. Monck concluded that the yellow stars must, as a class, be the closest to the Sun. He went so far to suggest that the Sun might be in a small cloud of solar-type yellow stars. But the fact remained that when he compared their distances and mean apparent brightnesses to the corresponding quantities for the other spectral classes, the solar-type stars came out the least luminous intrinsically. This meant that there were red stars brighter, and possibly larger, than the Sun. By 1893, not only Monck but also Kapteyn had come to this conclusion. Monck thus altered the "normal" course of evolution by placing the red stars of classes K and M before the solar-type G stars. In this he clearly was following the dictum of contraction, in spite of the fact that it played havoc with the accepted temperature history of stars.

In the next year, J.E. Gore, a friend of Monck's, showed in a popular text titled *The Worlds of Space* that there were red stars of great dimension. Using proper motions and brightness and neglecting colors, Gore found that these "giant stars" as he called them (borrowing terminology initiated by R.A. Proctor) were, as in the case of Arcturus, some 80 times the Sun's diameter or about the size of Venus's orbit. Thus, if Gore's calculations were anywhere near correct, how could solar stars cool and contract into red stars when there were red stars far larger than the Sun? These bright red stars at least could not have succeeded the yellow or blue stars, and must necessarily be quite young in their life histories. Gore did not mention the theories of Lockyer or Lane and Ritter, which would have supported his findings, but Monck did consider briefly the possibility of giant stars in his later work. He could not press the question, for he considered his data base too weak. Though spectra had become plentiful enough by that time, consistent measures of distance (and hence luminosity) from proper motions were still lacking, and far too few direct trigonometric parallaxes were available for any proper statistical analysis.

Monck therefore was not able to take the step taken by Hertzsprung just a few years later, when for the first time it was found that the reason red stars had greater mean brightnesses was the inclusion among them of giant stars. It is quite clear today that Monck's and Kapteyn's samples were affected by the great visibility of red giant stars. Though they are quite rare in space, they were the only red stars bright enough to be easily photographed for spectra.

In 1900 the problems just discussed in statistical astronomy were very much open. The proliferation of spectral classification schemes, and their interpretation, frustrated many. Further confusion came from a general lack of consensus over the physical meaning of spectra. It had long been believed that the normal spectral sequence revealed the temperature history of stars, with slight variations due to composition. But by the late 1890's, other physical variables such as density and atmospheric pressure demanded serious consideration as the primary causes. There were those, including the illustrious William Huggins, who felt that extensive masking by the stellar atmosphere, dependent upon atmospheric density, was the primary factor. In 1900 he suggested that selective absorption by an extensive stellar atmosphere might be great enough to cause a blue star to appear red. He saw the red stars as the most advanced in life, and therefore the densest. By Lane's law, they should also be the hottest, thought Huggins, who for some reason seemed to think that the stars remained perfectly gaseous throughout their lives. Thus, he intro-



One of the first diagrams published by Hertzsprung for the Hyades star cluster, adapted from Potsdam Publications **22** (1911), page 29. The horizontal coordinate represented apparent magnitude, the vertical one Hertzsprung's "color-equivalent," a measure of stellar color. Figure 5

duced masking to argue that the red stars were, in fact, the hottest, but appeared the coolest due to their selectively absorbing atmospheres. Huggins's ideas helped to confuse the interpretation of spectra, and hence it remained quite difficult to apply the radiation laws of Josef Stefan, Wilhelm Wien and Max Planck to the stars.

Ejnar Hertzsprung

Happily this situation did not stop the young Danish photochemist Ejnar Hertzsprung. As one of his earliest interests in astronomy, Hertzsprung applied the laws of radiation to find, in 1906, that Arcturus (the same star singled out by Gore) was the size of Mars's orbit. At the same time he also revived the statistical studies of Monck and Kapteyn, and entered directly upon the work that led him to construct the first "Hertzsprung–Russell" Diagram.

