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IONIZATION STATE IN AND REDDENING TO THE CENTER OF THE GALAXY

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ABSTRACT

Observations of the He I line at 2.06 μm and the Brackett lines of hydrogen at 2.17 and 4.05 μm at a number of positions in the Galactic center are reported. The intensity of the He I line peaks at IRS 16. The ionization state of the gas, as determined by the He I/Brγ line intensity ratio, also appears to be maximum at or near IRS 16. Objects in the vicinity of IRS 16 probably produce most of the ionizing radiation, although the possibility that other significant sources of ionizing radiation are present cannot be excluded. Measurements of the Brackett line intensities show that the reddening toward the central 0.′5 is approximately uniform and corresponds to $A_v \approx 27$ mag.

Subject headings: galaxies: nuclei — galaxies: The Galaxy — infrared: spectra — interstellar: matter

I. INTRODUCTION

Observations of the central regions of the Galaxy have revealed a rich variety of phenomena which are observed over a wide range of wavelengths and spatial scales (see reviews by Gatley and Becklin 1981; Brown and Liszt 1984). Of particular importance have been observations of Sgr A. West, the ionized gas in the central few parsecs (e.g., Lacy *et al.* 1980; Lo and Claussen 1983; Serabyn and Lacy 1985), yielding information on the distribution and dynamics of the gas and possibly pointing to the presence of a massive black hole in the region of the IRS 16 complex of infrared sources. Far-infrared observations of emission from dust (Becklin, Gatley, and Werner 1982), the detection of a ring of vibrationally excited (probably by shocks) molecular hydrogen (Gatley *et al.* 1984, 1986), and studies of the high-velocity gas in the vicinity of IRS 16 (Hall, Kleinmann, and Scoville 1982; Geballe *et al.* 1984, hereafter Paper I; Geballe *et al.* 1987) further point to the peculiar nature of the object or objects at the very center of the Galaxy.

Knowledge of the locations, strengths, and natures of the sources of ionizing radiation are fundamental to our understanding of the whole region. Only recently has evidence emerged that the IRS 16 complex is a significant, perhaps dominant, source of ultraviolet radiation (see, e.g., Becklin, Gatley, and Werner 1982; Paper I; Henry, DePoy, and Becklin 1984). However, this realization is based mainly on broad-band observations and indirect arguments concerning the ionization state of the gas. In principle, mapping of ionic lines with different ionization potentials should allow the positions of ionizing sources and their relative strengths to be determined. Because of the low ionization state of the gas in Sgr A West (e.g., Lacy, Townes, and Hollenbach 1982), there are very few lines to choose from for such an experiment. Two lines whose ratio may indicate the locations of the ionizing sources in the Galactic center under the conditions found there (ionizing source or sources of temperature around 35,000 K) are the He I (2.06 μm) and Brγ (2.17 μm) lines (see Paper I). An advantage in using these lines is their close proximity in wavelength and hence low differential extinction. This is particularly important as it has not been certain that spatial variations in the reddening to the Galactic center can be neglected (e.g., Willner and Pipher 1983; Rieke, Telesco, and Harper 1978; Lebofsky 1979). The extinction to the compact sources in the Galactic center, as deduced by broad-band photometry, amounts to about 30 mag of visual extinction (Becklin and Neugebauer 1968) and is thought to be interstellar in origin, with as little as 6 mag being attributable to the central 3 pc (Becklin *et al.* 1978). Clearly, knowledge of the amount and uniformity of the extinction is crucial to understanding observations of the region. Determining the extinction from the intensity ratio of H I recombination lines spaced widely in wavelength provides an alternative to using broad-band photometry and is one which has the advantage that it directly samples the ionized gas.

Thus, in order to measure the spatial dependence of the ionization state of the gas and to locate the positions of the ionizing sources, the intensities of the He I and Brγ lines were measured at a number of locations in the Galactic center. In addition, the intensity ratio of the Brα (4.05 μm) and Brγ lines was measured at several widely spaced locations in the nucleus in order to determine the extinction to the ionized gas there.

