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THE ELECTRON DENSITY IN THE GALACTIC CENTER AS DERIVED FROM THE S III 18.71/33.47 MICRON LINE RATIO

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ABSTRACT

We report high signal-to-noise ratio measurements of the S III lines 18.71 and 33.47 μm from the galactic center, Sgr A West. The average electron density is calculated for the S III–emitting region and is found to be 1800 ± 500 cm^{-3}. This value is much less than the rms electron density of the clumps as derived from radio observations. The implications for various models are discussed. The S III result is consistent with the electron density previously derived from low signal-to-noise ratio measurements of the O III lines at 88 and 52 μm, if newer values are used for the O III atomic constants.

Subject headings: galaxies: Milky Way — galaxies: nuclei — infrared: spectra

I. INTRODUCTION

The galactic center, Sgr A West, is an exciting, well-studied region of our Galaxy. Within the central parsec is a low-excitation ($T_* < 35{,}000$ K), high-luminosity ($L > 10^7$ $L_\odot$) H II region showing extreme high-velocity mass motions (± 250 km s^{-1}) (cf. Gatley and Becklin 1981; Lacy *et al.* 1980). Its morphological properties have been discussed extensively in the literature (cf. Oort 1977; Gatley and Becklin 1981), while the general nature of the dynamics and the excitation source(s) have also been considered (cf. Lacy, Townes, and Hollenbach 1982). Of particular interest are the physical properties of the ionized gas which directly reflect the chemical and dynamical evolution of this region.

There have now been a number of ions detected in Sgr A West through their observed infrared fine-structure line emission. These include Ar II (Willner *et al.* 1979; Lester *et al.* 1981), Ar III (Lacy *et al.* 1980), Ne II (cf. Aitken *et al.* 1976; Willner 1978; Lacy *et al.* 1980), S III (Herter *et al.* 1983, hereafter Paper I), and O III (Dain *et al.* 1978; Watson *et al.* 1980; Genzel *et al.* 1984). S IV has not been detected despite several attempts (Lacy *et al.* 1980). These ions give important information on the abundances in the galactic center and when intercompared provide details of the excitation. Equally important are the high-resolution radio continuum maps now available (Brown, Johnston, and Lo 1981; Brown and Johnston 1983) as well as extensive measurements of the hydrogen recombination lines Brα and Brγ (Willner and Pipher 1983).

A detailed analysis of the physical and chemical conditions in the galactic center using the observed infrared fine-structure line emission from the above ions requires a knowledge of the electron density. Until recently the only means of estimating the density of highly optically obscured H II regions was through radio continuum measurements which yield an rms density. However, electron density determinations have now been made using infrared fine-structure lines. In particular, the [O III] 51.8 μm and 88.4 μm lines (Melnick, Gull, and Harwit 1979; Moorwood *et al.* 1980; Watson *et al.* 1981), and the [S III] 18.7 μm and 33.4 μm lines (Herter *et al.* 1982*a*, *b*) have been used to measure densities in H II regions. It is found that densities derived in this fashion can differ considerably from the rms density determined from radio continuum observation indicating extensive clumping of the gas (cf. Herter *et al.* 1982*b*).

Recently, Genzel *et al.* (1984) detected [O III] 88.4 μm emission toward Sgr A West with a beam size comparable to the observation of [O III] 51.8 μm emission by Watson *et al.* (1980). They find that the [O III] emission is dominated by relatively high-density ionized gas ($n > 6000$ cm^{-3}), consistent with the clumps observed in the radio. There is no evidence for a lower density ($n < 10^3$ cm^{-3}) halo component suggested by the radio observations. Given the low-excitation state of the galactic center, it is quite likely that the dominant form of oxygen in the central parsec is O II and not O III; hence, the [O III] density estimate may not be representative of bulk of the ionized gas. To obtain another estimate of the electron density, we have measured the [S III] 18.7 μm and 33.4 μm lines. Although there is no guarantee that S III will dominate over S II in the galactic center since the detailed excitation conditions are as yet unknown, a S III density determination would aid in our understanding of this important and unique region.

The detection of the [S III] 18.7 μm line in Sgr A West was reported recently (Paper I). In the current work we report the detection of [S III] 33.4 μm line toward this region. In addition, we reobserved the [S III] 18.7 μm line to provide a calibration check and a comparison line for the 33.4 μm line observation. In the following sections we outline the observations and use the measured [S III] lines fluxes to estimate the electron density of the galactic center. This is followed by an analysis of the impact this new density determination will have on models of the galactic center.

