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INFRARED OBSERVATIONS OF THE GALACTIC CENTER. IV. THE INTERSTELLAR EXTINCTION

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ABSTRACT

Infrared observations of the compact sources and background in the galactic center are used to derive the 1.25–12.5 μm interstellar extinction law. The depth of the interstellar 10 μm silicate absorption feature is derived from observations of the M supergiant IRS 7. The ratio of visual to silicate extinction is found to be 8 $\pm$ 3. From the colors of individual sources and the background, it is concluded that there are no more than 6 mag of visual extinction within the central 3 pc of the galactic center.

Subject headings: galaxies: Milky Way — galaxies: nuclei — infrared: sources — interstellar: matter

I. INTRODUCTION

In the previous three papers (Becklin *et al.* 1978 [Paper I]; Willner 1978 [Paper II]; Neugebauer *et al.* 1978 [Paper III]) observations of the compact sources in the central region of the Galaxy are presented and discussed as they relate to the nature of the sources. The observations can also be used to determine the amount and wavelength dependence of the interstellar extinction to the compact sources, and such a discussion is, in fact, necessary to correct the energy distributions of the individual sources.

At a distance of 10 kpc, the galactic center suffers about 30 mag of visual extinction (Becklin and Neugebauer 1968, henceforth BN 68). While there are sources that probably suffer more extinction, most or all of the extinction in these sources is probably local to the source. Such local extinction can have properties different from the general interstellar extinction (Gillett *et al.* 1975). Furthermore, if the absorbing dust is sufficiently hot, radiative-transfer effects must be considered (e.g., Kwan and Scoville 1976). In contrast, it will be argued below that the extinction determined from the sources near the center of the Galaxy is predominantly interstellar. The measurements thus are complementary to, although independent of, the comprehensive study by Johnson (1968) and provide a measure of the extinction taken over a large path length of the Galaxy.

In this paper the observations of the compact sources in the galactic-center region are discussed with a view to defining the interstellar extinction from 1.25 to 20 μm. The observational techniques have been presented in Paper I. For a number of reasons, the determination of the amount and wavelength dependence of infrared interstellar extinction is almost always difficult. This is certainly true for the galactic-center region. Because of a number of unique advantages and the importance of the extinction in understanding galactic-center sources, we attempt in this paper to summarize our best understanding of the extinction to the galactic center. Some of the procedures and assumptions, particularly with regard to the extinctions near 10 and 20 μm, must, however, necessarily be *ad hoc*.

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II. SHORT-WAVELENGTH OBSERVATIONS

The observed magnitudes of the compact sources identified by Becklin and Neugebauer (1975, henceforth BN 75) in the galactic-center region are listed in Table 1. Three of the sources, IRS 7, IRS 11, and IRS 12, show photospheric CO absorption at 2.3 μm (Neugebauer *et al.* 1976; Soifer, Russell, and Merrill 1976; Treffers *et al.* 1976). It therefore can be assumed that these sources, at least, are stars.

There are several lines of argument which indicate that the short-wavelength background radiation from the galactic-center region is also stellar. First, the observed [1.65] − [2.2] colors of the stellar sources IRS 7, 11, and 12 are 2.6, 2.1, and 2.3 mag, in agreement with the [1.65] − [2.2] color—2.3 mag—of the background as measured by Becklin and Neugebauer (1969, henceforth BN 69) in large apertures (see Table 1). Second, as argued by BN 68, a comparison with the brightness and structure of the 2.2 μm flux from M31 indicates that the background is made up of stars. Finally, CO absorption indicative of supergiants has been observed in the background flux within a 32″ diaphragm (Paper III).

