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DETECTION OF [O I] 63 MICRON EMISSION FROM THE GALACTIC CENTER

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ABSTRACT

The detection of the 63 μm line of [O I] is reported for three positions in the H II region complex Sgr A at the galactic center. Velocity resolution of the line indicates that the emitting material has both rotational and radial motion of magnitude similar to that of the ionized gas in the core and that a substantial amount of the emitting material lies within the central few parsecs of the Galaxy. A model in which [O I] is collisionally excited by neutral hydrogen, either from the warm region ahead of an ionization front or behind a shock, is proposed and gives a total mass of hot, neutral gas within the central 3 pc of the Galaxy of between 10 and 10^3 $M_{\odot}$. A limit on the flux of this line has been set for Sgr B2.

Subject headings: galaxies: Milky Way — galaxies: nuclei — nebulae: H II regions

I. INTRODUCTION

Recent studies of Sgr A, the H II region at the center of our Galaxy, have shown that it is distinctive in a number of ways. Measurements of the spatial distribution of [Ne II] 12.8 μm emission (Lacy *et al.* 1979, 1980) suggest that the central parsec of Sgr A contains at least 10 dense, ionized clouds that have large relative velocities, ranging over more than 400 km s^{-1}, and superthermal internal velocity dispersions. While the large relative velocities are thought to be caused, in part, by Keplerian rotation of the ensemble of clouds in the gravitational field of a massive cluster of stars, the velocity field shows evidence for chaotic motions as well. The inferred expansion time scale for these clouds is comparable to their collision time scale, suggesting that cloud-cloud collisions may play an important role in their destruction. In this violent region, the formation of shocks in the ionized clouds and associated neutral gas might be expected. The estimated lifetime of these clouds is short enough that their formation must be frequent. If they are originally formed from neutral gas, whether stripped off stars or from pieces of a disintegrating molecular cloud, ionization fronts moving into the originally neutral matter could be a common phenomenon. The intercloud medium is traversed by ionizing radiation which, in proceeding outward, also encounters neutral material at some distance from the galactic center.

The 63 μm $^3P_1 - {}^3P_2$ [O I] line is expected to be an important coolant both in shock-heated neutral clouds and in ionization fronts moving into these clouds (Dalgarno and McCray 1972; Hill and Hollenbach 1978). This line has already been observed in several H II regions in which the emission is thought to originate in the neutral gas just ahead of the ionization front as it expands into an adjacent molecular cloud (Melnick, Gull, and Harwit 1979; Storey, Watson, and Townes 1979). We have looked for this line in Sgr A in an attempt to assess the importance of neutral gas in that region. We find that the [O I] line is spectrally resolved by our instrument, allowing a comparison of the velocity structure of the neutral gas with that of the ionized gas, and that the velocity of peak emission appears to vary systematically with position across the source, along the galactic plane. In addition, we have set an upper limit to the [O I] strength for the dense H II region Sgr B2.

II. OBSERVATIONS

Observations were made with the 91.4 cm telescope of the NASA Kuiper Airborne Observatory on 1980 July 8 during a flight to Honolulu, Hawaii. At the observing altitude of 12.5 km, the line-of-sight column density of precipitable water was about 15 μm. The instrument used was the tandem Fabry-Perot spectrometer described by Storey, Watson, and Townes (1980), with a Ge:Ga photoconductive detector. A 1′ beam (FWHM) was used with a chopper throw of approximately 3′.5 and a chopping frequency of 24 Hz. Wavelength calibration was provided by the strong H_2O line at 63.323 μm

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(McClatchey *et al.* 1973) seen through a sample cell against a spectrometer blackbody source. The same line is visible in the source spectra from the intervening terrestrial water, although the column density was large enough that the line is completely saturated and cannot itself be used for wavelength calibration. Flux calibration for the [O I] line is derived directly from the Sgr A continuum, which has been mapped with 30″ resolution by Becklin, Gatley, and Werner (1981). The spectrometer resolution was $\lambda/\Delta\lambda \sim 1600$ ($\Delta v \sim 190$ km s^{-1}). The observations represent 24 minutes of integration time during which the system noise equivalent power (NEP) was approximately 1×10^{-13} W $Hz^{-1/2}$.

