R associations I. *U B V* photometry and MK spectroscopy of stars in southern reflection nebulae

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Photoelectric *U B V* photometry and MK spectral types are presented for stars in van den Bergh and Herbst's (1975) catalogue of southern reflection nebulae. These data are used to identify and to derive distances to 20 new R associations. The galactic distribution of these associations is briefly discussed. The effects of possible contamination of the photometry by nebular light is considered in some detail.

I. INTRODUCTION

IN 1966, van den Bergh (1966) published a catalogue of stars embedded in reflection nebulosity visible on the Palomar Sky Survey prints. On the basis of their nonuniform distribution (which had also been noted by Cederblad 1946) he suggested the existence of associations of stars in reflection nebulae which he called R associations. Racine (1968a) obtained *UBV* photometry and MK spectral types for stars in van den Bergh's catalogue and used this data to confirm the existence of R associations.

The study of R associations has been fruitful in several areas of galactic astronomy. This work may be summarized under four main headings:

(1) R associations may be used as spiral tracers (Racine 1968a, 1969a; van den Bergh 1968; Racine and van den Bergh 1970). Because they are more numerous per unit area on the projected galactic plane, they map out local spiral structure somewhat better than the OB associations do.

(2) Membership in an R association can be used to determine distances for interesting or peculiar objects illuminating reflection nebulae. Racine (1968b, 1969b) determined the distance of the Cepheid SU Cas in this manner.

(3) Because of the large amounts of differential reddening found in many R associations, they are ideally suited to a determination of the ratio of total to selective extinction (*R*) by the variable extinction method. Herbst (1974a) and Racine (1974) have found large values of *R* in two R associations.

(4) Some R associations may be intermediate mass analogs of the OB and T associations, as suggested by van den Bergh (1966). This is supported by the fact that a few R associations contain Herbig Ae- and Be-type stars (Herbig 1960) as members (Herbst 1974b). These stars are young, and in some cases, pre-main-sequence objects (Strom *et al.* 1972). Other investigations dealing with the possible role of R associations in stellar evolution have been made by Racine (1967), Aveni and Hunter (1972), and Shemilt (1974).

As reported in a preceding paper [Astron. J. **80**, 208 (1975)], van den Bergh and Herbst have now extended the survey for stars in reflection nebulae to that portion of the Milky Way not covered by the Palomar Sky Survey. The results of an extensive program of *UBV* photometry and MK spectroscopy of stars in this southern catalogue are presented here. This data has been used to identify 20 new R associations.

II. OBSERVATIONS

The observations were carried out with the University of Toronto 24-in. telescope at Las Campanas Observatory in Chile. *UBV* photometry was obtained for every star in van den Bergh and Herbst's (1975) catalogue with the exception of No. 31. Stars were observed through small (9 or 13 sec) diaphragms in order to minimize contaminations by nebular light. Internal and external mean errors of the photometry are given in Table I.

Classification dispersion (112 Å/mm) spectrograms were obtained for as many of the program stars as possible, using a conventional camera for the bright stars ($B<9.8$), and a single-stage fiber-optics coupled ITT F 4708 image-tube camera for fainter ones.

TABLE I. Accuracy of photometry.

External mean errors

Range	V	$B-V$	$U-B$
$V<8$	0.009	0.007	0.011

Internal mean errors

Range	No. of stars	V	$B-V$	$U-B$
$V<12$	106	0.011	0.008	0.009
$12<V<14$	63	0.018	0.011	0.018
$V>14$	15	0.026	0.022	0.034

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TABLE II. Catalogue of illuminating stars.

No.	CPD/Name	HD	V	$B-V$	$U-B$	n	Sp.T.	Notes
1			12.45	+0.30	−0.22	3		
2			13.40	+0.51	+0.00	4		
3a1			11.43	+0.14	−0.17	3	B6 V	*
3a2			12.12	+0.51	+0.00	3		
3b			11.14	+0.18	−0.10	4	B9 V	
3c			12.27	+0.27	+0.16	3	A0 V	
4			9.77	+0.45	−0.39	3	B1 V	
5			13.47v?	+0.62	+0.27	7		*
6	RS Pup	68860	7.01	+1.49	+1.25	...	F8–K5	*
7	−38°2054	68982	7.59	+0.09	−0.56	3	B2 IV	*
8			11.03	+0.02	−0.36	3	B6 V	
9a			13.17	+0.52	−0.33	3		
9b			14.66	+0.84	−0.17	3		
10a			11.01	+0.33	+0.22	3	A0 V	
11b	−41°2351	70024	9.07	+0.05	−0.36	3	B5 V	*
12a	−49°1602	70584	9.17	+0.29	−0.17	2	B7 V	
12b			11.83	+0.75	+0.18	2		
13a	NGC 2580		10.18	+1.39	+1.46	3	K1 III	*
13b			13.11	+0.81	−0.22	1		
14a			9.63	+0.34	+0.33	3	A2 V	
14b			10.36	+1.24	+1.10	4	K0 III:	
15a			11.83	+0.78	−0.30	3		
15b			13.00	+0.58	−0.25	3		
15c			12.23	+0.46	−0.37	3		
15d			13.57	+0.56	−0.20	2		
16			15.60	+1.88	+0.08	1		
17a	NGC 2626		10.02	+0.46	−0.41	3	B1 V	
18			15.59	+1.22	+0.75	1		
19	−46°2738	73589	8.93	+0.04	−0.46	2	B5 V	
20			10.86	+0.19	−0.23	4	B6 V	
21a			12.22	+0.43	−0.28	4		*
21b			13.13	+0.52	−0.07	3		
22a			12.14	+0.38	−0.24	3		
22b			11.79	+0.70	−0.24	3		
22c			11.58	+0.30	−0.25	3	B5 V	
22d			12.83	+0.49	−0.30	3		
22e			14.15	+0.72	+0.03	4		
23			10.89	+0.32	+0.28	3	A0 V	
24	−42°3114	76534	8.04	+0.11	−0.57	3	B2 Vpe	*
25a	RCW 34		11.81	+0.92	−0.12	7	O9: I:pe	*
25b	−42°3140	76764	9.27	+0.10	−0.39	3	B5 V	
26			14.20	+1.21	+0.11	4		
27a			10.11	+0.09	−0.43	2	B3 V	
27b			13.00	+1.07	+0.37	3		
28			11.28	+0.72	+0.20	2	B5 Vp	*
29a			10.96	+0.43	+0.15	3	B5 V:	*
29b			11.97	+0.45	−0.04	3		
29c			12.42	+0.62	+0.19	3		
30			14.16	+1.36	+0.62	3		
32a			13.49	+0.54	−0.29	3		
33d			14.34	+0.46	+0.48:	4		
34a			12.65	+0.15	−0.41	4		
34c			12.26	+0.17	−0.23	6	B8 V	*
34d			11.93	+0.05	−0.48	3		
34e			12.32	+0.09	−0.37	3		
35			14.92	+0.63:	+0.04	3		
36			10.17	+0.01	−0.72	3	B1 V	
37	−58°2285	91533	6.03	+0.31	−0.07	3	A2 Ia	
38			13.04	+0.57	−0.18	3		
39a			14.48	+0.60	−0.14	3		
40a	−58°2372	92061	9.00	+0.07	−0.74	2	B1.5 III	*
40b			10.39	+0.50	−0.34	3	B2 II	*
40c			9.97	+0.67	−0.25	3	B1.5 II	*
41a	−58°2411	92207	5.52	+0.49	−0.20	3	A1 Ia+	
41b			13.78	+0.57	−0.38	3		
41c			11.86	+0.33	−0.47	3		
42a	−57°3621	92383	9.34	+0.07	−0.80	3	B1 IVn	*
42b			9.70	+0.08	−0.73	3	B0 V	*
43			11.30	+0.29	−0.64	3	B1 Ve	*
44a			9.46	+1.61	+1.96:	4	M0 II:	
44b			12.03	+0.21	−0.47	5	B2 Vpe?	*
44c			13.42	+0.46	−0.02	4		
44d			13.04	+0.32	−0.33	4		
44f			13.19	+0.48	+0.01	2		

TABLE II (*continued*)

