43. THE SPECTRUM-LUMINOSITY DIAGRAM

By Henry Norris Russell

Investigations into the nature of the stars must necessarily be very largely based upon the average characteristics of groups of stars selected in various ways—as by brightness, proper motion, and the like. The publication within the last few years of a great wealth of accumulated observational material makes the compilation of such data an easy process; but some methods of grouping appear to bring out much more definite and interesting relations than others, and of all the principles of division, that which separates the stars according to their spectral types has revealed the most remarkable differences, and those which most stimulate attempts at a theoretical explanation.

In the present discussion, I shall attempt to review very rapidly the principal results reached by other investigators, and shall then ask your indulgence for an account of certain researches in which I have been engaged during the past few years.

Thanks to the possibility of obtaining with the objective prism photographs of the spectra of hundreds of stars on a single plate, the number of stars whose spectra have been observed and classified now exceeds one hundred thousand, and probably as many more are within the reach of existing instruments. The vast majority of these spectra show only dark lines, indicating that absorption in the outer and least dense layers of the stellar atmospheres is the main cause of their production. Even if we could not identify a single line as arising from some known constituent of these atmospheres, we could nevertheless draw from a study of the spectra, considered merely as line-patterns, a conclusion of fundamental importance.

The spectra of the stars show remarkably few radical differences in type. More than ninety-nine per cent of them fall into one or other of the six great groups which, during the classic work of the Harvard College Observatory, were recognized as of fundamental importance, and received as designations, by the process of "survival of the fittest," the rather arbitrary series of letters B, A, F, G, K, and M. That there should be so very few types is noteworthy; but much more remarkable is the fact that they form a continuous series. Every degree of gradation, for example, between the typical spectra denoted by B and A may be found in different stars, and the same is true to the end of the series, a fact recognized in the familiar decimal classification, in which B5, for example, denotes a spectrum half-way between the typical examples of B and A. This series is not merely continuous; it is *linear*. There exist indeed slight differences between the spectra of different stars of the same spectral class, such as A0; but these relate to minor details, which usually require a trained eye for their detection, while the difference between successive classes, such as A and F, are conspicuous to the novice. Almost all the stars of the small outstanding minority fall into three other classes, denoted by the letters O, N, and R. Of these O undoubtedly precedes B at the head of the series, while R and N, which grade into one another, come probably at its other end, though in this case the transition stages, if they exist, are not yet clearly worked out.

From these facts it may be concluded that the principal differences in stellar spectra, however they may originate, arise in the main from variations in a single physical condition in the stellar atmospheres. This follows at once from the linearity of the series. If the spectra depended, to a comparable degree, on two independently variable conditions, we should expect that we would be obliged to represent their relations, not by points on a line, but by points scattered over an area. The minor differences which are usually described as "peculiarities" may well represent the effects of other physical conditions than the controlling one.

The first great problem of stellar spectroscopy is the identification of this predominant cause of the spectral differences. The hypothesis which suggested itself immediately upon the first studies of stellar spectra was that the differences arose from variations in the chemical composition of the stars. Our knowledge of this composition is now very extensive. Almost every line in the spectra of all the principal classes can be produced in the laboratory, and the evidence so secured regarding the uniformity of nature is probably the most impressive in existence. The lines of certain elements are indeed characteristic of particular spectral classes; those of helium, for instance, appear only in Class B, and form its most distinctive characteristic. But negative conclusions are proverbially unsafe. The integrated spectrum of the Sun shows no evidence whatever of helium, but in that of the chromosphere it is exceedingly conspicuous. Were it not for the fact that we are near this one star of Class G, and can study it in detail, we might have erroneously concluded that helium was confined to the "helium stars." There are other cogent arguments against this hypothesis. For example, the members of a star-cluster, which are all moving together, and presumably have a common origin, and even the physically connected components of many double stars, may have spectra of very different types, and it is very hard to see how, in such a case, all the helium and most of the hydrogen could have collected in one star, and practically all the metals in the other. A further argument—and to the [writer] a very convincing one—is that it is almost unbelievable that differences of chemical composition should reduce to a function of a single variable, and give rise to the observed linear series of spectral types.

