THE SPECTRUM-LUMINOSITY DIAGRAM FOR NGC 752*

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ABSTRACT

Spectra of 52 members of the galactic cluster NGC 752 have been classified. The main sequence in the cluster is observed from F2 to G0. In addition, there are one A0 dwarf, numerous subgiants of types F2–F6, and eight red giants. Spectroscopically, the stars belong to the weak-line group observed among the bright stars near the sun but do not resemble the extreme high-velocity stars or the globular cluster giants. The distance modulus derived for the cluster is 8.2 mag. corresponding to a distance of 435 parsecs. A comparison of the observed H-R diagram with theoretical H-R diagrams computed on the basis of the generalized Cowling model indicates a minimum age of about 1.5×10^9 years for the cluster.

The galactic cluster NGC 752 is particularly interesting because of its unusual H-R diagram. According to Trumpler (1930), the dwarf branch starts at F0, as compared to A3 for the latest of the other clusters in his catalogue. Thus this cluster plays an important role in discussions of stellar evolution. In addition, since, as in other galactic clusters, there is an appreciable range in luminosity among the stars at the early edge of the main sequence, this cluster provides an excellent set of F-type standard stars somewhat above the main sequence.

Ebbighausen (1939) measured the proper motions of all the stars in the region brighter than 14.0 mag. He divided these into five groups: (1) stars which have a high probability of being cluster members; (2) stars for which the probability is lower but which have a reasonable chance of being members; (3) stars which are probably not members; (4) stars which are definitely not members; (5) fainter stars whose proper motions are less accurate. Johnson (1953) published photoelectric colors and magnitudes on the B, V, U system for 94 of these stars. Among the latter, all the stars in Ebbighausen's classes 1 and 2 and one star in his class 5 (No. 157) were observed spectroscopically with the 110-mm camera on the Cassegrain spectrograph attached to the McDonald 82-inch telescope.

The large number of stars between spectral types F2 and F5 permits an intercomparison of these stars and a separation into five groups according to the increasing strength and development of the G band and the increasing weakness of the hydrogen lines. Since the colors seem to indicate that, at least systematically, this separation is significant, type F3 and the division of type F5 into two groups are retained. The faintest stars in each class are dwarfs; the brighter ones are class IV stars, with the exception of No. 108 at F5, which is closer to class III. Table 1 summarizes the data for the various spectral types; the F3 stars are included at F4, and the G7 and G9 giants are combined at G8 III. The table contains, for each spectral type, the number of stars presumed to be of the indicated luminosity class, their mean visual magnitude, the derived distance modulus, the mean observed and predicted blue-yellow color for all stars in each spectral type, and the mean observed and predicted ultraviolet-blue color for the main-sequence stars and the red giants (Johnson 1953; Johnson and Morgan 1953). The average of the distance moduli is 8.24, as is the mean for the F5–G0 stars for which the calibration is probably best determined. A comparison of the observed and predicted $B-V$ colors for the F-type stars indicates a reddening of about 0.024 mag. or a total visual absorption of about 0.07 mag. Thus the true distance modulus of the cluster is probably near 8.2 mag., corresponding to a parallax of 0\".0023 and a distance of 435 parsecs. This table also shows the

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small ultraviolet excess noticed by Johnson for the F dwarfs and apparently also present in the late-type giants.

Table 2 lists the observational data for the individual stars in the cluster. The columns contain, in order, the number of the star in Heinemann's catalogue (1926), the visual magnitude and two colors according to Johnson (1953), the spectral type on the MK system, and the absolute magnitude of the star based on the distance modulus 8.2 for the

TABLE 1

SUMMARY OF DATA

Type	No.	V	m−M	$(B-V)_{obs}$	$(B-V)_{pred}$	$(U-B)_{obs}$	$(U-B)_{pred}$
F2 V	3	10.9	+7.7	+0.39	+0.37	+0.01	0.00
F4 V	4	11.2	+7.9	+0.42	+0.40	− .03	.00
F5 V	6	11.5	+8.2	+0.46	+0.44	− .03	.00
F8 V	1	12.3	+8.4	+0.62	+0.53	+ .02	+ .02
G0 V	1	12.6	+8.3	+0.60	+0.60	− .04	+ .06
G8 III	2	9.1	+9.1	+0.90	+0.95	+ .55	+ .72
K0 III	5	9.2	+8.5	+1.00	+1.01	+0.76	+0.86

