The Astrophysical Journal, 588:344–352, 2003 May 1

A METHOD FOR SIMULTANEOUS DETERMINATION OF A_V AND R AND APPLICATIONS

Jorge R. Ducati, Daiana Ribeiro, and Sandro B. Rembold
Departamento de Astronomia, C.P. 15051, Universidade Federal do Rio Grande do Sul, CEP 91501-970 Porto Alegre, RS, Brazil;
ducati@if.ufrgs.br, daiana@if.ufrgs.br, rembold@if.ufrgs.br
Received 2002 March 13; accepted 2003 January 8

ABSTRACT

A method for the simultaneous determination of the interstellar extinction (A_V) and of the ratio of total to selective extinction (R), derived from the 1989 Cardelli, Clayton, & Mathis fitting of the interstellar extinction law, is presented and applied to a set of 1900 color excesses derived from observations of stars in *UBVRIJHKL*. The method is used to study the stability of A_V and R within selected regions in Perseus, Scorpius, Monoceros, Orion, Sagittarius, Ophiuchus, Carina, and Serpens. Analysis shows that R is approximately constant and peculiar to each sector, with mean values that vary from 3.2 in Perseus to 5.6 in Ophiuchus. These results are similar to published values by Aiello et al., He et al., Vrba & Rydgren, O'Donnell, and Cardelli, Clayton, & Mathis.

Subject headings: dust, extinction — open clusters and associations: general — techniques: photometric

1. INTRODUCTION

The function of interstellar reddening was described, e.g., by Nandy et al. (1975) and Seaton (1979). Equations that fit a mean observed reddening function have been proposed (Cardelli, Clayton, & Mathis 1989, hereafter CCM; Rieke & Lebofsky 1985) as tests to grain models or to predict the extinction in certain spectral regions. In these cases, the information collected in a given spectral region is used to estimate the extinction in another region. The reddening function of CCM can be used to evaluate the extinction parameters A_V and R; we present here a method based on this perception (J. Mathis 1993, private communication).

2. DATA

In preparing the data set to test the method to be presented in § 3, we compiled two lists of color excesses: one derived from intrinsic colors given by Ducati et al. (2001, hereafter DBRR) and a second one with intrinsic colors from Johnson (1966a) and Koornneef (1983). Observational data were collected from the literature and compiled in Ducati (1993).[1] These lists have approximately 1900 stars with color excesses in the colors from U to N in the Johnson system.

3. SIMULTANEOUS DETERMINATION OF A_V AND R

The CCM fit to the interstellar function

$$\frac{A_\lambda}{A_V} = a_\lambda + \frac{b_\lambda}{R} \tag{1}$$

can be used to derive extinction parameters. This has been done, for example, by O'Donnell (1994) using *UBVRIJHKL*, *uvby*, and ultraviolet data. Patriarchi et al. (2001) also used the CCM fit, with the extinction curve by Rieke & Lebofsky (1985), to derive A_V and R. In the present work, we take a different approach. Given the color excess definition $E(\lambda - V) = A_\lambda - A_V$, we have

$$E(\lambda - V) = (a_\lambda - 1)A_V + \left(\frac{b_\lambda}{R}\right)A_V , \tag{2}$$

which gives the theoretical extinction at each wavelength. The residual between predicted and observed color excesses for a given star, considering all colors, is

$$\chi^2 = \sum_\lambda \omega_\lambda \left[E(\lambda - V) - (a_\lambda - 1)A_V - b_\lambda \frac{A_V}{R}\right]^2 , \tag{3}$$

where the ω_λ are the weights associated with each color from U to N. Values of ω_λ were derived from the expected errors in the Johnson (1966a) 11-color photometry, as listed in Table 1 of the DBRR paper, and are U: 0.9; B and V: 1.0; R and I: 0.8; J, H, and K: 0.7; L: 0.6; M and N: 0.5. According to the CCM fitting, only colors from U to L were used.

To minimize χ^2, we make its derivatives with respect to A_V and R equal to zero. We obtain the following equations:

$$A_V = \frac{f_4 f_3 - f_2 f_5}{f_1 f_3 - f_2^2} , \tag{4}$$

$$R = \frac{f_3 A_V}{f_5 - f_2 A_V} , \tag{5}$$

which can be solved independently for each star. The functions f_1 to f_5 are defined by

$$f_1 = \sum_\lambda \omega_\lambda (a_\lambda - 1)^2 , \tag{6}$$

$$f_2 = \sum_\lambda \omega_\lambda (a_\lambda - 1) b_\lambda , \tag{7}$$

$$f_3 = \sum_\lambda \omega_\lambda b_\lambda^2 , \tag{8}$$

$$f_4 = \sum_\lambda \omega_\lambda E(\lambda - V)(a_\lambda - 1) , \tag{9}$$

$$f_5 = \sum_\lambda \omega_\lambda E(\lambda - V) b_\lambda . \tag{10}$$

[1] Available in electronic form at ftp://cdsarc.u-strasbg.fr/cats/II/237.

4. APPLICATION OF THE METHOD

From the method presented in § 3, we see that it is possible to obtain the A_V- and R-values for a given star if we have as many color excesses as possible from U to L. Nevertheless, some caution must be taken regarding contamination of infrared data from circumstellar emission. This effect for some stars can be increasingly important for longer wavelengths. To prevent this, we introduced a filter that only proceeds with the calculation if color excesses are monotonically increasing with λ^{-1}, thus avoiding possibly strong circumstellar emission in one of these colors. Furthermore, we took only those stars that have $E(B-V) > 0.25$, thus making sure that our color excesses come from reddened stars, well above the photometric errors indicated in DBRR.

Determinations of A_V and R were performed running the method on the two lists mentioned in § 2, giving results for ~1380 stars scattered all over the sky. To verify the consistency of our results, as well as to look for comparisons with other investigators, we made the supposition that A_V, and especially R, being space-dependent parameters, do not vary rapidly across the sky. This can be especially true within clusters and nebulae with homogeneous environments. From our sample of 1380 stars we found consistent groupings in eight regions, with diameters around 90′. These groups are the region of h and χ Persei (25 stars), the Scorpius OB1 association (15 stars), the Rosette Nebula in Monoceros (14 stars), the Trapezium in Orion (four stars), the Lagoon Nebula (M8/NGC 6523) in Sagittarius (five stars), the region around ρ Ophiuchi (six stars), the Carina complex (six stars), and a region of NGC 6611 in Serpens (five stars).

