OBSERVED VARIATIONS IN THE LAW OF INTERSTELLAR REDDENING

E. JOSEPH WAMPLER*
Yerkes Observatory

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ABSTRACT

New narrow-band, three-color observations of O stars in four galactic longitude regions confirm the rather large variation in the slope of the O-star reddening line with galactic longitude which had been found previously from published *U, B, V* data. Although observations of B supergiants indicate a less pronounced deviation, it is felt that this may be due to the larger uncertainties in the intrinsic colors of the B stars.

I. INTRODUCTION

In a previous paper (Wampler 1961), evidence was presented which indicated that the law of interstellar reddening for O stars varied with galactic longitude. Two-color plots constructed from both the *U, B, V* data of Hiltner and Johnson (1956) and from Borgman's seven-color photometry (Borgman 1960) indicated approximately the same amplitude for the effect. However, because of difficulty encountered with determining the intrinsic *U, B, V* colors of O-type stars, additional observations with narrow-band filters were obtained of early-type stars in several selected regions of the sky. This paper presents the results of those observations.

II. THE OBSERVATIONS

Stars selected for investigation fell into two spectral groups: stars whose spectral class lay between O5 and O8 inclusive and those whose class lay between B0 and B1.5, I*a* and I*b*. In all cases the spectral type was taken from published types by Morgan, Code, and Whitford (1955), Hiltner (1956), or Hiltner and Johnson (1956). The observations, for the most part, were restricted to four rather small regions of the Milky Way; $l^{II} = 0°$, $l^{II} = 17°$, $l^{II} = 78°$, $l^{II} = 133°$. In the first region ($l^{II} = 0°$), only B stars were observed. In order to facilitate the determination of the intrinsic colors of the stars on the new color system, a few nearly unreddened stars were observed beyond the arbitrary boundaries of the four regions. Except for HD 195213, which was chosen for observation because it had anomalous *U, B, V* colors, published *U, B, V* and C_1 colors were used only to insure that the program stars in each region would have a wide range of reddening.

Stellar magnitudes were obtained in three colors, by using interference filters, and, from these magnitudes, colors and slopes of reddening lines were calculated in complete analogy with the *U, B, V* system. The three interference filters had peak transmission at 3310 (28 per cent), 4500 (64 per cent), and 5500 A (62 per cent); the half-widths of the filters were 75, 150, and 200 A, respectively. Narrow-band filters were chosen, in order to diminish any instrument-produced curvature of the reddening line and also to facilitate the determination of extinction by reducing the second-order extinction coefficient. All observations presented in this paper were made during the summer of 1961 with the 36-inch reflector at McDonald Observatory, and with the set of three filters described above.

We define two colors $\mathfrak{U}$ and $\mathfrak{G}$

$$\mathfrak{U} = m_{3310} - m_{4500}\,, \qquad \mathfrak{G} = m_{4500} - m_{5500}\,.$$

These observed colors, together with the names and co-ordinates of the stars, are listed in Table 1. The galactic co-ordinates were derived from the new Lund co-ordinate

* Shirley Farr Research Assistant.

