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THE NATURE OF THE FAINT BLUE STARS*

JESSE L. GREENSTEIN
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology
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ABSTRACT

A spectroscopic survey of about one hundred faint blue stars, largely at the galactic poles, has been carried out with the 200-inch telescope of the Palomar Observatory for the past 10 years. The 190-Å/mm spectra can be classified so as to distinguish with some confidence among the subdwarfs, halo, or horizontal-branch stars, detect composite spectra of unresolvable hot and cool pairs, and recognize with certainty the white dwarfs. The unpublished colors of the Humason-Zwicky stars, measured by the late Daniel L. Harris III, are here given in Table 1, together with my spectra; the spectra and available colors for the Tonantzintla and Feige stars are in Tables 2 and 3. Few "normal" main-sequence stars are found. Statistical résumés are in Table 4, and in special detail for the faintest stars observed in Table 5. Among stars of $\langle m \rangle = +12.5$ mag., we find 30 per cent halo (main sequence and horizontal branch), 25 per cent hot subdwarfs, and 15 per cent white dwarfs; the faint group at $\langle m \rangle = +15.3$ mag. has 40 per cent subdwarfs and 40 per cent white dwarfs, for a $\langle M \rangle = +7$ mag. The eight faintest stars in Table 5 (including the Lick observations by Kinman) at $m > +16.0$ mag. include five white dwarfs.

Individually interesting stars in Tables 1–3 include many white dwarfs of type DA, and hot subdwarfs resembling type DO. None has continuous or featureless spectra, i.e., all are certainly stars, except Ton 202, which may be a DC or may have the weak emission features of an old nova, supernova, or blue galaxy. A résumé of my own unpublished line intensities and half-widths is found in Figures 5–7. Hydrogen lines are enhanced in the subdwarfs but nearly normal in halo stars; He I and He II lines are greatly enhanced in sdB and sdO by up to a factor of 5. They are also greatly widened in subdwarfs. The He I lines are generally weakened by up to a factor of 3 in the halo Bp stars. Section VI includes a first-order astrophysical discussion (excluding white dwarfs) of the behavior of the broadened lines of H, He I, and He II. The Stark broadening indicates luminosities down to $M_V = +6$. It is probable that the He/H ratio is high in some subdwarfs, but even more interesting is the fact that it is probably low in the halo stars. No metallic lines are seen, i.e., the group is almost certainly metal poor.

The possible extragalactic nature of some faint blue stars is only marginally tested by this survey which is poor in stars fainter than 16 mag. Nevertheless, no rapid transition to a quasi-stellar, supercompact galaxy population is possible at 15.5 mag., nor is it indicated even at 16.5 mag., of which we have only a very small sample. Possibly the faint star, Ton 202, and the star plus galaxy HZ 46 (not here observed spectroscopically) are the only objects suspected to be extragalactic out of over a hundred. A proper motion of Ton 202 would be important. The high percentage of white dwarfs at 15.5 mag. suggests that they would dominate until nearly 19 mag., while the horizontal-branch stars would disappear by 17.5 mag. In Figure 4, the photoelectric colors of QSRS's (Sandage) and BSO's (Sandage and Véron) with $\langle m \rangle = +17$ mag. overlap those of subdwarfs and white dwarfs. However, about one-third of their colors lie completely outside regions of the $B - V$, $U - B$ diagram studied here. The most promising candidates for small, distant galaxies are therefore to be found among objects with positive $B - V$ and large negative $U - B$.

I. THE SPECTROSCOPIC SURVEY OF FAINT BLUE STARS

Finding lists of blue stars near the galactic pole have been available for many years and have permitted discovery of interesting types of subluminous objects. The current interest in the possible extragalactic nature of some of these stars of faint apparent magnitudes (Sandage 1965) makes it worthwhile to publish now available data, for statistical purposes, on the prime-focus spectra I have obtained at Palomar. They were briefly described and illustrated by Greenstein (1960). The usual dispersion was 190 Å/mm, widened to 0.3 or 0.8 mm, with a very few at 380 Å/mm; a few coudé spectra were taken at 18 and 38 Å/mm. The sample was selected rather unsystematically on the following, sometimes contradictory criteria: (1) very blue photographic color estimates,

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(2) relatively bright apparent magnitude for convenience of observation, (3) the possibility of white-dwarf nature from *UBV* colors (where available). Proper-motion data were not criteria for selection, and in general were (and are) not available. Milton Humason kindly provided unpublished finding fields of the Humason-Zwicky (1947) star lists ("HZ" star numbers). I am particularly grateful to the late Daniel L. Harris III for his unpublished photoelectric colors of the HZ stars which are published and discussed in the next section. Charts by Luyten (1965) are now available.

The possible origins of selection effect should be considered. One major source of the brighter blue stars observed is the list ("F" star numbers) of Feige (1958), for which only rough color estimates existed. The photoelectric colors by Eggen and Sandage (1965) became available after the observing was completed. A small number of Tonantzintla blue stars ("Ton" star numbers) were also observed (Iriarte and Chavira 1957; Chavira 1958). Since some photoelectric colors were available, I took especially "interesting" stars, i.e., those likely to be very hot or possible white dwarfs. A few of the HZ stars have other designations, as do many of the F star list, especially those which are white dwarfs and appear in the Luyten proper-motion surveys ("L" designations). A few are in the Luyten blue-star surveys ("LB" designations). There could be a small statistical "motion" selection effect favoring the proper-motion white dwarfs in the F lists, but not in the HZ or Ton lists. I preferred not to obtain too many spectra of ordinary halo stars when $B - V$ colors were known to lie within ± 0.10 mag. of A0 (where horizontal branch and main sequence are nearly indistinguishable). They would have been largely halo, horizontal-branch stars, and so there is a strong selection effect in the HZ stars against such objects. Where no photoelectric colors were available at the time of observation, as in the F and faint Ton lists, there is no "photometric" selection.

The prime-focus spectra were sufficient for rough classification only, in that weak lines of C II, Mg II, Si III, and Si IV could not be seen—essentially only H, He I, He II, strong Mg II, Si II, and Ca II could be seen. Fractional types are given only for coudé spectra. Many spectra were very peculiar, and line-broadening effects were sometimes conspicuous in the hot subdwarfs as well as white dwarfs. The spectra usually extended far toward the ultraviolet, permitting the Balmer jump to be taken into account. Stars with weak helium lines are apparently frequent among hot, blue, halo objects. My low-dispersion classification of very blue stars as Ap (where "p" means peculiar, *not* magnetic) has often been given for objects which should be B or even O stars, by color temperature, unless the small Balmer jump was recognized. Some of the hot O stars show very weak or even no He II lines, but are so classified on the basis of the ultraviolet continuum. Stars with sharp hydrogen lines for their type are in general classified as "halo" or "horizontal-branch" stars, and called Op, Bp, or Ap, while those with somewhat broadened lines are called sdO or sdB. I cannot certainly distinguish, for hot weak-line stars, between sdO stars and very weak-lined white dwarfs of types DO (with He II lines) or DAn or DAwk (with only shallow hydrogen). A preliminary astrophysical discussion of line widths and central intensities as a function of color and type will be given later in § VI. The spectral classifications must be viewed as very rough but sufficient for distinction between major types of stars. An atlas of representative spectra and tables of equivalent and half-widths is in preparation.

II. THE PHOTOELECTRIC OBSERVATIONS OF THE HZ STARS MADE BY HARRIS

Daniel L. Harris III was a pioneer in the use of the *UBV* photoelectric color system for faint stars. When I began to observe spectra of the HZ stars, he was good enough to measure their colors with the 82-inch McDonald reflector and send me a manuscript copy of his results. To my knowledge they have not been published elsewhere, and my copy seems to be the only existing record of these invaluable data. The epoch was about 1953 to 1955; no details as to time of observation or number of nights are available. Table 1 gives the measures by Harris and his unaltered, exactly quoted conclusions as to

TABLE 1

DATA ON HZ STARS
INCLUDING COLORS BY D. L. HARRIS III

HZ	V	B-V	U-B	Remarks Harris	Remarks JLG Spectrum
1		----	----	--	sdOp, $M\sim+5$.
2	13^m.86	-0^m.05	-0^m.88	WD	DAwk
3	12.86	-0.14	-1.10	Like +28^{o}4211	sdO6, $M\sim+5$. H very weak. He-rich.
4	14.47	+0.15	-0.67	WD Hyades	DA
7	14.18	-0.03	-0.89	WD Hyades	DA, hot.
9	13.95	+0.33	-0.69	WD, composite Hyades	DAe, composite. Variable emission.
10	14.14	+0.17	-0.58	WD	DAs
12	12.53	+0.02	-0.73	Like HZ 15	B4pk sharp. C II strong.
14	13.83	-0.15	-1.04	WD Hyades	DA, hot.
15	12.56	-0.01	-0.75	Like HZ 12	B2pk. H sharp, carbon-rich.
16	14.65	-0.09	-0.27	--	--
17	15.50	-0.22	-1.00	--	sdBp, no He I. Very hot.
18	15.57	-0.22	-1.09	--	sdB. He I broad.
19	12.72	+0.13	-0.73	WD?	Composite, B+G star.
20	14.99	+0.08	-0.81	WD?	Probably composite, sdBp + Ca II.
21	14.72	-0.35	-1.25	Interesting star.	DO, He II > He I, $M\sim+7$.
22	13.16	-0.27	-1.04	--	B2-5k V. Spect. Binary.
23	13.89	-0.02	+0.02	--	--
24	11.89	-0.05	-0.15	--	B9k, weak metallic lines.
25	11.40	-0.21	-0.80	--	B3Vn. Rotating. Strong lines.
26	13.85	-0.06	-0.30	--	--
27	12.77	-0.03	-0.03	--	A0n, weak lines.
28	15.72	-0.04	-0.82	WD	DA, hot.
29	14.18	-0.23	-1.01	Interesting star.	DBpnn. He I very wide and complex.
30	13.61	-0.14	-0.62	--	Bp. Halo star. He I very weak.
31	13.05	-0.04	-0.09	--	B9.
32	15.66	+0.02	-0.87	WD?	Composite, A + F star.
33	14.89	-0.02	-0.03	--	--
34	15.63	-0.21	-1.25	--	DOp or DAp, H lines extremely wide.
35	15.80	-0.22	-1.13	--	--
36	14.56	-0.05	-0.02	--	--
37	12.52	-0.08	-0.18	--	A0 weak lines.
38	14.20	-0.27	-1.16	--	sdO, $M\sim+2$, He I > He II.
39	15.40	-0.24	-1.12	--	sdB or DAps, Hot, H rather sharp.
40	14.55	-0.24	-1.02	--	sdBp. Hot, He I very weak.
41	13.12	+0.25	-0.41	WD?	Probably composite F + B star.
42	14.61	-0.14	-0.54	--	--
43	12.68	-0.10	-1.14	WD	DAwk. H very shallow.
44	11.68	-0.29	-1.19	--	sdO, He, N rich.
45	12.80	-0.15	-0.57	--	B5p, all lines weak.
46	14.91	+0.28	-0.53	WD?	Suspected extragalactic plus star. (Luyten and Miller 1951).
47	15.34	-0.13	-0.74	--	--
48	13.84	-0.02	-0.08	--	--