TABLE 2

OBSERVATIONAL DATA

Heinemann	V	$B-V$	$U-B$	Sp. Type	M_v
209	9.70	+0.05	−0.01	A0	+1.5
193	10.17	+ .39	+ .09	F2	+2.0
196	10.24	+ .42	+ .04	F2	+2.0
96	10.35	+ .38	+ .06	F2	+2.2
254	10.90	+ .39	+ .01	F2	+2.7
263	10.91	+ .38	+ .02	F2	+2.7
222	10.94	+ .38	.00	F2	+2.7
300	9.58	+ .41	+ .02	F3	+1.4
61	10.02	+ .40	+ .04	F3	+1.8
126	10.08	+ .43	+ .04	F3	+1.9
105	10.22	+ .42	+ .06	F3	+2.0
219	10.52	+ .41	.00	F3	+2.3
74	10.73	+ .42	+ .01	F3	+2.5
189	11.26	+ .42	− .03	F3	+3.1
205	9.88	+ .42	+ .01	F4	+1.7
238	9.95	+ .45	+ .04	F4	+1.8
171	10.16	+ .44	+ .05	F4	+2.0
187	10.41	+ .42	.00	F4	+2.2
217	10.41	+ .43	+ .04	F4	+2.2
214	10.44	+ .38	+ .04	F4	+2.2
58	10.46	+ .40	+ .02	F4	+2.3
64	10.52	+ .38	+ .04	F4	+2.3
62	11.19	+ .42	− .04	F4	+3.0
135	11.20	+ .45	− .02	F4	+3.0
266	11.21	+ .43	− .03	F4	+3.0
108	9.14	+ .45	+ .07	F5	+0.9
41	9.80	+ .49	+ .07	F5	+1.6
206	10.01	+0.47	+0.05	F5	+1.8
10	10.12	+0.42	+0.02	F5	+1.9
117	10.23	+0.44	+ .05	F5	+2.0
234	10.66	+0.43	.00	F5	+2.5
259	11.38	+0.44	− .03	F5	+3.2
235	11.43	+0.48	− .04	F5	+3.2
197	11.58	+0.45	− .05	F5	+3.4
12	9.91	+0.48	+ .03	F5	+1.7
69	10.04	+0.51	+ .10	F5	+1.8
218	10.06	+0.46	+ .04	F5	+1.9
177	10.15	+0.48	+ .04	F5	+2.0
66	10.89	+0.45	− .04	F5	+2.7
55	11.40	+0.44	− .02	F5	+3.2
139	11.72	+0.47	− .05	F5	+3.5
88	11.73	+0.49	− .02	F5	+3.5
261	11.14	+0.49	− .03	F6	+2.9
237	12.31	+0.62	+ .02	F8	+4.1
157	12.56	+0.60	− .04	G0	+4.4
110	8.94	+0.84	+ .45	G7 III	+0.7
295	9.29	+0.96	+ .66	G9 III	+1.1
75	8.95	+1.01	+ .77	K0 III	+0.8
213	9.01	+0.99	+ .74	K0 III	+0.8
311	9.04	+1.03	+ .82	K0 III	+0.8
77	9.35	+1.02	+ .79	K0 III	+1.2
1	9.47	+0.96	+ .67	K0 III	+1.3
186	10.19	+0.94	+ .59	K0 III–IV	+2.0
208	8.94	+1.08	+0.83	K1 IV	+0.7

cluster. The increase in the $U-B$ color with increasing luminosity, noticed by Johnson (1953), is clearly evident. The H-R diagram of the cluster is illustrated in Figure 1. Particular attention should be called to two stars on this diagram. The A0 star may be an interloper, although its spectroscopic parallax and proper motion are consistent with cluster membership. In addition, according to Trumpler (private communication), the radial velocity of the star agrees well with the mean for the cluster. As the space motion of the cluster is small, the agreement of the motions is not conclusive but does seem to make membership in the cluster highly probable. If velocity is not considered, there is about a 10 per cent chance that an early A-type star would be found within a half-magnitude of this star and within the circle 25′ in radius encompassing the cluster. Unlike such clusters as the Hyades, in which the yellow giants form a compact group, in this cluster star No. 186 lies 1 mag. below the other stars at K0. Since it shows its faintness spectroscopically as well as photometrically, there is no reason to assume that it is not a member.

