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DETECTION OF SILICON IN THE GALACTIC CENTER

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ABSTRACT

We report the detection of the [Si II] 34.815 μm line in the Galactic center region, Sgr A West. This is the first detection of silicon in this source. Three positions were measured, IRS 16 and points ±1 pc from IRS 16 along the Galactic plane. The deduced [Si II] 34.8 μm/[O I] 63 μm line ratio is a factor of 3 higher than that observed for the photodissociation region (PDR) in the Orion Nebula. This could either reflect a difference in the gas-phase silicon abundance relative to oxygen or a difference in the PDR of the Galactic center relative to Orion. Genzel *et al.* have proposed in 1985 that gaseous O I is underabundant in the PDR associated with the Galactic center. However, our results indicate that silicon does not appear to be underabundant.

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

I. INTRODUCTION

The structure of the inner 10 pc (3′) of the Galactic center region is that of an ionized core (< 2 pc) surrounded by a rotating neutral-gas disk which comprises the photodissociation region (PDR) (Genzel *et al.* 1985); the PDR is a low-excitation H I zone ionized by photons longward of the Lyman edge. Detailed observational work, mainly through IR continuum and spectral line observations and radio recombination line and continuum measurements on the inner few parsecs (cf. Lacy, Townes, and Hollenbach 1982; Liszt, Burton, and van de Hulst 1985; Genzel *et al.* 1985; and references therein), indicates the possible presence of a massive black hole (cf. Serabyn and Lacy 1985, and references therein). It has been known for some time that the distribution of the ionized gas is clumpy (cf. Lacy *et al.* 1980; Watson *et al.* 1980); however, it has only recently been argued (Genzel *et al.* 1985) that the clumps in the ionized central region have neutral cores which produce O I line emission. On the basis of detailed measurements of [O I] 63 μm/[C II] 157 μm and [O I] 63 μm/[O I] 146 μm line ratios, Genzel *et al.* (1985) also deduce that the gas in the neutral disk is also highly clumped.

The [Si II] 34.8 μm line, recently detected in Orion by Haas, Hollenbach, and Erickson (1986), is an excellent probe of the neutral disk. Haas *et al.* found that in the Orion molecular cloud/H II region complex Si II emission arises from both within the molecular cloud near the H II region interface (the PDR) and the shocked molecular region seen within the BN/KL complex. The contribution to the Si II emission from the H II region itself is small due to the low ionization potential of Si II (16.3 eV), which limits the Si II zone inside an H II region to the transition zone between the ionized and neutral gas. The measurement of silicon is particularly important because of its expected depletion through the formation of dust grains (Spitzer 1978). Grain formation and destruction can be significantly effected by H II region molecular-cloud interactions and high velocity molecular shocks (Draine and Salpeter 1979a, b).

In the following paragraphs we demonstrate that in the case of the Galactic center the emission arises mainly from the photodissociation regions and not the shocked molecular component seen via H_2, CO, and OH lines (cf. Genzel *et al.* 1985). We also show that significant Si II emission is not expected from the ionized gas even though the Galactic center is a rather low-excitation H II region.

II. OBSERVATIONS

The Galactic center was observed on 1985 August 19–20 at an altitude above 12.5 km using the 91 cm telescope of the Kuiper Airborne Observatory (KAO) on a flight from Moffett NAS, Mountain View, California to Hickham AFB, Oahu, Hawaii. The long-wavelength mode of the Cornell dual-grating, helium-cooled spectrometer was used (Houck and Gull 1982). The three-element Ge:Be array system has resolution of 0.06 μm at 34.8 μm with a typical in-flight NEP of 5×10^{-14} W Hz$^{-1/2}$ per detector. The beam size, when this instrument is used on the KAO, is approximately 25″ in diameter (FWHM). IRC +10420 and Callisto were selected as calibrators. Because of recent changes in the flux of IRC +10420 at 34 μm (Herter and Houck 1986), Callisto and previous measurements the continuum level for the Galactic center (McCarthy *et al.* 1980; Herter *et al.* 1983, 1984) served as the primary flux calibrators. Systematic errors in this calibration are estimated to be ±15%.