No.	CPD/Name	HD	V	$B-V$	$U-B$	n	Sp.T.	Notes
44g			13.50	+0.63	−0.13	2		
45a			12.23	+0.41	−0.54	3		
45b			11.36	+0.44	−0.52	3	B1 Vp?	*
46a			10.46	+0.21	−0.68	4	B0 Ve	*
46b			11.33	+0.21	−0.61	3	B2 Ve	*
46c			11.34	+0.21	−0.58	3	B2 Ve	*
46d			11.38	+0.18	−0.61	3	B2 Ve	*
47a			12.07	+0.43	−0.55	3		
47b			12.99	+0.47	−0.41	3		
47c			13.79v?	+0.97	−0.24:	3		
48a			10.48	+0.11	−0.48	3	B2 V	
49a			14.12	+0.81	−0.09	3		*
50a	−63°1904	100099	8.08	+0.11	−0.82	3	O9 III	*
50b			12.52	+0.73	+0.20	3		
51			10.21	+0.08	−0.72	3	B0.5 V	*
52			13.11	+0.30	−0.36	3		
53a			13.07	+0.45	−0.40	4		
53b			15.39	+1.20	+0.27	1		
54			9.96	−0.01	−0.59	3	B3 V	
55a			11.15	+0.17	−0.25	3	B8 V	
56a	IC 2966		11.47	+0.44	−0.50	4	B0.5 V	
56b	IC 2966		12.16	+0.42	−0.41	3	B1 V	
57a			13.08	+0.80	+0.15	3		
58			12.36	+0.40	−0.19	3	B4 V	*
59			12.57	+0.82	−0.05	3		*
60a			10.79	+0.30	−0.54	2	B2 V	
60b			12.70	+0.35	−0.28	3		
60c			12.02	+0.49	−0.32	3		*
61			10.73	+0.09	−0.71	2	B1 V	
62a			14.12	+0.75	−0.03	3		
62b			11.63	+0.58	−0.24	3		*
62c			12.40	+0.67	−0.27	3		*
63	−64°3016	130079	10.49	+0.32	+0.16	2	B9 V:p?	*
64a			10.63	+0.32	−0.22	3	B3 V	
64b			11.25	+0.41	+0.17	4	B9 V	
65a			13.86v?	+1.84	+1.26:	5		*
65b			12.75	+1.13	+0.16	3		
66			11.64	+0.62	−0.11	4	B3 V	*
67			11.89	+0.70	+0.33	3		
68			11.00	+0.49	−0.40	4	B0.5 V	
69			11.27v	+2.56:	+2.23:	6	M6: III:	*
70			12.82	+0.95	−0.09	3		
71	−38°6420	148657	8.56	+0.28	+0.17	3	A0 V	
72a			11.03	+0.38	−0.30	5	B3 V	
72b			10.79	+0.41	−0.43	4	B2 V	
72c			11.50	+0.66	−0.29	3	B1 Vp?	*
73a	−41°7613		10.13	+0.17	−0.69	3	B2 V	*
73b			13.57	+0.87	+0.30	3		
73c			11.36	+0.43	−0.40	3		*
73d			14.28	+0.92	−0.08:	3		
73e			14.45	+0.80	−0.07:	3		
74			11.21	+0.15	−0.12	3	B8 V	
75			11.43v?	+0.35	−0.55	5	B1 Vp?	*
76			13.95	+1.04	−0.04	6		*
77			10.19	+0.68	+0.19	3	B5 III:	
78			13.13	+1.20	+0.02	3		
79	−45°8234	152979	8.19	+0.15	−0.60	4	B2 IV	*
80	CD −42°11721		11.43v	+1.28	−0.12	6	Bep	*
81a	−50°9813	153772	8.32	+0.06	−0.61	4	B2 V	
81b	−50°9812	153771	8.83	+0.07	−0.56	3	B3 V	
81c			11.41	+0.23	+0.09	3	A0 V	
81d			11.43	+0.59	+0.30	4		
81e			11.23	+0.12	−0.23	4	B8 V	
82			11.60	+0.62	−0.16	3	B3 V	
83			10.92	+0.33	−0.05	3	B8 V	
84			12.44	+0.99	+0.34	4	B2 V:	*
85a			11.86	+0.90	−0.12	3	B0 V	*
85b			13.23	+1.06	−0.01	3		
85c			12.25	+1.34	+0.05	3		
86a			11.09	+1.24	+0.04	3	O7	
86b			10.63	+1.14	+0.01	3	O7	
86c			12.67	+1.21	+0.10	4		
87			15.16	+0.99:	−0.14:	2		

TABLE II (*continued*)

No.	CPD/Name	HD	V	$B-V$	$U-B$	n	Sp.T.	Notes
88a			12.75	+0.85	+0.06	3		
88b			13.41	+0.71	+0.11	3		
88c			13.97	+0.93	+0.14	3		
89			12.77	+1.53	+0.23	3		*
90			10.62	+0.41	−0.22	3	B3 V	
91			11.02	+0.31	−0.37	3	Bep	*
92			12.58	+0.71	+0.02	4		
93a			11.80	+0.42	−0.14	3	B6 V	
93b			13.68	+0.83	+0.41	3		

Notes to Table II

3a1. a1 is SW of a2.
5. Possibly variable. Systematic decrease in V by 0.19 mag over 3 months of observation.
6. Cepheid RS Pup. Mean magnitude and colors from Schaltenbrand and Tammann (1971).
7. Double-line spectroscopic binary (Feast *et al.* 1955).
11b. Ca II lines relatively strong for spectral type; also possible shell cores at Hγ and Hδ.
13a. H emission lines superimposed on spectrum. This may be a nearby K star superimposed on a more distant H II region.
21a. Has faint visual companion ($\Delta m \sim 2$ to 3 mag).
24. Visual binary ($\Delta m \sim 1.5$ mag). Spectrum has Hβ emission and mild shell characteristics at Hγ and Hδ. Radial velocity is +17 km/sec (Thackeray *et al.* 1973).
25a. Emission spectrum consists of strong Hβ, weak Hγ, and the "nebular lines" of [O III] (λ4959 and λ5007). Underlying absorption spectrum shows very broad (almost invisible) lines characteristic of a late-O or early-B giant or supergiant.
28. Hβ is very shallow; it gives the appearance of being partially filled in by emission.
29a. Spectrum is very weak; this could be as late as B8.
34c. Visual binary (Δm very large).
40a. Classified by Dr. Nolan Walborn from spectrograms at 78 Å/mm obtained by him with the 60 in. at Cerro Tololo.
40b. See 40a.
40c. See 40a.
42a. Member of NGC 3293?
42b. Member of NGC 3293? Sp.T. could be as late as B1.
43. Emission spectrum consists of [O III] (λ4959 and λ5007), [O II] (λ3726–3728), Hβ, Hγ, and Hδ. It is probably due to the general nebulosity in this field which is very close to η Car.
44b. There appears to be emission at Hβ and a shell core at Hγ, however this is not definite.
45b. Hβ profile looks peculiar possibly due to emission.
46a. Slight Hβ emission. This could be due to surrounding nebulosity.
46b. See 46a.
46c. See 46a.
46d. See 46a.
47c. Large range in measured V mag (0.34 mag) indicates this star is probably variable.
49a. Association of this star with the nebula is not certain.
50a. Sp.T. from Garrison (1974).
51. Possibly some emission at Hβ present in spectrum.
53b. Visual binary ($\Delta m \approx 0$).
58. Possible trace of Hβ emission and shell core.
59. Very faint visual companion.
60c. Triple star with $\Delta m \sim 2$ and 3 mag.
62b. Very faint visual companion.
62c. Visual binary ($\Delta m \sim 2$ mag).
63. H lines are very strong. There also appear to be weak lines at the position of the G band, and at ∼λ4400. Contamination by solar spectrum is possible since the spectrogram was taken under partly cloudy conditions.
65a. Range in V mag ∼0.24 mag. Very peculiar colors, possibly those of a highly reddened supergiant.
66. Strong Ca II absorption.
69. This M-type giant star is definitely variable in V, the range in observations being 0.34 mag. It may also be variable in its colors.
72c. H lines, especially Hβ, are very wide.
73a. Some emission nebulosity present, yet spectrum is B2.
73c. Westmost star of a close pair.
75. Possibly variable. Same spectral peculiarity as 72c.
76. Variable star. Mean of two independent observations on 30–31 May 1973: $V=14.22$, $B-V=+0.96$, $U-B=+0.63$.
79. Possible member of NGC 6250. This star was called 79a by Herbst (1974a).
80. This star is almost certainly variable, as its range in measured V mag was 0.30 mag. Hydrogen emission lines are seen to Hζ and Fe II lines are also seen. This apparently is a very extreme Be star. No absorption could be seen in the weak underlying continuum. This star has been discussed by Carlson (1968).
84. Spectrogram obtained with widening of only 0.4 mm due to faintness of object.
85a. Hβ profile peculiar possibly due to emission. Ca II is strong.
89. Probably associated with NGC 6357.
91. Extreme Be star. H line emission visible to Hε and Fe II emission lines present. H lines have P Cygni profiles, however some absorption may be visible redward of emission lines. Hγ is sharp in absorption and the Ca II absorption is strong so this may be shell star. No He absorption lines are visible so the spectral type is B5 or later.

Spectrograms of MK classification standard stars were also obtained with both cameras and processed in the same manner as the program stars. The image-tube spectrograms were of poorer resolution (perhaps by a factor of 2) than the conventional ones and, consequently, more difficult to classify. Luminosity classification, especially, proved very difficult for the early-B stars and it may be that some stars classified V are actually class IV. The accuracy of the spectral types is ∼1 MK subclass.

Table II gives the observational results for all stars illuminating nebulae in van den Bergh and Herbst's catalogue. The column headings are self-explanatory except for the one labeled "n" which gives the number of independent UBV measures which were averaged to obtain the tabulated value. Identification charts are given in Plate I (pp. 255–262) of the previous paper (van den Bergh and Herbst 1975).

