THE ASTROPHYSICAL JOURNAL, Vol 155, March 1969

ON THE NATURE OF FAINT BLUE OBJECTS IN HIGH GALACTIC LATITUDES. II. SUMMARY OF PHOTOMETRIC RESULTS FOR 301 OBJECTS IN SEVEN SURVEY FIELDS

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Received June 19, 1968

ABSTRACT

The results of *UBV* photoelectric photometry for 301 blue objects in intermediate to high galactic latitudes are summarized. The magnitudes of all but three of the objects lie in the range $14\ 5 < V < 19.2$. The majority of the bluer objects lie near the black-body line. They generally avoid the luminosity class III–VI line of the $U - B$, $B - V$ diagram. The major constituents appear to be white dwarfs, quasi-stellar objects which are radio quiet to 9 flux units at 178 MHz, and F to G subdwarfs. Nine possible horizontal-branch stars in the range $0.05 \leq B - V < 0.25$ are present in the sample.

Estimates from three sets of data, including a first photoelectric study of faint blue objects with $19 < B < 22$ in SA 57, suggest that the number of QSOs per square degree brighter than magnitude B is at least as high as $\log N(B) \simeq 0.75\,B - 14.0$. The tentative nature of this first determination is stressed. If correct, there are of the order of 10^7 QSOs over the entire sky brighter than $B = 22$.

I. A NEW SURVEY PROGRAM

It was shown in Paper I of this series (Sandage and Luyten 1967) that radio-quiet QSOs and white dwarfs are the two major constituents of the bluest catalogued objects in the PHL field at 1^h36^m, $+6°$ (1855). The surface density of QSOs brighter than $B = 18.1$ was estimated to be ~ 0.4 QSO (sq deg)$^{-1}$, which is about 100 times greater than that expected for radio QSSs to the flux limit of the 3CR Catalogue (Bennett 1962). The surface density of white dwarfs was about 1 WD (sq deg)$^{-1}$ to the same magnitude limit. Minor constituents of the sample were horizontal-branch stars with $0.0 < B - V < 0.25$, RR Lyrae variables, and U Gem stars.

The answer to the nature of the faint blue objects in intermediate to high galactic latitudes depends on whether the results for this particular field can be generalized to other regions of the sky. We have therefore begun a wider study following the methods of Paper I. Six new blue-star survey fields, listed in Table 1, were chosen in the north galactic hemisphere so as to cover an appreciable range of galactic latitude in two separate zones of galactic longitude, separated by about 180°. The ultimate goal is (1) to study the isotropy of the distribution of blue objects, and (2) to determine the way in which the number of QSOs increases with successively fainter magnitude limits.

Three-image plates were taken of each field with the 48-inch Schmidt, using the filters and exposure times given by Haro and Luyten (1962). The plates have been searched for images which have an ultraviolet excess, and catalogues have been published for each of the six fields (Luyten and Sandage 1966; Luyten, Anderson, and Sandage 1967*a*, *b*, *c*, 1968*a*, *b*). The objects in each catalogue were separated into three color classes on the basis of the ratio of intensities of the ultraviolet to the blue images, with the blue-to-yellow ratio as a control. Objects of color class I have the largest ultraviolet-to-blue ratio, while those of class III have the smallest.

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II. PARTIAL PHOTOMETRIC RESULTS

As a first step in assessing the nature of the catalogued objects, we have begun photoelectric *UBV* photometry in the 8^h48^m and 15^h10^m fields. Although from photometry alone we cannot uniquely separate all white dwarfs from radio-quiet QSOs, we can find how many objects lie above the black-body line in the $U - B$, $B - V$ diagram. Past spectrographic studies have shown that a high percentage of such objects are QSOs.

In addition to the two mentioned survey fields of Table 1, *UBV* photometry has been carried out in five other fields which had previously been searched for blue objects. These include (1) the two original interloper fields (Sandage and Véron 1965) centered near $l^{II} = 108°$, $b^{II} = +81°$ and $l^{II} = 73°$, $b^{II} = +61°$; (2) the PHL field 1^h36^m, $+6°$ (1855) centered at $l^{II} = 145°$, $b^{II} = -54°$ which was partially studied in Paper I and is supplemented here with new data for additional objects; (3) the PHL field 0^h48^m, $+12°$ (1855) centered at $l^{II} = 124°$, $b^{II} = -50°$; and (4) the Richter and Sahakjan (1965) M3 II field near $l^{II} = 35°$, $b^{II} = +79°$.

