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EXTINCTION TO IONIZED GAS AT THE GALACTIC CENTER

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ABSTRACT

Measurements of Brα and Brγ fluxes of compact sources in the galactic center are used to derive extinctions. Extinction to the ionized gas is similar to or smaller than that previously determined for stellar sources; much larger extinction to the ionized gas is ruled out. IRS 6 shows about twice as much extinction as the other compact sources.

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

I. INTRODUCTION

There are several different types of compact infrared sources within 1 pc of the center of our Galaxy (for a review, see Gatley and Becklin 1981, and references therein). Many of the compact sources are thought to be stars or star clusters (Becklin *et al.* 1978*a*); these sources are relatively bright at wavelengths near 2 μm. Other sources, brighter at longer wavelengths, are thought to be dust emission (e.g., Rieke, Telesco, and Harper 1978; Becklin *et al.* 1978*a*) from compact objects that are probably associated with clouds of ionized gas (Lacy *et al.* 1980; Brown, Johnston, and Lo 1981). There is also spatially extended emission, probably from dust associated with ionized gas at lower density.

The extinction to the compact sources has been discussed by Becklin *et al.* (1978*b*) and Rieke, Telesco, and Harper (1978). These authors derived extinction from infrared observations in the 1.2 and 3.5 μm wavelengths by assuming that the bluest sources are stars or star clusters. Since the 1.65 to 2.2 μm colors of normal stars are only weakly dependent on spectral type (Persson *et al.* 1980), the measurements give the infrared color excess $E(H-K)$ directly. The conclusion reached was that the extinction was different for different sources, but only by ~ 20% of the total extinction. Moreover, if a "normal" reddening curve is adopted, the amount of extinction to the galactic center is equivalent to ~ 30 visual magnitudes.

On a slightly larger spatial scale, Lebofsky (1979) found differential extinction amounting to roughly a factor of 2. The lowest extinction appears to be in the vicinity of the compact sources, and both the infrared extinction and formaldehyde column density (Whiteoak, Rogstad, and Lockhart 1974) increase to the east.

Measurements of the silicate feature near 10 μm with a large beam (Woolf 1973; Aitken and Jones 1973) and with a small beam (Becklin *et al.* 1978*a*) suggest that the extinctions to most of the dust-emitting sources are roughly the same. Because the ratio of the extinction at 10 μm to that at near-infrared wavelengths has been measured for only a single star (Gillett *et al.* 1975*b*; Rieke 1974), it is difficult to compare the 10 μm and near-infrared extinctions to galactic center sources. An additional uncertainty is that the derived value of the silicate optical depth depends on the nature of the underlying continuum, which in this case is also unknown. Either underlying gray or silicate continuum emission has been proposed for galactic H II regions, with silicate emission being more likely. If silicate emission predominates in the galactic center dust-emitting sources, their optical depths near 10 μm are larger than the near-infrared extinction to the stellar component.

The extinction deduced from the far-infrared emission and assumed properties of dust grains is about a factor of 2 larger than the suggested near-infrared extinction (Andriesse and de Vries 1978), but the dust emissivities are at best poorly known. Moreover, the far-infrared measurements necessarily refer to a large solid angle, while both the silicate and near-infrared measurements refer only to the column of material directly in the line of sight. Nevertheless, there have been suggestions (e.g., Andriesse and de Vries 1978) that

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the stellar sources lie in front of the galactic center and suffer less extinction than the dust sources. An alternative view (e.g., Federman and Evans 1981) is that the line of sight to the densest cluster of compact sources suffers considerably less extinction than the average of nearby regions. This view is supported by the aperture synthesis H_2CO observations of Whiteoak *et al.*

Polarization measurements (Knacke and Capps 1977) also raise questions about the constancy of the extinction among the compact sources. Both the degree and position angle change, suggesting extinction variation of up to 50%.

In view of the limited data on the extinction to the galactic center and the somewhat questionable assumptions inherent in each method for deriving the extinction, it seemed worthwhile to attempt additional measurements. The ratio of Brα to Brγ fluxes can provide a useful extinction probe (Bally, Joyce, and Scoville 1979). The line ratio is nearly independent of temperature and density for normal H II regions (e.g., Osterbrock 1974), and observations of several galactic H II regions (Herter *et al.* 1981) show that the Brackett line ratio, the ratio of either Brackett line to the free-free radio emission, and the apparent silicate optical depth based on underlying silicate emission all give roughly consistent measures of the extinction. The main systematic effect is that if the extinction varies along the line of sight (i.e., if the absorbing dust is mixed with the emitting gas), the extinction measurement is weighted toward the nearest part of the H II region rather than being an average over the whole region. The result is a tendency to underestimate the total extinction corresponding to a given selective extinction (Mathis 1970). Another systematic error acts in the same direction: if the extinction varies across the measurement aperture, the average extinction is weighted toward the smallest values.