Some of the stars in Table II appeared to be members of small groups or clusters of stars, in which the other apparent group members did not illuminate reflection nebulae. Many of these "nonnebulous" stars were included in the program. Some turned out to be merely field stars. Slightly more than half, however, did appear to be at the same distance as the nebulous stars and are very likely associated with them. The observa-

TABLE III. Observations of stars in the vicinity of reflection nebulae.

No.	CPD	HD	V	$B-V$	$U-B$	n	Sp.T.	Notes
10b			10.83	+0.66	+0.08	1		
11a	−41°2353	70043	9.85	+0.16	+0.13	3	A1 V	1
11c			11.72	+0.57	+0.39	2		
11e			9.86	+0.89	+0.62	2	G8 V:	
11f			11.81	+0.02	+0.02	2		
11g			12.38	+0.45	+0.02	2		
15e			13.72	+0.66	+0.16	1		
17b			12.13	+0.28	−0.09	2		
25c	−42°3149	76838	7.31	+0.00	−0.71	5	B3 Ve	2
25d	−42°3145		9.03	+0.01	−0.63	2	B3 V	
25e			10.16	+0.14	−0.09	2	B8 Vp?	3
25f			11.39	+0.17	−0.04	2	B8 V	
25g			11.20	+0.45	+0.05	2		
25h			11.52	+0.26	+0.17	2	A1 V	
25i			11.30	+0.39	+0.03	2		
25j			11.85	+0.23	+0.12	4		
25k			14.10	+0.58	+0.10:	2		
25l			13.77	+0.56	−0.04	1		
25m			10.24	+0.43	−0.02	1		
25n	−42°3176	76967	9.16	−0.00	−0.53	1		
25o			11.17	+0.08	−0.12	1		
25p			10.83	+0.15	−0.10	1		
32b			13.09	+0.41	−0.21	4		
33a			10.40	−0.01	−0.37	4	B5 V	
33b	−58°1831	87403	9.30	+0.04	+0.00	4	A0 III:	
33c			11.33	+0.05	−0.06	5	B8 Vn	
33e			13.65	+0.18	−0.11	2		
33f			14.31	+0.99	+0.68	1		
34f			12.46	+0.31	+0.18	3		
34g			11.59	+0.10	−0.37	2		
34s	−59°2003	89202	9.49	−0.02	−0.30	3	B7 V	
39b			13.30	+0.58	+0.14	3		
39d			14.17	+0.93	+0.69	2		
39e			11.70	+0.35	+0.21	3		
45c			11.57	+0.40	−0.56	3	B0 V	
45d			10.75	+0.43	−0.60	4	O6–O7	
48b			11.51	+0.48	+0.00	2		
48e			13.10	+1.39	+1.52	1		
49b			12.27	+1.54	+1.52	1		
53c			12.77	+0.48	+0.26	1		
53d			12.59	+1.37	+1.14	1		
55b			11.62	+0.21	−0.27	3	B7 V	
56c			14.03	+0.70	+0.42	1		
57b			13.76	+0.73	−0.19	4		
57c			11.37	+0.34	+0.27	4	A1 V	
57d			10.50	+0.97	+0.61	3		
60d			10.59	+0.45	−0.42	2		4

Notes to Table III

1. H lines are very broad.
2. Visual binary ($\Delta m=2$ mag). Single-line spectroscopic binary (Feast *et al.* 1955). Hα emission star (Munch 1954).
3. Possibly shell cores at Hγ and Hδ.
4. Triple star.

tional results for the nonnebulous stars are given in Table III.

Figure 1 is the two-color diagram for all the stars in nebulosity (except for No. 16, as discussed below). A blue envelope, as in Racine (1968a), is shown along with two reddening lines of standard slope (Hiltner and Johnson 1956). It is apparent from this diagram that most of the program stars are of early spectral type with, in some cases, very large reddenings. Comparison with the two-color diagram for the northern reflection nebulae (Racine 1968a; Fig. 1) shows that the present selection of stars is more heavily weighted towards luminous, blue objects, and towards more highly reddened stars. This is, at least partially, a selection effect caused by inclusion in the present survey of fainter stars and stars in emission nebulae. The relative paucity of stars with very small reddenings in the present selection is notable. It reflects the fact that none of the program stars is very close to the Sun, and all of them are situated close to the plane of the Galaxy.

There are two highly reddened program stars which lie well above the reddening line for most luminous O-type stars in the two-color diagram. The most widely deviant point, No. 16, has not been plotted since it is a very faint star, observed only once, and its colors, therefore, are very uncertain. They do indicate, however, that it is probably a very highly reddened early-type star. Number 80 (CD −42°11721), at $B-V=+1.28$, falls above the limiting reddening line by 0.24 mag. It is a Bep star with very strong emission lines, which accounts for its peculiar position in the two-color diagram. Carlson (1968) has described the spectrum of this star and also given provisional photometric data from private communications by Henize and Westerlund. This data, and the data obtained during this investigation, indicate that the star is variable, not only in V, but also in $B-V$ and $U-B$. Several other stars lie slightly (≤ 0.1 mag) above the limiting reddening line in Fig. 1. One (No. 47c) has an uncertain $U-B$ value, is a possible variable star, and is located in a peculiar nebulosity. It would be of interest to obtain spectra of these stars as they are likely candidates for emission-line objects.

III. REDDENINGS AND DISTANCES

Intrinsic colors were derived for the stars in Tables II and III, adopting the MK-type and color–color relations given by Johnson (1963) [supplemented by Schmidt–Kaler's (1965) in the regions where Johnson's relations are incomplete]. Hiltner and Johnson's (1956) reddening line

$$\frac{E(U-B)}{E(B-V)}=0.72+0.05E(B-V)$$

was adopted. This is justified by Fig. 2 where all stars with spectroscopically determined color excesses are plotted, and

$$E(U-B)_c=E(U-B)-0.05E(B-V)^2.$$

An impartial least-squares fit to this data gives 0.74 ± 0.04 for the slope and -0.01 ± 0.01 for the intercept of the $E(U-B)_c$ axis, in excellent agreement with Hiltner and Johnson's result.

Absolute magnitudes for class V B stars were assigned according to their intrinsic color, adopting the ZAMS relations of Johnson (1963) and Schmidt-Kaler (1965). Stars of unknown spectral type were assumed to be on the ZAMS, a justifiable assumption since the large majority of stars with known spectral types illuminating reflection nebulae are of class V. Absolute magnitudes for brighter than class V were assigned according to Walborn's (1972) calibration if they were B2 or earlier, and according to Schmidt-Kaler's (1965) calibration if they were later than B2. The few class V stars with spectral types later then A0 were also assigned absolute magnitudes according to Schmidt–Kaler's (1965) calibration.

Table IV gives reddenings, absolute magnitudes, and distance moduli for the stars in Table II. $R=3.3$ (after Aanestad and Purcell 1973) was adopted in deriving the absorption-corrected distance moduli. Reddening values are means of the spectroscopic and photometric determinations in cases where the MK spectral type is known. Table V is a listing of the same quantities derived for the nonnebulous stars from the observational data in Table III. Also included in Table V is an estimate of the probability that the star is at the same distance as the nearby star(s) in nebulosity.

IV. CONTAMINATION BY NEBULAR LIGHT

An unavoidable problem encountered when doing photometry of stars in nebulosity is that light from the nebulae may contribute to the magnitudes and colors obtained for the stars. Such contamination will, of course, affect the quantities of astrophysical interest, in particular, the distance. It is usually impossible to measure and difficult to estimate what the contribution from the nebulosity will be in any given case, due to the irregular nature of the brightness and color distribution across the face of most reflection nebulae. Fortunately, reflection nebulae are generally of quite low surface brightness. Furthermore, the program stars were observed through small (9 or 13 sec) diaphragms. It seems unlikely, therefore, that the nebular contribution would be more than $\sim 10\%$ at worst, and generally much less.

What is the effect of such possible contamination on the reddenings, absolute magnitudes, and distance moduli derived for the illuminating stars? Racine

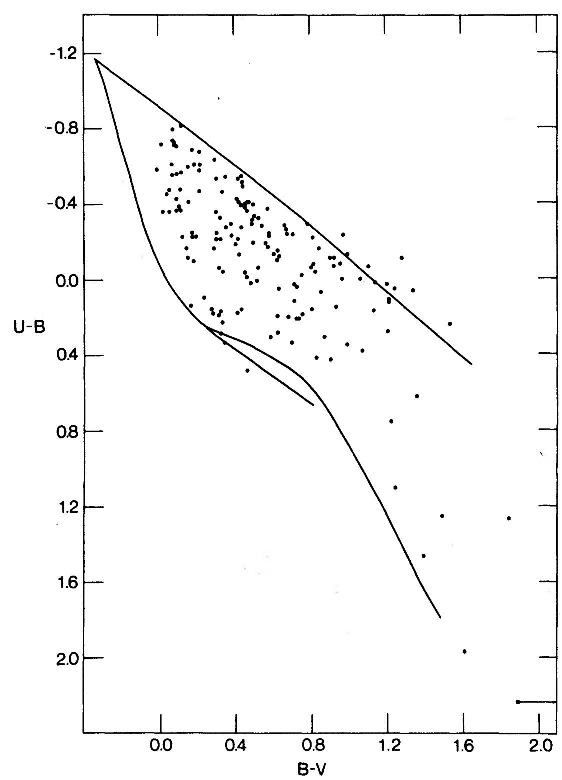

FIG. 1. Two-color diagram for stars in southern reflection nebulae. A blue envelope described in the text is shown along with two limiting reddening lines of standard slope. Number 69 ($B-V=+2.56$:, $U-B=+2.23$:) lies out of the range of this diagram and has been indicated at the bottom right by an arrow. Several stars lie above the reddening line for the earliest-O stars. These are discussed in the text.