I need not detain you with the recital of the steps by which astrophysicists have become generally convinced that the main cause of the differences of the spectral classes is difference of temperature of the stellar atmospheres. . . .

I will now ask your attention in greater detail to certain relations which have been the more special objects of my study.

Let us begin with the relations between the spectra and the real brightness of the stars. These have been discussed by many investigators—notably by Kapteyn and Hertzsprung—and many of the facts which will be brought before you are not new; but the observational material here presented is, I believe, much more extensive than has hitherto been assembled. We can only determine the real brightness of a star when we know its distance; but the recent accumulation of direct measures of parallax, and the discovery of several moving clusters of stars whose distances can be determined, put at our disposal far more extensive data than were available a few years ago.

Figure 1 shows graphically the results derived from all the direct measures of parallax available in the spring of 1913 (when the diagram was constructed). The spectral class appears as the horizontal coordinate, while the vertical one is the absolute magnitude, according to Kapteyn's definition,—that is, the visual magnitude which each star would appear to have if it should be brought up to a standard distance, corresponding to a parallax of 0″.1 (no account being taken of any possible absorption of light in space.) The absolute magnitude −5, at the top of the diagram, corresponds to a luminosity 7500 times that of the Sun, whose absolute magnitude is 4.7. The absolute magnitude 14, at the bottom, corresponds to 1/5000 of the Sun's luminosity. The larger dots denote the stars for which the computed probable error of the parallax is less than 42 per cent of the parallax itself, so that the probable error of the resulting absolute magnitude is less than $\pm 1^{m}.0$. This is a fairly tolerant criterion for a "good parallax," and the small dots, representing the results derived from the poor parallaxes, should hardly be used as a basis for any argument. The solid black dots represent stars whose parallaxes depend on the mean of two or more determinations; the open circles, those observed but once. In the latter case, only the results of those observers whose work appears to be nearly free from systematic error have been included, and in all cases the observed parallaxes have been corrected for the probable mean parallax of the comparison stars to which they were referred. The large open circles in the upper part of the diagram represent mean results for numerous bright stars of small proper motion (about 120 altogether) whose observed parallaxes hardly exceed their probable errors. In this case the best thing to do is to take means of the observed parallaxes and magnitudes for suitable groups of stars, and then calculate the absolute magnitudes of the typical stars thus defined. These will not exactly correspond to the mean of the individual absolute magnitudes, which we could obtain if we knew all the parallaxes exactly, but they are pretty certainly good enough for our purpose.

Upon studying Figure 1, several things can be observed.

1. All the white stars, of Classes B and A, are bright, far exceeding the Sun; and all the very faint stars,—for example, those less than $\frac{1}{50}$ as bright as the Sun,—are red, and of Classes K and M. We may make this statement more specific by saying, as Hertzsprung does, that there is a certain limit of brightness for each spectral class, below which stars of this class are very rare, if they occur at all. Our diagram shows that this limit varies by rather more than two magnitudes from class to class. The single apparent exception is the faint double companion to o^2 Eridani, concerning whose parallax and brightness there can be no doubt, but whose spectrum, though apparently of Class A, is rendered very difficult of observation by the proximity of its far brighter primary.

2. On the other hand, there are many red stars of great brightness, such as Arcturus, Aldebaran and Antares, and these are as bright, on the average, as the stars of Class A, though probably fainter than those of Class B. Direct measures of parallax are unsuited to furnish even an estimate of the upper limit of brightness to which these stars attain, but it is clear that some stars of all the principal classes must be very bright. The range of actual brightness among the stars of each spectral class therefore increases steadily with increasing redness.

3. But it is further noteworthy that all the stars of Classes K5 and M which appear on our diagram are either very bright or very faint.