III. RESULTS

Spectra of Sgr A taken at the nominal position of the 10 μm peak and 45″ north and south along the galactic plane are shown in Figures 1*b*, 1*a*, and 1*c*, respectively. Although the relative location of the three measured positions are well determined, the absolute pointing position is no better than ~ 30″. The spectrum of Sgr B2 was taken at the 60 μm continuum peak and is shown in Figure 1*d*. The [O I] line is clearly detected at all three points in Sgr A, but is not detected in Sgr B2. The spectra are smoothed to 1/12 of a resolution element and have been fitted with a Lorentzian plus a linear continuum. They have also been divided by scans of an internal blackbody calibration source in the spectrometer, which removes the transmission function of the instrument. The continuum slope is largely from the strong terrestrial water lines that obscure the source on the long wavelength side of the spectrum. The effect of these water lines has been estimated from the line-of-sight precipitable water vapor measurement and is shown in Figure 1*e* without instrumental broadening. This spectrum shows that the observed [O I] is substantially but not severely influenced by terrestrial water. Although observations with less line-of-sight water are clearly to be preferred, the effect of the water lines is cancelled to first order by scaling the [O I] intensity to the interpolated continuum beneath the lines. The observed line intensities in Sgr A are 7, 11, and 8×10^{-13} W m^{-2} at the northern, central, and southern positions, respectively, and less than 2×10^{-13} W m^{-2} from Sgr B2. The observed line intensities correspond to a luminosity of approximately $3.5 \times 10^3 L_\odot$ in the line at each position on Sgr A, with a projected beam diameter of approximately 3 pc.

The laboratory wavelength of the [O I] line is accurately known from the laser magnetic resonance study of Saykally and Evenson (1979) to be 63.170 μm. This allows us to conclude that the line-of-sight velocity of the emitting region at the center position is +15 ± 40 km s^{-1} with respect to the local standard of rest (LSR), which is consistent with that derived from the [Ne II] spectra. There is some evidence for a gradient in line center velocities, which range from +140 ± 40 km s^{-1} at the northern position to −10 ± 50 km s^{-1} at the southern position. This effect is similar in both direction and magnitude to the [Ne II] velocity field. There is no evidence for such a +140 km s^{-1} cloud in the H_2CO absorption data of Bieging *et al.* (1980) at the north position, although a cloud seen in the 21 cm H I map of Sinha (1979) may correspond to the source of the [O I] emission. The line at the north position has a width consistent with the instrumental response, while at the central and south positions the line is clearly resolved with an intrinsic width of ~ 200 km s^{-1}.

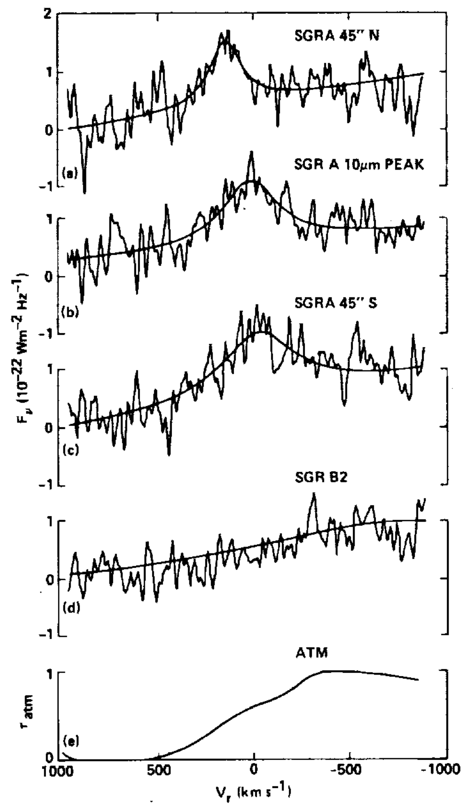

FIG. 1.—Spectra of Sgr A in a 1′ beam at (*a*) 45″ N, (*b*) 10 μm peak, and (*c*) 45″ S along the galactic plane. The resolution of the spectrometer is well represented by the [O I] profile at the northern position (*a*). The slope in the continuum is caused by residual telluric water absorption. The velocity scale is defined by the scan length of the Fabry-Perot, and the zero position is determined by laboratory wavelengths of [O I] and of H_2O in a reference sample cell. The shift in line center velocity across the source is evident as is a broadening of the [O I] line at the center and south position. (*d*) Spectrum of Sgr B2 at the 60 μm peak. No [O I] was detected in this source. (*e*) Synthetic atmospheric transmission spectrum for 15 μm of precipitable water. This spectrum is shown without instrumental broadening and line overlap. This spectrum was derived with a single slab atmosphere model based on the line parameters given in the McClatchey *et al.* (1973) compilation.