But what was it that allowed Hertzsprung to rediscover what Monck and Kapteyn had found but could not exploit? Hertzsprung stated at the outset of his first statistical study in 1905 that it was Maury's classification system that stimulated his interest in searching for what determines the differences in spectra among the stars. In particular he wanted to know why there were subdivisions among her spectra (a,b; c and ac). Hertzsprung began, as had Monck and Kapteyn, using proper motions statistically to derive relative distances and relative brightnesses for the different spectral classes. But, unlike the others, he had Maury's classification as a guide.

In his first analysis he found, as did the others, that the major spectral classes exhibiting greatest proper motion were the solar classes and not the red classes. But after a detailed analysis of the various groups defined on Maury's system he found that for all stars brighter than magnitude +5 the red ones had vanishingly small proper motions, and only a very few had parallaxes. But among stars of large proper motion or parallax he found mostly faint red and yellow stars. Hertzsprung was particularly intrigued that the former group contained c stars, and the latter, non-c stars. What made Hertzsprung's analysis extremely difficult was that, for the redder classes, the subdivisions were not distinct at all; so he had to construct an elaborate indirect process of analysis that allowed him to come to this conclusion.

Nevertheless, triggered by Maury's classification, Hertzsprung had found a filter by which he could distinguish intrinsically bright and faint red stars, depending upon which proper motion and brightness group they fell into. After he established the technique, he concluded that the total sample of yellow stars appeared fainter because there was a greater proportion of dwarf yellows relative to giant yellows in it. This was due to the fact that the dwarf yellows were just a bit brighter than the dwarf reds, and therefore appeared more frequently in general surveys.

After the publication of his first paper on the subject, in an obscure German photographic journal, Hertzsprung wrote to Pickering in March 1906 discussing his work and the resulting significance of the Maury system of subdivisions, which could now be used to detect luminosity differences wherever the subdivisions were distinct. Within this letter was a descriptive table outlining how he felt the c and non-c spectra should be examined so as to illustrate the great luminosity differences between them (see figure 3).

During 1906 Hertzsprung continued his work, and in 1907 he published a second paper with a slightly different selection of stars. Here he was concerned with refining the magnitude differences between the c and non-c stars by incorporating reliable parallax data, where available. He also discussed the space densities of stars in each class, finding correctly that giants of all classes were rare. With this second paper, Hertzsprung's local reputation grew. He had become a close friend of Karl Schwarzschild[4] and as a result followed Schwarzschild from Göttingen to Potsdam as a staff astronomer when the latter became the director there. But Hertzsprung's international reputation had not yet been made, even though his papers and letters were in Pickering's hands.

In 1908 when Hertzsprung received a copy of the latest *Harvard Annals* he realized with some surprise that Pickering had not taken his 1906 letter and 1905 paper seriously, for Maury's spectroscopic notation and subdivisions had not been reinstated in the publication (they were dropped in the 1901 *Harvard Annals* in Cannon's extension of the original alphabetic system). Hertzsprung wrote[5] to Pickering in July 1908 to voice his concern over the apparent neglect of so important a discovery:

> It is hardly exaggerated to say that the spectral classification now adopted is of similar value as a botany, which divide the flowers according to their size and color. 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 in classifying them together.

Hertzsprung wished that Maury's classification system would be reinstated so that stars of great luminosity could be identified. In early August Pickering responded cordially but skeptically, noting that he did not have enough faith in his own spectra to believe in Maury's subdivisions. He felt that the objective prism spectra she had used did not have the resolution or standardization one would need to be able to determine real differences in line structure, since slight instrumental changes could easily change the appearance of the lines. Pickering believed that her line differences could only be confirmed by the use of high-quality spectra taken with slit spectrographs—a conclusion he had first voiced in print in 1901.