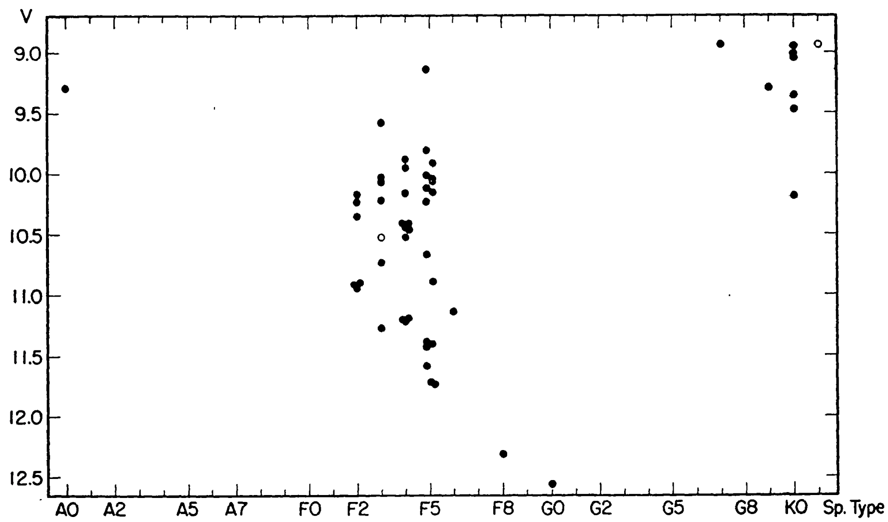

FIG. 1.—The H-R diagram of the cluster. Two stars which are probably not members are indicated by open circles.

Although the spectra, with a dispersion of 113 A/mm at $H\gamma$, were taken primarily for classification and no attempt was made to obtain more than one properly exposed plate of each star, the radial velocities were measured for most of the cluster members. These velocities have a mean error per plate of about 15 km/sec and hence are of little use individually. However, they do lead to a determination of the radial velocity of the cluster as -4.4 ± 2.5 km/sec. Moreover, they cast serious doubts on the membership in the cluster of two stars—No. 208, with a velocity of -52 km/sec from three plates, and No. 219, with a velocity of $+55$ km/sec from two plates. Star No. 208 appears to be nearer than the cluster, according to the spectroscopic parallax also.

There has been some speculation as to whether such clusters as NGC 752 and M67 are normal galactic clusters or are, perhaps, more closely related to the globular clusters. Various data seem to indicate that these clusters must be included with the galactic clusters as a peculiar type. For NGC 752 possibly the most convincing evidence is the relatively small membership and the low central condensation. Although the cluster is about 160 parsecs south of the galactic plane, its low space velocity definitely puts it in the class of galactic clusters. Except for the absence of A-type stars, the shape of the H-R diagram is typical of that for galactic clusters. Finally, the appearance of the spectra of the members establishes them as similar to the majority of stars near the sun rather than to the high-velocity stars or the globular-cluster giants.

However, there are features which distinguish NGC 752 from the more typical galactic clusters, such as the Hyades. Most striking, of course, is the almost complete absence of stars earlier than F2 and the presence of numerous F-type subgiants. The slope of the main sequence differs from that in other clusters to the extent that if the sequences are matched in the range F5–G0, the F2 stars are too bright by 0.6 mag. Spectroscopically, the members of the cluster belong to the weak-line group of stars; as an example, No. 213 is very similar to 19 Pup. The K0 giants definitely have stronger *CH* and stronger *Ca* I than do the Hyades giants, while the *CN* is probably somewhat weaker in the NGC 752 stars. Like the appearance of the spectra, the ultraviolet excess observed by Johnson (1953) is in the same sense, although much smaller in amount, as the effects observed in very high-velocity stars (Roman 1954; also unpublished).

It is interesting to investigate whether the unusual shape of the NGC 752 H-R diagram can be explained on the basis of the evolution of stars which originally occupied a main sequence similar to that found in more typical clusters. The assumption is usually made that young stars are built on the Cowling model with uniform composition throughout; as they age, the mean molecular weight of the core becomes greater, while that of the envelope remains constant until all hydrogen in the core is exhausted and the core becomes isothermal with a surrounding, energy-producing envelope; finally, the isothermal core grows until the Schönberg-Chandrasekhar (1942) limit is reached and further growth is prevented by the lack of stability of the resulting star. A rough calculation indicates that most of the stars in NGC 752 have not yet reached this limit.

