1967ApJ...147.1003G

SOME CHARACTERISTICS OF THE B AND A STARS IN THE UPPER SCORPIUS COMPLEX

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Received June 27, 1966

ABSTRACT

More accurate spectral classifications from new McDonald spectrograms are given for seventy-five *Henry Draper* B0–B9 stars in the region of the Upper Scorpius part of the Scorpio-Centaurus association, for which photometry by Hardie and Crawford is available. Classifications and photometry are also presented for the *HD* A0–F2 stars in the inner region defined by the asterism formed by α Sco, σ Sco, 22 Sco, and ρ Oph. A narrow main sequence is found for the B2–F0 members of this inner region.

Of special interest is the presence of peculiar Sr II stars in the inner region. These are probably members of the association, and their presence suggests that such stars occur in an early stage of evolution rather than a later one. In the larger Upper Scorpius region, a number of other peculiar stars are found which are probably association members.

A pronounced lack of agreement is found between many of the present spectral types and those derived from narrow-band photometry. For certain B7–B9 stars, located above the main sequence, the latter method gives, systematically, much higher temperatures. These discrepancies indicate that two-dimensional spectral types continue to be of astrophysical importance; their value is especially great when combined with accurate narrow-band photometry.

I. INTRODUCTION

The development of interest in the nearest associations has been traced recently by Blaauw (1964*a*). In the past, investigators have concentrated their efforts mainly on the O and B star population of these young groups. Little is known about the A stars, although in a very few cases photometric and objective prism studies have been extended to fainter stars.

The loose clustering of B stars in Upper Scorpius (Fig. 1) is the richest subsection of the nearest of all the associations, and since it is also out of the plane of the Milky Way, there should be few foreground stars. The inner region near ρ Ophiuchi (Fig. 2), where the dense streamers of obscuring dust converge, should contain very few background stars. Thus the A stars in this inner region have a strong a priori possibility of membership and for this reason have been chosen for the extension of the association main sequence.

The Scorpio-Centaurus moving cluster has had its geometrical distance determined most recently by Blaauw (1946) and Bertiau (1958). Thus it is an important region for the calibration of MK spectral types. It is also important for intercomparison of the MK types with narrow-band photometric classifications. Discrepancies between Bertiau's MK types and the types implied by the photometric measures have been shown graphically by the Walravens (1960, in their Fig. 11). For these reasons it was decided to study the classification of new spectra of all the *Henry Draper* B stars in as much detail as possible.

II. OBSERVATIONS

The McDonald Observatory 82-inch telescope and the Cassegrain spectrograph, with the 110-mm classification camera and glass optics, were used for this study; this combination gives a scale of 86 Å/mm at Hδ. Eastman IIaO plates were used and were developed in metol-sulphite. Extra-wide-slit spectrograms were obtained of seventy-five of the eighty *Henry Draper* B0–B9 stars in Upper Scorpius listed by Hardie and Crawford (1961). A number of the brighter stars were obtained by Dr. W. A. Hiltner and Mr.

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R. E. Schild in February, 1965, and the fainter ones were obtained by the author in August, 1965, with some overlap. In March, 1965, spectrograms were obtained of the thirty-six *Henry Draper* B8–F2 stars in the inner region of the association. This inner region was defined as the region containing the most dust and nebulosity, and not as the center of the apparent distribution of stars. Figures 1 and 2 show this region which includes α Sco, σ Sco, 19 Sco, 22 Sco, and ρ Oph, as well as the converging dark lanes. The approximate 1950 coordinates are 16^h15^m–16^h30^m and $-23°$–$27°$. Many of the brighter stars were observed again in the spring of 1965 with the MK spectrograph and the Yerkes 40-inch refractor. Some of the fainter stars were reobserved by the author at the 40-inch telescope with an image-tube spectrograph, which uses the RCA C33011 cascaded image tube provided by the Carnegie Image Tube Committee.

The *UBV* photometry of the *HD* B0–B9 stars has been carried out by Hardie and Crawford (1961). Photometry of the *HD* B8–F2 stars in the inner region was carried out by the author with the McDonald 36-inch reflector in June, 1965. The standard Yerkes photometric equipment, which includes a red leak filter, was used. Special care was used in the determination of the extinction, since the Scorpius stars were observed through nearly two air masses. In addition to *UBV* measurements, the standard stars were observed with filters centered at λ4680 and λ5500 Å with approximately 200 Å half-width, and these observations were used as a consistency check on the V and $B - V$ extinction determinations. Eight of the ten primary standards were observed at several different air masses each night to determine extinctions and transformations by the normal methods, and several secondary standards were used to determine the extinction by the method of Hardie (1959). The extinction and transformation were determined each night independently of Hardie and Crawford's observations. Approximately twelve of their stars were observed each night as part of the program in Scorpius. Excellent agreement was found with their photometry, consistent with the external errors quoted in their paper.

III. CLASSIFICATION OF THE B STARS

Bertiau (1958) has given MK classifications for fifty-six of the eighty *Henry Draper* B0–B9 stars in Upper Scorpius, and ten of those classifications were considered by him to be uncertain. Dr. W. W. Morgan and his present associates are in the process of refining the MK system, and the types given here reflect in part this revision. It is possible, with the new refinements, good spectra and adequate standards, to classify reasonably normal early B stars to approximately one-twentieth of a spectral class. This higher accuracy was confirmed by comparison of completely independent classifications of several groups of stars by Dr. W. W. Morgan, Mr. R. E. Schild, Mrs. J. R. Lesh, and the author. These included stars in h and χ Persei, NGC 2244 and Orion, the bright Scorpius stars, field stars, and the standards themselves. As a result of this intensive work, a few minor changes have been made in the system of MK standards as used by Morgan. A list of the stars used as standards and their types on the present system is given in Table 1. The types for NGC 2244 are from Morgan, Hiltner, Neff, Garrison, and Osterbrock (1965) except that their No. 14 is used here as B2 IV–V.

The present classification was carried out without reference to previous classifications, absolute magnitudes, membership in the association, H-R diagrams, or photometry. A list of the intrinsic colors used at Yerkes for the calculation of color excesses is given in Table 2. The data for the Upper Scorpius B stars are listed in Table 3. The *UBV* measurements are from Hardie and Crawford (1961); the E_{B-V} are the color excesses calculated from the intrinsic colors as indicated by the spectra (any significant difference between this and the photometric color excess is indicated in the Notes); a ratio of total to selective absorption of 3 is assumed for V_0; and an asterisk following the *HD* number indicates a remark in the Notes to Table 3.

As a general remark it should be noted that the hydrogen lines are strong relative to the field-star standards for many of the main-sequence types. Only in extreme cases is