TABLE 1

Star	α(1900)	δ(1900)	l^{II}	b^{II}	Sp	*V*	𝔊	𝔘	*n*
157857....	17ʰ20ᵐ7	−10°55′	13°0	+13°2	O7f	7 78	−0 81	1 21	Std.
−33°12242	17 29 6	−33 49	354 7	− 1 0	B1 I*a*	9 36	−0 01	2 41	6
161291	17 39 6	−27 11	01 5	+ 0 8	B1 I*ab*	8 89	−0 34	2 01	6
*	17 38 8	−29 53	359 1	− 0 4	B0 5 I*b*	10 75	−0 01	2 42	4
316311	17 41 2	−28 55	00 2	− 0 4	B1 I*b*	10 24	−0 18	2 16	2
163065	17 49 1	−30 32	359 7	− 2 7	B1 I*ab*	8 63	−0 67	1 48	4
164019	17 54 0	−28 36	01 9	− 2 6	B0 I*a*	9 31	−0 78	1 29	3
164032	17 54 1	−29 49	00 9	− 3 3	B1 I*b*	7 48	−0 89	1 27	5
164402	17 55 8	−22 46	7 3	− 0 2	B0 I*b*	5 73†	−1 00	1 03	6
164794	17 57 7	−24 22	5 9	− 1 0	O5	5 97	−0 96	1 00	Std.
166734	18 06 9	−10 46	18 9	+ 3 6	O8f	8 42	−0 02	2 20	7
167264	18 09 3	−20 46	10 5	− 1 7	B0 I*a*	5 42†	−0 95	1 08	7
167451	18 10 2	−13 36	16 8	+ 1 6	B0 5 I*b*	8 23	−0 29	1 99	3
−12°4964	18 11 8	−12 21	18 1	+ 1 8	O8	9 82	−0 20	2 05	3
−11°4586	18 12 5	−11 21	19 1	+ 2 3	O8(I?)	9 40	−0 10	2 17	7
167971	18 12 5	−12 17	18 3	+ 1 7	O8f	7 50	−0 31	1 91	3
168075 ..	18 12 9	−13 50	17 0	+ 0 8	O7	8 77	−0 57	1 52	4
−12°5009	18 14 7	−12 13	18 6	+ 1 3	O8	9 54	−0 40	1 76	4
−14°5037	18 19 3	−14 42	16 9	− 0 9	B1 5 I*a*(+?)	8 24	+0 24	2 69	6
169454	18 19 6	−14 02	17 5	− 0 7	B1 I*a*⁺	6 61	−0 19	2 13	Std.
169754	18 21 1	−11 25	20 0	+ 0 3	B0 5 I*a*	8 38	−0 06	2 41	6
170159	18 22 9	−13 04	18 8	− 0 9	B0 5 I*b*	8 36	−0 48	1 79	2
170716	18 25 8	−12 24	19 7	− 1 2	B0.5 I*b*	9 47	−0 63	1 55	2
171589	18 30 6	−14 12	18 6	− 3 1	O7f	8 28	−0 72	1 36	5
192281	20 09 0	+39 58	77 1	+ 3 4	O5f	7 55	−0 65	1 50	Std
192422	20 09 7	+38 28	75 9	+ 1 4	B0 5 I*b*	7 09	−0 54	1 73	6
192660	20 10 9	+40 01	77 3	+ 3 1	B0 I*a*	7 54	−0 44	1 88	5
193514	20 15 5	+38 57	77 0	+ 1 8	O7f	7 40	−0 60	1 65	6
193595	20 15 9	+38 44	76 9	+ 1 6	O7	8 72	−0 66	1 53	6
E228929	20 16 0	+39 36	77 6	+ 2 1	B0 5 I*b*	9 63	+0 02	2 55	5
193682	20 16 5	+37 30	75 9	+ 0 8	O5	8 41	−0 53	1 69	6
E229059	20 17 5	+37 05	75 7	+ 0 4	B1 5 I*ap*	8 70	+0 40	3 09	3
E229108	20 18 3	+39 08	77 4	+ 1 5	B0 5 I*b*	9 48	−0 26	2 13	5
194279	20 19 7	+40 26	78 6	+ 2 0	B1 5 I*a*	7 01	−0 08	2 42	5
E229202	20 19 8	+39 50	78 2	+ 1 6	O8 V:	9 53	−0 21	2 23	4
E229232	20 20 3	+38 47	77 4	+ 0 9	O5f	9 52	−0 28	2 17	4
+39°4168	20 20 7	+39 26	78 0	+ 1 3	O7	9 99	−0 04	2 47	5
194649	20 21 7	+39 54	78 4	+ 1 4	O6 5	9 00	−0 16	2 30	6
195213	20 24 9	+40 28	79 3	+ 1 2	O7	8 74	−0 22	2 03	6
VI Cyg 5	20 28 8	+40 58	80 1	+ 0 9	O7f	9 1‡	+0 52	3 34	5
VI Cyg 6	20 29 2	+41 05	80 3	+ 0 9	O8 (V)	10 67	+0 12	2 70	4
VI Cyg 9	20 29 6	+40 55	80 2	+ 0 7	O5f	10 80	+0 74	3 55	4
VI Cyg 8A	20 29 7	+40 58	80 2	+ 0 8	O6f	9 01	+0 15	2 63	3
VI Cyg 7	20 29 7	+41 00	80 2	+ 0 8	O6f	10 49	+0 31	2 86	4
197460	20 38 8	+36 02	77 5	− 3 7	B0 5 I*b*	8 14	−0 67	1 59	6
199579	20 53 1	+44 33	85 7	− 0 3	O6	5 96	−0 93	1 12	7
203064	21 14 8	+43 31	87 3	− 4 0	O8	5 06†	−0 98	0 99	7
204172	21 21 7	+36 14	83 4	− 9 9	B0 I*b*	5 84†	−1 05	0 96	Std.
206267	21 35 9	+57 02	99 3	+ 3 7	O6	5 62	−0 79	1 32	6
E235783	22 13 4	+53 59	101 7	− 1 9	B1 I*b*	8 68	−0 84	1 36	4
2905	00 27 3	+62 23	110 8	+ 0 1	B1 I*a*	4 16	−0 86	1 22	6
12993	2 02 1	+57 27	133 2	− 3 4	O5	8 98	−0 80	1 22	5
13256	2 04 5	+60 14	132 6	− 0 7	B1 I*a*	8 61	+0 09	2 40	5
13268	2 04 6	+55 41	134 1	− 5 0	O8 V*nn*	8 18	−0 86	1 19	5
13854	2 09 9	+56 36	134 5	− 3 9	B1 I*ab*	6 49	−0 72	1 43	Std
14052	2 11 4	+56 45	134 6	− 3 7	B1 I*b*	8 18	−0 71	1 55	4
14434	2 14 8	+56 27	135 0	− 3 8	O6	8 49	−0 82	1 22	6
14442..	2 14 9	+59 06	134 2	− 1 3	O5 5	9 22	−0 61	1 48	5
+60°470	2 15 8	+60 22	133 9	− 0 1	O8 V	9 88	−0 36	1 90	4
14633...	2 16 7	+41 02	140 8	−18 3	O8 V	7 44	−1 16	0 78	Std.
+61°411	2 19 0	+61 33	133 8	+ 1 2	O8:	10 19	−0 10	2 30	4
14947...	2 19 5	+58 25	135 0	− 1 7	O6f	8 01	−0 58	1 55	4
+60°493	2 23 3	+60 43	134 6	+ 0 6	B0 5 I*a*	8 44	−0 27	1 97	5
+60°497	2 24 3	+61 10	134 5	+ 1 1	O7	8 80	−0 47	1 69	5
15690	2 26 3	+57 05	136 4	− 2 7	B1 5 I*b*	8 02	−0 39	2 07	5
15785 ..	2 27 2	+60 06	135 3	+ 0 2	B1 I*ab*	8 34	−0 49	1 69	6
+57°687	2 58 7	+57 27	140 1	− 0 4	B1 I*b*	9 99	−0 16	2 19	4