Ledoux (1949) has tabulated the fraction of the stellar mass in the core, the fraction of this mass in a transition zone between the core and the envelope, and the radius and luminosity of the star in terms of the solar values for a model similar to the sun originally for various ratios of the mean molecular weight in the core to that in the envelope. It seems reasonable to assume, within the accuracy of the present comparison, that, for stars of other masses not differing from the solar mass by more than 70 per cent, the evolutionary tracks will be similar to that of the sun, although stars of larger mass (and luminosity) will proceed along their tracks more rapidly than stars of smaller mass. By comparing the instantaneous mass of hydrogen in the core with the mass of hydrogen which must be burned to sustain the instantaneous luminosity of the star, we can compute the mean molecular weight in the core and hence the position of the star on its evolutionary track as a function of time.

In order to determine the locus of stars of different mass at any time, it is necessary to know their locus at a particular time, such as $T = 0$. For the sake of consistency, it was assumed that originally the main sequence of the cluster stars was that predicted by the Cowling model,

$$L = C \kappa_0^{-1} M^{5.5} R^{-0.5} \mu^{7.5} ,$$

where C is a numerical constant, κ_0 is chosen to give the correct value of L, M, and R for the sun, $\mu = 0.55$, and M and R are assumed to obey the empirical mass-radius relation (Kuiper 1938*b*). This theoretical main sequence for stars in the range A5–G2 is shown in Figure 2, together with the locus of these stars after 1.5×10^9 years according to Ledoux's models. The same figure also illustrates the normal main sequence for stars near the sun and the observed main sequence for NGC 752. The latter is assumed to be defined by the fifteen faintest stars, omitting No. 261 at F6. The other observed quantities are derived from data given by Keenan and Morgan (1951) and by Kuiper (1938*a*, *b*). The vertical position of NGC 752 is entirely arbitrary. It is seen from this figure that while the normal and the theoretical main sequences do not coincide for $T = 0$, the difference between the normal and the NGC 752 main sequences is very similar to the change of the theoretical main sequence with time.

To obtain a more accurate indication of the extent to which the H-R diagram of NGC 752 can be explained by evolution, the detailed evolutionary tracks are shown attached to the empirical normal main sequence in Figure 3. This means that the rate of evolution is based on the theoretical luminosity for $T = 0$, while the actual luminosity plotted is based on the observed luminosity for normal stars of the same mass. Figure 3 also shows the computed locus of the same stars after various time intervals and the observed shape of the NGC 752 sequence. From this illustration it is apparent that we can explain both the unusual slope of the NGC 752 main sequence and the lack of stars earlier than F2 (the existence of the A0 star presents another problem) as a result of the evolution of stars built on the generalized Cowling model in a time of the order of 1.5×10^9 years. Since the main sequence to which the theoretical evolutionary tracks have been fitted may not be the true one for the time $T = 0$, the cluster must be at least this old, according to these considerations. Finally, it should be noted that these curves

