PHOTOELECTRIC MEASURES OF HYDROGEN-LINE ABSORPTION IN EARLY-TYPE STARS

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(Received 1961 December 27)†

Summary

Photoelectric determinations of Hγ absorption line intensity have been made of stars in selected clusters and associations as well as in the general galactic field. Interference filters having a width at half intensity of 45 A were used to isolate spectral regions centred on 4280 A, Hγ and 4410 A. The Γ indices derived, which represent a measure of the Hγ absorption, can be used in conjunction with unreddened values of either $(U-B)$ or $(B-V)$ for spectral and luminosity class determinations of stars in the spectral range O6 to A0. The separation of age loci is shown to exist on Γ, $(U-B)_0$ diagrams of clusters and associations having different ages. A Γ, M_v calibration for the young, or less evolved stars, has been derived. Tests of such a calibration have been made on the Orion Association and NGC 2362. The distance moduli thus obtained are in good agreement with the values derived from the colour magnitude arrays.

1. *Introduction.*—The early-type stars are very efficient spiral tracers by virtue of their high luminosity and the tendency that they exhibit to be confined to the spiral arms. The determination of the luminosities of these stars is, therefore, of much importance in studies of galactic structure. The most widely accepted procedure for such determinations has been the MK system of luminosity classification. The MK system is a two-dimensional system which provides for an accurate classification. Purely empirical methods, based on certain criteria which differ for different spectral types, yield results of fair accuracy, and a network of standard stars all over the sky ensures a minimum of errors in the classification. The main disadvantage, however, is their time-consuming feature, together with their inability to provide much data on the fainter stars.

Various other methods of luminosity classification have been suggested in recent years. Johnson and Morgan (1) have demonstrated the possibility of deriving accurate spectral types of *B* stars by measures on the *U*, *B*, *V* system. A parameter *Q* which is determined from the $U-B$ and $B-V$ colour indices is shown to be independent of interstellar reddening, while being correlated with spectral type. The method is limited to a narrow range of spectral types and luminosity.

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† Received in original form 1961 August 8.

Lindblad (**2, 3, 4**) has shown that the hydrogen-line intensities measured in early-type stars can be used as efficient luminosity indicators. Low dispersion spectroscopy can, therefore, achieve successful results utilizing hydrogen-line intensities as a luminosity criterion.

Barbier and Chalonge (**5**) and later Chalonge and Divan (**6**) have developed a method of luminosity classification which depends on the Balmer limit and a measure of the Balmer discontinuity. These two quantities bear a direct relationship with the temperature and surface gravity of the star and hence can be usefully employed for a two-dimensional classification. A plot of λ, D, which is the practical limit of the Balmer series and the magnitude of the Balmer discontinuity respectively, determined for the MK standards, yields a diagram wherein we can draw a series of curves that segregate the stars into a two-dimensional system. The λ, D system has the disadvantage that each pair of values of the two parameters can represent two stars of different spectral type. It becomes difficult to distinguish between an early and late sub-class of an A-type star when D has a value near the maximum. Chalonge and co-workers overcome this difficulty by the assignment of a third parameter to the star which defines the colour temperature of the continuous spectrum in the spectral region 3800 A–4000 A. This third parameter can, however, be successfully applied only to the unreddened stars.

The central depths as well as equivalent widths of many members of the Balmer series in early-type stars have been measured by several investigators using both low and medium dispersion spectra. Gunther (**7**), Williams (**8**), Hack (**9**), Barbier, Chalonge and Morguleff (**10**), Petrie (**11**) and Stock (**12**) have contributed considerably to this field. Petrie and collaborators (**11, 13, 14**), in particular, have investigated the behaviour of absorption-line intensities in several stars that are members of clusters and associations as well as binaries. Petrie's work enables one to derive the absolute magnitude of a star from its absorption-line intensity provided the spectral type is known. The method has also been used by him very successfully to determine luminosity differences in binary systems where the components have a high enough effective temperature to make the method feasible.

Mrs Hack (**9**) has measured on low dispersion spectra the central intensities of the Hγ absorption line and finds that measurement of the Balmer discontinuity D along with it provides a method of two-dimensional classification that is equivalent to the λ, D system in accuracy and scope. The choice of Hδ enables her to eliminate errors caused by the presence of emission seen in the early members of the Balmer series.

A very powerful method of attack on the luminosity determinations of early-type stars was made possible by Strömgren's application of the methods of narrow-band photoelectric photometry to the problem. Strömgren (**15**) and Crawford (**17**) have employed a measure of the Hβ line intensity and another observationally-derived quantity equivalent to the magnitude of the Balmer discontinuity to yield a two-dimensional classification. The accuracy of photoelectric methods by themselves surpasses any other technique of measurement we can currently employ. Together with this fact lies the possibility that such narrow-band photometry can extend the method to much fainter stars than is currently possible by the normal photographic methods employed in stellar spectroscopy.

One of the results easily apparent from a λ, D diagram of Chalonge is that the MK two-dimensional classification is represented on the diagram by a set of curvilinear quadrilaterals. The ranges of values in λ and D, specified by the dimensions of these quadrilaterals, are many times greater than the probable errors of the determination of a value of λ or of D. The MK system, therefore, lacks a certain amount of resolution in its definition of the luminosity and spectral type of a star and, hence, stars with slightly different characteristics are all grouped together under the same category. A valuable amount of information on the evolutionary characteristics of the star is thereby lost by the lack of an accurate technique which can decipher precisely these.

We have carried through a programme of measurement of Hγ absorption-line intensities using the methods of narrow-band photometry. The programme stars chosen covered a few clusters and associations as well as those in the general galactic field.

2. *The observations.*—The observations were made with a photoelectric photometer attached to the 10-inch refractor (focal length 148 inches) of the Uttar Pradesh State Observatory. The photo-multiplier used is an unrefrigerated 1P21 tube, the output of which is amplified by a d.c. amplifier and registered on a Brown recorder. The diaphragm used in the focal plane of the telescope is 2·2 mm in diameter and one which is in regular use on the telescope for B, V photometry. The limited wave-length region examined in this investigation would have permitted us to use a smaller aperture but we did not consider it necessary as the sky background was quite faint and there were not many bright stars in clusters within the scope of our telescopic power that were lost because of the presence of a close companion. The diaphragm of the photometer was arranged to lie in the focal plane corresponding to the wave-length of the Hγ line. Errors in centring would have had little effect because a Fabry lens focused the image of the objective on to the photocathode.

We chose the Hγ line for photometry for several reasons. One of these has been that, since the photo-sensitive surface of the photo-multiplier has a peak sensitivity near the wave-length of the Hγ line, a scheme of analysis can be developed which can be extended effectively to the faintest stars. Also, greater resolving power in the determination of luminosity would be available from absorption measures of the higher members of the Balmer series. An added attraction was the possibility of an effective tie-in with Petrie's extensive and highly accurate photographic measures of Hγ equivalent widths in the early-type stars. Ideally, the Hδ line would serve some of these criteria better and would be less prone to emission than the earlier members of the Balmer series.

We isolated three spectral regions centred on 4280 A, Hγ and 4410 A with the aid of interference filters. These are multi-layer dielectric filters manufactured by Baird Associates and have widths at half intensity of about 45 A, with a high peak transmission. The Hγ filter was tilted so as to be centred as well as possible on the Hγ line. The centring was checked visually with the aid of a medium dispersion spectrograph as monochromator and sunlight as source and the wave-lengths of peak transmission determined within ± 3 A. The filters were checked at the end of the investigation and were found to have peak transmission wave-lengths similar to those determined prior to our study. We thus assume that no changes due to ageing, larger than 3 Ångströms, took place during our investigation.