Spectra of at least nine data points each were taken in and about the [Si II] 34.81 μm line with a sampling interval of two points per spectral resolution element (FWHM) for three spatial positions. The beam was centered on Sgr A West (IRS 16) and at positions 20″ (approximately 1 pc) along the Galactic plane on either side of IRS 16 (Fig. 1). The pointing accuracy is better than 5″. A chopper throw of approximately 4′ perpendicular to the Galactic plane was employed. Following an initial offset to IRS 16 from an optical guide star a peak-up on the 33.5 μm continuum was performed. The [Si II]

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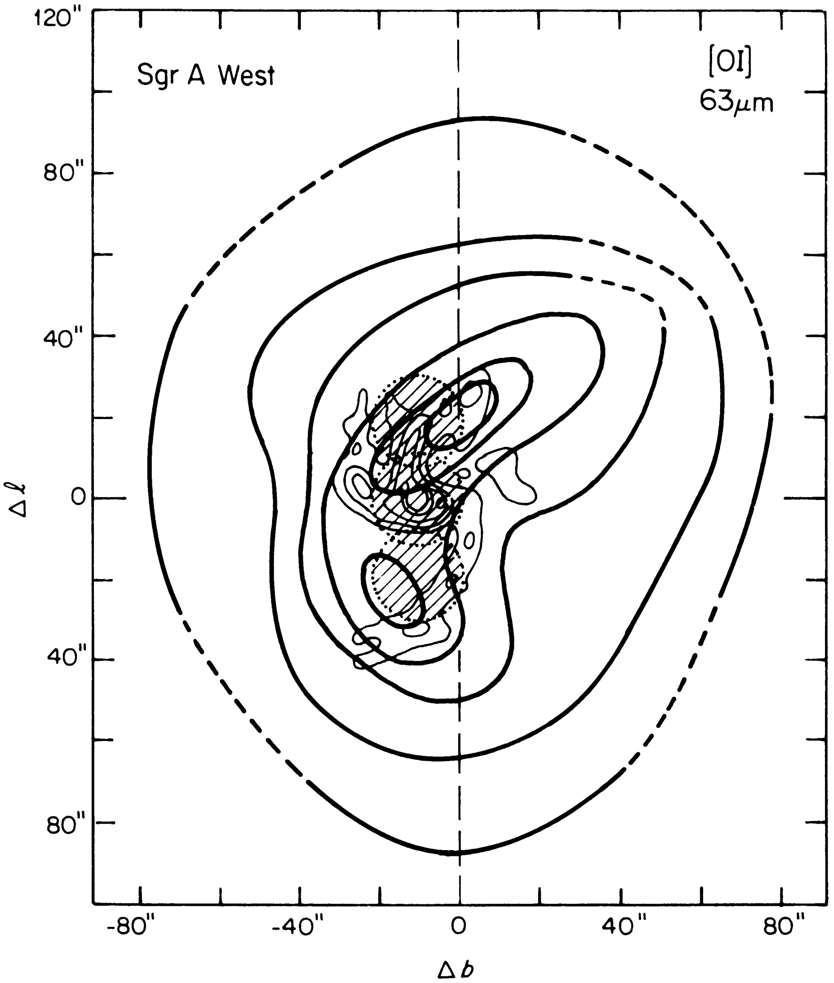

FIG. 1.—Contours of [O I] 63 μm integrated line flux (*dark lines*) and of 2 cm free-free radio continuum emission as a function of Galactic coordinates (after Genzel *et al.* 1985, by permission). [O I] contours were drawn by Genzel *et al.* degraded to 44" beam. Contours are in units of 2×10^{-17}W cm^{-2}. Positions sampled in the [Si II] 34.815 μm line are indicated by the 25" circles.

34.81 spectra are shown in Figure 2. Table 1 tabulates the measured fluxes for all three positions sampled. We assumed that the extinction correction employed by Herter *et al.* (1984) for the H II region is applicable to all three Si II positions measured and adopted an optical depth of 0.5 at 34 μm. The uncertainty in the extinction is difficult to estimate but could be quite large (25%–50%?). Extinction-corrected fluxes are also given in Table 1.

III. DISCUSSION

Galactic center region Si II emission is expected from the PDR, and the shocked molecular gas associated with the Galactic center, and perhaps from the low-excitation ionized gas. We explore each of these possibilities below to understand the origin of the Si II emission from the Galactic center.