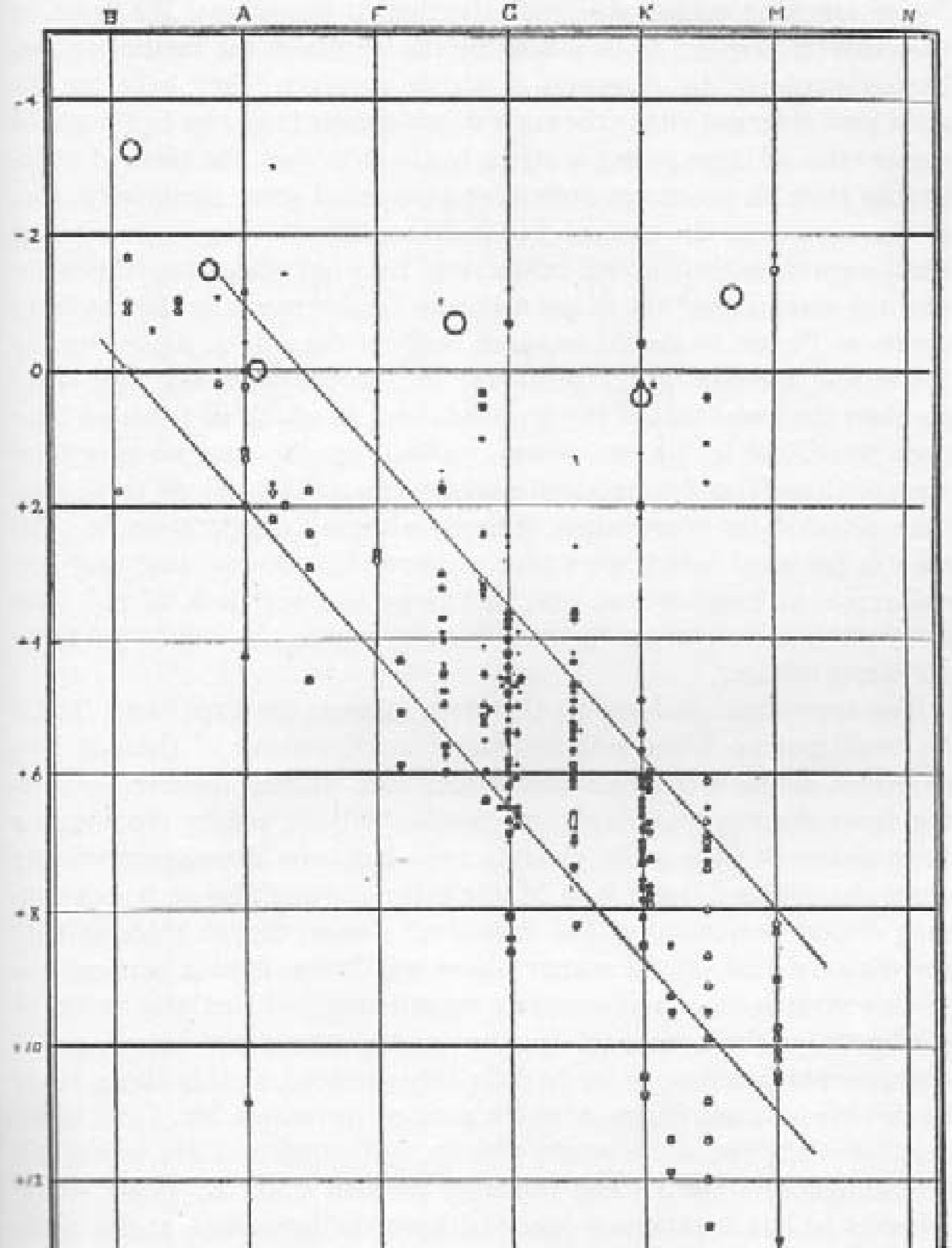

Fig. 1. The spectrum-luminosity diagram for bright stars. Ordinates are absolute magnitudes; abscissae, spectral classes.