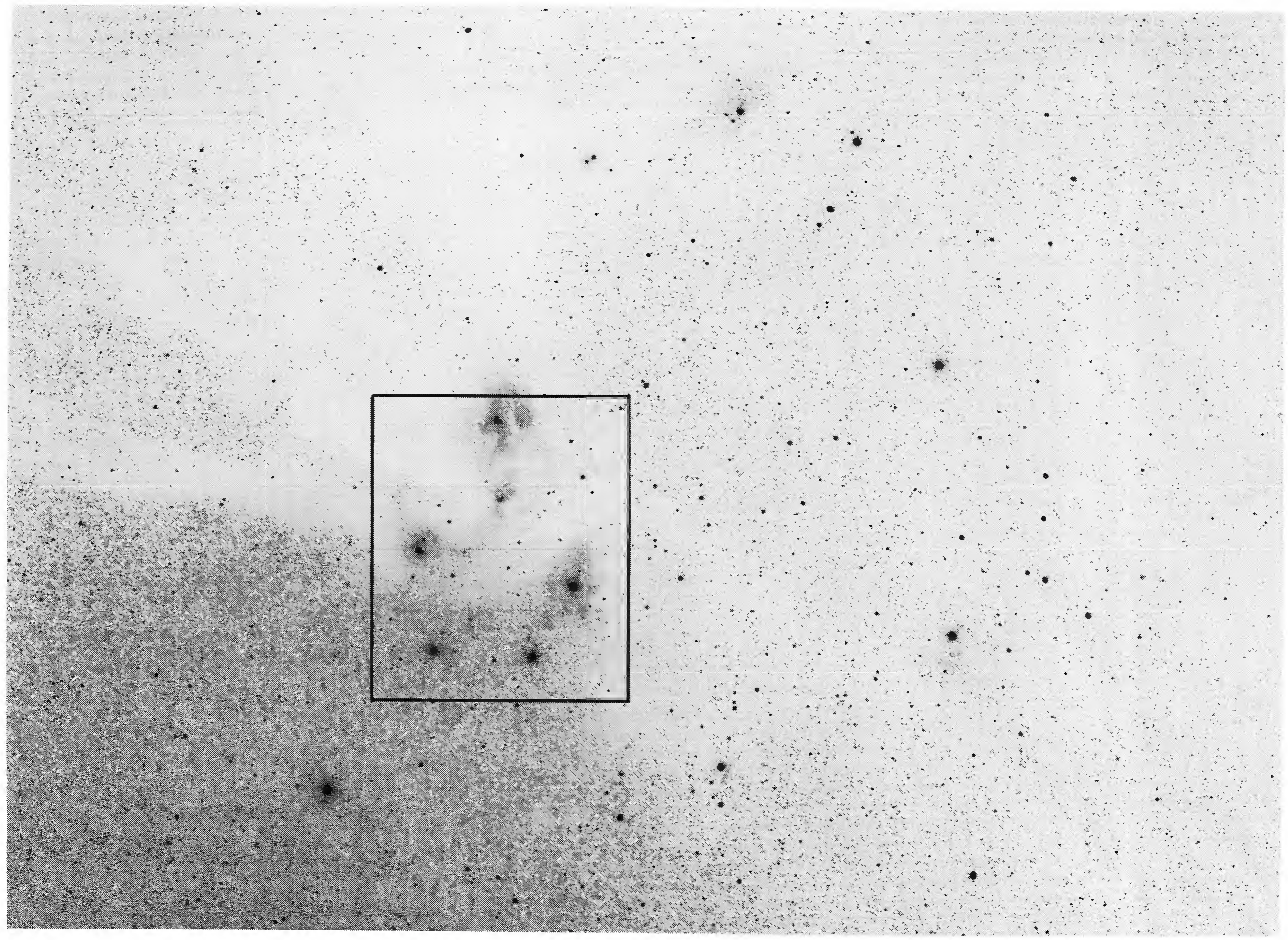

FIG. 1.—The Upper Scorpius region with the inner region marked. From negative copy of original from Ross-Calvert, *Milky Way Atlas*.

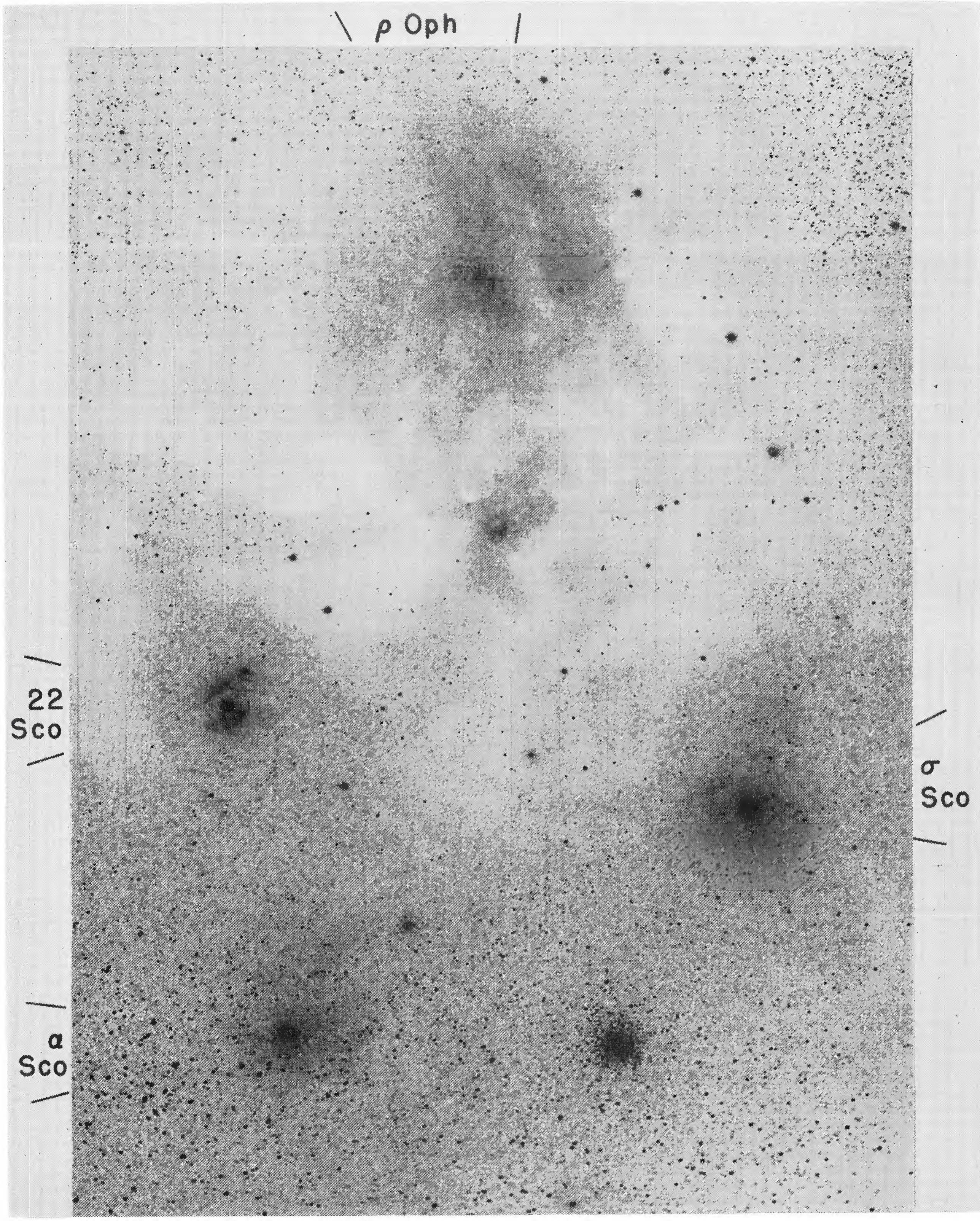

FIG. 2.—The inner region of the Upper Scorpius part of the Scorpio-Centaurus association. From negative copy of original from Barnard, *Milky Way Atlas*.

this noted. Taken as a luminosity indicator, independently of temperature, these strong hydrogen lines indicate low luminosity at a given type. This is also true of all other luminosity criteria. Wherever possible, the hydrogen lines were not used in the classification, and line ratios were relied on most heavily.

IV. CLASSIFICATION AND PHOTOMETRY OF THE A STARS

A catalogue of the *HD* A0–F2 stars in the inner region of Upper Scorpius is given in Table 4; it is similar to Table 3 except that the photometry is new. The classifications were carried out without reference to the photometry. The accuracy is probably about one-tenth of a spectral class and one luminosity class, since no refinements have yet been introduced into the A-star classification scheme.

TABLE 1

STANDARDS FOR CLASSIFICATION

Type	Luminosity Class		
	V	IV	III
O9	10 Lac		HD 193443
B0	NGC 2244 Main Seq. (B0–B2)		1 Cam (br)
B0.5		ϵ Per	κ Aql
B1			o Per
B2		γ Peg, δ Cet	π^4 Ori
B3	η Aur	.	. . .
B5	ν And, ρ Aur	τ Her	δ Per
B6	19 Tau	. . . .	.
B7	. . . .	16 Tau	η Tau
B8	18 Tau, β Lib	. .	27 Tau
B9	α Del	.	γ Lyr
B9.5	. . . . .	.	δ Cyg
A0	α CrB	.	α Dra

TABLE 2

INTRINSIC COLORS

Type	$(B-V)_0$	Type	$(B-V)_0$
B0 V	−0 30	A0 V	0 00
B0 5 V	− 28	A1 V	+ 03
B1 V	− 26	A2 V	+ 04
B2 V	− 23	A3 V	+ 09
B3 V	− 20	A5 V	+ 15
B5 V	− 15	A7 V	+ 20
B6 V	− 14	F0 V	+ 29
B8 V	− 11	F2 V	+ 38
B9 V	−0 07	F5 V	+0 45