II. OBSERVATIONS

The observation and calibration techniques employed in the current measurements are identical to those used in our previous observations of the galactic center (Paper I). Measurements were made on 1983 July 13–14 using the 91 cm telescope of the Kuiper Airborne Observatory (KAO) on a flight from Moffett Field, NASA/Ames Research Center, Mountain View, California. 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 was used (Houck and Gull 1982). A three-element Si:Sb detector array was employed for the measurement of the [S III] 18.7 μm line, while a three-element Ge:Be array was used for the [S III] 33.47 μm line measurement. The spectrometer resolutions are 0.033 μm and 0.06 μm at the short- and long-wavelength positions, respectively. Typical in-flight NEPs per detector are 3×10^{-14} and 5×10^{-14} W Hz$^{-1/2}$ for the Si:Sb and Ge:Be systems, respectively. The beam size, when the instrument is used on the KAO, is approximately 25″ in diameter on the sky. This is larger than the 20″ beam used in our previous measurement of S III in the galactic center (Paper I). IRC +10420 and the Moon 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 and 0.53×10^{-15} W cm^{-2} μm^{-1} at 33.47 μm (Forrest, McCarthy, and Houck 1979). The overall flux calibration is estimated to be accurate to $\pm 15\%$.

Nine data points were taken about each line position at a sampling interval of approximately two points per resolution element (FWHM). The beam was centered on Sgr A West, identical to that indicated in Paper I. Pointing accuracy is better than 5″. Figure 1 shows spectra obtained about the 18.7 μm and 33.4 μm lines, respectively. A chopper throw of approximately 4′ perpendicular to the galactic plane was employed. The observed continuum flux levels are consistent with those measured by McCarthy *et al.* (1980) and the continuum level reported in Paper I. The line fluxes are found to be $1.8 \pm 0.1 \times 10^{-17}$ W cm^{-2} and $2.6 \pm 0.4 \times 10^{-17}$ W cm^{-2} for the 18.7 μm and 33.47 μm lines of S III, respectively. The 18.71 μm line is consistent with that measured previously (Paper I). The line width of 18.71 μm of 0.0385 ± 0.003 μm found for the present measurement is nearly identical to that obtained in Paper I. This line width 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).

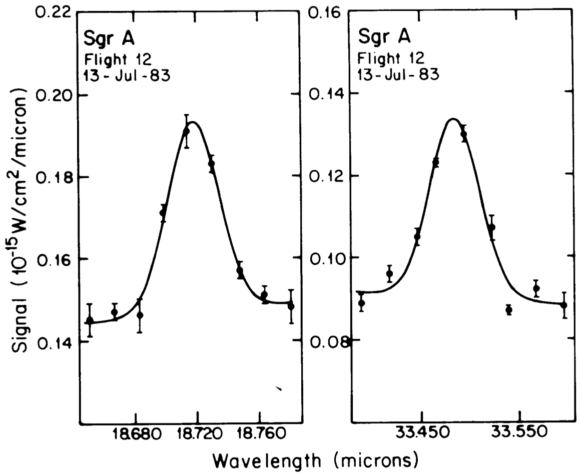

FIG. 1.—Spectra of S III forbidden lines in the galactic center are shown. No reddening correction has been performed. A beam diameter of 25″ (FWHM) and resolutions of 0.03 at ~ 18 μm and 0.06 at ~ 33 μm were used to obtain the data on the Kuiper Airborne Observatory.

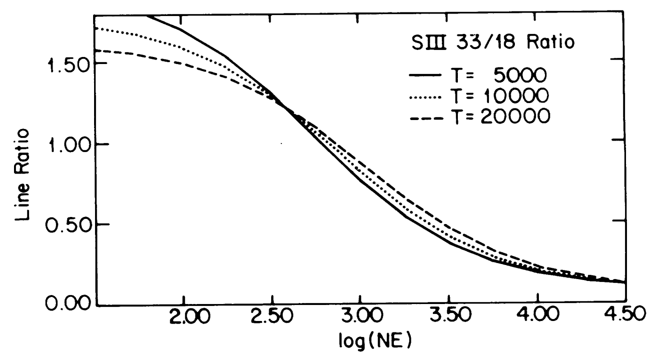

FIG. 2.—A plot of the S III line ratio as a function of electron density is shown. Data are included for several different values of electron temperature.

III. ELECTRON DENSITY

The electron density in the galactic center can be determined from the relative strength of the [S III] 18.71 μm and 33.47 μm lines, as outlined in Herter *et al.* (1982*a*). This procedure assumes a single density component and a uniform distribution of S III relative to hydrogen for the observed region. The electron density is derived using the relation for the relative volume emissivities plotted in Figure 2. Figure 2 is an updated version of a similar figure shown in Herter *et al.* (1982*a*, *b*). The current figure was generated from a five-level atom calculation for S III using the latest collision strengths as tabulated by Mendoza (1983).

There have been significant changes to the collision strengths since the early plot was generated. These differences change the volume emissivities but have little net effect on the line ratio versus density plot. The observed 33.4 μm to 18.7 μm line ratio must be dereddened to obtain an emitted ratio for comparison with Figure 2. The extinction to the galactic center was considered in Paper I and will only be briefly mentioned here. An optical depth of 1.4 at 18.7 μm was adopted. Using $\tau_{18.7}/\tau_{33.4} = 3.1$ (Forrest, McCarthy, and Houck 1979), this implies an optical depth of 0.5 at 33.4 μm. This results in a 33.4 to 18.7 dereddened line ratio of 0.6 ± 0.1.