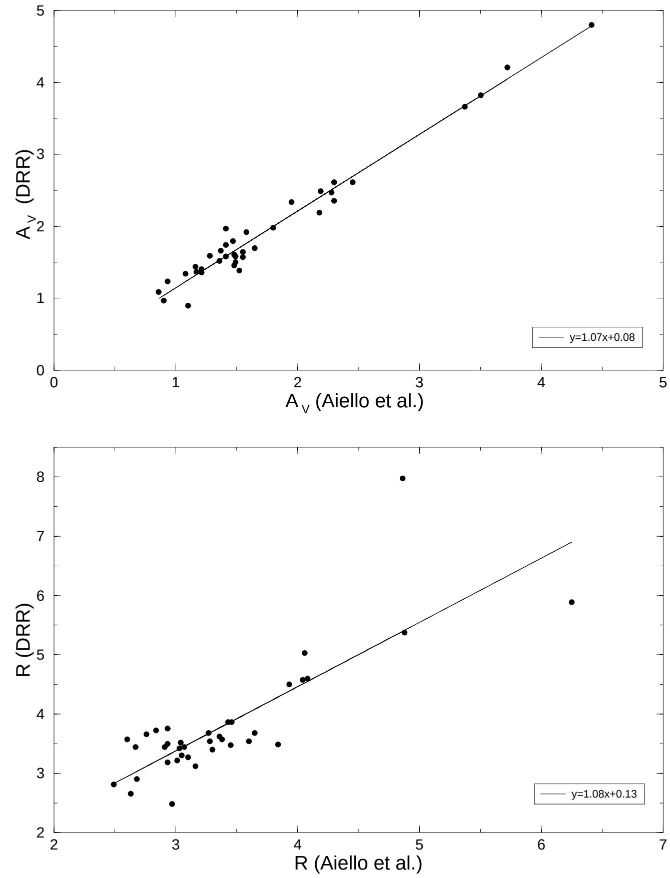

FIG. 1.—Comparison with results of Aiello et al. (1988)

5. RESULTS

Table 1 compares the A_V- and R-values given by Aiello et al. (1988), He et al. (1995), Vrba & Rydgren (1985), O'Donnell (1994), and CCM with our results for A_V and R, using color excesses calculated from the intrinsic colors of Johnson (1966a) and Koornneef (1983) and from DBRR. Figure 1 presents the comparison for the 37 stars in common between our results and Aiello et al. (1988).

Table 2 shows the results for the regions listed in § 4. We present values for A_V and R derived from color excesses either using DBRR's intrinsic colors or from Johnson (1966a) and Koornneef (1983) calibrations. In the column "Reference," we see that our observational data were obtained, for each region, from several investigators. This excludes possible biases that could arise if data came from only one set of observations.

For each group of stars, R-values are concentrated around a mean value, characteristic of the group since the dispersion of the mean is relatively small. Values of R near 3.0 are found in h and χ Per, as expected, since these clusters are known to be free of heavy differential extinction and strong star-forming processes. All other seven regions are associated with star formation and dark and/or emission nebulae, making our findings of unusual R-values expected.

In results presented in Table 2 we see that the calibrations for intrinsic colors of DBRR or from Johnson (1966a) and Koornneeff (1983) produce results that, although being slightly higher for A_V and R derived from the DBRR calibration, are in general agreement. This indicates that the tables of intrinsic colors recently proposed by DBRR give valid results. Since the DBRR calibration comes from a much bigger set of observational data, in the forthcoming discussion we use only A_V and R derived from DBRR intrinsic colors.

6. ERROR ANALYSIS

An error analysis includes components intrinsic to the method and components with their origin in the sample. The first group is composed from tables of intrinsic colors and the a_λ and b_λ parameters from the CCM fitting. Errors derived from these factors apply equally to all stars. The second group is composed from uncertainties in the spectral type and luminosity class (sp/lc) for each star and the photometric error of each color for each star. The impact of these errors varies from star to star.

Regarding intrinsic colors, we have first of all to point out that there are several calibrations that can be used. In this paper, we present results from the Johnson/Koornneef tables and from DBRR. Each calibration is independent and comes from different methods. With respect to the DBRR calibration, intrinsic colors were derived from the envelope that is the locus of zero reddening in color-temperature diagrams. The a_λ and b_λ are from the CCM fitting. These parameters contain uncertainties that are not given by the authors. However, changes in intrinsic colors or in a_λ- and b_λ-values lead to a collective shift in all A_V's and R's, with no impact in individual dispersions. In the