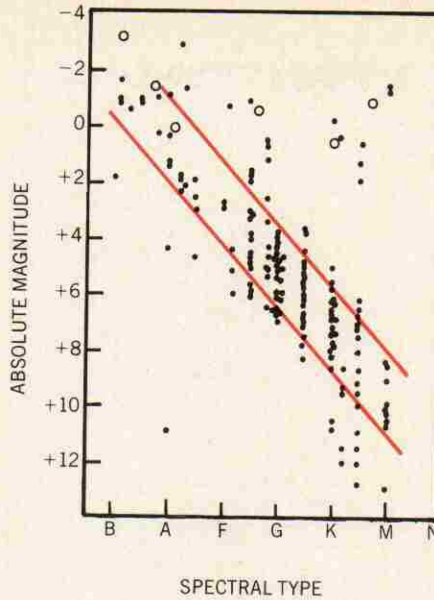
It is understandable that Pickering would be very cautious about using Maury's subdivisions. At the time, his main concern was putting the general Harvard Spectral Classification system on a sure footing in the astronomical community. At the time no system was generally preferred, and many of Pickering's colleagues, for example George Ellery Hale, continued to use the earlier systems of Secchi and Vogel. Pickering was all too aware of the inconsistencies found in many classification systems that had tried to say too much in the past, and strove to keep his own as simple and unambiguous as possible. Still, after 17 years and tens of thousands of stars classified, there was no generally accepted standard.

But this did not comfort Hertzsprung. He had also noticed that in addition to line-width variations, line ratios in the two subdivisions were different. Further, as he wrote back to Pickering arguing his point:[6]

> The fact that none of the stars called c by Antonia Maury has any certain trace of proper motion is, I think, sufficient to show that these stars are physically very different from those of divisions a and b.

By October 1908 Hertzsprung sent a new manuscript to Pickering before he submitted it to the *Astronomische Nachrichten.* In private to Schwarzschild he had expressed his bitter disappointment over Pickering's attitude[7] but to Pickering he maintained a diplomatically firm air, noting that his paper was intended for publication with or without Pickering's approval. If, however, Pickering wished to provide commentary, Hertzsprung would find it most welcome. The *Astronomische Nachrichten* paper did appear in 1909, and was a partial restatement and expansion of Hertzsprung's earlier work. These three papers contained tabulated data sufficient for a Hertzsprung–Russell Diagram, but no diagrams appeared. These only came in 1910 and 1911.

To place Pickering's skepticism into proper context, we have to provide a fuller picture of his involvement in the development of the diagram, which centered upon support for the work of Henry Norris Russell.



Russell's 1914 diagram. The vertical coordinate is absolute magnitude derived from his parallax work. The horizontal coordinate is spectral class on the Harvard System. The large open circles along the upper part of the diagram represent mean absolute brightnesses for bright stars whose parallaxes were on the order of their probable errors. All these stars had very small proper motions, indicating a statistically distant sample. Adapted from H. N. Russell, "Relations Between the Spectra and Other Characteristics of the Stars," in *Popular Astronomy* **22** (1914) page 285, figure 1. Figure 6

Henry Norris Russell

It is not rare in the history of science to find the most pivotal and crucial discoveries and studies made independently by different people at about the same time. In many cases the time was right, the need was apparent, and the discovery was "in the air." Though there is good evidence that this is true here, the universal nature of the diagram allowed for its discovery by workers interested initially in different goals.

The influences upon Russell causing him to come to the diagram, or to the relationship behind it, are quite different from those upon Hertzsprung. While Hertzsprung was intrigued by Maury's classifications, and attempted to unravel their meaning hoping for a better understanding of the apparently anomolous statistical behavior of the red stars, Russell came to the problem primarily from an interest in evolution stimulated by Lockyer's writings.

After a brilliant student career at Princeton, Russell spent several postgraduate years (1902–05) studying at Cambridge University and developing, with A.R. Hinks, Chief Assistant at the Cambridge University Observatory, one of the first photographic parallax programs ever attempted. Though this was clearly a pilot program, the 55 stars selected for study included 21 common to a recently published (1902) list of stellar spectra by Lockyer. Lockyer had selected only the brightest stars for his listing, while Hinks and Russell said their criteria for choosing parallax stars included brightness only as a minor consideration. Understandably, they preferred the more fruitful criteria of large proper motion and previous parallax measurement in choices of parallax candidates. Thus it is surprising that half their stars were on Lockyer's list. Further, when one examines the distribution of stellar types they chose, it is obvious that the Lockyer stars chosen were just those that could best test his double-branched temperature arch (see figure 2).

