A STUDY OF THE ORION AGGREGATE OF EARLY-TYPE STARS

STEWART SHARPLESS
Yerkes Observatory
Received June 10, 1952

ABSTRACT

A catalogue of spectroscopic and photoelectric observations of 190 members of the Orion aggregate is given. The photoelectric observations were made with the 82-inch and 13-inch reflectors of the McDonald Observatory; the spectrograms were taken with the 40-inch refractor of the Yerkes Observatory. A spectroscopic distance modulus of 8.5 mag. was obtained for the aggregate. This material has also made possible an investigation of the anomalous reddening in Orion, the absolute magnitudes of the O-type stars associated with the aggregate, and the radial distribution of color excess within the Orion Nebula. The high ratio of total to selective absorption found by Baade and Minkowski for the Trapezium stars is found to apply also to other reddened stars in the aggregate; however, their hypothesis of a transparent region in the center of the nebula is not confirmed. The correlation between reddening and the diffuse interstellar features in the spectra of the Orion stars is discussed.

I. INTRODUCTION

Investigations of the great aggregates of early-type stars such as h-χ Persei, the Cygnus region, and Orion have proved to be of considerable importance in the field of galactic structure. The work of Hubble[1] and Baade[2] on extragalactic nebulae has shown that spiral arms consist primarily of just such concentrations of bright blue stars as well as regions of ionized hydrogen and obscuring matter. In these three respects, the Orion aggregate is a typical population I object. Recent results have indicated that a knowledge of the detailed structure of our own galaxy[3] in the vicinity of the sun can be obtained through investigations of the B-star aggregates and the *H* II regions.

Various methods have been employed in the past to obtain the parallax of the Orion Nebula or of the aggregate of early-type stars with which it is associated. Some of them, however, have led to widely differing results. The present investigation is based on a series of spectroscopic and photoelectric observations of the brighter B stars in Orion obtained recently at the Yerkes and McDonald Observatories. These are described in Sections III and IV below. In Sections V and VI the problem of the spectroscopic parallax of the Orion aggregate and of the stars in the immediate vicinity of the nebula is reexamined in the light of these new data.

Photoelectric observations of the colors and magnitudes of B stars in an aggregate which suffer various amounts of interstellar absorption can be used to investigate the relation between reddening and total absorption for the region considered. This problem is discussed in Sections V and VII, and the results are used in evaluating the total absorption for the Orion stars. The color excesses of the stars immersed in the Orion Nebula are also considered in Section VI.

The determination of the absolute magnitudes of the O-type stars has presented a difficult problem because of their scarcity and the fact that they are often associated with dense nebulosity, which makes it difficult to evaluate their interstellar absorption accurately. Since a number of O stars are associated with the Orion aggregate, their absolute magnitudes can be obtained from their colors and magnitudes and the distance modulus of the aggregate. These results are listed in Section V.

A possible explanation of the anomalous reddening in Orion is discussed in Section VIII, and an attempt is made to correlate it with existing observations of the diffuse interstellar features in the spectra of the Orion stars.

[1] *Ap. J.*, **63**, 236, 1926; **69**, 103, 1929.

[2] *Problems of Cosmical Aerodynamics* (Dayton, Ohio: Central Air Documents Office, 1951), p. 185.

[3] Morgan, Sharpless, and Osterbrock, *A.J.*, **57**, 3, 1952.

II. HISTORICAL

The first attempt to obtain the distance of the Orion Nebula was made by Pickering[4] in 1917 and was based on a statistical investigation[5] of the brightness of the stars within about 1° of the nebula. Color indices were found by comparing photographic magnitudes with visual magnitudes determined earlier by Bond. Counts of the blue stars in this region indicated a frequency maximum at 13.0 mag. and a mean magnitude of 10.5. An average spectral type of B3 and a mean absolute magnitude of -1 was assumed for these stars, and a distance of 2000 parsecs was obtained.

Kapteyn,[6] in the same year, investigated the somewhat larger group of B stars, which he designated the "Nebula-group," extending from R.A. 5^h20^m to 5^h40^m and Dec. $-7°$ to $+2°$. A mean parallax for the B stars in several regions outside the Nebula-group was obtained from an analysis of proper motions in the Boss catalogue. The frequency-curves of apparent magnitudes for the Nebula-group and the surrounding regions were then compared, to find the ratio of the parallaxes for the stars within and outside the Nebula-group. From this, a parallax of $0''.0054 \pm 0''.0009$ was adopted for the Orion stars, corresponding to a distance of 185 parsecs.

These two determinations of the distance of the Orion Nebula were discussed by Pickering[7] in 1919. The discrepancy between the two values was attributed primarily to the differences in the selection of the stars considered, since Kapteyn included in his investigation only the brighter B stars surrounding the nebula. The faintness of the stars investigated by Pickering, hence the overestimation of their distance, is probably due to the greatly increased absorption in the region of the nebula and to the fact that he may have included more distant field stars. Adopting more recent values for the absolute magnitudes of the B stars, Pickering revised his value of the parallax of the nebula to $0''.0020$, which corresponds to 500 parsecs. An important result of this investigation was the recognition of the great range of intrinsic luminosity among the B-type stars. The dwarf nature of the variable stars in the nebula was also established in this discussion.

Pannekoek,[8] in 1929, in his investigation of the B stars in the *Henry Draper Catalogue* found a concentration in Orion elongated parallel to the galactic plane from 5^h18^m, $+5°$, to 5^h32^m, $-7°.5$. He distinguished three subgroups centered on ψ Orionis, the "belt," and the "sword" of Orion but assumed that they formed a physically connected system. He ascribed the great differences in apparent brightness of the Orion stars both to differences in intrinsic brightness and to interstellar absorption. From mean absolute magnitudes for the Draper classes he derived an apparent distance modulus of 7.6 mag., corresponding to a distance of 330 parsecs. Plots made by Pannekoek of the distribution of A stars in the Orion region indicate no concentration for those stars brighter than 8.75 mag. but indicate a decided concentration for those between 8.75 and 9.25 mag. For the K stars brighter than 9.25 mag. in this region there appears to be no concentration.

In 1931 the Trapezium cluster[9] was discovered by Trumpler. A photograph, taken in the spectral region from 7000 to 7600 A in order to suppress the nebulosity, showed a small cluster centered on θ^1 Orionis and containing sixty-two stars within a radius of two minutes of arc. Apparent distance moduli were found for sixteen stars in the cluster from their spectral types and apparent magnitudes. A mean absorption of 0.6 mag. was estimated from the observed color excesses. The distance of the Trapezium cluster thus obtained was 500 parsecs. Another determination based on the classification and angular diameter of the cluster yielded a distance of 690 parsecs. The same two methods were then applied to NGC 1981, which lies 1° south of the Trapezium cluster and which was assumed to be at the same distance. A final mean of 540 parsecs was adopted by Trumpler as the distance to the Orion Nebula.

[4] *Harvard Circ.*, No. 205, 1917.

[5] *Harvard Ann.*, Vol. **32**, 1895.

[6] *Ap. J.*, **47**, 146, 1918.

[7] *Pub. A.S.P.*, **31**, 86, 1919.

[8] *Pubs. Astr. Inst. Amsterdam*, No. 2, 1929.

[9] *Pub. A.S.P.*, **43**, 255, 1931.

The Trapezium cluster was later independently discovered by Baade and Minkowski.[10] As compared with other clusters of similar stellar content, it was found to be smaller than average by a factor of about ten. Baade and Minkowski concluded that it is a normal cluster which is blotted out by the obscuring matter of the nebula except for a small region about the Trapezium, i.e., that in the immediate vicinity of the exciting stars the nebula is less opaque than elsewhere. To obtain more data on the optical properties of the nebula, three of the Trapezium stars, θ^1 (A), (C), and (D) Orionis, were investigated spectrophotometrically and the resulting extinction-curves were found to deviate appreciably from those of reddened B stars in other parts of the sky. This peculiarity in the reddening of θ^1 Orionis has been confirmed by the six-color observations of Stebbins and Whitford.[11] Baade and Minkowski analyzed their extinction-curves on the basis of the known optical constants of iron and carbon and found that the effective size of the absorbing particles in the Orion Nebula was larger by a factor of 2 than in other regions. They attributed this to the effect of radiation pressure from the exciting stars which has removed the smallest particles, shifting the frequency maximum to a larger size. A new determination of the distance of the Orion Nebula was later made by Minkowski[12] in the light of this investigation. After making certain assumptions regarding the properties of the interstellar dust in the center of the nebula, the total absorption was estimated, and the resulting corrected distance modulus was found to be 7.38 mag., corresponding to a distance of 300 parsecs.

A study of the Orion region was made by Markowitz[13] in 1948, based on spectroscopic, photometric, and radial-velocity data available at that time. Stars in the central region of Orion, i.e., the region of the "sword" and "belt," were found to have a mean radial velocity of about 9 km/sec greater than the value expected from the solar motion and galactic rotation. Having thus confirmed the existence of an extended cluster of B stars in Orion, he obtained a spectroscopic distance modulus of 8.57 mag. from observations of normally colored stars of spectral types B1–B3 in Orion. This value agrees well with the one found in the present investigation.

It is apparent that the aggregate of B stars in Orion and the stars in the immediate vicinity of the Orion Nebula have often in the past been treated separately, even though there is little doubt as to their physical connection and common distance. In the present investigation an attempt has been made to obtain observations which are as homogeneous as possible of stars throughout the entire region. Special emphasis, however, has been placed on the region within several degrees of the Orion Nebula with regard to both the spectroscopic and the photoelectric observations. The limits of the Orion aggregate have been taken to be from R.A. 5^h00^m to 5^h48^m, and from Dec. $+6°$ to $-8°$.