The observed color of the background, when the flux from the resolved sources at the center is excluded, is uniform for all diaphragms centered on the galactic center between 15″ and 110″ (BN 69). The uniformity in color over such a large area argues that the extinction is interstellar rather than local to the sources. In the subsequent discussion we will assume that the extinction as determined from the background sources in the galactic center is, in fact, interstellar. Such extinction is likely to be the minimum to any

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TABLE 1

MEASURED MAGNITUDES AND ADOPTED EXTINCTION CORRECTIONS*

Source	1.25 μm†	1.65 μm†	2.2 μm†	3.5 μm†	4.8 μm†	8.7 μm‡	9.5 μm‡	11.2 μm‡	12.5 μm‡	20 μm‡§
1	...	11.1	8.4	5.4	3.5	0.3	0.7	−0.6	−1.5	−2.9
2	...	...	...	...	...	1.7	2.2	+0.5	−0.8	> −1.4
3	...	...	...	5.1	2.5	0.8	2.5	+0.8	−0.9	−0.6
4	...	...	...	...	...	3.4	4.1	+1.7	+0.3	
5	...	...	...	...	...	2.0	2.7	+1.0	+0.1	−1.8
6	...	...	...	...	...	1.9	2.7	+1.0	−0.5	−1.2
7	13.8	9.3	6.7	4.5	3.8	3.1	4.1	+2.6	+0.8	> −0.2
8	...	> 15.3	10.1	6.1	3.9	1.4	2.4	+1.0	−0.2	−1.2
9	...	11.1	8.7	6.4	4.3	1.6	2.3	+0.5	−0.8	> −1.6
10	...	...	...	...	...	1.0	1.6	+0.2	−0.8	−2.2
11	...	10.9	8.8	7.2	6.2‖	...	...	...	...	
12	...	10.3	8.1	5.7	3.7	...	...	...	...	
16	...	10.4	8.3	6.4	4.4	...	...	...	...	
19	...	10.6	8.1	6.5	6.0‖	...	...	...	...	
20	...	...	...	...	...	2.0	2.6	+0.7	−0.6	−2.1
Adopted extinction correction	7.7	4.7	2.7	1.4	0.8	2.4	3.8	+2.8	+1.3	+0.9

* Statistical errors less than 0.1 except as noted.

† Measured with 3″8 diaphragm, except for IRS 12 and IRS 19 which were with a 5″0 diaphragm.

‡ Measured with 2″3 diaphragm.

§ From 20 μm map in Fig. 2 of Paper I; uncertainty = ±0.5 contour = ±6 Jy. See text of Paper I.

‖ Statistical error 0.4 (IRS 11) and 0.3 (IRS 19).

source in the galactic-center region; in fact, as discussed in Paper I, IRS 3 apparently shows a large amount of intrinsic extinction.

The relative shape of the extinction curve from 1.25 to 3.4 μm can be derived from the data of Table 1, if the shape of the underlying spectrum is assumed. In Table 2, the extinction corrections necessary to make the colors of the background consistent with those of M6 stars (Lee 1970) are shown. No measurements exist for the background at 1.25 μm, so the extinction at that wavelength was derived from the measurements of IRS 7. IRS 7 is redder by 0.3 mag in its [1.65] − [2.2] color than the background. If this observed color difference is assumed to result from a local reddening amounting to 15% of the total reddening to IRS 7, then IRS 7 suffers 0.8 mag of local reddening in its [1.25] − [2.2] color. The [1.25] − [2.2] color of the background has therefore been assumed to be 6.3 mag—0.8 mag less than the observed [1.25] − [2.2] color of IRS 7. This correction is within the uncertainty of the procedure, and the resultant color excesses agree with those found by Spinrad *et al.* (1971) at 1.06 μm. If the color difference between IRS 7 and the background results from a redder intrinsic photosphere of IRS 7, the correct value of [1.25] − [2.2] to use is uncertain, but extrapolation of existing color-color diagrams (Lee 1970) would lead to a value similar to the one used above.

The data of Table 2 can be fitted with curve 15 of van de Hulst (1946; see Johnson 1968) to rederive the total extinction at 2.2 μm. The resultant fit gives $A(2.2\ \mu m) = 2.7$ mag, in agreement with the determination of BN 68. This value is also in agreement with the total extinction obtained in Paper III from a comparison of Bγ line data with radio maps of Ekers *et al.* (1975).

