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THE INTERSTELLAR EXTINCTION LAW FROM 1 TO 13 MICRONS[1]

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ABSTRACT

Measurements from 1 to 13 μm are reported for *o* Sco and for stars in the galactic center. The interstellar extinction law toward these sources and toward VI Cyg No. 12 is the same from 1 to 13 μm. An improved estimate of the extinction law beyond 3 μm is presented, including an improved ratio of total to selective extinction, $R \approx 3.09 \pm 0.03$, and an improved ratio of total extinction to optical depth in the 10 μm silicate absorption, $A_v/\tau_{Si} = 16.6 \pm 2.1$.

Subject headings: infrared: spectra — interstellar: matter

I. INTRODUCTION

Shortward of 3.5 μm, virtually all the available observations (see, e.g., Schultz and Wiemer 1975; Sneden *et al.* 1978) are consistent with a uniform interstellar extinction law (Savage and Mathis 1979). Except for regions of very high density of interstellar matter, the earlier indications of regional variations in this law (e.g., Johnson 1968) resulted from inadequate corrections for circumstellar emission. Beyond 3.5 μm, the extinction law is poorly determined. Outside dense clouds, the silicate absorption which dominates the extinction near 10 μm has been measured for only two stars; VI Cyg No 12 (Rieke 1974; Gillett *et al.* 1975) and galactic center source 7 (Becklin *et al.* 1978). These measurements have been interpreted to show different extinction laws toward these stars (Becklin *et al.* 1978), in contrast with the uniformity of the extinction at shorter wavelengths.

We report measurements from 1 to 13 μm of the extinction toward the A5 II star *o* Sco and toward a number of stars in the galactic center. We do not find any significant variations in the extinction law over this spectral region.

II. NEW OBSERVATIONS

Our observations are summarized in Table 1. For the galactic center, the source nomenclature is as in Lebofsky *et al.* (1982). Photometry shortward of 10 μm was obtained with the UAO 1.54 m and 2.3 m telescopes with beams 5″.6 to 7″.8 in diameter and relative to reference areas approximately 10″ to the east and west of the sources. Observations of the galactic center sources at 10 μm were obtained with the IRTF with a beam 5″.8 in diameter and relative to reference areas about 7″ to the north and south; measurements of *o* Sco were obtained with both the IRTF and the UAO 2.3 m with this beam size and reference beam positioning. All of the observations were made with the UAO infrared photometers and were calibrated as described in Johnson (1966) and Low and Rieke (1974); in the near infrared, 58 Oph and 22 Sco were used as local standards, while 58 Oph, Ψ Oph, and γ Sgr were used in this manner at 10 μm.

In addition to measurements in the standard infrared photometric bands, we made narrow-band observations at 10.4 μm. Together with the broad-band *N* measures at nearly the same effective wavelength, these observations can be used to determine the depth of the silicate absorption feature near 10 μm (Lebofsky and Rieke 1979).

Source 22 in the galactic center showed evidence for interference by strong nearby sources with colder spectra at 5 and 10 μm. We have therefore not included any photometry of this source beyond 2.2 μm. There were minor problems of a similar nature for source 23 at 10 μm; we do not believe that the photometry is significantly affected.

For completeness, Table 1 also includes the previous photometry of VI Cyg No. 12 (Harris, Woolf, and Rieke 1978) and of galactic center source 7 (Becklin *et al.* 1978).

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TABLE 1
MEASUREMENTS OF OBSCURED STARS

Source	*J*	*H*	*K*	*L*	*M*	*N*	10.4/*N*
o Sco	2.24	1.73	1.54	1.39		1.50	0.929 ± 0.011
G.C. Source 7	13.73	9.15	6.55	4.5[a]	3.8[a]	2.2[a]	
G.C. Source 22	13.47	9.61	7.86				
G.C. Source 23	...	10.30	8.07	6.67	5.82	5.2	0.23 ± 0.04
G.C. Source 24	...	10.69	8.35	6.58	5.75	4.90	0.26 ± 0.04
Kob 9	...	8.7[b]	6.4[b]	4.8[b]		3.4	0.48 ± 0.02
VI Cyg No. 12	4.38[c]	3.28[c]	2.72[c]	2.22[c]			

[a] From Becklin *et al.* 1978.
[b] From Kobayashi *et al.* 1982.
[c] From Harris, Woolf, and Rieke 1978.