the nature of the stars, based only on his three-color data. The last column "JLG remarks," gives my own current spectroscopic results. WD is Harris's abbreviation for "white dwarfs." Harris also had sent me numerous early lists of his colors of the brighter white dwarfs. They have all, by now, been published elsewhere, either included in my own earlier lists of white dwarfs or superseded by other measures. Harris (1956) himself published only Hyades and a few other white-dwarf colors; ten white dwarfs measured by him were remeasured by Eggen and appear in Eggen and Greenstein (1965). There is no systematic difference in V or $U - B$, but $B - V$ by Harris is $+0.02$ mag. redder than Eggen's measures. The mean errors of the individual differences for the white dwarfs, are ± 0.04 mag. in V and ± 0.02 mag. in $B - V$ and $U - B$, which can be taken as the maximum mean errors for the data in Table 1.

Figure 1 shows the Harris $U - B$, $B - V$ colors and the normal relation for main-sequence stars (Eggen 1963). The colors expected of a black body (Matthews and Sandage 1963) are shown along the upper straight line. Stars HZ 1–15 lie near the galactic plane, near the Hyades; the balance are near the north galactic pole. With the exception

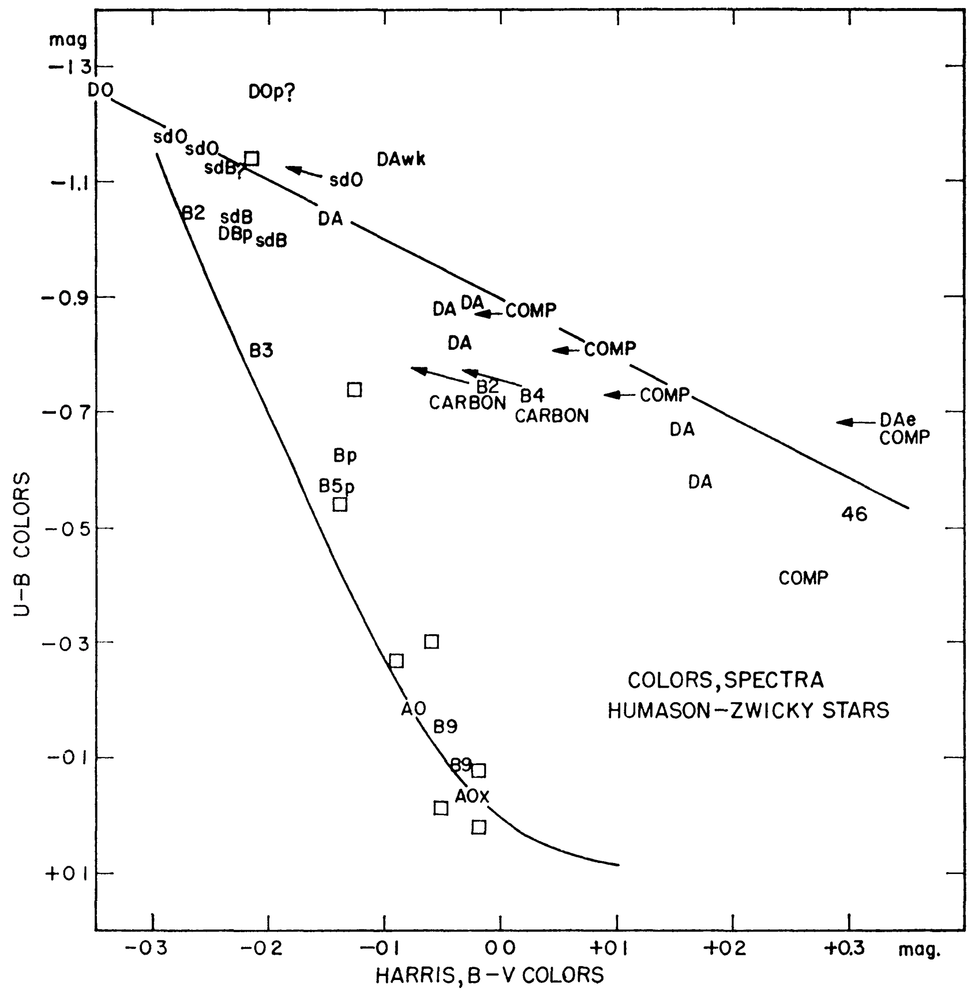

FIG. 1.—The hitherto unpublished UBV colors by Daniel L. Harris III and types by Greenstein for both high- and low-latitude HZ stars. The carbon stars HZ 12 and HZ 15 are reddened; arrows indicate direction (not size) of reddening correction; the subdwarf HZ 3 is also reddened. The normal main-sequence and black-body loci are shown. Open squares mean no spectrum available; "sd" is subdwarf, "p" halo star, "comp." means a composite star. HZ 46 is possibly a star plus extragalactic nebula.

of a very hot white dwarf, HZ 43, and an unusual, nearly unclassifiable star, HZ 34 (either DOp or DApwk), the colors are normal for the kinds of stars involved. The white dwarfs lie near to, but mostly below, the black-body line; HZ 9, a composite DA star in the Hyades, with an unresolved dMe companion, lies above it. The two carbon-rich stars, HZ 12 and HZ 15, which are probably not subluminous, are marked with arrows to show the direction (not magnitude) of the correction for interstellar reddening. They are more luminous than most of the other HZ objects; since they are near the galactic plane, they are reddened. The hot subdwarf near the plane, HZ 3, may also be slightly reddened. The possible small systematic difference in Harris's $B - V$ colors would shift all points 0.02 mag. to the left, slightly improving the fit to the unreddened main sequence. The hot star, labeled DOp?, HZ 34, with Harris color (−0.21, −1.25 mag.) lies closer to the black-body line if the Eggen color (−0.28, −1.26 mag.) is used. The other high point, HZ 43 (DAwk) at (−0.10, −1.14 mag.), does not have an Eggen color; it does have a visual, faint, close red companion, which may affect the Harris color. In résumé, the spectra and colors of this group of stars give a sample of mean apparent magnitude, 13.7 mag. Of the thirty-three stars with observed spectra, there are eleven white dwarfs, nine hot subdwarfs, five composite, five halo (i.e., horizontal branch), and five nearly normal stars. (Note that one white dwarf and one subdwarf are composite and are counted twice.) The first conclusion is that, because of the high frequency of very different species of blue stars, white dwarfs, and composites, *UBV* colors alone should not be used to determine spectral types, or the nature of stars, especially when interstellar reddening is present, as in the galactic-plane group HZ 1–15. We will omit HZ 1–15 from most subsequent statistical discussions. Then, near the galactic pole, among twenty-three stars, there are six white dwarfs, six subdwarfs, four composite, five halo, and three nearly normal stars.

III. THE TONANTZINTLA STARS

Table 2 contains the results of a less complete spectral survey of stars near the galactic poles from the two galactic pole surveys by Iriarte and Chavira (1957) and Chavira (1958). Stars are listed in order of catalog number, "Ton" being for the north galactic pole. "Ton S" numbers are for the south galactic pole; photoelectric colors are mostly not available, but only original estimates "d.v.," meaning decidedly violet, and "m.v.," extremely violet. The photoelectric colors by Iriarte (1958) appeared during this survey and spectra of some colorimetrically interesting objects were preferentially observed. Table 2 gives a résumé of my results, together with colors from Iriarte and Eggen. A comparison of four stars common to the latter two sources indicates that $U - B$ by Iriarte is −0.03 mag. more negative than by Eggen. But some other source of error (or much less probably a very peculiar type of object) must exist in Iriarte's $B - V$ colors. For example, he gives the extraordinary colors (−0.43, −1.04 mag.) for Ton 165 and (−0.48, −1.14 mag.) for Ton 257. Nevertheless, in Figure 2 they are plotted as given. Table 2 also contains some miscellaneous *UBV* measures kindly provided by staff and students at the 60-inch Mount Wilson reflector; their systematic accuracy is not assured. The color of Ton 139 is very peculiar; that of the DB star, Ton 547, is badly needed. The NGP star numbers are from Slettebak, Bahner, and Stock (1961). In spite of the faint mean apparent magnitude of these Ton objects, near 14.7 mag., there is only one genuinely puzzling spectrum among the twenty-eight observed, that of Ton 202. This faint object has an extraordinary color, near or above the black-body line, and could be a white dwarf without lines, i.e., type DC; in fact, it is so listed, as EG 109, in Eggen and Greenstein (1965). However, several elusive, broad, weak emission lines have been suspected, similar to those seen in a quasi-stellar radio source (QSRS). Their presence is not certain, and the star could still be a white dwarf. Other DC stars of $U - V$ color −0.54 mag. have $M_v \approx +12.3$, so that a parallax of 0\".020 and a proper motion of $\mu \approx 0\".10$ are to be expected. Unfortunately, no proper motion is now available. Sandage (private

