THE HERTZSPRUNG-RUSSELL DIAGRAM FROM PHOTOELECTRIC OBSERVATIONS OF NEARBY STARS

(Introductory Paper)

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The progress in the investigation of the spectrum-luminosity diagram. The spectrum-luminosity diagram, or the Hertzsprung-Russell diagram, is of extreme importance in stellar astronomy, astrophysics and stellar cosmogony. A number of stellar characteristics can be read from the diagram, as well as the theoretical paths of stellar evolution. A very significant problem is the improvement of the diagram, i.e. the accumulation of more precise data concerning the subdivision into sequences, the contours of the latter (mean lines, dispersions, gaps) and other characteristics (masses, axial rotations, chemical composition, space-kinematical properties).

During the last decades we have witnessed a gradual improvement and complication of the diagram. This can be clearly seen from the history of the empirical investigations of the HR diagram (see the following table). Now there are practically no blank spaces on the diagram, probably except for white dwarfs with M from + 5 to + 9. Even the interval between M-giants and M-dwarfs is now more or less occupied, at least in T-associations [1].

History of the investigation of the HR diagram

Solar neighbourhood	Binary stars	Clusters and associations	Reference	Content of the work
1	2	3		4
1905			[1]	Hertzsprung (and Russell, 1913) : stars were divided into giants and dwarfs.
		1911	[2]	Hertzsprung : open clusters were found to consist chiefly of the main sequence stars.
1914	1914		[3]	Adams : the companion of Sirius was found to be a white and not a red star. Eddington (1922) named these stars "white dwarfs".
		1920	[4]	Shapley : the diagram for globular clusters M 3 and M 11 was found to be an unusual one—the brighter stars are redder than the fainter ones.
	1928		[5]	Shajn : the companions of Algol and some other white eclipsing binaries are not early type stars and are placed between giants and dwarfs. In 1930 Sitterly named such stars "subgiants".
		1929	[6]	Hertzsprung : The divergence of the brightest stars of the main sequence for the Pleiades from the usual main sequence was established.
1932			[7]	Strömberg : The existence of subgiants was statistically established for G-K stars in the solar neighbourhood.

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Solar neighbourhood	Binary stars	Clusters and associations	Reference	Content of the work
1	2	3		4
1935			[8]	Adams, Joy, Humason, Brayton : many subgiants were found spectroscopically, as well as six A5sp stars (F5VI according to the modern classification), "intermediate white dwarfs". Afterwards they were found to be early subdwarfs.
1938			[9]	Kuiper : subdwarfs belonging to different spectral classes were discovered. The term "subdwarf" was introduced.
1943			[10]	Morgan, Keenan, Kellman : stars of luminosity classes III and IV were also found among early type stars.
1945			[11]	Parenago : subdwarfs form a sequence below the main sequence, and in most cases have high velocities. Kuiper (1947) has found the same.
1946			[12]	Vorontsov-Velyaminov : A white-blue sequence running vertically on the diagram was found. According to Kukarkin (1949) and Kopylov (1955) this sequence has no evolutionary meaning.
	1948		[13]	Struve : there are close binary stars deviating from the mass-luminosity relation.
1949			[14]	Parenago : according to stellar motions the main sequence is not homogeneous. It divides into two parts between F and G, and the kinematics of the G-K subgiants correspond to the second part of the main sequence, but not to the giants. It may be said that they are more like "superdwarfs", than "subgiants".
	1949		[15]	Parenago and Massevitch : each sequence has its own mass-luminosity-radius relation (1). The main sequence divides into two parts near class G5.
		1949 1953	[16]	Parenago : the diagram for the Orion association looks unusual. The main sequence continues up to A5 and a cloud of F-M subgiants reaches the main sequence.
1950			[17]	Eggen : the subdwarfs cross the main sequence at P-V = + 0.55 (B-V = + 0.65) and $M_v = + 5.5$.
1952			[18]	Luyten : white dwarfs form a sequence running parallel to the main sequence.
		1952- 1954	[19]	Arp, Baum, Sandage established the diagram for absolutely faint stars in globular clusters.
		1954	[20]	Johnson : the upper parts of the main sequences for different open stellar clusters were found to have a more or less pronounced deviation upwards from the initial main sequence.
		1956 1957	[21]	Walker : diagrams for very young clusters NGC 2264 and 6530 are similar to the diagram for the Orion association : stars later than A are systematically brighter than for the main sequence.
1957			[22]	Parenago : the whole sequence for the spherical population of the Galaxy is present in the solar neighbourhood from subdwarfs to Arcturus-type giants and coincides with the diagram for globular clusters. Dispersions of many sequences on the HR diagram are small.
		1958	[23]	Kholopov : diagrams for all T-associations are similar to each other and to that for the Orion-association. The subgiants reach M6.