III. SPECTROSCOPIC OBSERVATIONS

Spectral classifications for many of the B stars in Orion were determined from slit spectrograms taken with the one-prism spectrograph attached to the 40-inch telescope. The dispersion is about 125 A/mm at $H\gamma$. Many of the plates[14] were taken for the Yerkes program of spectroscopic parallaxes. In addition, a special program was undertaken with the same equipment to obtain spectrograms of most of the remaining B stars in Orion brighter than 8.0 mag. and various fainter stars of special interest, particularly in the nebulous regions. Spectral types and luminosity classes were assigned to these stars according to the criteria of the Yerkes *Atlas of Stellar Spectra*.[15] Many of the brighter Orion stars are fundamental O- and B-type standards in the MKK system.

Special attention was given to the region 5° in diameter centered on the Orion Nebula.

[10] *Ap. J.*, **86**, 119 and 123, 1937.

[11] *Ap. J.*, **102**, 318, 1945.

[12] *Pub. A.S.P.*, **58**, 356, 1946.

[13] *A.J.*, **54**, 111, 1948.

[14] Dr. W. W. Morgan kindly put these plates at the author's disposal.

[15] By Morgan, Keenan, and Kellman (Chicago: University of Chicago Press, 1943).

Spectral types from slit spectrograms of about thirty-five B stars in this region were determined, and spectral types for the remaining stars to about the tenth magnitude were estimated from two objective-prism plates taken with the 24–36-inch Schmidt camera of the Warner and Swasey Observatory.[16] Stars whose spectral types were known from slit spectrograms were used to set up a sequence of standards on the objective-prism plates, and the remaining stars were classified according to these. The intensities of the *He* I lines and the visibility of the K line were used as criteria.[17] The accuracy of the classification of the objective-prism spectra is necessarily somewhat lower than that of the slit spectrograms. It is sufficient, however, for the assignment of normal colors, which will be used in investigating the color excesses in this region.

IV. PHOTOELECTRIC OBSERVATIONS

The photoelectric observations of the colors and magnitudes of the B stars in Orion were made in November and December, 1951, at the McDonald Observatory. Observations were made on eleven nights with the 13-inch and three nights with the 82-inch telescopes. The time with the 13-inch was devoted primarily to the B stars in the Orion aggregate brighter than 8.0 mag. in relatively unobscured areas. This limiting magnitude corresponds approximately to spectral type B8. Several multiple stars in this category could not be observed because of the limited resolving power of the 13-inch. The 82-inch observations were restricted to the following B stars in Orion: (1) stars involved in bright nebulosity where a high resolving power is necessary to evaluate the brightness of the nebula in the immediate vicinity of the star, (2) close multiple stars, and (3) highly obscured stars in the region of the nebula and elsewhere. While almost all the brighter stars in the aggregate were observed, it was not possible to obtain completeness in the case of the fainter stars. For the latter, priority was given to those for which slit or objective-prism spectra were available.

The same photometer and amplifier were used for both the 13-inch and the 82-inch observations. The amplifier was designed and constructed by H. L. Johnson, and both the amplifier and the photometer have been described elsewhere.[18] An independent calibration of the gain of the amplifier in terms of magnitude steps was made during the interval over which the observations extended. This calibration was used in the computation of the magnitudes. Observations were made through three filters, a Corning 3384 (yellow), a Corning 5030 + Schott GG 13 (blue), and a Corning 9863 (ultraviolet). The effective wave lengths of the filter-photomultiplier combination are approximately 5540, 4420, and 3550 A. A Brown recording potentiometer was used to record the observations.

The deflections were made symmetrically in the three colors. Only the results of the blue and yellow deflections will be discussed in this paper. In practically every case the star deflections were followed immediately by a sky reading with the same diaphragm and a deflection from a standard light-source. All star deflections were corrected for sky in the usual manner and were referred to the standard source in order to eliminate the effects of cell fatigue. The observed colors, C_{y0}, and the observed magnitudes, m_{y0}, both uncorrected for extinction, were computed as follows:

$$C_{y0} = 2.5 \log \frac{y}{b},$$

$$m_{y0} = -2.5 \log \frac{y}{100},$$

where y and b represent the yellow and blue deflections.

[16] The author is indebted to Dr. J. J. Nassau for the use of these plates.

[17] W. W. Morgan, *Pub. Obs. U. Michigan*, Vol. **10**, 1951.

[18] H. L. Johnson and W. W. Morgan, *Ap. J.*, **114**, 522, 1951.

The extinction determinations were made following the method of Johnson and Morgan.[19] Ten stars of differing color and in different parts of the sky were selected as extinction standards: 10 Lac, HR 875, α Ari, HR 8832, β Cnc, η Hya, π^3 Ori, π^4 Ori, υ Ori, and Cin 705. When possible, two observations were made of each extinction star on each night: one observation at culmination and one at two or more air masses. On the nights when the 82-inch was used, fewer observations were made on these stars, and four additional standards—HD 37526, 36559, 35640, and 37481—within 3° of the Orion Nebula were each observed twice in the same manner. It was assumed for each extinction observation that C_y, the color of an extinction star outside the atmosphere, is given by the relation

$$C_y = C_{y_{mi}} - K_m \sec z_{mi} ,$$

where $C_{y_{mi}}$ and Z_{mi} are the observed color and the zenith distance for the ith observation on the mth night, and K_m is the color extinction coefficient for that particular star on the mth night. For each extinction star a simultaneous least-squares solution was made over all nights for a single value of C_y and the various K_m's. This method assumes

TABLE 1

EXTINCTION COEFFICIENTS

Date 1951	K_1	K_2	Date 1951	K_1	K_2
Nov. 6....	0.075±0.003	−0.033±0.004	Nov. 19....	0.081±0.003	−0.027±0.004
Nov. 7....	.095	− .024	Nov. 20....	.084	− .031
Nov. 8....	.087	− .030	Nov. 26....	.082	− .028
Nov. 12*...	.086	− .027	Nov. 27....	.098	− .018
Nov. 13....	.084	− .029	Nov. 28....	.094	− .025
Nov. 14....	.092	− .025	Dec. 2....	.085	− .026
Nov. 18....	0.089	−0.026	Dec. 6....	0.069	−0.035

* Mean coefficients were used on this night because of the insufficiency of extinction observations.

that the color of the extinction star outside the atmosphere is the same on all nights, and greater leverage in the least-squares solution for nightly extinction coefficients is thus obtained. The computed values of C_y and K_m were then regrouped according to nights, and for each night it was assumed that the relation

$$K_m = K_1 + K_2 C_y$$

was valid for all the extinction stars. For each night the coefficients K_1 and K_2 were computed by least squares. The individual values of K_1 and K_2 are listed in Table 1. Natural colors were then computed for all the observed stars by means of the relation

$$C_y = \frac{C_{y_0} - K_1 \sec z}{1 + K_2 \sec z} .$$

The values of C_y for the extinction stars resulting from the above-mentioned least-squares solution are not of the highest accuracy, since the weight of the observations is divided in the solution among C_y and about ten extinction coefficients. Consequently, values of C_y for the extinction stars were recomputed by means of the above formula. Separate averages of these values were then made for the observations with the 82-inch

[19] *Loc. cit.*

and 13-inch telescopes. A comparison of these values indicated a small zero-point difference between the two telescopes amounting to 0.015 mag. This probably arises from slightly different reflective properties of the two mirrors. All observations made with the 82-inch were corrected by this amount to put them on the color system of the 13-inch.

It was not possible to compute nightly magnitude extinction coefficients in the same manner as the color extinction coefficients because of night-to-night variations in the absolute sensitivity of the equipment and in the intensity of the standard light-source. Thus a mean magnitude extinction coefficient, $\overline{Q}_y$, was computed by least squares for each extinction star, using as the equation of condition:

$$m_y = m_{y_0} - \overline{Q}_y \sec z ,$$

where m_y is the magnitude outside the atmosphere referred to a full-scale deflection. It was then assumed that, for each extinction star,

$$\overline{Q}_y = \overline{Q}_{y_1} + \overline{Q}_{y_2} C_y .$$

The quantities $\overline{Q}_{y_1}$ and $\overline{Q}_{y_2}$ were computed by least squares, with the result that

$$\overline{Q}_{y_1} = 0.129 ,$$

$$\overline{Q}_{y_2} = -0.004 .$$

The ratio of $\overline{Q}_{y_1}$ and the mean of K_1 was found, and similarly the ratio of $\overline{Q}_{y_2}$ and the mean of K_2. This ratio was assumed to be the same on all nights, and the nightly magnitude extinction coefficients, Q_{y_1} and Q_{y_2}, were then given by the relation

$$Q_{y_1} = 1.506 K_1 ,$$

$$Q_{y_2} = 0.157 K_2 .$$

Natural magnitudes could then be computed from the relation

$$m_y = m_{y0} - (Q_{y_1} + Q_{y_2} C_y) \sec z .$$

Zero-point corrections to the magnitudes were found from the nightly means of m_y for the ten standard stars. This correction arises from the night-to-night variability of the standard source. A mean of all the 13-inch observations of m_y for each standard star and the deviation from the mean of each value of m_y were found. For a given night the deviations were averaged to obtain the zero-point corrections, Z, for all observations made on that night. These corrections ranged from 0.001 to 0.161 mag., with an average probable error of $\pm .003$ mag. The 82-inch observations were then referred to the means of the 13-inch observations, and the zero-point corrections for these nights were found in the same way. The quantity mag_y was then computed for all observations where

$$\text{mag}_y = m_y + Z + S ,$$

where S is a correction to refer all observations to the same amplifier gain.