* No 34 (W W Morgan, G Gonzalez, and G Gonzalez, 1953, *Ap J*, **118**, 345)

† Visual magnitude from W W Morgan, A D Code, and A E Whitford, *Ap J Suppl*, **2**, 41, 1955

‡ VI Cyg 5 is an eclipsing binary (H L Johnson and W W Morgan, 1954, *Ap J*, **119**, 344) No change of color was noted however

tables based on the pole at R.A. $12^{h}49^{m}$; Decl. $+27\overset{\circ}{.}4$ (1950). The listed magnitudes are mostly published V magnitudes of the U, B, V system. The last column gives the number of times the star was observed. All the stars were observed on at least two different nights, and in general, except for the B stars around Decl. $-30°$, no stars other than the standards were observed more than once a night. Extinction was calculated nightly for the seven best nights, and mean colors were obtained for the standard stars from these nights. For the remaining nights, extinction was obtained by comparing the observed color of the standards with adopted above-the-atmosphere colors and assuming that the instrumental color system was not changing. Empirically, there appeared to be little, if any, change in the instrumental system during the observational period. Also the extinction-curves appeared to be linear and independent of spectral type.

The probable error of a single measurement as determined from all the stars was $\sigma_{\mathfrak{G}} = \pm 0.011$, $\sigma_{\mathfrak{U}} = \pm 0.020$. The major contributing elements to the random error of a measurement appear to be uncertainties in the extinction. Although colors of the stars around $l^{\mathrm{II}} = 0°$ are somewhat suspect, partially because they are rather too far south to determine accurately the extinction correction and partially because it was possible to obtain observations of them on only a few nights, the colors of the remaining stars should be satisfactory.