(1) Eggen (AJ **61**, 361, 1956) did not confirm this conclusion, but in the papers by van de Kamp (AJ **59**, 447, 1954) and Petrie (JRAS Canada **51**, 46, 1957) the above mentioned division is clearly seen. The last two authors did not refer to the papers by Parenago and Massevitch.

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THE CLASSIFICATION OF THE STARS INTO THE SEQUENCES

The abundance of photoelectric observations of stellar magnitudes and colour-indices (altogether 16 series) permitted us to establish the very small dispersion for the spectrum-colour relation within a given sequence. This permits exact establishment of the sequence to which a given star of late type belongs (Fig. 1). One catalogue value of a colour-index gives the spectral class with an exactness of about $\pm$ 0.06 of a class. The exactness of modern determination of spectral class according to Mustel and his collaborators [2] is about the same. Recently B. Strömgren has obtained very exact determinations of Sp and M from his three colour photometry; very good classification was also made with the help of three parameters developed in France by D. Chalonge (see their reports in the present symposium). Thus we have the three following methods for the establishment of sequences to which the stars belong :

1. M and Sp, when very good parallaxes were known,
2. Classifications by the luminosity classes,
3. According to the U, B, V, measurements.

For subgiants (IV) and subdwarfs (VI) some special methods were developed; for details see my original work [3].

The HR diagram for nearby stars. This diagram includes only A to M stars. All known photoelectric measurements, spectral class and parallax determinations were combined. To the

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trigonometric parallaxes, the orbital velocity parallaxes and dynamical parallaxes were added (the latter only for luminosity classes III and V, because according to our work with A. Massevitch only for these classes is the normal mass-luminosity relation fulfilled). Particularly, Franz's determinations were also used [4]. For each star, spectral class was determined as a mean from direct determinations and from calculations according to B-V, U-B and C_{23}

