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DETECTION OF SULFUR IN THE GALACTIC CENTER

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ABSTRACT

A strong detection at the [S III] 18.71 μm line is reported for the galactic center region, Sgr A West. A line flux of $1.7 \pm 0.2 \times 10^{-17}$ W cm^{-2} is found for a 20″ beam size measurement centered on IRS 1. A preliminary analysis indicates that the S III abundance relative to hydrogen is consistent with the cosmic abundance of sulfur, 1.6×10^{-5}, if a filling factor of unity within the known clumps is assumed. However, the sulfur abundance in the galactic center may be as much as a factor of 3 overabundant if a filling factor of 0.03 is adopted, a value found to hold for some galactic H II regions.

Subject headings: interstellar: abundances — interstellar: matter

I. INTRODUCTION

The galactic center, Sgr A West, represents an inherently interesting region, rich in phenomena and perhaps unique as an object of study in our Galaxy. Within the central parsec there exists a high-luminosity H II region with clumps whose motions have projected line-of-sight velocities ranging from -250 km s^{-1} to $+250$ km s^{-1}, possibly indicating the presence of a massive object ($\approx 10^6\ M_\odot$) (cf. Oort 1977; Lacy *et al.* 1980; Gatley and Becklin 1981). Extreme visual obscuration, $A_v \approx 30$ mag, prohibits optical observations; hence, the infrared and radio have been the dominant wavelength regimes used for studying this region. Much of the continuum infrared work has concentrated on delineating the nature and structure of the central few parsecs at different wavelengths. These investigations show the presence of numerous late-type stars as well as an extensive H II region complex with a total optical/ultraviolet luminosity of $\sim 10^7\ L_\odot$ (Becklin and Neugebauer 1975; Gatley *et al.* 1977; Becklin *et al.* 1978; Rieke, Telesco, and Harper 1978; Becklin, Gatley, and Werner 1982).

Measurements of infrared forbidden-line emission play a key role in the understanding of the dynamics and excitation of the galactic center. Although Ne II (12.8 μm) had been detected previously (Aitken, Jones, and Penman 1974; Wollman *et al.* 1976, 1977; Willner 1978), it was not until recently that sufficient spatial and spectral resolution was achieved to produce a coherent display of the wealth of motions within the central parsec (Lacy *et al.* 1979, 1980).

While Ne II has been the main dynamical probe of the central parsec, other ions have also been detected in the infrared and used as abundance and excitation indicators. These include Ar III (Lacy *et al.* 1980), Ar II (Willner *et al.* 1979: Lester *et al.* 1981*a*), O III (Dain *et al.* 1978; Watson *et al.* 1980), and O I (Lester *et al.* 1981*b*). These observations indicate a highly luminous, low-excitation H II region with $L > 10^7\ L_\odot$ and an effective temperature of $\leqslant 35{,}000$ K for the exciting source or sources (Lacy *et al.* 1980). There is some indication that argon and neon may be overabundant (Lacy *et al.* 1980; Lester *et al.* 1981*a*). Additional information could be gained by observing other ions usually detected in H II regions such as S III and S IV. Although there have been searches for both these ions (McCarthy *et al.* 1980; Lacy *et al.* 1980), neither has been detected previously. Lacy *et al.* (1980) have placed a strong upper limit on the S IV abundance, $\leqslant 0.08$ times the cosmic elemental abundance. However, the upper limit on the S III abundance obtained by McCarthy *et al.* (1980) is consistent with the cosmic elemental abundance of sulfur.

The current investigation reports on a second search for S III in Sgr A West with higher spectral resolution than that of McCarthy *et al.* (1980) and positive detection ($\geqslant 8\ \sigma$) of [S III] 18.71 μm line emission.

II. OBSERVATIONS

The observations reported here were made on 1982 June 18–19, using the 91 cm telescope of the Kuiper Airborne Observatory (KAO) on a flight from Moffett NAS, Mountain View, California, to Hickom AFB, Oahu, Hawaii. Flight altitude was in excess of 12.5 km with less than 15 μm of precipitable water vapor in the line of sight for both sources and calibrators. A dual-grating, liquid-helium-cooled spectrometer containing a three-element Si : Sb detector array was used for the measurements (Houck and Gull 1982). The resolution of the spectrometer (FWHM) is 0.033 μm at 18.71 μm. The beam size, when used on the KAO, is approximately 20″ in diameter on the sky. IRC +10420 and

Callisto were used as calibrators. The flux of IRC +10420 is assumed to be 2.4×10^{-15} W cm^{-2} μm^{-1} at 18.7 μm (Forrest, McCarthy, and Houck 1979), while the brightness (and color) temperature of Callisto is taken to be 146 K at the time of the observations (Forrest, Houck, and McCarthy 1980). The overall flux calibration is estimated to be accurate to $\pm 15\%$.