II. OBSERVATIONS

All of the measurements reported here were obtained during 1984 and 1985 using the UK Infrared Telescope on Mauna Kea, Hawaii. The instrument used was the common user, seven-channel, cooled grating spectrometer (Wade 1983). Standard chopping and nodding techniques were employed with east-west beam separations of ~60″. Flux calibration was obtained by repeated observations of the stars BS 6616 (F8) and BS 7063 (G5). The spectra of both stars contain H I absorption lines, Brα and Brγ in BS 6616 being easily evident at the present spectral resolution. In terms of fractional absorption, these lines are weak (~7% and 12%, respectively, in BS 6616); however, unless corrected for, they would significantly change the estimated Brackett line strengths at Galactic center positions where the line-to-continuum ratio is low. Such corrections were made, with some assistance from high-resolution solar (G2) spectra (Delbouille *et al.* 1981). Wavelength calibrations were achieved by observing H I and He I lines in the planetary nebulae NGC 6572 and BD +30°3639.

Measurements of the He and Brγ lines at a variety of Galac-

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TABLE 1

HELIUM AND Brγ LINE FLUXES[a]

Position Name	Offset from IRS 16 (R.A., decl.)[b]	He I 2.06 μm Line Flux (10^{-20} W cm^{-2})	Brγ 2.17 μm Line Flux (10^{-20} W cm^{-2})	Line Ratio He I/Brγ
IRS 16...	0, 0	3.4 ± 0.6	5.7 ± 0.6	0.60
IRS 1....	4.5, 0	2.0 ± 0.5	4.2 ± 0.6	0.48
IRS 21...	1, −4	2.1 ± 0.4	4.1 ± 0.6	0.51
IRS 2....	−4, −2.5	2.7 ± 0.5	7.0 ± 0.8	0.39
	−5, 0	2.4 ± 0.4	5.2 ± 1.0	0.46
	0, −5	1.8 ± 0.4	4.9 ± 0.6	0.37
IRS 9....	4.5, −5	1.7 ± 0.3	4.0 ± 0.5	0.43
	5, 5	2.0 ± 0.3	4.0 ± 0.6	0.50
	−5, −5	1.5 ± 0.3	3.9 ± 0.7	0.38
IRS 6....	−7, 3	1.9 ± 0.5	2.7 ± 0.8	0.70
IRS 10...	6, 6	0.8 ± 0.3	2.3 ± 0.4	0.35
	−10, 0	0.9 ± 0.3	2.0 ± 0.4	0.45
IRS 5....	7, 11	0.9 ± 0.3	2.3 ± 0.4	0.39
IRS 4....	14, 6	0.8 ± 0.3	2.4 ± 0.4	0.33
IRS 8....	1, 31	<0.3	0.6 ± 0.2	<0.5

[a] Measured in a 5″ beam.
[b] In arc seconds; IRS 16 position: R.A. = $17^h42^m29^s.48$, decl. = −28°59′19″.5 (1950); offsets accurate to ±1″.

tic center locations were carried out during 1984 June and 1985 June. At each position the two line measurements were made essentially simultaneously, using a 5″ beam. The instrumental resolution was 550 km s^{-1} at 2.06 μm and 500 km s^{-1} at 2.17 μm (similar to Paper I). In 1984, observations were made at the positions of specific infrared sources in the Galactic center; in 1985 the lines were measured on a grid of points spaced by 5″. In all cases offsets were made with respect to IRS 7. In 1984 July nearly simultaneous measurements of Brα and Brγ were made, for the purpose of determining the reddening, again using the 5″ aperture and at the positions of specific infrared sources. The Brα measurements were obtained at 550 km s^{-1} resolution.