TABLE 2

TONANTZINTLA STARS

Ton	V	B−V	U−B	Spectrum	Remarks
139	$12^{m}.8$	$+0^{m}.12$	$-0^{m}.75$	Fp	Slettebak NGP 232. Horizontal branch or composite?
165	15.5	− .43	−1.04	sdB	λ4009 very strong. H weak, shallow.
181	14.7	+ .16	−0.69	Ap	Horizontal branch.
197	15.3	− .11	−1.03	DA	
199	13.9	− .15	−1.04	Bp	He I very weak.
202	15.7	+ .22	−0.76	C(em?)	Suspected broad emission lines? QSG?
209	12.5	− .20	−1.01	Bp	Hot, He I very weak.
245	13.9	− .24	−0.90	sdB	He I very weak.
257	15.9	− .48	−1.14	sdOp	Very hot. He II strong, H very broad.
261	16.2	− .28	−0.96	sdOp	He I, He II strong, H broad. Nearly DO.
264	14.1	− .05	− .98	sdB	Possibly composite. Weak Ca II.
266	14.9	+ .05	− .83	sdB	Composite. H shallow, weak. Ca II present.
299	15.2	− .30	− .99	sdB	Hot.
320	15.4	− .40	−1.14	sdOp	Very hot; H, He I weak. Like nucleus of planetary nebula.
322	13.8	+ .02	−0.03	Ap	
502	14.4	+ .38	− .10	sdG	
547	15.4	+ .15	− .55	DA	
573	15.0:	m.v.	-----	DB	No colors available.
780	14.9	− .25	− .98	Bp	Hot, He I extremely weak or absent.
788	13.2	− .18	−1.00	sdB	Spectroscopic binary.
803	14.1	− .25	−1.21	sdO	He II strong, H weak.
S 12	15.8:	d.v.	-----	DA,Fs?	Possible broad K line.
S 103	14.7	− .23	−1.06	sdOp	He II, He I very strong, H nearly absent.
S 120	15.5:	d.v.	-----	Em.	Possibly old nova or U Gem. Very broad emission, H, He I, He II. Possibly abs. Ca II.
S 135	13.2	− .18	−0.80	sdB	He I weak.
S 144	12.8	− .15	−1.08	sdO	He I, He II strong, broad.
S 151	16.0:	m.v.	-----	DAs?	Could be Bp.
S 243	15.6:	m.v.	-----	DA	

communication) has obtained several unwidened spectra which do not completely settle this question. The strong emission-line object Ton S 120 could be a U Gem star but is more probably an old nova with broad emission lines of very high excitation and large velocity amplitude. It is probably more than 1 kpc below the galactic plane and has, of course, small velocity. The statistical résumé of the twenty-eight Tonantzintla spectra shows four certain plus three probable white dwarfs, one old nova, thirteen hot subdwarfs (or twelve if Ton 261 is DO), two composite, five halo stars, *no* normal stars, two

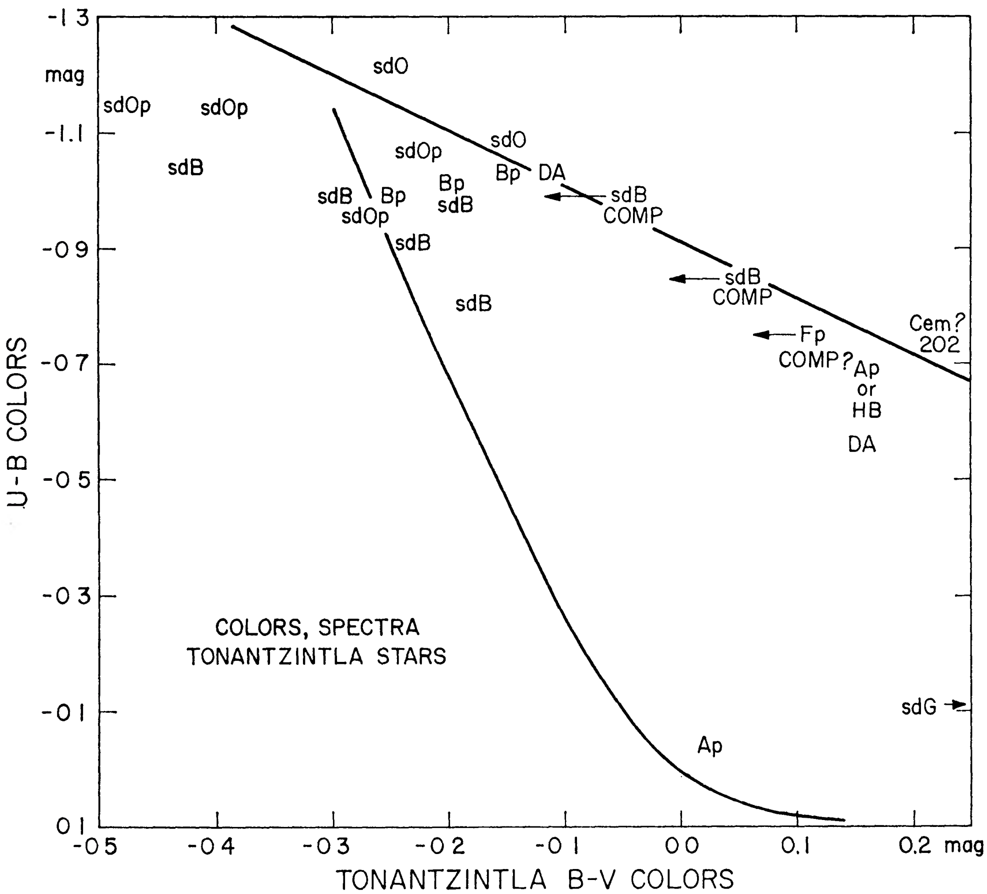

FIG. 2.—The UBV colors of Tonantzintla stars for which spectra exist. The very large negative $B - V$ colors probably are incorrect but are plotted here as published. The object Ton 202, labeled "Cem?" may be a BSO, a QSRS, an old nova, or a white dwarf of type DC.

subdwarfs or cooler horizontal-branch stars (i.e., what must essentially be mistakes in original color estimate) and one (Ton 202) which possibly may be a quasi-stellar galaxy (QSG) like those discussed by Sandage (1965). Sandage found that Ton 730, possibly identified by Iriarte (1958, 1959) as a galaxy, shows a redshift of 0.0877 and Ton 256 one of 0.1307. These two objects have outstandingly large negative $U - B$ for their $B - V$ in Figure 1 of Iriarte (1958), resembling the quasi-stellar radio sources in Figure 1 of Sandage (1965). My own spectra, and the Tonantzintla colors are shown in Figure 2. Colors of Ton stars measured by Iriarte (1959) for which no spectra exist are *not* plotted here. Because of the possible errors of up to 0.1 mag. in Figure 1 of Iriarte (1959), I have arbitrarily plotted his bluest stars at -0.35 mag. $B - V$, in my own later figures. Some Ton stars are at galactic latitudes as low as 30°, but this should introduce negligible reddening.

IV. THE FEIGE STARS

A number of much brighter objects in both polar caps were tabulated in a survey by Feige (1958) and have all been observed without knowledge of photoelectric colors. Of these, forty-four spectra were observed, and two are rejected in my statistics because of low galactic latitude (F112, F113). The balance are tabulated in Table 3 and plotted in Figure 3. The brightness of some of the Feige stars resulted in the use of coudé dispersion and, therefore, of more detailed spectral classification. At 38 Å/mm interstellar K-lines can be seen, as well as rotation, and details are sometimes listed in Table 3. Many of these stars are bright enough to merit detailed spectroscopic investigation. The mean apparent magnitude is 12.2 mag., and there are no type DC or other objects even slightly suggestive of QSRS or QSG nature. Eight were white dwarfs; ten subdwarfs; nineteen Op, Bp, and Ap; five (and possibly seven) are composite; one must have a mistaken color[1]

[1] *Added in proof:* Several corrections to Table 3 were made available: F11 has colors of −0.26, −1.02 mag. by Klemola; F23 was apparently misidentified by him, and a preliminary measure by Krzeminski is 11.91, −0.11, −0.44 mag. Therefore the remark "composite" should be deleted for F23. The color of F49 is probably a misprint in Eggen and Sandage (1965), where it is given as $U - B = -0.01$ mag. I misidentified the star F74 because of an incorrect chart, so that the spectrum "G" should be deleted. F111 has Klemola colors of +0.02, and −0.13 mag.