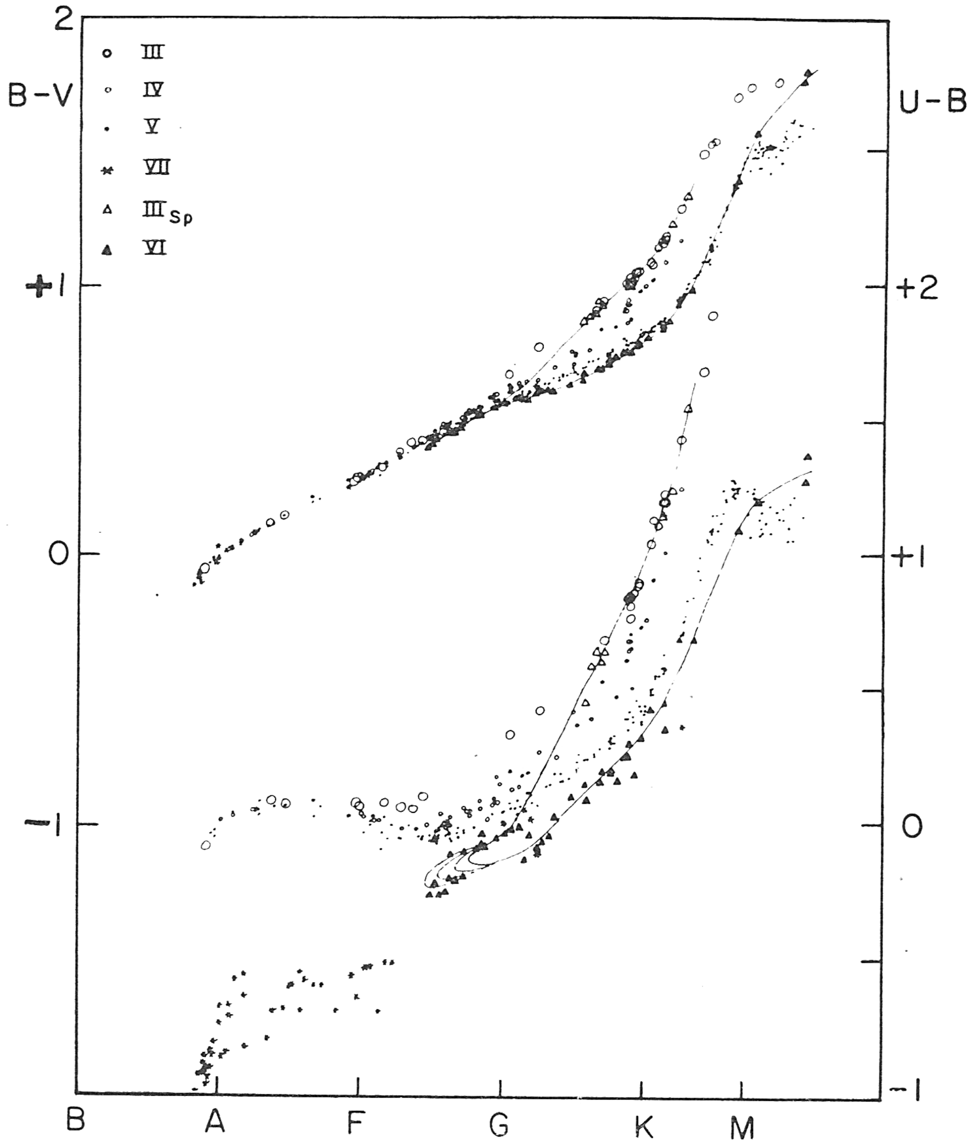

FIGURE 1. The separation of stars of various luminosity classes according to their B-V and U-B photoelectric colors. The various luminosity classes are distinguished by different symbols. Class VI are subdwarfs, Class VII white dwarfs.

(the Crimean colour index). The exactness of such mean spectral classes is not far from $\pm$ 0.03. The whole number of stars used in the present investigation is 870. The HR diagram obtained is shown in Fig. 2.

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The main sequence V. The dispersion freed from the errors of observation is surprisingly small :

Sp	B7-A9	Fo-F9	Go-G9	Ko-K6	Mo-M8
σ	± 0.25	± 0.00	± 0.10	± 0.23	± 0.24
n	31	85	91	139	196

Evidently the dispersion for earlier stars is greater.

Giants III. There is an almost complete absence of giants F6-G5 with absolute magnitudes 0 and + 1 (Hertzsprung's gap) and with M = + 2. At the same time, for earlier

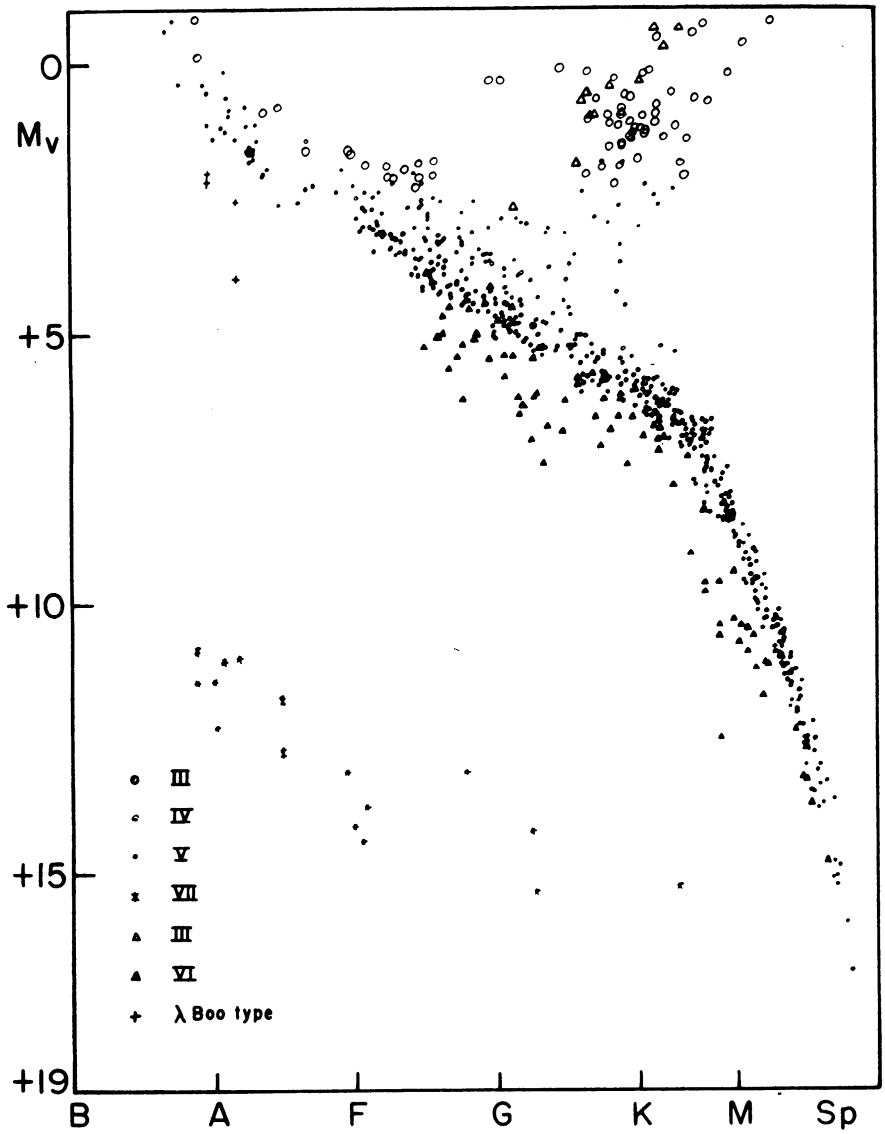

FIGURE 2. The resulting HR diagram for stars classifiable from the photoelectric colors.