III. DISCUSSION

a) Near-infrared Extinction

Longward of 0.55 μm, the observed colors of *o* Sco correspond closely to those of a normal star of its spectral type (Johnson 1966) obscured by $A_V = 2.92$ with the average interstellar extinction law from the observations of Schultz and Wiemer (1975) and Sneden *et al.* (1978). For details of this comparison, see Table 2. Shortward of 0.55 μm, the colors are much bluer than expected from the stellar type and average extinction law, leading to the assignment of $R = A_V/E_{B-V} = 4.0$, substantially larger than the average value of $R = 3.09$ (see below). It is unclear whether the large value of R indicates an exception to the "universal" extinction law or a departure from the colors of a normal A5 II star; in either case, the value of R seems to have little influence on the reddening in the red and infrared. Because of this uncertainty in R, we have determined the extinction law by setting $E_{V-K}/E_{B-V} = 2.744$, the weighted average of the measurements of Schultz and Wiemer (1975) and Sneden *et al.* (1978).

As an additional comparison, we show in Table 2 the reddening toward VI Cyg No. 12, based on the photometry summarized by Harris, Woolf, and Rieke (1978) and under the assumption that $E_{V-K}/E_{B-V} = 2.744$.

Since none of the galactic center sources has been detected shortward of 1 μm, A_V cannot be measured directly for them. However, most of the obscuring dust lies well in front of the galactic center (see, e.g., Rieke, Telesco, and Harper 1978) and therefore an abnormal extinction law would not be expected. We therefore again assume $E_{V-K}/E_{B-V} = 2.744$ and compute color excesses for the remaining infrared colors in Table 2. In these calculations, we assumed that the galactic center stars have normal colors for their spectral types (Lebofsky, Rieke, and Tokunaga 1982; Lebofsky and Rieke, unpublished); i.e., for Kob 9 (Kobayashi *et al.* 1982) and source 7, $J-K = 1.13$, $H-K = 0.30$, $K-L = 0.15$, and $K-M = -0.21$; for sources 22, 23, and 24, $J-K = 1.25$, $H-K = 0.35$, $K-L = 0.21$, and $K-M = -0.19$. To allow for photometric errors (which are nominally less than 10%), possible anomalous colors in the stars, and the additional uncertainties in the photometry due to the very steep spectral slopes imposed by extinction at the shorter wavelengths, we assumed errors of 0.4 in $J-K$ and 0.2 in the other colors. Because of the strength of the extinction, the small uncertainties in spectral types for these stars have negligible effect on the derived extinction law.

Table 2 shows the derived color excesses of the galactic center stars, assuming the equivalent total extinction indicated for each star and taking $R = 3.09$ (see below). In all cases the total extinction derived from the photometry in this paper is consistent with that derived from the slopes of the stellar continua measured by spectrophotometry between 2.0 and 2.5 μm (Lebofsky, Rieke, and Tokunaga 1982; Lebofsky and Rieke, unpublished). The uncertainty in the value of R contributes negligibly to the uncertainty in the color excesses; the errors in the average color excesses are primarily a result of the assumed errors in infrared colors. Table 2 demonstrates that the extinction law for the galactic center does not differ significantly from those for *o* Sco or VI Cyg No. 12, so we have computed an average extinction law based on the seven stars for which we have obtained measurements. This average is then compared with the "universal" extinction law derived by Schultz and Wiemer (1975) and Sneden *et al.* (1978); again, there are no significant differences. We have therefore combined the three sets of measurements into the interstellar extinction law summarized in Table 3.

b) The Value of R

Given a universal red to near-infrared extinction law, the measurements of the galactic center stars constrain the ratio of total to selective extinction, $R = A_V/E_{B-V}$. Increasing R adds a neutral component of extinction; an upper limit to the neutral extinction can be derived from the luminosity of source 7. A slightly weaker limit can be derived from Kob 9.