Russell's interest in Lockyer's hypothesis can be seen in lecture notes he prepared for a course in 1907 at Princeton. For a lecture in March 1907 on stellar evolution he first reviewed spectral classification, then the two possible courses for evolution, clearly preferring Lockyer's (see figure 4). Of great interest, though, is how he chose to represent the classical theory due primarily to Vogel. He showed it as a descending line quite like what one would expect from a rudimentary representation of the main sequence in a Hertzsprung–Russell Diagram. Unfortunately, since Russell did not label his axes, we cannot say that he knew in 1907 that for main sequence stars, brightness diminished with increasing redness. At best, this sketch represents Russell's keen intuitive powers.

To exploit his parallax work fully, Russell needed to reduce his parallaxes to account for the probable parallactic motions of the reference stars. For whereas parallaxes based upon visual meridian circle measures yielded fundamental positions and motions relative to the terrestrial observer, photographic parallaxes revealed only motion relative to the selected background reference stars. These background stars could also have their own parallactic motions, which would have to be taken into account before the actual parallactic motion of the program star could be determined. To do this Russell resorted to Kapteyn's established technique of statistically derived proper motions based upon brightness and spectral class. Thus Russell needed spectra and magnitudes, best available from Harvard and Pickering.

It was actually Pickering who approached Russell, having heard of his needs.[8] This is of interest because, by the time Russell and Pickering were in contact, Pickering had already received Hertzsprung's early paper and arguments for why the K and M red stars did not, as a group, have the largest proper motions. Yet Pickering suggested to Russell in late April 1908 that Harvard would produce the spectra of the parallax and reference stars, and added[9]: "The material would perhaps be sufficient to determine which were the most distant, stars of Class A or Class K."

After Russell sent Pickering identifications for the stars in need of spectra and magnitude, a long gestation period set in. By September 1909 Russell had received most of the data from Pickering and found at the outset that:

> . . .the fainter stars average redder than the brighter ones. I do not know of any previous evidence on this question . . . I would not now risk reversing the proposition and saying that the red stars average intrinsically fainter—some of them certainly do; but Antares and α Orionis are of enormous brightness, and the average may be pretty high.

These conclusions[10] are strikingly close to Hertzsprung's and so should have prompted Pickering to reply with mention of Hertzsprung's work, if only to state that Russell had come to the same conclusions but from a much more direct and reliable data base. But Pickering remained silent, quite possibly so skeptical

	O Oa-Oe	B Bo-B5	A B8-A3	F A5-F2	G F5-Go	K G5-K2	M K5-Mb	N Na-Nb	R Ro-R8
-6.0		2	1						
-4.5	1	5	2	2	1	1	1		
-3.0		5	5	1	1	5	3		
-1.5	3	29	29	4	7	17	7	1	
0.0	5	74	83	20	18	63	24		
+1.5	2	122	201	31	40	167	49	7	1
+3.0	2	140	522	89	72	418	120	11	2
+4.5	5	58	809	271	199	817	189	10	4
+6.0	3	50	855	469	448	1123	196	11	3
+7.5	1	25	465	396	806	844	92	7	3
+9.0		7	280	140	726	566	26	1	2
+10.5			68	16	277	331	9		
+12.0			7	6	47	115	12		
+13.5					5	16	7		
+15.0					1	4	2		
+16.5					1		2		
+18.0			1						

Unpublished Russell diagram clipped to a note from Lockyer to Russell dated June 1913, while Russell was in London. Russell evidently had this diagram with him when he visited Lockyer. Russell attempted here to indicate the number of stars found in each magnitude and spectral class range. The photograph on the left shows Henry Norris Russell as he appeared prior to World War I. The diagram is reproduced from the Russell Papers, Princeton University Library; the photograph is in the American Institute of Physics Margaret Russell Edmondson Collection. Figure 7

of Hertzsprung's use of Maury's data that he had decided to keep the matter to himself for fear of misleading Russell.

The earliest diagrams

It should now be clear that the fundamental empirical relationship between the spectra or colors of stars and their intrinsic brightnesses was established independently by Hertzsprung and by Russell well before it was ever put into the form of a diagram. Russell had the model as early as 1907—if we are allowed to read between the lines—and could have produced a diagram easily by 1909. A.V. Nielsen has shown that Hertzsprung, as early as 1908, had created a diagram of an open cluster of stars, but kept it from publication because of instrumental errors.[11]

The first diagram to see print was for the Pleiades cluster, in a paper written in June 1910 by H. Rosenberg, Hertzsprung's assistant at Potsdam. Hertzsprung's own diagrams of the Pleiades and Hyades clusters came soon after (see figure 5).