The measures of stars reported here were obtained on 33 nights, mostly during the period 1959 January–March. An observation of a star on a night consisted of six to eight sets of deflections flanked by measures on the sky taken through each of the three filters. A set of measures comprised three deflections obtained consecutively through each of the three filters. A gamma index Γ defined as

$$\Gamma \times 10^{-3} = -2{\cdot}5 \log [(LS)^{1/2}/\gamma]$$

may then be calculated for each star, where L, S and γ indicate the respective deflections through the filters that isolate respectively the continuum on the long and short sides and the radiation at the position of the Hγ line. The standard error for a mean Γ value of 170 is 3·5 Γ units or 2 per cent. For a Γ value of 260 encountered among stars of high luminosity the standard error is 6·6 Γ units or 2·5 per cent. The close proximity of the two comparison wave-lengths to the Hγ line made the effects of interstellar reddening negligible. Also, extinction corrections were reduced to a minimum. An unaccountable scatter of the order of 5 units in Γ exists occasionally in the measures, and these could not be correlated systematically with hour angle or declination. Presumably this arises from flexure of the filterslide in its holder within the photometer. The Hγ filter in particular would be most sensitive to the minor changes in wave-lengths of peak transmission caused by such flexure. We have eliminated serious interference of this factor in the overall accuracy of the results by frequent reference to the adopted standard stars and adequate night corrections to the Γ indices.

A network of primary standards was established over most of the sky, and specially in the proximity of the clusters and associations included in the programme. Repeated measures on several nights of these standards alone enabled us to establish a reliable scale and zero-point for the Γ indices. On nights when field stars and associations were measured, the measures were tied-in to the nearby standards. The homogeneity in the overall system, from one area of the sky to the other, is thus ensured with the aid of frequent reference to these primary standards. The stars observed under this category are given in Table I with their respective MK classifications and Γ indices. The main programme of measurement included the brighter members of a few galactic clusters and associations and some bright stars in the general galactic field. Apart from about fifty such field stars, we measured bright stars in (1) the Orion Association; (2) the ζ Persei association; (3) the α Persei cluster; (4) the Coma cluster; (5) Praesepe; (6) NGC 2362; (7) NGC 2264; (8) the Pleiades; (9) h and χ Persei; (10) the northern part of the Scorpio–Centaurus association; (11) the Ursa Major stream. Table II gives for these stars the measured Γ indices together with their other known measured characteristics.

TABLE I

The primary standards

Star	Sp type	Γ	Star	Sp type	Γ
γ Ori	B2 III	240	α Vir	B1 V	242
κ Ori	B0·5 Ia	260	ν Cen	B2 IV	231
ν Ori	B3 V	215	η UMa	B3 V	202
η Leo	A0 Ib	228	χ Cen	B2 V	221
α Leo	B7 V	192	π Sco	B1 V	234
ρ Leo	B1 Ib	254	δ Sco	B0 V	242
γ UMa	A0 V	112	α Lyr	A0 V	110
γ Crv	B8 III	190			

The most extensive and homogeneous measures of the equivalent width of the Hγ line by the method of photographic spectrophotometry are those made at Victoria by Petrie and collaborators (**11, 13, 14**). Forty stars in Petrie's lists have been included in our programme. The transformation between Petrie's equivalent widths W and our indices is linear as can be seen in Fig. 1. The relation is:

$$W_{\text{Petrie}} = 22{\cdot}653 - 0{\cdot}0762\Gamma.$$

Other measures of equivalent widths of Hγ made photographically are those of Gunther (**7**) and Williams (**8**). The transformations obtained are given below:

$$W_{\text{Gunther}} = 24{\cdot}734 - 0{\cdot}0863\Gamma,$$
$$W_{\text{Williams}} = 27{\cdot}67 \;\; - 0{\cdot}0983\Gamma.$$

Mrs Hack has measured on low-dispersion spectra central intensities of Hγ with respect to the continuum. A linear relation

$$I_r/I_c = -0{\cdot}0043 + 0{\cdot}0032\Gamma$$

is valid over the range in Γ from 170 to 280. The limit Γ = 170 corresponds to a main sequence spectral type B8 as will be seen in a later section. For stars later than this spectral class the above relation is not valid. This is as it should be, since the increase in equivalent width will be caused mostly by increased absorption in the wings rather than at the line centre.

Photoelectrically-determined values of equivalent widths of Hγ are those obtained by Stock (**12**) with the aid of a Schmidt camera–objective prism combination and an analysing slit of width 35·3 A in the focal plane. We have included 41 stars on our programme which have also Hγ measures made by Stock. The linear relation derived between the two systems is shown in Fig. 1. The transformation used is

$$W_{\text{Stock}} = 27{\cdot}949 - 0{\cdot}09616\Gamma.$$

Crawford's study of early-type stars, by isolating the Hβ line with the aid of interference filters, would be the most accurate one to compare with our investigation in order to check our overall accuracy. We have measured 75 stars that are included in Crawford's list. A least-squares solution for the best fit between the β and Γ systems yields the relation given below:

$$\beta = 3{\cdot}1658 - 0{\cdot}00227\Gamma.$$

It is interesting to note that Crawford finds a linear relation between the β values and the central intensities of Hδ as measured by Mrs Hack. Crawford's 15 A filter is perhaps too narrow to accommodate the line wings as one reaches spectral type A. Such a conclusion is also borne out by the deviation from linearity of the β, W_{Petrie} relation for β values in excess of 2·85.

3. Γ *indices and the determination of spectral type*.—A two-dimensional spectral classification is easily carried out on early-type stars when we have at our disposal one more observational parameter in addition to the Γ index. Strömgren (**15**) has measured the Balmer discontinuity with the aid of filters and expressed the magnitude of it in terms of the index c. This index is independent of interstellar reddening. Crawford utilized values of $(U-B)$ that have been corrected for interstellar reddening and has shown that a linear