TABLE 2

Region l	Adopted $E(\mathfrak{U})/E(\mathfrak{G})$	0 594 $E(\mathfrak{U})/E(\mathfrak{G})$	$E(U-B)/E(U-V)$	$E(\mathfrak{U})/E(\mathfrak{G})$ Including HD 195273 and $+61°411$
17° .	1 31	0 78	0 76	1 31
78°.	1 48	88	88	1 47
133°	1 36	0 81	0 80	1 38

To determine the intrinsic colors of the O stars, published $B - V$ colors were plotted against $\mathfrak{G}$, and a three-parameter curve was fitted to the observations. Assuming that $(B - V)_0 = -0.32$, the corresponding intrinsic $\mathfrak{G}$ color in the $\mathfrak{U}$, $\mathfrak{G}$ system was determined from the empirical curve to be -1.239. Given $(B - V)_0$, it is estimated that this intrinsic color, designated $\mathfrak{G}_0$, is uncertain by about ± 0.01 mag. Reddening-curves were then computed for the three regions in which O-star observations were made by fitting straight lines to the data, using the method of least squares. The intercepts of these three reddening-curves with $\mathfrak{G} = \mathfrak{G}_0$ provide three estimates for the unreddened ultraviolet color, $\mathfrak{U}_0$. The total spread of these three values for $\mathfrak{U}_0$ is 0.004 mag., a result which is somewhat fortuitous but which does allow one to calculate the reddening lines without having to force a fit at $\mathfrak{G}_0$, $\mathfrak{U}_0$. This agreement may also be interpreted as indicating that the observed O stars are not systematically different in these three regions of galactic longitude. The adopted values for the unreddened colors are $\mathfrak{G}_0 = -1.24$, $\mathfrak{U}_0 = +0.66$. The slopes of the reddening-curves were then recalculated, requiring that the reddening lines go through $\mathfrak{G}_0$, $\mathfrak{U}_0$. Both HD 195213 (O7) and BD $+61°411$ (O8:) appear to have anomalous reddening for their region; this anomaly is also present in their U, B, V colors as determined by Hiltner and Johnson. When slopes of the reddening lines on the U, B, V system were computed, the inclusion of these two stars left the slopes virtually unaffected because of the relatively large number of stars obeying the "normal" law for their region. Although the two stars were observed on the new system, their inclusion in the determination of the new reddening lines appeared unwarranted, since only a sample of the stars which exhibited "normal" reddening was chosen. The reddening slopes are presented in Table 2.

The adopted slopes on the new system are given in the second column; the third column lists the values of the slopes normalized to give +0.88 in Cygnus; and the fourth column lists the slopes of the reddening lines as determined for these regions from the Hiltner-Johnson catalogue (Wampler 1961). Slopes obtained with the inclusion of HD 195273 and BD +61°411 are presented in the fifth column for comparison. As may be seen, the inclusion of these stars does not greatly affect the mean slope.

The O-star colors are plotted in Figure 1, and the three mean reddening curves are indicated. The separation is clear cut, and Table 2 indicates that the agreement with the U, B, V results is also excellent. Because the O stars in any given direction of galactic

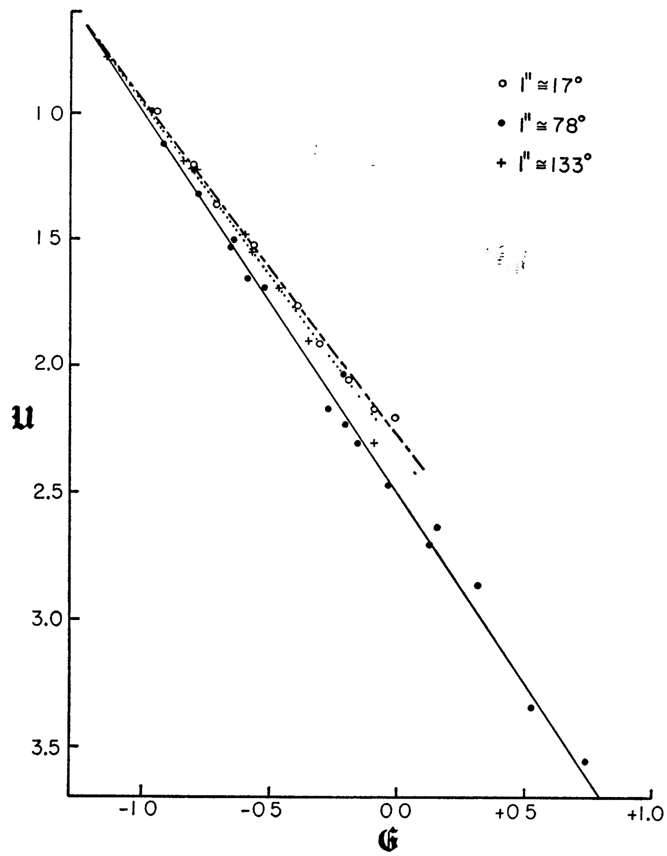

FIG. 1.—The O-star color-color diagram obtained by using narrow-band interference filters. The reddening lines found for O stars in three galactic-longitude regions are indicated.

longitude show little scatter about their reddening line and the slope of the mean line varies significantly from region to region, it is somewhat difficult to avoid the conclusion that these variations in the reddening law are due to systematic variations over large regions in space and not to individual peculiarities of the stars themselves or to local modifications of the dust caused by the O stars. If this is true, one should expect the B stars in any given region to exhibit roughly the same law of reddening as the O stars in that region.