Russell first heard of Hertzsprung's work from Schwarzschild during a meeting of astronomers at Harvard in August 1910, and in 1911 he wrote to Pickering suggesting that they might follow up Hertzsprung's cluster diagrams with spectra of the stars he included, instead of the color-equivalents Hertzsprung was using. The primary reason for the lapse of time between 1910 and late 1913—when Russell became capable of producing a diagram and when he actually did so—was his own concern for the meaning of the great luminosity difference found between "giants" and "dwarfs" (terminology he had created while attempting to describe his findings in correspondence with Pickering). The differences could be due to mass or to volume. Russell's chief activity in this interval was to establish that it was a volume difference, from studies of binary stars he had initiated and that were carried out at Mount Wilson by his graduate student Harlow Shapley. Russell had earlier developed a method for determining the densities of eclipsing binaries, had maintained considerable interest in stellar densities and binary reductions all the while, and by 1910 had strong evidence that there were stars of extremely low density and hence enormous volume—giants in size but not in mass. While Shapley continued his own observations through 1912, Russell began to realize that the mass range among all stars was quite small compared to variations in other physical characteristics. Shapley's examination of about 90 binary systems helped confirm Russell's first results, which then only awaited the proper opportunity for presentation. This arose in June 1913, while Russell and a small band of American astronomers stopped briefly in London en route to the summer meetings of the International Solar Union held in Bonn.

While in London, the Americans were invited to present results of recent research to the Royal Astronomical Society. Russell presented his discussion "Relations Between the Spectra and Other Characteristics of the Stars"—a title he had kept prepared for several years. His paper was brief, due to the usual time limitations, and did not appear in print for a few months. Its first appearance was without the diagrams, though his text referred to them.

Reactions to Russell's work

Initial reactions to Russell's work were positive. Arthur Stanley Eddington worried a bit at first about Russell's thoughts on evolution, which went against the established grain, but in correspondence he admitted a deep interest and fascination. Whatever Eddington felt about Russell's evolution, which was literally a revival of Lockyer's old ideas, he was sure of the great value of the diagram (see figure 6) and wanted to publish one in a book about to see print. While Russell was in London, he met and discussed his ideas with Lockyer, who for obvious reasons was delighted with the turn of events this American had brought. A note from Lockyer to Russell (found in Russell's papers at Princeton) discussing this meeting in 1913 was clipped to three rudimentary Diagrams, and a histogram picturing the mean apparent brightnesses of the various spectral classes. I include one here, for it may be Russell's earliest attempt to represent his findings graphically (see figure 7).

In the years following Hertzsprung's and Russell's presentations the Diagram became better refined. Its primary function to picture the vast differences between giants and dwarfs was strongly supported by the invention and application of the technique of spectroscopic parallaxes, which allowed absolute luminosities to be determined by a means independent of trigonometric parallaxes. In 1920 the angular diameter of a giant star was measured by A.A. Michelson and Francis Pease at Mount Wilson and was found to be very close to predicted values.

Thus, while the diagram itself remains as an empirical fact, its interpretation has changed radically in past years.[12] Russell saw the giant branch and main sequence as a continuous series of homologously contracting gas spheres. While they were giants they behaved as perfect gases and thus heated upon contraction. But they turned into relatively incompressible fluids once on the main sequence—causing further contraction to result from cooling only.

The main sequence persisted as an evolutionary track until the mid-1920's, and the position of the giants in evolution remained unsolved until the early 1950's. Many aspects of theoretical astrophysics had to develop and mature before our present interpretation of the Hertzsprung–Russell Diagram became possible. In Russell's time, stars were purely convective, fully mixed and capable of contraction only. The many advances needed to change these 19th-century views represent the mainstream of progress in stellar astronomy over the past sixty-five years. It is a tribute to Russell's memory that he had something to do with almost all of them.

* * *

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