Haas *et al.* have argued that significant Si II emission arises from a wind *J* shock in Orion. In a *J*-type shock, molecules and dust grains containing Si are destroyed, producing gas-phase atomic Si. In addition H_2 is destroyed. Si II production will be enhanced relative to H_2 over that from a *C*-type shock in which the hydrogen is remains molecular and Si II reacts to form molecular species (cf. Haas *et al.*). Since molecular shock emission has been observed for the Galactic center (cf. Gatley 1983; Gatley *et al.* 1984; Genzel *et al.* 1985), the contribution to the observed [Si II] emission from these shocks must be considered. In the case of the shocked Orion gas, the [Si II]/[O I] ratio of 0.1–0.3 is not significantly different from the ratio expected for PDR emission (Haas, Hollenbach, and Erickson 1985; Werner *et al.* 1984). However, the H_2 $S(1)/$[O I] line ratio is about two orders of magnitude smaller for the Galactic center than the Orion shocked gas (Genzel *et al.* 1985). Although a *J*-type shock decreases the H_2/O I ratio by destroying H_2, comparison with the Orion shocked region, in which Haas *et al.* suggest a *J*-type shock exists, makes it unlikely that the contribution to the observed [Si II] line emission from these shocks will be appreciable.

Given the low-excitation state of the H II region in the central 2 pc of the Galactic center, Si II may exist within the ionized gas in sufficient quantities to make significant contributions to the observed line emission. However, it is straightforward to see that this component will be unimportant. Since Si I ionizes at 8.15 eV while Si II ionizes at 16.35 eV, we consider the ratio of the number of photons which can ionize

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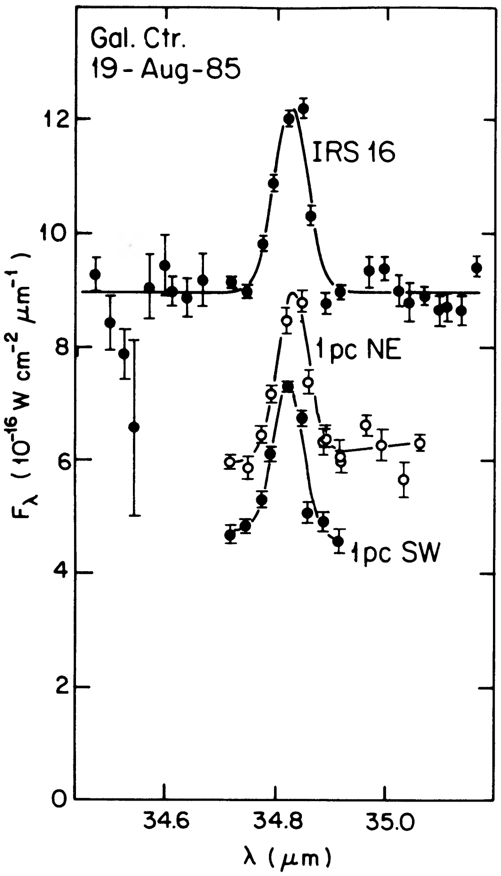

FIG. 2.—Si II 34.815 μm spectra of Galactic center for IRS 16, and 1 pc NE and SW of IRS 16. A beam size of approximately 25″ and a chopper throw of 4′ perpendicular to the Galactic plane were employed. The short-wavelength dip in the spectrum of IRS 16 is due to incomplete correction for a deep telluric water vapor absorption line at 34 μm. The solid lines are Gaussian fits to the [Si II] data.

TABLE 1

Si II AND O I LINE FLUXES

POSITION	FLUXES (10^{-17} W cm^{-2})	
	[Si II] 34.815 μm[a]	[O I] 63 μm[b]
IRS 16.......	2.3 ± 0.1; 3.8 ± 0.2[c]	6.9
1 pc NE	1.9 ± 0.2; 3.1 ± 0.3[c]	6.7
1 pc SW	1.7 ± 0.1; 2.8 ± 0.2[c]	5.8

[a] Errors are 1 σ and exclude any contribution due to systematic effects.

[b] Estimated from the data in Fig. 1 of Genzel *et al.* 1985 including reduction in fluxes by a factor of 0.69 to account for differing beam size.

[c] Extinction corrected assuming an optical depth of 0.5 at 34.815 μm (see text).

Si I but not H I (create Si II in the neutral gas) to the number of photons which can ionize Si I and H I without ionizing Si II (create Si II in the ionized gas). Using the Kurucz (1979) stellar atmosphere models, we find that for stars of 30,000 K and 35,000 K (the range of excitation expected for the Galactic center; cf. Lacy, Townes, and Hollenbach 1982) this ratio is approximately 60 and 15, respectively. The ratio represents a limit to the expected volumes of the PDR and H II region which contribute to the Si II emission. The contribution from the PDR will be enhanced further because of the ultraviolet radiation longer than the Lyman edge from the ionized gas within the H II region. Unfortunately a detailed knowledge of the exciting spectrum of the Galactic center is needed to examine this problem in detail, but it is unlikely that the H II region will contribute significantly. This analysis demonstrates that as the effective temperature of the exciting source decreases the Si II emission from the PDR increases relative to that from the H II region, an effect that may seem counterintuitive. We therefore assume that all of the observed Si II emission arise from the PDR.

