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ON THE NATURE OF FAINT BLUE OBJECTS IN HIGH GALACTIC LATITUDES. I. PHOTOMETRY, PROPER MOTIONS, AND SPECTRA IN PHL FIELD 1:36+6° AND RICHTER FIELD M3, II

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ABSTRACT

Astrometric, photometric, and spectrographic data are given for a representative sample of objects in a single field of 40 sq deg of the PHL catalogue. F and G subdwarfs, white dwarfs, and "radio-quiet" quasi-stellar galaxies (QSG) are the most frequent types of objects, although a few horizontal-branch stars, U Gem variables, and RR Lyrae stars are also present.

Ten positive QSG identifications have been made from spectra of candidate objects in a list compiled from the bluest objects of small proper motion. The redshifts, $\Delta\lambda/\lambda_0$, of PHL 1127, 1194, and 3424 are 1.990, 0 298, and 1.847, respectively. Spectra of PHL 1027, 1070, 1072, 1186, 1222, 1226, and 3375 prove these to be definite QSG also, but with undetermined redshifts. PHL 1092 is a possible QSG.

A firm lower limit for the surface density of QSG in this field is $S = 0\ 25$ QSG/sq deg to $B = 18$ mag, based on ten QSG in 40 sq deg, but the true density is undoubtedly larger, since not all objects in the field have been spectrographically sampled An upper limit is $S = 0\ 5$ QSG/sq deg to $B = 18$ mag A small photometric sample of the Richter-Sahakjan list gives S between 1 QSG/sq deg and 3 QSG/sq deg to an optical limit of 19.7 mag

These values far exceed $S = 0\ 004$ QSS/sq deg for *radio* quasi-stellar sources in the 3C R catalogue. It is shown that very strong observational selection operates against finding QSGs of small absolute radio power when optical identifications are made from existing radio catalogues (Fig 4). The number of QSGs may exceed 100,000 over the entire sky to an optical limit of $B = 19.7$ mag.

I. INTRODUCTION

The nature of faint blue objects found in large numbers at high galactic latitudes (Malmquist 1927, 1936; Humason and Zwicky 1947; Luyten—many papers since 1953 in the series *A Search for Faint Blue Stars;* Iriarte and Chavira 1957; Chavira 1958, 1959; Cowley 1958; Feige 1958; Slettebak and Stock 1959; Haro and Luyten 1962; Richter and Sahakjan 1965; van den Bergh 1966; Rubin, Moore, and Bertiau 1967; and others) is still a major unsolved problem. Work by Luyten (cf. 1953, *op. cit.*), Cowley (1958), Klemola (1962), Berger (1963), Sandage (1965), Kinman (1965), Lynds and Villere (1965), Greenstein (1966), and others has shown that a sample of the brighter objects contains a mixture of many types, among which are white dwarfs, subdwarfs, stars with composite spectra, blue main-sequence stars, and globular-cluster-like horizontal-branch stars. It is also known (Sandage 1965; Scheuer and Wills 1966) that a fraction of the fainter objects are radio quasi-stellar sources (QSS) and quasi-stellar-like objects (QSG) that are radio "quiet" to 9 flux units, and fainter, at 178 Mc/s. To date, the list of QSG objects is very small, and no reliable estimate of the surface density of such objects is yet available, although preliminary discussions have been given (Sandage 1965; Kinman 1965; Lynds and Villere 1965).

The purpose of the present series of papers, of which this is the first, is to identify positively the types among the faint blue objects using astrometric, photoelectric, and spectrographic methods, and ultimately to obtain distances, absolute luminosities, and relative frequencies.

II. THE ASTROMETRIC AND PHOTOELECTRIC DATA

We have selected a single field in the PHL catalogue (Haro and Luyten 1962) at 1^h36^m, $+6^0$ (1855) for the present reconnaissance study. This particular field was chosen because of the very early epoch of the *Sky Survey* plate, which provides a long base line for proper motions. Luyten and Smith (1966*a*) have measured the proper motions for 103 of the 365 objects catalogued in this field. Measurements were obtained for all 44 of the bluest objects (PHL Table II), for 45 objects of the intermediate color class (PHL Table III), and for 14 of the reddest color class (PHL Table IV). Haro and Luyten (1962) named these color classes "very definitely blue," "blue," and "bluish or white," which we designate as classes, I, II, and III, respectively. The objects in our field in each color class are contained between PHL running numbers 1007 and 1237, 3372 and 3963, and 7219 and 7596.

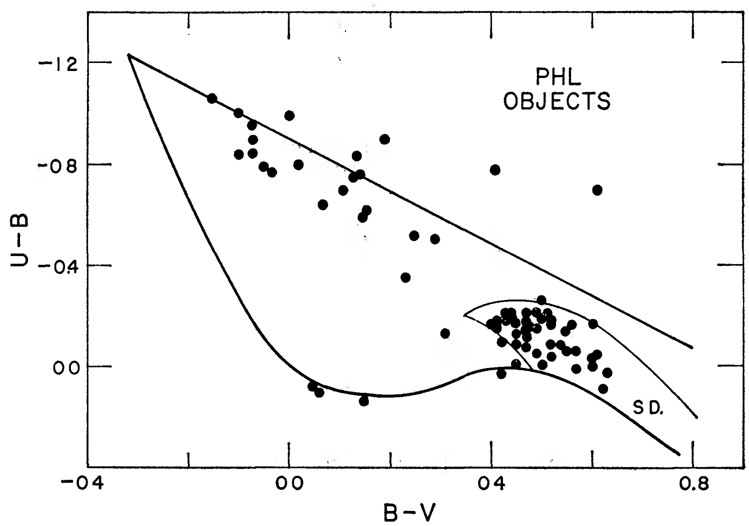

FIG. 1 —The two-color diagram for 69 objects from the PHL catalogue in the 1:36 + 6° field. The data are from Table 1. The standard main-sequence relation is shown, together with the black-body line and the area occupied by F and G subdwarfs.

Three-color photoelectric photometry was obtained for sixty-nine objects chosen at random from each of the three color classes before the proper motions were known. Consequently, the photometric sample is unbiased as regards astrometric properties. The photometry, done at the prime focus of the 200-inch telescope, should be accurate to about ± 0.02 mag mean error in each of the three wavelength bands. Photometry of twenty-one blue objects in the list of Richter and Sahakjan (1965) was also obtained, but proper motions exist for only one of these objects (Luyten and Smith 1966*a*).