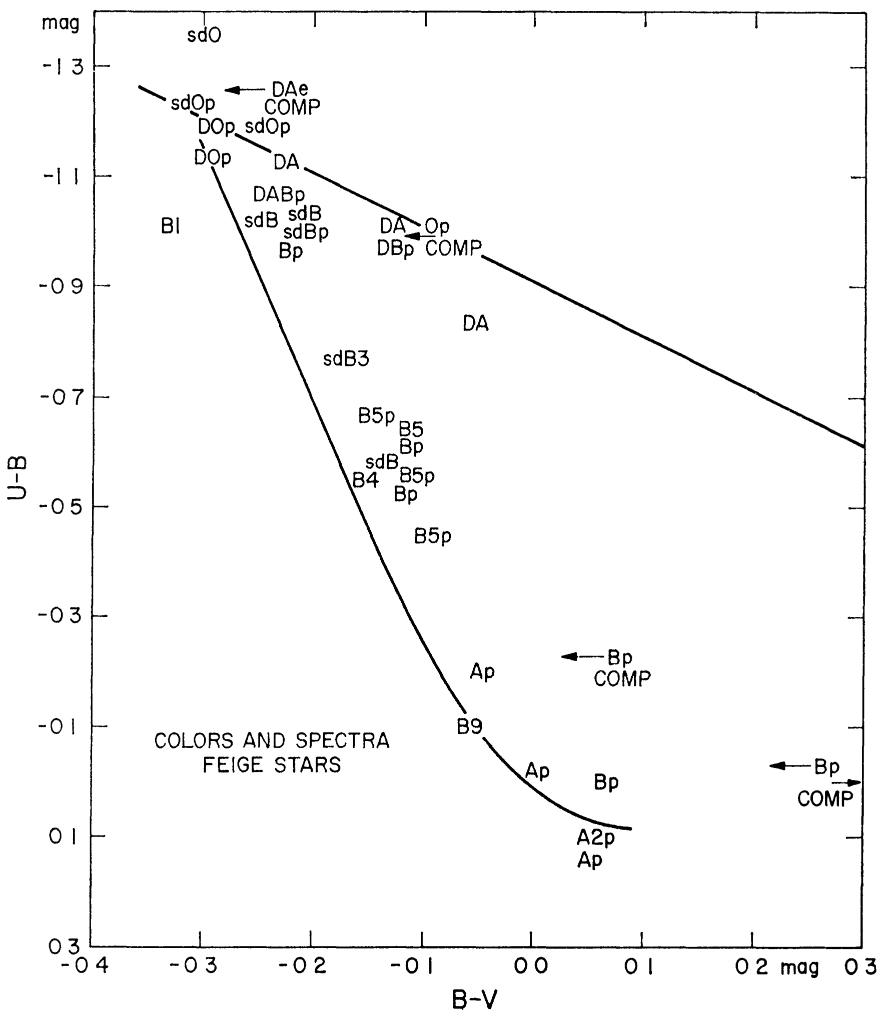

FIG. 3.—The *UBV* colors and spectra of Feige stars including a few low-latitude objects and composites. The Bp at the right is far off scale but has composite spectrum.

TABLE 3

FEIGE STARS

Feige	Mag. or V	Color est. or B-V	U-B	Spectrum	Remarks
2	$13^m.1$	$-0^m.4$	-----	Bp	He I very weak. High velocity.
4	15.2	- .12	$-0^m.97$	DB	He I very broad. H weak or absent.
11	11.5	- .5	-----	Bp	He I very weak.
14	12.5	- .5	-----	sd0	He II, He I very weak.
15	10.4	+ .06	.00	Bp	Color probably incorrect.
22	12.6	- .06	- .83	DA	
23	11.1	+ .49	+0.02	Bp	Composite? He I very weak. Ca II weak.
24	12.2	- .23	-1.25	DAe	H, Ca II em. lines, probably composite.
26	12.9	- .5	-----	D0ps	All lines very broad. He II strong. Could be sd0.
27	11.8	+ .08	- .23	Bp	He I very weak. Possibly composite.
29	10.3	- .16	- .55	B4k	Normal, sharp metallic lines.
34	11.1	- .30	-1.35	sd0	Low luminosity like $+28^{o}4211$.
36	12.5	- .25	-1.02	sdB	He I very weak.
38	12.9	- .22	-1.00	sdBp	He I weak or absent.
40	11.1	- .12	-0.64	B5	Normal except for diffuse Ca II? Composite?
42	13.2	+ .05	+ .12	Ap	
43	14.9	- .13	-1.00	DA	
46	13.2	- .30	-1.13	sd0	He I very strong, H strong, He II weak. Could be D0s.
48	13.1	- .2	-----	Ap	
49	12.9	- .33	-1.01	B1n	Looks normal but very weak interstellar K line.
51	10.2	- .10	-0.45	B5pnk	Rotating, strong interstellar K.
56	11.0	- .12	- .57	B5pk	Weak lines.
59	11.6	- .06	- .10	B9nn	Normal.
65	12.0	- .22	-1.03	sdB2	NGP 177. He I, C II sharp, weak. Horizontal branch?
66	10.5	- .26	-1.19	sd0p	Malmquist 299. All lines weak. He I sharp.
67	11.8	- .32	-1.22	sd0p	He II strong. Nearly D0.
68	12.2	+ .05	+ .10	A2p	Horizontal branch? H very sharp.
74	11.6	- .2	-----	G	Poor plate.
80	11.3	- .10	-1.00	0p	He II sharp. Possibly composite, weak Ca II.
81	13.5	- .22	-1.02	Bp	Possible weak He I.
82	10.4	.00	- .01	Apk	Weak lines. Interstellar Ca II?
84	11.8	- .17	- .74	sdB3	λ4144 strong. Possibly composite, broad Ca II.
86	10.0	- .15	- .68	B5pk	Sharp weak He I, Ca II.
92	11.4	- .12	- .62	Bpk	He I very weak.
93	15.3	- .23	-1.12	DA	
95	13.0	- .23	-1.06	Bp	Composite? Weak broad Ca II.
99	10.0	- .12	- .52	Bpk	Weak lines.
101	11.5	- .05	- .20	Ap	Weak lines.
107	10.1	- .13	- .59	sdBk	
108	12.9	- .28	-1.06	DAs	
110	12.5	- .30	-1.20	D0s	He I weak, HeII strong, sharp.
111	11.2	- .2	-----	Bpk	
112	12.8	- .2	-----	A2	H sharp. Omit, low latitude.
113	12.0	- .3	-----	Bp	Sharp weak He I. Composite? Omit, low latitude.

(F74); and four are apparently normal. The latter stars have moduli up to 12 mag., i.e., occur up to nearly 2500 pc from the galactic plane. The high yield of white dwarfs for such bright stars is interesting; the proportion, eight in forty-three, is not much lower than the eleven out of thirty-three HZ stars, which are in the mean 1.5 mag. fainter.

The relations between $U - B$, $B - V$ and type shown in Figure 3 are much like those of the other lists. The large number of nearly normal and Bp and Ap stars (presumably halo stars with a nearly normal color-color relation) permit us to establish a systematic shift of the stars to the right of the unreddened $U - B$, $B - V$ curve. If the groups of normal, Bp, and Ap stars have a mean luminosity, $M \approx 0.0$, their distance is very large. As a group they would lie outside most of the absorbing material and suggest an upper limit of 0.04 mag. for $E(B - V)$ at the galactic pole. Eggen and Sandage derived a slightly smaller value without knowledge of the spectral types. We cannot use the Tonantzintla stars for this purpose because of some unexpectedly blue $B - V$ colors found in Figure 2. Without a very exact calibration of the Harris color system for normal stars, and in view of the +0.02 mag. difference in $B - V$ between Harris and Eggen, it seems unprofitable to attempt to obtain the reddening at the north galactic pole from the HZ stars.

TABLE 4

SPECTROSCOPIC STATISTICAL RÉSUMÉ

Sample	$\langle V \rangle$	n'	White Dwarfs	Hot Subdwarfs	Halo Blue	Composite, Old Nova	Normal or Late Type	QSG?	$\langle M \rangle$
HZ	13 7	35	11	9	5	5	5	0	+5 3
Ton	14 7	28	6	13	5	1	2	1	+4 2
Feige	12 2	49	8	10	19	5	7	0	+2 8
All	13 3	111	25	32	29	11	14	1	+3 9
Bright (V<14.5)	12 5	80	13	19	26	8	14	0	+2 9
Faint (V>14 5)	15 3	30	12	12	2	4	0	1	+6 9

V. STATISTICAL RÉSUMÉ

I have obtained spectra for 105 stars so far. The entire galactic-pole, blue-star sample in Tables 1 to 3 includes 94 stars, comprised of 20 white dwarfs, 1 old nova, 29 hot subdwarfs, 29 blue halo stars, 11 composite, 7 normal blue stars, 3 later-type, and possibly 1 quasi-stellar galaxy. (Some composite stars are counted twice in the preceding list.) Special interest attaches to the properties of the faintest stars, and those with colors are shown in Figure 4 (which will be discussed fully in § VII). Four faint white dwarfs lack photoelectric colors, and 10 F and HZ stars lack spectra. No Ton stars without spectra are plotted since the Ton photoelectric colors have an uncertain $B - V$ scale. In all, there are 34 objects with both spectra and colors known fainter than $V = 14.5$ mag. They have a mean $U - V$ color of -1.00 mag., and $\langle V \rangle = 15.25$ mag. (The $U - V$ color is used as an indicator of the ultraviolet flux, which is apparently critical in the discovery of very blue stars with Schmidt telescopes or aluminized reflectors.) Of this group of faint stars, 29 have spectra; they include 12 white dwarfs, 1 old nova, 10 hot subdwarfs, 2 blue halo stars, 3 composite, and 1 possibly quasi-stellar galaxy. The difference in brightness between the bright and faint sample is 2.7 mag., and the change in the fractional populations is quite significant.