Humphreys (1981) has shown that there is an upper limit to the luminosity of M supergiants. It is thought that this limit arises because of atmospheric instabilities that result in rapid mass loss before the star becomes a red supergiant, if its initial mass is too large. Table 4 lists the most energetic red supergiants in the local group (excepting M31, where no adequate survey for these stars exists). Source 7 is of a spectral type and luminosity to make it closely comparable to these stars.

An estimate of the luminosity of source 7 depends on the distance to the galactic center and on the value of R. Estimates of the distance to the galactic center range from 7 kpc (Frenk and White 1982) to 9 kpc (Rybicki, Lecar, and Schaefer 1974; see also Graham 1979). Adopting 6.5 kpc as a lower limit, we have computed lower limits to the luminosity of source 7 as a function of R. These limits are entered in Table 4, where it can be seen that values of $R > 3.15$ require source 7 to have an uncomfortably large luminosity.

TABLE 2

COLOR EXCESSES

Source	A_V	E_{V-J}/E_{B-V}	E_{V-H}/E_{B-V}	E_{V-K}/E_{B-V}[a]	E_{V-L}/E_{B-L}	E_{V-M}/E_{B-V}
o Sco	2.92	2.16	2.57	2.744	2.90	
VI Cyg No. 12	9.65	2.21	2.56	2.744	2.90	
G.C. 7	35	2.21	2.54	2.744	2.91	3.01
G.C. 22	23	2.16	2.56	2.744		
G.C. 23	27.5	...	2.54	2.744	2.88	3.02
G.C. 24	31	...	2.55	2.744	2.90	3.02
Kob 9	29	...	2.53	2.744	2.90	
Average		2.19	2.55	...	2.90	3.02
		±0.04	±0.02	...	±0.02	±0.02
Schultz and Wiemer 1975		2.23	...	2.744	2.93	3.03
+ Sneden et al. 1978		±0.02	...	±0.024	±0.03	±0.04

[a] For all sources $E_{V-K}/E_{B-V} = 2.744$ was assumed.

TABLE 3

INTERSTELLAR EXTINCTION LAW

λ	$E(\lambda - V)/E(B-V)$	A_λ/A_V	van de Hulst No. 15
U	1.64[a]	1.531	1.555
B	1.00[b]	1.324	1.329
V	0.0[b]	1.000	1.000
R	−0.78[b]	0.748	0.738
I	−1.60[b]	0.482	0.469
J	-2.22 ± 0.02	0.282	0.246
H	-2.55 ± 0.03	0.175	0.155
K	-2.744 ± 0.024	0.112	0.0885
L	-2.91 ± 0.03	0.058	0.045
M	-3.02 ± 0.03	0.023	0.033
N	−2.93	0.052	0.013
8.0 μm	−3.03	0.020 ± 0.003	
8.5	−2.96	0.043 ± 0.006	
9.0	−2.87	0.074 ± 0.011	
9.5	−2.83	0.087 ± 0.013	
10.0	−2.86	0.083 ± 0.012	
10.5	−2.87	0.074 ± 0.011	
11.0	−2.91	0.060 ± 0.009	
11.5	−2.95	0.047 ± 0.007	
12.0	−2.98	0.037 ± 0.006	
12.5	−3.00	0.030 ± 0.005	
13.0	−3.01	0.027 ± 0.004	

[a] From Nandy *et al.* 1976.
[b] From Schultz and Wiemer 1975.