Table 1 lists the photoelectric and proper-motion data for the sixty-nine PHL objects, while Table 2 gives the photometric data for the Richter-Sahakjan field. A classification of the objects is given in each of these tables, either from the photometric criteria discussed in the next section or, in the case of certain of the PHL objects, from spectrographic information. Those objects where a spectroscopic classification was made are marked by an asterisk.

III. THE $U - B$, $B - V$ DIAGRAM

As a first step in analyzing the data, we show the two-color diagram for the PHL field in Figure 1. The most striking features are (1) the absence of blue stars near the normal main-sequence relation for $B - V < 0.0$; and (2) the large number of F and G

TABLE 1

PHOTOMETRY AND PROPER MOTIONS FOR 69 PHL OBJECTS IN THE FIELD 1:36+6°

PHL	V	$B-V$	$U-B$	Absolute* μ_x	μ_y	Type**
1007......	17.48	−0.05	−0.79	+0.″021	+0.″005	DA*
1018......	16.35	+ .11	− .70	+ .092	+ .013	WD
1019......	16.27	+ .07	− .64	+ .063	− .152	WD
1023......	17.54	− .07	− .90	+ .051	− .034	WD
1024......	17.86	+ .16	− .62	+ .011:	+ .003	DA*
1027......	17.04	− .03	− .77	+ .009	+ .014	QSG*
1028......	16.59	+ .15	− .59	− .090	− .023	WD
1029......	16.57	+ .06	+ .10	− .030	− .030	HB
1031......	17.10	+ .14	− .76	+ .066	− .047	WD
1049......	17.26	+ .61	− .70	− .011	+ .018	C*
1050......	16.94	+ .25	−0.52	+ .186	− .060	WD
1058......	16.40	− .15	−1.06	+ .026	+ .020	DA*
1105......	15.50:	+ .23:	−0.35:	+ .008	− .003	DA*
1112......	16.68	+ .02	− .80	− .075	− .076	WD
1127......	18.29	+ .14	− .83	− .020	− .007	QSG*
1131......	15.87	+ .05	+ .08	+ .003	.000	HB
1176......	17.65	− .10	− .84	− .049	− .037	WD
1194......	17.50	− .07	−0.85	− .033	+ .026	QSG*
1196......	17.52	− .10	−1.00	− .008	− .036	DB*
1213......	18.37	.00	−0.99	+ .015	− .013	DB*
1222......	17.63	+ .41	− .78	+ .003	+ .003	QSG*
1236......	17.80	− .07	− .95	+ .015	− .011	DB*
3372......	17.08	+ .47	− .18	+ .026	+ .008	SD
3375......	18.02	+ .29	− .51	+ .005	+ .003	QSG*
3383......	15.78	+ .43	− .21	+ .009	+ .008	SD
3394......	15.92	+ .50	− .26	......	......	SD
3401......	16.22	+ .55	− .06	......	......	SD
3402......	16.59	+ .50	− .19	+ .005	− .039	SD
3415......	17.34	+ .40	− .17	......	......	SD
3418......	17.32	+ .52	− .18	......	......	SD
3424......	18.25	+ .19	− .90	+ .001	+ .012	QSG*
3429......	16.30	+ .45	− .13	......	......	SD
3430......	16.61	+ .60	.00	......	......	SD
3437......	16.72	+ .61	− .05	+ .013	+ .016	SD
3438......	17.30	+ .49	− .15	+ .026	− .030	SD
3443......	16.61	+ .41	− .15	+ .018	+ .008	SD
3444......	17.66	+ .47	− .08	− .003	+ .016	SD
3448......	16.75	+ .44	− .21	− .012	− .026	SD
3632......	18.15	+ .13	− .75	+ .022	+ .016	QSG
3654......	17.73	+ .31	− .13	+ .022	− .001	SD?
3683......	16.65	+ .57	+ .01	......	......	SD
3684......	17.08	+ .44	− .19	......	......	SD
3696......	15.99	+ .42	− .10	......	......	SD
3732......	17.54	+ .45	− .09	......	......	SD
3803......	16.58	+ .60	− .04	+ .013	− .026	SD
3867......	17.65	+ .63	+ .02	+ .009	− .001	SD
3898......	16.16	+ .52	− .17	+ .018	− .009	SD
3905......	15.91	+ .15	+ .14	+ .043	− .030	HB
3909......	17.66	+ .56	− .17	− .020	− .022	SD
3926......	16.81	+ .54	− .09	+ .030	− .001	SD
3939......	16.81	+ .52	− .04	− .024	− .005	SD
3942......	16.03	+ .41	− .18	+ .013	− .022	SD
3958......	16.32	+ .50	− .01	+ .034	+ .037	SD
7220......	17.09	+ .47	− .21	+ .017	− .003	SD
7229......	16.35	+ .47	− .14	+ .009	+ .003	SD
7233......	16.71	+ .62	+ .09	+ .013	+ .003	SD
7234......	17.13	+ .57	− .06	− .029	− .026	SD
7235......	16.70	+ .43	− .19	......	......	SD
7244......	17.30	+ .45	− .17	− .003	− .018	SD
7248......	16.64	+ .51	− .21	+ .039	− .026	SD
7253......	16.59	+ .52	− .09	+ .008	+ .003	SD
7254......	16.93	+ .49	− .21	+ .005	− .030	SD
7267......	17.05	+ .55	− .14	− .008	− .009	SD
7318......	16.17	+ .60	− .17	......	......	SD
7332......	17.33	+ .42	+ .04	− .012	+ .012	RR Lyr?
7334......	16.75	+ .45	− .01	+ .005	+ .008	SD
7380......	17.62	+ .49	− .05	− .020	− .018	SD
7405......	17.76	+ .47	− .13	+ .013	− .018	SD
7556......	17.75	+0.48	−0.15	+0.001	−0.009	SD

*Mean errors of the motions are ±0.″013 for color class I; ±0.″018 for color classes II and III.