There are none comparable with the Sun in brightness. We must be very careful here not to be misled by the results of the methods of selection employed by observers of stellar parallax. They have for the most part observed either the stars which appear brightest to the naked eye or stars of large proper motion. In the first case, the method of selection gives an enormous preference to stars of great luminosity, and, in the second, to the nearest and most rapidly moving stars, without much regard to their actual brightness. It is not surprising, therefore, that the stars picked out in the first way (and represented by the large circles in Figure 1) should be much brighter than those picked out by the second method (and represented by the smaller dots). But if we consider the lower half of the diagram alone, in which all the stars have been picked out for proper-motion, we find that there are no very faint stars of Class G, and no relatively bright ones of Class M. As these stars were selected for observation entirely without consideration of their spectra (most of which were then unknown), it seems clear that this difference, at least, is real, and that there is a real lack of red stars comparable in brightness to the Sun, relatively to the number of those 100 times fainter.

The appearance of Figure 1 therefore suggests the hypothesis that if we could put on it some thousands of stars, instead of the 300 now available, and plot their absolute magnitudes without uncertainty arising from observational error, we would find the points representing them clustered principally close to two lines, one descending sharply along the diagonal, from B to M, the other starting also at B, but running almost horizontally. The individual points, though thickest near the diagonal line, would scatter above and below it to a vertical distance corresponding to at least two magnitudes, and similarly would be thickest near the horizontal line, but scatter above and below it to a distance which cannot so far be definitely specified, so that there would be two fairly broad bands in which most of the points lay. For Classes A and F, these two zones would overlap, while their outliers would still intermingle in Class G, and probably even in Class K. There would however be left a triangular space between the two zones, at the right-hand edge of the diagram, where very few, if any, points appeared; and the lower left-hand corner would be still more nearly vacant.

We may express this hypothesis in another form by saying that there are two great classes of stars,—the one of great brightness (averaging perhaps a hundred times as bright as the Sun), and varying very little in brightness from one class of spectrum to another; the other of smaller brightness, which falls off very rapidly with increasing redness. These