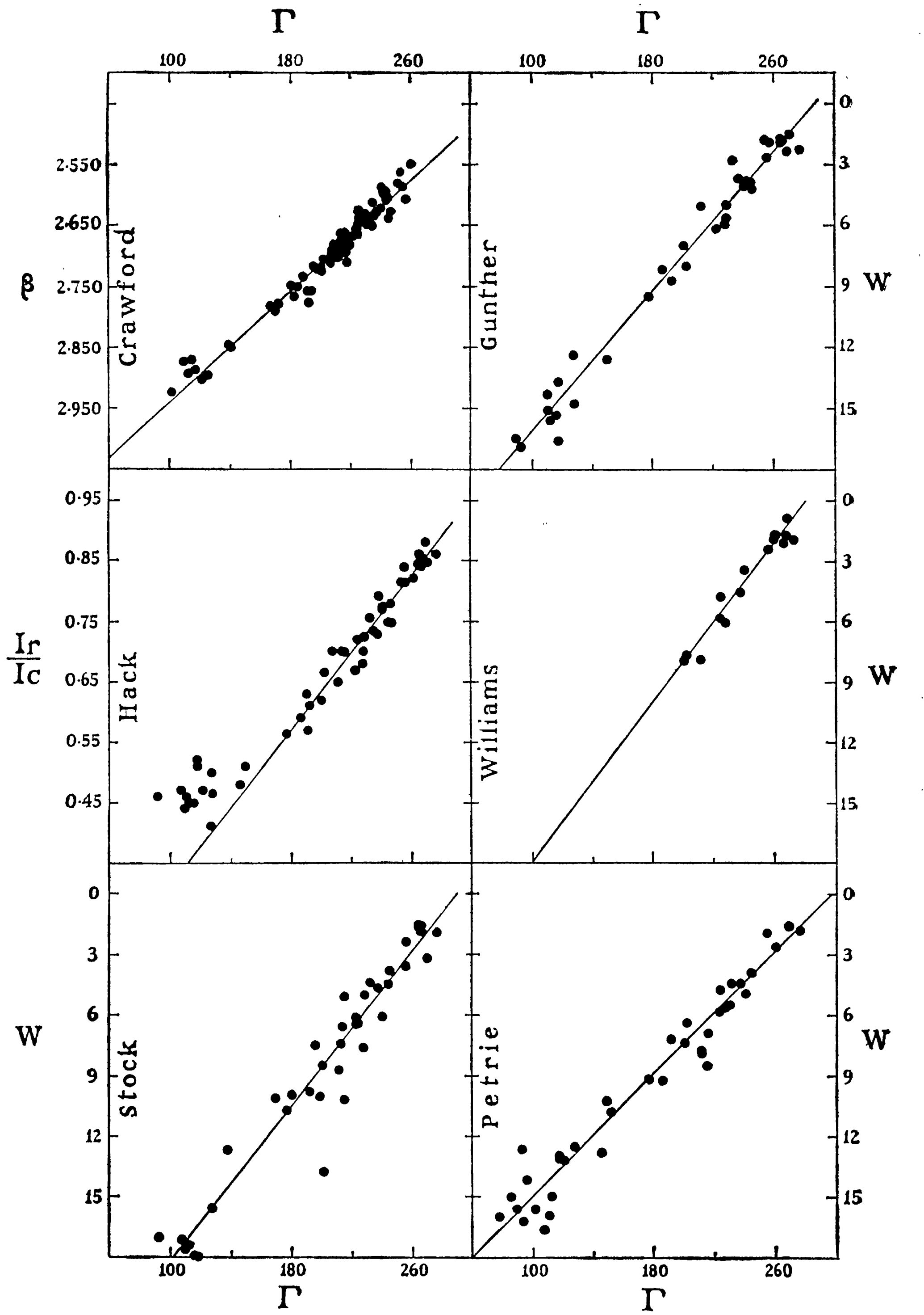

Fig. 1

relationship exists between $(U-B)_0$ and the D index used by Chalonge and Divan (6). A similar linear relation holds good between $(U-B)_0$ and the index c obtained by Strömgren. The change in Balmer discontinuity is correlated with colour temperature in the range of spectral types O–A. Hence, an unreddened value of $(B-V)$ or $(U-B)$ would serve just as well as a direct measure of the amount of Balmer discontinuity. The range in $(U-B)$ obtained for the spectral range O6–A0 is greater than that in $(B-V)$ by over a factor of two. The use of $(U-B)_0$ values, therefore, would yield greater resolution in any study where their variation with Γ index for different luminosity classes is sought.

The observational data listed in Table II are sufficiently numerous to permit a calibration of the MK system in terms of Γ indices and $(U-B)_0$. Most of the

TABLE II

Γ *values*

Star	HD	Sp	V_0	$(U-B)_0$	Γ	Association or cluster
	12953	A1 Ia	5·02		270	h and χ Persei
	13051	B1 III	7·55	−0·96	238	,,
	13267	B5 Ia	5·16	−0·78	263	,,
	13476	A3 Iab	4·60		243	,,
	13744	A0 Iab	5·50	−0·52	260	,,
	13841	B2 Ib	6·20	−0·91	267	h and χ Persei
	13854	B1 Iab	5·11	−0·98	272	,,
	14143	B2 Ia	4·65	−0·96	267	,,
	14322	B8 Ib	5·80	−0·53	262	,,
	14434	O6	7·06	−1·14	281	,,
	14535	A2 Iap	5·28		264	h and χ Persei
	14542	B8 Ia	5·11	−0·60	264	,,
	14818	B2 Ia	4·84	−0·96	269	,,
	14899	B8 Ib	6·05	−0·53	244	,,
	14956	B2 Ia	4·58	−0·96	255	,,
29 Per	20365	B3 V	4·77	−0·68	224	α Persei
	20391	A1 V	7·64	−0·04	101	,,
31 Per	20418	B5 V	4·67	−0·65	228	,,
HR 1011	20809	B5 V	4·96	−0·65	212	,,
	20961	A0 V	7·16	−0·11	125	,,
HR 1029	21071	B6 V	5·85	−0·56	188	α Persei
	21091	A0 V	7·29	−0·11	121	,,
	21181	B9 V	6·60	−0·29	171	,,
HR 1034	21278	B3 V	4·71	−0·62	200	,,
HR 1037	21362	B6 V	5·26	−0·53	211	,,
	21375	A1 V	7·17	−0·08	112	α Persei
	21398	B9 V	7·13	−0·24	140	,,
34 Per	21428	B3 IV	4·33	−0·68	216	,,
	21479	A2 V	6·98	−0·07	127	,,
	21481	A0 V	7·32	−0·07	128	,,
HR 1051	21551	B8 IV	5·62	−0·40	182	α Persei
	21672	B8 V	6·39	−0·40	166	,,
HR 1063	21699	B8 III	5·27	−0·64	206	,,
HR 1074	21843	B3 III	5·39	−0·76	226	ζ Persei
	21856	B1 V	5·25	−1·03	235	,,
	22951	B0·5 V	4·13	−0·84	223	ζ Persei
	23060	B2 Vp	6·52	−0·96	219	,,
o Per	23180	B1 III	2·91	−0·99	241	,,
	23478	B3 IV	5·84	−0·70	217	,,
	23625	B2 V	5·74	−0·72	213	,,

TABLE II (*continued*)