**Starred objects are classed by spectra as listed in Table 4.

subdwarfs with $B - V > 0.40$. Because most of our objects are fainter than $B = 16$ mag, the first result confirms the change of color characteristics between the brighter and fainter blue objects, as discussed in a preliminary way by Klemola (1962) and later by Sandage (1965, Fig. 2) using more extensive material. The second result was unexpected. Of the sixty-nine objects studied, forty-two are subdwarfs of the galactic-halo population with ultraviolet excess values ranging from $\delta(U - B) = 0.00$ to a maximum value of $\delta(U - B) = -0.28$ for PHL 3394. These stars occupy the area marked "SD," whose boundaries are taken from a separate photometric study of nearby field subdwarfs discussed elsewhere (Sandage 1964, Fig. 1). Subdwarfs have long been expected to be numerous among the fainter stars in the galactic polar caps, and indeed they have been found in other studies (Eggen 1965, Fig. 1; Becker 1965). But it is somewhat surprising that such a large percentage of the PHL objects are of this type since the selection criteria of the PHL study were designed to exclude stars of such red $B - V$ and $U - B$ values. Apparently the ultraviolet excess of the subdwarfs is sufficiently great to make

TABLE 2

PHOTOMETRY OF THE RICHTER-SAHAKJAN STARS IN THEIR M3, II FIELD

Object	V	$B-V$	$U-B$	Predicted Class*	Object	V	$B-V$	$U-B$	Predicted Class*
R1	15 69	−0 19	−0 94	WD-QSG	R25	17 45	−0 09	−0 63	WD-QSG
2	16 05	+ 37	−0 22	SD	28	18 46	+ 27	− 75	QSG-(WD)
7	17 17	+ 16	−0 77	QSG-(WD)	29 .	18 24	− .10	− 86	WD-QSG
9	16 69	+ 43	−0 26	SD	31	18 67	+ .14	− 92	QSG-(WD)
11	18 35	+ 06	−0 84	WD-QSG	37 .	17.66	+ 33	− 45	WD-QSG
12	18 61	+ 57	−0 90	QSG	41	17 18	+ .42	− 17	SD
13	17 94	+ 47	−0 71	QSG	42 ..	15 86	+ 37	− .20	SD
17	15 42	− 28	−1 07	WD-QSG	45	16 10	+ .48	− 05	SD
19	16 09	+ 62	+0 02	SD	48 ...	15 58	+ 44	− 25	SD
20	18 35	− 05	−1 09	QSG-(WD)	52 ...	16 36	+0 45	−0 22	SD
24 .	17 20	+0 34	−0 10	SD					

* Based on position in $U - B$, $B - V$ diagram. The least likely type is inclosed in parentheses. Ambiguities exist for objects below the black-body line These are designated WD-QSG

the images peculiar enough on the three-image plates to be included in the catalogue. It is significant that no subdwarfs appear in color class I, but are confined exclusively to the redder stars in Tables III and IV (color classes II and III) of the PHL list.

Figure 1 also shows that there are three stars near the main-sequence relation in the range $0.15 \geq B - V \geq 0.05$. These may be horizontal-branch stars of the globular-cluster population. We discount the possibility that they are young, unevolved A-type main-sequence stars because of their great distances of nearly 10000 pc ($M_V \simeq +2$ if they are main-sequence stars; $M_V \simeq +0.5$ if horizontal-branch objects, with V in the range 14 to 16 for PHL 1029, PHL 1131, and PHL 3905). All three objects have small proper motions that could be zero to within the 3 σ measuring error—a condition which must be satisfied if the objects are at the large distance required by this classification.

The remaining objects of Figure 1 are scattered near the black-body relation, five lying above and eighteen below the line. The occupied region is the domain of the known white dwarfs (Eggen and Greenstein 1965, Fig. 6), and of quasi-stellar radio sources (Sandage 1965, Fig. 1).

Many of these objects must be white dwarfs, as evidenced from their large proper motions. We list in Table 3, parts A and B, the white-dwarf candidates chosen, such that the total motion, μ_T, is greater than three times the probable error of $\pm 0''.013$. Part A of Table 3 lists the candidates where photometry is available. We do not yet have photometry for objects in part B of Table 3 but, since no subdwarfs occur in color Class I in our photometric sample, and since subdwarfs and horizontal-branch stars at these apparent magnitudes must have small proper motions, we are convinced that objects listed in part B of Table 3 are very probably white dwarfs.

All of the objects in Table 3 are of color class I. However, the photoelectric and astrometric results show that a few white dwarfs and QSG candidates occur among color class II (PHL Table III) objects. PHL 3850 is a good white-dwarf candidate with a proper motion of $\mu_x = +0\overset{''}{.}064$, $\mu_y = +0\overset{''}{.}029$ (Luyten and Smith 1966*a*). Photometry shows that PHL 3375, 3424, and 3632 could be white dwarfs on the basis of colors, although they do have small proper motions. Our data suggest that about 10 per cent of PHL Table III objects will lie near the black-body line of Figure 1, and some of these will be white dwarfs.

The composition of the PHL color classes as regards white dwarfs and F and G subdwarfs is then as follows:

Most of the white dwarfs occur in PHL Table II. The overwhelming majority of the objects in PHL Table III and IV (color classes II and III) are F and G subdwarfs. There

TABLE 3*

WHITE-DWARF CANDIDATES CHOSEN ON THE BASIS OF PROPER MOTION ALONE

A FROM PHOTOMETRIC LIST OF TABLE 1			B ADDITIONAL FROM ASTROMETRIC LIST OF PHL, TABLE II OBJECTS		
PHL	μ_T	$\mu_T/0\overset{''}{.}013$	PHL	μ_T	$\mu_T/0\overset{''}{.}013$
1018	$0\overset{''}{.}093$	7 2	1033	$0\overset{''}{.}049$	3 8
1019	165	12 7	1075	080	6 2
1023	062	4 8	1111	054	4 2
1028	093	7 2	1124	049	3 8
1031	081	6 2	1129	073	5 6
1050	.196	15 1	1177	051	3 9
1112	107	12 1	1217	052	4 0
1176	0 061	4 7	1219	0 093	7 2

* No spectra are available for these objects The white-dwarf classification is based on the motions

are exceptions. Besides those noted above, it is known that PHL 2871 (3C 9) and PHL 3740 are of color class II, and PHL 5200 and 6638, discussed by Scheuer and Wills (1966), are bright in $U - B$ and lie near the black-body line, but these exceptions form only a small percentage of PHL Tables III and IV.