In Table 4, which contains résumés for all stars, n' is the total number of entries (not of stars) since some composite stars appear twice. The fraction of white dwarfs climbs very rapidly in the faint sample, and the hot subdwarfs replace the blue halo stars. The normal stars disappear. If we assume that a blue white dwarf has a mean luminosity of $M =$

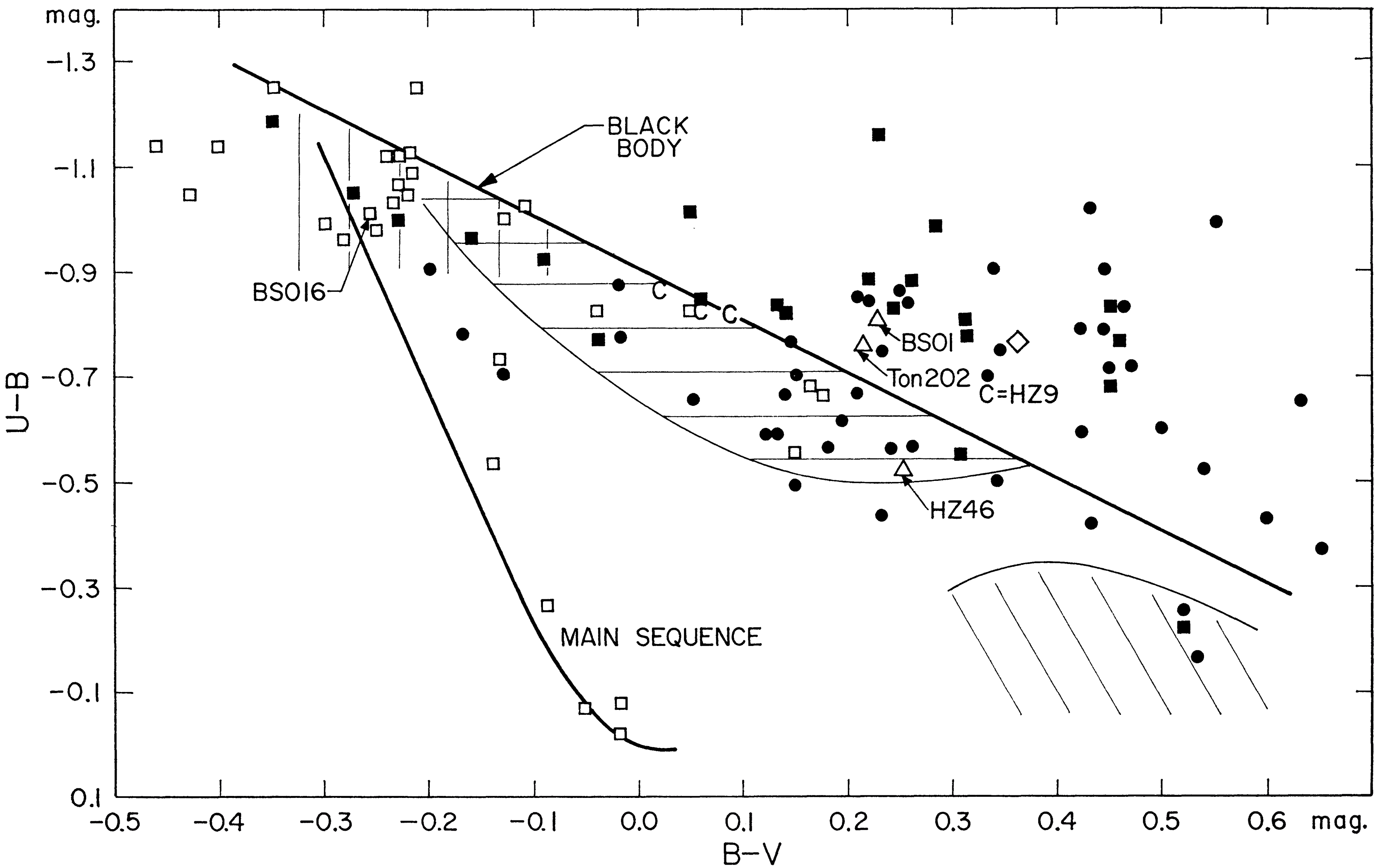

FIG. 4.—All spectra of HZ, F, and Ton stars with $V > 14.5$ mag. are plotted as open squares. The probable radio sources, QSRS's (Sandage), are filled circles; the "interlopers," which may be stars, BSO's, or possible QSG's (Sandage and Véron) are filled squares. The distant galaxy BSO 1, and Ton 202 (a possible second example) are open triangles; the open diamond is BSO 8, with a continuous spectrum; HZ 46 is a triangle; BSO 16 is known to be a star. The shaded areas locate: horizontal shading, white dwarfs; vertical shading, hot subdwarfs; diagonal shading, F and G subdwarfs. Note that one-third of the interlopers (mainly those of yellow B-V) lie completely outside the region occupied by stars; many are above the black-body line, where only extreme composite stars (C), like HZ 9 (DA + dMe) are found.

+12, subdwarfs $M = +3$, halo stars $M = 0$, composites (which are probably subdwarfs plus G dwarfs) $M = +4$, and "normal" blue stars $M = -1$, we find the $\langle M \rangle$ given in the last column of Table 4. Note that the mean modulus, $\langle V \rangle - \langle M \rangle$ is +9.6 mag. for the brighter group of stars and +8.4 mag. for the fainter! Apparently, we exhaust all the normal and most of the horizontal branch stars by modulus 10 mag., at a distance of 1000 pc, and the luminosity of the fainter stars tends toward that of the white dwarfs. A group at mean visual magnitude 15 mag. has an absolute magnitude halfway between the horizontal branch and the white dwarfs.

The predicted proper motion for a tangential motion equal to the reflex of the solar galactic rotation would be 0".050/year for the entire sample. But even the white dwarfs, highly selected by proper motion, have a lower tangential speed. Inspection of Figure 13 of Eggen and Greenstein (1965) shows that half the white dwarfs have both $|U|$ and $|V| < 30$ km/sec, i.e., a tangential velocity < 45 km/sec. The expected space motions for the whole group may be larger than that for the white dwarfs, since the pure halo stars will have larger motions than a mixed population like the white dwarfs. Thus the mean proper motions should lie within the range from 0".010/year for a mean tangential velocity of 50 km/sec to 0".025/year for a mixture of white dwarfs and halo stars.

VI. INTERPRETATION OF THE SPECTRA

A full study of line profiles and intensities, insofar as they are measurable at low dispersion, is required to clarify the physical properties of the halo and subdwarf stars. Properties of an unpublished, preliminary network of models for hydrogen and helium stars with a moderate range of T and g have been studied by Oke, Mihalas, and Arpigny. The spectral scans made by Oke have been used to estimate T by Mihalas (unpublished); T can be very high in sdO stars and the range of g derived from Hγ-profiles is from above to well below that on the main sequence.

Rough classification criteria have been given (Greenstein 1960), but stars with a bewildering variety of line intensities, line widths, and luminosities still remain undescribed. On my available spectra (usually only one per star), equivalent widths, W_λ, and widths at half central intensity, $w_{0.5}$, have been measured; the first results of this spectrophotometry are presented in Figures 5 and 6. The line intensities in main-sequence stars are taken from Kopylov (1958), and spectral types have been transformed to unreddened, main-sequence $B - V$ colors (a very uncertain process for hot stars). In Figure 5 Kopylov's main-sequence Hγ strengths and my own (Eggen and Greenstein 1965) white-dwarf Hγ are plotted, together with results for some individual hot or peculiar white dwarfs. All faint blue stars from Tables 1–3 are shown with spectral type and peculiarity labeled. A few stars that may be reddened, marked by an arrow, should be shifted to the left, as should stars with composite spectra. Because of the low accuracy of the W_λ in this investigation, for most stars the mean of Hγ and Hδ is plotted. The few normal objects and most of the "halo" stars, i.e., Bp or Ap, lie close to the main-sequence relation between W_λ and $B - V$. Nearly all stars classified as subdwarfs, sdO or sdB, lie between the white dwarfs and the main sequence. It is the large Stark broadening coefficient, Γ_s, that permits luminosity classification. The strong Balmer lines have $W_\lambda \propto (N_2\Gamma_s/k)^{0.4}$ approximately, and the stars shown in Figure 5 have line strengths up to four times those in main-sequence stars. Assume hydrogen to be the only opacity source, so that the number of atoms in state 2, N_2, divided by the opacity, k, which measures the number photo-ionized from higher states, is a slow function of temperature, $[f(T)]^{-1}$ (see below). Then $\Gamma_s \propto W_\lambda^{5/2}$; but $\Gamma_s \propto P_e$ and $P_e \propto g^{1/2}$ for hot stars, so that $\Gamma_s \propto g^{1/2}$ and finally $g \propto W_\lambda^5$. *The observed range of W_λ represents about a factor of 10^3 in g, and therefore in luminosity*, L. The subdwarfs may give g up to 10^7 cm/sec^2, as compared to white dwarfs with 10^8 or 10^9 cm/sec^2; since $L \propto g^{-1}$, the extreme subdwarfs should have $M_v \lesssim +6$. There are several objects with abnormally *weak* hydrogen lines, and it is possible that the H/He ratio varies. Only extraordinarily high helium or metal opacity could weaken the H-lines at this temperature. Very hydrogen-poor objects do exist among the white dwarfs, but whether this is true also in the subdwarfs will require careful study.

The strength of the helium lines is shown in Figure 6. Kopylov's data on normal stars are included. I use $0.5[W_\lambda(4471) + W_\lambda(4026)]$, for the He I triplets, in B and O stars and $W_\lambda(4686)$ for He II in O stars. Fewer stars are plotted both because the helium lines are weaker and harder to measure and because most composite and reddened stars have been omitted. The reddened carbon-rich stars, HZ 12 and HZ 15, and the probably reddened