The following equations of condition were used to relate the natural system of colors and magnitudes described above to the $B - V$ system:[20]

$$B - V = A + BC_y ,$$

$$V = \mathrm{mag}_y + C + D\,(B - V) .$$

In addition to the observations of the ten extinction stars, from one to five observations each were made of twenty-six stars in various parts of the sky for which V and $B - V$ had been observed by Johnson. The means of these observations were then used to solve for the four transformation coefficients by least squares. In the least-squares solution the means of the values of C_y and mag_y of the ten extinction stars were given weights

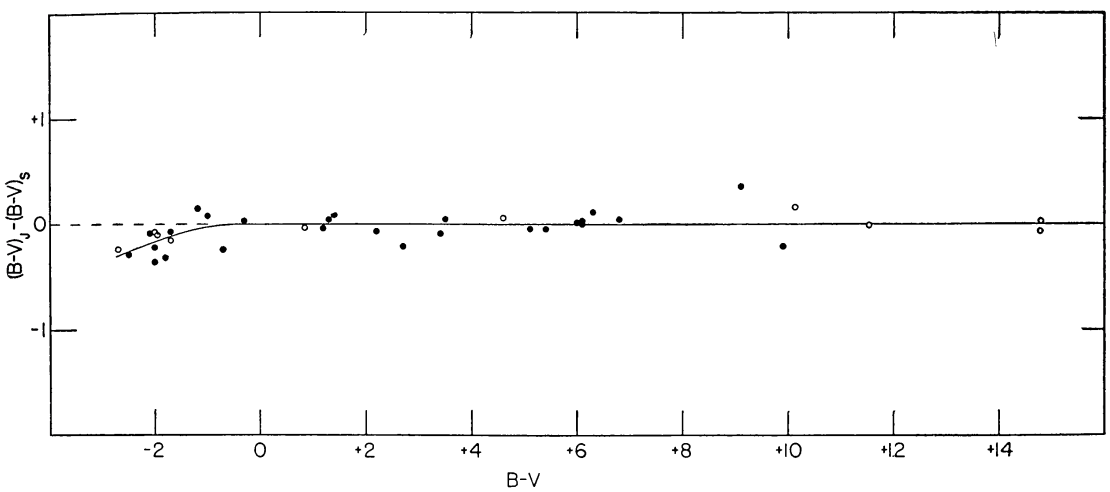

FIG. 1.—A comparison between the colors obtained by Johnson and those by Sharpless. The solid line represents the adopted transformation. The open circles represent the ten extinction standards.

corresponding to five observations, although the actual number of observations of each was considerably greater. The coefficients of the transformation were found to be:

$$\begin{aligned} A &= 0.916 \pm 0.003 , \\ B &= 1.131 \pm 0.004 , \\ C &= -0.614 \pm 0.004 , \\ D &= -0.086 \pm 0.006 . \end{aligned}$$

Values of V and $B - V$ were then computed for the thirty-six standard stars by the use of the transformation derived above. Figure 1 gives a comparison between these values and those obtained by Johnson. The open circles represent the ten extinction stars and consequently have greater weight. This comparison indicates a slight non-linearity at the extreme blue end of the color system derived here as compared with that of Johnson. This is interpreted as due to a slightly different ultraviolet cutoff of the blue filters used in the two investigations. Although the filters are of the same type, their characteristics are evidently not identical. The observed colors of the bluest stars are thus quite sensitive to the slightly different amount of ultraviolet light transmitted.

All observations of blue stars were corrected by the necessary amount, as read from Figure 1, to put them on the $B - V$ system as defined by Johnson. Table 2 lists the natural and transformed magnitudes and colors of the thirty-six standard stars. The

[20] H. L. Johnson and W. W. Morgan, unpublished.

values of V and $B - V$ listed in Table 2 have been corrected for the nonlinearity described above. For comparison, the observations of Johnson have been included. All observations of the Orion stars were similarly transformed.

The internal probable errors for the natural colors and magnitudes were computed on the basis of those Orion stars which were observed two or more times, and were found to be:

$$\left.\begin{array}{l} C_y\text{: p.e.} = \pm 0^{\mathrm{m}}.008 \\ m_y\text{: p.e.} = \pm 0^{\mathrm{m}}.012 \end{array}\right\} \text{for one observation .}$$

The observations on which these probable errors are based were made at an average air mass of about 1.5.

The results of the observations of the Orion stars are given in Table 3. The first column

TABLE 2

COLORS AND MAGNITUDES OF STANDARD STARS

Star	Sp.	$\overline{C_y}$	$\overline{\mathrm{mag}_y}$	$B-V$*	$B-V$†	V*	V†	No.
β Cas.....	F2 IV	−0.505	2.920	+0.35	+0.345	2.25	2.28	2
50 And.....	F8 IV–V	−0.329	4.765	+0.54	+0.544	4.08	4.10	5
HR 483.....	G2 V	−0.263	5.621	+0.63	+0.618	4.94	4.95	5
β Ari.....	A5 V	−0.694	3.289	+0.14	+0.131	2.62	2.56	5
α Ari.....	K2 III	+0.210	2.717	+1.153	+1.154	1.99	2.00	18
δ Tri.....	G0 V	−0.271	5.519	+0.61	+0.609	4.86	4.85	3
16 Per.....	F2 III	−0.502	4.871	+0.34	+0.348	4.22	4.23	2
HR 875.....	A1 V	−0.732	5.775	+0.085	+0.088	5.17	5.15	18
ι Per.....	G0 V	−0.281	4.713	+0.60	+0.598	4.04	4.05	5
κ Cet.....	G5 V	−0.213	5.500	+0.68	+0.675	4.82	4.83	4
ε Eri.....	K2 V	−0.038	4.401	+0.91	+0.873	3.75	3.71	4
ζ Per.....	B1 I*b*	−0.699	3.465	+0.13	+0.125	2.83	2.84	4
ε Per.....	B0.5 V	−0.954	3.479	−0.17	−0.17	2.88	2.88	4
π^3 Ori.....	F6 V	−0.408	3.838	+0.46	+0.454	3.16	3.19	22
π^4 Ori.....	B2 III	−0.947	4.272	−0.17	−0.17	3.70	3.67	20
β Eri.....	A3 III	−0.701	3.403	+0.12	+0.123	2.77	2.78	2
β Ori.....	B8 I*a*	−0.839	0.770	−0.03	−0.033	0.15	0.16	1
τ Ori.....	B5 III	−0.905	4.173	−0.10	−0.108	3.60	3.57	2
HD 35299...	B1 V	−0.988	6.264	−0.21	−0.22	5.71	5.67	2
HD 35899...	B5 V	−0.929	8.123	−0.12	−0.14	7.56	7.52	2
HD 36591...	B1 V	−0.967	5.911	−0.20	−0.19	5.36	5.31	2
Cin 705.....	M1 V	+0.495	8.704	+1.48	+1.476	7.96	7.96	18
υ Ori.....	B0 V	−1.027	5.200	−0.27	−0.27	4.59	4.61	18
α Lep.....	F0 I*b*	−0.610	3.205	+0.22	+0.226	2.61	2.57	1
ι Ori.....	O9 III	−1.006	3.348	−0.25	−0.25	2.74	2.75	2
ε Ori.....	B0 I*a*	−0.955	2.264	−0.20	−0.18	1.71	1.66	1
κ Ori.....	B0.5 I*a*	−0.940	2.682	−0.18	−0.16	2.04	2.08	1
δ Aur.....	K0 III	+0.084	4.405	+0.99	+1.011	3.69	3.70	2
χ^2 Ori.....	B2 I*a*	−0.552	5.243	+0.27	+0.291	4.63	4.60	1
ι CMa.....	B3 II	−0.850	5.024	−0.07	−0.046	4.36	4.41	2
β Cnc.....	K4 III	+0.502	4.260	+1.478	+1.484	3.53	3.52	15
η Hya.....	B3 V	−0.974	4.879	−0.196	−0.20	4.31	4.28	13
10 Lac.....	O9 V	−0.980	5.472	−0.200	−0.21	4.87	4.88	20
HR 8832....	K3 V	+0.071	6.255	+1.013	+0.996	5.56	5.56	20
υ Peg.....	F8 IV	−0.274	5.092	+0.61	+0.606	4.38	4.43	1
ι Psc.....	F8 V	−0.355	4.788	+0.51	+0.514	4.13	4.13	2

* From H. L. Johnson and W. W. Morgan, unpublished.

† Computed values.

TABLE 3

OBSERVATIONS OF STARS IN THE ORION AGGREGATE

Star	V	$B-V$	ϵ	Sp.	E_y	Remarks
30836	3.67	−0.17	2	B2 III	+0.06	π^4 Ori
31237	3.70	− .20	5	B2 III	+ .03	π^5 Ori (var.)
−3°1013	10.12	+ .24	6	B9 V	+ .31	
33647	6.68	− .05	6	B8 V	+ .05	
34179	8.02	− .03	6	B8 V	+ .07	
34317	6.41	− .02	6	A0 V	− .02	
34511	7.39	− .10	6	B5 V	+ .06	
34748	6.30	− .10	6	B1.5 V	+ .15	
34959	6.50	− .11	6	B5p	+ .05	
34989	5.78	− .13	6	B1 V	+ .14	
35007	5.65	− .12	6	B3 V	+ .08	
35008	7.09	− .11	8	.....	.....	
35039	4.72	− .16	6	B2	+ .07	22 Ori
35079	7.06	− .03	6	B3 V	+ .17	
35149	.....	.....	.....	B2	.....	23 Ori
35203	7.97	− .09	8	B6 V	+ .06	
35298	7.88	− .14	6	B9 V	− .07	
35299	5.67	− .22	6	B1 V	+ .05	
35407	6.31	− .16	6	B5 V	.00	
35411	3.33	− .19	6	B1 V	+ .08	η Ori
35439	4.92	− .21	6	B2e	+ .02	25 Ori
35501	7.42	− .06	6	B8 V	+ .04	
35502	7.35	− .03	6	B5 V	+ .13	
35575	6.41	− .17	6	B3 V	+ .03	
35588	6.15	− .18	6	B3 V	+ .02	
35640	6.24	− .05	3	B9 V:	+ .02	
35673	6.50	.00	6	B9 V	+ .07	
35715	4.56	− .23	6	B2	.00	ψ Ori
35718	8.72	+ .03	6	B8–9	+ .11	OP
35730	7.20	− .15	6	B5p	+ .01	
35762	6.74	− .18	6	B2 V	+ .05	
35777	6.60	− .18	6	B2 V	+ .05	
35792	7.20	− .14	6	B3 V	+ .06	
35834	7.67	− .05	6	B8 V	+ .05	
35881	7.77	− .09	6	B8 V	+ .01	
35882	7.74	− .06	8	.....	.....	
35899	7.52	− .14	6	B5 V	+ .02	
35901	9.04	− .02	8	B8–9	+ .06	OP
35910	7.58	− .10	6	B6 V	+ .05	
35912	6.35	− .18	6	B2	+ .05	
36012	7.24	− .10	6	.....	.....	
36013	6.88	− .13	6	B1.5 V	+ .12	
36120	7.96	− .03	6	B8–9	+ .05	OP
36133	6.94	− .09	8	B2 V	+ .14	
36151	6.71	− .13	8	B5 V	+ .03	
36166	5.76	− .20	6	B1.5 V	+ .05	
36219	7.59	− .06	6	.....	.....	
36234	8.64	− .07	6	B8–9	+ .01	OP
36267	.....	.....	.....	B5 V	.....	32 Ori
36285	6.33	− .17	8	B1.5 V	+ .08	
36324	9.00	+ .08	8	A0	+ .08	OP
36351	5.42	− .18	6	B1.5 V	+ .07	33 Ori
−3°1119	10.33	+ .21	8	B8–9	+ .29	OP
36366	8.09	+ .12	8	A0	+ .12	OP
36392	7.56	− .14	6	B3 V	+ .06	
36411	9.71	+ .10	8	B8–9	+ .18	OP
36429	7.56	− .13	6	B5 V	+ .03	
36430	6.23	− .15	8	B2 V	+ .08	
36486	2.19	− .21	6	O9.5 II	+ .10	δ Ori (var.)
36487	7.81	− .11	8	B8–9	− .03	OP
36512	4.61	− .27	2	B0 V	+ .03	υ Ori
36513	9.50	+0.03	8	B8–9	+0.11	OP