The nature of the remaining objects which scatter near the black-body line and which have small proper motions is now a question. A few can, of course, be white dwarfs of small transverse motion, but all of them cannot be of this type for the following reasons:

a) Five of the objects (PHL 1049, 1127, 1213, 1222, and 3424) fall above the black-body line in Figure 1 in a region nearly devoid of white dwarfs (Eggen and Greenstein 1965, Fig. 6).

b) Some of the objects vary in light. We have taken a new Schmidt plate of the field on 103aO emulsion and have blinked this against the original *Sky Survey* plate. All of the forty-four objects of color class I were marked and examined. PHL 1027, 1065, 1106, 1194, and possibly 1070 vary in light from 0.4 to 1.0 mag between the plates. The absolute mean motions of these variables are only $\langle \mu_x \rangle = -0\overset{''}{.}001$ and $\langle \mu_y \rangle = +0\overset{''}{.}001$.

Because quasi-stellar radio sources (QSS) are known to possess properties (*a*) and (*b*) and also have vanishingly small proper motions (Luyten 1963; Jeffreys 1964; Luyten and Smith 1966*a*, *b*; Sanders 1966), we tentatively identified the objects in question as "radio-quiet" QSS, i.e., QSG. This is suggested not only by the present data but also by an earlier discussion of BSO 1, Ton 256, and Ton 730 (Sandage 1965), and by the subsequent identification of PHL 938 (Kinman 1966), Ton 1530, and Ton 1542 (Hiltner, Cowley and Schild 1966) with QSG. This conclusion is strengthened by Scheuer and Wills' (1966) identification of 4C objects with PHL entries, and by Berger's finding (1965) that PHL 2871 coincides with 3C 9.

A list of fifteen QSG candidates was drawn up from Table 1 using the following criteria: (1) the ratio of total proper motion to mean error ($\pm 0''.013$) must be less than 3; and (2) the object must lie near the black-body line. Fourteen additional candidates were added from the complete astrometric list (Luyten and Smith 1966*a*) for those objects of color class I which satisfy condition 1 but for which no photometry exists. We did not expect all of these objects to be QSG, but certainly if QSG exist they would be in this candidate list.

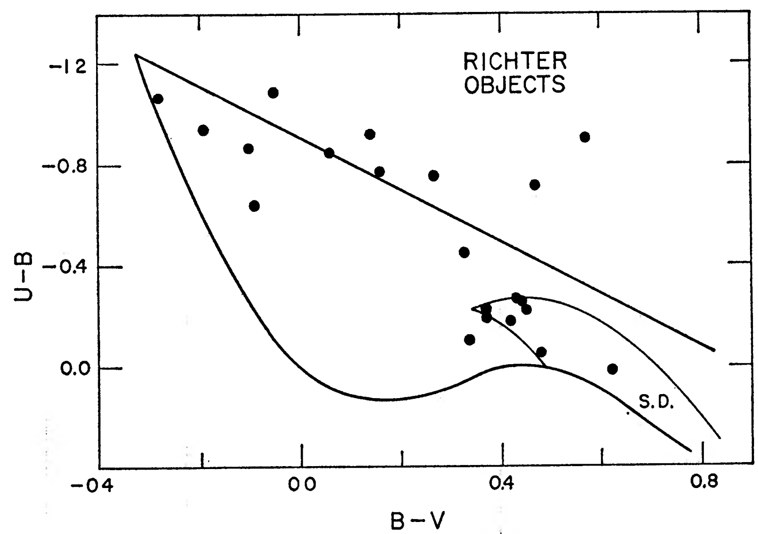

FIG. 2.—Same as Fig. 1 but for the Richter-Sahakjan objects taken from Table 2

Spectra were obtained for twenty-seven of the candidates. The results, discussed in the next section, show indeed that there is an appreciable component of highly redshifted blue, stellar-like objects in Tables II and III of the PHL, together with real stars of the white-dwarf and U Gem class.

A less complete analysis is available for the twenty-one objects in the Richter-Sahakjan list in their M3, II field. Figure 2 shows the two-color diagram. The distribution is similar to that of Figure 1 except that the percentage of subdwarfs is greatly reduced. This is because Richter and Sahakjan have listed only the more extreme ultraviolet-excess objects determined by iris photometry on their plates. The percentage of objects which lie above the black-body line is greater than in Figure 1, which shows that the potential QSG-candidate ratio is high in the RS list. The best two QSG candidates are RS 12 and RS 13, which fall well above the line. Less certain candidates are RS 7, RS 20, RS 28, and RS 31. Without benefit of proper motions we cannot cleanly separate the WD and QSG candidates as was done in the PHL field. But, if we assume that an equal number of QSG occur above and below the black-body line (Sandage 1965, Fig. 1), we obtain a minimum number of four QSG candidates in the twenty-one-star sample and a maximum number of twelve. Adopting six candidates gives 20 per cent of the entire RS list as possible QSG. Spectra are not yet available to test this prediction, but observations will be attempted during the coming observing season.

IV. SPECTRA

Spectrograms of twenty-seven candidate objects were obtained with the 200-inch telescope using a grating spectrograph operating at 400 Å/mm. The plates were baked Eastman IIaO and IIaD, giving a spectral range of λλ 3190–5000 Å and λλ 3190–6500 Å, respectively. Ten of the candidates are definitely confirmed as QSG. In three objects (PHL 1127, 1194, and 3424), two or more broad emission lines are present, identified with Ly α (1216), N v (1240), Si IV (1403), C IV (1550), Mg II (2800), and [O II] (3727). These lines give redshifts of $\Delta\lambda/\lambda_0 = 1.990$, 0.298, and 1.847, respectively. Reproductions of the spectra of these three objects are shown in Figure 3 (Plate 4).

Equally certain QSG are PHL 1027, 1070, 1072, 1186, 1222, 1226, and 3375, where one or more broad emission lines occur at peculiar wavelengths, but where the data are not yet sufficient for a redshift determination because most of the plates were IIaO and do not extend into the red region.