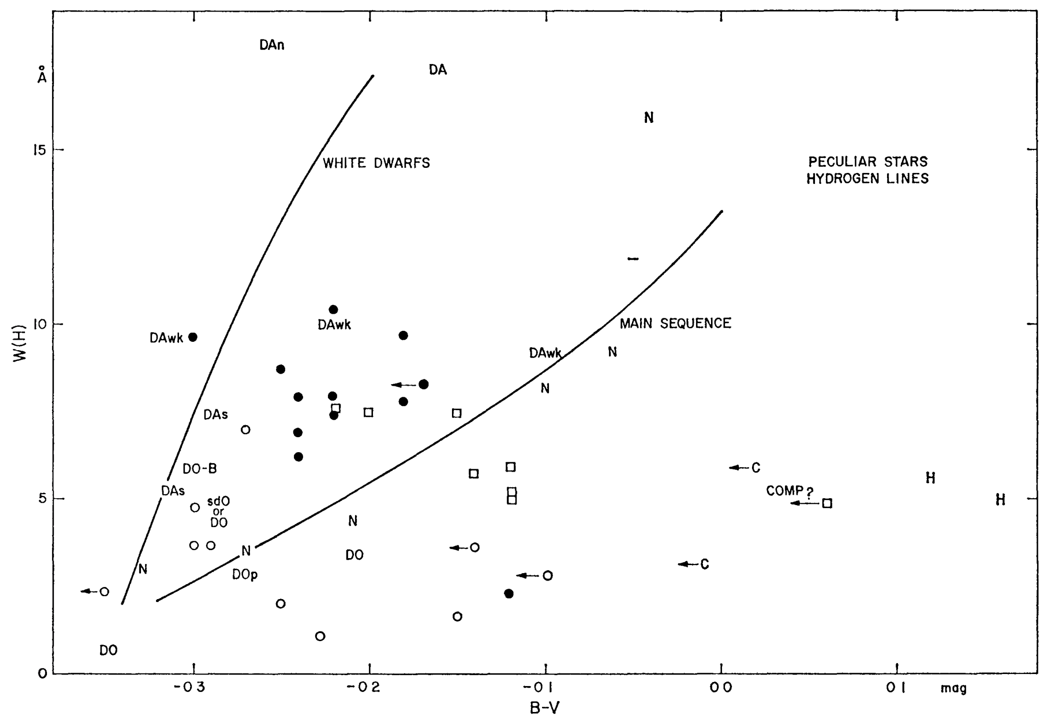

FIG. 5.—Equivalent widths, $W(H) = \frac{1}{2}[W(H\gamma) + W(H\delta)]$, are plotted for normal stars (Kopylov), DA, and DAs (Eggen and Greenstein). Individual points give $W(H)$ for subdwarfs (sdO, *open circles;* sdB, *filled circles*), and for halo stars (Bp, *open squares;* Ap, *dashes*). Most subdwarfs obviously have hydrogen stronger than do main-sequence stars, while the halo stars hardly differ. Normal stars are labeled "N," horizontal-branch "H," reddened carbon stars HZ 12, 15 are "C" and the reddened subdwarf, HZ 3, an open circle with an arrow.

sdO, HZ 3, are included, with arrows. Filled circles show He II lines and open squares show He I for the faint blue stars. A few individual DO stars are included to show how much they differ from the subdwarfs. In spite of the low accuracy of the measures, a very important conclusion from Figure 6 is that pressure broadening alone cannot be the only source of differences of line intensity at a given color in these objects. The very blue stars classified as sdO usually have λ 4686, but sometimes this is too weak to measure. But only two out of sixteen subdwarf B and O stars with measured He I lines have He I weaker than in the main-sequence stars, and *all but one* sdO stars with measured λ 4686 show it more strongly than do main-sequence stars. (My classification procedure distinguishing between sdO and sdB and halo stars is not completely foolproof, but He II was not found or measured in any sdB or Bp star.) Finally, and quite unexpectedly, no star called Bp (i.e., halo or horizontal branch) has the He I triplet lines as strong as in the main sequence (except for the object at $B - V = +0.06$ mag. Either the color is incorrect or it is composite). HZ 12 and HZ 15, which are reddened and carbon-rich, may also be He rich.

Let us consider the expected value of the absorption in a pressure-broadened wing of a line of either He I or He II. Let the numbers of all atoms of an element be N, of neutral atoms N_0, of ionized atoms N_i, and let numbers of excited atoms be denoted by an asterisk. The opacity, k, will be assumed to be proportional to the number of hydrogen atoms, in level $n = 3$ or higher, a summation which will be abbreviated as N_3 The pressure broadening of He I triplets is complex, but it will not produce a large error if we use N_i(H), or N_e(H) (unless the helium abundance is very high), to measure the total pressure-broadening coefficient, Γ. In fact, we will write it as $\Gamma = \Gamma_0 P_e$, where Γ_0(H) is Stark broadening, and Γ_0(He) is more complex. Quadratic Stark effect could increase line broadening at high surface gravity. The hydrogen will be very highly ionized, helium

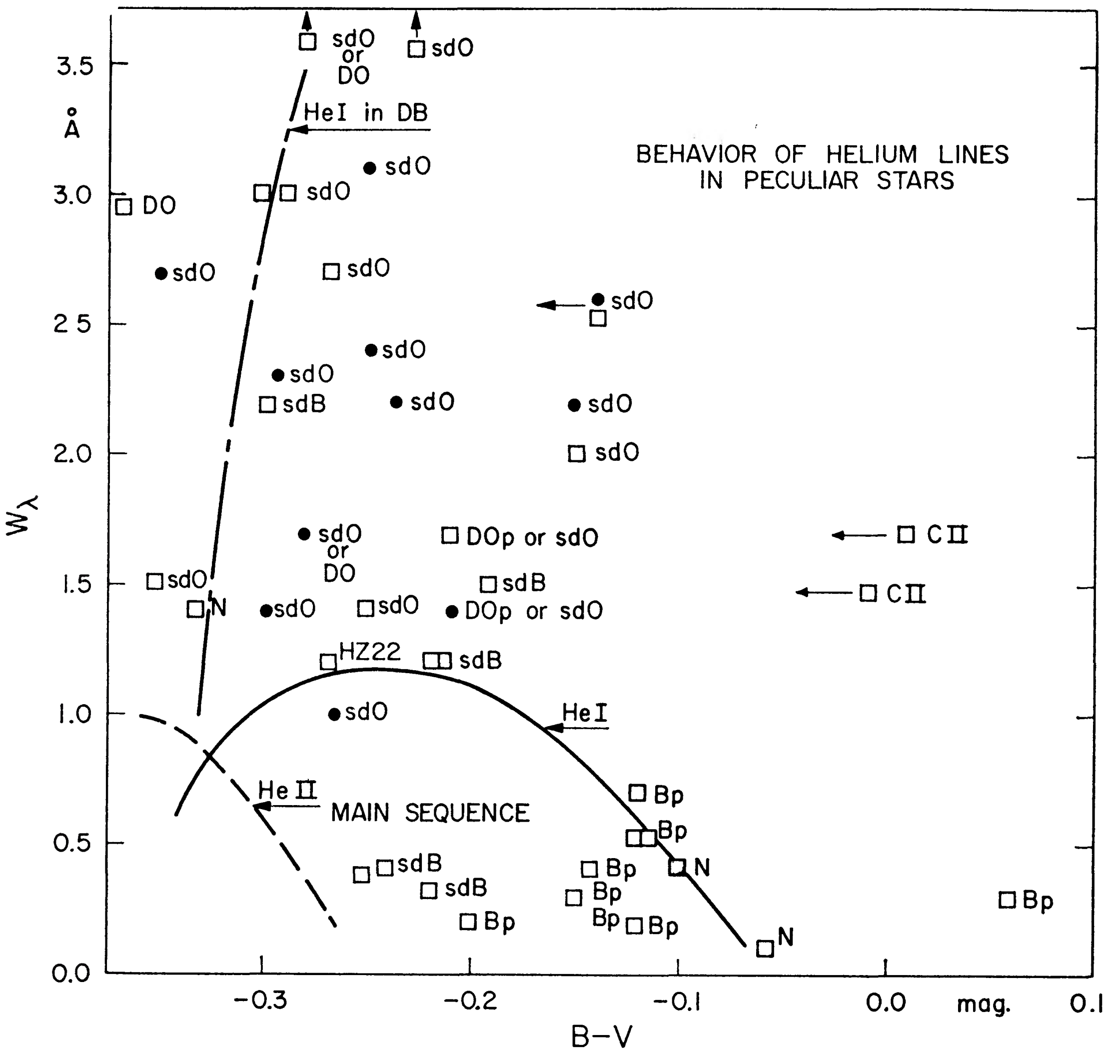

FIG. 6.—The equivalent widths of He I triplet lines, $\frac{1}{2}[W(\lambda\, 4472) + W(\lambda\, 4026)]$ are plotted as open squares and of He II $\lambda\, 4686$ as filled circles, for individual stars. The means of He I (*solid*) and He II (*dashed*) in normal stars are shown from Kopylov; the loci for white dwarfs are also shown. A few normal stars from this program are labeled "N." Note that nearly all halo Bp stars have weak He I, while nearly all subdwarfs have very strong He I; very strong He II is particularly common in sdO. The helium deficiency, in halo Bp stars, is large.

once ionized. If $P_e \approx 10^7$, He is largely He^+ up to $T = 50000°$ K and if $P_e \approx 10^5$, this is still true up to 40000° K. We will express the various concentrations of atoms or ion in B stars (moderate T) and O stars (high T) by retaining only the exponential terms in T, as

$$N(\mathrm{H}) \propto N_{\mathrm{H}} P_e 10^{13.54\theta} , \tag{1a}$$

$$k(\mathrm{H}) \propto N_3(\mathrm{H})[f(T)]^{-1} \propto N(\mathrm{H}) P_e 10^{1\ 50\theta}[f(T)]^{-1} , \tag{1b}$$

$$\left.\begin{aligned} N_0^*(\mathrm{He}) &\propto N_{\mathrm{He}} P_e 10^{3\ 61\theta} & \text{(2a)} \\ N_i^*(\mathrm{He}) &\propto N_{\mathrm{He}} 10^{-48\ 16\theta} & \text{(2b)} \end{aligned}\right\} \text{(moderate } T) ,$$

$$\left.\begin{aligned} N_0^*(\mathrm{He}) &\propto N_{\mathrm{He}} P_e^2 10^{57\ 77\theta} & \text{(3a)} \\ N_i^*(\mathrm{He}) &\propto N_{\mathrm{He}} P_e 10^{5\ 99\theta} & \text{(3b)} \end{aligned}\right\} \text{(high } T) .$$