A recent paper by Brown *et al.* presents VLA observations of the galactic center sources and estimates Brγ fluxes from the maps of Neugebauer *et al.* (1978) to assess extinction to the compact sources. These estimates are rough, but suggest 2.2 μm extinctions of 2–3 mag, in reasonable agreement with the stellar sources.

This paper reports measurements of Brα and Brγ line fluxes at 11 positions in the galactic center. Both lines were measured at each position with the same setting of the telescope so the measurements should refer to the same column of gas. The line ratios for the five positions where both lines were detected are interpreted in terms of the extinction to those sources.

II. OBSERVATIONS

All of the observations were made with the 4 m telescope at the Cerro Tololo Inter-American Observatory on the nights of 1980 June 29 and July 1–3. Sources were located with respect to the maps of Becklin and Neugebauer (1975), Rieke, Telesco, and Harper 1978, and Becklin *et al.* (1978*a*) by offsetting from IRS 7. Except for IRS 5 and 20, it was then possible to peak up at a wavelength where each source was the brightest relative to nearby sources. The chosen position was maintained by guiding on a visible star seen through a dichroic beam splitter. The derived or assumed positions and the beam sizes and chopper spacings used are shown in Table 1. The chopper was oriented north-south; for IRS 4 and 8 the telescope was beam switched to the east and north, respectively, in order to produce as little flux as possible in the reference beam, based on the 2 μm continuum map. The line flux in the reference beam was probably negligible, because the surface brightness falls off rapidly farther than ~ 30″ from the center (Neugebauer *et al.* 1978).

TABLE 1

LINE SURFACE BRIGHTNESSES AND EQUIVALENT WIDTHS

Source (IRS)	Offset[a]	Beam	Chop	I(Brα) (10^{-17} W m^{-2} arcsec^{-2})	I(Brγ) (10^{-17} W m^{-2} arcsec^{-2})	W(Brα) (nm)	W(Brγ) (nm)
1	5″S, 5″E	3″.9	20″	10±9	6.1±3.3	1.1±1.0	2.8±1.5
2	15 S, 6 W	3″.9	60	48±7	5.9±1.4	6.2±0.9	3.4±0.8
4	11 S, 15 E	3″.9	60[b]	19±1	2.2±0.5	44. ±2.7	5.1±1.2
5	4 N, 9 E	3″.5	60	21±2	2.5±0.3	12. ±0.9	3.9±0.5
6	5 S, 9 W	3″.5	60	43±6	1.4±0.5	16. ±2.4	1.9±0.7
8	25 N, 1 E	3″.9	5[b]	−2±4	0.7±0.9	−0.4±0.8	1.2±1.6
11	7 N, 9 W	3″.9	6	−5±5	1.2±1.7	−5.6±5.0	1.0±1.4
16	5 S, 1 E	3″.9	20	6±3	6.1±3.3	10.8±5.1	2.4±1.3
17	1 N, 12 E	3″.9	10	−10±2	0.7±1.2	−20. ±3.	0.7±1.2
19	24 S, 15 E	3″.9	15	−15±3	2.1±2.2	−10.4±2.4	1.2±1.2
20	11 S, 1 E	3″.5	60	51±4	5.2±0.7	20. ±1.8	3.2±0.4

[a] From IRS 7.

[b] Beam switch different from chop.

1983ApJ...265..760W

TABLE 2

COLOR EXCESSES AND CALCULATED EXTINCTIONS[a]

SOURCE (IRS)	$E(2.17–4.05)$ (mag)	$\tau_{2.17}$[b]	$\tau_{2.17}$[c]	$\tau_{2.17}$[d]	$\tau_{4.05}$[e]	$\tau_{9.7}$ Type I	$\tau_{9.7}$ Type II
2	1.08	2.3	1.7	2.5	1.4	2.4	3.8
4	1.15	2.5	1.8	2.5	1.0	3.1	4.6
5	1.12	2.4	1.8	2.5	1.5	2.5	3.8
6	2.53	5.5	4.0	(2.3)[f]	(0.4)[f]	3.1	4.5
				4.0	2.1		
20	1.29	2.8	2.0	2.3	1.3	...	...

[a] In mag.

[b] From E and $1/\lambda$ extinction law.

[c] From E and Becklin *et al.* 1978*b* extinction law.

[d] From $F\mathrm{Br}\gamma/S'\nu$.