TABLE IV. Distance moduli of illuminating stars.

No.	CPD/Name	l	b	$E(B-V)$	M_v			V_0-M_v	Notes
					Sp.T.	Color	Adopted		
1		260.4	−8.0	0.46		−0.40		11.3	
2		249.0	+0.1	0.65		−0.05		11.3	
3a1		255.5	−4.2	0.26	−0.05	+0.55	+0.25	10.3	
3a2		255.5	−4.2	0.65		−0.05		10.0	
3b		255.5	−4.2	0.25	+1.05	+0.70	+0.90	9.4	
3c		255.5	−4.1	0.28	+1.50	+1.40	+1.45	9.9	
4		255.6	−3.1	0.71	−2.35	−2.35	−2.35	9.8	
5		252.9	−1.9	0.69		+0.85		10.6	
6	RS Pup	252.4	−0.2	0.60				11.3	*
7	−38°2054	255.7	−2.3	0.32	−3.10			9.6	
8		253.8	−0.9	0.15	−0.05	+0.00	−0.03	10.6	
9a		254.0	−0.6	0.77		−2.25		12.9	
9b		254.1	−0.6	1.13		−3.90		14.8	
10a		259.3	−3.8	0.34	+1.45	+1.50	+1.47	8.4	
11b	−41°2351	259.2	−3.6	0.20	−0.40	−0.10	−0.25	8.7	
12a	−49°1602	266.3	−7.8	0.42	+0.25	+0.00	+0.10	7.7	
12b		266.1	−7.8	0.89		−0.15		9.0	
				(0.19)		(+1.50)		(9.7)	
13a	NGC 2580	254.7	+0.2	0.32:	+1.00			8.1:	
13b		254.7	+0.2	1.12:		−4.65		14.1::	
14a		258.3	−2.0	0.29	+1.60	+1.58	+1.59	7.1	
14b		258.3	−1.9	0.25:	+1.20:			8.3:	
15a		259.8	−2.8	1.13		−5.70		13.8	*
15b		259.7	−2.8	0.92		−2.00		12.0	
15c		259.7	−2.9	0.71		−2.20		12.1	
15d		259.6	−2.9	0.77		−1.50		12.5	
16		267.7	−7.3	2.23:		−5.75:		14.0::	
17a	NGC 2626	260.0	−0.0	0.72	−2.35	−2.25	−2.30	9.9	
18		259.1	+0.9	1.29:		+0.95:		10.4::	
19	−46°2738	265.4	−3.7	0.21	−0.40	−0.70	−0.55	8.8	
20		260.3	+0.7	0.32	−0.05	+0.00	−0.02	9.8	
21a		263.5	−0.4	0.64		−1.40		11.5	
21b		263.7	−0.2	0.69		−0.60		11.5	
22a		268.2	−2.7	0.56		−0.90		11.2	
22b		268.2	−2.7	0.97		−3.00		11.6	
22c		268.3	−3.2	0.47	−0.40	−0.60	−0.50	10.5	
22d		268.3	−3.1	0.72		−1.80		12.3	
22e		268.3	−3.1	0.91		−0.95		12.1	
23		267.0	−1.3	0.33	+1.50	+1.55	+1.53	8.3	*
24	−42°3114	264.5	+1.0	0.35	−1.90	−1.75	−1.85	8.7	
25a	RCW 34	264.4	+1.4	1.21	−6.2:			14.0:	*
25b	−42°3140	264.4	+1.4	0.27	−0.40	−0.55	−0.50	8.9	
26		267.7	−1.1	1.52		−4.80:		14.0:	*
27a		264.3	+1.9	0.28	−1.10	−0.70	−0.90	10.1	
27b		264.3	+1.9	1.24		−0.55		9.5	
28		264.9	+1.6	0.86	−0.40	+0.20	−0.10	8.5	
29a		268.1	+1.8	0.50	−0.40:	+0.90	+0.90	8.4	
29b		267.9	+1.8	0.56		+0.25		9.9	
29c		267.9	+1.8	0.72		+0.50		9.5	
				(0.26)		(+1.50)		(10.1)	
30		270.8	+0.8	1.54		−0.80		9.9	
31		271.2	+1.4						*
32a		281.8	−1.9	0.79		−2.05		12.9	
33d		282.9	−3.1	0.49		+1.55		11.2	
34a		284.8	−3.1	0.34		−0.85		12.4	
34c		284.8	−3.1	0.28	+0.70	+0.10	+0.40	10.9	
34d		284.8	−3.1	0.24		−0.85		12.0	
34e		284.8	−3.5	0.25		−0.35		11.8	
35		285.4	−3.4	0.78:		−0.30		12.6:	
36		284.1	−0.3	0.27	−2.35	−2.25	−2.30	11.6	
37	−58°2285	285.7	−0.5	0.34	−6.7:			11.6:	*
38		287.2	−3.0	0.78		−1.50		12.0	
39a		286.3	−1.3	0.81		−1.35		13.2	
40a	−58°2372	286.3	−0.5	0.32	−4.20			12.1	
40b		286.0	−0.8	0.72	−4.5:			12.5:	
40c		285.9	−0.8	0.90	−5.0:			12.0:	
41a	−58°2411	286.3	−0.3	0.50	−7.1:			11.0:	*
41b		286.2	−0.2	0.86		−3.70		14.6	
41c		286.1	−0.0	0.59		−2.25		12.2	
42a	−57°3621	286.1	+0.4	0.35	−4.00			12.2	
42b		286.0	+0.4	0.37	−4.20	−3.05	−3.65	12.1	
43		287.9	−0.9	0.57	−2.35	−4.35	−2.35	11.8	*

TABLE IV (*continued*)