PHL 1092 is less certain as a QSG because only a single, moderately narrow emission line appears at λ 3904 Å. There is also a slight suggestion of Hβ at λ 4865, but this is marginal at best. If Hβ is actually present, one could suspect our wavelength measurement of the strong line, although two plates gave λ 3899 Å and λ 3909 Å, for a mean of λ 3904 Å. These results suggest that the wavelength cannot be as small as λ 3889 of He I at rest. We therefore prefer to classify PHL 1092 as a possible QSG rather than a star, in which case the observed line need not be identified with He I (3889) and Hβ would be considered to be absent.

TABLE 4

SPECTRAL TYPES FOR 27 PHL OBJECTS IN THE 1:36+6° FIELD

Object (PHL)	Type	Object (PHL)	Type	Object (PHL)	Type
1007	DA	1079	DA	1194	QSG
1024	DA	1092	QSG?	1196	DB
1027	QSG	1105	DA	1213	DB
1049	C	1114	C	1222	QSG
1053	C	1119	C or DB?	1226	QSG
1058	DA	1127	QSG	1236	DB
1065	U Gem	1139	DA	1237	DA
1070	QSG	1141	C	3375	QSG
1072	QSG	1186	QSG	3424	QSG

Five objects (PHL 1049, 1053, 1114, 1119, and 1141) have continuous spectra. Four of them could be white dwarfs of class DC, but PHL 1049 cannot be of this type because of its anomalously high position in the $U-B$, $B-V$ diagram. Alternatively, the objects could be QSG with spectra like 3C 93 and 3C 216, where no lines have yet been detected.

The variable star PHL 1065 shows broad Hβ, Hγ, Hδ, and Hε emission lines at rest. It may be a U Gem variable at a distance of about 600 pc [$M_V \simeq +7.5$ after Kraft and Luyten (1965); $V = 16.6$].

The remaining ten objects appear to have ordinary white-dwarf spectra—seven of class DA, where only broad hydrogen lines of Hβ through Hε are visible, and three of class DB, where shallow, broad He absorption lines are seen at λ 4471 and λ 4026.

Spectra were not obtained for two objects (PHL 1106 and 3632) in the candidate list.

Table 4 lists all objects for which spectra are available. In summary, the division of types of the twenty-seven objects is eleven positive or probable QSG; five continuous spectrum objects, four of which could be either DC white dwarfs or continuous spectra QSG, and one (PHL 1049) possible lineless composite star or a continuous-spectrum

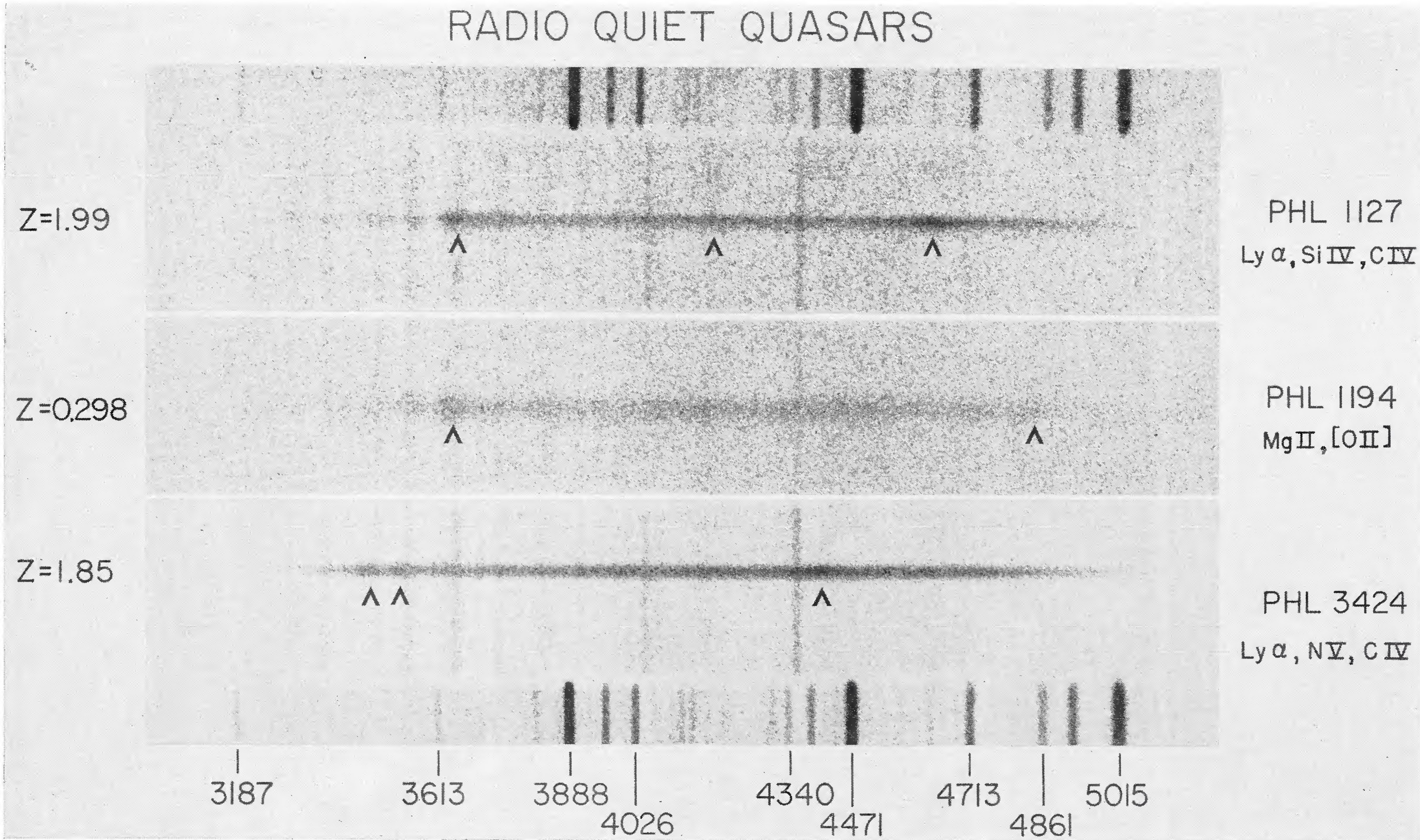

FIG. 3.—Spectra of PHL 1127, 1194, and 3424 taken with the prime-focus spectrograph of the Hale reflector. The comparison arc is He. Emission lines of Ly-α (1216), N V (1240), Si IV (1403), C IV (1550), and [O II] (3727) are clearly visible. Numerous airglow lines cross the spectra. The increasing intensity of these nightsky features is due to the approaching sunspot maximum. Redshifts are 1.99, 0.298, and 1.85, respectively. Original dispersion was 400 Å/mm.