Nine data points were taken about the line position at a sampling interval of approximately two points per resolution element (FWHM). Figure 1 displays the relative position and beam size of the current measurement on the 20 μm map of Sgr A West obtained by Becklin *et al.* (1978). The resulting spectrum is shown in Figure 2. For these observations a chopper throw of 6′ nearly perpendicular to the galactic plane was employed. An observed continuum level of $\approx 1.2 \times 10^{-15}$ W cm^{-2} μm^{-1} is consistent with the flux of $1.57 \pm 0.04 \times 10^{-15}$ W cm^{-2} μm^{-1} observed at 18.9 μm by McCarthy *et al.* (1980) in a 30″ beam. The line flux of S III at 18.71 μm is found to be $1.7 \pm 0.2 \times 10^{-17}$ W cm^{-2}, consistent with the upper limit of 1.9×10^{-17} W cm^{-2} found by McCarthy *et al.* (1980). The measured line width of 0.039 ± 0.004 μm is marginally broader than the instrumental resolution of 0.033 μm and consistent with the velocities observed for Ne II (Wollman *et al.* 1976; Lacy *et al.* 1979, 1980).

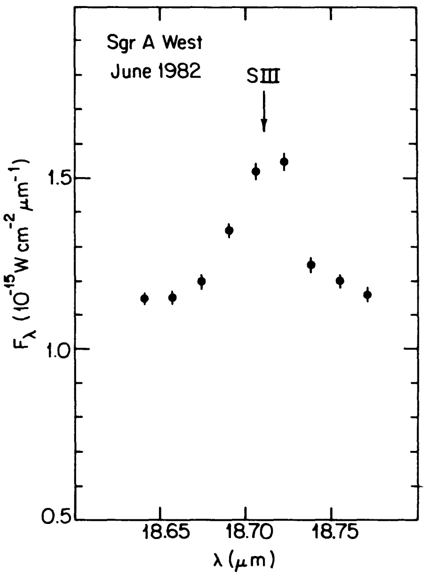

FIG. 2.—The 18.7 μm spectrum of Sgr A West obtained with a 20″ aperture centered on IRS 1. The resolution is $\lambda/\Delta\lambda \approx 600$.

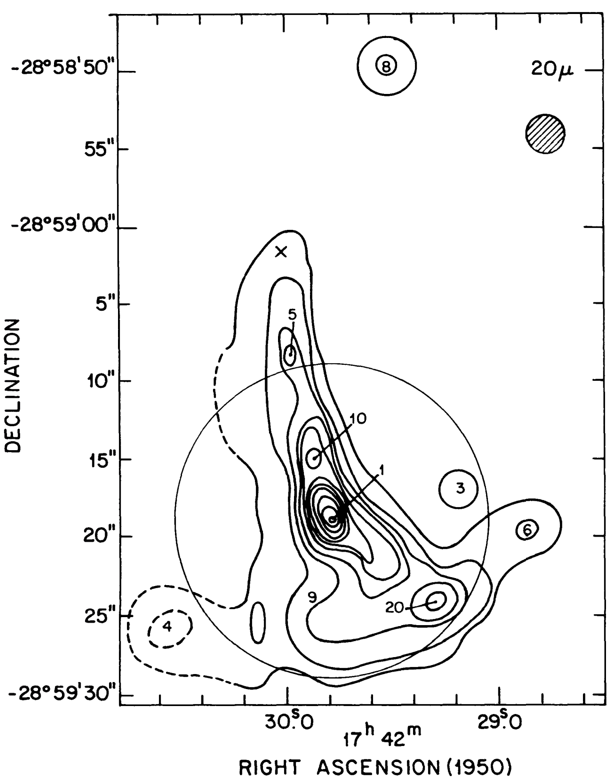

FIG. 1.—The 20 μm map of Sgr A West obtained by Becklin *et al.* (1978), by permission. Numbers are infrared sources. The circle (*thin line*) centered on IRS 1 indicates the beam position and size (FWHM) of the current measurement.

III. IONIC ABUNDANCE

The relative ionic abundance of S III can be obtained from the present measurements if we know (1) the column density of the ionized hydrogen in the beam, (2) the extinction at 18.71 μm, and (3) the temperature and density of the emitting region.

a) H II *Column Density*

Comparing the 6 cm VLA map of Brown, Johnston, and Lo (1981) with Figure 1 indicates that, of the sources which have significant radio emission, only sources 1, 2, 10, and 20 will be contained within our beam. Including these point sources with the "corrected" 5 GHz fluxes of Brown, Johnston, and Lo (1981) plus 50% of the extended ridge emission they measure, the total thermal radio emission appropriate for comparison with the current measurement should be approximately 6 Jy.