No.	CPD/Name	l	b	$E(B-V)$	M_v Sp.T.	M_v Color	M_v Adopted	V_0-M_v	Notes
44a		286.8	+2.9	0.06:	−2.5:			11.7:	
44b		286.8	+2.9	0.44	−1.90	−1.50	−1.70	12.3	
44c		286.8	+2.9	0.59		0.00		11.5	
44d		286.8	+2.9	0.52		−1.15		12.5	
44f		286.8	+2.9	0.60		+0.10		11.1	
44g		286.8	+2.9	0.84		−1.45		12.2	
45a		290.3	−3.0	0.71		−4.20		14.1	
45b		290.3	−3.0	0.72	−2.35	−4.35	−3.35	12.3:	*
46a	NGC 3503	289.5	+0.1	0.51	−4.20	−3.85	−4.00	12.8	
46b	NGC 3503	289.5	+0.1	0.47	−1.90	−2.80	−2.35	12.1	
46c	NGC 3503	289.5	+0.1	0.46	−1.90	−2.40	−2.15	12.0	
46d	NGC 3503	289.5	+0.1	0.43	−1.90	−2.40	−2.15	12.1	
47a		291.2	−0.7	0.75		−4.80		14.4	
47b		291.2	−0.8	0.74		−2.80		13.3	
47c		291.3	−0.8	1.32		−5.7:		15.1:	
48a		291.9	+2.1	0.33	−1.90	−1.15	−1.55	10.9	
49a		293.8	−1.7	1.06		−2.35		13.0	
50a	−63°1904	294.1	−2.3	0.43	−5.6			12.3	*
50b		294.1	−2.3	0.86		+0.00		9.7	
51		294.3	−1.9	0.36	−3.15	−2.90	−3.05	12.1	
52		295.4	−2.7	0.51		−1.30		12.7	
53a		296.3	−3.6	0.71		−2.40		13.1	
53b		296.3	−3.5	1.45:		−2.10:		12.7:	
54		295.5	+0.5	0.20	−1.10	−1.30	−1.20	10.5	
55a		295.7	−0.3	0.28	+0.70	+0.00	+0.35	9.9	
56a	IC 2966	296.5	−2.8	0.73	−3.15	−4.05	−3.60	12.7	
56b	IC 2966	296.5	−2.8	0.68	−2.35	−2.35	−2.35	12.3	
57a		299.7	−0.6	0.97		−0.55		10.4	
58		303.7	−3.4	0.57	−0.70	−0.65	−0.68	11.2	
59		305.0	+0.5	1.03		−2.00		11.2	
60a		306.1	+0.1	0.56	−1.90	−2.70	−2.30	11.2	
60b		306.1	+0.1	0.54		−1.00		11.9	
60c		306.0	+0.0	0.73		−1.95		11.6	
61		306.2	−0.3	0.36	−2.35	−2.90	−2.60	12.1	
62a		317.0	+1.0	0.96		−1.50		12.5	
62b		317.0	+1.0	0.81		−1.85		10.8	
62c		317.0	+1.0	0.95		−3.15		12.4	
63	−64°3016	314.9	−5.1	0.36	+1.05	+1.25	+1.15	8.1	
64a		318.4	−0.7	0.50	−1.10	−0.50	−0.80	9.8	
64b		318.3	−0.7	0.47	+1.05	+1.05	+1.05	8.6	
65a		316.9	−4.0					10.5	*
65b		317.1	−4.2	1.39		−2.60		10.8	
66		318.6	−4.3	0.83	−1.10	−1.35	−1.20	10.1	
67		325.1	−1.9	0.78		+0.75		8.6	
68		328.2	−0.5	0.77	−3.15	−2.90	−3.05	11.5	*
69		331.6	+0.1	0.76:	−1.0:			9.8:	
70		332.4	+0.6	1.25		−4.20		12.9	
71	−38°6420	343.2	+6.8	0.29	+1.50	+1.40	+1.45	6.2	
72a		336.6	−1.4	0.59	−1.10	−1.30	−1.20	10.3	*
72b		336.3	−1.3	0.66	−1.90	−2.40	−2.15	10.8	*
72c		336.3	−1.4	0.93	−2.35	−3.40	−2.85	11.3	*
73a	−41°7613	343.0	+2.7	0.43	−1.90	−3.55	−2.7:	11.4:	*
73b		343.0	+2.7	1.01		−0.05		10.3	
73c		343.0	+2.8	0.66	−1.10	−2.35	−1.75	10.9	
73d		343.0	+2.7	1.20		−3.4:		13.7:	
73e		342.9	+2.8	1.04		−2.1:		13.1:	
74		338.0	−2.1	0.23	+0.70	+0.70	+0.70	9.8	*
75		345.0	+1.8	0.63	−2.35	−3.55	−2.95	12.3	*
76		340.9	−1.9	1.27		−4.60		14.4::	
77		345.0	+1.2	0.82	−2.2:			9.7:	
78		345.4	+1.5	1.55		−5.7:		13.7:	*
79	−45°8234	340.7	−2.2	0.40	−3.10			10.0	*
80		343.3	−0.1						
81a	−50°9813	337.2	−5.9	0.29	−1.90	−1.70	−1.80	9.2	
81b	−50°9812	337.2	−5.9	0.28	−1.10	−1.45	−1.25	9.2	
81c		337.2	−5.9	0.25	+1.50	+1.25	+1.35	9.2	
81d		337.2	−5.9	0.33		+1.60		8.7	
81e		337.2	−5.9	0.22	+0.70	+0.30	+0.50	10.0	
82		346.3	+0.6	0.83	−1.10	−1.55	−1.30	10.2	
83		344.9	−2.1	0.43	+0.70	+0.35	+0.55	9.0	
84		348.1	+0.2	1.15	−1.90:	−0.45	−0.45	9.1	
85a		351.3	+1.0	1.19	−4.20	−3.85	−4.00	11.9	

TABLE IV (*continued*)

No.	CPD/Name	l	b	$E(B-V)$	M_v Sp.T.	Color	Adopted	V_0-M_v	Notes
85b		351.2	+0.6	1.36		−4.35		13.1	
85c		351.3	+0.7	1.69		−5.70		12.4	
86a		351.0	+0.6	1.58	−5.15	−5.70	−5.40	11.3	
86b		351.0	+0.6	1.47	−5.15	−5.40	−5.25	11.0	
86c		351.0	+0.6	1.52		−5.00		12.7	
87		344.7	−4.3	1.34::		−5.7::		16.4::	*
88a		341.9	−3.9	1.06		−1.45		10.7	
88b		342.0	−3.8	0.87		−0.45		11.0	
88c		342.1	−3.7	1.14		−1.35		11.6	
89		353.2	+0.9	1.88		−5.7		12.3	
90		352.0	−0.4	0.60	−1.10	−0.95	−1.05	9.7	
91		349.9	−3.5						
92		358.3	−1.9	0.92		−1.35		10.9	
93a		358.7	−2.3	0.56	−0.05	−0.50	−0.25	10.2	
93b		358.6	−2.3	0.50		+1.50		10.5	
				(0.92)		(+0.60)		(10.0)	

Notes to Table IV

6. Distance modulus determined by Havlen (1972) using phase relation between star and nebula light variations. Possible member of Pup OB3 (Westerlund 1963). Reddening taken from Sandage and Tammann (1969).
15a. The derived distance modulus is likely too large since: (1) The colors are those of a highly reddened, early-O star, yet the nebula is reflection, not emission. (2) The other stars in this group have smaller distance moduli. Perhaps this is an emission-line star.
23. This star sits below the limiting reddening line for class V stars in the color–color diagram by ~0.05 mag.
25a. This star is probably a peculiar member of Vela R2 which has a distance modulus of 9.7.
26. The derived distance modulus is likely too large since: (1) It has the colors of a reddened O9 star but the nebula appears to be reflection rather than emission. (2) It appears to be associated with the dust-filled H II region RCW 38 which is located at a distance of not over 2 kpc and probably much less (Radhakrishnan *et al.* 1972).
31. No observations are available for this star since it could not be found with the 24-in.
33d. This star sits below the limiting reddening line in the color–color diagram.
37. The absolute magnitude calibration for A supergiants is very uncertain. Schmidt-Kaler's (1965) values were adopted.
41a. See 37.
43. Due to the presence of emission in the spectrum, the colors are not an accurate indicator of M_V. The large $U-B$ excess is probably due to Balmer continuum emission.
45b. There is a large discrepancy between the two M_V determinations of this star, which also has a somewhat peculiar spectrum (see notes to Table II).
47c. Sits above reddening line for earliest-O stars. Also variable and located in a peculiar nebula (see Table II).
50. Member of IC 2944 according to Thackeray and Wesselink (1965).
65a. The distance modulus for this peculiar object was determined assuming it to be a member of Cir R2.
68. Possibly a member of Norma OB1.
72a. Located in a region with a high value of R.
72b. See 72a.
72c. See 72a.
73a. Large discrepancy in M_V determinations. Also see notes to Table II.
74. See 72a.
75. See 73a.
78. Sits above reddening line for earliest-O stars.
79. See 72a. This star was labeled 79a by Herbst (1974a).
87. Location at edge of obvious dark cloud indicates that the distance to this object is really much smaller than derived.

(1971) has shown from his observations of the bright reflection nebula Ced 201 and from observations of Merope by Elvius and Hall (1967) that the color differences between nebula and illuminating star at different spots in the nebula fall along the standard reddening line in the two-color diagram. Points closer to the star are bluer than it. Therefore, with increasing contamination, the apparent reddening of the star will decrease while its apparent visual magnitude will, of course, brighten.

It is not immediately obvious how V_0 or M_V will behave with increasing contamination. This depends on the amount of contamination and on the color difference between the star and the nebula at 0° offset. If we define

$$X \equiv \frac{I(V)_{\text{neb}}}{I(V)_{\text{star}}},$$

where $I(V)$ is the intensity in the V bandpass, and $\delta(B-V) \equiv (B-V)_{\text{star}} - (B-V)_{\text{neb}}$ at 0° offset, then

$$\Delta V \equiv V_{\text{neb+star}} - V_{\text{star}} = -2.5 \log (1+X).$$

Assuming a reddening-line slope of 0.72 and the standard ZAMS intrinsic color relation for B stars, an expression for $\Delta E(B-V)$ in terms of X and $\delta(B-V)$ may be derived. For stars in the range $-0.95 \leq (U-B)_0 \leq 0.00$, the slope of the $M_V-(U-B)_0$ relation is ~4.35. Assuming a value of 3 for R, it is, therefore, possible to calculate the variation of $\Delta(V_0-M_V)$ with X is $\delta(B-V)$ is known.

Unfortunately, it is virtually impossible to measure an accurate value for $\delta(B-V)$ due to the problem of scattered light from the illuminating star near 0° offset. Furthermore, it is risky to extrapolate from measures at large offsets because of the probable rapid variation of the colors near 0° offset (Greenberg and Hanner 1970). The measured value for Merope, obtained by

TABLE V. Distance moduli of stars in the vicinity of relection nebulae.