TABLE 1
COMPARISON WITH OTHER INVESTIGATORS

Star	Spectral Type	A_V	$A_{V_{DRR}}$	R	R_{DRR}	References
HD 162978	O8 III	1.21	1.36	3.46	3.86	1
HD 154445	B1 V	1.16	1.44	2.76	3.66	1
HD 183143	B7 Ia e	3.72	4.21	2.91	3.44	1
HD 190603	B1.5 Ia	2.19	2.49	3.04	3.52	1
HD 198478	B3 Ia	1.58	1.92	2.93	3.50	1
HD 199579	O6 V(f)	1.10	0.90	2.97	2.48	1
HD 199478	B8 Ia	1.41	1.74	2.93	3.76	1
HD 206165	B2 Ib	1.17	1.37	2.49	2.81	1
HD 207198	O9 Ib/II	1.55	1.57	2.63	2.65	1
HD 200775	B2 Ve	3.37	3.66	6.25	5.89	1
HD 216898	O8.5 V	2.28	2.47	2.68	2.90	1
HD 2905	B1 Ia	0.86	1.09	2.60	3.57	1
HD 21291	B9 Ia	1.48	1.46	3.60	3.54	1
HD 30614	O9.5 Ia	0.90	0.97	3.01	3.22	1
HD 23060	B2 IV/V	0.93	1.24	2.67	3.44	1
HD 41117	B2 Ia	1.28	1.59	2.84	3.72	1
HD 46106	B0 V	1.49	1.58	3.38	3.57	1
HD 46149	O8.5 V	1.41	1.58	2.93	3.18	1
HD 46150	O6 V	1.36	1.52	3.03	3.42	1
HD 37903	B1.5 V	1.37	1.66	3.93	4.50	1
HD 47240	B1 Ib	1.08	1.34	3.27	3.68	1
HD 38087	B5 V	1.41	1.97	4.86	7.98	1
HD 48279	O8 V	1.65	1.70	3.84	3.49	1
HD 69464	O6.5	2.30	2.36	3.65	3.68	1
HD 73882	O9 III	2.45	2.61	3.45	3.48	1
HD 93129	O6 Vf	2.18	2.19	4.04	4.58	1
HD 93222	O8	1.80	1.98	4.88	5.37	1
HD 114213	B1 Ib	3.50	3.82	3.10	3.27	1
HD 122879	B0 Ia	1.21	1.40	3.36	3.62	1
HD 151515	O6 V(f)	1.47	1.79	3.07	3.44	1
HD 152236	B1.5 Ia	2.30	2.61	3.43	3.87	1
HD 152249	O9 Ib	1.55	1.64	3.30	3.40	1
HD 152233	O6 V	1.48	1.61	3.28	3.54	1
HD 152247	O9.5 Iab/Ib	1.49	1.50	3.05	3.30	1
HD 152246	O9 Ib	1.52	1.39	3.16	3.12	1
HD 147889	B2 V	4.41	4.80	4.08	4.60	1
HD 147933/4	B2 V + B2 IV	1.95	2.34	4.06	5.03	1
HD 75860	B1.5 Ia	3.03	3.46	3.33	3.73	2
HD 78344	O9.5 Ia	4.05	4.01	2.91	3.15	2
HD 96880	B1 Iab/Ib	2.54	2.43	3.85	3.76	2
HD 142468	B1 Ia/Iab	2.22	2.55	2.88	3.30	2
HD 328209	O9.5 Ia:	3.06	3.16	2.97	2.91	2
HD 161291	B0.5 Iab	2.77	3.00	2.92	3.10	2
HD 316332	B3 Ia	4.23	4.58	2.82	3.24	2
HD 169034	B2 Ia	4.54	5.16	3.36	3.71	2
HD 170938	B1 Ia	3.40	3.86	3.30	3.76	2
HD 29647	B8 V	3.48	3.96	3.55	3.85	3
HD 14250	B1 III	1.65	1.85	2.85	3.06	4
HD 34078	O9.5 V	1.78	1.97	3.42	3.71	4
HD 37022	O6 p	1.71	1.91	5.50	5.67	4
HD 37023	B0.5 V	1.94	1.95	5.23	4.82	4
HD 37903	B1.5 V	1.48	1.66	4.11	4.49	4
HD 46202	O9 V	1.49	1.76	3.12	3.70	4
HD 48099	O7 V	0.95	1.04	3.52	3.82	4
HD 144217	B0.5 V	0.84	0.97	4.00	4.61	4
HD 147889	B2 V	4.58	4.79	4.20	4.60	4
HD 149757	O9.5 V	0.99	1.09	3.09	3.34	4
HD 154445	B1 V	1.23	1.44	3.15	3.66	4
HD 161056	B1/2 V	1.95	2.13	3.09	3.44	4
HD 167771	O7 III:(n)((f))	1.45	1.60	3.48	3.81	4
HD 193322	O9 V:((n))	1.25	1.31	3.05	3.12	4
HD 73882	O8.5 V((n))	2.44	2.62	3.39	3.48	5
HD 93222	O7 III((f))	1.99	1.98	4.98	5.37	5
HD 147888	B3 V:	2.15	2.33	4.13	4.70	5
HD 147933/4	B2 IV + B2 V	2.04	2.34	4.34	5.03	5
HD 204827	B0 V	2.89	3.06	2.60	2.68	5
BD +56°524	B1 Vn	1.65	1.80	2.75	3.04	5

REFERENCES.—(1) Aiello et al. 1988; (2) He et al. 1995; (3) Vrba & Rydgren 1985; (4) O'Donnell 1994; (5) CCM.