TABLE 3

HD B0–B9 STARS IN UPPER SCORPIUS

STAR	HD	V	$B-V$	$U-B$	E_{B-V}	V_0	MK
. .	139094*	7 37	+0 08	−0 28	0 20	6 77	B7 V
HR 5801	139160	6 18	+ 01	− 42	0 13	5 79	B7 IV
τ Lib	139365*	3 67	− 17	− .66:	0 04	3 55	B2 5 V
	139486	7 65	+ 02	− 09	0 06	7 47	B9 5 V
	140543	8 92	+ 01	− 89	0 29	8 05	B0 5 IIIn
	141180	8 28	− 04	− 26	0 07	8 07	B8 V
. .	141404	7 70	+ 13	+ 02	0 20	7 10	B9 5 V
1 Sco .	141637	4 61	− 03	− .72	0 21	3 98	B1 5 Vn
. . . .	141774	7 70	+ .09	− 12	0 16	7 22	B9 V
λ Lib	142096*	5 02	− 02	− 58	0 19	4 45	B2 5 V
2 Sco .	142114*	4 60	− .07	− 64	0 14	4 18	B2 5 Vn
HR 5906	142165*	5 37	− .02	− .40	0 12	5 01	B6 IVn
HR 5907	142184	5 40	− .04	− .62	0 17	4 89	B2 5 Vn
HR 5910	142250*	6 13	− .07	− .44	0 07	5 92	B6 Vp
3 Sco	142301*	5 86	− .06	− .58	0 05	5.71	B8 p
. . . .	142315	6 86	+ .04	− .20	0 15	6 41	B8 V
47 Lib. .	142378*	5.96	.00	− .53	0.20	5 36	B3 V
ρ Sco A	142669*	3.88	− .22	− .82	0 01	3 85	B2 IV–V
. . . . .	142805	7.14	+ .16	+ .03	0 16	6 66	A0 III
HR 5934 . .	142883	5.84	+ .02	− .48	0 22	5 18	B3 V
. . . . .	142884*	6 80	+ .01	− .45	0 08	6.56	B9 p(Si λ4200)
HR 5942 . .	142990	5.42	− .09	− .65	0 06	5.24	B5 IV
π Sco . . .	143018*	2.89	− .18	− .91	0 08	2.65	B1 V+B2 V
δ Sco .	143275*	2 32	− .11	− .91	0.17	1 81	B0 5 IV
. . . .	143567	7.19	+ .08	− .10	0 15	6 74	B9 V
. . . .	143600	7.33	+ .10	− .06	0 17	6 82	B9 Vn
β Sco AB	144217*	2.61	− .05	− .87	0 23	1 92	B0 5 V
β Sco C.	144218*	4 92	− .02	− .70	0 21	4 29	B2 IV–V
HR 5988 .	144334*	5.92	− .08	− .56	0 03	5 83	B8 p
ω′ Sco . . .	144470	3.97	− .04	− .83	0 22	3 31	B1 V
HR 5998. .	144661*	6.32	− .06	− .52	0 07	6.11	B7 III (p?)
HR 6003 .	144844*	5 88	+ .02	− .32	0.09	5.61	B9 IV (p?)
. . . .	144941	10 11	+ .05	− .71	. . . .	. . . .	. . . .
. . . . . .	145102*	6 58	+ .07	− .17	0 14	6 16	B9 p(Si λ4200)
. . . .	145353	6.89:	+ .10	− .09	0 17	6 38	B9 IV
13 Sco . . .	145482*	4.57	− .17	− .76	0 06	4 39	B2 V
12 Sco A 12 Sco B	145483A}* 145483B}	5.66	.00	− .20	0 07	5 45	{B9 V {F2 V
ν Sco C . . . ν Sco D. . .	145501A}* 145501B}	6.23	+ .12	− .39	0.19	5 66	{B9 III {B9 p
ν Sco AB	145502AB*	4 01	+ .05	− .65	0 28	3.17	B2 IV
. . . .	145519	7 98	+ .25	+ .01	0 32	7 02	B9 Vn
. . .	145554	7 64	+ .14	− .09	0 21	7 01	B9 Vn
.	145556*	8 90	+ .07	− .39	0 21	8 27	B6 V
. . . .	145631	7 58	+ .16	− .04	0 20	6 98	B9 5 Vn
HR 6042	145792*	6 41	+ .04	− .46	0 19	5 84	B5 V
HR 6054	146001	6 04	+ .04	− .37	0 17	5 53	B7 IV
. .	146029	7 38	+ .07	− .08	0 14	6 96	B9 V
.	146284*	6.70	+ .16	− .16	0 27	5 89	B8 IV
. .	146285	7.94	+ .23	− 10	0 34	6 92	B8 V
. . . . . .	146332*	7 59	+ .20	− 36	0 35	6 54	B5 II
HR 6066	146416	6 60	+ .02	− .16	0 09	6 33	B9 V
. .	147009	8 08	+ .30	+ .17	0 33	7 09	B9 5 V
. . .	147010*	7 41	+ .16	− .25	0 12	7 05	A p
σ Sco A	147165*	2 93:	+ .13	− .69:	0 39	1 76:	B1 III
. . .	147196*	7 03	+ 18	− .18	0 29	6 16	B8 Vnnp
. . .	147701*	8 35	+ .57	− 08	0 72	6 19	B5 V
ρ Oph D	147888*	6 74	+ 32	− .34	0 47	5 33	B5 V
. . .	147889*	7 86	+ 85	− .16	1 08	4 62	B2 V
. .	147890*	7 64	+ .26	− .18	0 30	6 74	B9 5 p (Si)
ρ Oph A ρ Oph B . . .	147933}* 147934}	4 59	+0 24	−0 57	0 47	3 18	{B2 IV {B2 V

TABLE 3—*Continued*

Star	HD	V	$B-V$	$U-B$	E_{B-V}	V_0	MK
χ Oph ...	148184*	4 34	+0 30	−0.75	0 53	2.75	B2 III pe
	148199*	7 00	+ .10	−0 22	06	6.82	A p
.	148499	9 86	+ .39	+0 05	....	....	....
.....	148579*	7 34	+ .28	−0.03	.35	6.29	B9 V
.....	148594*	6 90	+ .10	−0 26	.21	6 27	B8 Vnn
22 Sco ...	148605*	4 79	− 12	−0.70	.11	4.46	B2 V
....	148860	8 05	+ .15	−0 07	.19	7 48	B9 5 V
.	149168	9 93	+ 08	−0 31	.20	9 33	B7 V
....	149367*	8 50	+ .15	−0 13	.22	7.84	B9 V
....	149387	9 19:	+ .18	−0 35	....	....	....
τ Sco	149438*	2 82	− .25	−1.04	.05	2.67	B0 V
....	149464*	8 56	+ .22	−0 05	.29	7 69	B9 Vn
....	149827	9 63	+ .22	−0 08	....	....	....
.....	149883	8 42	+ .15	−0 06	.22	7.76	B9 V
. .	150035*	8 65	+ .24	+0.12	.09	8 38	A5 p(Sr–Cr)
..	150347	8 96	+ .11	−0 12	.18	8.42	B9 V:
.	150514*	8 60:	+ .13	−0 23	.24	7 88:	B8 III
.	151310	9 42	+ .03	−0.60	.26	8.64	B2 V
.	151346*	7 90	+ .41	−0.20	.54	6.28	B7 p
..	151831	10 56:	+ 08:	−0 34:	......	....	....
	151865	8 85	+0 19	−0.18	0 30	7.95	B8 V

NOTES TO TABLE 3

139094: Sharp-lined star.

139365: On one of the plates, two spectra are visible in the form of shadings to the violet of most lines. Variable radial velocity has been reported. This indicates a possible correction of about 0.6 mag to V_0. The hydrogen lines are strong, and ionized silicon and magnesium are weak for the helium type given.

142096: Variable radial velocity has been confirmed by van Hoof, Bertiau, and Deurinck (1963), who have found a period of 11.5 days. This indicates a possible correction of about 0.3 mag to V_0. Ionized silicon and magnesium are weak and the hydrogen lines are strong for the helium type given.

142114: ADS 9823.

142165: New radial velocity by van Hoof *et al.*(1963) is consistent with membership whereas previous ones were not.

142250: He I λ4026 is sharp; series He I λλ4387, 4144, 4009 is diffuse; Hγ and Hδ have sharp cores. Otherwise this star resembles 19 Tau.

142301: The spectrum resembles that of 27 Tau (B8 III) except that the wings of the hydrogen lines are weaker and Hγ and Hδ have sharper cores. Si II may be slightly stronger than in 27 Tau but is certainly not outstanding. The spectrum is definitely inconsistent with photometric temperature classifications.

142378: ADS 9834. The spectrum is similar to that of No. 17 in NGC 2244 (Morgan *et al.* 1965) in which the hydrogen lines are strong; however, the effect is not quite so pronounced.

142669: ADS 9846.

142884: Hydrogen and helium are both weak as in late-B-type giants, but the K-line of ionized calcium is very weak. The spectrum is definitely inconsistent with photometric temperature classifications.

143018: ADS 9862. Two spectra are clearly visible on one of the plates, and the spectral type of the secondary has been estimated. This indicates a possible correction to V_0 of about 0.5 mag.

143275: Variable radial velocity has been confirmed by van Hoof *et al.* (1963), who have given a period of 20 days. This indicates a possible correction of about 0.3 mag to V_0.

144217: ADS 9913 AB. This is probably a multiple system. It is a well-known spectroscopic binary with a period of 6.8 days, and there is evidence of a third spectroscopic companion. Two spectra have been previously reported. This indicates a possible correction of more than 0.6 mag to V_0.

144218: ADS 9913 C.