Although the galactic center cannot be observed at visual wavelengths, it is customary to express the amount of extinction in visual magnitudes. Van de Hulst's curve 15 implies that $[A(1.65\ \mu m) - A(2.2\ \mu m)]/A_v = 0.07$ (Johnson 1968), or $A_v \approx 30$ mag. The uncertainty in intrinsic color of the stars observed in the background leads to an uncertainty of 4 mag in this estimate.

TABLE 2

NEAR-INFRARED COLORS

Parameter	Color (mag) [1.25] − [2.2]	[1.65] − [2.2]	[2.2] − [3.5]
M6 III star*	1.3	0.3	0.3
Observed:†			
IRS 7	7.1	2.6	2.2
IRS 11	...	2.1	1.6
IRS 12	...	2.2	2.4
110″ aperture‡	...	2.3	1.6
Adopted color	6.3§	2.3	1.6
Derived reddening	5.0	2.0	1.3
van de Hulst curve 15‖	0.16	0.07	0.04

* Lee 1970.

† Uncertainty is typically less than ±0.2 mag.

‡ BN 69.

§ See text.

‖ Normalized to $A_v = 1$.

III. SILICATE EXTINCTION

The dominant form of extinction at wavelengths from 8 to 20 μm appears to be silicate absorption (see, e.g., Rieke 1974; Gillett *et al.* 1975). The relative silicate optical depth as a function of wavelength from 8 to 13 μm has been determined for a variety of objects and is nearly the same in all of them (Forrest, Gillett, and Stein 1975; Willner 1977 and references therein). A typical set of color excess ratios $\eta(\lambda) = [A(9.5\ \mu\text{m}) - A(\lambda)]/[A(9.5\ \mu\text{m}) - A(12.5\ \mu\text{m})]$ is given in Figure 1.

It is more difficult to determine the extinction curve to the galactic center in the wavelength region around 10 μm, since the shape of the intrinsic energy distribution of the sources is uncertain. The only identified stellar source in the galactic-center region which is sufficiently bright to be measured at 10 μm is IRS 7. Several different underlying energy distributions for IRS 7 in the 10 μm region were compared with the data of Table 1 to determine the relative extinction to the galactic center. These included energy distributions like those of blackbodies at various temperatures from 150 through 600 K; if the energy distribution is like that of a blackbody, only a temperature of approximately 350 K is consistent with an extinction curve that fits the known shape of the silicate absorption band. Underlying energy distributions which showed an intrinsic silicate emission feature or an intrinsic absorption feature were also used to determine the shape of the extinction curve. For the emission feature, the measured energy distribution of the M3 supergiant HD 143183 (Humphreys and Ney 1974) was used; its luminosity and spectral type are probably similar to those of IRS 7 (Paper I). To represent an energy distribution with an absorption feature, a 350 K blackbody was reddened with

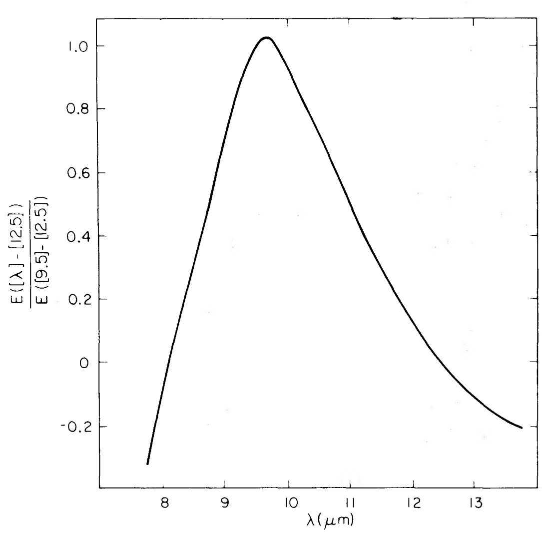

FIG. 1.—The relative extinction in the 7.75–13.5 μm region determined by the observations of Forrest, Gillett, and Stein (1975) and Willner (1977 and references therein).

the curve of Figure 1 by an amount corresponding to 1.2 mag at 9.5 μm; from the near-infrared colors this is approximately the maximum local extinction allowed to exist to IRS 7. The resultant depth of the interstellar silicate feature to the galactic center as measured by the [9.5 μm] − [12.5 μm] color excess is 2.5 mag for the 350 K blackbody, 3.7 mag for the emission feature, and 1.7 mag for the absorption feature. The latter two values can be considered to be the extreme values possible, while the former value was used for the calculations in this paper and in Paper I.