TABLE 2

Extinction

Region	Number	Star	Spectral Type	A_{V_1}	A_{V_2}	R_1	R_2	Reference
h and χ Per	1	HD 13841	B2 Ib	1.22	1.46 ± 0.03	3.11	3.68 ± 0.16	1
	2	HD 13854	B1 Iab	1.57	1.70 ± 0.03	3.35	3.61 ± 0.13	1, 2, 3
	3	HD 14052	B1 Ib	1.33	1.45 ± 0.04	2.63	2.87 ± 0.11	1
	4	BD +56°502	B1 V	1.48	1.71 ± 0.04	2.77	3.18 ± 0.11	1
	5	BD +56°510	B1.5 V	1.22	1.46 ± 0.04	2.32	2.75 ± 0.10	1
	6	BD +56°513	B1 V	1.50	1.74 ± 0.04	2.65	3.04 ± 0.10	1
	7	BD +56°515	B0.5 Vn	1.48	1.67 ± 0.04	2.45	2.76 ± 0.09	1
	8	BD +56°516	B2 V	1.38	1.62 ± 0.04	2.64	3.07 ± 0.11	1
	9	BD +56°517	B1.5 V	1.40	1.63 ± 0.04	2.73	3.16 ± 0.11	1
	10	BD +56°519	B1.5 V	2.14	2.36 ± 0.04	3.55	3.89 ± 0.11	1
	11	BD +56°518	B1.5 V	1.42	1.65 ± 0.04	2.32	2.69 ± 0.08	1
	12	BD +56°520	B1 Vn	1.31	1.55 ± 0.04	2.23	2.62 ± 0.09	1
	13	HD 14134	B3 Ia/Iab e	1.51	1.80 ± 0.03	2.60	3.09 ± 0.09	1, 2, 3, 4, 6, 7
	14	BD +56°524	B1 V	1.57	1.80 ± 0.04	2.67	3.04 ± 0.09	1
	15	HD 14143	B1.5 Ia	2.04	2.22 ± 0.03	3.00	3.27 ± 0.08	1, 2, 3, 4, 6, 7
	16	HD 14250	B0.5 V:n	1.66	1.85 ± 0.03	2.77	3.06 ± 0.09	1, 8
	17	HD 14322	B8 Ib e	1.09	1.30 ± 0.04	3.08	3.62 ± 0.17	4, 6
	18	HD 14434	O6.5 V:	1.19	1.29 ± 0.03	2.52	2.70 ± 0.11	1
	19	BD +56°566	B2 Ve	2.42	2.67 ± 0.04	4.42	4.87 ± 0.14	1
	20	HD 14433	A1 Ia	1.39	1.49 ± 0.03	2.57	2.77 ± 0.09	1, 2, 3, 4, 6
	21	HD 14443	B2 Ib	...	1.26 ± 0.03	...	2.43 ± 0.10	1
	22	BD +56°571	B1 V	1.28	1.52 ± 0.04	2.32	2.74 ± 0.09	1
	23	HD 14489	A2 Ia	0.98	1.08 ± 0.04	3.23	3.57 ± 0.21	2, 3, 7
	24	BD +56°586	B1 V	2.65	2.87 ± 0.04	5.14	5.51 ± 0.16	1
	25	HD 14535	A2 Ia	1.81	1.94 ± 0.03	2.80	3.02 ± 0.08	1, 4, 6
Sco OB1	1	HD 152003	O9.7 Ia	2.14	2.17 ± 0.03	3.32	3.36 ± 0.09	10, 11
	2	HD 152147	B0 Ia	2.17	2.21 ± 0.03	3.33	3.39 ± 0.09	10, 11
	3[a]	HD 152235	B1 Ia	2.51	2.64 ± 0.03	3.43	3.59 ± 0.08	10, 11, 12, 13, 14
	4	HD 152236	B1.5 Ia	2.42	2.61 ± 0.03	3.61	3.87 ± 0.09	10, 11, 12, 13, 14, 15
	5[a]	HD 152218	O9 V	1.63	1.77 ± 0.03	3.42	3.68 ± 0.12	12
	6[a]	HD 152234	B0.5 Ia	1.44	1.55 ± 0.03	3.55	3.83 ± 0.15	10, 11
	7	HD 152245	B0 Ib	0.96	1.00 ± 0.03	2.72	2.84 ± 0.14	12
	8[a]	HD 152233	O6 V	1.51	1.61 ± 0.03	3.35	3.54 ± 0.13	10
	9[b]	HD 152246	O9 Ib	1.43	1.39 ± 0.03	3.18	3.12 ± 0.12	10, 12
	10[a]	HD 152249	O9 Ib	1.67	1.64 ± 0.03	3.45	3.40 ± 0.12	10
	11	HD 152247	O9.5 Iab/Ib	1.51	1.50 ± 0.03	3.28	3.30 ± 0.12	10, 12
	12	HD 152405	B0 Ia	...	1.41 ± 0.03	...	3.56 ± 0.15	12
	13	HD 152424	B0 Ib/II	2.13	2.17 ± 0.03	3.31	3.39 ± 0.09	11
	14[b]	HD 152560	B2 V:n	...	1.10 ± 0.04	...	3.63 ± 0.20	12
	15	HD 152667	B2 Iab/Ib	1.48	1.73 ± 0.03	3.41	3.93 ± 0.14	10, 11, 12, 14, 16
Rosette Nebula	1	HD 259172	B2 V	1.37	1.60 ± 0.04	3.11	3.61 ± 0.14	17
	2	HD 46056	O8 V	1.42	1.51 ± 0.04	2.81	2.98 ± 0.11	17
	3	HD 259012	B2 V	1.67	1.93 ± 0.04	4.23	4.86 ± 0.19	17
	4	HD 46106	B0 V	1.42	1.58 ± 0.03	3.24	3.57 ± 0.15	6, 17, 18
	5	HD 259105	B2 V	1.22	1.45 ± 0.04	3.33	3.96 ± 0.18	17
	6	HD 46149	O8.5 V	1.49	1.58 ± 0.03	3.00	3.18 ± 0.11	2, 17, 18
	7	HD 46150	O6 Vf e	1.42	1.52 ± 0.03	3.23	3.42 ± 0.14	6, 17, 18, 19, 20
	8	HD 259135	B1: V:n	1.37	1.60 ± 0.04	3.51	4.08 ± 0.17	17
	9	HD 46202	O9 V	1.62	1.76 ± 0.03	3.43	3.70 ± 0.13	17
	10	HD 259268	B8 V	1.18	1.45 ± 0.04	4.07	4.98 ± 0.26	17
	11	HD 259300	B3 V	2.03	2.31 ± 0.04	3.85	4.35 ± 0.13	17
	12[c]	HD 46485	O9 V	2.03	2.17 ± 0.03	3.29	3.50 ± 0.09	12, 14, 21
	13[c]	HD 46484	B1 V	1.89	2.12 ± 0.03	3.36	3.75 ± 0.11	14, 18, 21
	14[c]	HD 46867	B0.5 V	1.53	1.72 ± 0.06	3.10	3.46 ± 0.15	18
Trapezium	1	HD 37020	O7 V	1.72	1.76 ± 0.04	4.58	4.64 ± 0.20	22
	2	HD 37021	B0 V	2.76	2.90 ± 0.04	4.38	4.57 ± 0.12	22
	3	HD 37022	O7 V	1.83	1.91 ± 0.04	5.49	5.67 ± 0.25	22, 24, 25
	4	HD 37023	B0.5 V	1.77	1.95 ± 0.04	4.44	4.82 ± 0.20	22
Lagoon Nebula	1	HD 164865	B9 Iab	3.32	3.48 ± 0.03	3.78	3.95 ± 0.07	14
	2	HD 166033	B1 V	2.21	2.41 ± 0.04	5.00	5.42 ± 0.17	32
	3	HD 314031	B0.5 V	1.67	1.86 ± 0.04	3.58	3.96 ± 0.15	32
	4	HD 166056	B4 Ib	2.41	2.74 ± 0.04	5.70	6.40 ± 0.21	32
	5	HD 166107	B2 V	1.02	1.28 ± 0.04	3.80	4.71 ± 0.27	32

TABLE 2—*Continued*

Region	Number	Star	Spectral Type	A_{V_1}	A_{V_2}	R_1	R_2	Reference
Oph	2	HD 147196	B8 IV/Vn	1.14	1.42 ± 0.06	4.76	5.84 ± 0.39	33
	3	HD 147889	B2 V	4.56	4.80 ± 0.03	4.38	4.60 ± 0.07	12, 14, 21, 34, 35, 36
	4	HD 147888	B3.5 V	2.05	2.33 ± 0.03	4.16	4.70 ± 0.14	14, 21
	5	HD 147932	B5 V	2.22	2.52 ± 0.03	5.16	5.81 ± 0.19	14, 21
	6	HD 147933/4	B2 V + B2 IV	2.11	2.34 ± 0.03	4.58	5.03 ± 0.16	12, 14
	8	HD 150193	A1 V	3.88	4.08 ± 0.06	7.37	7.69 ± 0.21	33, 37
η Carinae complex	1	HD 93027	O9.5 V	1.13	1.29 ± 0.03	3.66	4.12 ± 0.20	38
	2	HD 93129	O6 (V)f	2.10	2.19 ± 0.03	4.41	4.58 ± 0.15	20, 38
	3	HD 93130	O6 (V)	2.19	2.28 ± 0.03	3.74	3.88 ± 0.10	38
	4	HD 93146	O6.5 V	1.83	1.92 ± 0.03	5.30	5.50 ± 0.23	20, 38
	5	HD 305523	O9.5 III	2.12	2.28 ± 0.03	4.90	5.22 ± 0.17	38
	6	HD 93222	O8	1.89	1.98 ± 0.03	5.16	5.37 ± 0.21	12, 38
NGC 6611	1[d]	BD −12°4970	B0.5 Ia	3.98	4.09 ± 0.03	3.25	3.34 ± 0.05	10
	2[c]	HD 167971	O8 f e	3.71	3.80 ± 0.03	3.45	3.53 ± 0.05	6, 10, 12, 14, 19, 39, 40
	3	HD 168075	O7	2.64	2.73 ± 0.04	3.51	3.61 ± 0.08	41
	4	BD −13°4930	O9.5 V	1.63	1.80 ± 0.04	2.93	3.22 ± 0.10	41
	5	HD 168137	B3 Ib	1.45	1.75 ± 0.04	3.21	3.87 ± 0.14	41

NOTES.—The values of A_{V_1} and R_1 used the intrinsic colors of Johnson 1966a and Koornneef 1983. The values of A_{V_2} and R_2 used the intrinsic colors of DBRR. The object identification numbers correspond to Figs. 2–5.