IV. ANALYSIS OF LINE STRENGTHS

The [O I] fluxes from Sgr A can be compared with those of other H II regions by scaling to the optically thin radio flux. The ratio of [O I] flux to radio flux in Sgr A is comparable to that seen in DR 21, M17, and the Trapezium region of M42 (Melnick, Gull, and Harwit 1979; Storey, Watson, and Townes 1979). While the nature of Sgr A is very different from that of these other H II regions, the relative similarity in [O I] power does suggest that similar excitation mechanisms may be considered. Collisional excitation of [O I] has been proposed for galactic H II regions, and the applicability of this to Sgr A is considered in detail in this section.

a) *Ion Impact Excitation*

Excitation by electron and proton impact may be important in regions where neutral oxygen coexists with a substantial amount of ionized gas. The similarity of ionization potentials for neutral oxygen and hydrogen suggests that this region will be restricted to the edge of the H II region where the gas is only partially ionized. In fact, the ionization potentials are so close that charge exchange of neutral oxygen with protons is nearly a resonance process (Field and Steigman 1971), and the product of neutral oxygen density and ion density is constrained to peak in a narrow region at the boundary of the H II region. Using the electron impact collision strength from Saraph (1973) and the proton impact collision strength derived from the approximate formulae in Bahcall and Wolf (1968), the total neutral mass can be derived. Assuming an abundance fraction of neutral oxygen of $10^{-3}f$ by number, where f is the fraction of oxygen and hydrogen remaining neutral, we find a total mass in the region of oxygen excitation of

$$M \sim 10^4/f(1-f)n_H M_\odot$$

for

$$n_e \sim (1-f)n_H < n_{\rm crit} \sim 10^3 \text{ cm}^{-3},$$

and $M \sim 10/f\, M_\odot$ for $n_e > n_{\rm crit}$, where $n_{\rm H}$ is in cm^{-3} and a temperature of 10^4 K has been used. This can be compared with the mass $7 \times 10^5/n_e\, M_\odot$ of ionized gas in the same beam in Sgr A derived from the 5 GHz flux of Ekers *et al.* (1975). In the low-density limit, the minimum inferred mass occurs at $f = 0.5$. This minimum mass, assuming ion impact excitation, is comparable to the mass of ionized gas ($\sim 100\, M_\odot$ for $n_e \sim 10^4$ cm^{-3}) seen in the [Ne II] clouds. In the higher density regime, $10^4 < n_e < 10^5$ cm^{-3}, which is considered to best represent the [Ne II] clouds, a dominant part of Sgr A would be required to be only partially ionized. The substantial ionization of neon throughout the region argues against a large amount of partially ionized gas, however, and suggests that ion impact excitation of [O I] is not important in the [Ne II] clouds. It may, however, apply at the edges of neutral clouds surrounding the ionized region.

b) *Neutral Hydrogen Impact Excitation*

It is also necessary to consider the excitation of [O I] by neutral impact. In the galactic center this could occur either in the warm neutral gas just outside an ionization front (Hill and Hollenbach 1978) or in gas which is shock heated. At velocities and densities similar to those found in the ionized gas at the galactic center, the destruction in shocked gas of any molecules in which oxygen and hydrogen might be bound up (CO, OH, O_2, H_2) is expected to be complete (Hollenbach and McKee 1979). This should be true either in a shock that moves ahead of an advancing ionization front or in the more violent shocks that might be expected as a result of cloud-cloud collisions. Cross sections for atomic oxygen excitation by neutral hydrogen impact have been published by Launay and Roueff (1977). These yield, for

$$n_{\rm H} < n_{\rm crit} \sim 3 \times 10^5 \text{ cm}^{-3},$$

a neutral mass

$$M \sim 1.4 \times 10^6 (10^3/T)/fn_{\rm H} M_\odot.$$

Assuming a uniform density within the beam and a temperature of 10^3 K, we find $n_{\rm H} \sim 2 \times 10^3$ cm^{-3} and a mass $M \sim 700\, M_\odot$ for $f = 1$. It is very likely that any neutral gas is, in fact, distributed very nonuniformly, in view of the manifest evidence for clumpiness in the ionized gas from the [Ne II] studies. As the assumed clumpiness increases, our estimate of the neutral mass decreases until the limit $n_{\rm H} > n_{\rm crit}$ is reached. In this case, the energy levels in the neutral oxygen are statistically populated, and the estimated mass is the same as that derived in the same limit for ion impact excitation—approximately 10 $M_\odot$ in the region of excitation.