144334: In Figure 4 the spectrum is compared with that of a B5 V and a B8 III. It resembles 27 Tau (B8 III) except that the lines are somewhat weaker and the hydrogen-line cores are sharper. The spectrum is definitely inconsistent with photometric temperature classifications. Hardie and Crawford (1961) list this star as a non-member in their Table 3. However, its motion and its positions in the color-magnitude, Hβ, and H-R diagrams are consistent with membership in spite of the inconsistency between the spectrum and the photometry. It is probably a member of the association.

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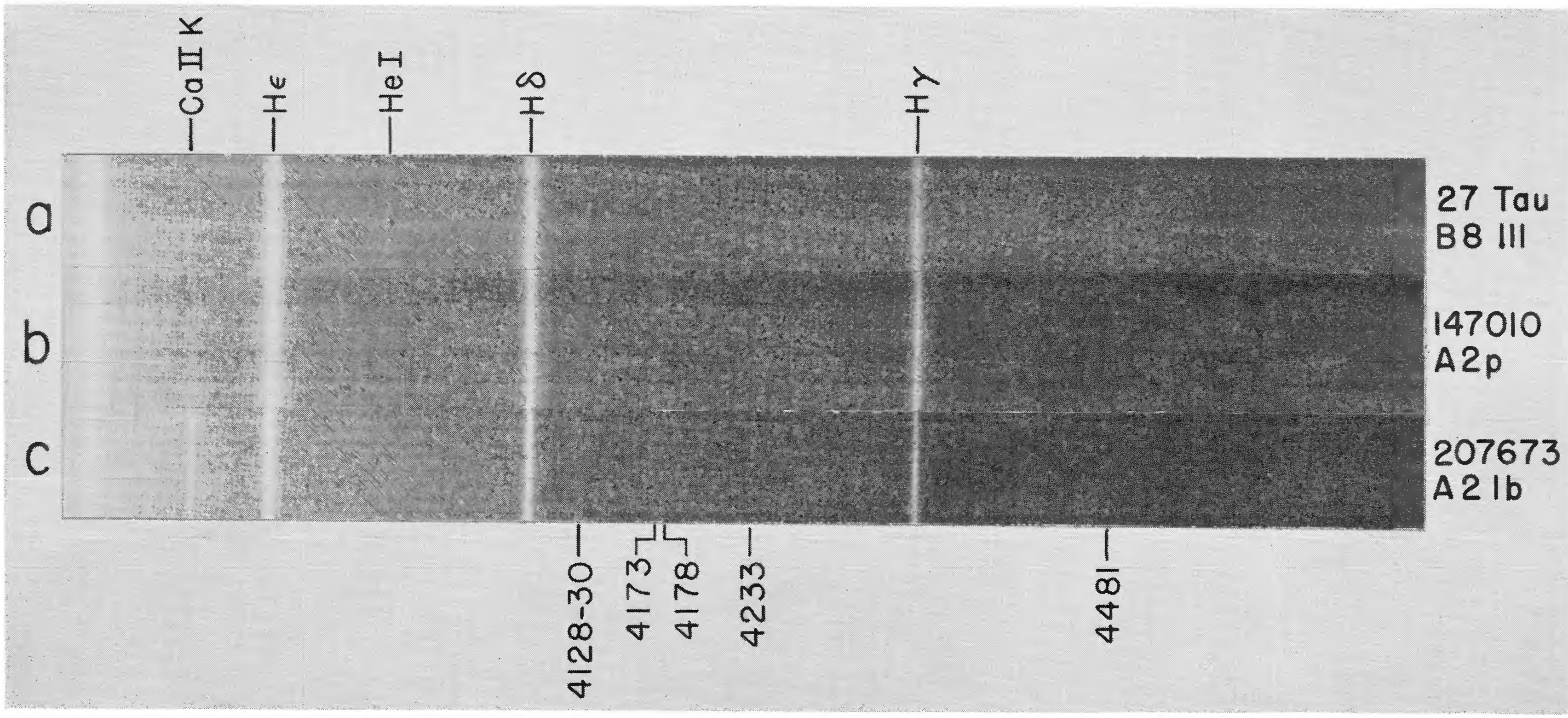

FIG. 3.—(*a*) 27 Tau (B8 III standard); (*b*) HD 147010 (A2 p); (*c*) HD 207673 (A2 Ib standard). The hydrogen lines of (*b*) resemble those of (*a*), but the metallic lines more closely resemble those in (*c*), and Ca II K is broad and shallow.

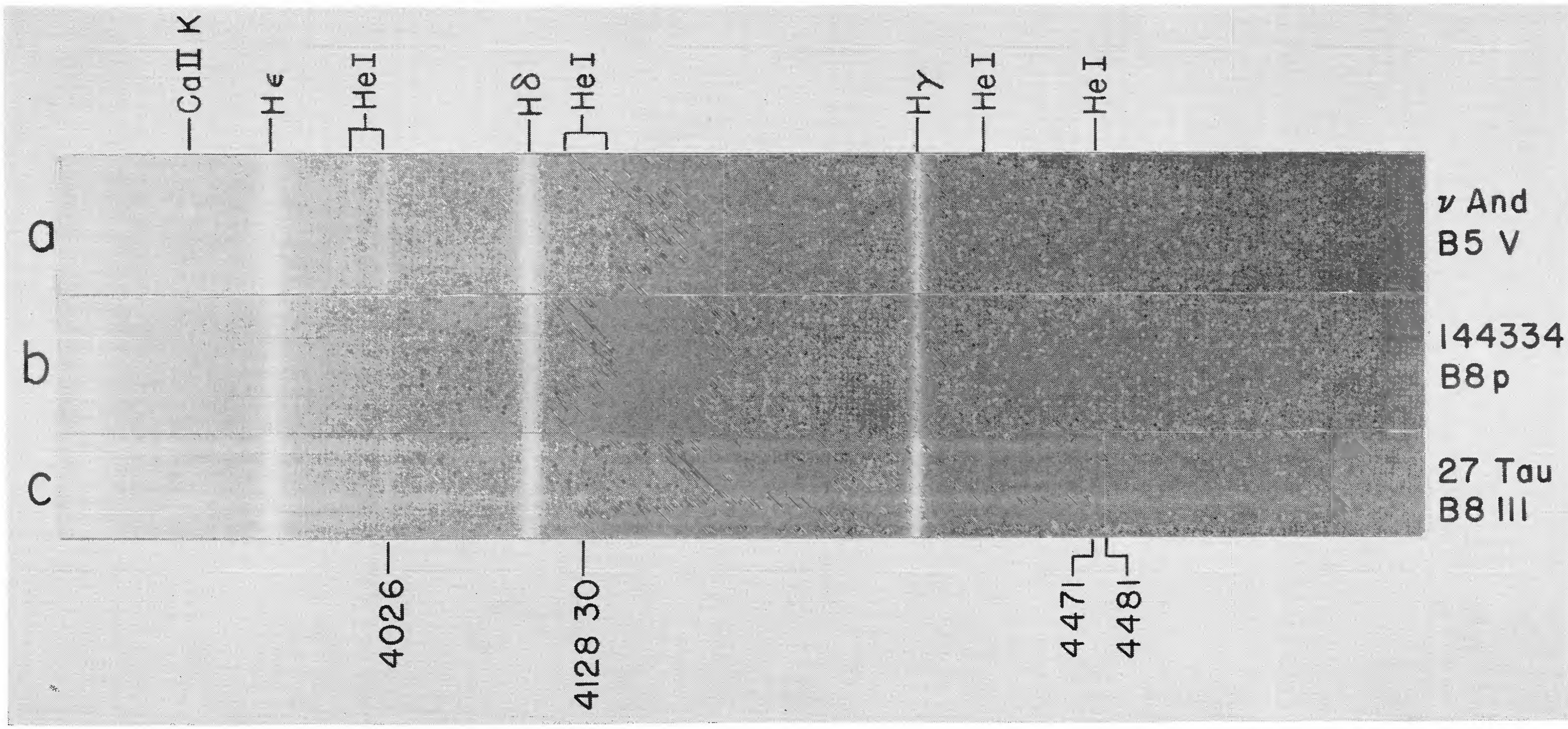

FIG. 4.—(*a*) ν And (B5 V standard); (*b*) HD 144334 (B8 p); (*c*) 27 Tau (B8 III standard). The line spectrum of (*b*) more closely resembles (*c*) than (*a*), but all photometry indicates a type earlier than (*a*).