[a] Member of NGC 6231.

[b] Member of Tr 24.

[c] Nonmember.

[d] Member of NGC 6604.

REFERENCES.—(1) Tapia et al. 1984b; (2) Sneden et al. 1978; (3) Hackwell & Gehrz 1974; (4) Johnson 1966a; (5) Cohen & Gaustad 1973; (6) Johnson 1965; (7) Barlow & Cohen 1977; (8) Tapia et al. 1984a; (9) Gillett, Merrill, & Stein 1971; (10) Leitherer & Wolf 1984; (11) Schild, Neugebauer, & Westphal 1971; (12) The, Wesselius, & Janssen 1986; (13) Whittet, van Breda, & Glass 1976; (14) Whittet & van Breda 1980; (15) Abbott, Telesco, & Wolff 1984; (16) Wolff & Beichman 1979; (17) Perez, The, & Westerlund 1987; (18) Smyth & Nandy 1978; (19) Castor & Simon 1983; (20) Tapia 1981; (21) Whittet & van Breda 1978; (22) Ney, Strecker, & Gehrz 1973; (23) Glass & Penston 1974; (24) Lee 1968; (25) Breger, Gehrz, & Hackwell 1981; (26) Odell & Lebofsky 1984; (27) Groote & Kaufmann 1983; (28) Groote, Hunger, & Schultz 1980; (29) Bonsack & Dyck 1983; (30) Kroll et al. 1987; (31) Johnson 1966b; (32) Herbst et al. 1982; (33) Elias 1978; (34) Harris, Woolf, & Rieke 1978; (35) Macmillan 1978; (36) van Breda, Glass, & Whittet 1974; (37) Davies et al. 1990; (38) The et al. 1980; (39) Johnson 1967; (40) Leitherer et al. 1987; (41) Walsh & White 1982.

results presented in Table 2, this implies that each group maintains a characteristic value of R.

Uncertainties in the spectral type and in the luminosity class affect color excesses for individual stars. However, A_V and R are evaluated for each star independently, for which the sp/lc can be correct or not. Therefore, a standard error propagation method, because of this factor, cannot be applied to the whole sample.

Photometric uncertainties are present in all observational samples but vary in magnitude for each star. To handle photometric errors, we apply standard error propagation methods. As photometric errors in the 11-color system, we used the following values, in magnitudes: U: 0.03; B: 0.02; V: 0.01; R and I: 0.03; J and H: 0.04; K: 0.05; L: 0.06. Values for $JHKL$ were extracted from Table 1 in DBRR. Errors given in Table 2 were derived from those photometric errors.

Simulations were carried out with respect to spectral types and the CCM parameters. Values for A_V and R were recalculated for selected stars, with spectral type and luminosity class changed by one subtype and two classes, respectively. Variations in A_V and R give a measure of the sensitivity of the method to misclassifications. We verified that the method is sensitive to changes in sp/lc, and in some cases variations can be as large as 0.5 mag in A_V and 1.8 in R. However, looking at the results in Table 2 and the discussion in §§ 7.2–7.9, we see that dispersions of the values of R for each group are far smaller than they would be if mismatches in sp/lc were frequent. We conclude that, in general, the stars in our sample have adequate classifications.

A similar simulation was performed for a_λ and b_λ. Their values were changed by amounts that brought, for example, a_U close to a_B, and so on. New values of A_V and R did not differ from old ones by more than 0.1 and 0.3, respectively, indicating that the method is less sensitive to those fitting parameters.

7. DISCUSSION

7.1. *Comparison with Other Investigators*

Table 1 and Figure 1 show a good agreement between our results and those of other investigators, in spite of the fact that the methods used were completely different. A comparison with A_V derived from parallaxes given by the *Hipparcos* database was inconclusive, since absolute magnitudes needed to calculate A_V contain large errors in their calibrations that result in large variations in the derived values of A_V.

The relation of the value of R to the nature of the interstellar medium has been discussed for many years, as early as in Johnson (1968). Johnson (1977b) rediscussed the law of interstellar extinction, showing that R has values higher than an average of 3.0 in several regions. Szomoru & Guhathakurta (1999) point out that values of R should be a function of the size population of dust grains, with visual and infrared optical depth dominated by large grains and the extinction in blue and ultraviolet being modulated by small grains. Grains can differ not only in size but also in structure and chemical composition (Greenberg 1987).

Given that environments in the eight regions studied in the present paper show important variations, it is not surprising that the mean R-values in each region present the variations listed in Table 2.

7.2. *h and χ Persei*

The 25 stars for this region, presented in Table 2, belong to the Per OB1 association, which contains h and χ Per open clusters. The membership of HD 14434 is not certain (Garmany & Stencel 1992). The mean value of R for this region is 3.24 ± 0.70. The average A_V, $\overline{A_V}$, is 1.72 ± 0.42. Tapia et al. (1984b) give $\overline{A_V} = 1.85 \pm 0.12$.

Considering only stars with probable or recognized membership in both clusters, this region presents a mean R that is not very different from the value in general use. This is in fact known since the work of Johnson (1977b), which gives $R = 3.0$ for this region.

7.3. *Scorpii OB1*

The Sco OB1 region comprises several open clusters, of which NGC 6231 and Tr 24 have stars listed in Table 2 . The mean R for the 15 stars is 3.48 ± 0.30, and the mean A_V is 1.77 ± 0.50. The smallest A_V and R are for HD 152245, which is the most distant star from the fields of the open clusters. The homogeneity of A_V and R suggests that the interstellar medium through Sco OB1 is, in general, uniform. The general value of R for the Sco region given by Johnson (1977b) is 3.6.

7.4. *Rosette Nebula*

The region displayed in Figure 2 shows the central part of NGC 2244, within the Rosette Nebula. We note that the smallest R is for HD 46056, which is far from the early-type stars near the center of NGC 2244. Still outside the "hole," nearing the border, is HD 259012, with $R = 4.86$, one of the biggest of the region. Inside the cavity, HD 259268 and HD 259300 also have large R (4.98 and 4.35). The seven stars in the central part have a smaller and more stable R ($\overline{R} = 3.56 \pm 0.37$) and A_V ($\overline{A_V} = 1.59 \pm 0.09$). It seems that the interstellar medium does not change appreciably through the central area. The nonmember stars HD 46484, HD 46485, and HD 46867 (Marschall, van Altena, & Chiu 1982) have high extinctions and R-values of the same order as the stars in the central nebula.