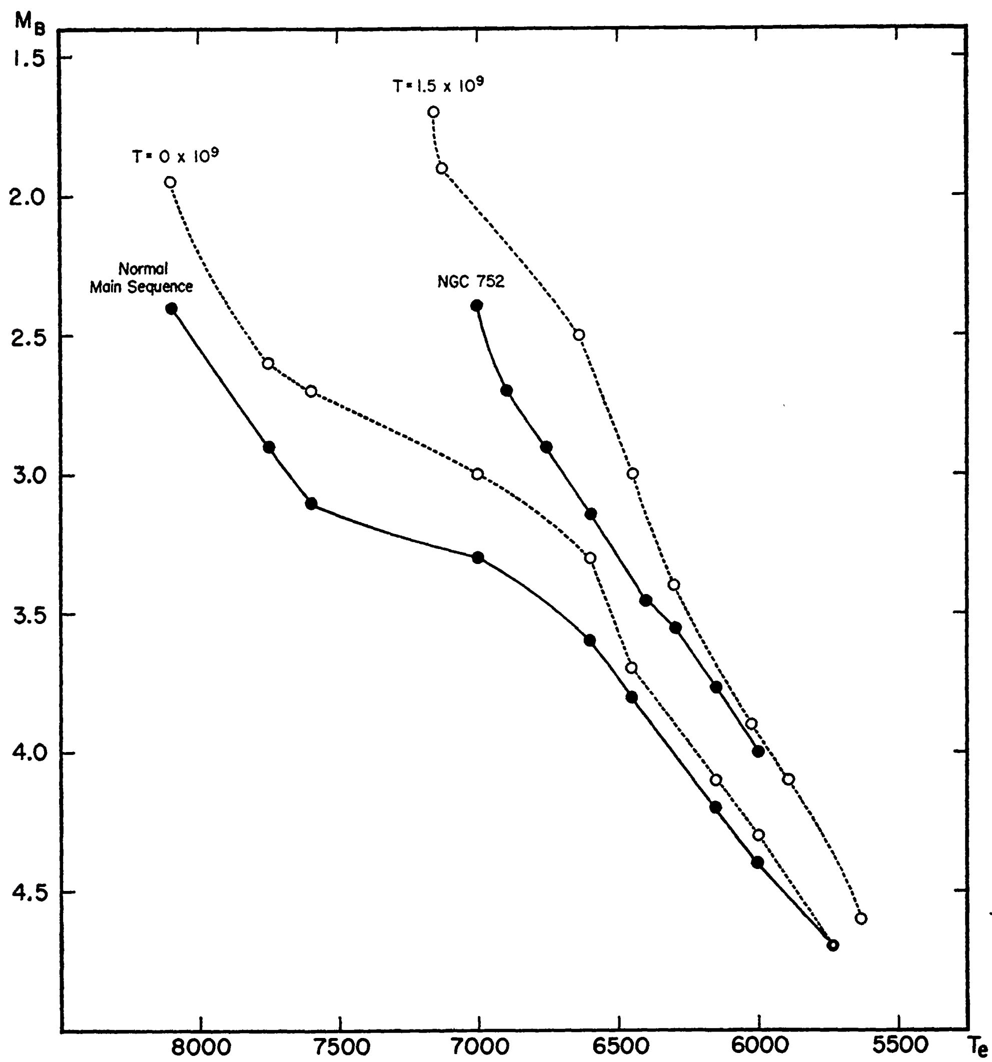

FIG. 2.—The theoretical main sequence predicted by the Cowling model for $T = 0$ and its predicted position after 1.5×10^9 years are shown by the dashed curves. The solid curves show the normal observed main sequence and the NGC 752 main sequence. The vertical position of the latter is arbitrary.

show that the stars between F5 and G0 are already 0.4 mag. brighter than they were originally. Hence this should lead us to underestimate the distance modulus of the cluster by this amount. This may explain the fact that the distance modulus derived from the late-type giants is 0.3 mag. larger than the one derived from the mean of all of the stars or from the F5–G0 dwarfs. On the other hand, these giants have undoubtedly changed also with time.