144661: The spectrum resembles that of η Tau (B7 III) except that Hγ may have a sharp core and faint lines are present which may be similar to those in α And (B9 p, Mn). Higher dispersion is needed for definite identification, however. The spectrum is somewhat inconsistent with photometric temperature classifications.
144844: Faint lines are present which may be similar to those in HD 144661 and should be examined with higher dispersion. The spectrum is somewhat inconsistent with photometric temperature classifications.
145102: Si II is somewhat enhanced and λ4200 is present.
145482: The spectrum is very similar to that of 22 Sco and indicates low luminosity at B2.
145483: ADS 9953. Hydrogen is strong in A.
145501: ADS 9951 CD. The hydrogen lines in D are weak, with sharp cores resembling those in HD 144334. C resembles γ Lyr, although the hydrogen cores may be somewhat sharper. The spectra are definitely inconsistent with the photometric temperature classifications. There is a reflection nebulosity and some dust surrounding ν Sco.
145502: ADS 9951 AB. Van Hoof *et al.* (1963) have found variable radial velocity with a period of 5.93 days. A correction to V_0 of a few tenths of a magnitude is possible.
145556: The Ca II K-line is strong and probably interstellar.
145792: ADS 9967. He I λ4026 is rather sharp while other helium lines are diffuse, and Hγ and Hδ have somewhat sharp cores. These effects are not as pronounced as in HD 142250.
146284: This star is listed as a visual binary by Jeffries, van den Bos, and Greeby (1963).
146332: ADS 9983. The various photometric classifications do not agree among themselves.
147010: This star is very peculiar. Its spectrum is shown in Figure 3 with an A2 Ib and a B8 III. The lines of Si II and Fe II are sharp and very strongly enhanced as in a supergiant at about A2. Other lines present seem, at this low dispersion, to be lines of Ti II, Fe I, and Cr II. However, the weak Ca II K-line is so shallow and broad that it is barely visible and the hydrogen lines are considerably broader than in a supergiant. HD 9393, described by Osawa (1965), may have some similarities to this star. The spectrum is definitely inconsistent with the photometry.
147165: ADS 10009. This β CMa variable is surrounded by an H II region.
147196: A range of excitation from B5 to B9 is apparent. Hardie and Crawford consider this a field star because of its position in the Hβ diagrams. The Hβ luminosity is quite different from that implied by Borgman's or Walravens' photometry. The hydrogen lines are so broad that it is possible that the interference filter does not include all of Hβ. It is probably not a foreground star because it is in the dust west of ρ Oph and is reddened.
147701: ADS 10034. This star is quite heavily reddened. V should be 8.35 mag as given here; the value given by Hardie and Crawford is a misprint.
147888: ADS 10045. This has a fairly bright companion and its V_0 should be corrected by almost 0.5 mag; ρ Oph is surrounded by very strong nebulosity and heavy dust. The various photometric systems give different results and none are consistent with the appearance of the spectrum.
147889: The helium and hydrogen spectrum indicates a low-luminosity star at B2 and yet O II is faintly present and Si II is somewhat stronger than in other stars in Scorpius at B2. The star is very heavily reddened (over 3 mag of absorption) and also is surrounded by strong, non-uniform nebulosity.
147890: ADS 10048. The photometry implies a higher temperature.
147933, 4: ADS 10049. The photometry implies a higher temperature.
148184: On the present spectrogram of this well-known Be star, hydrogen and the α Cygni lines are in emission. It seemed possible to get an accurate luminosity class from features other than hydrogen, especially He I, Si II, O II, and Mg II.
148199: This star is located near HD 147890 in the southern portion of the Upper Scorpius region, but its spectrum resembles the very peculiar star HD 147010 except that its lines are not as sharp. There is no nebulosity and very little dust. The spectrum is definitely inconsistent with photometric temperature classifications.
148579: The hydrogen lines in the spectrum resemble those of α Del very closely. However, Crawford's (1958) Hβ photometry implies anomalously low luminosity. There is very strong reflection nebulosity and dust, which surrounds 22 Sco and in which this star is immersed.
148594: This star resembles HD 147196 except that the range of excitation is not so great.
148605: The spectrum indicates low luminosity.
149367: ADS 10119. About 0.3 mag correction can be applied to the V_0 for duplicity.
149438: The V_0 is slightly low for both Hβ measurements and the appearance of the spectrum. There is a faint H II region around τ Sco.
149464: This star is located very close to τ Sco and its position in the H-R diagram is, similarly, low.
150035: The K-line of Ca II is weak.
150514: The K-line of Ca II is strong and probably interstellar.
151346: The spectrum resembles that of η Tau (B7 III) except that the hydrogen lines have sharp cores similar to those in HD 144334. The star is located in a dust lane running east from 22 Sco. The spectrum is definitely inconsistent with photometric temperature classifications.

TABLE 4

HD A0–F2 STARS IN UPPER SCORPIUS INNER REGION

HD	V	$B-V$	$U-B$	n	E_{B-V}	V_0	MK
146706.	7.55	+0.14	−0 09	3	0 21	6 92	B9 V
146899. . .	10 22	+ .63	+ .36	3	.43	8 93	A7 V
146998* . .	9 56	+ .63	+ .33	3	.43	8 27	A7 p(Sr–Cr)
147012* .	9 75	+ .52	+ .20	3	.59	7 98	B9 V
147013*	9 10	+ .45	+ .24	3	.45	7.75	A0 V
147084 (19 Sco)*	4 54:	+ .84	+ .63	3	.74	2 32:	A5 II
147105*. .	8 81	+ .50	+ .29	3	.35	7 76	A5 p(Sr)
147283*. .	10 27	+ .81	+ .63	4	.72	8 11	A3 V
147343*. . .	9 36	+ .66	+ .40	4	.63	7 47	A1 Vn
147384 . . .	8.62	+ .41	+ .21	3	.45	7 27	B9 5 V
147592. . .	8 90	+ .30	+ .16	3	.27	8 09	A1 V
147648*. . .	9 42	+ .78	+ .19	3	.89	6 75	B8 V
147649. .	9 60	+ .44	+ .23	3	.24	8 88	A7 V
147702. . .	9.14	+ .46	+ .28	3	.37	8 03	A3 V
147703	7 47	+ .18	− 01	3	.25	6 72	B9 Vn
147809	8 60	+ .42	+ .22	3	.39	7 43	A1 V
147932 (ρ Oph C)	7 27	+ .32	− .35	4	.47	5 86	B5 V
147955. .	8 07	+ .25	+ .01	3	.29	7 20	B9 5 V
148117*.	10 53	+ .27	+ .08	3	.07:	10 32:	A7 p(Cr–Eu)
148118 .	9 45	+ 45	+ .27	3	.30	8 55	A5 V
148302.	10 01	+ .49	+ .24	3	.29	9 14	A7 V
148321*.	6 99	+ .18	+ .11	4	.03:	6.90:	A5 mp(Sr)
148334. .	9 96	+ .22	− .11	3	29	9 09	B9 V
148352* . .	7.51	+ .41	− .02	4	00	7.51	F3 V
148479 (α Sco B)*	. . . .	. . . . .	. . . .	.	. . .	. . . .	B2 5 V
148562.	7 81	+ 18	+ 09	3	09	7 54	A3 V
148563.	8 62	+ .24	+ .13	3	.20	8 02	A2 V
148624 .	10 38	+ .40	+ .23	3	.20	9 78	A7 IV
148822	9 65	+ .48	+ .14	3	19	9 08	F0 V
148842. .	10 62	+ 26	+ .14	2	23	9 93	A1 V
149069	10 50	+ .21	+ 12	2	18	9 96	A1 V
149228 .	9 97	+0 33	−0 18	3	0 40:	8 77:	B9 p(Si λ4200)

NOTES TO TABLE 4

146998: The strength of λ4215 is probably variable. λ4205 is quite strong and probably due to europium, but higher dispersion should be used for definite identification.

147012: This star is located near σ Sco, but is more heavily reddened than σ Sco and the three others near it.

147013: The hydrogen lines are stronger than in the standards at A0 V.

147084: Small amplitude variations in V are suggested by the present observations. λ4481 may be variable. This heavily reddened luminous star was shown to be a member of the association by Blaauw, Morgan, and Bertiau (1955).

147105: The Ca II K-line is very weak.

147283: Heavily reddened.

147343: Heavily reddened.

147648: Heavily reddened.

148117: The Ca II K-line is weak. The star is located near the southern boundary of the inner region.

148321: This star shows characteristics of a metallic-line star but, in addition, the lines of Sr II are abnormally strong. On the present spectrogram λ4215 is about equal to λ4226. It is a known peculiar star but has been classified variously as a peculiar Sr II star and a metallic-line star. Babcock (1958) has classified it as an Sr II intermediate peculiar metallic-line star. The classification of this star was discussed with Dr. W. P. Bidelman.

148352: This is the only obvious example of a completely unreddened foreground star; it lies 2 mag above the main sequence.