Genzel *et al.* (1985) have made detailed studies of the neutral gas in the Galactic center. They find that the [O I] 63 μm/[C II] 158 μm and [O I] 63 μm/[O I] 145 μm line ratios are the same as for the Orion Nebula PDR. From these line ratios they conclude that the neutral gas is heavily clumped with a volume filling factor of $0.06^{+0.09}_{-0.03}$, a hydrogen density of 10^5 cm^{-3}, and a temperature of 350^{+650}_{-150} K. They also argue on the basis of their line measurements and estimates of the hydrogen column density (see below) that the C and O in the neutral gas are depleted in the Galactic center relative to Orion by about an order of magnitude each.

Because of the limited spatial coverage and velocity resolution, a detailed excitation and dynamical analysis of the Si II emission is not possible at this time. However, the gas-phase silicon abundance in the neutral disk can be investigated. Expected [O I] 63 μm line emission at the measured Si II positions can be obtained by interpolating the line fluxes deduced from Figure 1 of Genzel *et al.* (1985) to our spatial positions. These values are listed in Table 1. Because their measurements were performed with a 30″ beam, we have scaled their measurements to our 25″ beam size assuming the flux scales as the beam area (uniform source distribution). This assumption is justified since the O I emission is extended (cf. Fig. 1).

Table 1 indicates that the [Si II] 34.8 μm/[O I] 63 μm line ratio is approximately the same at the three positions observed. Assuming an extinction law which decreases with wavelength as the −1 (−2) power from 35 μm to 63 μm and an optical depth of 0.5 at 34 μm, the dereddened [Si II] to [O I] line ratio ranges from 0.35 to 0.42 (0.40–0.47) for the three spatial positions observed. Note that the deduced [Si II] to [O I] ratio is only moderately affected by uncertainties in the extinction correction. Since the variation in the deduced line ratio is only weakly dependent on spatial position and the assumed extinction law, we adopt a single value of 0.4 for the observed [Si II]/[O I] line ratio in the Galactic center region and use this value in the discussion below.

The observed [Si II]/[O I] line ratio in the Galactic center is about a factor of 3 higher than the ratio of 0.13 observed at the Trapezium position of the Orion Nebula (Haas, Hollenbach, and Erickson 1985; Tielens and Hollenbach 1985*a*, *b*). This difference can be due to a factor of 3 higher abundance of Si II relative to O I in the Galactic center compared to the Orion Nebula and/or differences in the PDRs in these two regions. Tielens and Hollenbach (hereafter TH) have presented models of PDRs. Their results indicate

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that the [Si II] 34.8 μm to [O I] 63 μm line ratio for PDRs should be nearly independent of both the ambient density and the incident far-ultaviolet (FUV) radiation field (see Figs. 10 and 11 of TH), although for very large O I column densities self-absorption in the 63 μm line may influence this ratio. Calculations indicate that the optical depth in the [O I] 63 μm line is 0.5–1.0 for Orion and significantly less than this for the Galactic center (Genzel *et al.* 1985; TH; Watson 1986). These results indicate that the observed difference between the [Si II]/[O I] line ratios in the Galactic center and Orion represents a true differences in relative abundances of these ions. The larger optical depth in the 63 μm line in Orion than the Galactic center indicates that the abundance ratio is in fact greater than the factor of 3 observed for the line ratio (all other factors associated with the PDRs being equal).