However, the B supergiants indicate a somewhat smaller variation in the law of reddening than the O stars. The two-color plot for the B stars is shown in Figure 2. The reddening line for the B stars in the region $l^{\mathrm{II}} = 78°$ is a least-squares fit to the observations and has a slope of +1.47, in agreement with the O stars in this region. The dashed line is a line with the same slope as the O stars in the region $l^{\mathrm{II}} = 17°$ fitted through the point $\mathfrak{U} = +0.90$, $\mathfrak{G} = -1.10$; the approximate reddened colors for the B stars as obtained from a transformation from the U, B, V system. It was found necessary to add a correcting factor to the ultraviolet color of the I*a* supergiants, in order to make the colors of the I*a* stars agree with the I*b* stars. The adopted correction was +0.04 mag. and has a rather large uncertainty. This correction is not included in the colors given in Table 1. Since most of the I*a* stars are highly reddened, the slopes of the reddening lines are sensitive to the value of this correcting factor. In selecting stars for observing, I*b* stars were chosen in preference to I*a* stars because of their higher space density. If one attempts to determine a reddening line based only on observations of I*b* stars, one finds that there

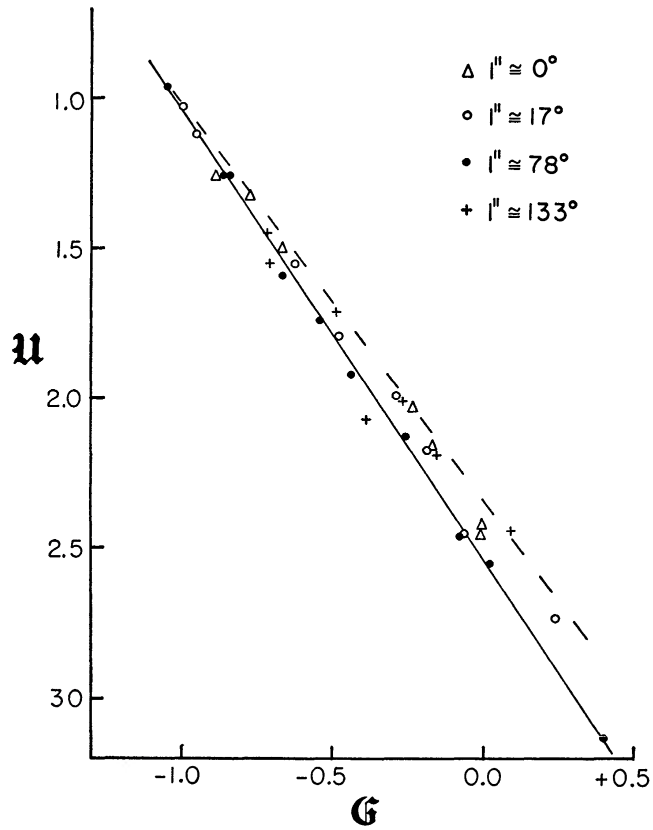

FIG. 2.—The color-color diagram obtained for the B supergiants. The solid line is a least-squares fit to the observations for stars in the region $l^{II} = 78°$. The dashed line is a line with the same slope as O stars in the region $l^{II} = 17°$ fitted to the approximate unreddened color of the B stars.

are not enough highly reddened stars known to determine accurately the deviations in the reddening law. Also there is the fact that stellar luminosities form a continuum and that the normal errors of classification would, to some extent, mix the luminosity classes. Thus one may expect more scatter for the B stars on a diagram like this than for the O stars, simply because of the larger spread in intrinsic colors for the B stars. It is tentatively assumed that uncertainties in the intrinsic colors of the B stars explain their deviation from the law of reddening as determined from the O stars.