In Paper I, the extinction curve whose shape has been derived by using an intrinsic 350 K blackbody spectrum for IRS 7 has been applied to the observations of several sources in the galactic-center region. Figure 7 of Paper I shows that all but one of these sources exhibit an intrinsic silicate emission feature; a silicate absorption feature is seen in IRS 3. The shape of the emission peak in each of these is similar to that observed by Forrest *et al.* for the emission from the Trapezium region in Orion. This similarity is additional evidence that the adopted extinction is reasonable; in particular, if a larger extinction correction were adopted, the silicate peak in the other sources would be stronger than that observed in the Trapezium. There is no evidence that those sources which were not detected in the near-infrared have intrinsically different silicate emission from those which were seen at the shorter wavelengths.

The amount of gray extinction at 10 μm is unknown. As a working hypothesis, the extinction can be extrapolated from $\sim$3.5 μm to the continuum at the short-wavelength side of the silicate absorption (Fig. 1) by using a λ^{-1} relation. This assumption results in $A(7.75\ \mu\text{m}) = 0.6$ mag, which is taken as gray extinction across the 10 μm band. The extinctions (Table 1) at the wavelengths of the narrow-band filters are the sum of this gray extinction plus the relative extinction implied by Figure 1, obtained by using the color excess of IRS 7 discussed above.

The extinction at 20 μm is even more uncertain than that at 10 μm. The ratio of 20 μm to 10 μm optical depths has been measured for meteorites (Penman 1976) and lunar rocks (Knacke and Thomson 1973). The ratio measured in two OH sources appears to be much smaller (Simon and Dyck 1975), but that may be because the dust that absorbs at 10 μm is warm enough to emit at 20 μm; presumably this would not be the case for interstellar absorption. The picture is complicated by the variation of the absorption ratio with temperature (Day 1976). For Papers I and II, it was assumed, on the basis of the lunar rock and meteorite measurements, that the absorption averaged over the bandpass of the 20 μm filter is $A(20\ \mu\text{m}) = A(9.7\ \mu\text{m})/4$.

The extinction curve extended from 1.2 to 20 μm is shown in Figure 2. The ice band at 3.1 μm which has been seen in many sources has been searched for and not seen in the interstellar material to the galactic center (Soifer, Russell, and Merrill 1976). If curve 15 of van de Hulst (Johnson 1968) is used to extrapolate

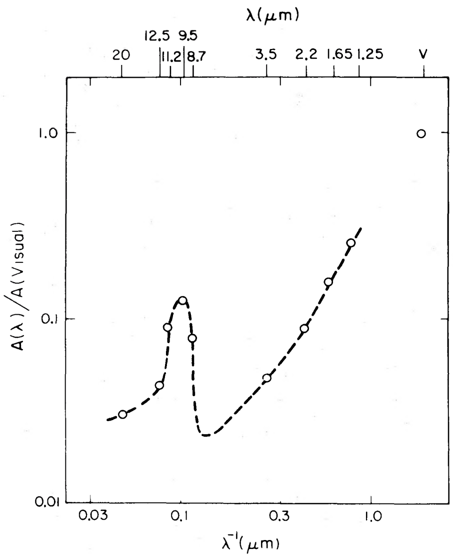

FIG. 2.—The interstellar extinction curve between 0.54 and 20 μm normalized to $A_v = 1.0$ at 0.54 μm. The shape of the curve in the region between 1.25 and 12.5 μm has been found from the observations presented in this paper. The 20 μm extinction is based on measurements of lunar rocks and meteorites (see text). The extrapolation of the curve to 0.54 μm and the zero point in the 1.25–3.4 μm region were found by using curve 15 of van de Hulst (Johnson 1968). The zero point in the 10 μm region was found by assuming a $1/\lambda$ extinction law between 3.5 and 7.75 μm.