A lower limit can be placed on R by requiring that the extinction at M, 8, and 13 μm be greater than zero, yielding $R > 2.99$. A slightly less conservative but still plausible limit would require that the extinction decrease between L and M no more rapidly than Rayleigh scattering, which would require $R > 3.03$. Interpreting our upper and lower limits as being valid roughly at a 2 σ level of significance, we estimate that $R = 3.09 \pm 0.03$.

c) *Extinction at* 10 μm

In the following, we define the optical depth in the silicate absorption, τ_{Si}, relative to a power-law continuum fitted through spectral points at 8 and 13 μm. Silicate emission features are characterized by negative values of τ_{Si}. This definition has been used previously with regard to VI Cyg No. 12 (Rieke 1974).

The shape of the silicate emission feature is nearly the same, whether it is observed in a circumstellar shell (Russell, Soifer, and Forrest 1975) or an H II region (Forrest, Gillett, and Stein 1975). Our measurements used a two-filter technique (Lebofsky and Rieke 1979) which does not determine the feature shape independently and which measures the depth of the feature slightly to the red of its maximum. Therefore, τ_{Si} was computed from our measurements by convolving the feature shape (Russell, Soifer, and Forrest 1975; Forrest, Gillett, and Stein 1975) with the filter transmission functions. The values of τ_{Si} are entered in Table 5.

TABLE 4

BRIGHT M SUPERGIANTS

Galaxy	Star	Spectral Type	M_V	R
SMC	Case 107–1	K5–M0 Ia	−8.3	
MW	μ Cep	M2 Ia	−8.2	
LMC	Case 46–44	M1 Ia	−8.1	
IC 1613	V 38	M0 Ia	−8.1	
LMC	Case 46–32	M0 Ia	−8.0	
SMC	Case 106–1A	M0 Ia	−8.0	
MW	Source 7	M1 Ia	< -8.4	3.16
	Source 7		< -8.1	3.13
	Source 7		< -7.8	3.10

TABLE 5

CALCULATIONS OF τ_{Si}

Source	Observed τ_{Si}	Intrinsic τ_{Si}	Interstellar τ_{Si}	A_V/τ_{Si}
o Sco	0.17 ± 0.03	0	0.17 ± 0.03	17 ± 4
VI Cyg 12	0.42 ± 0.05[a]	0	0.42 ± 0.05	24 ± 4
G.C. 7	2.3 ± 0.3[b]	−0.5	2.8 ± 0.5	12.3 ± 3
G.C. 23	2.55 ± 0.3	0.3	2.2 ± 0.5	
G.C. 24	2.4 ± 0.25	−0.1	2.5 ± 0.5	
Kob 9[c]	1.4 ± 0.1	−1.0	2.4 ± 0.5	

[a] From Rieke 1974.
[b] From Becklin *et al.* 1978.
[c] Source 9 in Kobayashi *et al.* 1982.

The two-filter technique we have used to measure the silicate absorption can be confused by the interstellar emission features at 8.8 and 11.3 μm (Lebofsky and Rieke 1979; Aitken, Roche, and Phillips 1981). These features are seen only in regions with strong emission by hot dust; they are therefore very unlikely to influence our measurements of *o* Sco. For the galactic center sources, the extreme depth of the 10 μm absorption and the absence of the 3.3 μm emission feature (Pipher and Willner 1982), which usually accompanies those near 10 μm, both argue against any significant error in our estimates in τ_{Si} from this cause.