7.5. *Orion Trapezium*

Johnson (1977a), discussing his spectral data of the Orion Trapezium, demonstrates that excess infrared radiation does not come from cool stars, since the spectral features of these stars are not observed in the spectra of the Trapezium stars. It is, therefore, legitimate to attribute the peculiar R-values in Ori to intrinsic properties of the interstellar medium in which the stars are embedded. These stars have reasonably stable values for A_V and R ($\overline{A_V} = 2.13 \pm 0.52$ and $\overline{R} = 4.93 \pm 0.51$). Johnson (1977b) gives, for the Orion sword, $R = 5.2$.

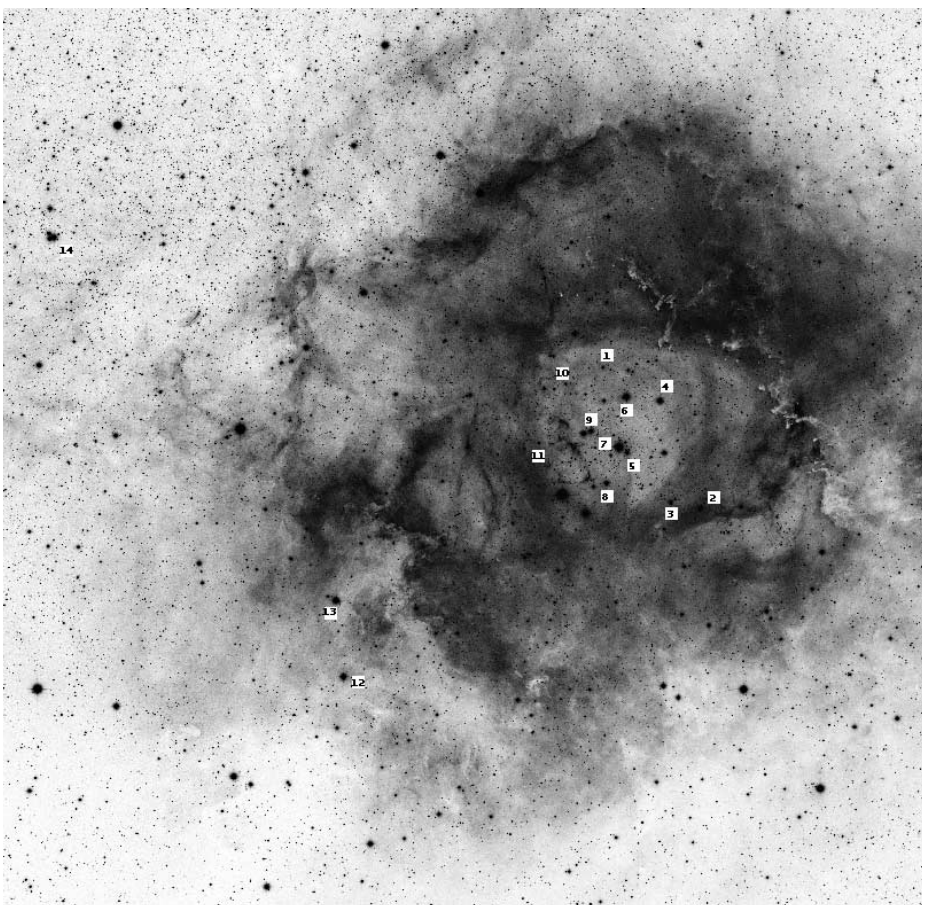

FIG. 2.—Rosette Nebula region

7.6. *Lagoon Nebula*

Figure 3 displays the Lagoon emission nebula with HD 164865 and four stars in its vicinity. It is interesting to note that the highest extinction and the lowest R are associated with HD 164865, well embedded in the nebula. The value of A_V decreases, and R increases, eastward, where some nebulosity is still conspicuous. Regardless, the whole region presents a high R, with a large dispersion ($\overline{A_V} = 2.35 \pm 0.84$ and $\overline{R} = 4.89 \pm 0.93$).

7.7. *Ophiuchus*

The region of ρ Oph is displayed in Figure 4. Even if the region presents high R ($\overline{R} = 5.61 \pm 1.15$), the highest value (HD 150193: $R = 7.69$) is quite far from ρ Oph, in which vicinity (including HD 147888, HD 147932, and HD 147933/4) R is relatively stable and around 5.2. The entire region has high R, well above the value given by Johnson (1977b), which is 3.2. The fact that R is high not only around ρ Oph but as far as 1° indicates that these values must be a feature of the interstellar medium in the sector and not only an effect due to processes occurring around ρ Oph.

7.8. *η Carinae Complex*

The six stars in Figure 5 are embedded in the heavily absorbed region surrounding η Car (indicated by a circle in the figure). Our data indicate high values of A_V and R, with relatively low dispersions ($\overline{A_V} = 1.99 \pm 0.38$, $\overline{R} = 4.78 \pm 0.68$).

7.9. *NGC 6611*

The three stars that are members of NGC 6611 have a much smaller A_V than the two nonmembers; however, R is relatively homogeneous in this sector. NGC 6604, of which BD $-12°4970$ is a member, is closer than NGC 6611 but has a much greater A_V, indicating that the interstellar medium in the direction of NGC 6611 is less dense, even if its properties tend to be constant in the region. Mean values for NGC 6611 are $\overline{A_V} = 2.10 \pm 0.55$, $\overline{R} = 3.57 \pm 0.33$.

8. CONCLUSIONS

The method presented here was shown to produce results that compare well with those of other investigators; however, our values of A_V and R tend to be slightly higher, which can be linked to the fact that we used the new tables of intrinsic colors derived in DBRR. When the method is applied to color excesses derived from older calibrations, A_V and R are smaller. Originating from a far bigger data set, the new calibration is expected to be more accurate, implying that our A_V- and R-values are more realistic. From the point of view of the stability of R through space, we note that the results derived here agree with the published values for several regions and also that the dispersion of R ithin each region is of the same order or slightly bigger than the typical expected errors of any R. Since this method