TABLE 1

COORDINATES OF THE SIX NEW SURVEY FIELDS

Name	α(1855)	δ(1855)	l^{II}	b^{II}
O/E 62	8^h48^m	+18°	210°	+35°
O/E 25	9 32	+24	207	+47
O/E 58	10 24	+18	223	+56
O/E 99	11 16	+30	202	+71
O/E 64	12 34	+30	170	+87
O/E 87	15 10	+24	35	+57

A total of 301 blue objects have so far been measured in the *UBV* system with the 200-inch Hale reflector. The photometry is not yet complete in any given field, although close to 80 per cent of the available objects in color class I have been measured in the 1^h36^m and 8^h48^m areas. Although the final objective of the project cannot be realized for several years because complete spectrographic data must be obtained, the photometric results now in hand are of sufficient interest in themselves for a preliminary discussion.

Figure 1 shows the distribution of the available objects in the $U - B$, $B - V$ diagram. All but three of the 301 objects are fainter than $V = 14.5$ mag. Measurements have been made to the limit of the present catalogues at $V = 19.2$ for the deepest survey. No pre-selection has been made according to the initial estimate of $u - b$ within color class I, and the distribution in Figure 1 should be unbiased for these bluest objects.

The most pronounced feature of Figure 1 is the near absence of stars along the luminosity class III–VI line for $B - V$ values bluer than 0.0. The objects with the most negative values of $U - B$ in the present sample are concentrated near the black-body line, in marked contrast to the known color distribution of most of the brighter high latitude blue stars with $V \lesssim 14.5$. Our present results confirm the conclusion drawn from earlier studies (Iriarte 1959; Klemola 1962; Sandage 1965, Fig. 2) that there is a major difference in the distribution of $U - B$, $B - V$ colors between stars brighter and fainter than $V \simeq 14.5$. Although the transition is not abrupt, objects fainter than this limit generally avoid the luminosity class III–VI line, while many of the brighter objects lie along it.

Figure 1 shows that we also have an appreciable population of subdwarfs in the material. Whether or not subdwarfs are listed in color class I depends critically on the ultraviolet transparency for any particular three-image plate. Because the ratio of the u to the b image determines the estimated color class in the catalogues, subdwarfs with high

$\delta(U - B)$ excess values will be included in color class I on those plates where the effective u/b exposure ratio is not quite standard. On more optimally exposed plates, these stars would normally be catalogued in class II or III.

The subdwarfs in Figure 1 come mostly from two fields. In Paper I, a special effort was made to observe class II and III objects in the 1^h36^m field, and these stars are included here. In the 8^h48^m field, the color balance of the u and b images on the plate evidently permits objects with $(U - B)_{p.e.} \leq 0.0$ to be listed in color class I, and the subdwarfs so observed are plotted. No color class II and III objects have yet been measured in the 8^h48^m field, but, in view of the results of Paper I, we expect that most of the redder objects in this field will also be subdwarfs.

The subdwarfs in our present sample all have apparent magnitudes between $V = 15.6$ and $V = 18.4$. As in Paper I, these stars range in distance from about 1500 to $\sim$5000 pc. Their pronounced ultraviolet excess is consistent with the expectation that stars in

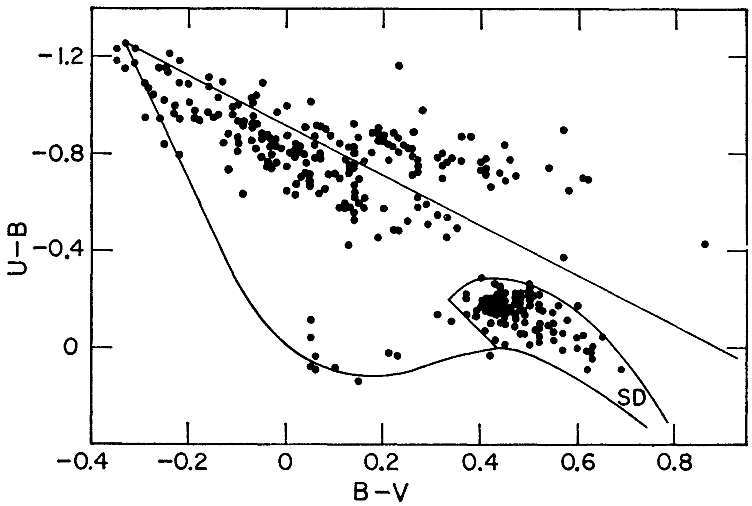

FIG. 1.—The $(U - B, B - V)$-diagram for 301 blue objects in seven survey fields discussed in the text. The measuring errors are generally less than ± 0.03 mag in each color. The region occupied by Population II F–G subdwarfs is indicated.