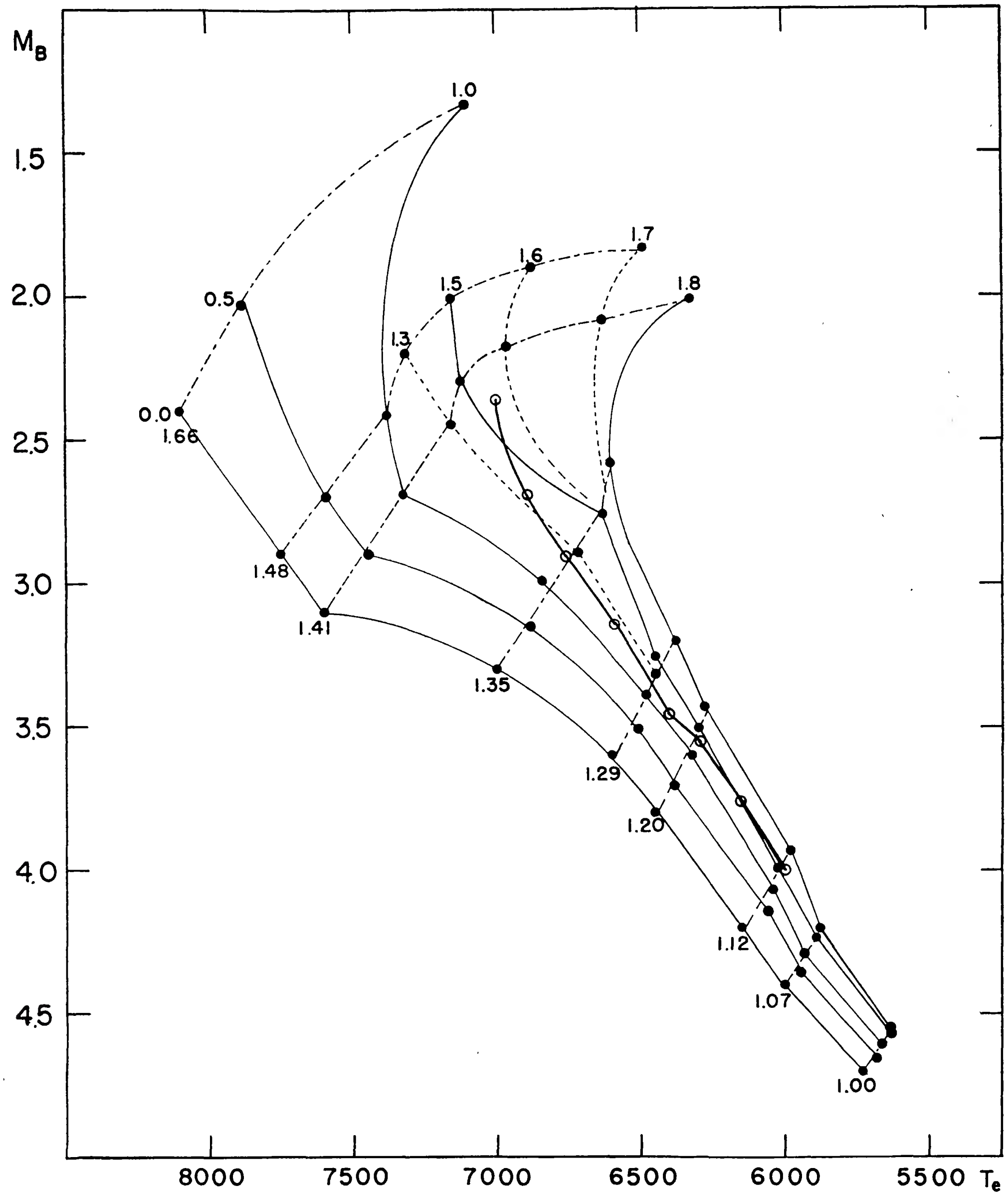

FIG. 3.—The theoretical evolutionary tracks for stars of various masses (*dashed curves*) and the locus of the main sequence after various time intervals (*solid* or *dotted curves*). In addition, the heavy curve connecting the open circles indicates the position of the main sequence observed for NGC 752. The zero point of the bolometric magnitudes is arbitrary for the observed curve. The theoretical curves are labeled according to the time elapsed in units of 10^9 years or according to the mass of the star in units of the solar mass.

These considerations of the evolution of the H-R diagram in this cluster are similar to the ideas Sandage and Schwarzschild (1952) applied to the H-R diagrams of globular clusters. However, because of the much greater age of the latter, Sandage and Schwarzschild could ignore the path by which the stars reached the Schönberg-Chandrasekhar limit, assuming only that the stars had passed this limit. In NGC 752 we see that the shape of the H-R diagram changes noticeably well before this limit is reached and that evolutionary models such as those computed by Ledoux are important to the understanding of the development of galactic clusters.

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REFERENCES

Cowling, T. G. 1935, *M.N.*, **96**, 42.
Ebbighausen, E. G. 1939, *Ap. J.*, **89**, 431.
Heinemann, Karl. 1926, *A.N.*, **227**, 193.
Johnson, H. L. 1953, *Ap. J.*, **117**, 356.
Johnson, H. L., and Morgan, W. W. 1953, *Ap. J.*, **117**, 313.
Keenan, P. C., and Morgan, W. W. 1951, in J. A. Hynek (ed.), *Astrophysics* (New York: McGraw-Hill Book Co.), p. 12.
Kuiper, G. P. 1938*a*, *Ap. J.*, **88**, 429.
———. 1938*b*, *ibid.*, p. 472.
Ledoux, P. 1949, *Contribution à l'étude de la structure interne des étoiles et de leur stabilité.* Liége, Belgium.
Roman, N. G. 1954, *A.J.*, **59**, 307.
Sandage, A. R., and Schwarzschild, M. 1952, *Ap. J.*, **116**, 463.
Schönberg, M., and Chandrasekhar, S. 1942, *Ap. J.*, **96**, 161.
Trumpler, R. J. 1930, *Lick Obs. Bull.*, **14**, 154.