[e] From $F\mathrm{Br}\alpha/S'\nu$.

[f] These values of $\tau_{4.05}$, $\tau_{2.17}$ refer to an assumed $S'_\nu = 450$ mJy (see text for explanation).

The observations consisted of measurements with the CTIO circular variable filter wheel (CVF) spectrometer of the flux density at the line wavelengths and at nearby continuum wavelengths. Measurements were made no more than one resolution element apart and at from five to 14 wavelengths for each line. The observations were calibrated by comparison with early-type standards, except near the wavelength of Brγ, where the inverse instrumental sensitivity was required to be a linear function of wavelength. This requirement was imposed on the basis of observations of late-type stars that should have no Brγ absorption. A corresponding correction at Brα was unnecessary both because the early-type standards show less Brα than Brγ absorption and the equivalent width of the emission line is considerably greater.

The line fluxes were derived by fitting the observations to the sum of a power-law continuum and a Gaussian line profile of known wavelength and width. The uncertainties given were derived from the fitting procedure and are the statistical uncertainties only. Most of the uncertainty comes from the measurement of the line profile rather than from the uncertainty in the continuum. Systematic errors in the continuum are harder to evaluate, but we believe they are small enough not to affect the conclusions of this paper. Such errors are most likely for Brα, for which there is limited spectral coverage at longer wavelengths, but in all cases the line to continuum ratio for Brα is large enough that continuum uncertainties are insignificant. For Brγ the continuum level is more important, but there was good coverage at both longer and shorter wavelengths. The spectral resolution was derived from the manufacturer's data on the circular variable filter; the assumed values are 0.013 and 0.011 of the wavelength for Brγ and Brα, respectively. If the spectral resolution and the degree of a polynomial fitted to the continuum were also varied, a range of line fluxes and uncertainties were derived with approximately identical values of χ^2. While the statistical uncertainty for all cases was similar, the range of derived line fluxes suggest an absolute uncertainty of 30%.

The observational results are given in Table 1, and Table 2 gives the derived color excess between the wavelengths of Brγ and Brα. The intrinsic line ratio was taken to be 3.00, based on departure coefficients calculated by Brocklehurst (1971) and $T_e = 5000$ K (Rodriguez and Chaisson 1979*a*, *b*). The effects of the uncertainties on the derived results are discussed below.

III. DISCUSSION

a) *Comparison with Previous Observations*

Neugebauer *et al.* (1978) observed Brγ at a large number of positions with beam sizes from $3\farcs3$ to 32″. Although few positions were measured in common, it is clear that the present results give systematically larger line fluxes, while the continuum flux densities agree. The discrepancy can be seen from the line equivalent widths given in Table 1; Neugebauer *et al.* observed an equivalent width of 2.0 nm in a 32″ beam and found that an equivalent width of 1.7 nm was consistent with observations at most of their positions. Our observations, on the other hand, give a weighted average equivalent width of 3.0 ± 0.3 nm.

Different reduction procedures account for only a small part of the difference between our results and those of Neugebauer *et al.* G. Neugebauer kindly made available to us some of his original data; applying our procedure to his data on the assumption that the spectral resolution was 1.25% gave equivalent widths that were 20% larger than Neugebauer *et al.* deduced. An assumed spectral resolution of 1% better fit their data and eliminated the discrepancy in average equivalent width. Their reduction procedure, on the other hand, implicitly derived the spectral resolution independently for each observation, which results in line fluxes independent of assumptions about the resolution at the expense of larger statistical uncertainties.

The greatest difference between our data set and that of Neugebauer *et al.* is in the selection of regions sampled. Half of our positions, and all of the ones with high weight, were located on or near the ridge of 10 μm emission that extends from IRS 10 to IRS 2. Although almost half of the Neugebauer *et al.* positions were also near the ridge, those positions were generally of no higher weight than the remaining observations, and many of the positions were not centered on any compact source. The line equivalent width was already known to increase near the ridge (Neugebauer *et al.*), and recent evidence (Nadeau *et al.* 1981) suggests considerable clumpiness in the distribution of ionized gas. Thus, our results probably tend to refer to individual gas clouds, while the results of Neugebauer *et al.* may be more characteristic of the entire galactic center region. Caution should certainly be used in interpreting results based on a limited data set.