Star	HD	Sp	V_0	$(U-B)_0$	Γ	Association or cluster
HR 1191	24131	B1 V	5·00	−1·01	227	ζ Persei
	24190	B2 V	6·60	−0·81	207	,,
ζ Per	24398	B1 Ib	1·95	−1·05	252	,,
HR 1215	24640	B2 V	4·87	−0·96	234	,,
ξ Per	24912	O7	3·08	−1·24	251	,,
H 117	23288	B7 IV	5·30	−0·37	180	Pleiades
H 126	23302	B6 III	3·69	−0·41	207	,,
H 150	23324	B8 V	5·58	−0·38	184	,,
H 156	23338	B6 V	4·26	−0·47	195	,,
H 216	23387	A1 V	6·77	−0·01	124	,,
H 242	23408	B7 III	3·71	−0·43	213	Pleiades
H 255	23432	B8 V	5·66	−0·25	169	,,
H 265	23441	B9 V	6·38	−0·16	157	,,
H 323	23480	B6 Vnn	3·95	−0·48	214	,,
H 341	23489	A2 V	7·23	+0·09	93	,,
H 542	23630	B7 III	2·86	−0·33	222	Pleiades
H 520	23631	A2 V	7·34	+0·07	94	,,
H 510	23632	A1 V	6·98	+0·05	96	,,
H 540	23642	A0 V	6·59	0·00	117	,,
H 722	23753	B8 V	5·38	−0·33	190	,,
H 870	23850	B8 III	3·59	−0·37	207	Pleiades
H 878	23862	B8 pec	5·05	−0·29	219	,,
H 910	23873	A0 V	6·59	−0·12	140	,,
H 977	23923	B9 V	6·16	−0·19	166	,,
π^4 Ori	30836	B2 III	3·49	−0·87	244	Orion
	35575	B3 V	6·32	−0·75	218	Orion
	35777	B2 V	6·51	−0·77	225	,,
	35792	B3 V	7·08	−0·67	200	,,
	35882		7·47	−0·53	193	,,
	35899	B5 V	7·43	−0·64	211	,,
	36151	B5 V	6·65	−0·59	200	Orion
	36285	B2 V	6·12	−0·94	230	,,
	36430	B2 V	6·02	−0·82	209	,,
	36487		7·69	−0·57	193	,,
υ Ori	36512	B0 V	4·58	−1·08	254	,,
	36541		7·54	−0·49	192	Orion
	36591	B1 V	5·07	−1·01	239	,,
VV Ori	36695	B1 V	5·01	−0·98	225	,,
	36779	B2 V	6·15	−0·83	215	,,
ι Ori	37043	O9 III	2·63	−1·10	255	,,
ε Ori	37128	B0 Ia	1·30	−1·12	267	Orion
	37397	B3 V	6·65	−0·80	222	,,
ζ Ori	37742	O9·5 Ib	1·48	−1·12	265	,,
	37756	B3 III	4·91	−0·85	245	,,
	37776	B2 V	6·64	−0·95	231	,,

TABLE II (*continued*)

Star	HD	Sp	V_0	$(U-B)_0$	Γ	Association or cluster
κ Ori	38771	B0·5 Ia	1·66	−1·15	260	Orion
55 Ori	39291	B2	5·18	−0·91	246	,,
Walker 7			7·50	−0·71	202	NGC 2264
Walker 50		B3 Vp	7·81	−0·79	216	,,
Walker 131		O7	4·44	−1·13	257	,,
Walker 202		B2 V	8·02	−0·85	211	NGC 2264
Walker 212		B2·5 V	7·26	−0·80	213	,,
τ CMa	57061	O9 III	4·39	−1·12	272	NGC 2362
Johnson 20		B2 V	8·78	−0·95	224	,,
KW 265	73710	A1	6·61	+0·02	104	Praesepe
KW 276	73711	A3	7·54	+0·13	114	Praesepe
Trumpler 107	107966	A4p	5·18	+0·08*	95	Coma Berenices
Trumpler 132	108382	A4p	5·00	+0·08*	96	,,
Trumpler 144	108642	A4 ML	6·54	+0·08*	114	,,
Trumpler 160	108945	A3p	5·46	+0·07*	101	,,
β Aur	40183	A2 IV		+0·04	117	Ursa Major
β UMa	95418	A1 V		+0·02	117	,,
δ Leo	97603	A4 V			109	,,
γ UMa	103287	A0 V	2·38	−0·01	112	,,
ε UMa	112185	A0p		−0·03	127	,,
80 UMa	116842	A5 V	4·01		108	Ursa Major
α CrB	139006	A0 V	2·17	−0·04	149	,,
ν Cen	120307	B2 IV	3·36	−0·90	231	Scorpio–Centaurus
μ Cen	120324	B2 Vpne	2·79		242	,,
φ Cen	121743	B2 IV	3·80		217	,,
υ^1 Cen	121790	B2 IV	3·85		219	Scorpio–Centaurus
χ Cen	122980	B2 V	4·32	−0·80	221	,,
η Cen	127972	B3 III	2·36		249	,,
β Lup	132058	B2 IV	2·66	−0·89	235	,,
κ Cen	132200	B2 V	3·06	−0·77	225	,,
δ Lup	136298	B2 IV	3·21	−0·88	228	Scorpio–Centaurus
ϕ^2 Lup	136664	B5 V	4·64		205	,,
τ Lib	139365	B2·5 V	3·56	−0·69	213	,,
ψ^2 Lup	140008	B6 V	4·77		196	,,
1 Sco	141637	B2·5 Vn	4·26		226	,,
λ Lib	142096	B3 V	4·70	−0·72	197	Scorpio–Centaurus
ρ Sco	142669	B2 V	3·81	−0·86	225	,,
π Sco	143018	B1 V	2·71	−0·98	234	,,
δ Sco	143275	B0 V	1·83	−1·05	242	,,
ω1 Sco	144470	B1 V	3·39	−1·01	231	,,
13 Sco	145482	B2·5 Vn	4·45	−0·80	216	Scorpio–Centaurus
σ Sco	147165	B1 III	1·66	−1·00	243	,,
22 Sco	148605	B2 V	4·53	−0·78	221	,,
τ Sco	149438	B0 V	2·70	−1·09	240	,,
μ_1 Sco	151890	B1·5 V	2·92		234	,,

TABLE II (*continued*)

Star	HD	Sp	V_0	$(U-B)_0$	Γ	Association or cluster
μ_2 Sco	151985	B2 IV	3·51		233	Scorpio–Centaurus
θ Oph	157056	B2 IV	3·23	−0·91	229	,,
κ Cas	2905	B1 Ia			265	Field
ζ Cas	3360	B2 V			237	,,
o Cas	4180	B2 V			224	,,
δ Cas	8538	A5 V	2·68	0·00	115	Field
δ Per	22928	B5 III	3·03	−0·52	227	,,
η Aur	32630	B3 V	3·14	−0·69	211	,,
β Ori	34085	B8 Ia	0·08	−0·69	264	,,
τ Ori	34503	B5 III			215	,,
ρ Aur	34759	B5 V			199	Field
γ Ori	35468	B2 III			240	,,
β Tau	35497	B7 III	1·65	−0·48	200	,,
χ Aur	36371	B5 Iab			276	,,
δ Ori	36486	O9·5 II			270	,,
υ Ori	36512	B0 V	4·57	−1·09	257	Field
θ Aur	40312	A0 p			177	,,
χ^2 Ori	41117	B2 Ia	3·34		269	,,
ν Ori	41753	B3 V			215	,,
3 Gem	42087	B2·5 Ib			258	,,
13 Mon	46300	A0 Ib			228	Field
γ Gem	47105	A0 IV	1·93		127	,,
θ Gem	50019	A3 III			121	,,
ι CMa	51309	B3 II	4·03		249	,,
ε CMa	52089	B2 II			238	,,
o^2 CMa	53138	B3 Ia			264	Field
γ CMa	53244	B8 II			212	,,
λ Gem	56537	A3 V	3·52		101	,,
η CMa	58350	B5 Ia			261	,,
β CMi	58715	B8 V			187	,,
η Hya	74280	B3 V	4·31	−0·74	223	Field
κ UMa	77327	A0			152	,,
α Hya	83754	B5 V			201	,,
o Leo	83809				207	,,
21 LMi	87696	A7 V	4·48		116	,,
η Leo	87737	A0 Ib			228	Field
α Leo	87901	B7 V	1·36	−0·38	192	,,
30 Sex	90994	B6 V			188	,,
ρ Leo	91316	B1 Ib			254	,,
θ Leo	97633	A2 V			127	,,
γ Crv	106625	B8 III	2·60		190	Field
α Vir	116658	B1 V	0·96	−0·94	242	,,
ζ Vir	118098	A3 V			105	,,
η UMa	120315	B3 V	1·86	−0·68	202	,,
α Dra	123299	A0 III	3·64		145	,,
109 Vir	130109	A0 V	3·74	−0·03	139	Field
α Lyr		A0 V		−0·01	110	,,