148479: ADS 10074. The spectrogram was obtained, on a night of excellent seeing, by trailing in declination. This star is not plotted in the H-R diagrams because it has no accurately determined magnitude or colors. The Δm given by Jeffries *et al.* (1963) differs from earlier estimates by over 1 mag. A very rough independent estimate can be made from a comparison of the absolute-energy distributions for an M2 IA (α Ori) and a B3 V (η UMa) (Code 1960) by assuming that α Sco and its companion have equal intensity near the H- and K-lines of Ca II (as indicated by the exposures). In this way a Δm of roughly 4.0 mag is obtained which is closer to that of Jeffries *et al.* than to previous ones. If α Sco is assigned a mean V of 1.2 mag the companion should have about $V = 5.2$ mag with several tenths leeway. The reddening, judging from that of the other apparent members near α Sco (HD 148302, HD 148365, and HD 148822) should be about 0.25 mag, which leads to a very rough V_0 of 4.4 mag. This is consistent with the present spectral type and removes the apparent inconsistency between the spectroscopic characteristics of α Sco B and its luminosity (see, e.g., Stone and Struve [1954] and the references therein).

V. THE H-R DIAGRAMS

The H-R diagram for all the stars in the inner region is plotted in Figure 5 from data in Tables 3 and 4. It is notable for the narrow main sequence which extends from B2 to F0, especially since there is a 1-mag range in the amount of reddening. Much of the scatter which is present can be accounted for by multiplicity.

A ratio of total to selective absorption much higher than 3 for the Upper Scorpius region does not seem justified. If a ratio of 6 were used, the resulting scatter diagram would be inconsistent in the sense that the most heavily reddened stars would be foreground stars, while those with little or no reddening would be behind them. The comparison between HD 147889 and 22 Sco is very sensitive to the ratio of total to selective absorption and indicates that it is less than 3.2.

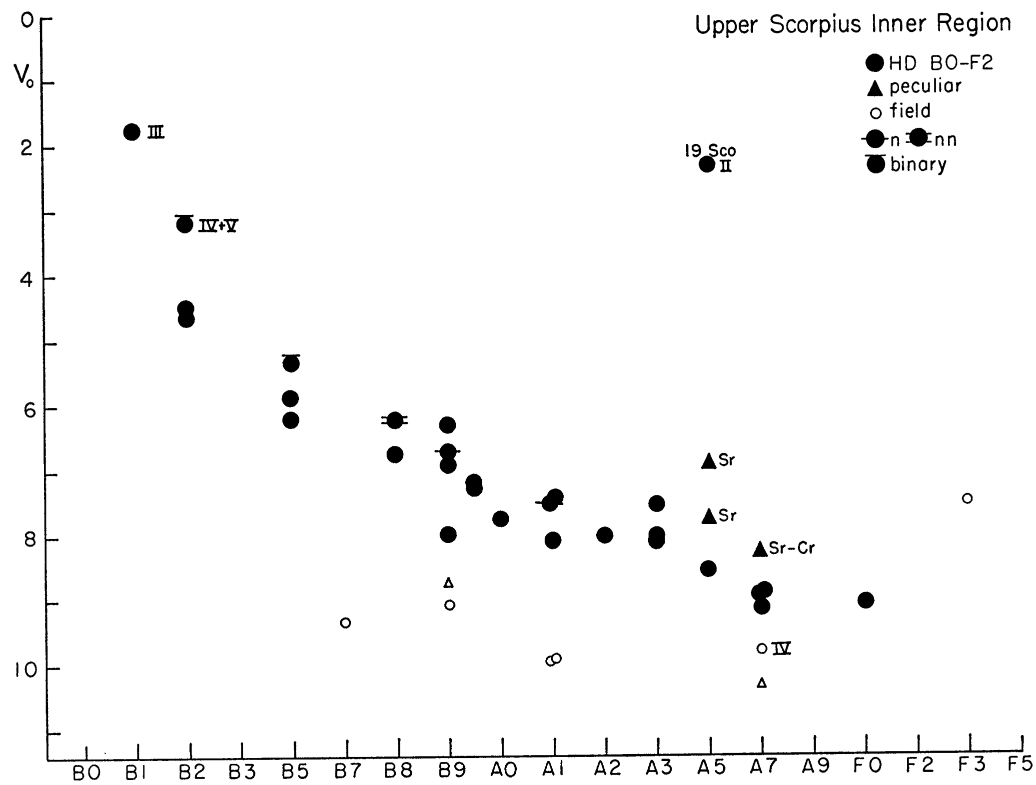

FIG. 5.—H-R diagram for the inner region of Upper Scorpius. No corrections have been made for duplicity. α Sco B is not plotted.

The turnoff from the main sequence begins near B2 for the inner region. The most evolved member of the association is α Sco (M1 Ib). The other evolving stars are 19 Sco at A5 II and σ Sco at B1 III. A comparison of the diagram for the inner region with that for all of the Upper Scorpius stars (Fig. 6) shows that, while there is little significant difference in the position of the main sequence, the earliest main-sequence stars, τ Sco, β Sco, π Sco and ω′ Sco, are all in the outer region. It should be noted that χ Oph, the only Be star, is not located in the inner region but lies several degrees to the north. Its position in the H-R diagram has been discussed by Schild (1966) in relation to the Be stars in h and χ Persei.

The main sequence for all the stars is considerably narrower than that given by Bertiau (1958), especially near B2. This is mostly due to the fact that his diagrams included the Centaurus and Lupus sections of the association and, as Blaauw (1958, 1964*a*) has pointed out, there is probably a considerable spread in ages for the various subdivisions of an association in the sense that the dispersed parts are older. Except in a few cases, Bertiau's types have not been changed by more than one-tenth of a spectral class or one luminosity class, but the effect of the refinements and better spectrograms has been to reduce the scatter.

Another source of scatter is the distance range within the association. From the angle subtended in the sky by the Upper Scorpius part, one would expect a total spread in the main sequence of about 0.5 mag, and yet in Bertiau's individual distances for the bright

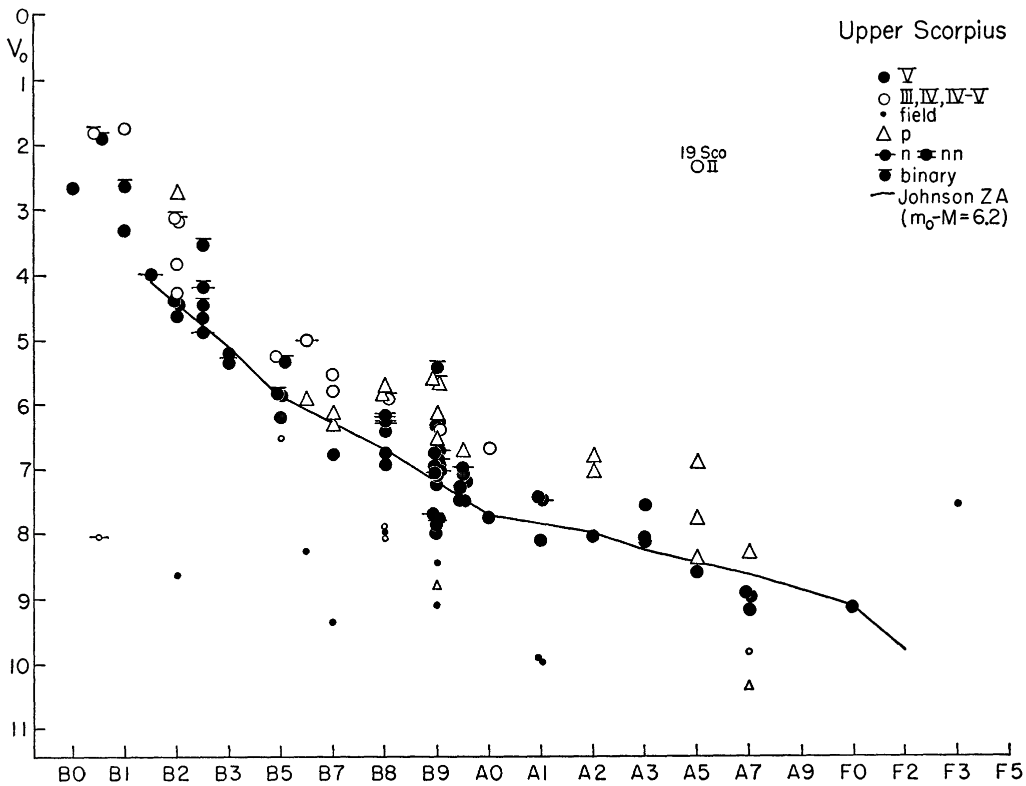

FIG. 6.—H-R diagram for the entire Upper Scorpius region, including the inner region. No corrections have been made for duplicity. *α* Sco B is not plotted. The apparent deficiency of stars later than A0 is due to the smaller sample of A stars.