from A(1.65 μm) − A(2.2 μm) to A_v, A_v/A(9.5 μm) = 8 ± 3. This is smaller than the value of 13 found for the ratio in VI Cyg No. 12 by Gillett *et al.* (1975), who used the same extinction curve adopted here to find A(9.5 μm). Rieke (1974) has derived a value A_v/A(9.5 μm) = 22; when his data are reinterpreted with the same extinction curve adopted here, a value A_v/A(9.5 μm) = 15 results.

Since A_v has not been measured directly in the galactic center and since the value of A(9.5 μm) cannot be determined without uncertain assumptions, a more direct comparison can be made with the color ratio R' = [A(1.65 μm) − A(2.2 μm)]/[A(9.5 μm) − A(12.5 μm)], a quantity which depends only on the observations and the assumed intrinsic energy distribution of the source. If the intrinsic energy distribution of IRS 7 follows that of a 350 K blackbody near 10 μm as discussed above, R' = 0.8. If IRS 7 has a silicate emission feature of the size observed by Humphreys and Ney (1974) in the M supergiant HD 143183, then the value of R' in the galactic center is 0.5. If the intrinsic spectrum of IRS 7 has a silicate absorption corresponding to A(9.5 *μm*) = 1.2 mag imposed on a 350 K blackbody, R' can be as high as 1.2. Using Rieke's (1974) data along with Johnson (1968), one finds a value for VI Cyg No. 12 of R' = 1.4. This difference may indicate that the interstellar extinction curve to VI Cyg No. 12 is different from that to the galactic center, or that VI Cyg No. 12 shows a silicate emission feature in its intrinsic spectrum.

IV. EXTINCTION WITHIN 3 PARSECS OF THE GALACTIC CENTER

An examination of Table 1 shows that the [1.6] − [2.2] μm color of all but one of the sources measured at short wavelengths is similar to that of the three sources which are established to be stellar. In this interpretation, this single source—IRS 8—must be intrinsically redder than the remaining compact sources. This conclusion is corroborated by its relative brightness at 10 and 20 μm. As noted above, the source IRS 7 is marginally redder than the other sources and may also suffer local extinction. With the assumption that the sources are stellar, there is no evidence in the [1.65] − [2.2] μm colors for local extinction in excess of 20% of the interstellar extinction for any of the objects except possibly IRS 8.

As discussed above, the silicate emission feature found after application of the absorption correction to all of the sources is nearly the same for all sources except IRS 3 and IRS 7. In particular, the strength of the silicate emission is independent of the emission at 2 μm relative to the 10 μm intensity. The small dispersion among sources in the implied value of A(9.5 μm) matches that found for shorter-wavelength extinction. Such small dispersion is again most easily explained if most of the absorption is interstellar rather than local to the sources.

It should be noted that Capps and Knacke (1976) and Knacke and Capps (1977) have observed infrared polarization to the galactic center which requires an A(9.5 μm) of at least 0.5 mag. The direction of polarization changes from source to source and is roughly perpendicular to the galactic plane, whereas interstellar polarization is normally along the plane; Capps and Knacke therefore suggest that most of the observed polarization occurs very near the galactic center. A local absorption of 0.5 mag is consistent with the dispersion found here.

V. CONCLUSIONS

The principal conclusions of this work are:

1. The relative extinction curves for the interstellar medium in the 1.25–3.5 μm and 8–12.5 μm regions have been derived from observations of the galactic center and are presented in Table 1 and Figure 2. The interstellar extinction curve derived represents an average of the extinction over a significant portion of the Galaxy. The ratio $A_v/(9.7$ μm) is 8 ± 3, based largely on observations of the supergiant IRS 7.

2. Observations of the compact sources in the galactic center both in the 1.65–2.2 μm color and in the depth of the silicate absorption show no evidence for more than 6 mag of local extinction within 3 pc of the center.

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