III. DISCUSSION

As this new investigation confirms the results previously found, using both the U, B, V data and Borgman's seven-color data, variations in the law of reddening for O stars with galactic longitude seem rather well established. Also the observed gross variations in the law of reddening for the O stars which are presented here do not seem to be caused either by intrinsic differences in the stars (Divan 1956; Rogers 1961) or by the O stars modifying their surroundings, as was suggested by Johnson and Morgan (1955) and more recently in an unpublished doctoral thesis by Hallam (Code 1960). In fact, no correlation was found between the observed reddening law and the cluster membership of a star. In particular, the two most heavily reddened stars in the region around $l = 17°$ appear to be field stars, and, while in the region of Perseus, $l^{\mathrm{II}} = 133°$, the most heavily reddened star, BD +61°411, is associated with the nebula IC 1795 ($l^{\mathrm{II}} = 134°$), although its colors indicate a Cygnus-type reddening law.

The larger deviations of the O stars from an appropriate mean line as shown in Figure 1 appear to be real not only because the instrumental probable errors of the colors are much smaller than these deviations but also because the deviations appear in approximately the same sense and magnitude in the U, B, V colors given by Hiltner and Johnson (1956). The O7 star HD 195213, also noticed by Borgman (1961), is an extreme example of this deviation. The spectral classification was published by Morgan, Code, and Whitford (1955) and has no peculiarity noted. The star appears on the Mount Palomar Sky Survey plates to be a field star. It is, as yet, unclear whether these deviations should be attributed to variations in the intrinsic colors of the O stars or whether they are due to local fluctuations of the law of reddening superimposed on the galactic-longitude effect.

Recently several papers have appeared which predict that the alignment of interstellar dust particles by a galactic magnetic field should cause the law of reddening to vary with galactic longitude (Greenburg and Meltzer 1960; Wilson 1960). Although the data presented in this paper are in general agreement with these predictions, one finds, on closer inspection, that the observations do not support this theory in detail. If the observed variations in reddening are caused by particle alignment, one would expect local fluctuations in the alignment to cause local deviations from some appropriate mean reddening line. Since these fluctuations in alignment should also cause variations in the measured polarization of the starlight, one could expect some correlation between the measured polarization and these deviations. No such correlation has been found. In a previous paper (Wampler 1961) attention was called to the fact that the stars which indicated the lowest value for the reddening slope were not found in the region around $l^{\mathrm{II}} = 133°$, where, from polarization studies, the alignment of particles appears to be best. One could also mention the nebula S 274-8 ($l^{\mathrm{II}} = 118°$, $b^{\mathrm{II}} = +5°$), which contains three O stars—BD +66°1661, +66°1674, and +66°1675. All three of these stars have published U, B, V colors (Hiltner 1956; Osterbrock 1957). BD +66°1675 has also been observed by Borgman (1960) on his narrow-band system. The polarization of BD +66°1661 and +66°1675 as measured by Hiltner is 0.087 and 0.113 mag., respectively. Despite the fact that this high polarization would indicate a low value for the reddening slope, the observed colors of these stars place them on the reddening line defined by the Cygnus O stars. Even though it is possible to explain these deviations from the predicted law of reddening by assuming special local conditions for such things as particle size, intrinsic colors of the stars, etc., perhaps, at the present time, one should adopt the view that these observations, while confirming a variation in the law of reddening with galactic longitude, do not conclusively establish the theory that this variation is caused by alignment of interstellar dust particles.

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REFERENCES

Borgman, J. 1960, *B.A.N.*, **15**, 255.
———. 1961, *ibid.*, **16**, 99.
Code, A. D. 1960, *A.J.*, **65**, 569.
Divan, L. 1956, *Ann. d'ap.*, **19**, 255.
Greenburg, J. M., and Meltzer, A. S. 1960, *Ap J.*, **132**, 667.
Hiltner, W. A. 1956, *Ap. J. Suppl.*, **2**, 389.
Hiltner, W. A., and Johnson, H. L. 1956, *Ap. J.*, **124**, 367.
Johnson, H. L., and Morgan, W. W. 1955, *Ap. J.*, **122**, 142.
Morgan, W. W., Code, A. D., and Whitford, A. E. 1955, *Ap. J. Suppl.*, **2**, 41.
Osterbrock, D. E. 1957, *Ap. J.*, **125**, 622.
Rogers, A. W. 1961, *M.N.*, **122**, 413.
Wampler, E. J. 1961, *Ap. J.*, **134**, 861.
Wilson, R 1960, *M.N.*, **120**, 51