Upper Scorpius stars there is a total range of only 0.2 mag. It should also be noted that the extreme values of 6.07 and 6.26 mag for the distance moduli are near the western and eastern edges, respectively.

The greatest spread in the main sequence, which cannot be accounted for in terms of known multiplicity, occurs at B9. The stars with very faint V_0 are obviously non-members, and 12 Sco may be a non-member. There are several stars which give spectroscopic evidence of being above the main sequence, but after these have been accounted for there are still a few stars above and below the large compact group near $V_0 = 7.0$ mag. It is possible that these stars represent the beginning of the inclusion of background and foreground stars, but it is not so easy to reject some of them because of inconsistencies between position in the H-R diagram and the amount of reddening. For example, HD 148579 has a bright V_0 for B9 V, and yet it has far too much reddening to be a foreground star, especially since it is located very close to 22 Sco and is more heavily reddened. It should be noted that this star and most of the B9 V stars which lie in the upper portion of the main-sequence band are similar to *α* Del, and most of the remaining B9 V stars have stronger hydrogen lines but otherwise resemble *α* Del.

The main sequence for all stars in Upper Scorpius seems to be almost 0.6 mag below the line corresponding to the most recent absolute-magnitude calibrations (Blaauw 1963; Keenan 1963) when a geometrical distance modulus of about 6.2 mag is used (Bertiau 1958). It is assumed that the recent objections raised by Eggen (1961), Petrie (1962), and others to the distance determination have been satisfactorily answered by Blaauw (1964*a*, *b*). This main-sequence line is very close to the "zero-age" main sequence as given by Johnson (1963), which is included in Figure 6 for comparison. Investigators using narrow-band photometric techniques for luminosity classification have also arrived at and discussed this result (e.g., Crawford 1958). The evidence from the spectra taken for the present study indicates that part of this is probably due to the intrinsically lower luminosity of the stars, which has been suggested by Blaauw in all of his recent work. In addition to the strong hydrogen lines, all other luminosity criteria are consistent with low luminosity at each spectral type. These low-luminosity characteristics would seem to verify Blaauw's statements.

The present classifications, with this discussion and the remarks to the tables, should provide a framework for the calibration of absolute magnitudes and photometric or spectroscopic systems.

VI. PECULIAR A STARS

The Jascheks (1962), in their discussion of the evolutionary stage of the peculiar and metallic-line A stars, listed the clusters and associations in which such stars had been found up to that time. The resulting trend implied that associations were too young to contain any peculiar A stars, which gave support to the suggestion advanced by Bidelman (1960) and others, that these are stars which have passed through the red-giant stage and have returned to the vicinity of the main sequence. Fowler, Burbidge, Burbidge, and Hoyle (1965) constructed a theory of the resulting synthesis and destruction of elements as a possible origin of the peculiar abundances found in these objects.

At that time no systematic studies of A stars in associations had been made, but Bertiau (1958) had already noted the peculiar classification, and possible membership in the Scorpio-Centaurus association, of HD 145102 and HD 147890. These two stars, as well as HD 142884, are probably members. The Si II lines in the spectrum of HD 145102 are not as outstanding as in the other two. These three stars lie fairly close to each other in the H-R diagram. It is known (e.g., Deutsch 1947) that the colors for the peculiar late-B stars are bluer than is indicated by their helium spectral types, which are given here. The only other late-B star showing an obvious silicon peculiarity is HD 149228 in Table 4, but its position to the east of the association and its relatively large absorption, as well as its very low position in the H-R diagram, suggest that it is a background object. As noted in the Notes to Table 4 there are two stars which may prove to be manganese stars when observed with higher dispersion. These are probably members.

There are three peculiar Sr II stars listed in Table 4 and plotted in Figure 5, all of which are probably members. HD 146998 and HD 147105 are very near *σ* Scorpii. Their reddening indicates that they are not foreground stars, and their positions in the H-R diagram indicate that they are not background objects. HD 148321 is located southwest of 22 Sco in a fairly clear region. This is the only one of the peculiar Sr II stars for which a proper motion is available, but unfortunately it has a very high probable error. The position of HD 150035 (Table 3 and Fig. 6) in the H-R diagram is not inconsistent with membership, but it is located to the east of *τ* Sco where there are very few members. The southern location of HD 148117 (Cr-Eu) and its position in the H-R diagram suggest that it is a background object, although its reddening is small. While accurate motions for these stars are not yet available, it should be pointed out that for most peculiar A stars in clusters, motions are not available as criteria for membership. If these stars were all considered to be non-members, then the stellar population in the vicinity of the association would have far too high a percentage of peculiar A stars.

It is extremely likely that most of these peculiar stars are members of the association, and any theory of the origin of the peculiarities in the A and late B stars should take into account their membership in a young association.

VII. DISCREPANCIES WITH NARROW-BAND PHOTOMETRY

The present types for the B stars are plotted against $(U - B)_0$ in Figure 7 for stars in Upper Scorpius that are not obvious field stars. Table 5 is a list of those omitted. Similar plots for the narrow-band photometries of the Walravens (1960), Borgman (1960), and Borgman and Blaauw (1963) show essentially the same results. In a number of

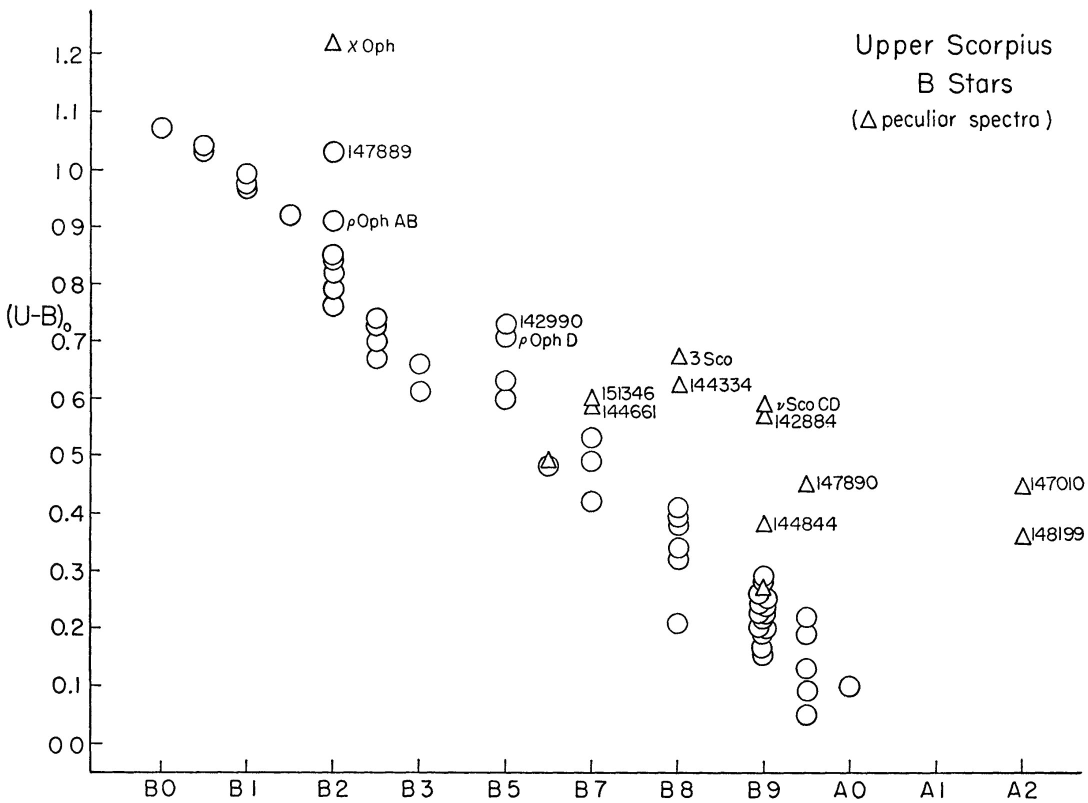

FIG. 7.—The spectrum-color diagram for the Upper Scorpius B stars. Obvious field stars from H-R diagram considerations (Table 5) have been omitted.

TABLE 5

OBVIOUS FIELD STARS FROM H-R DIAGRAM CONSIDERATIONS

Inner Region	Outer Region	Inner Region	Outer Region
HD 148117.	HD 140543	HD 148842	HD 150347
148334	141180	149069	150514
148352	145556	149168	151310
148624	146332	149228	151865

cases, the MK types are significantly later than the type implied by the photometry. The outstanding stars were re-examined, and in no case was it possible to make any changes in the direction indicated by the photometry.

The stars in this study which are significantly discrepant (two-tenths of a class or more) can be grouped as follows (the isolated Be star, χ Oph, is omitted from the discussion):

a) Stars immersed in very strong nebulosity and dust;
b) Peculiar A and late B stars with apparent abundance anomalies. These are discussed in § VI;
c) HD 147010 and HD 148199. The former is shown in Figure 3 with an A-type supergiant and a B8 III for comparison;
d) Stars which resemble late-B-type giants such as η Tau and 27 Tau except that the hydrogen lines are weak and have sharp cores.