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and later spectra such giants are present. The giants B-F5 form a well defined sequence with a dispersion of almost zero, while the giants G6-M form a band with a large dispersion $\pm$ 0.56. Both sequence can hardly coincide. More probably, stars B—F5 III, together with B-F5 IV form the upper boundary of a great main sequence while the giants G6-M are stars of a radically different nature.

Subgiants IV. From A (and B) to F5 there is a well defined sequence with practically no dispersion, which further along becomes wider and wider, the dispersion being $\pm$ 0.22 for F5-F9 and $\pm$ 0.86 for G0-K3. However it is possible that here we have two (or three?) sequences, one of which runs above the main sequence ($\sigma = \pm$ 0.19) and the other connects the F5 giants with the G6-K giants ($\sigma = \pm$ 0.30). It is not possible to solve this problem at present and numerous observations of colours, accurate spectral classes and parallaxes are necessary for its solution. As mentioned above, B-V and especially U-B, give a very good means for the determination of sequence (the luminosity class) for G-K stars. But the existence of a cloud, but not a sequence, of subgiants, like in the Orion association [5], is not excluded and I myself support this assumption.

The sequence of the spherical component of the Galaxy. III sp + VI. (the giants of the spherical component + subdwarfs). The sequence corresponds to the diagram for globular clusters, which was recently investigated in detail by Sandage, Arp and Baum. In the solar vicinity, subdwarfs and rare giant stars with definite peculiarities in their spectra of the type α Boo, δ Lep and γ Leo, belong to this sequence. The velocity dispersion for such stars is very large ($\pm$ 100 km/sec). According to all stellar characteristics this sequence is not identical with the main sequence and subgiants. The diagram for the well known stars of the sequence of the spherical component coincides very well with that for the globular cluster M 3 which gives for the mean absolute magnitude of RR Lyr variables the value of + 0.9.

White stars of λ Boo type. Four stars, A0-A2, are below the main sequence by about 1.6 mag. Two of these stars were studied spectroscopically and show subdwarf characteristics (Burbidges and Slettebak). However, the small velocities of all the stars do not permit us to assign them with assurance to the sequence of the spherical component. These stars deserve further attention.

The distribution of components of visual double stars according to sequences. This distribution is given in the following table. There is a little selection in favour of stars with well determined orbits. All the components of multiple stars were counted separately.

Main star \ Satellite	III	IV	V	VII	III_{sp}	VI	?	All
III	2	—	16	—	—	—	—	25
IV	—	7	15	1	—	—	14	37
V	—	1	131	4	—	2	34	172
VII	—	—	1	—	—	—	—	1
III_{sp}	—	—	—	—	1	—	1	2
VI	—	—	1	—	—	10	1	12

Combinations of objects of the flat and intermediate components on one hand (III, IV, V, VII) and of the spherical components on the other (III_{sp} and VI) are frequent, while the opposite combinations are very rare. Stars of the main sequence are often found together. Giants and subgiants are more often found together with a component belonging to the main sequence, although it would be easier to detect the combinations III-III and IV-IV, so that here we have a sharply pronounced peculiarity. The absence of combinations III-IV and VII-VII is very strange, as it should be very easy to detect such cases.

Some evolutionary considerations. There are 8 sequences (or their parts) running approximately parallel to the lines of equal radii on the diagram (V, VI, VII, IV B-F and a part of G-K, III B-F5, earlier II, I*b*, I*a*) and 8 sequences running approximately perpendicular to those lines (III G6-M, the bright IV G-K, III_{sp}, later II, I*b*, I*a*, cepheids of the flat and of the spherical components). There are no sequences occupying an intermediate position. The transition regions are very small and the number of stars in those regions is very small (the only one exception is at the turn at VI where the number is not small). This means that independently from theoretical suppositions, if the evolutionary track of a star coincides with a sequence (no matter in what direction), the star evolves with the smallest possible or largest possible change of radius. Almost the same statement can be made about the densities.