TABLE 3—*Continued*

Star	V	$B-V$	ϵ	Sp.	E_y	Remarks
36527	9.48	+0.14	8	A	.....	OP
36540	8.11	+ .05	8	B8–9	+0.13	OP
36541	7.69	− .08	8	B8–9	.00	OP
36550	.....	.....	.....	B8–9	.....	OP
36559	8.81	− .05	4	B8–9	+ .03	OP
36560	8.28	− .09	8	B8–9	− .01	OP
36591	5.31	− .19	6	B1 V	+ .08	
36607	9.23	− .04	8	B8–9	+ .04	OP
36627	7.56	− .11	6	B6 V	+ .04	
36629	7.64	+ .02	8	B2 V	+ .25	
36646	.....	.....	.....	B3 V	.....	
36655	8.60	− .04	3	B8–9	+ .04	OP
36670	8.94	− .01	8	B8–9	+ .07	OP
36695	5.31	− .17	6	B1 V	+ .10	VV Ori (var.)
36697	8.67	+ .06	8	B8–9	+ .14	OP
36741	6.58	− .20	6	B2 V	+ .03	
36779	6.24	− .19	6	B3 V	+ .01	
36783	9.50	+ .01	8	B8–9	+ .09	OP
−3°1140	10.22	+ .26	8	B8–9	+ .34	OP
36824	6.69	− .15	6	B3 V	+ .05	
36842	8.09	− .11	8	B3	+ .09	OP
36865	7.40	− .07	8	B8–9	+ .01	OP
36867	9.30	− .02	8	B8–9	+ .06	OP
36883	7.22	− .08	8	B8–9	.00	OP
36898	7.04	− .07	6	.....	.....	
36899	9.63	+ .05	8	B8–9	+ .13	OP
36916	6.73	− .10	8	B8–9	− .02	OP
36917	7.96	+ .16	6	A0	+ .16	OP
36918	.....	.....	.....	B	.....	OP R
36936	7.52	− .11	8	B5	+ .05	OP
36938	8.88	+ .07	8	B8–9	+ .15	OP
36939	9.01	+ .01	8	B8–9	+ .09	OP
36954	6.92	− .09	6	B3 V	+ .11	
36957	8.83	+ .05	8	B8–9	+ .13	OP
36958	7.36	− .07	8	B3	+ .13	OP
36959	5.67	− .22	8	B1 V	+ .05	
36960	4.77	− .25	6	B0 V	+ .05	
36981	7.83	− .10	6	B3	+ .10	OP
−3°1143	9.88	+ .17	8	B8–9	+ .25	OP
36982	8.45	+ .12	8	B1.5 Vp	+ .37	R
36983	9.19	.00	8	B8–9	+ .08	OP
36998	8.98	.00	8	B8–9	+ .08	OP
36999	8.48	− .09	6	B8–9	− .01	OP
37000	7.49	− .13	6	B5	+ .03	OP
37001	8.89	− .06	8	B8–9	+ .02	OP
37016	6.22	− .17	8	B3 V	+ .03	
37017	6.54	− .14	8	B1.5 V	+ .11	
37018	4.59	− .20	6	B2	+ .03	42 Ori
−4°1181	9.54	+ .32	8	B3	+ .52	OP
37019	9.37	+ .04	8	B8–9	+ .12	OP
37020	6.75	+ .06	8	B1:	+ .33	θ^1(C) Ori = Bond 619
37021	7.96	+ .24	8	B3:	+ .44	θ^1(D) Ori = Bond 624
37022	5.14	+ .06	5	O6	+ .44	θ^1(A) Ori = Bond 628
37023	6.70	+ .11	5	B1:	+ .38	θ^1(B) Ori = Bond 640
37025	7.17	− .12	6	B3	+ .08	OP
37040	6.29	− .14	8	B2–3	+ .08	
Bond 669	9.73	+ .25	8	B2:	+ .48	
37041	5.07	− .05	8	O9 V	+ .27	θ^2 Ori
37042	6.38	− .05	8	B1 V	+ .22	
37043	2.75	− .25	6	O9 III	+ .07	ι Ori
37055	6.40	− .12	8	B3 V	+ .08	
37056	8.36	− .06	6	B8–9	+ .02	OP
37057	9.29	+ .02	8	B8–9	+ .10	OP
37058	7.34	− .16	6	B2 Vp	+ .07	R
37059	9.10	−0.02	8	B8–9	+0.06	OP

TABLE 3—*Continued*

Star	V	$B-V$	ϵ	Sp.	E_y	Remarks
37060	9.38	+0.02	8	B8–9	+0.10	OP
37061	6.86	+0.29	8	B1 V	+0.56	
37062	8.24	+0.05	8	B5 V	+0.21	
−5°1328	9.89	+0.09	8	A0:	+0.09	OP
37114	8.99	−0.04	8	B8 V	+0.06	
37115	7.08	−0.06	6	B6 V	+0.09	
37128	1.66	−0.18	8	B0 I*a*	+0.12	ϵ Ori
37129	7.13	−0.14	8	B2 Vp	+0.09	R
37130	9.99	+0.16	8	B8–9	+0.24	OP
37150	6.57	−0.19	6	B3 V	+0.01	
37151	7.40	−0.08	8	B8 V	+0.02	
37174	9.17	−0.03	8	B8:	+0.07	
37187	8.12	−0.01	6	B9 V	+0.06	
−3°1154	9.68	+0.02	8	B8–9	+0.10	OP
37209	5.71	−0.23	8	B2	0.00	
37210	8.10	−0.07	8	B8–9	+0.01	OP
37232	6.09	−0.18	6	B1.5 V	+0.07	
37273	9.94	+0.16	8	B8–9	+0.24	OP
37303	6.02	−0.20	8	B1 V	+0.07	
37321	7.08	−0.08	6	B3 V	+0.12	
37322	9.80	+0.07	8	B8–9	+0.15	OP
37330	7.32	−0.05	6	B6 V	+0.10	
37334	7.19	−0.17	8	B3	+0.03	
37342	8.00	−0.12	5	B5 V	+0.04	
37356	.....	.....	.....	B1.5 V	.....	
37357	8.85	+0.12	8	B8–9	+0.20	OP
37373	8.30	−0.09	8	B8–9	−0.01	OP
37390	9.48	+0.17	8	B8–9	+0.25	OP
37397	6.83	−0.15	6	B3 V	+0.05	
37411	9.88	+0.16	8	B8–9	+0.24	OP
37428	8.82	+0.15	8	B8–9	+0.23	OP
37468	3.73	−0.24	8	O9.5 V	+0.07	σ Ori
−6°1273	10.40	+0.31	8	B8–9	+0.38	OP
37469	9.62	+0.22	8	B8–9	+0.30	OP
37470	8.22	+0.06	8	B8–9	+0.14	OP
37480	9.21	+0.01	8	B8–9	+0.09	OP
37481	5.96	−0.23	3	B1 V	+0.04	
37490	4.41	−0.06	6	B2e	+0.17	R
37526	7.61	−0.12	4	B3 V	+0.08	
37547	9.33	0.00	8	B8–9	+0.08	OP
37606	6.90	−0.07	6	B8 V	+0.03	
37641	7.53	−0.05	8	.....	.....	
37663	9.19	−0.02	8	B8–9	+0.06	OP
37700	7.96	−0.09	6	B8–9	−0.01	OP
37742	1.72	−0.21	6	O9.5 I*b*	+0.10	ζ Ori
37744	6.20	−0.23	6	B1 V	+0.04	
37745	9.20	+0.02	8	B8–9	+0.10	
37756	4.91	−0.22	6	B2	+0.01	
37776	6.97	−0.14	6	B2	+0.09	
37807	7.89	−0.09	8	B2	+0.14	OP
37887	7.70	−0.01	6	A0 V	−0.01	
37888	9.21	+0.05	8	B8–9	+0.13	OP
37889	.....	.....	.....	B2 V	.....	
37903	7.80	+0.09	8	B1.5 V	+0.34	
38051	8.53	+0.38	8	B3	+0.57	OP
38087	.....	.....	.....	B3:	.....	
38088	9.69	+0.16	8	B8–9	+0.24	OP
38120	9.10	+0.04	8	B8–9	+0.12	OP
38239	9.22	+0.06	8	A0	+0.06	OP
38563(Cl)	10.49	+0.62	5	.....	+0.78	M78 (A)
" "	10.73	+1.23	6	B1	+1.50	M78 (B) R
38755	7.68	−0.11	6	B6 V	+0.04	
38771	2.08	−0.16	8	B0.5 I*a*	+0.13	κ Ori
39291	5.33	−0.19	6	B2	+0.04	55 Ori
39777	6.54	−0.19	6	B2 V	+0.04	

NOTES TO TABLE 3

36918	The spectrum overlaps with that of BD−6°1232.
36982	The hydrogen lines in the spectrum are stronger than normal.
37058, 37129	The helium lines in the spectrum are weaker than normal. This effect appears to be characteristic of certain stars situated near the bottom edge of the main sequence. Such stars should be discussed separately from normal main-sequence members.
37490	A small nebulosity is associated with this star.
38563	The magnitudes of the components are estimated to be 11.0 and 12.5.

contains the number of the stars in the *Henry Draper Catalogue*. For stars not listed in the latter, the BD or Bond number is given. The second and third columns contain the observed magnitude, V, and color, $B - V$. The fourth column lists a quantity ϵ such that the probable error of $B - V$ is $\pm 0.0010\ \epsilon$ and the probable error of V is $\pm 0.0015\ \epsilon$. The spectral type appears in the fifth column. The color excess, as described below, is listed in the sixth column. In those cases where the spectral classification was made from objective-prism spectra, "OP" is indicated in the last column.