No.	CPD	$E(B-V)$	M_v Sp.T.	M_v Color	M_v Adopted	V_0-M_v	Membership	Notes
10b		0.81:		−0.30:		8.5:	y	
		(0.10:)		(+1.50:)		(9.0:)		
11a	−41°2353	0.14	+1.70	+1.55	+1.60	7.8	y	
11c		0.67		+1.40		8.1	y	
11e		0.16:	+5.5:			3.8:	n	
11f		0.64		+0.00		9.7	y?	
11g		0.56		+0.35		10.2	y?	
15e		0.79:		+0.05:		11.1:	y?	
		(0.67:)		(+1.50:)		(10.0:)		
17b		0.39		+0.40		10.4	y	1
25c	−42°3149	0.23	−1.10	−2.20	−1.65	8.2	y	2
25d	−42°3145	0.22	−1.10	−1.65	−1.35	9.7	y	
25e		0.22	+0.70	+0.85	+0.80	8.6	y	
25f		0.24	+0.70	+1.00	+0.85	9.8	y	
25g		0.55		+0.45		8.9	y	
25h		0.25	+1.70	+1.45	+1.60	9.1	y	
25i		0.49		+0.55		9.1	y	
25j		0.25		+1.35		9.7	y	
25k		0.70		+0.15		11.1	n?	
25l		0.73		−0.55		11.9	n?	
25m		0.55		+0.20		8.2	y	
25n	−42°3176	0.19		−0.90		9.4	y	
25o		0.15		+0.90		9.8	y	
25p		0.23		+0.80		9.3	y	
32b		0.59		−0.80		11.9	y	1
33a		0.13	−0.40	+0.05	−0.20	10.0	y	1
33b	−58°1831	0.05	+0.10:			9.0:	y?	1
33c		0.11	+0.70	+1.25	+1.00	10.0	y	
33e		0.27		+0.65		12.1	y	
33f		0.12:		+6.2:		7.8::	n?	
34f		0.33		+1.35		10.0	y	
34g		0.26		−0.40		11.1	y	
34s	−59°2003	0.13	+0.25	−0.65	−0.20	9.3	n	
39b		0.68		+0.40		10.7	n?	
39d		0.04		+6.3:		7.7::	n?	
39e		0.37		+1.35		9.1	n?	
		(0.18)		(+1.60)		(9.5)		
45c		0.71	−4.20	−3.00	−3.60	12.8	y	
45d		0.76	−5.15	−5.7:	−5.15	13.4	y	
48b		0.61		+0.00		9.5	n?	
48e							n	3
49b							n	3
53c		0.52:		+1.20:		9.9	n	
53d							n	3
55b		0.35	+0.25	−0.30	−0.05	10.5	y	1
56c		0.70:		+1.50:		10.2:	n?	
57b		0.99		−2.70		13.2	n?	1
57c		0.31	+1.70	+1.55	+1.60	8.7	n	
57d							n	3
60d		0.72		−2.70		11.4:	y	1, 4

Membership classes:
y = likely member of group of stars at same distance as nebulosity.
n = unlikely to be a member of such a group.

Notes to Table V

1. Possibly in very faint nebula.
2. See notes to Table IV.
3. Probably a foreground K giant or dwarf.
4. Triple star. 0.5 mag added to V_0-M_v.

extrapolating the observations of Elvius and Hall (1967) is $\delta(B-V)=0.6$. From the theoretical work of Greenberg and Hanner (1970), a reasonable range for the quantity is $0.2\leq\delta(B-V)\leq0.8$.

Figure 3 shows the variation of several quantities of astrophysical interest with X, for various assumed values of $\delta(B-V)$ in the expected range. The V magnitude is brightened and the reddening reduced by contamination, as expected. M_V (determined from photometry) is also always brightened by contamination. V_0 and the distance moduli, on the other hand, depend on $\delta(B-V)$ not only for the magnitude, but also for their direction of change. In all three cases there are values of $\delta(B-V)$ for which contamination will not affect the derived quantities. The variation of the absorption-corrected distance modulus is, unfortunately, quite severe for $\delta(B-V)\geq0.6$. However, if $X\leq0.1$, then $\Delta(V_0-M_V)\leq0.4$ and much less if

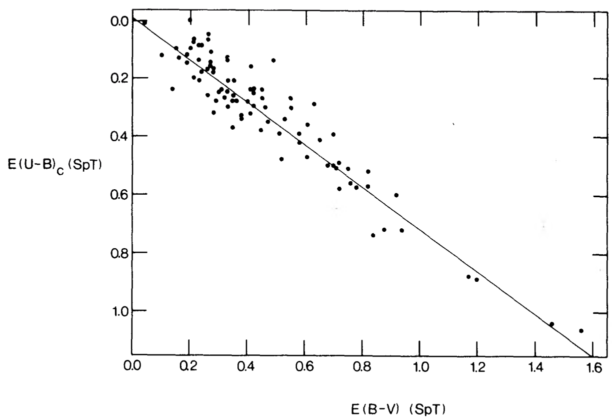

FIG. 2. Color excesses for all program stars of known spectral type. Intrinsic colors were determined solely on the basis of MK spectral type. $E(U-B)_c = E(U-B) - 0.05E(B-V)^2$. An impartial least-squares fit to this data gave $E(U-B)_c/E(B-V) = 0.74 \pm 0.04$ and $E(U-B)_c$ intercept $= -0.01 \pm 0.01$, and this regression line is shown.

$\delta(B-V) \leq 0.6$. This error is comparable with or less than the error caused by uncertainties in the absolute-magnitude calibration. Also, the discussion above assumed that the absolute magnitude was derived solely on the basis of photometry. If, as is the case for many of the program stars, M_V is determined from the spectral type of the star, it will be unaffected by contamination. In this case the variation of $\Delta(V_0 - M_V)$ will reduce to the variation of ΔV_0, which, as Fig. 3 shows, is less severe.

The effect of contamination on $V - M_V$ and $E(B-V)$ is fairly small, an important point since these quantities are used in determining the ratio of total to selective extinction (eg., Herbst 1974a; Racine 1974). Furthermore, no systematic effect on R would be expected since it seems unlikely that, in general, the degree of contamination is a function of reddening. In the case of Ara R1 (Herbst 1974a) there is some evidence that the degree of contamination decreases with increasing reddening for the three most highly reddened objects 72a, b, and c. Inspection of Plate II of Herbst's (1974a) paper shows that the nebulosity surrounding the least-reddened star 72a is considerably brighter relative to the star than is the nebulosity surrounding the most highly reddened star 72c. The effect of such systematic contamination would most likely be to lower the derived value of R from its "true" value, or to leave it unchanged.

The main conclusions to be drawn from the discussion above may be summarized as follows:

(1) The effects of contamination are a brightening of V and M_V, a decrease in the reddening, and *probably* an overestimation of the distance.

(2) While, in general, it is impossible to tell exactly how the derived distance modulus will be affected by contamination, in the large majority of cases the effect will be quite small, and even in the worst case, the error should be less than 0.4 mag.

V. THE SOUTHERN R ASSOCIATIONS

The process of identifying associations of stars in nebulae is one which requires a good deal of judgment. The best criterion for establishing the physical association of an apparent group is obvious connection with a single dark dust cloud. Unfortunately, very few associations meet this criterion, an important exception being Ara R1 (Herbst 1974a). In most cases one must resort to comparing distance moduli of possible association members. This, unfortunately, can give misleading evidence in the case of peculiar stars. Approximately 85% of the stars in Table II were assigned to an association. In many cases subgroups were found within larger associations. Membership lists and brief comments for the 20 newly identified R associations are given in Table VI. In contrast with the northern R associations, fewer are found to be associated with

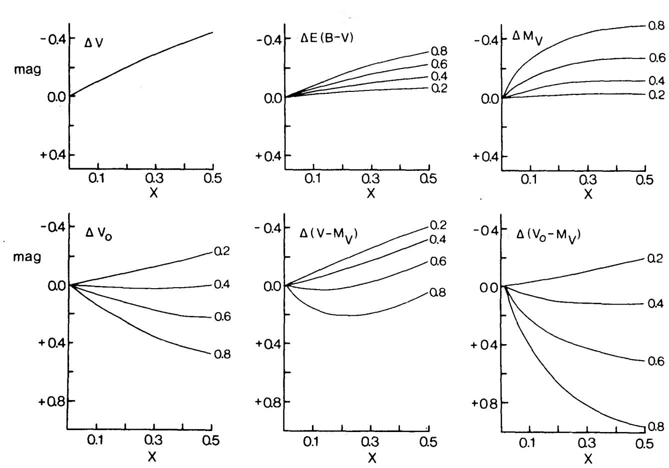

FIG. 3. The variation of six quantities derived for stars in nebulosity with increasing contamination of the photometry by nebular light. See text for definition of symbols. ΔV is independent of $\delta(B-V)$. The other quantities depend on it and four solutions are given, in each case labeled by the assumed value of $\delta(B-V)$. Note that negative values of $\Delta(V_0 - M_V)$ mean that the distance is underestimated due to nebular contamination, while positive values mean it is overestimated.

TABLE VI. Southern R associations.