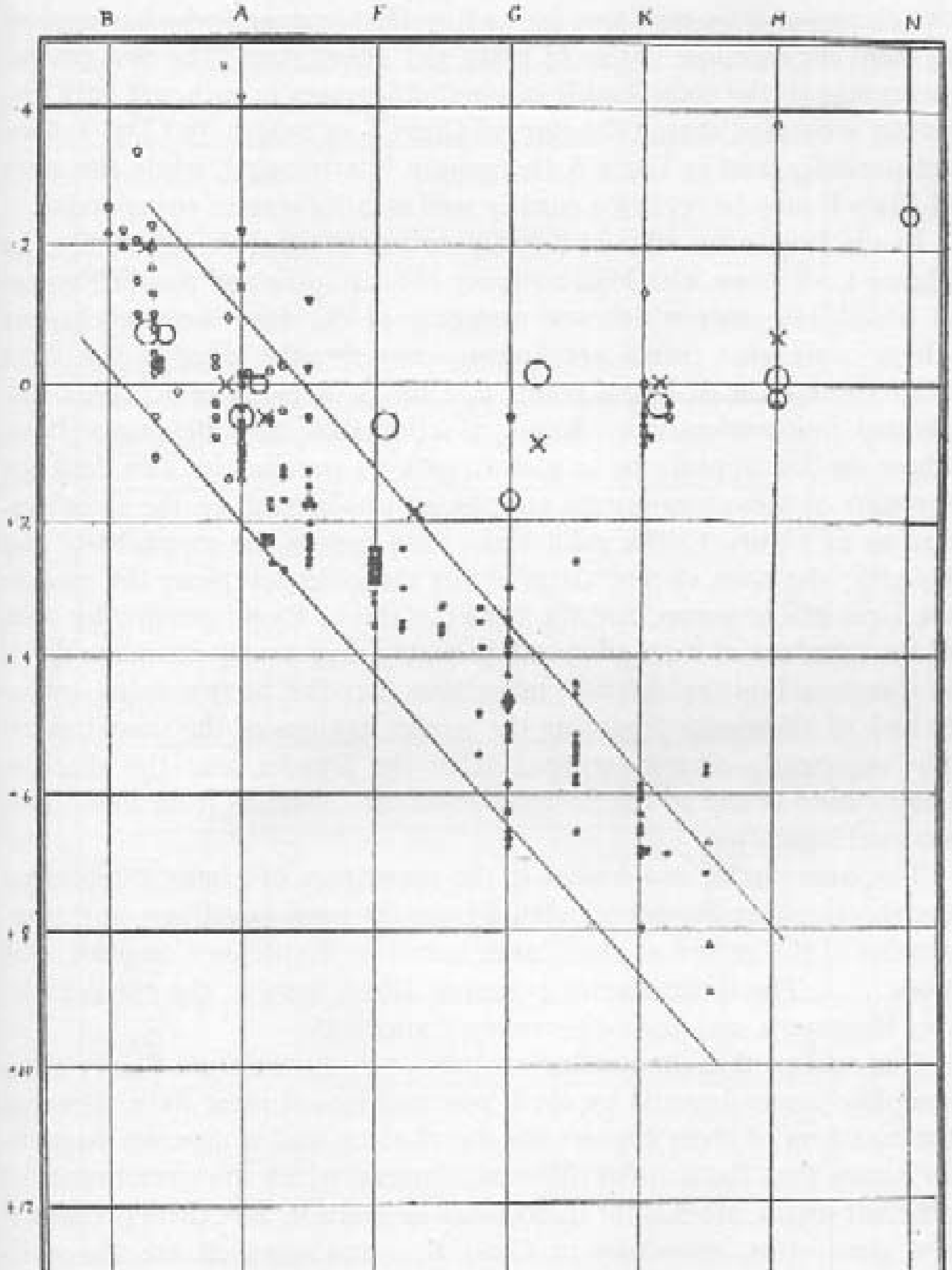

Fig. 2. Spectrum-luminosity diagram for bright groups of stars.

two classes of stars were first noticed by Hertzsprung,[1] who has applied to them the excellent names of *giant* and *dwarf* stars. The two groups, on account of the considerable internal differences in each, are only distinctly separated among the stars of Class K or redder. In Class F they are partially, and in Class A thoroughly intermingled, while the stars of Class B may be regarded equally well as belonging to either series.

In addition to the stars of directly measured parallax, represented in Figure 1, we know with high accuracy the distances and real brightness of about 150 stars which are members of the four moving clusters whose convergent points are known,- namely, the Hyades, the Ursa Major group, the 61 Cygni group, and the large group in Scorpius, discovered independently by Kapteyn, Eddington, and Benjamin Boss, whose motion appears to be almost entirely parallactic. The data for the stars of these four groups are plotted in Figure 2, on the same system as in Figure 1. The solid black dots denote the members of the Hyades; the open circles, those of the group in Scorpius; the crosses the Ursa Major group, and the triangles the 61 Cygni group. Our lists of the members of each group are probably very nearly complete down to a certain limiting (visual) magnitude, but fail at this point, owing to lack of knowledge regarding the proper motions of the fainter stars. The apparently abrupt termination of the Hyades near the absolute magnitude 7.0, and of the Scorpius group at 1.5 arises from this observational limitation.

The large circles and crosses in the upper part of Figure 2 represent the absolute magnitudes calculated from the mean parallaxes and magnitudes of the groups of stars investigated by Kapteyn, Campbell, and Boss. . . . The larger circles represent Boss's results, the smaller circles Kapteyn's, and the large crosses Campbell's.