the galactic halo with $Z \gtrsim 1000$ pc have a low metal abundance relative to Hyades stars (Eggen, Lynden-Bell, and Sandage 1962; Eggen 1965). Because the halo extends beyond 10 kpc, albeit with a steep density gradient (Becker 1967; Fenkhart 1967), we must expect to find subdwarfs with $M_V \simeq +4$ in future surveys which reach as faint as or fainter than $V \simeq +21$ mag, although the log $N(m)$ function will, of course, increase much more slowly than $0.6m$ at these faint magnitudes.

There are nine stars in Figure 1 in the color range $0.25 > B - V \geq 0.05$, $+0.15 > U - B \geq -0.11$. These could be either RR Lyrae stars measured at random phases of their light curves or horizontal-branch stars similar to those in globular clusters (see, e.g., Sandage and Walker 1966, Fig. 5). The two faintest of our sample stars occur in the 8^h48^m field at $V = 17.8$. If $M_V \simeq +0.5$, their distance is 29 kpc, which gives a height above the plane of 17 kpc for this region at 35° latitude.

III. DETECTION OF QUASI-STELLAR OBJECTS

The photometry is only the first phase of the over-all problem. Maarten Schmidt has begun the more arduous task of obtaining spectra of all candidate objects in the 8^h48^m and 15^h10^m fields of Table 1. The photometric and spectrographic details of each field will be published, together with finding charts, as each field is completed. One of Schmidt's preliminary results is that in the two mentioned survey fields virtually all the new objects above the black-body line are QSOs. He has further shown that many of the objects below the black-body line are also QSOs in these two fields, although, as expected (Lynds and Villere 1965; Kinman 1965; Sandage and Luyten 1967), there is an appreciable contamination of the sample by white dwarfs. Schmidt's result is consistent with the statistics of radio QSOs (Sandage 1967, Fig. 1), where about equal numbers of these objects are above and below the black-body line in the color range $0.0 < B - V < 0.7$.

Similar results have been obtained by Lynds and Braccesi in a parallel study of one of the original "interloper" fields at $13^h + 36°$. In this work spectra were obtained of seventeen candidate objects for which both *UBV* photometry and near-infrared photography gave indications of QSO-like photometric properties (Braccesi, Lynds, and Sandage 1968). All the candidates above the black-body line which were observed spectroscopically proved to be radio-quiet extragalactic objects with redshifts ranging from $\Delta\lambda/\lambda_0 = 0.060$ to $\Delta\lambda/\lambda_0 = 2.084$.

A preliminary indication that the number $N(m)$ of QSOs brighter than apparent magnitude m is a steep function of m is available from these two sets of data. Braccesi's catalogue of objects which have both an infrared and an ultraviolet excess in the $13^h + 36°$ field contains 300 entries in 42 square degrees to $B = 19.4$. The spectroscopic evidence available from an unbiased sample of these candidates (Braccesi, Lynds, and Sandage 1968) suggests that most, but not all, of these special candidates will be QSOs. Taking into account that not all QSOs show an infrared excess, we estimate that a conservative value of the QSO surface density to $B = 19.4$ is 5 (sq deg)$^{-1}$ in this field. This is to be compared with 0.4 QSO (sq deg)$^{-1}$ to $B = 18.1$ obtained for the 1^h36^m field in Paper I.

A third set of data is available to fainter magnitude limits. In a study of the blue objects in the range $19.4 < B < 22$ in SA 57, Becker (1968) has isolated fifteen objects with $B - V < 0.4$ mag in an area of 0.042 sq deg on 200-inch plates exposed in two colors. Becker found that two of the objects are variables and are, therefore, excellent candidates for QSOs. Photoelectric photometry in the *UBV* system has been obtained by Sandage for twelve of Becker's fifteen objects. In addition to the two variables, two other objects lie above the black-body line, and three others lie just below this line in the region of white dwarfs and QSOs. Some of these latter three may be QSOs, and there may be additional QSOs with $B - V > 0.4$ which were not measured. In spite of the obvious difficulties with the statistics of small numbers, it seems conservative to take an estimate of four QSOs in 0.042 square degrees, giving a lower limit of ~ 100 QSO (sq deg)$^{-1}$ brighter than $B = 21.4$. The fact that at least four objects whose photometric properties resemble QSOs were found in this small area points to the probable existence of a sizable population of QSOs to $B \approx 22$.