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QSG; and ten white dwarfs. Of the two objects left to be studied, PHL 1106 is a prime QSG candidate because it varies in light. There is, of course, a possibility that it is a U Gem or SS Cyg star (Haro 1959; Luyten and Haro 1959; Haro and Chavira 1960).

V. THE SURFACE DENSITY OF QSG TO $B = 18$ MAG

An *absolute minimum* value of the surface density, S, is obtained by assuming that our ten definite QSG are the only ones that exist in this field. The search area is about 40 sq deg, giving $S(\text{min}) = 0.25$ QSG/sq deg. But this must be a considerable underestimate because we have neglected (1) the contribution of the two candidate objects whose spectra are not yet known; (2) the one possible QSG (PHL 1092) whose redshift is not established; (3) the five continuous-spectrum objects, some of which could be QSG; (4) the contribution from color class II object which were not included in the candidate list; and (5) the incompleteness of the PHL catalogue itself. Neglecting item 5, we can obtain a *maximum* surface density by assuming that there are eleven probable QSG by spectra, perhaps another two from the continuous-spectrum objects (PHL 1049, 1053, 1114, 1119, and 1141), one from the two unobserved objects in the candidate list, and 5 per cent of the 155 objects in PHL Table III—a percentage judged from the three objects which scatter near the black-body line out of thirty-one photometrically sampled from PHL Table III (giving 10 per cent as photometric candidates), and assuming that half of these will be white dwarfs. The possible number of QSG in our field is then twenty-one in 40 sq deg, or $S \simeq 0.5$ QSG/sq deg to the limit of the PHL at $B \simeq 18$ mag (see Appendix). It seems more reasonable, however, again neglecting the incompleteness of the PHL, that the actual value may be closer to 0.4 QSG/sq deg.

We can also estimate the surface density of possible QSG in the Richter-Sahakjan field. The discussion in § III shows that a minimum of four and a maximum of twelve possible QSG exist in our twenty-one-star photometric sample. There are fifty-three objects in the RS list, giving minimum and maximum numbers of ten and thirty QSG to the optical limit of $B \simeq 19.7$ (see Appendix). The RS search area is 10 sq deg, giving $S(\text{min}) = 1$ QSG/sq deg, and $S(\text{max}) = 3$ QSG/sq deg. These values are higher than that for the PHL field by a factor of perhaps 5. However, the RS search reaches 1.6 mag fainter than the PHL, and since it is known that the number of blue objects increases approximately like a constant density law ($\log N(m) \propto 0.6\, m$), as first derived by Luyten (1958) and later by others, we expect a factor of about 9 between the PHL and RS lists, which is reasonably close to our estimated value.

Our present value of S for QSG in the PHL catalogue is very much higher than the surface density of radio QSS. The systematic optical identification of radio sources in the 3C R catalogue (Longair 1965; Véron 1965; Wills and Parker 1966; Wyndham 1966; and others) gives about 30 per cent of the 3C R sources as QSS. A total of about 100 radio QSS to 9 flux units at 178 Mc/s in the northern hemisphere from $\delta = +90°$ to $\delta = -5°$ over an area of 22425 sq deg requires that $S = 0.0045$ QSS/sq deg, which is about 100 times smaller than our estimate of 0.4 QSG/sq deg to $B = 18$ mag. The significance of this is discussed in the next section.

VI. THE MEANING OF "RADIO QUIET"

As far as is known, the QSG are identical to radio QSS in all optical properties. They differ only by an absence of radio emission to 9 flux units at 178 Mc/s. We believe that the QSG are actually QSS of small absolute radio power near the lower end of the radio-luminosity function. They have remained undetected only because radio telescopes of sufficient power are not yet available.

Figure 4 presents the evidence for this view. Plotted is the log of the absolute radio power in ergs/sec as ordinate, against distance modulus $m - M$ as abscissa for all radio galaxies and QSS whose redshifts were known to June, 1966. The k correction has been applied to the apparent radio flux, and L_R was computed in the usual way from this flux, the redshift, a Hubble constant of 100 km/sec Mpc, and $q_0 = +1$.

Although the diagram shows many interesting features (Sandage 1967), we emphasize here only the effect of observational selection, which *apparently* causes L_R to increase as the square of the redshift. This, of course, is due entirely to the fact that most of these objects have been identified optically from the 3C R catalogue, which has a well-defined flux limit at 9 f.u. at 178 Mc/s. This means that all the points must lie above this limiting line, which indeed forms the lower envelope of the distribution. Any QSS (open triangles in Fig. 4) with $\log L_R \geq 0.4\,(m - M) + 27.4$ will not be observed as a *radio object* but will appear as a "radio quiet" QSG as long as radio catalogues with flux-density limits of 9 f.u. at 178 Mc/s are searched for optical identifications. Similar statements apply for fainter L_R values if fainter limits of radio flux density are reached. Consequently, the entire area of Figure 4 below the relevant limiting flux-density ine is the domain of the optical astronomer in his search for QSG.