V. THE ORION AGGREGATE

This section will be devoted to an investigation of the brighter stars and the obscuring matter within the limits from R.A. 5^h00^m to 5^h48^m, and from Dec. $+6°$ to $-8°$. The pronounced clustering of B stars within these limits is shown in Figure 2, where the stars brighter than 7.0 mag. and of types B3 and earlier have been plotted from the *Henry Draper Catalogue*.

The nebulous background in Orion consists of a complex network of bright and dark markings.[21] The emission nebulosities include the Orion Nebula itself, which is one of the brightest and most dense of the nearer *H* II regions. It is surrounded by an extended region of feeble hydrogen emission. Also appearing in emission is Barnard's Great Curved Nebula, which extends about 12° on the eastern side of the aggregate. In view of Strömgren's analysis[22] of *H* II regions, there seems to be little doubt that the star responsible for the ionization of hydrogen in these nebulae is the O-type star, θ^1(A) Orionis, the brightest star of the Trapezium. The central position of the latter with respect to these nebulae helps confirm this identification. The object IC 434, which contains the Horsehead Nebula, and NGC 2024 are both apparently excited by the O9.5 star ζ Orionis.

Numerous nebulae which shine by reflection are also to be found in Orion. Typical of these is the group of nebulae—NGC 2064, 2067, 2068, and 2071, several degrees northeast of ζ Orionis. This group will be considered in more detail later.

Extended dark markings are also a noticeable feature of the Orion aggregate, especially since many of these can be seen superposed on the bright nebulosities. The Horsehead Nebula is evidently a superposition of dark matter on IC 434, and the Orion Nebula seems to be separated from NGC 1981 only as a result of a somewhat nearer obscuring cloud.[23] Other dark markings are apparent from the variations in the surface density of the stars, in particular on the eastern side of the aggregate.

The foregoing remarks suggest that the Orion aggregate may have an appreciable extension in depth. The coexistence of both emission and reflection nebulae at approximately the same angular distance from the Trapezium can most probably be explained as being due to an appreciable difference in linear distance, i.e., an extension along the line of sight. The overlapping of dark and bright nebulae indicate the same thing. If the extension of the aggregate along the line of sight is equal to the maximum transverse dimension, then the true distance modulus of a member can differ from the mean by as much as 0.2 mag. This will have the effect of increasing the dispersion of the observed main sequence and introducing additional uncertainties in the absolute magnitudes of the higher-luminosity stars.

[21] See Ross, *Atlas of the Milky Way* (Chicago: University of Chicago Press, 1934), Pl. 34.

[22] *Ap. J.*, **108**, 242, 1948.

[23] This was pointed out by Dr. Morgan.

The data in Table 3 can be used to compute the color excesses of the Orion stars. The normal colors on the $B - V$ system for the stars of spectral types O6–A0 were derived by H. L. Johnson[24] from observations of near-by B stars and various galactic clusters. These are listed in Table 4. The relation between color excesses on the $B - V$ and C_1 systems is established by transformations derived by Johnson[24] and is given by

$$E_1 = 0.425\, E_y\,,$$

where E_y is the color excess on the $B - V$ system.

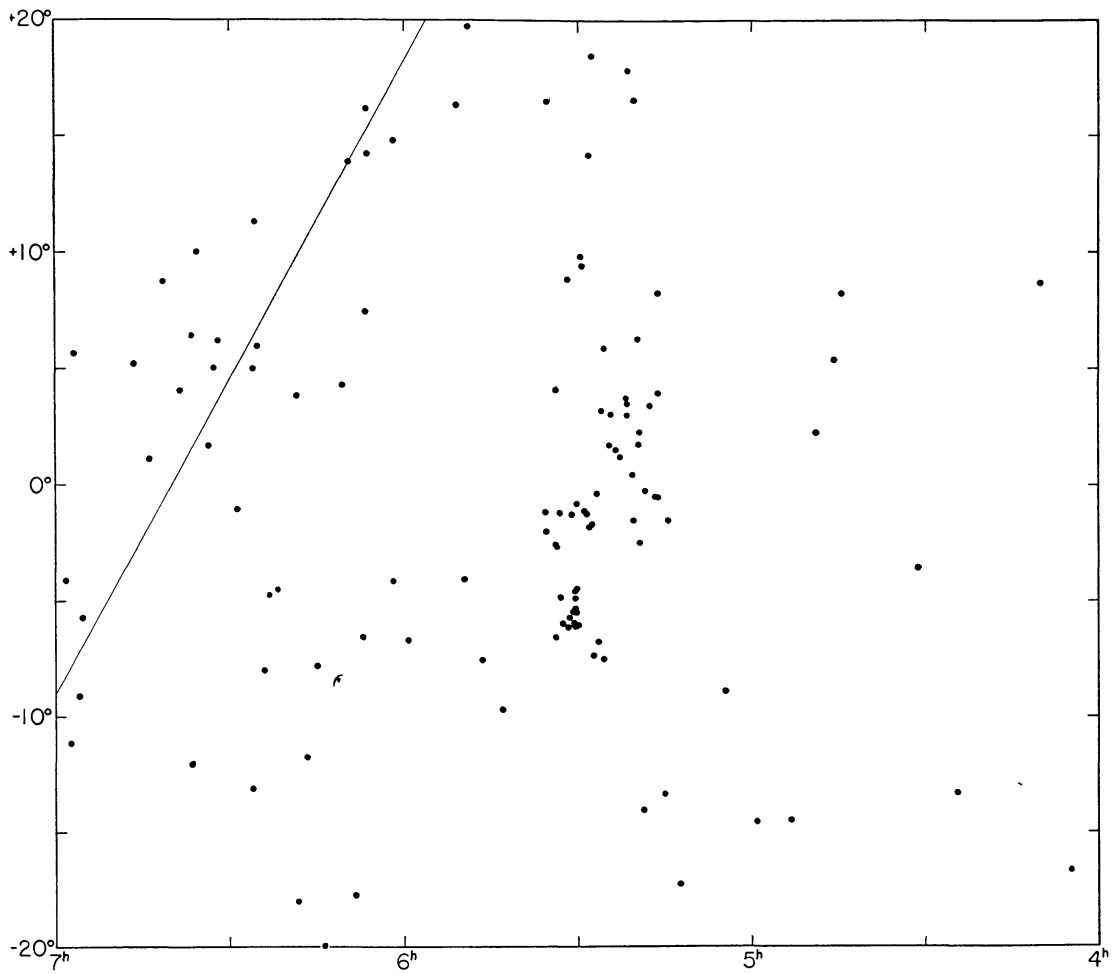

FIG. 2.—The apparent distribution of stars in the *Henry Draper Catalogue* brighter than 7.0 mag. of types B3 and earlier. The diagonal line represents the galactic equator.

TABLE 4

NORMAL COLORS OF THE O AND B STARS ($B - V$ SYSTEM)

O6.....	−0.38	O9.5.....	−0.31	B1.5.....	−0.25	B6.....	−0.15
O7.....	− .36	B0.....	− .30	B2.....	− .23	B8.....	− .10
O8.....	− .34	B0.5.....	− .29	B3.....	− .20	B9.....	− .07
O9.....	−0.32	B1.....	−0.27	B5.....	−0.16	A0.....	0.00

[24] Unpublished.