The masses. It is found that the main sequence stars, types F9-K1 have practically the same mean masses (0.9 ☉), with a rather small dispersion. Afterwards, the mass-luminosity relation has a break. The masses of stars belonging to the sequence of the spherical component are 3 to 4 times smaller than the masses of ordinary giants and dwarfs of the same spectral types.

The kinematics of stars of different sequences. The stars selected above for the study of HR diagram have well determined parallaxes and the study of their space velocities can be made with great certainty [6]. The main sequence, the kinematics of which differ essentially from those of the subdwarfs and generally from the sequence of the spherical component, distinctly divides into two parts at F7. The dispersion of the first part of the main sequence increases from stars of earlier spectral classes to those of latter spectral classes. The apex and the direction to the vertex also changes sharply at F7. The kinematics of the A-F subgiants and giants practically do not differ from those of stars of the first part of the main sequence. The G-K subgiants, according to their kinematics, were found to be similar to the second part of the main sequence but not to the giant G-K, which have a noticeably smaller dispersion. Thereby, the conclusions of my work of 1949 are confirmed. We can make the conclusion that for A-F stars the luminosity classes III and IV have another meaning than for G-K stars and that A-F III-IV stars are only more luminous stars than A-F V stars. Probably the terms "subgiants" and "giants" are not appropriate for A-F stars.

The stars of the sequence of the spherical component have a very great dispersion of velocities and the apex and vertex for these stars differ very much from those for other stars of flat and intermediate component of the Galaxy. As was first stated by Ambartsumian in 1939 [7] the velocity dispersion varies in the Galaxy so slowly that only groups of stars with similar kinematics may be in "ties of blood" one with another (but not in other cases). But when the kinematics is not similar then the "ties of blood" are wholly excluded (during intervals of time of the order of 10^{10} years). Then we see that the main sequence stars cannot be related to subdwarfs and other stars of the sequence of the spherical component. Double stars always belong to the kinematics of those sequences and their parts to which the brighter star (but not the companion) belong.

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Discussion

Schatzman : Is that mixture of stars in double stars a mixture of stars of different sub-systems (which I do not believe), or a mixture of stars of different luminosity class, but of the same sub-system?

Parenago : The classification is made only according to sub-systems of all possible spectral classes.

Schatzman : One of my students, Dr. Rigal, has shown, by a careful analysis of the observational selection effects, that the kinematical difference between the first and second part of the main-sequence is very likely not to be real. For example, the dispersion of velocities as a function of spectral type does not show the large difference which Prof. Parenago found in 1950.

Van Regemorter : Nous avons cherché à déterminer les températures effectives et les gravités correspondant aux étoiles de la série principale. Les calculs ont été faits au moyen de modèles radiatifs en utilisant deux couples de critères spectraux différents :

la discontinuité de Balmer et le gradient Φ_b de Chalonge.

la discontinuité de Balmer et la largeur de la raie H_δ.

Avec ces deux couples différents on retrouve le même résultat : les gravités ainsi déterminées sont plus faibles que celles que l'on trouve à partir des magnitudes absolues de Morgan-Keenan-Parenago.

Il est intéressant de noter que, par contre, nos résultats coïncident avec ceux d'un travail récent de Rigal. Ce chercheur a montré par une étude statistique des vitesses radiales et des mouvements propres qu'il fallait relever considérablement la séquence principale du diagramme HR dans la région des étoiles A5 à F5 (environ d'une magnitude).

Par l'étude des données purement photométriques, nous arrivons à la même conclusion, et les gravités déterminées d'après les magnitudes de Rigal coïncident avec les nôtres, dont la détermination est tout à fait indépendante.

Mrs. Burbidge : With regard to Prof. Parenago's paper, I should like to make two points. The first is the effect of low metal abundance in causing differing blanketing effect in different spectral regions, which will cause dispersion in the B-V colors for stars of the same effective temperature. Stars in the halo population may have a range of metal abundance, relative to hydrogen, and some spread in the main sequence region of the M_v, B-V diagram due to this effect may be expected.

The second point concerns recent work by Sandage and Van den Bergh on the cluster NGC 188. This has proved to be a very old cluster, older than M67, and it passes right through the position of δ Eridani and μ Herculis in the color-magnitude diagram.

Parenago : (1) The blanketing effect is, of course, great for μ Her and in the table on p. 185 of my published paper [3] the dispersion is followed by a sign for uncertainty. For earlier stars, I believe, the blanketing effect must be much less.

(2) The globular cluster M3 is of course, an old one. The good coincidence on Figure 5 of my paper means that the stars of the spherical component in the solar neighbourhood are also old.

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