* $(U-B)_0$ values derived from spectral types.

stars in Table II have well-observed values of $(U-B)$ and $(B-V)$, since they are members of prominent galactic clusters or associations or else field stars that are photoelectric standards set up over the sky by Johnson and Morgan. From the actual observed values of $(U-B)$ and $(B-V)$ we determined $(B-V)_0$ and $(U-B)_0$ using the nomogram of Johnson (18) for this purpose. Almost all the stars studied have reliable MK classifications. We work only on luminosity classes Ia, Ib, III and V, since we have very few stars of types II and IV to merit study. Even so, the sample of Ia and Ib members included in this study is quite small and the values derived later are meant more to indicate the pattern followed by the supergiants rather than to produce an accurate calibration which can be put to use immediately in galactic research. We determined, separately, a mean Γ value for each spectral class, the main sequence stars, giants and the supergiants. Smoothed curves through these representative points, weighted on the basis of the population of points in each category, yielded the value of Γ representative of the spectrum and luminosity classes. Tables III and IV give the Γ and corresponding $(U-B)_0$ and $(B-V)_0$ values respectively for the different spectral

Table III

Values of Γ *and* $(U-B)_0$ *for different spectral types*

	Ia		Ib		III		V	
Sp	Γ	$(U-B)_0$	Γ	$(U-B)_0$	Γ	$(U-B)_0$	Γ	$(U-B)_0$
O7							265	−1·14
O8							261	−1·13
O9			269	−1·12	263	−1·12	258	−1·12
B0	(270)	−1·07	267	−1·05	258	−1·09	250	−1·08
B1	269	−1·00	265	−0·96	247	−0·96	231	−0·93
B2	269	−0·96	264	−0·91	243	−0·89	225	−0·86
B3	268	−0·87	262	−0·82	235	−0·74	211	−0·71
B5	266	−0·78	259	−0·72	223	(−0·59)	199	−0·56
B6	264	−0·73	257	−0·67	215	(−0·51)	193	−0·49
B7	263	−0·68	256	−0·62	207	(−0·44)	185	−0·42
B8	263	−0·60	253	−0·53	194	(−0·32)	170	−0·30
B9	263	−0·56	(251)	−0·48	180	(−0·20)	156	−0·19
A0							121	0·00

Table IV

Values of Γ *and* $(B-V)_0$ *for different spectral types*

	Ia		Ib		III		V	
Sp	Γ	$(B-V)_0$	Γ	$(B-V)_0$	Γ	$(B-V)_0$	Γ	$(B-V)_0$
O7							265	−0·32
O8							261	−0·31
O9			269	−0·28	263	−0·31	258	−0·31
B0	(270)	−0·22	267	−0·22	258	−0·30	250	−0·30
B1	269	−0·18	265	−0·18	247	−0·26	231	−0·26
B2	269	−0·16	264	−0·16	243	−0·24	225	−0·24
B3	268	−0·12	262	−0·12	235	−0·20	211	−0·20
B5	266	−0·08	259	−0·08	223	−0·16	199	−0·16
B6	264	−0·06	257	−0·06	215	−0·14	193	−0·14
B7	263	−0·04	256	−0·04	207	−0·12	185	−0·12
B8	263	−0·01	253	−0·01	194	−0·09	170	−0·09
B9	263	+0·02	(251)	+0·02	180	−0·06	156	−0·06
A0							121	0·00

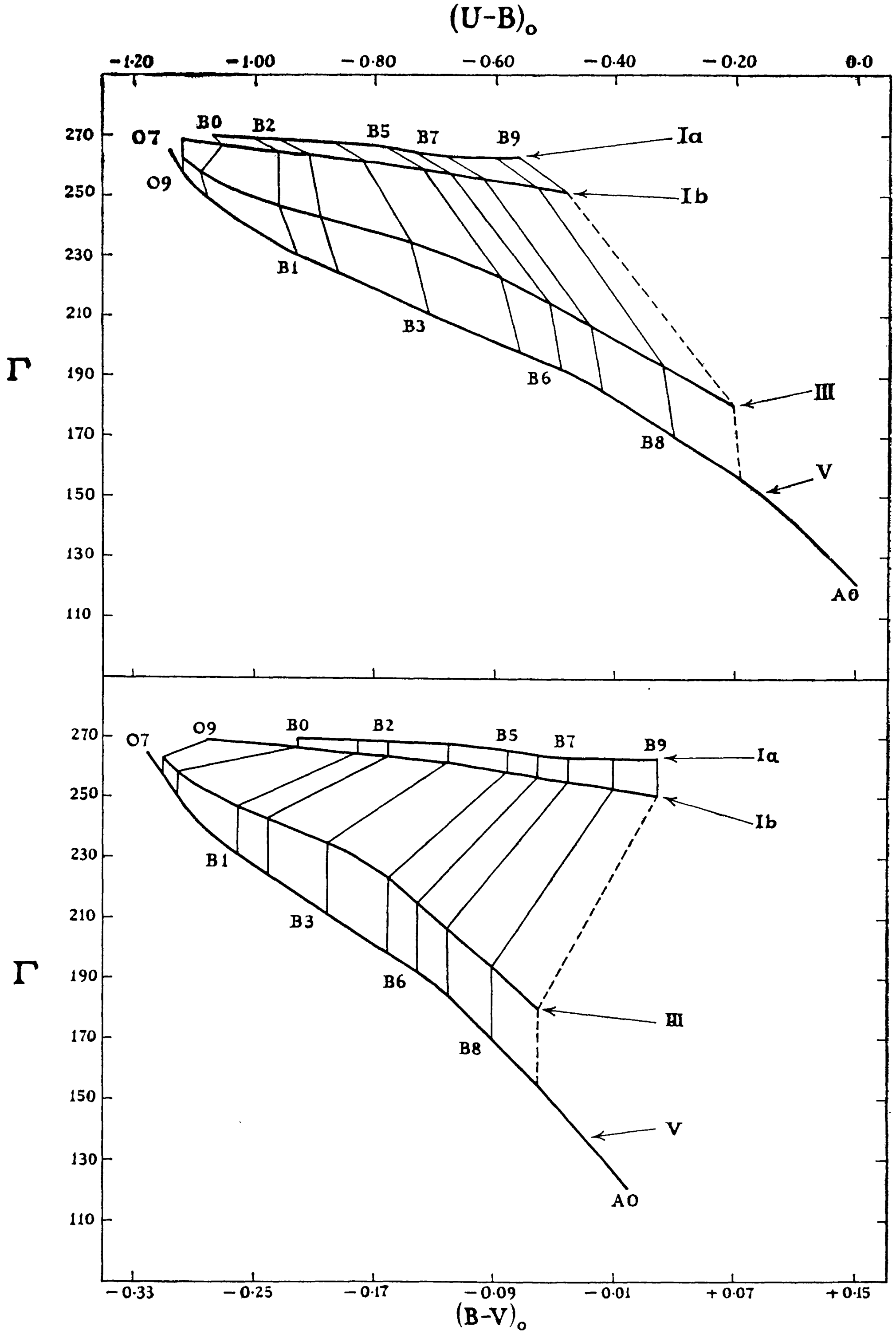

FIG. 2

and luminosity classes. The unreddened values of $(U-B)$ and $(B-V)$ are those derived by the method of Johnson. Fig. 2 shows diagrammatically the relations between Γ, spectral type and luminosity class for both $(U-B)_0$ and $(B-V)_0$ values. The value of Γ for spectral class B9 III is provisional and hence we have linked this point by dotted lines with the rest of the spectral classification network in both sections of Fig. 2.