All of the major disagreements are in the same sense; that is, the star is bluer than the spectrum would indicate. In case (*a*) the effect is large enough to be almost certainly due to the star itself and not the nebulosity. This is also apparent from the multiple star ρ Oph in which the discrepancy is the same for both the bright and faint components, whereas one might expect the faint component to be more affected by the nebulosity.

The two very peculiar stars which form group (*c*) may be shell stars, but there are at least two reasons for not giving this interpretation. One is that Pleione and other shell stars usually show a strong K-line of Ca II in the shell stage. The other is that HD 148199 does not have, on the present spectrogram, the sharp lines usually associated with shell stars. The photometry indicates that the stars are near B8 and of intermediate luminosity (Borgman) or main-sequence luminosity (Crawford). HD 147009 (Table 3), HD 147103 (A0 V from a recent Yerkes spectrogram), and HD 147104 (B9.5 V) form a very interesting group with HD 147010. Figure 8 shows all four encased in a small complex of Pleiades-type nebulosity with a bridge of heavy dust between the two pairs. A fifth star, HD 146834, seems to be connected with the group by means of a faint nebulosity. It is considered to be a probable member of the Ursa Major stream (Roman 1949). However, the proper motions of HD 147009 and HD 147010 are consistent with membership in the Scorpio-Centaurus stream, but no radial velocities are available. The fact that the two peculiar stars of category (*c*) fall on opposite sides of the association and yet lie very close together in the H-R diagram is an additional argument in favor of their membership in the Scorpius association.

The stars of group (*d*) lie in a fairly compact region of the H-R diagram near B7–9 with V_0 near 5 or 6, whereas the photometry implies that they should fall close to B3–5 V. In Figure 4, HD 144334 is compared with the standard stars for B5 V and B8 III. Some difference in the profiles of the hydrogen lines should be apparent even in reproduction. In any case it can be easily seen that the star more closely resembles B8 III than B5 V. Similar discrepancies can be found in other clusters, but it is not known whether the spectra of the stars show similarly peculiar hydrogen lines. Crawford (1963) has published a catalogue of Hβ and *UBV* photometry of bright *Henry Draper* B8 and B9 stars. From Figures 1 and 2 of his paper, it is evident that many of the stars have quite blue colors. Many of these have only *Henry Draper* classifications, but there are some cases in which stars reliably classified as B8 or B9 III or IV by W. W. Morgan or one of his associates have significantly earlier colors. One of the most notable examples of a star with disparate color-spectrum characteristics is HR 1063 = HD 21699, which is a member of the α Persei cluster. This star has been classified as B8 III by Roman and Morgan (1950) and yet has a $(U - B)_0$ of -0.62 mag. Another example is HD 36919 in the ι Orionis clustering, studied by Morgan and Loden (1966). The reddening in the cluster is very small so that possible variations in the reddening law do not affect the

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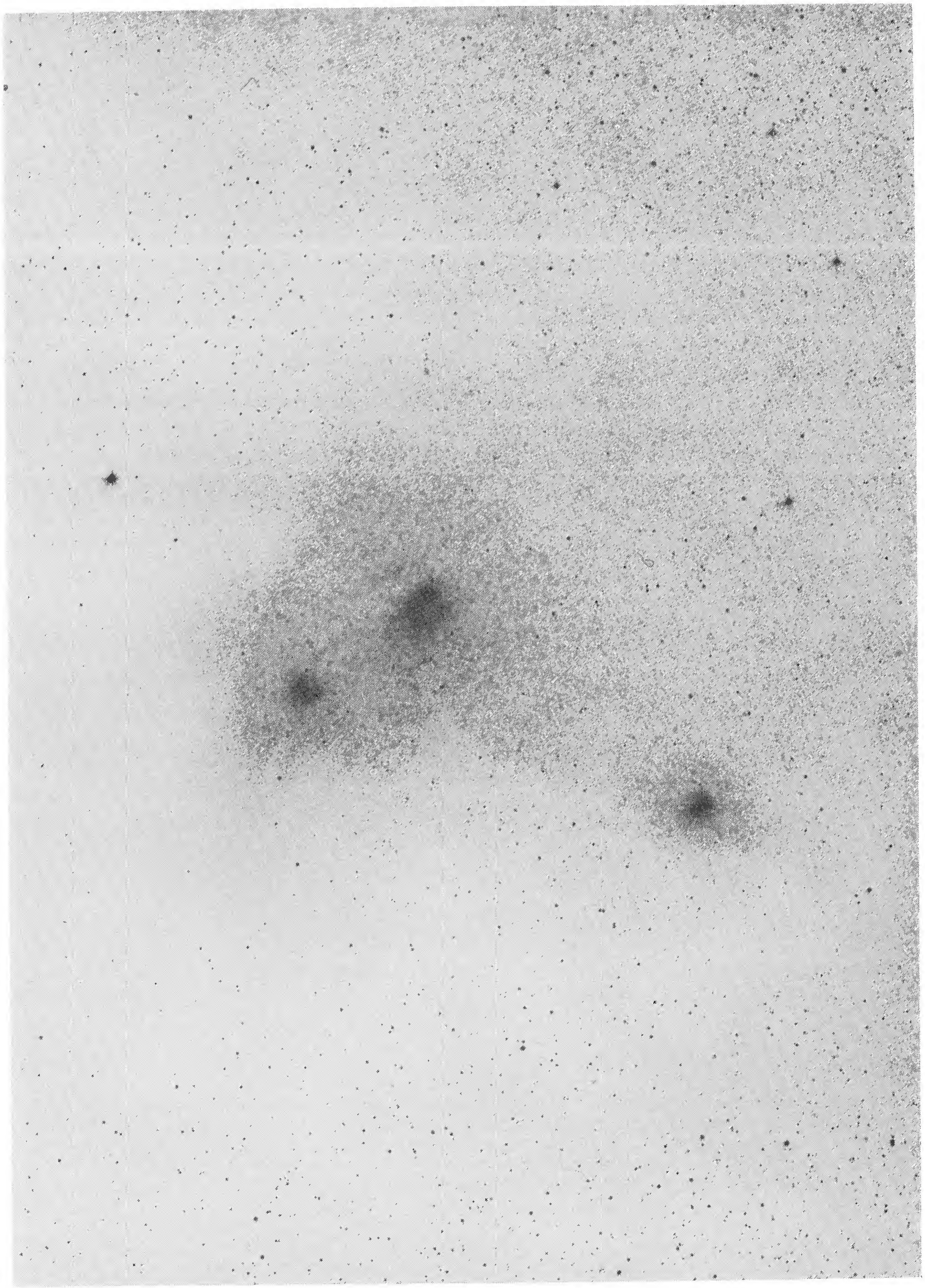

FIG. 8.—Nebulosity surrounding HD 147009 and HD 147010, HD 147103 and HD 147104. A filament can be seen leading to HD 146834. From negative copy of *National Geographic Society–Palomar Observatory Sky Survey.*

intrinsic color of the star. The star has been classified as B8 III by Morgan, and yet the *UBV* measurements place it very close to the intrinsic color of a B5 or B6 star.

In connection with the discrepancies between the photometry and the line spectra, it should also be noted that the various photometric systems do not always give the same result for a given star. Since the individual photometric measurements are of high accuracy, most of the differences are probably due to the fact that the photometric measurements are of only a few features of one element, which may not be consistent with other features in the spectrum. These discrepancies suggest that the determination of two-dimensional spectral types continues to be important. With the increasing use of image tubes, spectral classification of faint stars is becoming feasible.

VIII. CONCLUSIONS

1. The classifications of the Upper Scorpius stars have been discussed in detail in order to provide a reliable framework for the calibration of absolute magnitudes and photometric or spectroscopic systems.
2. The main sequence for the inner region of Upper Scorpius has been extended through the A stars. As suspected, most of them are probably members of the association, and the resulting narrow main sequence should provide a good basis for determining the distances to other associations.
3. At least six peculiar A stars are probably members, thus establishing their existence in a very young group of stars. They fall into two categories: a silicon peculiarity near B9 and a strontium peculiarity near A5.
4. Some stars whose spectra resemble those of B7–9 giants (except for peculiar hydrogen lines) have been found to have very discrepant colors in all photometric systems.

I gratefully acknowledge Dr. W. W. Morgan's suggestion of this research and his very helpful advice throughout. I am indebted to Dr. W. A. Hiltner for his assistance with observational techniques and his encouragement. This work was supported by a grant to Dr. W. W. Morgan from the National Science Foundation.

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