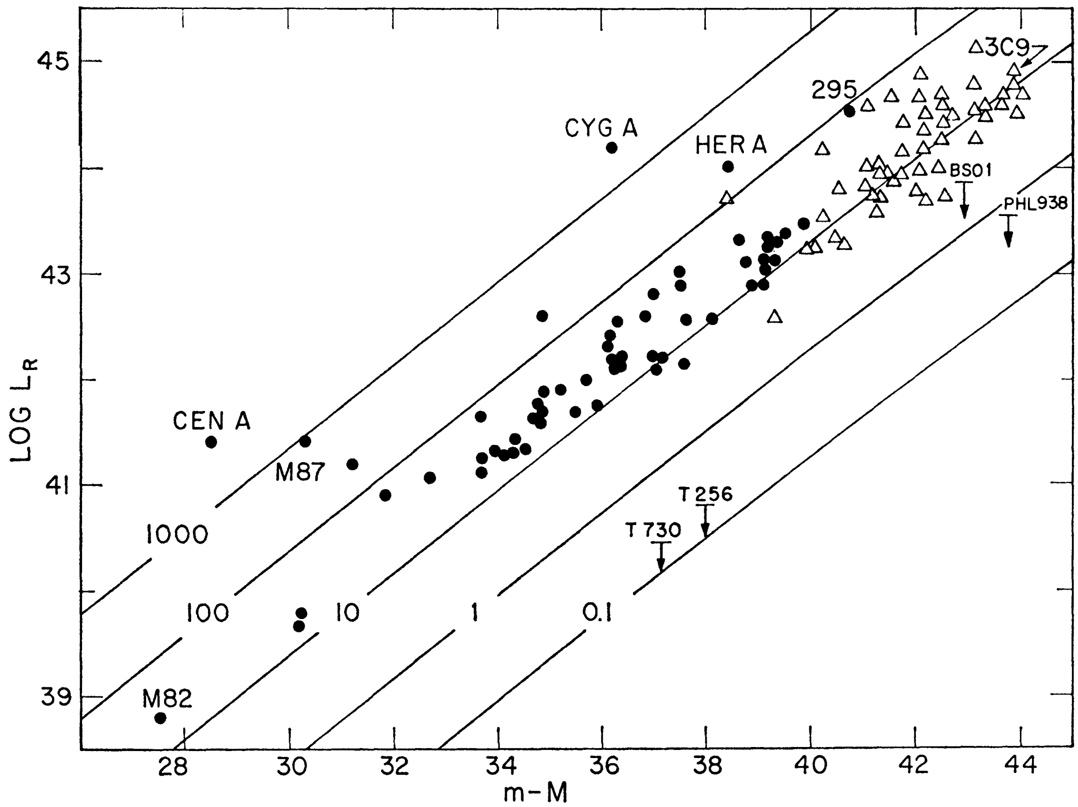

FIG. 4.—The *apparent* correlation of absolute radio power with distance modulus, showing the effect of observational selection in the optical identification of radio sources. The domain of the QSG is below the 9-flux-unit line for $m - M \geq 38$. *Filled circles*, radio galaxies; *triangles*, QSS.

The statement that QSG are 100 times more frequent than QSS to $B \simeq 18$ mag means only that the radio luminosity function $\phi(L_R)$ is such that 100 times more quasars lie below the 9 f.u. line than above. We expect that many of the QSG will be detected as radio sources when the radio flux limits are pushed to lower levels.

VII. THE FREQUENCY OF WHITE DWARFS

A more extensive study of the present kind should be capable of improving the statistics on white dwarfs. The present data are not complete enough for a significant discussion of the space density, but we can estimate the surface density of objects found so far. Table 3 lists sixteen first-class candidates for white dwarfs, based on the proper motion alone. Table 4 lists ten more white dwarfs identified by spectra. Four more (PHL 1053, 1114, 1119, and 1141) *might* be DC white dwarfs, and an additional two objects from the QSG candidate list could conceivably be white dwarfs with small transverse motion, but we believe that a more realistic estimate is one. Finally, probably 5 per cent of the catalogued objects of color class II (PHL Table III) may be white dwarfs by the argument of § V. This gives a total of thirty-nine white dwarfs in 40 sq deg, or about 1 WD/sq deg to $B = 18$. Surveys to fainter magnitudes should greatly increase this value because at $B = 18$ we reach, on the average, only to about 160 parsecs ($\langle M_B \rangle \simeq +12$), and the white dwarfs must extend well beyond this limit.

VIII. SUMMARY AND DISCUSSION

Using photometry, astrometry, and spectroscopy, we have identified six classes of objects among the fainter PHL entries in the $1{:}36 + 6^\circ$ field.

1. The bulk of PHL Tables III and IV is composed of F and G subdwarfs, similar to main-sequence stars in globular clusters. If the distribution of objects within each color class of Table 1 represents the entire PHL, then 89 per cent of the objects of color classes II and III are subdwarfs. The catalogue, taken as a whole, contains 80 per cent subdwarfs, but none appears in the bluest color class (PHL Table II). The average photometric distance of these stars is about 3000 pc, ranging from 1500 pc to 5400 pc as determined from the V, $B - V$, and $\delta(U - B)$ values using the normal calibration methods with blanketing corrections.
2. A few horizontal-branch stars are present, constituting perhaps 10 per cent of the PHL Table II objects.
3. A probable RR Lyrae variable (PHL 7332) is present in the photometric sample, found in the experiment discussed in § III. The classification is based on the color ($V = 17.33$, $B - V = +0.42$, $U - B = +0.04$), which is normal for this type of variable.
4. Many white dwarfs are present. They are largely confined to PHL Table II objects (color class I), although a few do occur in PHL Table III (color class II). An estimated number of thirty-nine such objects gives about 10 per cent of the entire catalogue as white dwarfs, and a surface density of about 1 WD/sq deg to $B \simeq 18$. White dwarfs constitute perhaps 70 per cent of PHL Table II (color class I) objects.
5. One probable U Gem star (PHL 1065) is present in our photometric sample.
6. We have positively identified ten radio-quiet QSS, i.e., QSG, in the 40 sq deg field. There may be as many as twenty-one such objects in this field, but a more conservative estimate is sixteen. Most of these objects will be in PHL Table II (color class I), but a few are in PHL Table III and occasionally in Table IV. A maximum of 35 per cent of PHL Table II could be of this type, but, again, a more conservative estimate is 20 per cent. At least 5 per cent of PHL Table III objects may be QSG.

The surface density of 0.4 QSG/sq deg is about 100 times greater than that for *radio* QSS from the 3C R catalogue, but this factor will undoubtedly decrease when radio surveys reach fainter flux limits because QSG are probably radio emitters at relatively low power levels.