The deduction of the actual ionic abundance of Si II is difficult and uncertain because of the relative inaccuracies in the relevant collision cross sections and the difficulty in determining the hydrogen column density, $N_{\rm H}$. Genzel *et al.* (1985) have estimated $N_{\rm H}$ from dust continuum measurements and find a column density comparable to that obtained from the 21 cm data of Liszt, Burton, and van de Hulst (1985). They find that the O I and C II ionic abundances are a factor of 5–20 lower than those found in the solar neighborhood depending upon the assumed value of $N_{\rm H}$. If these low abundances are due to the depletion of oxygen and carbon onto grains (as opposed to a larger molecular abundance in the neutral gas) then their $N_{\rm H}$ estimate is probably too large by perhaps as much as a factor of 2. This is because the dust-to-gas ratio will be larger than in the solar neighborhood, implying that the factors they used for converting from far-infrared opacity to visual extinction (A_v) and from A_v to $N_{\rm H}$ are most likely incorrect. The detailed behavior of these conversion factors with increased depletion will depend on how the grain size distribution changes. (Genzel *et al.* 1985 do note that the dust-to-gas ratio in the Galactic center may differ from that implied from their adopted conversion factors; hence, their uncertainty in $N_{\rm H}$ is probably larger than quoted.) The direction of any net change in the O I and C II abundances would be toward smaller depletion factors. Our results indicate that even if their estimates are correct, the larger relative Si II abundance reduces the likelihood of depletion being the major factor for the reduced O I and C II abundances because silicon would probably be significantly affected as well. Local studies of highly reddened stars indicate that the depletion factors for silicon, carbon, and oxygen are generally similar (cf. Salpeter 1977 and references therein).

IV. CONCLUSIONS

We have made the first detection of silicon in the Galactic center region through a high signal-to-noise ratio measurement of the [Si II] 34.8 μm line. The [Si II] 35.8 μm line emission, like the [O I] 63 μm, [O I] 145 μm, and [C II] 157 μm line emissions, originates in the photodissociation region (PDR) associated with the neutral disk. The ratio of [Si II] 35.8 μm to the [O I] 63 μm line emission (Genzel *et al.* 1985) is approximately 0.4 for the three positions observed; IRS 16 and ±1 pc along the plane from IRS 16. This ratio is about a factor of 3 higher than that observed in the Orion PDR indicating less depletion of silicon or a greater overall abundance of silicon relative to oxygen and carbon in the Galactic center than Orion.

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REFERENCES

Draine, B. T., and Salpeter, E. E. 1979*a*, *Ap. J.*, **231**, 77.
______. 1979*b*, *Ap. J.*, **231**, 438.
Gatley, I. 1983, in *Galactic and Extragalactic Infrared Spectroscopy*, ed. M. F. Kessler and J. P. Phillips (Dordrecht: Reidel), p. 351.
Gatley, I., Jones, T. J., Hyland, A. R., Beattie, D. H., and Lee, T. J. 1984, *M.N.R.A.S.*, **210**, 565.
Genzel, R., Watson, D. M., Crawford, M. K., and Townes, C. H. 1985, *Ap. J.*, **297**, 766.
Haas, M. R., Hollenbach, D. J., and Erickson, E. F. 1986, *Ap. J.* (*Letters*), **301**, L57.
Herter, T., Briotta, D. A., Jr., Gull, G. E., Shure, M. A., and Houck, J. R. 1983, *Ap. J.* (*Letters*), **267**, L37.
Herter, T., and Houck, J. R. 1986, in preparation.
Herter, T., Houck, J. R., Shure, M., Gull, G. E., and Graf, P. 1984, *Ap. J.* (*Letters*), **287**, L15.
Houck, J. R., and Gull, G. E. 1982, *Proc. Soc. Photo-Opt. Instr. Eng.*, **363**, 46.
Kurucz, R. 1979, *Ap. J. Suppl.*, **40**, 1.
Lacy, J. H., Townes, C. H., Geballe, T. R., and Hollenbach, D. J. 1980, *Ap. J.*, **241**, 132.
Lacy, J. H., Townes, C. H., and Hollenbach, D. J. 1982, *Ap. J.*, **262**, 120.
Liszt, H. S., Burton, W. B., and van de Hulst, J. M. 1985, *Astr. Ap.*, **142**, 237.
McCarthy, J. F., Forrest, W. J., Briotta, D. A., Jr., and Houck, J. R. 1980, *Ap.J.*, **242**, 965.
Salpeter, E. E. 1977, *Ann. Rev. Astr. Ap.*, **15**, 267.
Serabyn, E., and Lacy, J. H., 1985, *Ap. J.*, **293**, 445.
Spitzer, L. 1978, *Physical Processes in the Interstellar Medium* (New York: Wiley).
Tielens, A., and Hollenbach, D. J. 1985*a*, *Ap. J.*, **291**, 722 (TH).
______. 1985*b*, *Ap. J.*, **291**, 747.
Watson, D. M. 1986, private communication.
Watson, D. M., Storey, J. W. V., Townes, C. H., and Haller, E. E. 1980, *Ap. J.* (*Letters*), **241**, L43.
Werner, M. W., Crawford, M. K., Genzel, R., and Hollenbach, D. J. 1984, *Ap. J.* (*Letters*), **282**, L81.

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