III. RESULTS

a) *Ionization State*

The He I 2.06 μm and Brγ line intensity measurements, which were made at 15 positions in the Galactic center, are summarized in Table 1. IRS 16 was found to have the brightest He I line and the second highest ratio of helium to Brγ line intensity. The line intensities at IRS 16 are consistent with earlier measurements (Hall, Kleinmann, and Scoville 1982; Paper I), after allowing for differences in aperture size. They indicate that the He/Brγ line ratio increases with decreasing beam size at IRS 16. This implies that the IRS 16 region contains a source of ionizing radiation, as has been suggested earlier (Paper I). Most of the line ratio determinations at other positions have large uncertainties; however, as a group they show a surprising uniformity (observed line ratio between $\frac{1}{3}$ and $\frac{1}{2}$, except for IRS 6), and little tendency for the ratio to fall off with distance from IRS 16.

b) *Brackett Line Ratios and Reddening*

The results of the reddening experiment are given in Table 2. Within the uncertainties the reddening between 4.05 μm and 2.17 μm is uniform at 1.9 mag over the central region of Sgr A. Assuming the reddening curve derived by Rieke and Lebofsky (1985), the average visual extinction to the Galactic center is 27 mag. This value is similar to those obtained by Becklin *et al.* (1978) and Rieke and Lebofsky from infrared photometry. From the curve of Rieke and Lebofsky the extinctions to the nucleus are 1.2 mag at 4.05 μm, 3.1 mag at 2.17 μm, and 3.4 mag at 2.06 μm. Thus the emitted He I/Brγ line ratios in the Galactic center are ∼30% higher than the values in Table 1. Our values of ∼1.9 mag for $E(2.17–4.05)$ at IRS 2, 4, 5, and 6 are considerably different from the most likely values of Willner and Pipher (1983), which are ∼1.1 mag for the first three objects and 2.5 mag for the last. We note that the present measurements have somewhat higher signal-to-noise ratios and were made at higher spectral resolution, which greatly reduces the chance of systematic errors caused by the bright continuum.

IV. DISCUSSION

a) *Sources of Ionizing Radiation*

Taken by itself, the result that the ionization state of the gas, as determined from the ratio of He I and H I lines, is rather uniform throughout Sgr A West might be interpreted as evidence that the ionizing sources are distributed uniformly throughout the central parsec. However, other measurements provide little evidence for such a distribution. Gezari *et al.* (1985) find from the mid-infrared color temperatures of the thermal infrared sources in the central 1.5 pc of the Galaxy that

TABLE 2

EXTINCTION

Name	R.A.[a] 17^h42^m	(1950) decl.[a] −28°59′	Line Flux[b] Brγ (10^{-20} W cm^{-2})	Line Flux[b] Brα (10^{-20} W cm^{-2})	$A_{2.17}$–$A_{4.05}$[c] (mag)	A_V[d] (mag)
IRS 1.......	29.75	−18.0	4.9 ± 0.6	85 ± 6	1.9 ± 0.2	27 ± 3
IRS 2.......	29.12	−22.0	7.8 ± 0.6	117 ± 6	1.8 ± 0.2	25 ± 3
IRS 4.......	30.47	−26.0	1.5 ± 0.3	33 ± 2	2.2 ± 0.3	31 ± 4
IRS 5.......	30.00	−8.8	3.3 ± 0.3	44 ± 3	1.7 ± 0.2	24 ± 3
IRS 6.......	28.82	−17.5	3.8 ± 0.5	68 ± 4	2.0 ± 0.2	28 ± 3
IRS 9.......	29.67	−25.0	3.8 ± 0.5	66 ± 4	1.9 ± 0.2	27 ± 3
IRS 16......	29.43	−19.3	7.3 ± 1.0	118 ± 8	1.9 ± 0.2	27 ± 3

[a] Offsets made from star A; assumed coordinates for it are R.A. = $17^h42^m30^s.00$, decl. = −28°59′02″.0 (1950).
[b] Measured in a 5″ diameter beam.
[c] Assumes Brα/Brγ = 2.9 (Menzel's case B, T_e = 7500 K, n_e = 10^4 cm^{-3}).
[d] Assumes reddening curve of Rieke and Lebofsky 1985.