Although we caution that the three sets of data are highly preliminary, they do suggest that $N(m)$ is a steep function of m for QSOs. The data as they stand, with 0.4 QSO (sq deg)$^{-1}$ to $B = 18.1$, 5 QSO (sq deg)$^{-1}$ to $B = 19.4$, and ~ 100 QSO (sq deg)$^{-1}$ to $B = 21.4$, give $b \equiv d \log N(m)/dm \simeq 0.75$. The uncertainties are such that the constant-density case of $b = 0.6$ is not excluded, but the results are also consistent with Schmidt's finding (1968) that $b > 0.6$ for a smaller, but more homogeneous, sample of positively identified radio QSOs.

IV. DISCUSSION AND CONCLUSIONS

1. Candidates for quasars which are radio quiet to 9 flux units at 178 MHz have been found in all survey fields studied so far that reach limiting magnitudes of at least $B \simeq 18$. Spectrographic data given in Paper I, together with new results by Schmidt, and by Braccesi and Lynds for the new fields studied here, show that most candidates which lie above the black-body line are quasi-stellar objects.

2. Other constituents of the sample of blue objects fainter than $V \simeq 15$ include white dwarfs, subdwarfs, horizontal-branch stars, RR Lyrae variables, U Gem stars, and stars with combination spectra. It appears that all but the white dwarf and subdwarf components are quite minor.

3. The nature of the blue objects changes gradually, but clearly, near $V \simeq 14.5$. Most of the stars brighter than this limit lie near the luminosity class III–VI line of the $U - B$, $B - V$ diagram. Spectrographic studies by many authors (e.g., Slettebak, Bahner, and Stock, 1961; Klemola 1962; Berger 1963; Greenstein 1966; and Sargent and Searle 1968) have shown that the stars in the bright sample have absolute luminosities which range between perhaps $-4 < M_V \lesssim +5$. A similar range has been derived for these brighter stars by Luyten (1956, 1959, 1960, 1963) and by Luyten and Anderson (1962) from the proper motions alone. The spectrographic work shows that this bright star sample is composed predominantly of runaway main-sequence B stars, hot subdwarfs, and horizontal-branch stars. For apparent magnitudes fainter than about $V = 14.5$ we evidently reach so far into the halo for stars of this type that the number of such objects has become negligibly small due to the steep density gradient perpendicular to the plane.

On the other hand, the volume surveyed for white dwarfs, whose absolute luminosities are fainter than $M_V \simeq 10$, begins to become large enough at $V \gtrsim 14.5$ so that stars of this type begin to appear in great numbers and to dominate the sample. The nature of the color distribution in the $U - B$, $B - V$ diagram begins, therefore, to change from along the luminosity class III–VI line to along the black-body line near this magnitude limit.

This result, which we have obtained here from the *UBV* photometric results alone, is similar to that obtained earlier from the proper motion studies. Luyten and Anderson (1962) state in their summary of the results from Papers 1–30 of the *Search For Blue Star* series, "Our conclusion from the proper motions remains as before: among the faint stars in high galactic latitude, genuine white dwarfs constitute an insignificant fraction brighter than $m = 15$, but this fraction may rise steeply for fainter stars."

4. Few QSOs are known brighter than $V \approx 15$, but the number increases rapidly with increasing magnitude, eventually overtaking the white-dwarf population at perhaps $B \simeq 19$.

5. With a strong word of caution concerning the tentative nature of our present statistics, and a reminder that the ultimate purpose of the present program is to improve the data, we can give a first approximation to the $N(m)$ function for QSOs derived from the high latitude fields of 1^h36^m ($b = -54°$); 13^h, $+36°$ ($b = +81°$), and SA 57 ($b = +86°$). The available data are consistent with

$$\log N(B) = 0.75B - 14.0\,, \tag{1}$$

where $N(B)$ is the number of QSOs brighter than magnitude B per square degree. It should be pointed out that this probably gives a lower limit to the actual number of QSOs at any given magnitude because of the conservative nature of our surface density estimates.

If equation (1) is approximately correct, there are of the order of 10^7 QSOs over the entire sky brighter than $B = 22$.

It is a pleasure to thank Dr. Jerome Kristian for reading and commenting on the manuscript.

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