In plots of Γ against MK spectral class, one finds a scatter of the points about a mean Γ, representative of the spectral class. As an example we shall consider the scatter about the mean for spectral class B2 V. We have measured Γ indices for twenty main-sequence stars of spectral class B2. All but two of the stars are members of the aggregates NGC 2362, NGC 2264, ζ Persei, Orion and the Scorpio–Centaurus cluster. The MK classifications for nineteen stars originated from investigations carried out at the Yerkes and McDonald Observatories and so the classifications may be considered to be quite homogeneous. Yet the Γ values range from 209 to 237 if we exclude a peculiar star that has a Γ value of 242. Similarly, Crawford has 15 stars of type B2 V which range from 2·691 to 2·639 in β or 209 to 232 in Γ. Since our standard error for a Γ index is very much less than the scatter, we conclude that the low resolution of the MK classification contributes predominantly to the scatter.

4. *Age effects in the* Γ, $(U-B)_0$ *diagram.*—Strömgren (**16**) has indicated that age effects are easily noticeable on Hβ–Balmer discontinuity diagrams for field stars and clusters. The observations have been extended further by Crawford (**17**) who measured β indices in a few clusters and associations of different ages. Crawford's average location curves for these associations and clusters have demonstrated clearly the shifting trend towards weaker hydrogen absorption-line intensities with increasing age.

Our investigation, aimed at confirming such an age effect, shows that the changes are noticed in the Γ, $(U-B)_0$ diagrams that we have derived. We have confined ourselves primarily to main-sequence stars in the ζ Persei association, the Scorpio–Centaurus cluster, the Orion association, the α Persei cluster, the Pleiades and NGC 2264. The $(U-B)_0$ values that we employed were obtained from Johnson's nomograms as indicated earlier. We had to omit from the Γ, $(U-B)_0$ plots some of the Scorpio–Centaurus cluster members that we have measured for Γ indices, because of the lack of $(U-B)$ colour indices for these stars.

Fig. 3 is a combined plot of the smoothed Γ, $(U-B)_0$ curves for main-sequence stars of the different aggregates we have studied. Included in the diagram are some field stars for which measures of $(U-B)$ exist. The dashed line, extending from $(U-B)_0 = -1{\cdot}0$ to $(U-B)_0 = -0{\cdot}6$, represents the mean Γ, $(U-B)_0$ line for NGC 2264, the ζ Persei association, the Orion association and the Scorpio–Centaurus cluster. Current ideas on stellar evolution indicate that all four of these star clusters are younger than five million years. We therefore consider them in Fig. 3 as a group of "young stars" essentially for purposes of comparison with the α Persei cluster and the Pleiades. Mitchell and Johnson (**19**) have determined an age of 150×10^6 years for the Pleiades on the basis of the turn-off point in the colour-magnitude array. Similar considerations have led von Hoerner (**20**) to assign an age of 10×10^6 years for the α Persei cluster. These ages may be revised in the future, but they nevertheless indicate the relative degree of evolutionary change that the members of each cluster have experienced since their formation. We then note that on the Γ, $(U-B)_0$ diagram the mean line for the stars younger than 5×10^6 years is located differently from the α Persei line. The separation of the two groups is noticeable only for the earlier spectral types in each of the two groups since the mean line for the young stars merges with the α Persei line at $(U-B)_0 = 0{\cdot}58$. A similar separation may be seen between the α Persei line and that of the Pleiades, the two appearing to merge in the neighbourhood of $(U-B)_0 = +0{\cdot}1$ and $\Gamma = 95$. The Γ-spectral type relation indicates that the range in Γ is larger near B9 or A0 than it is for the earlier types. The merger of the α Persei line and the Pleiades line near $\Gamma = 95$ points out that the Pleiades stars near this spectral type and later have experienced very little evolutionary changes since their formation, a conclusion that has in recent years been very evident from the colour-magnitude arrays determined for these clusters.