A serious uncertainty in determining the interstellar silicate absorption toward the galactic center arises from the probable presence of intrinsic silicate absorption or emission features in the sources. This problem is particularly severe for the brightest 10 μm sources, since their nature is unclear. Therefore, we have confined our measurements to single stars of well-determined spectral type (Lebofsky, Rieke, and Tokunaga 1982; Lebofsky and Rieke, unpublished). Stars of similar type generally have circumstellar shells contributing excess emission at 10 μm; the strength of the intrinsic silicate feature from these shells ranges from $0.3 \geq \tau_{Si} \geq -1.0$ (Merrill and Stein 1976*a*, *b*). The colors of the stars in the galactic center imply that they also have excess emission. If the same interstellar extinction law applies to all four galactic center stars, then the interstellar silicate absorption will be proportional to E_{H-K} for these stars. If we assume that the total range of intrinsic feature strengths is the same as found for stars away from the galactic center, i.e., $0.3 \geq \tau \geq -1.0$, there is a unique separation of the observed silicate absorptions into interstellar and circumstellar components. This separation is illustrated in Table 5: it indicates that Kob 9 has an optically thin shell with a strong emission feature similar to that of μ Cep; source 7 has an optically thick shell which contributes a very large excess across the whole 10 μm window, similar to that of VX Sgr; and sources 23 and 24 have optically thick shells contributing more modest excesses, similar to that of RS Cnc (Merrill and Stein 1976*a*, *b*). The lucky circumstance that the four stars observed in the galactic center exhibit the full range of intrinsic silicate features observed in similar stars allows us to eliminate the uncertainty in the strength of the interstellar feature that would otherwise arise because of intrinsic emission.

A_V can be estimated for the galactic center stars from their spectral types, near-infrared color excesses, and an assumed value of R. Taking $R = 3.09$, the ratio A_V/τ_{Si} is shown in Table 5; note that the estimates are not independent because of the method used to separate intrinsic and interstellar silicate features. Therefore, $A_V/\tau_{Si} = 12.3 \pm 3$ for the galactic center. Including *o* Sco and VI Cyg No. 12, the weighted average of the three independent determinations of A_V/τ_{Si} is 16.6 ± 2.1; no single estimate differs significantly from this average. Within their errors, our observations are consistent with a universal extinction law through 13 μm.

The above discussion has defined the silicate optical depth in terms of the strength of the observed feature, which would normally be estimated relative to a power-law continuum between 8 and 13 μm. Some (e.g., Gillett *et al.* 1975) have defined τ_{Si} as the total absorption depth including an allowance for absorption at 8 and 13 μm. With this definition, the extinction law in Table 3 yields $A_V/\tau_{Si} = 12.7 \pm 1.6$.

d) The Interstellar Extinction Law

The interstellar extinction law is summarized in Table 3. Shortward of 1 μm, the entries are based on the work of Schultz and Wiemer (1975), Nandy *et al.* (1976) and Sneden *et al.* (1978); longward of 1 μm, they are weighted averages of their results and those reported in this paper.

For wavelengths between 1 and 5 μm, the color excesses in Table 3 were determined directly, and the total extinction was calculated assuming $R = 3.09$. The error in the color excesses is dominated by the uncertainty in E_{V-K}/E_{B-V}. Between 8 and 13 μm, A_λ/A_V was computed directly, assuming that the wavelength dependence of opacity of the interstellar grains went as the average of the emission spectra of μ Cep (Russell, Soifer, and Forrest 1975) and the Trapezium (Forrest, Gillett, and Stein 1975) and that $A_V/\tau_{Si} = 16.6$. The uncertainty in the tabulated extinctions is dominated by the uncertainty in the ratio of A_V to silicate absorption depth. The color excesses between 8 and 13 μm were derived from the extinctions. Finally, the extinction in the N photometric band was estimated by integrating the derived narrow-band extinctions over the photometric bandpass, including atmospheric absorptions as part of the effective bandpass.

Table 3 also compares the interstellar extinction law of van de Hulst's (1949) curve No. 15, which has been considered a virtually perfect theoretical representation of the interstellar extinction law. Of course, van de Hulst did not anticipate the silicate absorption at 10 μm; note moreover that the correspondence between curve 15 and the observed extinction is poor at all wavelengths beyond 1 μm.

IV. CONCLUSION

We have measured the interstellar extinction law beyond 1 μm toward *o* Sco and the galactic center. We find

1) Within the measurement errors, the extinction law outside dense molecular clouds appears to be uniform.