those objects do not contain luminous sources of ultraviolet radiation, but rather are density enhancements in the ionized gas. The volume-averaged density of this gas is considerably lower than that of the cooler molecular gas just outside it (Becklin, Gatley, and Werner 1982), much of the ionized gas existing in filamentary structures within a cavity (Lo 1986) and in a thin layer on the walls of the cavity, with little material between it and IRS 16 (e.g., Serabyn and Lacy 1985). Under these circumstances a clearly observable stratification of ionization states, as in a planetary nebula, would not be expected to occur, even in the case of a single, dominant source of ultraviolet radiation. However, in that case one might expect to see a slightly higher ionization state at the coordinates of the central ionizing object and a rather constant (and somewhat lower) ionization state elsewhere. This is indeed what has been observed. To summarize, in view of the peculiar morphology of the ionized gas in the Galactic center, the present results do not provide conclusive evidence as to the existence or nonexistence of a single dominant ultraviolet source, or cluster of sources. The He I/Brγ line intensity ratio at IRS 16 exceeds that at any other position, with the possible exception of IRS 6. This may indicate that IRS 6 is an ionizing source in its own right. However, the signal-to-noise ratio of the line ratio at IRS 6 is poor, so this result should be treated with caution.

The He I ^12P–^12S line at 2.06 μm can be comparable in strength to Brγ if there is sufficient trapping of the permitted 584 Å transition between the upper level of the 2.06 μm transition and the ground state (e.g., Treffers *et al.* 1976), a condition apparently achieved in the Galactic center (Paper I). In Paper I the greater ratio of wing to line core intensity at IRS 16 in the He I line than in H I lines was attributed to the density-dependent rate of collisional transfer of $2P$ triplets to $2P$ singlets (Osterbrock 1974). The densities derived for the broad-line region are consistent with this interpretation (Geballe *et al.* 1987). However, the enhancement may also be caused in part because the broad-line region lies totally within the He^+ zone, whereas the narrow-line emission seen toward IRS 16 (and other locations) originates in part from neutral helium/ionized hydrogen zones remote from IRS 16. Indeed, at most positions the dereddened He I/Brγ line ratios are typically $\sim$0.6, whereas values of about unity would be expected for a normal He abundance if helium is entirely singly ionized (Paper I). A third possible explanation for the high He I/H I ratio in the wings of the lines is an actual enhancement of He/H in the high-velocity gas. This would suggest that the wings are an outflow of material from an unusual object.

b) Extinction to the Ionized Gas

The measurements reported here yield two important results. First, the reddening of the ionized gas in the Galactic center is similar to that measured toward the stars there (Becklin *et al.* 1978; Rieke and Lebofsky 1985). Second, there is not a large spatial variation in the extinction toward the ionized gas, such as had been suggested by the measurements of Willner and Pipher (1983).

On the basis of the depth of the 10 μm silicate absorption feature it has been suggested by Rieke, Telesco, and Harper (1978) that additional extinction of up to $A_V = 20$ mag may be present in front of the 10 μm sources in the Galactic center. This would suggest that the gas and dust in this region suffer different extinctions and hence may not be coincident. Roche and Aitken (1985), however, propose that the increased depth of the silicate feature is the result of a reduction in the number of carbon stars in the central regions of the Galaxy. Such a reduction lowers the ratio of visual and near-infrared extinction to silicate absorption, so that there is no requirement for additional extinction to the 10 μm sources. The uniformity of our results and their similarity with other values of the extinction are most consistent with the hypothesis that the gas, dust, and stars all suffer very similar extinctions, the bulks of which are interstellar, rather than local to the Galactic center.

V. CONCLUSION

The ionization state of Sgr A appears to have a mild maximum at IRS 16 and to be uniformly lower at almost all other positions observed. This is consistent with the existence of a source of ultraviolet photons at IRS 16 and with the low filling factor of the ionized gas. The extinction to the ionized gas is spatially quite uniform and has a value of $A_V \approx 27$ mag.

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