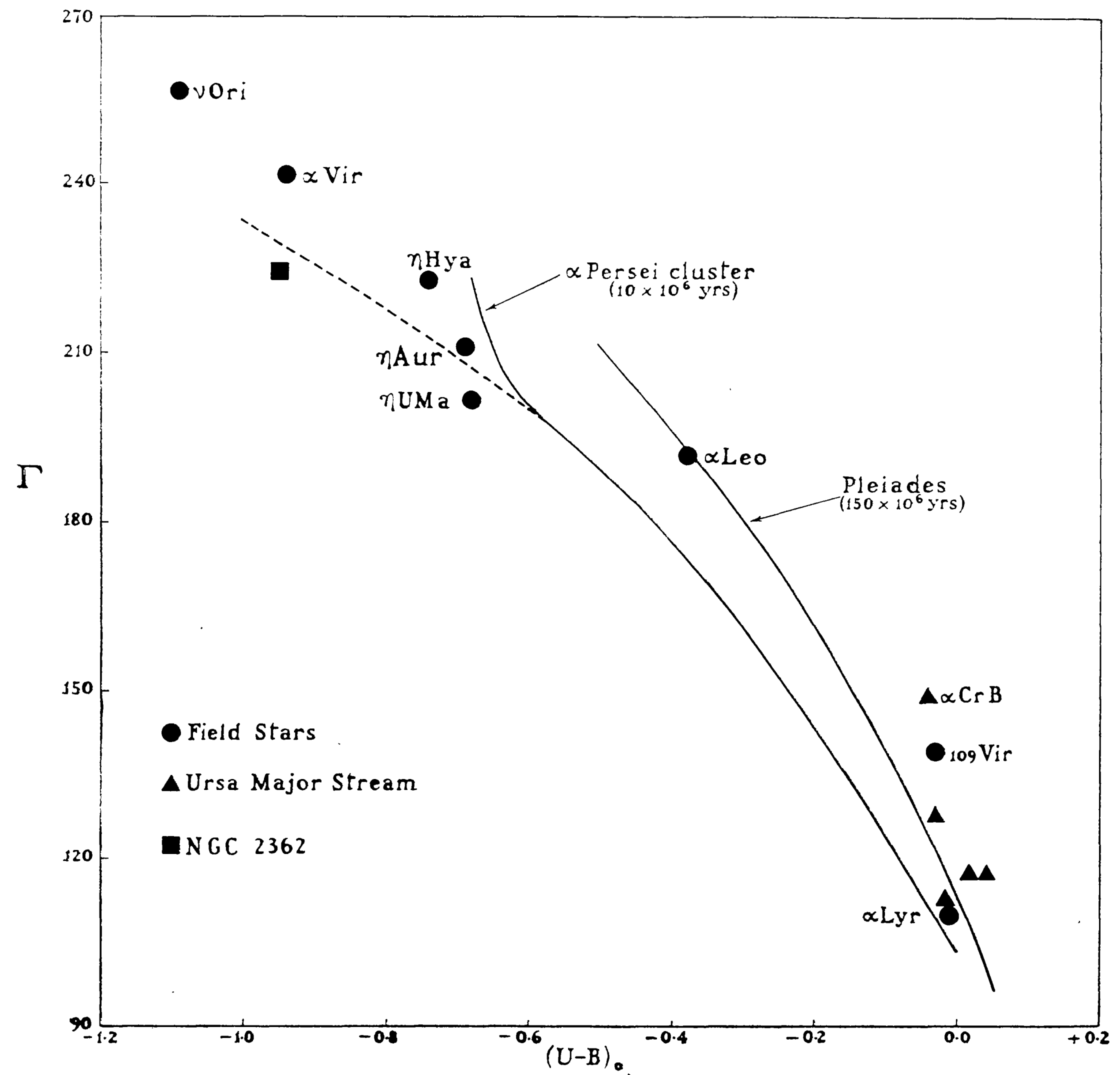

FIG. 3

We have included in Fig. 3 five members of the Ursa Major stream. One of these lies below the Pleiades line. The four others are above this line, of which ε UMa, β UMa, β Aur, can be accommodated within the expected scatter about the Pleiades line. α Coronae Borealis, however, is well above the Pleiades line. von Hoerner's age of 300×10^6 years for the Ursa Major stream would lead us to expect such a departure from the Pleiades line for an A0 V star that has evolved more than its counterpart in the Pleiades. One can probably separate with confidence the Ursa Major line from that of the Pleiades only when more observations of the Ursa Major cluster in the Γ range 120–150 become available.

Fig. 4 is a Γ, $(U-B)_0$ plot of the stars younger than five million years. Also shown as a straight line is a least-squares fit for stars of the Orion association. With the exception of three stars, the Scorpio–Centaurus stars systematically fall above the straight line representative of the Orion association. Similarly, except for four stars, the members of NGC 2264, ζ Persei and NGC 2362 appear to fall below the Orion mean line. In any one association or cluster a scatter exists in the Γ, $(U-B)_0$ plot. These may be ascribed to accidental errors or scatter due to unsuspected duplicity of some of the stars, or even due to different ages for the stars in any cluster. Despite the possibility of such a scatter it will

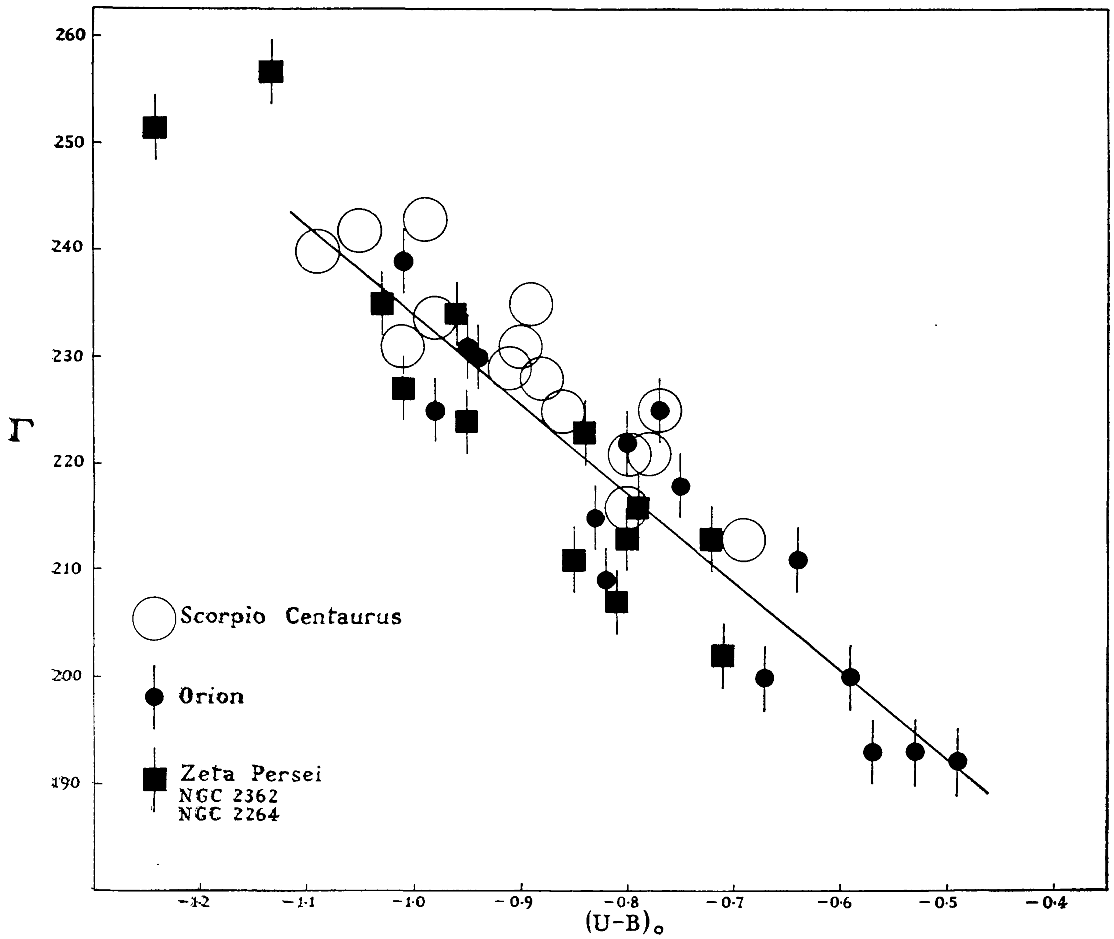

FIG. 4

be difficult to reconcile the Scorpio–Centaurus stars with the straight line fit drawn for the Orion stars. We therefore offer the suggestion that the Scorpio–Centaurus stars we have observed are older than those in the Orion association. An actual derivation of the age difference between the two associations must await more extensive observations, with better precision than we have achieved.

Age determinations at present for individual stars are possible only if the stars are members of a cluster, since a colour-magnitude array for the cluster permits the evaluation of the age. A well-calibrated Γ, $(U-B)_0$ diagram would enable the assignment of an age to any main-sequence star earlier than A0 since a direct determination of the distance modulus of the star is unnecessary to achieve such a result. Such a calibration would depend largely on a correct determination of cluster ages and the proper evaluation of unreddened $(U-B)$ values. It is likely that these will be possible in the near future.

5. *Determination of absolute magnitudes from* Γ *indices.*—Perhaps the most important application, in the field of galactic structure, of measures of hydrogen absorption-line intensities in early-type stars lies in the possibility of determining the absolute magnitudes. The efforts in particular of Petrie and of Petrie and Maunsell using Hγ measures and of Strömgren and Crawford who utilized β indices have shown the usefulness of such measures for absolute magnitude determinations. The age effect discussed in the previous section, however, prevents the accurate derivation of a value of absolute magnitude from any mean relation between Γ indices and M_v, unless the appropriate age-corrections are applied. To do so, it is necessary to have a M_v calibration utilizing stars that are as close as possible to the lower boundary in a Γ, M_v diagram which can be considered as the locus of the very young stars. Stars younger than 20×10^6 years can be used for such a Γ, M_v calibration.