The excitation and ionization temperatures have been assumed equal; $f(T)$ corrects the population of the $n = 3$ hydrogen level for higher levels to permit writing the opacity as a slowly varying function of T instead of the step-wise sum that must otherwise be computed. Then, in the shallow wing of an electron-pressure-broadened line, where $A_\lambda \propto \eta_\lambda$,

$$A_\lambda \propto N^* P_e \Gamma_0 / k(\mathrm{H}) . \tag{4}$$

We find for the He I triplets, combining equations (1b) and (2a) or (3a),

$$A_\lambda(\text{He I}) \propto \frac{N_{\mathrm{He}}\Gamma_0(\mathrm{He})}{N_{\mathrm{H}}} P_e 10^{2\ 11\theta} f(T) \qquad (\text{moderate } T) , \tag{5a}$$

$$A_\lambda(\text{He I}) \propto \frac{N_{\mathrm{He}}\Gamma_0(\mathrm{He})}{N_{\mathrm{H}}} P_e^2 10^{56\ 27\theta} f(T) \qquad (\text{high } T) . \tag{5b}$$

For $\lambda 4686$ of He II, combining equations (1b) and (2b) or (3b):

$$A_\lambda(\text{He II}) \propto \frac{N_{\mathrm{He}}\Gamma_0(\mathrm{He}^+)}{N_{\mathrm{H}}} 10^{-49\ 66\theta} f(T) \qquad (\text{moderate } T) , \tag{6a}$$

$$A_\lambda(\text{He II}) \propto \frac{N_{\mathrm{He}}\Gamma_0(\mathrm{He}^+)}{N_{\mathrm{H}}} P_e 10^{4\ 49\theta} f(T) \qquad (\text{high } T) . \tag{6b}$$

Use of equations (5a) and (6b) is quite easy, and they are insensitive to T. The transition to the high T forms of the equations depends on P_e but will occur near $\theta \lesssim 0.1$; at this point an error of 0.02 in θ (i.e., temperature error of 20 per cent) produces a change by a factor of 10 in A_λ, so that cases (5b) and (6a) are not as intractable as may appear. In fact, the appearance of the term P_e^2 may be more serious. Where He is largely He^+, probably true for all but the hottest sdO stars, we can use He I lines; where it is largely He^{++} we use the He II line, and obtain in both cases the combination $N_{\mathrm{He}} P_e / N_{\mathrm{H}}$ and a weak dependence on θ. The relation between W_λ and A_λ is less simple for He I than for H. The broadening coefficient, $\Gamma_0(\mathrm{He})$, varies from line to line for He I, and W_λ should be obtained from A_λ by integration over the line profile.[2]

[2] When helium is largely neutral, in the cooler B stars, H is still ionized, and a low T form of equations (5a) and (5b) is

$$A_\lambda(\text{He I}) = \frac{N_{\mathrm{He}}\Gamma_0(\mathrm{He})}{N_{\mathrm{H}}} 10^{-22\ 4\theta} f(T) .$$

This displays the great temperature sensitivity for the later B's. The He deficiency is best studied in the middle B's.

Among the subdwarfs, only three have helium W_λ less than in normal stars. The majority have much stronger He I lines, reaching up to a factor of 5 times normal. Then $N\Gamma \gtrapprox 25$ times that in normal stars; we have already estimated from hydrogen lines that P_e varied in the range of 10 to 10^3 times normal. The increase of H and He I line strengths is more or less parallel, and we need not immediately invoke a He/H abundance change if the moderate T case is valid (eq. [5a]). In equation (5b) the P_e^2 term would cause so great a change with luminosity that it is probably equation (5a) that is usually valid. In the sdO stars, $\lambda_e 4686$ is usually more than five times that in main-sequence stars. If equation (6a) is valid, the P_e does not enter. Either the subdwarfs have a different temperature than the main sequence (θ smaller by about 0.03), or $N_{\mathrm{He}}/N_{\mathrm{H}}$ is, in fact, higher. If equation (6b) holds, then H and He II behave similarly, and it will be the actual, exact value of P_e that determines whether the He/H abundance is normal. The sdO stars with He II, He I, and H all enhanced seem probably to be good candidates for He-rich objects.

The low intensities of He I lines in Bp stars (moderate T case, eq. [5a]) can be explained by low P_e, surface gravity, and mass on the horizontal branch, or by a lower He/H ratio than in normal young stars. Clearly, detailed studies of spectrophotometric

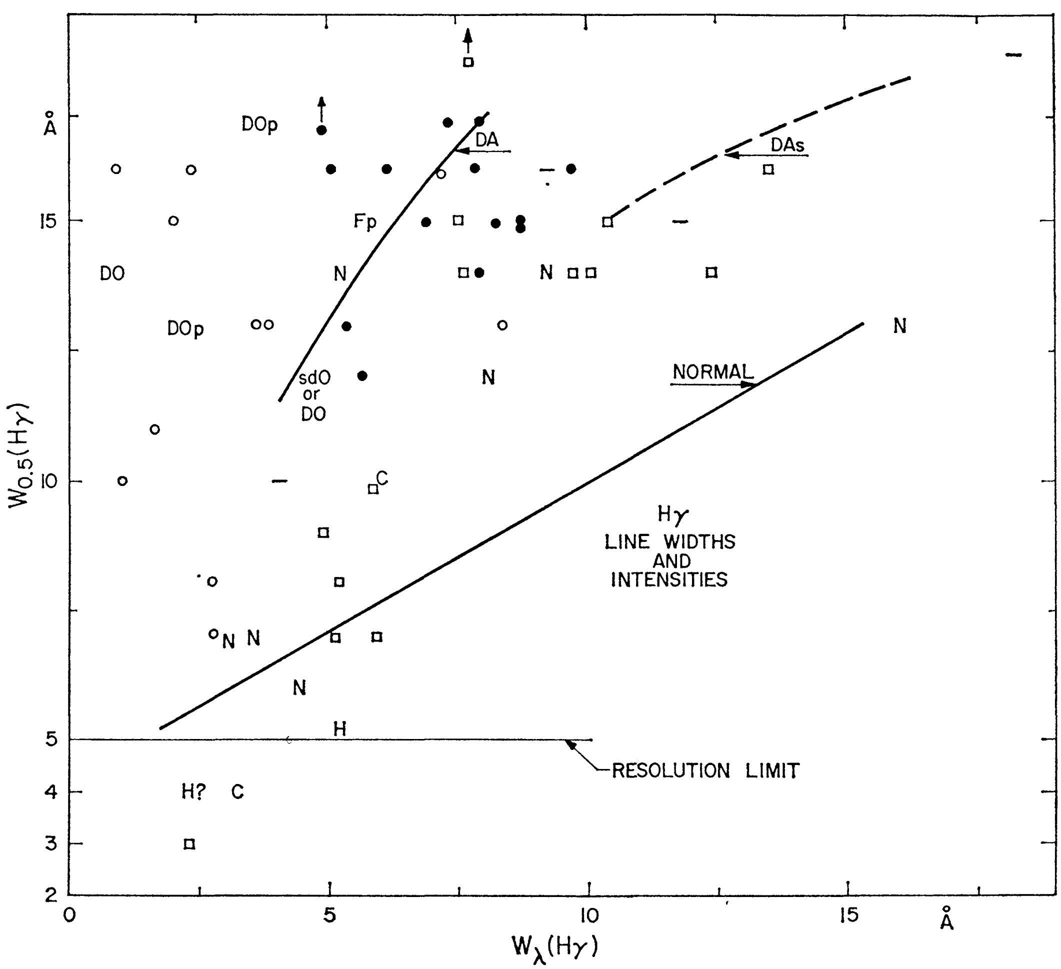

FIG. 7.—The observed relation between the width at half of central intensity, $w_{0.5}$, for Hγ and its equivalent width W_λ. The resolution limit is taken as the slit width; the lines drawn show the correlations for ordinary and sharp-line white dwarfs and from this investigation that for normal stars. Individual stars are plotted as: open circles, sdO; filled circles, sdB; open squares, Bp; dashes, Ap; N, normal; C, carbon; H, horizontal branch. The Bp and horizontal-branch stars lie near the normal relation.

scans, model atmospheres, and compositions of the brighter of the horizontal-branch and hot subdwarfs will be needed. Their spectra are very different from those of normal stars; many are exceedingly hot and possibly either helium-rich (i.e., highly evolved and mixed) for the subdwarfs or helium-poor (i.e., formed at an early phase of the Galaxy with low He/H ratio) for the horizontal-branch stars.

It is very probable that most of these stars have low heavy-element abundances. The Mg II line is seen in only a very few normal or Bp stars and never in a sdB star. The N III and Si IV lines are strong in HZ 44, but C II, N III, Si III, or Si IV are not seen in most other hot subdwarfs. Most of these stars are members of halo population II, with low abundances of elements heavier than He. Detailed tables of the Hγ, He I, and He II line intensities and widths used in this section will be published later.

Because of the low dispersion and low accuracy of the spectrophotometry, measured half-widths of these lines are only very rough approximations. But some effects are already so striking as to become significant and require a preliminary discussion. Most stars were observed only once, at 190 Å/mm; some at 85 Å/mm and a few at 38 or 18 Å/mm. The profiles were drawn on smoothed tracings and plotted on an intensity scale; equivalent widths, W_λ, of Hγ and widths at half central absorption, $w_{0.5}$, were then obtained. The preliminary relation between these is shown in Figure 7; the resolution limit sets an asymptotic value of $w_{0.5}$ as shown. Few normal stars were available; however, they have the sharpest lines observed. The lines in horizontal-branch stars, Bp and Ap, are also very sharp, on the average. The sdB stars often have a $w_{0.5}/W_\lambda$ ratio approaching that of the white dwarfs, and many sdO stars have lines which are even wider for their equivalent widths than the average white dwarf. Of course, many individual DO stars have even wider lines. The line profiles change from deep to shallow as we go from Bp to sdO; even at the low dispersion used, the visual impression that the lines are broad and shallow proves meaningful. The hottest stars must have smallest central absorptions; since $W_\lambda = pA_c w_{0.5}$, with $p = 1$ for a triangular profile, the sdO stars should show a large $w_{0.5}/W_\lambda$ ratio. However, the line-shape parameter, p, though always near unity for a Voigt profile, depends on the shape of the line-absorption coefficient. A line dominated by extended pressure-broadened wings will have a larger p than a rectangular line. The approximate value of pA_c can be estimated from Figure 7; it changes by a factor of about 3, which is more than A_c should change for a saturated line in these hot stars. On the infrared side of the Planck energy maximum, A_c reaches an asymptotic, roughly constant value given by the boundary and effective temperatures as $(1 - T_0/T_e)$. Consequently, Figure 7 demonstrates the importance of varying amounts of pressure broadening in DO and sdO stars. It suggests also that the horizontal-branch stars do not have very different line profiles from normal stars, unless they have abnormal values of A_c because of low surface gravity.