Since the ratio of total to selective absorption is known to be peculiar in the case of θ^1 Orionis,[25] it is of interest to investigate it for the Orion aggregate as a whole. The relation between the apparent magnitude of a star, m, and the apparent magnitude corrected for interstellar absorption, m_0, is given by

$$m_0 = m - AE ,$$

where E is the color excess and A is the appropriate ratio of total to selective absorption. If one selects from the Orion stars a group of stars having as nearly as possible the same spectral characteristics, e.g., those classified as B2 V, then for such a group the dispersion in absolute magnitude will be relatively small. If these stars are assumed to be at about the same distance, then the corrected apparent magnitude, m_0, will be approxi-

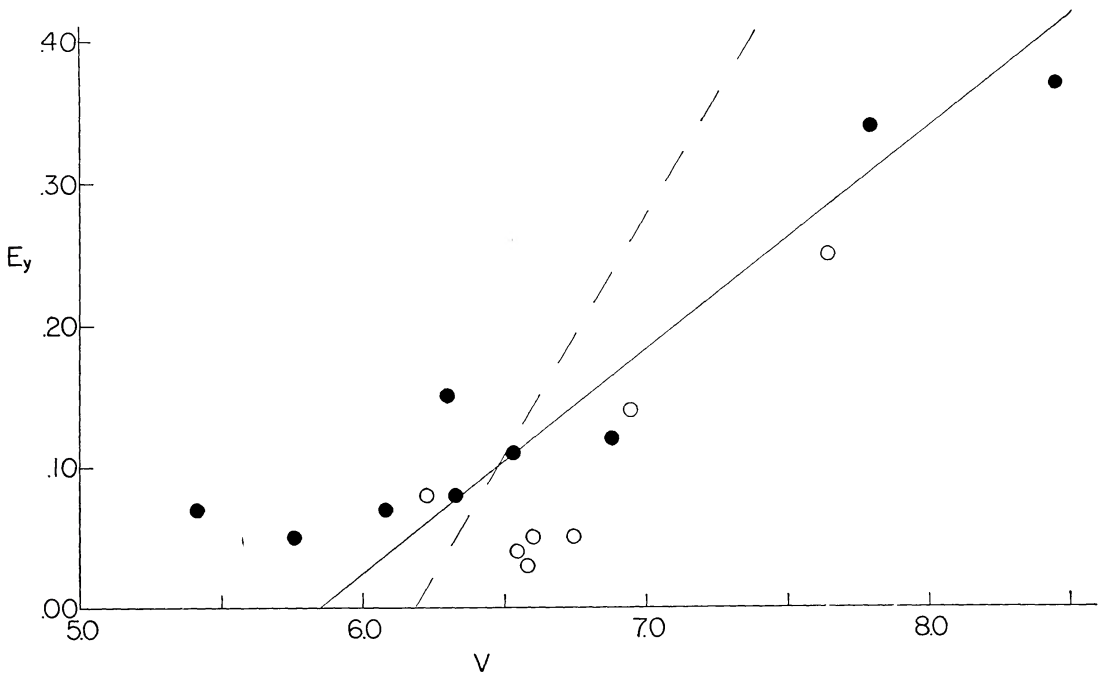

FIG. 3.—The relation between color excess and apparent visual magnitude for the B1.5 V stars (*solid circles*) and the B2 V stars (*open circles*) in the Orion aggregate. The dotted and solid lines correspond to ratios of total to selective absorption of 3 and 6, respectively, on the $B - V$ system.

mately the same for all. As a consequence, a linear relation will exist between m and E, the slope of which will give the ratio of total to selective absorption for the stars considered. This relation is plotted in Figure 3 for the B1.5 V and B2 V stars in Orion. The solid line has been drawn to fit the points, whereas the dotted line has a slope corresponding to the normal ratio of total to selective absorption. Apparently, the ratio is abnormally high for stars in the aggregate other than the Trapezium stars. The ratio for these stars was estimated from Figure 3 to be 6 on the $B - V$ system, or 14 on the C_1 system. The latter value agrees fairly well with the value of 16 ± 1 predicted by van de Hulst[26] for θ^1 Orionis on the basis of the six-color observations of Stebbins and Whitford. Figure 4 contains a similar plot for the B8–9 stars within $2\frac{1}{2}°$ of the Orion Nebula. A similarly high ratio of total to selective absorption is indicated by these stars.

The relation between m and E illustrated in Figures 3 and 4 is complicated by the

[25] van de Hulst, *Utrecht Pub.*, Vol. 11, No. 2, 1949.

[26] *Ibid.*

fact that the Orion aggregate may have an appreciable extension in depth as compared with its distance. This will have the effect of introducing a dispersion in m of the points about the line in Figure 3 of an amount corresponding to the dispersion in distance, i.e., about 0.2 mag. This will be added to the dispersion of the points resulting from a true spread in the absolute magnitudes of the stars considered. The latter quantity, however, is considerably larger, amounting to about 0.5 mag. Neither of these effects will alter the observed ratio of total to selective absorption but will decrease the accuracy with which it can be determined. If the obscuring material in Orion were distributed more or less uniformly throughout the aggregate, however, the effect would exist that the more distant stars in the aggregate are also, on the average, redder as a result of their being seen through a thicker layer of interstellar material. They will also be, on the average, slightly

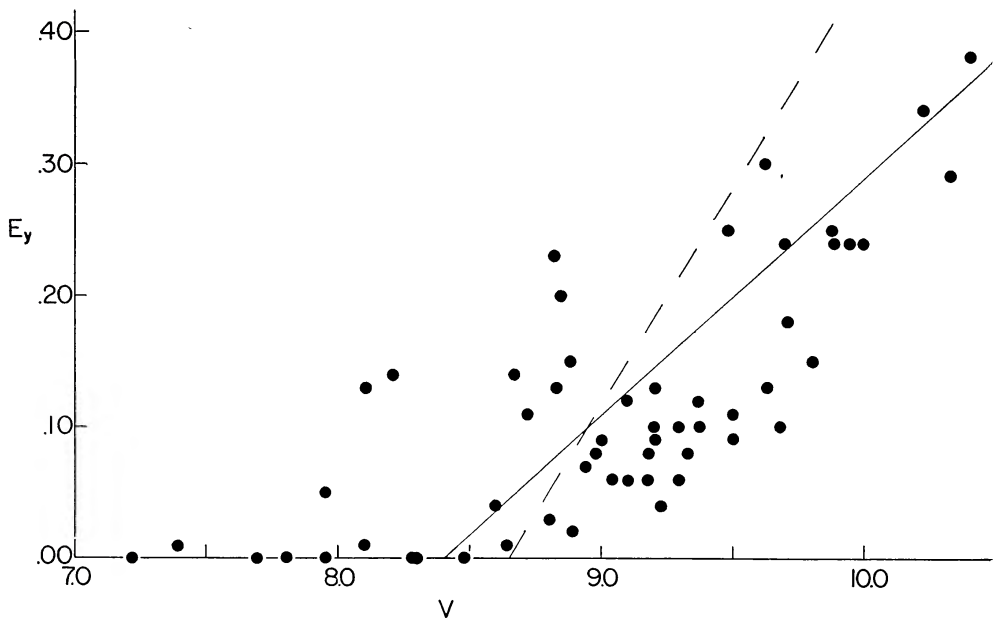

FIG. 4.—The relation between color excess and apparent visual magnitude for the B8–B9 stars within $2\frac{1}{2}°$ of the Orion Nebula. The dotted and solid lines correspond to ratios of total to selective absorption of 3 and 6, respectively, on the $B - V$ system.

fainter by virtue of their greater distance. This will have the effect of causing a spurious increase of the ratio of total to selective absorption as derived from Figure 3. If it is assumed that C_1 increases systematically by 0.025 mag. per 10 parsecs along the line of sight within the aggregate, then the true ratio of total to selective absorption will be smaller than the ratio determined above by about 1 on the C_1 system. Since this represents an extreme case, it will be assumed that the ratio determined from Figure 3 is correct within the observational errors. Reddened stars of other spectral types also confirm a high ratio of total to selective absorption, although the scatter is again fairly large. The stars in the northern part of the aggregate are practically unreddened; hence the present discussion does not apply to them. Owing to the uncertainties mentioned above, a probable error of ± 1 is estimated for the ratio of 6 on the $B - V$ system determined above, and in the following it will be assumed that this ratio applies to the Orion stars in general. An exception to this will be discussed below. The precise ratio for particular parts of the aggregate or for particular stars can be found only from multicolor observations of the type made and described by Whitford.[27]

[27] *Ap. J.*, **107**, 102, 1948.

In Figure 5 the H-R diagram has been plotted for the stars in Orion for which both slit spectrograms and photoelectric observations are available from Table 3. All the brighter B stars in Orion are included, with only two exceptions: γ Ori and 32 Ori. These, on the basis of their individual spectroscopic parallaxes, were judged to be nonmembers. Other stars which, on the basis of the H-R diagram, are probably not members of the aggregate are indicated in Figure 5 by open circles. The mean corrected apparent magnitude, m_0, was estimated from Figure 5 for the main-sequence stars of types B1, B2, B3, and B5. These were then subtracted from the corresponding absolute magnitudes[28]

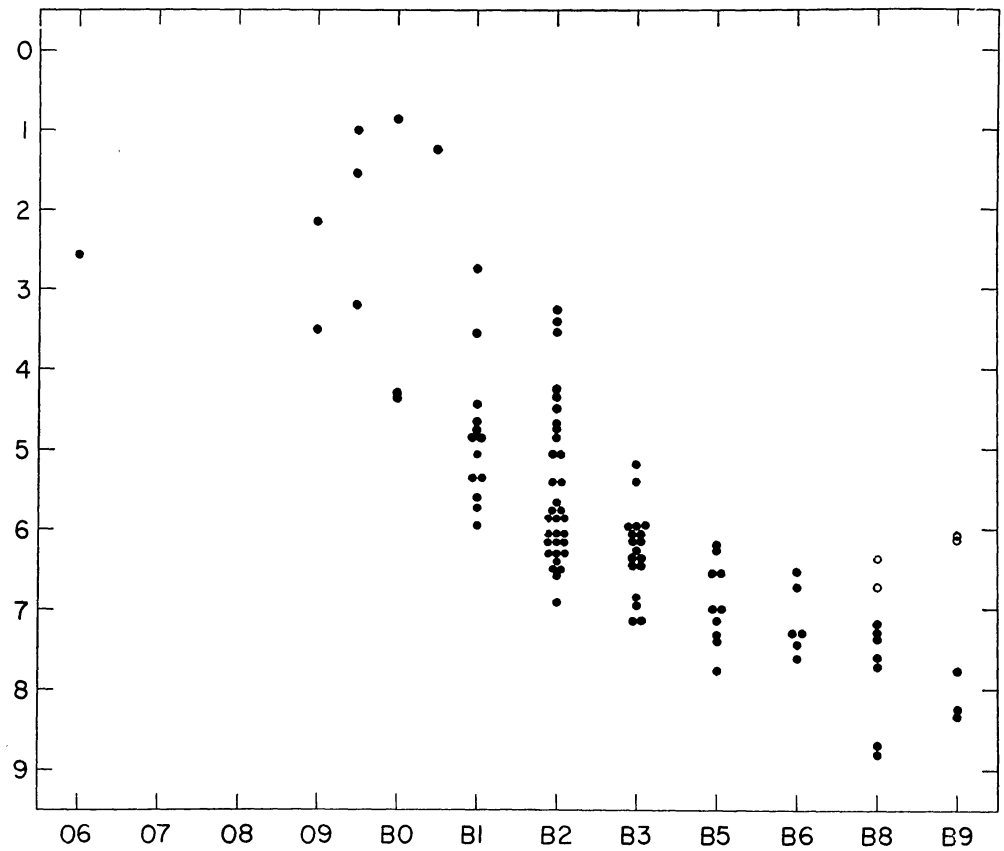

FIG. 5.—The H–R diagram for the brighter stars in the Orion aggregate. Apparent visual magnitude corrected for interstellar absorption is plotted against spectral type. Open circles represent stars which are probably not members of the aggregate. Stars of type B1.5 have been grouped with those of type B2.

to obtain a distance modulus. These values are shown in Table 5. Stars of spectral type later than B5 were not used in obtaining the distance modulus, since the corresponding portion of the H-R diagram is not complete and is complicated by an admixture of field stars which causes a spurious turning-up of the main sequence with later types. The mean distance modulus resulting from the data in Table 5 is 8.5 mag., corresponding to a distance of 500 parsecs. An uncertainty of about ± 0.3 mag. is estimated.