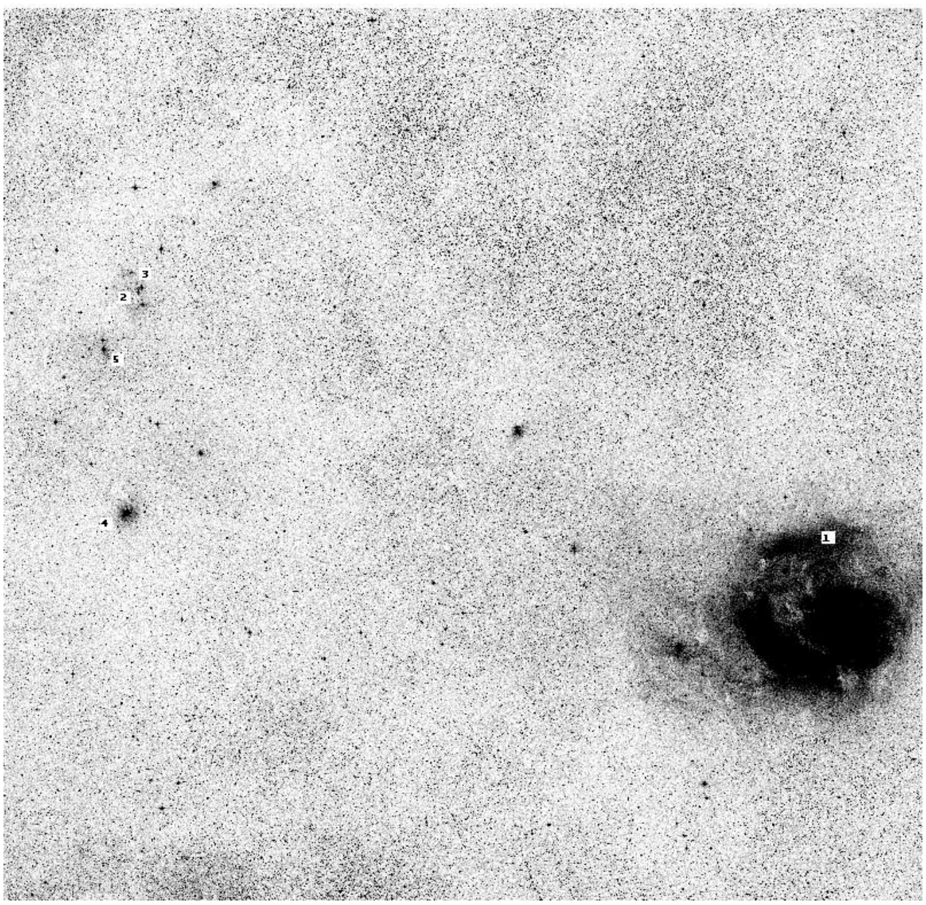

FIG. 3.—Lagoon Nebula

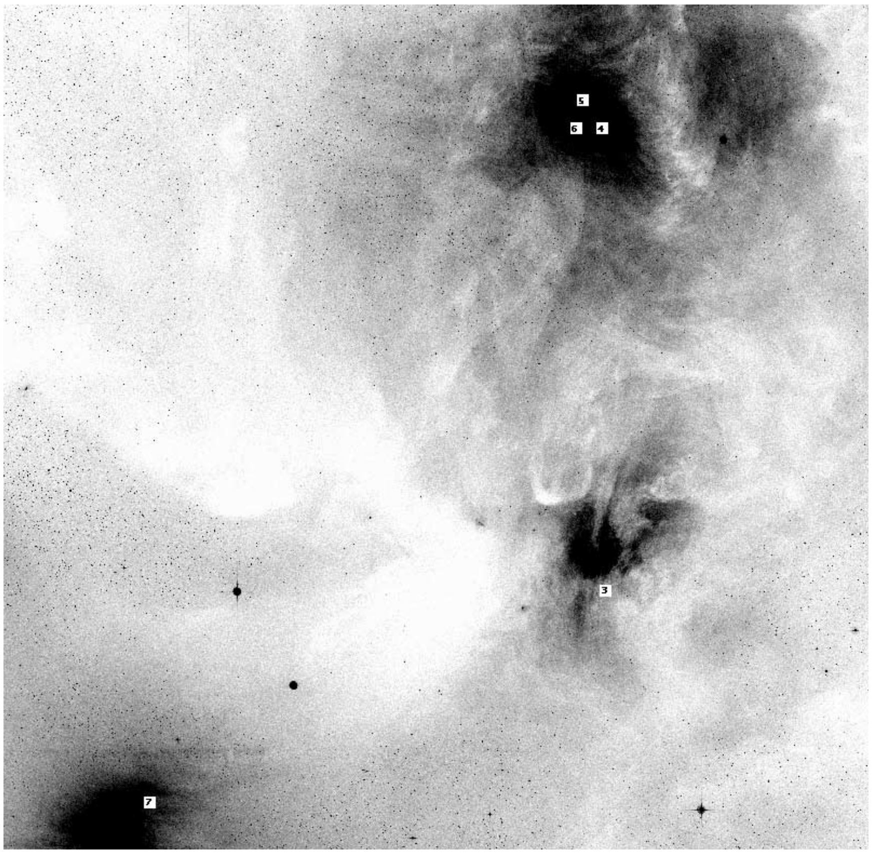

FIG. 4.—Region around ρ Oph

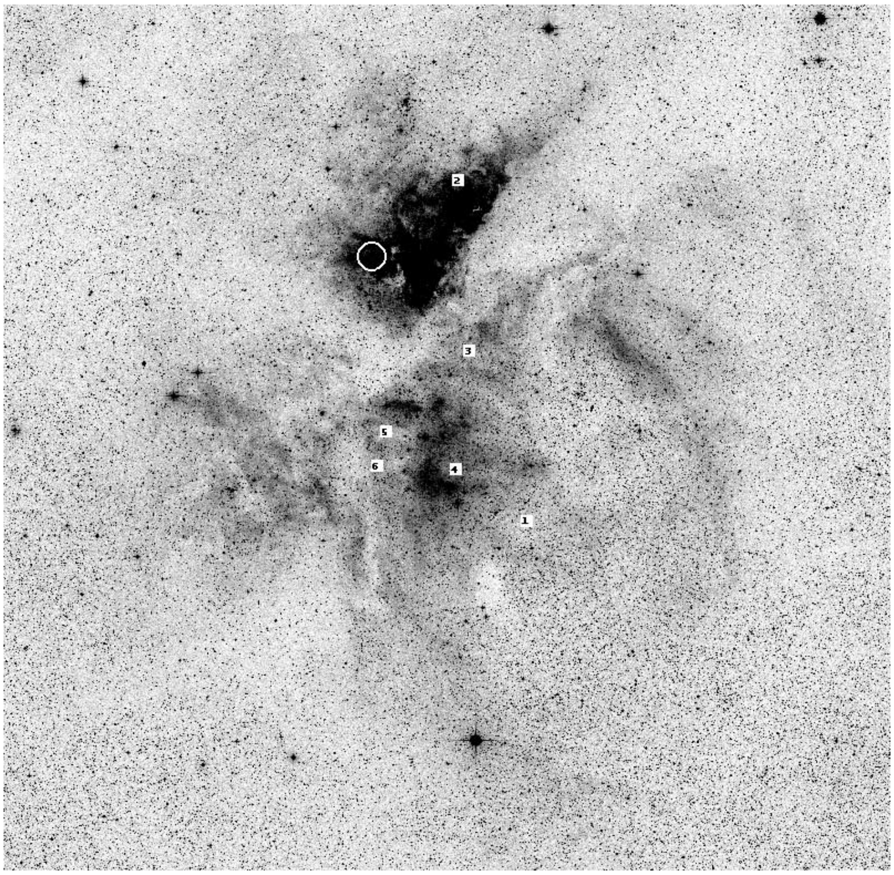

FIG. 5.—Carinae complex region. The location of η Car is indicated by a circle.

is based on the CCM fits to the law of interstellar extinction, R and A_V are better derived for a large range of color excesses, preferably from U to L; lack of data in the longer wavelengths tends to produce larger R, an expected result that will be studied in a forthcoming paper.