VII. "INTERLOPERS," QUIET STELLAR GALAXIES, OR STARS?

Spectroscopic investigations are necessarily limited to the brighter of the faint blue objects already known. It is difficult to distinguish clearly between an object with weak emission lines on a continuous background and a white dwarf of type DC. From a practical standpoint, a spectrum of 380-Å/mm dispersion widened to 0.11 mm can be obtained in 1 hour at 16.5 mag.; therefore 18.0 mag. is nearly the limit of observability and night airglow lines would be troublesome. Unless the very small extragalactic objects have *strong* emission lines (like Seyfert galaxies or compact blue galaxies) it remains possible to confuse the spectrum of a blue, starlike galaxy with that of a nearby white dwarf of continuous spectrum (DC) or of a very weak-hydrogen-line hot object (DAwk). However, in my survey, only one spectroscopically dubious object was found, Ton 202. The white dwarfs which cause confusion range from $B - V = -0.2$ to $+0.3$ mag., at large negative $U - B$, and cannot be distinguished from possible blue galaxies by photometry alone. Stars with composite spectra cause confusion also. They will have large

$U - B$ excess, although composite objects substantially above the black-body line will not appear at negative $B - V$. Yellower composites can appear near or above the line, as does HZ 9, at $B - V = +0.33$ mag., $U - B = -0.69$ mag. No object studied in this paper has colors like the redder "interlopers," the possible BSO's measured by Sandage and Véron (1965). In my Figure 4, their measures are plotted as filled squares, and display the remarkable property of only slight dependence of $U - B$ on $B - V$. The BSO's with $B - V < -0.05$ mag. are well mixed with white dwarfs, and at $B - V < -0.20$ mag. with hot subdwarfs. Those of $+0.20 > B - V > +0.05$ mag. fall close to stars with composite spectrum, but those with $B - V > +0.2$ mag. have $U - B$ far too negative to resemble any of the objects for which I have spectra. From Figure 4, about half of the Sandage and Véron BSO's lie in a region completely empty of spectroscopically observed stars and above the stars with observed composite spectra. The mean apparent magnitude of the Sandage and Véron objects is 17.6 mag., i.e., 2.3 mag. fainter than the faint stars whose statistical properties are discussed in Table 4.

It is clear that the present sample of spectra does not reach to a magnitude where the galaxy population becomes an appreciable fraction of the stellar population, for stars with largely negative $B - V$. The suggestion by Sandage (1965) that a significant change from stars to galaxies occurs as bright as 14.5 mag. for all blue-star surveys needs to be modified.

TABLE 5

SPECTRA OF THE FAINTEST BLUE STARS (INCLUDING KINMAN'S DATA)

m	White Dwarfs	Sub-dwarfs	Bp, Ap	Comp or Old Nova	QSG?	n
14 5–14 9	2	2	2	1	0	7
15 0–15 4 .	5	4	1	0	0	10
15 5–15 9 .	6	6	2	1	1	16
16 0–16 4 ...	3	1	1	1	0	6
≥16 5	2	0	0	0	0	2
≥14 5 .. .	18	13	6	3	1	41

In addition to my own observations, after the work was substantially complete, Kinman (1965) kindly supplied in preprint form the results of his survey of twelve northern, faint Tonantzintla stars from Lick spectra. Their mean magnitude was given as 15.1 mag., but Kinman finds that a systematic correction near +0.7 mag. must be added to the Tonantzintla photographic magnitudes. If the same correction must be added to those I have observed in the southern galactic polar region (for which photoelectric magnitudes are lacking), we can further extend the magnitude limit to which stars completely dominate. Kinman has been kind enough to permit me to inspect and classify his and Burbidge's Lick spectra. The dispersion is 200 Å/mm, the widening less than the Palomar spectra, but the quality excellent. None have emission lines or only continuous spectrum, i.e., all the spectra clearly show absorption lines. I have included them in a new statistical recompilation of data on the very faintest stars, with results shown in Table 5. The Ton magnitudes are corrected by a constant +0.7 mag. unless they are photoelectrically determined. For these faintest stars (my Tables 1–3 and Kinman's) photoelectric colors and magnitudes are badly needed, as well as further photoelectric colors for future spectroscopic observations. Note that if any blue horizontal-branch with nearly normal UBV colors are found at 16.5 mag., they are 15 kpc or more from the galactic plane.

It is important to recognize that the spectroscopic surveys have never included the objects of the color range that distinguishes the yellower interlopers and the quasi-stellar radio sources most sharply from stars. From Figure 1 of Sandage (1965) on radio sources, the QSRS's, and the data in Sandage and Véron (1956) on BSO or QSG suspects, it is clear that the most unusual excess ultraviolet colors occur in the range $+0.1 < B - V < +0.5$ mag., with $U - B$ as negative as -1.0 mag. Many of these "yellowish" objects could well have been rejected in the Haro and Luyten (1962) search on Palomar Schmidt plates. Perhaps special attention to yellowish "stars" with excessive ultraviolet would be most profitable. In this search, however, even a small ultraviolet filter leakage could have a large effect on $B - V$ estimated in photographic surveys, when $U - B$ is very negative. In fact, it must be admitted that the recognition of "blue" faint stars with any photographic technique is a complicated and somewhat uncontrolled process. The refractor produces large violet halos that brighten the blue image. The reflector, unless a strong minus UV filter is used, gives apparently blue colors for stars as late as sdF.

In fact, examination of Figure 4 gives some indication of the possibility of a considerable systematic difference between the colors of stars and of the BSO's, interloper objects. The figure shows that the QSRS's and the BSO's largely overlap and are outstandingly unusual in having large negative $U - B$ colors at positive $B - V$. The extragalactic BSO 1, and my possible BSO Ton 202 lie very close together at positive $B - V$. Most very blue interlopers with $B - V < +0.1$ mag. fall within the white dwarf and hot subdwarf region and may be largely stars. Sandage notes that BSO 16 is a star, and it falls, with some other BSO's, in a region occupied by common halo and white dwarf objects (see my Figs. 1–3). However, ten of the available BSO colors, if all correct, are so violently different from those of all known types of stars that we may hazard an estimate that as many as one-third of the interlopers will be extremely abnormal objects. They could be stars with emission lines, planetary nebulae, galaxies, or synchrotron-emitting stars. If they are galaxies, these colors could arise from red-shifted emission lines or abnormal continua (composite spectra rich in hot stars, synchrotron or two-photon continua). It is noteworthy for the hypothesis that galaxies may be abundant that the four faint stars with composite spectra, plotted in Figure 4, lie on or even above the black-body line; composite systems could lie even further above. Figure 4 provides one explanation of why the spectroscopic study of conventional blue stars did not by accident reveal further QSG's with emission lines. Kinman and I have observed stars that are far too blue to resemble either radio sources or stellar galaxies! On the other hand, a disturbing feature of the colors of the proposed identifications of faint radio sources QSRS's in Figure 4 should be remembered. Not all have observed redshifts. Since nearly one-half of these lie within the region of the UBV diagram occupied by common types of high-latitude stars, the identifications are not final.

I hesitate to use only statistical methods involving only poorly known stellar density distributions in the Galaxy to decide so important a problem as the existence or frequency of a new type of extragalactic object. Many more spectra must be obtained. My own, and Kinman's, work suggest an increasing fraction of white dwarfs among the faintest blue stars. The statistics are subject to some selection effects, but the change from 15 per cent white dwarfs (Table 4) at 12.5 mag. to 13 out of 33, or 40 per cent, at $14.5 \leq m \leq 15.9$ (Table 5), and even 5 out of 8, or 60 per cent, at $m > 16.0$ must be significant.

The W-velocity component of the white dwarfs can be estimated from the UVW given by Eggen and Greenstein (1965). We cannot use those at the poles, where the (unknown) radial velocity would dominate. Excluding all for which the radial velocity contributes more than 35 per cent of its value to W, I find that the average value of $|W|$ is about 25 km/sec (or less, considering effects of errors in proper motion and parallax). Oort (1958) gave about 28 km/sec based on nearby stars selected by proper motion. The scale height $|w|$ from his relation between $|W|$ and $|w|$ is about 400 pc. If $|M_v| \approx +12$, there will be substantially no exponential density decrease in the z-direction till 400 pc, i.e., twentieth magnitude. The logarithm of the numbers of bright white dwarfs should increase by 0.6 per unit apparent magnitude increase, beginning to deviate below this value before about 19 mag. According to Kinman (1965) the horizontal-branch stars, like the RR Lyrae stars, should first increase as 0.4 Δm, dropping off much more rapidly by 16.5 mag. Sandage (1965) suggests that the numbers of highly redshifted blue galaxies of high luminosity should increase rapidly at $m > 16.5$, but the present evidence suggests that the ratio of blue QSG to white dwarfs should not be very high until $m \geq 19$. White dwarfs represent at least 0.3 or 0.4 of the 16 mag. stars. Observations beyond 17.5 mag. would be critical in the discovery of QSG, which would have to become a much more significant fraction when all faint blue stars other than white dwarfs disappear.

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