It is evident that the conclusions previously drawn from Figure 1 are completely corroborated by these new and independent data. Most of the members of these clusters are dwarf stars, and it deserves particular notice that the stars of different clusters, which are presumably of different origin, are similar in absolute magnitude. But there are also a few giant stars, especially of Class K, (among which are the well-known bright stars of this type in the Hyades); and most remarkable of all is Antares, which, though of Class M, shares the proper motion and radial velocity of the adjacent stars of Class B, and is the brightest star in the group, giving out about 2000 times the light of the Sun. It is also clear that the naked-eye stars, studied by Boss, Campbell and Kapteyn, are for the most part giants.

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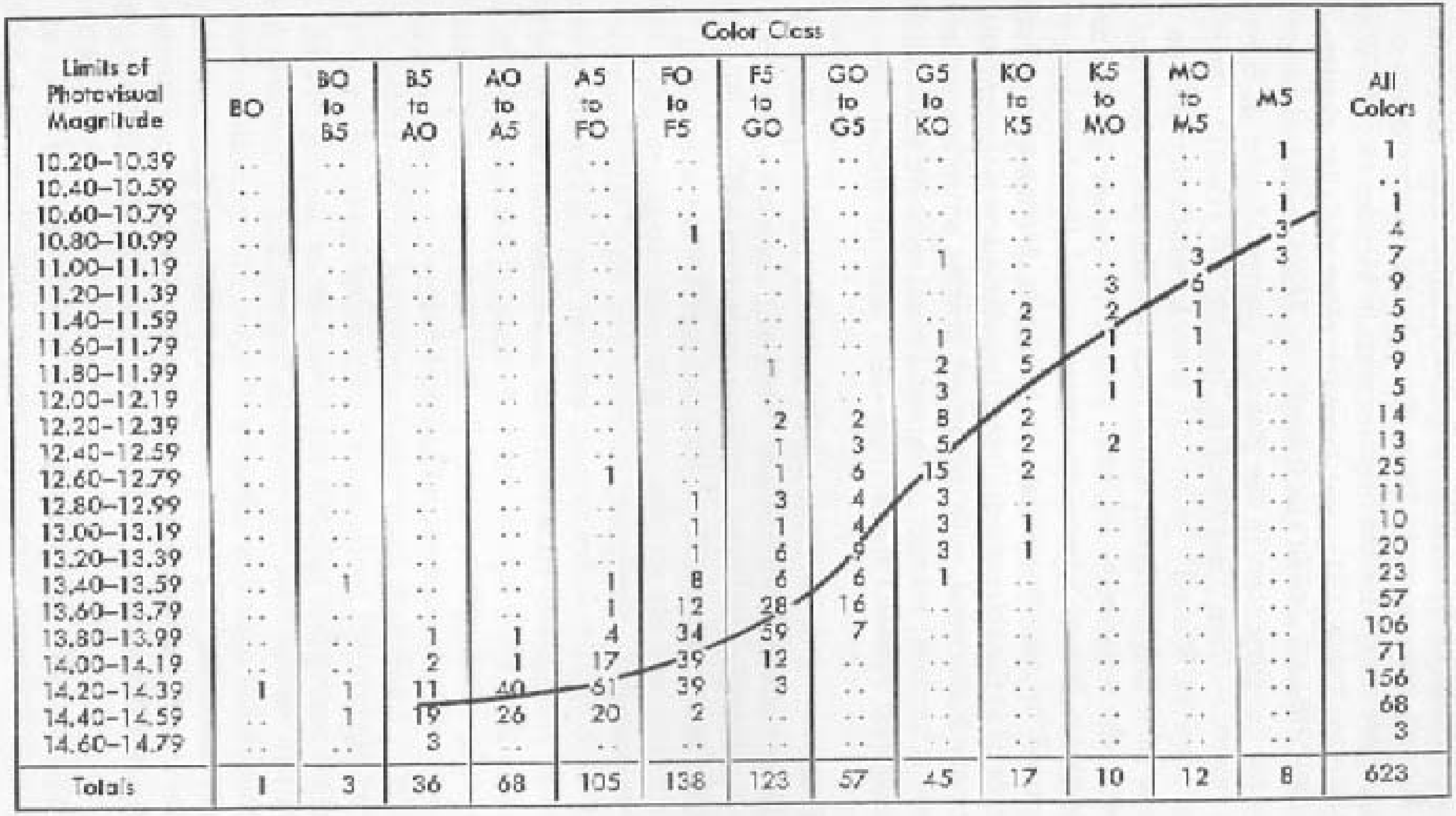
[1] *Zeitschrift für Wissenschaftliche Photographie 3*, 442 (1905).