V. DISCUSSION AND CONCLUSIONS

Sgr A is unlike giant H II regions in the spiral arms in that it shows neither optically thick far-infrared emission nor strong, localized molecular line emission—characteristics of dense molecular clouds associated with H II regions. The velocity structure of the [O I] line in the direction of Sgr A strongly suggests that its source is close to the ionized core of the Galaxy. For these reasons, our observations constitute the first definitive detection of neutral gas within the central few parsecs of the galactic center.

We have considered two excitation mechanisms for [O I] in § IV. Excitation by neutral hydrogen impact in compressed, heated regions can account for the observed emission without requiring unduly large amounts of neutral gas. Excitation by ion impact in an advancing ionization front, however, requires a large amount of partly ionized gas, a prediction which conflicts with our understanding of the ionization equilibrium in the [Ne II] clouds. We cannot exclude, however, the possibility that the line is produced in a more diffuse, partially ionized region exterior to the core.

Assuming excitation by neutral hydrogen collisions, the above discussion has shown that 10 $M_{\odot}$ is a lower limit to the mass of hot, neutral gas within the central 3 pc. Even if the high-density limit is applicable, this is likely to underestimate the total neutral mass in Sgr A, because the [O I] emission will arise only from regions heated to $T \geq 228$ K and in which the bulk of the oxygen is in atomic rather than molecular form. By comparison, the amount of ionized gas in the [Ne II] emitting clouds is less than 100 $M_{\odot}$, and the total amount of ionized gas in the central 1′ is probably less than 500 $M_{\odot}$.

It is of great interest to understand the relationship of the neutral gas to the ionized clouds. Similar velocity dispersions suggest that their relation may be intimate. One possibility is that the clouds are only partially ionized and that the [O I] is excited outside the ionization fronts eating into the clouds (Hill and Hollenbach 1978). In this picture, we would expect the same velocity peaks seen in the [Ne II] spectra to appear in higher spectral and spatial resolution [O I] spectra, and the spatial distribution of [O I] and [Ne II] to be similar. Although our three beam positions suggest that the [O I] is more extended than the [Ne II], the limited spatial coverage in both lines, and the fact that the [O I] beam positions overlap somewhat, makes this result preliminary. Alternatively, the [O I] emission may arise in shock fronts produced by colliding neutral clouds. This would again produce discrete [O I] velocities, although not necessarily the same as those in the [Ne II] clouds. Finally, the neutral gas may be not in the form of individual inclusions but more widely spread. In this case, discrete [O I] velocities would probably not be seen.

It is also possible that the neutral gas is in organized rather than chaotic motion. The velocity dispersion at the center position and the evident velocity gradient along the galactic plane might then indicate that the [O I] emission is associated with an expanding or contracting ring of neutral gas which is rotating about the axis of the Galaxy. The unusual ringlike distribution of far-infrared emission seen in Sgr A by Becklin, Gatley, and Werner (1981) makes this a particularly attractive possibility. More extensive mapping and observations with higher spectral resolution will be of great value in testing these hypotheses.

Sgr B2 is a source in which an H II region is seen embedded in a dense molecular cloud and, for this reason, strong [O I] emission is expected from the transition region at the ionization front. The lack of [O I] emission in Sgr B2 is perhaps best understood on the basis of infrared continuum results. The absence of near-infrared emission from this source and the large far-infrared optical depth inferred by Gatley *et al.* (1978) suggest that the H II region is obscured completely by its parent molecular cloud, even at 63 μm. Continuum emission at 63 μm must then come from well in front of the H II region, and the ionization front is not exposed at this wavelength. A similar effect has been noted by Storey, Watson, and Townes (1981) from the absence in Sgr B2 of NH_3 lines around 120 μm, a wavelength at which the cloud should be less opaque than at 63 μm.

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