Previous observations of Brα have been made by Bally, Joyce, and Scoville (1979). The surface brightness we measured for our brightest positions is comparable to their brightest positions. However, the two measurements of sources 1, 16, and 17 are apparently discrepant. We do not understand the source of disagreement, but one possibility is the difference in measurement beam sizes.

b) *Differential Extinction*

Most of the color excesses in Table 2 are equal within their uncertainties, the only exception being IRS 6. In order to have the same color excess as the other sources, IRS 6 would have to have a Brγ flux 3.6 times larger than we measured. This source is the westernmost one we observed and might be expected to have the smallest extinction (Lebofsky 1979). That it has almost twice as much as the other sources suggests that this amount of extinction probably arises in the vicinity of the galactic center. However, IRS 6 appears to be spatially coincident with the -6.6 to -15 km s^{-1} components to the H_2CO absorption spectra (Whiteoak, Rogstad, and Lockhart 1974), although comparison of the radio and infrared maps is uncertain because of differing spatial resolutions. Federman and Evans deduced the visual extinction to the galactic center cluster from H_2CO observations, excluding what they call the -14.5 km s^{-1} feature because of its westerly location. They concluded that the extinction of that molecular cloud corresponded to $A_V = 10$ mag. The near equality of the color excesses at the other positions is a bit surprising, but presumably we are observing gas that is not behind any of the dust directly associated with the center. Even so, there is no evidence on the spatial scale of several arc seconds for the extinction gradient found on larger spatial scales (Lebofsky 1979).

c) *Near-Infrared Reddening*

Comparison of the [2.17–4.05] color excesses derived here with the $H-K$ color excesses derived previously depends on the reddening law adopted. For comparison, we have considered two possible reddening laws that should represent the extremes presently thought to be reasonable. The first law is $A(\lambda) \propto 1/\lambda$ from 1.65 to 4.05 μm. The second law is the one used by Becklin *et al.* (1978*b*); it is similar to van de Hulst curve 15 (Johnson 1968) and can be represented as $A(\lambda) = A(V)(0.11/\lambda + 0.65/\lambda^3 - 0.35/\lambda^4)$ for wavelengths λ beyond 1 μm. The second curve matches the Whitford curve near 0.9 μm. The color excesses given in Table 2 are much smaller than expected for either reddening curve, with the exception of IRS 6. If $E(H-K) = 2.0$ mag (Becklin *et al.* 1978*b*), the first curve gives an expected 2.17 to 4.05 μm color excess of 2.8 mag, and the second gives 1.85 mag. As can be seen from Table 2, the observed color excesses are ~ 1.2 mag. Even a mistake in estimating the spectral resolution is unlikely to increase the observed color excesses to greater than 1.5 mag.

The question of whether the dust-emitting sources suffer a different extinction than the stellar sources is difficult to answer on the basis of the measured reddenings. If most of the extinction is external to the region of the galactic center, so that a "normal" reddening law applies, at least some of the ionized gas suffers less reddening than the stellar sources. Even if a considerable portion of the extinction is internal, a true extinction as high as double the value estimated for the stellar sources seems unlikely. Of course, there is no guarantee that the ionized gas and the dust-emitting sources are coincident, although there is apparently spatial coincidence between the 10 μm maps of Becklin *et al.* (1978*b*) and the continuum VLA maps of Brown, Johnston, and Lo (1981).

In addition to the color excesses, Table 2 presents extinctions calculated in various ways. Columns (3) and (4) contain the extinctions calculated from the color excesses and the two assumed extinction curves.

The Brγ and Brα optical depths, $\tau_{2.17}$ and $\tau_{4.05}$, were also estimated from the radio results of Brown *et al.* They assumed a 5″ source diameter, and $T_e = 8500$ K in estimating equivalent optically thin radio flux densities for these sources. Note that the source labeled 21 by Brown *et al.* is in the same location as IRS 20 as designated by Becklin *et al.* (1978*b*) and used here. We used the observed flux density S_ν^0 of Brown *et al.* and recalculated the 5 GHz optical depth τ corresponding to an assumed $T_e = 5000$ K to obtain a corrected flux density $S_\nu' = [\tau/(1-e^{-\tau})]S_\nu^0$ for use in our calculations.