b) *Extinction*

Numerous authors have estimated the extinction to the stars and H II region at the galactic center; however, the most comprehensive determinations are those of Willner and Pipher (1983) who have measured Brα and Brγ fluxes from 11 sources in the galactic center at better than 4″ spatial resolution. They find that the extinction is fairly uniform with the possible exception of source 6 which appears to have a somewhat higher extinction. In particular, sources 2, 4, 5, 6, and 20 have 2.5, 2.5, 2.5, 4.0, and 2.3 mag of extinction at 2.17 μm respectively. Since the relative radio strength of source 6 is small and it lies outside our beam (Brown, Johnston, and Lo 1981), an extinction of 2.5 mag at 2.17 μm is adopted. Using the Brγ flux of Neugebauer *et al.* (1978) measured in a 32″ beam and the adopted extinction, the predicted radio flux at 5 GHz is 8.2 Jy (Brocklehurst 1971; Giles 1977), for an assumed electron temperature of 5000 K (Rodriguez and Chaisson 1979). This estimate of the radio flux compares favorably with the previous estimate of the radio flux contained within a 20″ beam. Adding up all the point sources expected to be contained within a 32″ beam and including all of the extended ridge emission yields 11 Jy at 5 GHz (Brown, Johnston, and Lo 1981). These comparisons give one an idea of the uncertainty in our estimate of the ionized hydrogen column density in our beam.

Willner and Pipher (1983) demonstrated that, for the galactic center sources, with the possible exception of source 6, the extinction derived from Brα and Brγ measurements agrees well with the extinction found from type I model fits to the silicate absorption feature (Gillett *et al.* 1975). These fits assume an underlying blackbody continuum attenuated by cold silicate dust. This result differs from most galactic H II regions which usually agree better with type II fits (cf. Herter *et al.* 1981). Type II fits assume an underlying Trapezium-like silicate emission. McCarthy *et al.* (1980) found, from modeling the 19 μm silicate feature, optical depths at 18.9 μm of 0.9 and 2.1 from type I and II fits respectively. Taking $\tau_{18.9} = \tau_{18.7}$ and $\tau_{18.7}/\tau_{2.17} \approx 0.6$ (Herter *et al.* 1981), then 2.5 mag of extinction at 2.17 μm yields $\tau_{18.9} = 1.4$ which is midway between the estimates of the optical depth of McCarthy *et al.* (1980).

c) *Electron Density and Temperature*

The derived S III ionic abundance relative to hydrogen is $1.3 \pm 0.2 \times 10^{-6}$ assuming $\tau_{18.7} = 1.4$, an rms electron density of 20,000 cm^{-3} (Brown, Johnston, and Lo 1981), and an electron temperature of 5000 K (Rodriguez and Chaison 1979). We have used the transition probabilities and collision strengths compiled by Mendoza (1982). The above estimate does not include an error term for the uncertainty in the extinction correction. If $\tau_{18.7}/\tau_{2.17}$ changes by 10%, then the resulting change in the derived ionic abundance is 14%. The cosmic elemental abundance of sulfur is 1.6×10^{-6} (Allen 1973). If the region is clumped on a scale smaller than the VLA beam size of Brown, Johnston, and Lo (1981), then the S III ionic abundance will be higher. Filling factors, as found from S III lines for local H II regions, may be as small as 0.03 (Herter *et al.* 1982*a*, *b*). Decreasing the filling factor to 0.03 increases the derived S III abundance by a factor of 3.

Rodriguez and Chaisson (1979) find an electron temperature of 5000 $\pm$ 1000 K for Sgr A West. This is somewhat lower than that deduced for local H II regions which typically have $T_e \approx 8000$ K (Silvergate and Terzian 1979; Wilson, Pauls, and Ziurys 1979; Mezger *et al.* 1979). A temperature as low as ~ 5000 K is also consistent with the Brα and Brγ measurements of Willner and Pipher (1983). Increasing the assumed temperature to 8000 K only decreases the deduced sulfur abundance by about 15%.

The electron temperature and the abundances are not independent; increases in the abundance of heavy elements result in lower electron temperatures. A temperature of 5000 K implies a factor of 3 overabundance in coolants (cf. Mezger *et al.* 1979). If most sulfur is in the form of S III as in the case of typical H II regions (cf. McCarthy, Forrest, and Houck 1979; Herter, Helfer, and Pipher 1983), and the sulfur/oxygen abundance ratio is cosmic, i.e., 0.024 (see, however, Talent and Dufour 1979), then the above analysis requires a filling factor of ~ 0.03 for the galactic center. A similar analysis by Watson *et al.* (1980) for the [O III] 51.8 μm line indicates a filling factor ranging from 1 to 0.01, depending on the relative amounts of the O II and O III present. However, in such low-excitation objects, the ratio of O II to O III is a very strong function of the detailed excitation conditions. The filling factor as derived from S III, however, is much less susceptible to excitation changes.

IV. FURTHER WORK

The wealth of ions now observed in Sgr A West makes it feasible to attempt a synthesis of the data into a coherent framework. Because different infrared lines are sensitive indicators of density over a wide range of densities and because various line ratios are sensitive indicators of the excitation conditions, a consistent picture of abundances, electron densities, and excitation in the galactic center can be developed. In a paper to be submitted to *The Astrophysical Journal* (Part 1), a more detailed analysis of the implications of the currently available observations is explored (Herter and Houck 1983).

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