This work benefited from data extracted from the SIMBAD database, Strasbourg Data Center, France, and the Canadian Astronomy Data Centre. We thank the referee, John Mathis, for his rigorous and constructive criticism. Scholarships from Propesq/UFRGS and Fapergs and support from PRONEX/CNPq are acknowledged.

REFERENCES

Abbott, D. C., Telesco, C. M., & Wolff, S. C. 1984, ApJ, 279, 225
Aiello, S., Barsella, B., Chlewicki, G., Greenberg, J. M., Patriarchi, P., & Perinotto, M. 1988, A&AS, 73, 195
Barlow, M. J., & Cohen, M. 1977, ApJ, 213, 737
Bonsack, W. K., & Dyck, H. M. 1983, A&A, 125, 29
Breger, M., Gehrz, R. D., & Hackwell, J. A. 1981, ApJ, 248, 963
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245 (CCM)
Castor, J. I., & Simon, T. 1983, ApJ, 265, 304
Cohen, M., & Gaustad, J. E. 1973, ApJ, 186, L131
Davies, J. K., Evans, A., Bode, M. F., & Whittet, D. C. B. 1990, MNRAS, 247, 517
Ducati, J. R. 1993, preprint (Wisconsin Astrophys. 504)
Ducati, J. R., Bevilacqua, C. M., Rembold, S. B., & Ribeiro, D. 2001, ApJ, 558, 309 (DBRR)
Elias, J. H. 1978, ApJ, 224, 453
Garmany, C. D., & Stencel, R. E. 1992, A&AS, 94, 211
Gillett, F. C., Merrill, K. M., & Stein, W. A. 1971, ApJ, 164, 83
Glass, I. S., & Penston, M. V. 1974, MNRAS, 167, 237
Greenberg, J. M. 1987, Adv. Space Res., 7(5), 33
Groote, D., Hunger, K., & Schultz, G. V. 1980, A&A, 83, L5
Groote, D., & Kaufmann, J. P. 1983, A&AS, 53, 91
Hackwell, J. A., & Gehrz, R. D. 1974, ApJ, 194, 49
Harris, D. H., Woolf, N. J., & Rieke, G. H. 1978, ApJ, 226, 829
He, L., Whittet, D. C. B., Kilkenny, D., & Spencer Jones, J. H. 1995, ApJS, 101, 335
Herbst, W., Miller, D. P., Warner, J. W., & Herzog, A. 1982, AJ, 87, 98
Johnson, H. L. 1965, Comm. Lunar Planet. Lab., 3, 79
———. 1966a, ARA&A, 4, 193
Johnson, H. L. 1966b, Comm. Lunar Planet. Lab., 4, 99
———. 1967, ApJ, 147, 912
———. 1968, Nebulae and Interstellar Matter (Chicago: Univ. Chicago Press), 167
———. 1977a, Rev. Mexicana Astron. Astrofis., 2, 71
———. 1977b, Rev. Mexicana Astron. Astrofis., 2, 175
Koornneef, J. 1983, A&AS, 51, 489
Kroll, R., Schneider, H., Catalano, F. A., & Voigt, H. 1987, A&AS, 67, 195
Lee, T. A. 1968, ApJ, 152, 913
Leitherer, C., & Wolf, B. 1984, A&A, 132, 151
Leitherer, C., et al. 1987, A&A, 185, 121
Macmillan, R. S. 1978, ApJ, 226, 417
Marschall, L. A., van Altena, W. F., & Chiu, L. G. 1982, AJ, 87, 1497
Nandy, K., Thompson, G. I., Jamar, C., Monfils, A., & Wilson, R. 1975, A&A, 44, 195
Ney, E. P., Strecker, D. W., & Gehrz, R. D. 1973, ApJ, 180, 809
Odell, A. P., & Lebofsky, M. 1984, A&A, 140, 468
O'Donnell, J. E. 1994, ApJ, 422, 158
Patriarchi, P., Morbidelli, L., Perinotto, M., & Barbaro, G. 2001, A&A, 372, 644
Perez, M. R., The, P. S., & Westerlund, B. E. 1987, PASP, 99, 1050
Rieke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
Schild, R. E., Neugebauer, G., & Westphal, J. A. 1971, AJ, 76, 237
Seaton, M. J. 1979, MNRAS, 187P, 73
Smyth, M. J., & Nandy, K. 1978, MNRAS, 183, 215
Sneden, C., Gehrz, R. D., Hackwell, J. A., York, D. G., & Snow, T. P., Jr. 1978, ApJ, 223, 168
Szomoru, A., & Guhathakurta, P. 1999, AJ, 117, 2226
Tapia, M. 1981, MNRAS, 197, 949
Tapia, M., Roth, M., Costero, R., & Navarro, S. 1984a, in IAU Symp. 105, Observational Tests of the Stellar Evolution Theory, ed. A. Maeder & A. Renzini (Boston: Kluwer), 353
———. 1984b, Rev. Mexicana Astron. Astrofis., 9, 65
The, P. S., Bakker, R., Tjin, A., & Djie, H. R. E. 1980, A&A, 89, 209
The, P. S., Wesselius, P. R., & Janssen, I. M. H. H. 1986, A&AS, 66, 63
van Breda, I. G., Glass, I. S., & Whittet, D. C. B. 1974, MNRAS, 168, 551
Vrba, F. J., & Rydgren, A. E. 1985, AJ, 90, 1490
Walsh, J. R., & White, N. J. 1982, MNRAS, 199P, 9
Whittet, D. C. B., & van Breda, I. G. 1978, A&A, 66, 57
———. 1980, MNRAS, 192, 467
Whittet, D. C. B., van Breda, I. G., & Glass, I. S. 1976, MNRAS, 177, 625
Wolff, S. C., & Beichman, C. A. 1979, ApJ, 230, 519