2) The ratio of total to selective extinction is $R = 3.09 \pm 0.03$.

3) The ratio of $A_V/\tau_{Si} = 16.6 \pm 2.1$, where τ_{Si} is measured relative to power-law interpolation between 8 and 13 μm. If τ_{Si} is taken to be the total extinction (including an allowance for absorption at 8 and 13 μm), $A_V = 12.7 \pm 1.6$.

4) The interstellar extinction law is as given in Table 3.

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REFERENCES

Aitken, D. K., Roche, P. F., and Phillips, M. M. 1981, *M.N.R.A.S.*, **196**, 101P.
Becklin, E. E., Matthews, K., Neugebauer, G., and Willner, S. P. 1978, *Ap. J.*, **220**, 831.
Forrest, W. J., Gillett, F. C., and Stein, W. A. 1975, *Ap. J.*, **195**, 423.
Frenk, C. S., and White, S. D. M. 1982, *M.N.R.A.S.*, **198**, 173.
Gillett, F. C., Jones, T. W., Merrill, K. M., and Stein, W. A. 1975, *Astr. Ap.*, **45**, 77.
Graham, J. A. 1979, in *IAU Symposium Large Scale Characteristics of the Galaxy*, ed. W. B. Burton (Dordrecht: Reidel), p. 195.
Harris, D. H., Woolf, N. J., and Rieke, G. H. 1978, *Ap. J.*, **226**, 829.
Humphreys, R. M. 1981, in *The Most Massive Stars*, ed. S. D'Odorico, D. Baade, and K. Kjar (Munich: ESO), p. 5.
Johnson, H. L. 1966, *Ann. Rev. Astr. Ap.*, **4**, 193.
———. 1968, in *Nebulae and Interstellar Matter*, ed. B. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press), p. 167.
Kobayashi, Y., Sato, S., Okuda, H., Jugaku, J., and Dyck, H. M. 1983, *Pub. Ast. Soc. Japan*, **35**, 101.
Lebofsky, M. J., and Rieke, G. H. 1979, *Ap. J.*, **229**, 111.
Lebofsky, M. J., Rieke, G. H., Deshpande, M. R., and Kemp, J. C. 1982, *Ap. J.*, **263**, 672.
Lebofsky, M. J., Rieke, G. H., and Tokunaga, A. T. 1982, *Ap. J.*, **263**, 736.
Low, F. J., and Rieke, G. H. 1974, in *Methods of Experimental Physics*, Vol. **12**, ed. N. Carleton (New York: Academic Press), p. 415.
Merrill, K. M., and Stein, W. A. 1976*a*, *Pub. A.S.P.*, **88**, 285.
———. 1976*b*, *Pub. A.S.P.*, **88**, 294.
Nandy, K., Thompson, G. I., Jamar, C., Monfils, A., and Wilson, R. 1976, *Astr. Ap.*, **51**, 63.
Pipher, J. C., and Willner, S. P. 1982, preprint.
Rieke, G. H. 1974, *Ap. J.* (*Letters*), **193**, L81.
Rieke, G. H., Telesco, C. M., and Harper, D. A. 1978, *Ap. J.*, **220**, 556.
Russell, R. W., Soifer, B. T., and Forrest, W. J. 1975, *Ap. J.* (*Letters*), **198**, L41.
Rybicki, G., Lecar, M., and Schaefer, M. 1974, *Bull. A.A.S.*, **6**, 453.
Savage, B. D., and Mathis, J. D. 1979, *Ann. Rev. Astr. Ap.*, **17**, 73.
Schultz, G. V., and Wiemer, W. 1975, *Astr. Ap.*, **43**, 133.
Sneden, C., Gehrz, R. D., Hackwell, J. A., York, D. G., and Snow, T. P. 1978, *Ap. J.*, **223**, 168.
van de Hulst, H. C. 1949, *Rech. Astr. Obs. Utrecht*, Vol. **11**, Part 2.

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