A comparison of the H-R diagrams of the Orion aggregate and the h-χ Persei cluster[29] indicates several significant differences between the two groups of stars. The B-type supergiants in h-χ Persei have spectral types in the range B0.5–B3, whereas the super-

[28] Hynek, *Astrophysics* (New York: McGraw-Hill Book Co., Inc., 1951), p. 23. A zero-point correction of -0.10 mag. has been applied to these values to put them on the $B - V$ system.

[29] W. P. Bidelman, *Ap. J.*, **98**, 61, 1943.

giants in Orion—ζ, ϵ, and κ Orionis—have spectral types which are, on the average, somewhat earlier, i.e., O9.5–B0.5. In addition, the number of O stars in Orion seems to be significantly larger, since in h–χ Persei there is only one star earlier than O9.5. The most striking difference between the two diagrams, however, lies in the presence of A- and M-type[30] supergiants in the double cluster. There is no evidence for the association of supergiants of spectral types later than B with the Orion aggregate.

Once the distance of the aggregate has been determined from the main-sequence stars, the absolute magnitudes of the high-luminosity stars in Orion can be derived from their distance modulus and their apparent magnitudes corrected for interstellar absorption. Table 6 contains these results for the stars of spectral types B0.5 and earlier. A maximum error of 0.3 mag. is estimated for these values on the basis of the possible extension of the aggregate along the line of sight and the uncertainty of the color excesses.

TABLE 5

DETERMINATION OF DISTANCE MODULUS FOR BRIGHTER STARS OF ORION AGGREGATE

Sp.	$\overline{m_0}$	M_v	$\overline{m_0}-M_v$
B1 V	5.1	−3.3	8.4
B2 V	6.1	−2.7	8.8
B3 V	6.4	−2.1	8.5
B5 V	6.9	−1.4	8.3
Mean	.....	.....	8.5

TABLE 6

ABSOLUTE MAGNITUDES OF EARLY-TYPE STARS IN ORION

	V	III	II	I*b*	I*a*
O6	−6.0	.....	.....	.....	.....
O9	−5.0	−6.2	.....	.....	.....
O9.5	−5.2	.....	−6.9	−7.4	.....
B0	−4.0	.....	.....	.....	−7.6
B0.5	.....	.....	.....	.....	−7.2

The absolute magnitudes of the stars of luminosity class I*a* average slightly higher than the value of −7.2[31] obtained for stars of types A5–M2 from the equation of galactic rotation. For class B0 V the agreement with the presently adopted absolute-magnitude calibration is within the uncertainties mentioned above. In the case of the O-type dwarf stars, the absolute magnitudes average several tenths of a magnitude brighter than those determined in a similar way by Roman[32] for the O stars in the Cygnus concentration of early-type stars. In both cases the absolute magnitudes are similar to what would be expected from an extrapolation of the main sequence to earlier types. The late O stars belonging to the giant and intermediate supergiant classes, however, have considerably higher luminosities than the B stars of similar luminosity classes. They apparently are similar in absolute magnitude to the supergiant stars of types F and later. A complete

[30] W. P. Bidelman, *Ap. J.*, **105**, 492, 1947.

[31] Hynek, *op. cit.*, pp. 22, 23.

[32] *Ap. J.*, **114**, 492, 1951.

absolute-magnitude calibration of the luminosity classes for the O stars, however, will require studies of additional concentrations of early-type stars.

VI. THE REGION OF THE ORION NEBULA

The region of the "sword" of Orion is of particular interest, in that it contains the three earliest O stars of the aggregate and one of the brightest hydrogen-emission regions in the sky. It contains a rather compact group of bright stars which seems to form a subsystem in the Orion aggregate.

The H-R diagram for the stars within $2\frac{1}{2}°$ of the Orion Nebula is plotted in Figure 6. The observations in this region are complete to about tenth magnitude; consequently

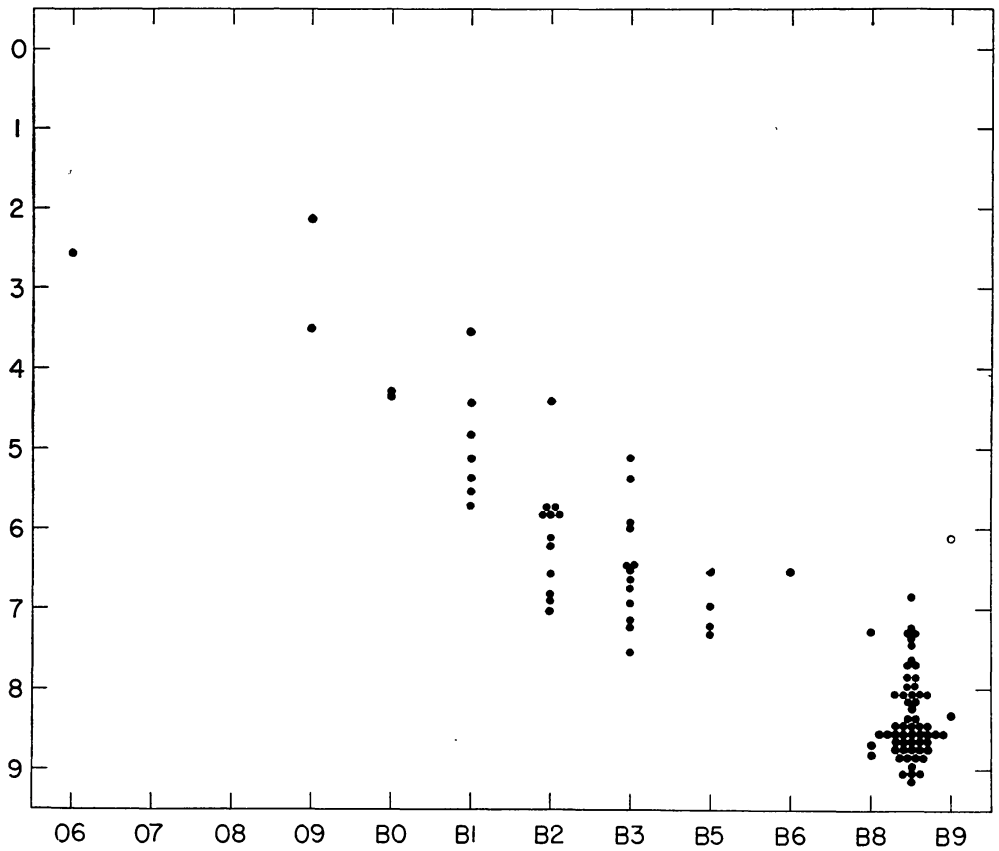

FIG. 6.—The H–R diagram for the stars within $2\frac{1}{2}°$ of the Orion Nebula. Apparent visual magnitude corrected for interstellar absorption is plotted against spectral type. The star represented by the open circle is probably not a member of the aggregate.

the H-R diagram can be expected to be reasonably complete to B9. The distance modulus was obtained for these stars in the same way as for the stars brighter than 8.0 mag. in the aggregate, the result being that $m_0 - M = 8^{m}.6$. This does not differ greatly from the value of 8.5 mag. determined for the aggregate as a whole. The latter value will be adopted as the mean distance modulus of the entire aggregate, since it is based on a greater number of stars. If the aggregate is assumed to be elongated as a result of the shearing effects of galactic rotation, then the part of the aggregate at higher galactic longitude, i.e., that containing the nebula, would be expected to be at a somewhat greater distance. The internal accuracy of the distance moduli determined here, however, is not quite high enough to attribute their difference to this effect.