Limits of Photovisual Magnitude	Color Class													All Colors
	BO	BO to B5	B5 to AO	AO to A5	A5 to FO	FO to F5	F5 to GO	GO to G5	G5 to KO	KO to K5	K5 to MO	MO to M5	M5	
10.20–10.39	..	..	..	..	..	..	..	..	..	..	..	..	1	1
10.40–10.59	..	..	..	..	..	..	..	..	..	..	..	..	..	..
10.60–10.79	..	..	..	..	..	..	..	..	..	..	..	..	1	1
10.80–10.99	..	..	..	..	..	1	..	..	..	..	..	..	3	4
11.00–11.19	..	..	..	..	..	..	..	..	1	..	..	3	3	7
11.20–11.39	..	..	..	..	..	..	..	..	..	..	3	6	..	9
11.40–11.59	..	..	..	..	..	..	..	..	..	2	2	1	..	5
11.60–11.79	..	..	..	..	..	..	..	..	1	2	1	1	..	5
11.80–11.99	..	..	..	..	..	..	1	..	2	5	1	..	..	9
12.00–12.19	..	..	..	..	..	..	..	..	3	..	1	1	..	5
12.20–12.39	..	..	..	..	..	..	2	2	8	2	..	..	..	14
12.40–12.59	..	..	..	..	..	..	1	3	5	2	2	..	..	13
12.60–12.79	..	..	..	..	1	..	1	6	15	2	..	..	..	25
12.80–12.99	..	..	..	..	..	1	3	4	3	..	..	..	..	11
13.00–13.19	..	..	..	..	..	1	1	4	3	1	..	..	..	10
13.20–13.39	..	..	..	..	..	1	6	9	3	1	..	..	..	20
13.40–13.59	..	1	..	..	1	8	6	6	1	..	..	..	..	23
13.60–13.79	..	..	..	..	1	12	28	16	..	..	..	..	..	57
13.80–13.99	..	..	1	1	4	34	59	7	..	..	..	..	..	106
14.00–14.19	..	..	2	1	17	39	12	..	..	..	..	..	..	71
14.20–14.39	1	1	11	40	61	39	3	..	..	..	..	..	..	156
14.40–14.59	..	1	19	26	20	2	..	..	..	..	..	..	..	68
14.60–14.79	..	..	3	..	..	..	..	..	..	..	..	..	..	3
Totals	1	3	36	68	105	138	123	57	45	17	10	12	8	623

Fig. 3. The color-luminosity diagram for the bright stars in the globular cluster Messier 22.

[The first evidence of a stellar population other than that depicted here by Russell came soon, in 1915, through the determination of the color-magnitude arrays for the brighter stars in Messier 13 (Mt. Wilson Contr. No. 116, Table XII), and later for other globular clusters. To illustrate the difference from the Russell "reversed seven" distribution, the array for the giant stars in the globular cluster Messier 22 is reproduced in Figure 3 (from "Star Clusters," pp. 29, 205 [1930]); the array shows no trace of Russell's giant-star branch, which depends on the stars of the solar neighborhood, and it does reveal a steep rise from the blue stars to the red giants.

[These early globular cluster observations and the steep rise were also discussed by ten Brugencate in his book, *Sternhaufen* (Berlin, 1927). Since 1950 the color-magnitude arrays for a few globular clusters have been much extended, with important bearing on stellar evolution problems, by Sandage, Johnson, Arp, and Baum, working with the 200-inch telescope on Mount Palomar.]