The quoted error on the dereddened line ratio is somewhat optimistic. Both errors in the extinction and extrapolation of the extinction curve from shorter wavelengths where the extinction estimate was made (Paper I) lead to additional uncertainties in the corrected line ratio. Unfortunately, at present we have no quantitative means to assess this additional uncertainty, thus making it difficult to include in the analysis. This additional error is almost certainly greater than the 17% error quoted above. Although not included in the analysis below, these extinction-related uncertainties should be kept in mind.

Choosing an electron temperature of 7500 K, comparison of the computed line ratio with Figure 2 yields an electron density of 1800 ± 500 cm^{-3}. The S III–derived density appears somewhat lower than the lower limit determined by Genzel *et al.* (1984) on the basis of their [O III] 88 μm

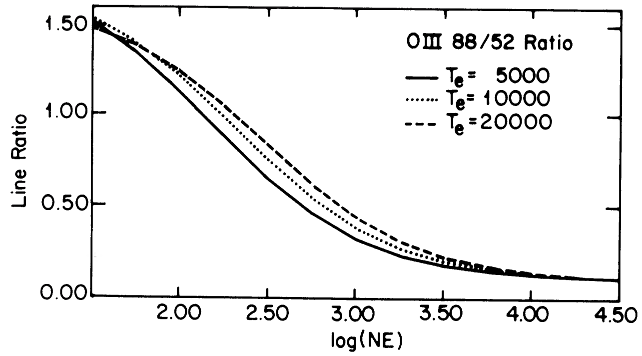

FIG. 3.—A plot of the O III line ratio as a function of the electron density is shown. Data are included for several different values of the electron temperature.

measurement and the 52 μm measurement of Watson *et al.* (1980). They concluded that the observed O III line ratio was consistent with densities greater than 6000 cm^{-3}. However, on the basis of their computed O III 88 to 52 μm line ratio of $0.13 + 0.05$, the electron density is $8000\ (-5000, +\infty)\ cm^{-3}$. Using a 3 σ upper limit to their O III line ratio of 0.28 yields a lower limit on the density of 1000 cm^{-3}, a factor of 6 below the value obtained by Genzel *et al.* The difference between our O III analysis and that of Genzel *et al.* is due to our use of more updated collision strengths for O III (Aggarwal 1983). In view of the changes that have occurred in collision strengths recently, even the newest calculations should be treated skeptically. For reference we provide in Figure 3 a plot of the relative 88 to 52 μm O III line emission as a function of density using the updated cross sections. Although the O III observations were obtained with a larger beam size (60″) than the S III measurements, it is quite evident then that the O III results are consistent with the S III findings.

IV. IMPLICATIONS

Radio observations of the galactic center indicate an H II region complex consisting of dense clumps (20,000 cm^{-3}) surrounded by a more diffuse halo (Brown, Johnston, and Lo 1981). It is not known whether these clumps are of higher or lower excitation than the diffuse gas. If each clump is ionized by its own internal source, then the clumps will be of higher excitation compared to the diffuse gas than if there is a single ionizing source for the entire region. Suppose, for instance, that the clumps contain no other ionization state of sulfur besides S III. This implies that there must be some S III present in the diffuse gas to obtain the correct line ratio. The total radio flux from the compact components of the S III measurement beam is approximately 2.2 Jy. Taking this component to be at density of 20,000 cm^{-3}, only 0.3 Jy of radio emission are needed from the diffuse region to obtain the observed line ratio, assuming the low-density component has a density less than 100 cm^{-3}. If the density of the diffuse gas is higher, either due to clumping within this region or simply due to a higher mean density, then the required radio flux from the diffuse component increases. For instance, if a density of $1 \times 10^3\ cm^{-3}$ is assumed, then the required radio flux increases to 2 Jy. Since the observed radio emission is on the order of 10 Jy, S II may dominate much of the volume occupied by the diffuse component. In fact, no S II need be present at all if the density of the diffuse gas is 1800 cm^{-3}. Unfortunately, it is not possible on the basis of the S III measurements alone to separate clumping and excitation effects. If it is assumed that the abundance of sulfur in the galactic center is approximately cosmic, relative to hydrogen 1.6×10^{-5}, then the density of the diffuse component would be about 600 cm^{-3} with a radio flux from the diffuse S III component of ~ 1 Jy.

If S III is not in the high-density clumps, the above discussion does not really change in substance, and the observed density applies only to the low-density component. Similar arguments can be made for O III when high signal-to-noise ratio observations are available. It is important, however, that O III measurements with greater signal-to-noise ratios be obtained. Because of the O II–O III mix in a low-excitation H II region is different than that of S II–S III, an accurate O III density determination may help distinguish between the nature of the high-density clumps and the more diffuse component in the galactic center. A high O III density would imply that the clumps are dominated by O III while the diffuse gas contains only O II. Under this circumstance each clump would have its own internal source of ionizing radiation.

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