Figure 6 illustrates the great numbers of B8–9 stars relative to those of earlier spectral types. The theory of the dynamics of star clusters[33] predicts that the square of the ratio of the velocity dispersion to the radius of the cluster is proportional to the density. Since the stars within several degrees of the nebula are known to have a lower velocity dispersion than the other B stars in Orion,[34] it follows that the density of the aggregate as a whole should be at least as great as in the region of the nebula. This suggests that the B8–9 stars should be at least as frequent throughout the entire aggregate. Although

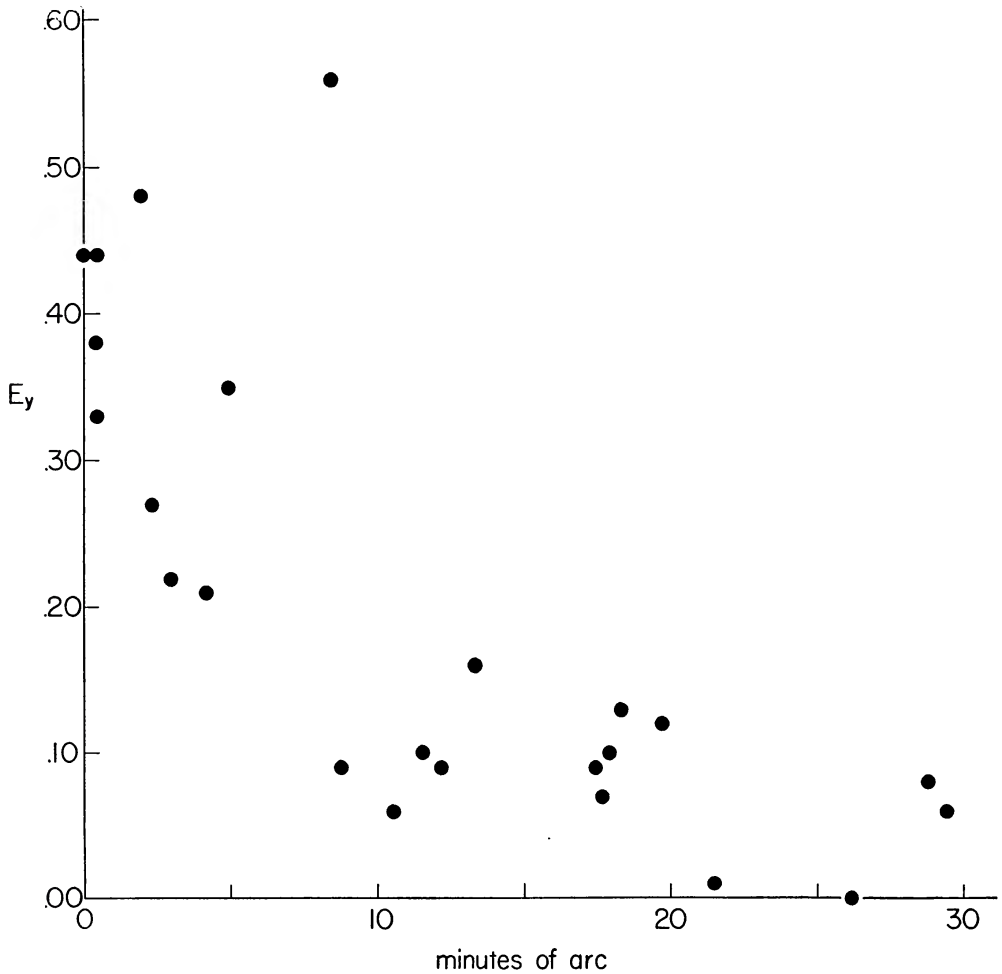

FIG. 7.—The relation between color excess and angular distance from θ^1(A) Orionis for the B stars in the Orion Nebula. The star having a color excess of +0.56 is located in a dense, detached part of the nebula.

the present investigation does not go sufficiently faint to prove this, counts of stars in the *Henry Draper Extension*[35] seem to confirm it.

It is of interest to examine the distribution of color excesses within the Orion Nebula. In Figure 7 the color excesses of all the B stars within 30 minutes of arc of the center of the Trapezium are plotted against angular distance from the latter. It is apparent that,

[33] S. Chandrasekhar, *Principles of Stellar Dynamics* (Chicago: University of Chicago Press, 1942).

[34] Bendler, unpublished thesis, University of Michigan Libraries.

[35] *Harvard Ann.*, Vol. 112, 1949.

on the average, the color excesses increase smoothly with decreasing distance from the Trapezium and that the Trapezium stars themselves, at the extreme left of the diagram, have color excesses which are not out of line with those of the surrounding stars. The hypothesis that the central part of the Orion Nebula is more transparent than elsewhere is evidently not confirmed by observations of color excesses. In order for the total absorption in the Trapezium region to be low, the ratio of total to selective absorption there would have to be correspondingly low, but this is doubtful in view of the abnormally high ratio elsewhere in the aggregate and would require that the four Trapezium stars have lower than average luminosities for their spectral types.

VII. REFLECTION NEBULAE IN ORION

Several highly obscured stars in reflection nebulae in Orion have been observed and are included in Table 3. Since there seems to be no doubt that these are illuminated portions of the general obscuring material in Orion, the illuminating stars can be considered members of the aggregate.

NGC 2068 = M78 and its companions NGC 2067 and NGC 2064 have been studied by Collins[36] and by Struve and Story[37] and are illustrated in Figure 8. The photograph suggests that they are portions of the same nebula partially obscured by nearer dark matter. That they are situated in a region of extremely high obscuration is indicated by the very low surface density of stars there. NGC 2068 contains two tenth-magnitude stars, designated M78 (A) and M78 (B), of which photoelectric observations were obtained, and a third star several magnitudes fainter. Together they form the cluster HD 38563. M78 (A) occupies a central position with respect to NGC 2068. The nebula, however, shades off evenly in all directions except to the north, where a sharp, ragged boundary again suggests nearer obscuring material. It thus seems possible that M78 (B), the northernmost star of the three, may occupy the true central position in the nebula and be primarily responsible for its illumination. This star is a visual binary with $\Delta m = 1^{m}.5$. Several slit spectrograms were obtained, and the spectral type is B1 V. If the absolute magnitude were assumed to be -3.3 and the distance modulus the same as for the other Orion stars, the apparent magnitude corrected for interstellar absorption would be 5.2. Since, from Table 3, the apparent magnitude is approximately 11.0, the amount of absorption would be 5.8. This, combined with the color excess, results in a ratio of total to selective absorption between 8 and 9 on the C_1 system. The spectral type of the brighter star in NGC 2068 was not obtained in the present investigation but is listed by Hubble[38] as B5. This spectral type, combined with the photoelectric data in Table 3 and an assumed distance modulus of 8.5 mag., leads to a ratio of total to selective absorption of about 10. The values of the ratio for the stars in NGC 2068 are nearer to the normal ratio than to that estimated earlier for the other Orion stars.

The reflection nebula NGC 1788, which has been illustrated by Collins,[39] is situated on the opposite side of the Orion aggregate from NGC 2068. It contains two illuminating stars, the brighter being BD$-3°3013$, for which a slit spectrogram was obtained. The spectral type is B9 V. The photoelectric observations are included in Table 3. Assuming an absolute magnitude of -0.1 and a distance modulus, again, of 8.5 mag., the total absorption is 1.7 mag. This results in a ratio of total to selective absorption of 12 on the C_1 system.

The differences in the values of the ratio of total to selective absorption found, on the one hand, for BD$-3°3013$ and the Orion aggregate as a whole and, on the other hand, for the stars in NGC 2068 cannot be explained entirely on the basis of the uncertainties of the observed quantities. The explanation may lie in the extreme density of the interstellar dust of which NGC 2068 forms an illuminated part. If the

[36] *Ap. J.*, **86**, 529, 1937.

[37] *Ap. J.*, **84**, 219, 1936.

[38] *Ap. J.*, **56**, 400, 1922.

[39] *Loc. cit.*

FIG. 8.—A photograph of NGC 2068 taken with the Yerkes 24-inch reflector. The scale is approximately $2\frac{1}{2}'$ per inch. NGC 2071 is at the upper left, while NGC 2067 and NGC 2064 are to the right of NGC 2068.

optical thickness of the matter along the path between θ^1 Orionis and NGC 2068 is high enough, the pressure of radiation, to which the high ratio of total to selective absorption is attributed, may be inoperative near the latter. Observations in more than two colors would be necessary for a complete description of the reddening in NGC 2068.

VIII. INTERSTELLAR FEATURES

An additional peculiarity of the absorbing material in Orion, as was first pointed out by Morgan,[40] is that the interstellar band at λ 4430 is abnormally weak in the spectra of the Orion stars as compared with other stars of comparable reddening. It was suggested that the radiation from the hottest stars modifies the surrounding interstellar material so that it cannot absorb λ 4430 as strongly as in other regions. Recent measurements made by Duke[41] of the central intensities of λ 4430 indicate that the band is at least 25 per cent weaker in the Orion stars than in other stars of similar reddening. The star M78 (B), which has a color excess of 0.70 mag. on the C_1 system, has a barely visible λ 4430 band, whereas a central absorption of over 20 per cent would be expected on the basis of its reddening. In view of the abnormally low color excesses of the Orion stars for a given amount of total absorption, one might expect the opposite effect.

The equivalent width of the diffuse interstellar feature at λ 6284 has been measured[42] in the spectrum of θ^1 (A) Orionis. The relationship between the equivalent width of λ 6284 and color excess found by Merrill and Wilson[43] predicts a value of about 0.5 A for a star having a color excess similar to that of θ^1 (A) Ori. The measured equivalent width, however, is 0.26 A, which suggests that λ 6284 may also be abnormally weak in the spectra of the Orion stars. Observations of more stars, however, would be needed to establish this.

It was first suggested by Baade and Minkowski[44] that the peculiar reddening in Orion might be due to the removal of the smaller interstellar particles by the radiation pressure of the hotter stars. The theoretical extinction-curves computed by van de Hulst indicate that an increase of the mean particle size by about 20 per cent will increase the ratio of total to selective absorption from the normal value to one similar to that observed in Orion. This relative decrease in the number of smaller particles in Orion may also explain the weakening of the diffuse interstellar features there, assuming that the latter are produced by, or are connected in some way with, small interstellar particles.

Observations of the equivalent widths of the sodium D lines in eight of the Orion stars indicate that the empirical relation between color excess and $0.5 \times (D_1 + D_2)$ is, within the observational errors, the same for them as for stars in general.

In addition to their valuable advice and discussions, the author is indebted to Dr. W. W. Morgan for suggesting this investigation and for making available to him much of the observational material on which it is based; to Dr. Bengt Strömgren for the use of the observational facilities at the Yerkes and McDonald Observatories; and to Dr. Harold Johnson for the use of his photoelectric equipment. He is also indebted to Dr. J. J. Nassau for the use of objective-prism plates taken at the Warner and Swasey Observatory.

[40] *A.J.*, **51**, 21, 1944.

[41] *Ap. J.*, **113**, 100, 1951.

[42] Merrill, Sanford, Wilson, and Burwell, *Ap. J.*, **86**, 274, 1937.

[43] *Ap. J.*, **87**, 9, 1938.

[44] *Op. cit.*