APPENDIX

SYSTEMATIC MAGNITUDE AND COLOR CORRECTIONS TO THE PHL AND RICHTER-SAHAKJAN PHOTOGRAPHIC PHOTOMETRY

Photoelectric colors and magnitudes now exist for seventy-nine objects in the PHL fainter than $m_{pg} \simeq 16$, and for twenty-one objects in the RS list. The overlap sample with PHL objects consists of sixty-nine entries from Table 1 of the present paper, eight entries from the objects identified by Scheuer and Wills (1966) as coincident with 4C radio sources (photometry given by Sandage 1966), PHL 938 (Kinman 1966), and PHL 2871, which corresponds to 3C9 (Berger

1965). In addition, sixteen brighter PHL stars have photoelectric values (see Lynds and Villere [1965] for the list). The color corrections differ between the bright and faint sample, as discussed below.

Figure 5 is the comparison of the photoelectric B values with the tabulated PHL m_{pg} values for the seventy-nine faint objects. Two objects (PHL 938 with $m_{pg} - B = -0.58$, and PHL 7332 with $m_{pg} - B = -0.55$) are not shown because they fall far from the general distribution. As mentioned earlier, PHL 7332 is a variable of amplitude at least 1 mag, and we therefore suspect that PHL 938 may also vary because of its large $m_{pg} - B$ value.

A systematic error exists in the PHL magnitude scale, ranging from $m_{pg} - B \simeq 0.0$ at $m_{pg} = 16.5$ and rising, in the mean, to $m_{pg} - B = +0.8$ at $m_{pg} = 18.9$. This shows that the catalogue limit is about $B = 18.1$ rather than the tabulated value of $m_{pg} = 18.9$.

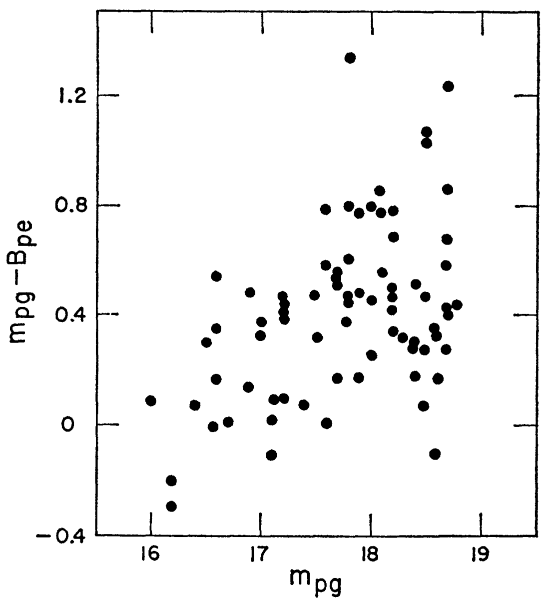

FIG. 5.—Comparison of photographic and photoelectric magnitudes for 79 objects in the PHL catalogue fainter than $m_{pg} = 16$. Unplotted points for 16 PHL objects between $m_{pg} = 12$ and $m_{pg} = 15$ show no systematic magnitude correction greater than 0.1 mag in this range.

Comparison of the photoelectric and photographic *colors* of the PHL objects fainter than $B \simeq 16$ mag shows that the catalogued values average 0.27 mag too blue in $B - V$ and 0.44 too red in $U - B$. The $U - B$ correction is similar to but slightly larger than that discussed by Haro and Luyten, where they estimated a factor of $\frac{3}{2}$ to correct their tabulated $U - B$ values. As shown in Figure 1, these color corrections are sufficient to move the PHL Table II objects from their tabulated position in the two-color diagram into the white-dwarf-QSS domain. Therefore, the dilemma concerning the colors of PHL-4C objects discussed by Scheuer and Wills (1966) is removed.

The magnitude equation for the sixteen brighter overlap objects tabulated by Lynds and Villere (1965, Table 1) appears to be systematically zero to within 0.1 mag. The same is true for the color equation in $B - V$ for these bright objects. The $\Delta(B - V)$ is only -0.03 mag, with the PHL values being too red (which is the opposite sense from the fainter objects), and $\Delta(U - B) = -0.56$ (the PHL values are again too red). This illustrates two points: (1) There appears to be a systematic difference in the $B - V$ correction between bright and faint objects in the catalogue. As just mentioned, the tabulated $B - V$ colors for objects brighter than $B \simeq 15$ are systematically correct, but they are too blue by about 0.3 mag for the fainter objects. (2) The fundamental change in the distribution of bright and faint objects over the face of the $U - B$, $B - V$ diagram, pointed out by Klemola (1962) and by Sandage (1965, Fig. 2), is consistent with these results.

We wish to point out in passing that this color correction makes uncertain part of the analysis of Lynds and Villere (1965) in their hypothetical composition of the PHL catalogue. The color boundaries of the fainter stars are not as they postulated. Their suggested composition of the luminosity function and their subsequent $N(m)$ calculation therefore needs some revision. For example, they have no F- and G-type subdwarfs, but, in fact, the bulk of Tables III and IV of the PHL appear to be composed of such stars. Similar difficulties in the Lynds-Villere luminosity function are implicit in the analysis of star counts in high latitudes by Luyten (1960), where he used a similar luminosity function and obtained results which contradicted the observed star count and color data obtained with the Palomar Schmidt.

The comparison of the Richter-Sahakjan photometry with our Table 2 shows that the RS magnitude scale is systematically too faint by $\Delta B \simeq 0.15$ mag until $B_{\rm RS} \simeq 17.5$, at which point the sense of the correction reverses, reaching a value of about 0.4 too bright at $B_{\rm RS} \simeq 18.5$. If this trend continues to the limit of their list, one estimates that the true limiting magnitude in the M3, II field may be as faint as $B \simeq 19.7$.

The comparison of the photoelectric and RS colors shows that there is a small or negligible *systematic* correction to $B - V$, but that the scatter in the residuals is about 0.5 mag in $B - V$ and 0.6 mag in $U - B$. This is large enough to cause concern on Richter's statistics of the number of objects which lie above the black-body line in his fields (Richter 1965, Fig. 3). Nevertheless, the Richter lists are valuable because they are pre-selected for the most ultraviolet objects and must, therefore, contain a relatively rich population of QSG candidates.

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