No.	l	b	Sp.T.	$E(B-V)$	V_0-M_V
			ARA R1		
72a	336.6	−1.4	B3 V	0.59	10.3
72b	336.3	−1.3	B2 V	0.66	10.8
72c	336.3	−1.4	B1 Vp?	0.93	11.3
74	338.0	−2.1	B8 V	0.23	9.8
79	340.7	−2.2	B2 IV	0.40	10.0
			CARINA R1		
32a	281.1	−1.9	···	0.79	12.9
32b	281.8	−1.9	···	0.59	11.9
33d	282.9	−3.1	···	0.49	11.2
34a	284.8	−3.1	···	0.34	12.4
34c	284.8	−3.1	B8 V	0.28	10.9
34d	284.8	−3.1	···	0.24	12.0
34e	284.8	−3.1	···	0.25	11.8
35	285.4	−3.4	···	0.78:	12.6:
36	284.1	−0.3	B1 V	0.27	11.6
37	285.7	−0.5	A2 Ia	0.34	11.6:
38	287.2	−3.0	···	0.78	12.0
39a	286.3	−1.3	···	0.81	13.2
40a	286.3	−0.5	B1.5 III	0.32	12.1
40b	286.0	−0.8	B2 II	0.72	12.5
40c	285.9	−0.8	B1.5 II	0.90	12.0
41a	286.3	−0.3	A1 Ia+	0.50	11.0
41b	286.2	−0.2	···	0.86	14.6
41c	286.1	−0.0	···	0.59	12.2
42a	286.1	+0.4	B1 IVn	0.35	12.2
42b	286.0	+0.4	B0 V	0.37	12.1
43	287.9	−0.9	B1 Ve	0.57	11.8
44a	286.8	+2.9	M0 II:	0.06:	11.7:
44b	286.8	+2.9	B2 Vpe?	0.44	12.3
44c	286.8	+2.9	···	0.59	11.5
44d	286.8	+2.9	···	0.52	12.5
44f	286.8	+2.9	···	0.60	11.1
44g	286.8	+2.9	···	0.84	12.2
46a	289.5	+0.1	B0 Ve	0.51	12.8
46b	289.5	+0.1	B2 Ve	0.47	12.1
46c	289.5	+0.1	B2 Ve	0.46	12.0
46d	289.5	+0.1	B2 Ve	0.43	12.1
			CARINA R2		
45a	290.3	−3.0	···	0.71	14.1
45b	290.3	−3.0	B1 Vp?	0.72	12.3:
45c	290.3	−3.0	B0 V	0.71	12.8
45d	290.3	−3.0	O6–O7	0.76	13.4
47a	291.2	−0.7	···	0.75	14.4
47b	291.2	−0.8	···	0.74	13.3
47c	291.3	−0.8	···	1.32	15.1:
				Mean 0.73	13.6±0.5
			CENTAURUS R1		
58	303.7	−3.4	B4 V	0.57	11.2
59	305.0	+0.5	···	1.03	11.2
60a	306.1	+0.1	B2 V	0.56	11.2
60b	306.1	+0.1	···	0.54	11.9
60c	306.1	+0.1	···	0.73	11.6
60d	306.1	+0.1	···	0.72	11.4:
61	306.2	−0.3	B1 V	0.36	12.1
				Mean 0.64	11.5±0.3
			CENTAURUS R2		
50a	294.1	−2.3	O9 III	0.43	12.3
50b	294.1	−2.3	···	0.86	9.7
51	294.3	−1.9	B0.5 V	0.36	12.1
52	295.4	−2.7	···	0.51	12.7
53a	296.3	−3.6	···	0.71	13.1
53b	296.3	−3.6	···	1.45:	12.7::
56a	296.5	−2.8	B0.5 V	0.73	12.7
56b	296.5	−2.8	B1 V	0.68	12.3
				Mean 0.61	12.5±0.3
			CENTAURUS R3		
48a	291.9	+2.1	B2 V	0.33	10.9
54	295.5	+0.5	B3 V	0.20	10.5
55a	295.7	−0.3	B8 V	0.28	9.9
55b	295.7	−0.3	B7 V	0.35	10.5
57a	299.7	−0.6	···	0.97	10.4
				Mean 0.42	10.4±0.2
			CIRCINIS R1		
62a	317.0	+1.0	···	0.96	12.5
62b	317.0	+1.0	···	0.81	10.8
62c	317.0	+1.0	···	0.95	12.4
				Mean 0.91	11.9±0.8
			CIRCINIS R2		
63	314.9	−5.1	B9 V:p?	0.36	8.1
65a	316.9	−4.0	···	···	···
65b	317.1	−4.2	···	1.39	10.8
66	318.6	−4.3	B3 V	0.83	10.1
				Mean 1.11	10.5±0.4
			PUPPIS R1		
15a	259.8	−2.8	···	1.13	13.8
15b	259.7	−2.8	···	0.92	12.0
15c	259.7	−2.9	···	0.71	12.1
15d	259.6	−2.9	···	0.88	12.5
				Mean 0.88	12.6±0.6
			PUPPIS R2		
3a1	255.5	−4.2	B6 V	0.26	10.3
3a2	255.5	−4.2	···	0.65	10.0
3b	255.5	−4.2	B9 V	0.25	9.4
3c	255.5	−4.1	A0 V	0.28	9.9
4	255.6	−3.1	B1 V	0.71	9.8
7	255.7	−2.3	B2 1V	0.32	9.6
17a	260.0	−0.0	B1 V	0.72	9.9
17b	260.0	−0.0	···	0.39	10.4
18	259.1	+0.9	···	1.29:	10.4::
20	260.3	+0.7	B6 V	0.32	9.8
				Mean 0.43	9.9±0.2
			PUPPIS R3		
2	249.0	+0.1	···	0.65	11.3
5	252.9	−1.9	···	0.69	10.6
6	252.4	−0.2	F8–K5	0.60	11.3
8	253.8	−0.9	B6 V	0.15	10.6
				Mean 0.52	11.0±0.3
			SCORPIUS R2		
81a	337.2	−5.9	B2 V	0.29	9.2
81b	337.2	−5.9	B3 V	0.28	9.2
81c	337.2	−5.9	A0 V	0.25	9.2
81d	337.2	−5.9	···	0.33	8.7
81e	337.2	−5.9	B8 V	0.22	10.0
				Mean 0.27	9.3±0.3
			SCORPIUS R3		
88a	341.9	−3.9	···	1.06	10.7
88b	342.0	−3.8	···	0.87	11.0
88c	342.1	−3.7	···	1.14	11.6
				Mean 1.02	11.1±0.3

TABLE VI (*continued*)

No.	l	b	Sp.T.	$E(B-V)$	V_0-M_V
			SCORPIUS R4		
73a	343.0	+2.7	B2 V	0.43	11.4:
73b	343.0	+2.7	···	1.01	10.3
73c	343.0	+2.8	···	0.66	10.9
73d	343.0	+2.7	···	1.20	13.7:
73e	342.9	+2.8	···	1.04	13.1:
75	345.0	+1.8	B1 Vp?	0.63	12.3
77	345.0	+1.2	B5 III:	0.82	9.7:
78	345.4	+1.5	···	1.55	13.7:
			Mean	0.77	11.2±0.8
			SCORPIUS R5		
82	346.3	+0.6	B3 V	0.83	10.2
83	344.9	−2.1	B8 V	0.43	9.0
84	348.1	+0.2	B2 V:	1.15	9.1
90	352.0	−0.4	B3 V	0.60	9.7
			Mean	0.75	9.5±0.4
			SCORPIUS R6		
85a	351.3	+1.0	B0 V	1.19	11.9
85b	351.2	+0.6	···	1.36	13.1
85c	351.3	+0.7	···	1.69	12.4
86a	351.0	+0.6	O7	1.58	11.3
86b	351.0	+0.6	O7	1.47	11.0
86c	351.0	+0.6	···	1.52	12.7
89	353.2	+0.9	···	1.88	12.3
			Mean	1.53	12.1±0.5
			SCORPIUS R7		
92	358.3	−1.9	···	0.92	10.9
93a	358.7	−2.3	B6 V	0.56	10.2
93b	358.6	−2.3	···	0.50	10.5
			Mean	0.66	10.5±0.2

No.	l	b	Sp.T.	$E(B-V)$	V_0-M_V
			VELA R1		
10a	259.3	−3.8	A0 V	0.34	8.4
10b	259.3	−3.8	···	0.81:	8.5:
11a	259.2	−3.6	A1 V	0.14	7.8
11b	259.2	−3.6	B5 V	0.20	8.7
11c	259.2	−3.6	···	0.67	8.1
14a	258.3	−2.0	A2 V	0.29	7.1
14b	258.3	−1.9	K0 III:	0.25:	8.3:
12a	266.3	−7.8	B7 V	0.42	7.7
12b	266.1	−7.8	···	0.89	9.0
19	265.4	−3.7	B5 V	0.21	8.8
			Mean	0.40	8.2±0.5
			VELA R2		
24	264.5	+1.0	B2 Vpe	0.35	8.7
25a	264.4	+1.4	O9: I:pe	1.21	···
25b	264.4	+1.4	B5 V	0.27	8.9
27a	264.3	+1.9	B3 V	0.28	10.1
27b	264.3	+1.9	···	1.24	9.5
28	264.9	+1.6	B5 Vp	0.86	8.5
29a	268.1	+1.8	B5 V:	0.50	8.4
29b	267.9	+1.8	···	0.56	9.9
29c	267.9	+1.8	···	0.72	9.5
30	270.8	+0.8	···	1.54	9.9
			VELA R3		
22a	268.2	−2.7	···	0.56	11.2
22b	268.2	−2.7	···	0.97	11.6
22c	268.3	−3.2	B5 V	0.47	10.5
22d	268.3	−3.1	···	0.72	12.3
22e	268.3	−3.1	···	0.91	12.1
			Mean	0.73	11.5±0.5

Notes to Table VI

Ara R1: Ara R1 has been fully discussed by Herbst (1974a). It is associated with the galactic cluster NGC 6193 and the H II region RCW 108. It is a good example of an R association whose members are connected with a single dark dust cloud. The ratio of total to selective extinction in this association was found to be abnormally large by Herbst (1974a).