We have utilized for such a calibration, the α Persei cluster, the Scorpio–Centaurus cluster, the double cluster in Perseus, the ζ Persei association and NGC 2264. The absolute magnitudes of members of the Scorpio–Centaurus cluster used are those derived by Bertiau (**21**). The distance moduli for h and χ Persei, the ζ Persei association and NGC 2264 listed by Johnson (**22**) were used in conjunction with the cluster-photometry results of Johnson and Morgan (**23**), Harris (**24**) and Walker (**25**) for the above three clusters. Table V gives in detail the values of Γ for a range in absolute magnitude of over 8·5 magnitudes, for stars earlier than spectral type A2. The spectral type corrections for the values in Table V are given in Table VI. To start with, we made a redetermination of the distance modulus of the α Persei cluster by calibrating these stars against the fainter stars of the Pleiades cluster for which we have Γ indices. The *U*, *B*, *V* photometry data for α Persei are that of Harris (**24**). The fitting of the Γ, M_v curves of the α Persei cluster to that of the Pleiades was made at Γ values of 120 and 160. The distance modulus derived from both values was 6·0 mag. with an estimated standard error of $\pm 0{\cdot}23$ mag. or even less. Since this fit was made in the region of $M_v = +1{\cdot}0$, a likely error in the distance modulus that will originate because of the advanced evolutionary stage of the Pleiades is less than 0·10 mag. or within the limits of probable error of our distance determination. We have, therefore, adopted a value of distance modulus of 6·0 mag. for the α Persei cluster.

Such a determination from Γ indices of the distance of the α Persei cluster is based on a tie-in with the Pleiades values of Γ. We have assumed that the distance modulus of the Pleiades cluster is 5·5 mag. This value was derived by Mitchell and Johnson (**19**) by fitting the Pleiades main sequence to that of the Hyades. The distance of the Pleiades has been accurately derived by photometric main-sequence fits and hence it seems unlikely that a revision of the Pleiades distance modulus by over $\pm 0{\cdot}1$ mag. will be necessary. Our value of a distance modulus of 6·0 mag. for the α Persei cluster agrees very well with the value of $6{\cdot}06 \pm 0{\cdot}15$ mag. derived by Mitchell (**26**) from *U*, *B*, *V* measures.

Having adopted a distance modulus for the α Persei cluster, the Γ, M_v calibration was extended to higher luminosities with the aid of the Scorpio–Centaurus cluster, the double cluster in Perseus and NGC 2264. With the aid

TABLE V

The Γ, M_v calibration

Γ	M_v 0	2	4	6	8
110	+2·8	+2·75	+2·75	+2·7	+2·7
120	+2·65	+2·65	+2·6	+2·55	+2·55
130	+2·5	+2·5	+2·45	+2·4	+2·35
140	+2·3	+2·3	+2·25	+2·2	+2·15
150	+2·1	+2·05	+2·0	+1·9	+1·85
160	+1·8	+1·7	+1·65	+1·55	+1·5
170	+1·4	+1·3	+1·2	+1·1	+1·0
180	+0·9	+0·8	+0·7	+0·6	+0·5
190	+0·35	+0·25	+0·1	−0·05	−0·2
200	−0·35	−0·5	−0·6	−0·8	−0·9
210	−1·1	−1·2	−1·35	−1·5	−1·65
220	−1·85	−2·0	−2·15	−2·35	−2·5
230	−2·65	−2·8	−2·95	−3·15	−3·35
240	−3·5	−3·7	−3·9	−4·1	−4·25
250	−4·45	−4·65	−4·9	−5·1	−5·4
260	−5·6	−5·8	−6·1	−6·3	−6·6
270	−6·9	−7·25	−7·6	−7·9	

TABLE VI

The spectral type corrections to Table V

Sp	Correction	Sp	Correction
O	0·0	B6	−0·6
B0	0·0	B7	−0·75
B1	0·0	B8	−1·00
B2	0·0	B9	−1·2
B3	−0·15	A0	−1·35
B5	−0·4	A1	−1·5

of calibration and spectral-type corrections given in Tables V and VI respectively we have carried through, as a test, the determination of the distance moduli of the Orion association and NGC 2362. Table VII gives the data for the 23 stars of the Orion association for which we have Γ indices. The U, B, V photometry results are those obtained by Sharpless (**27, 28**). All but four of these stars have MKK spectral types. For the remaining four stars, spectral types were determined with the aid of the Γ indices and $(U-B)_0$ values, as indicated earlier. The distance modulus of 8·1 mag. thus obtained for the Orion association is in good agreement with the value of 8·0 mag. derived by Johnson (**22**). The scatter in $m-M$ values is mainly due to the reason that for most of the Orion association stars, we could have only one observation of the Γ index for each star.

A similar calculation for the two stars of NGC 2362 that we have observed for Γ indices, yields a mean value of $m-M=11{\cdot}0$ mag. $\pm 0{\cdot}5$ mag., a value in fair agreement with Johnson's determination of 10·8 mag.

TABLE VII

The distance modulus of the Orion association

HD	$(U-B)_0$	Sp	Γ	V_0	Sp Corr.	M_v Uncorr.	M_v Corr.	$m-M$
30836	−0·87	B2 III	244	3·49		−3·9	−3·9	7·39
35575	−0·75	B3 V	218	6·32	−0·15	−1·65	−1·80	8·12
35777	−0·77	B2 V	225	6·51		−2·25	−2·25	8·76
35792	−0·67	B3 V	200	7·08	−0·15	−0·30	−0·45	7·53
35882	−0·53	B5 V*	193	7·47	−0·40	+0·20	−0·20	7·67
35899	−0·64	B5 V	211	7·43	−0·40	−1·15	−1·55	8·98
36151	−0·59	B5 V	200	6·65	−0·40	−0·30	−0·70	7·35
36285	−0·94	B2 V	230	6·12		−2·65	−2·65	8·77
36430	−0·82	B2 V	209	6·02		−1·00	−1·00	7·02
36487	−0·57	B5 V*	193	7·69	−0·40	+0·20	−0·20	7·89
36512	−1·08	B0 V	254	4·58		−4·90	−4·90	9·38
36541	−0·49	B6 V*	192	7·54	−0·60	+0·25	−0·35	7·89
36591	−1·01	B1 V	239	5·07		−3·40	−3·40	8·47
36695	−0·98	B1 V	225	5·01		−2·25	−2·25	7·26
36779	−0·83	B2 V	215	6·15		−1·45	−1·45	7·60
37043	−1·10	O9 III	255	2·63		−5·00	−5·00	7·63
37128	−1·12	B0 Ia	267	1·30		−6·50	−6·50	7·80
37397	−0·80	B3 V	222	6·65	−0·15	−2·00	−2·15	8·80
37742	−1·12	O95 Ib	265	1·48		−6·25	−6·25	7·73
37756	−0·85	B3 III	245	4·91	−0·15	−4·00	−4·15	9·06
37776	−0·95	B2 V	231	6·64		−2·75	−2·75	9·39
38771	−1·15	B05 Ia	260	1·66		−5·60	−5·60	7·26
39291	−0·91	B2 III*	246	5·18		−4·05	−4·05	9·23

Mean $m-M=8{\cdot}1$ mag.

* Spectral types derived from Table III.

The two cases treated above indicate clearly the validity of our Γ, M_v calibration for the young stars. The convenient way in which such determinations can be carried out, even with telescopes of medium to small aperture, makes the photoelectric technique of hydrogen absorption line-measurements a useful tool for galactic research.

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1961 *December* 19.

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