The intrinsic ratios of $F(\mathrm{Br}\alpha)/S_\nu'$ and $F(\mathrm{Br}\gamma)/S_\nu'$ were assumed to be 4.5×10^{12} and 2.49×10^{12} Hz, respectively, from the data of Giles (1977), Brocklehurst (1971), and Osterbrock (1974), assuming no doubly ionized helium. The low value of the electron temperature assumed here ($T_e = 5000$ K) is suggested by the large beam recombination line observations of Rodriguez and Chaisson (1979*a*, *b*). If the galactic center regions are overabundant in primary coolants, the lower temperature can be understood. Lester *et al.* (1981) infer a possible overabundance of argon at the galactic center; they argue that although the large density of the compact ionized regions (Lacy *et al.* 1979) can suppress cooling by metals, the apparent overabundance of argon cannot be explained solely by $T_e > 5000$ K, because the Ar^+ emissivity would also be substantially lower at higher temperatures. Since the value of the electron temperature is uncertain, we note that the ratios $F(\mathrm{Br}\alpha)/S_\nu$ and $F(\mathrm{Br}\gamma)/S_\nu$ are proportional to $T_e^{-0.85}$ and $T_e^{-0.75}$, respectively. Columns (5) and (6) of Table 2 contain extinctions $\tau_{2.17}$ and $\tau_{4.05}$ deduced from the measured and intrinsic Brackett line fluxes. Our assumptions on the electron temperature and $\mathrm{He}^{++}/\mathrm{H}$ lead to the minimum likely extinction; a temperature of 10^4 K and $\mathrm{He}^{++}/\mathrm{H} = 0.1$ would increase the calculated extinctions by 1 mag.

The extinctions determined for IRS 6 under the assumptions above have too large a ratio to be consistent with either extinction law. The discrepancy would be removed if the optically thin radio flux density were larger or the line fluxes were smaller. Because we observed more than one data point in each line, we have confidence in the line fluxes. We therefore suggest that the radio source size of IRS 6 is smaller than 5″ and the optical depth is larger. A source diameter of 2″.2 gives a ratio of $\tau_{2.17}/\tau_{4.05} = 1.9$, the average for the other four sources. This smaller source size is consistent with the 10 μm map of Rieke, Telesco, and Harper (1978).

Willner (1976) has obtained 8–13 μm spectroscopy of some of the galactic center sources reported here. A 10 μm extinction is deduced from these spectra, under the assumption of underlying graybody emission (type I) or underlying silicate emission (type II) attenuated by cold silicate dust (see Gillett *et al.* 1975*a* or Willner 1976 for a description of the technique). These values of $\tau_{9.7}$ are included as the last two columns of Table 2.

In comparing the variously determined values of the extinction, we first consider IRS 2, 4, 5, and 20. The average ratio of $\tau_{4.05}/\tau_{2.17} = 1.9 \pm 0.2$ determined from the ratios of the Brackett fluxes to radio fluxes suggest that a $1/\lambda$ extinction law is more appropriate, since $\tau_{4.05}/\tau_{2.17} = 1.85$ for that law and 2.78 for the Becklin *et al.* extinction law. Reducing the assumed source diameters, or increasing the assumed temperature or He^{++} abundance, would make the extinction ratio smaller than 1.9, and larger source diameters are unlikely on the basis of the infrared and radio maps. The values of $\tau_{2.17}$ determined for these four sources from the radio to Brγ ratio compare favorably with the values determined from $E(2.17\text{–}4.05)$ and a $1/\lambda$ law, as would be expected. The $1/\lambda$ law gives a 2.2 μm extinction that agrees with that found by Becklin *et al.*, but much less extinction at 1.65 μm. Either the extinction law steepens rapidly below 2 μm, or, to an even greater extent than noted at the beginning of this section the ionized gas and the stars have different extinctions.

The ratio of silicate to near-infrared extinction can be compared to the values found for nearby H II regions (Herter *et al.* 1981). Generally, $\tau_{9.7}$ (type II) is equal to $\tau_{2.17}$, while for the galactic center, $\tau_{9.7}$ (type II) is consistently larger. The same conclusion was reached by Becklin *et al.* (1978*b*) on the basis of different near-infrared and comparison data. Alternatively, if the extinction law to the galactic center is the same as elsewhere, a graybody underlying emission spectrum for the dust is suggested near 10 μm.

IRS 6 is apparently anomalous. First, the silicate extinction to IRS 6 is apparently similar to that deduced to IRS 4. Our observations at Brα and Brγ are consistent with a higher extinction to IRS 6: if this is correct, $\tau_{9.7}$ (type II) $\approx \tau_{2.2}$. Whether a different extinction law is appropriate for IRS 6 than for the ridge sources or whether the 10 μm and near-infrared observations refer to different sources is not clear.

IV. CONCLUSIONS

Extinctions to sources of ionized gas at the galactic center determined from Brackett line observations are similar to or smaller than the extinctions to stellar sources. A much larger extinction to the ionized gas than to the stellar sources is ruled out.

One source shows much larger extinction than the others. The present data are meager, but there is no obvious correlation with the pattern seen on larger spatial scales.

Higher resolution radio observations and better sampled infrared line maps (preferably made with higher spectral resolution) would allow a better determination of the extinction to the sources in the galactic center.

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