Car R1: The Carina region contains one of the highest concentrations of reflection nebulae in the sky, yet all of these nebulae appear to be members of only two associations. Car R1 is the largest R association in terms of both volume and number of members. It is in the same region and probably connected with the Carina nebula (NGC 3372). A full discussion of this important association will be published separately (Herbst 1975a).

Car R2: The smaller association in Carina, Car R2, consists of two well-defined subgroups formed of the stars numbered 45 and 47. The 47 subgroup is associated with the emission nebulosity RCW 57a (NGC 3576). Two peculiar stars are members of Car R2: 45b is a possible emission-line star, and 47c has peculiar colors (placing it above the reddening line for the earliest O stars), is a probable variable, and is located in nebulosity with a peculiar "hour-glass" form. These two stars have been omitted from the determination of mean reddening and distance modulus.

Cen R1: Number 58 is separated from the others by ∼4°, but has been included as a member of Cen R1 on the basis of its distance modulus. This association is located at the edge of the southern Coalsack. It is probably associated with Cen OB1 which also has a corrected distance modulus of 11.5 (Klare 1967).

Cen R2: Number 49a ($V_0-M_V=13.0$) is another possible member of Cen R2, however the association of this star with nebulosity is not certain. Number 50b appears to illuminate part of the same cloud as 50a yet its distance modulus is discrepant. This suggests that No. 50b may be a giant, however, no spectrogram is available for the star. This association lies in the region of IC 2944/2948, an extensive H II region and cluster near λ Cen. The cluster has a corrected distance modulus of 11.5 according to Thackeray and Wesselink (1965) and, hence may not be associated with Cen R2 (although No. 50a was included as a cluster member by Thackeray and Wesselink). Numbers 50b and 53b were omitted from the determination of mean reddening and distance modulus.

Cen R3: This is a very loose association spreading over 7° in galactic longitude; nevertheless, the range in corrected distance modulus among the members is quite small and the group is identified mostly on this basis.

Cir R1: This group could possibly be associated with Cir R2.

Cir R2: On the basis of its distance, the possibly peculiar star Number 63 may not be a member of this small group and has not been included in the determination of the mean reddening and distance modulus. Another peculiar object, No. 65a, which is located in a comet-like nebula, has peculiar colors (possibly those of a highly reddened supergiant), and is probably variable, is definitely associated with 65b and 66. Its corrected distance modulus may thus be taken as the group mean.

Pup R1: This small chain of reflection nebulae may also include the (nonnebulous) star 15e ($V_0-M_V=11.1$:). Number 15a is an interesting object since its colors are those of a reddened O star, yet its nebulosity is reflection. This peculiarity, as well as its discrepant distance modulus, could be accounted for if it were an emission-line star.

Pup R2: This large association has two subgroups, one at $l=255°$ and one at $l=260°$. Number 18, a faint star observed only once, has been omitted from the determination of the mean reddening and distance modulus.

Pup R3: Number 6 is the Cepheid RS Pup. Its distance has been determined by Havlen (1972) using geometrical arguments based on the phase relationship between the light variations of the star and those of its reflection nebula. This distance agrees well with the determination by Westerlund (1963) who assumed that

Notes to Table VI (*continued*)

RS Pup was a member of Pup OB3, for which he derived $V_0-M_v=11.2$. Fernie (1974) has used the geometrical distance determination to show that the ratio of total to selective extinction in the direction of RS Pup is $R=2.85\pm0.5$, in agreement with the normally accepted value of 3.3 (Aanestad and Purcell 1973). The good agreement in distance modulus between Pup R3 and Pup OB3 indicate that the two are physically associated. Four other nebulae, Nos. 9a, 9b, 13a, and 13b, are found within the boundaries of Pup R3 but do not have distance moduli in agreement with the other members, so have not been included in the list above.

Sco R2: This small cluster of stars illuminating a single nebula and located at the edge of a small dark cloud may also contain a number of fainter stars.

Sco R3: Sco R3 is a small chain of faint nebulae.

Sco R4: This is a very interesting group in the same region as Sco OB1. The subgroup of stars numbered 73 is located in a very dark irregular cloud. Numbers 75, 77, and 78 are located near RCW 116—a patch of emission nebulosity. The mean reddening and distance modulus were determined from the three stars not marked as uncertain. This distance is in good agreement with that of Sco OB1, $V_0-M_V=11.5$, obtained by averaging the distances to 17 members of the association which have spectral types determined by Walborn (1972, 1973).

Sco R5: This loose association may also contain No. 91, a Bep star.

Sco R6: This is actually an association of O and early-B stars connected with emission nebulosity. Numbers 85a, b, and c and 86a, b, and c are associated with RCW 127, and No. 89 is associated with RCW 131.

Sco R7: The galactic cluster NGC 6451 is in the same region of the sky but probably not associated with Sco R7.

Vela R1: The first seven members above form a well-defined subgroup which may also include the nonnebulous stars 11f and 11g. Numbers 23 and 26 might also be included as members, however they are more likely associated with Vela R2. Numbers 10b and 14b were omitted from the determination of mean reddening and distance modulus.

Vela R2: This interesting association contains the emission nebulae RCW 34 (excited by star No. 25a) and RCW 36. There is evidence that it is a generically associated group of young B-type stars, including several which are still in the pre-main-sequence contraction stage of evolution. A detailed investigation of Vela R2 will be published separately (Herbst 1975b).

Vela R3: This is a small, well-defined association.

known OB or T associations. This is most likely purely a selection effect caused by the much scantier observational material in the southern hemisphere resulting in a lower number of known OB and T associations. In some cases stars from Table III have been included as members of the R associations due to the strong likelihood of their association with stars in nebulosity.

VI. THE GALACTIC DISTRIBUTION OF R ASSOCIATIONS

Using the data given by Racine (1968a, 1969a, 1974), van den Bergh (1968), Herbst (1974a), and in this paper, it is possible to plot the distribution of R associations projected on the galactic plane. This has been done in Fig. 4, adopting a value of 3.3 for the ratio of total to selective extinction. The following features of this diagram may be noted.

(1) The northern R associations and the southern ones between 245° and 270° mark the local optical spiral feature quite well. It can be traced as a continuous feature for over 6 kpc and is seen tangentially in the directions of Cygnus and Vela.

(2) There is a definite "gap" between the local and next inner (Carina–Sagittarius) spiral feature.

(3) The absence of R associations at distances greater than 1 kpc between 80° and 245° is an observational selection effect caused by the restriction of the northern survey for stars illuminating reflection nebulae to bright (BD or CD) objects.

A more detailed interpretation of this diagram, including a comparison between the R-association distribution and that of other well-known spiral tracers will be published separately.

VII. SUMMARY

This paper has presented the observational material on which future investigations utilizing stars in reflection nebulae may be based. Later papers in this series will apply this material to two problems of galactic astronomy: (1) the determination of the ratio of total to selective extinction, and (2) the investigation of local optical spiral structure.

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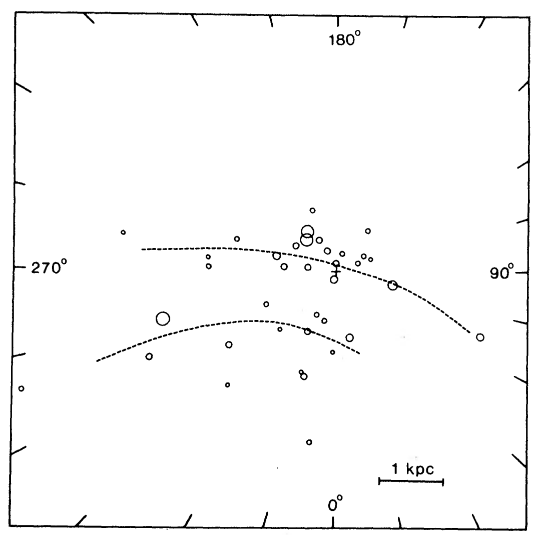

FIG. 4. The distribution of R associations projected on the galactic plane. The size of each circle is proportional to the number of association members. The position of the Sun is marked by a plus sign. The R associations outline two spiral features, indicated by the dotted lines: (1) the local feature, passing just outside the Sun's position and extending in the directions $l\sim70°$ (Cygnus) and $l\sim265°$ (Vela), and (2) the inner (−I) arm, seen tangentially at $l\sim290°$ (Carina). One distant R association at $l\sim355°$ (Sco R6) is probably located in the −II arm. The absence of distant R associations in the top half of the diagram ($70°<l<240°$) is purely a selection effect caused by the restriction of the northern survey to bright stars.

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