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FINE-SCALE STRUCTURE IN THE −185 KILOMETERS PER SECOND ABSORPTION BY HCO^+ IN THE GALACTIC CENTER

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ABSTRACT

We present a high-resolution (8."5 × 4") study of the HCO^+ ($J = 1 \rightarrow 0$) absorption by the "high-velocity gas" (Güsten & Downes 1981) at velocities between −170 and −200 km s^{-1} in Sgr A West. The absorption against the continuum radiation from the ionized gas features in Sgr A West (in particular the "bar") is stronger than it is against Sgr A* which is separated from the ionized gas by a few arcseconds. The positions of peak HCO^+ opacity coincide with the positions of [Ne II] emission at these velocities (Serabyn et al. 1988). These observations suggest that, even though emission is detected from gas at these high velocities over several arcminutes, some of the absorbing molecular gas may be mixed in with the ionized gas close to Sgr A*. Simple calculations show that sufficient shielding can exist in the ionized features to allow molecules to survive very close to the ionizing source.

Subject headings: galaxies: nuclei — Galaxy: center

1. INTRODUCTION

Recent observations of the Galactic center have begun to reveal the relationships between the ionized, atomic, and molecular gas components in this complex region. The ionized gas streamers that make up the "minispiral" of the H II region, Sgr A West, are believed to be gas that has broken off from the circumnuclear molecular ring and is falling in toward the center (Lo & Claussen 1983; Ekers et al. 1983). The velocity structures of the northern and eastern arms of the "minispiral" have been modeled successfully as that resulting from acceleration by a central point mass of 10^6 $M_\odot$ (Serabyn & Lacy 1985) located at or near the compact, nonthermal radio source Sgr A*. The east-west bar-shaped feature at the center of the "minispiral," located a few arcseconds south of Sgr A*, however, has a complex velocity structure that is yet to be fully explained.

A series of blueshifted spectroscopic features have been seen in absorption against the ionized gas, suggesting the existence of a number of line-of-sight components moving away from the Galactic center. The features at −30, −50, and −135 km s^{-1} are believed to be due to galactic rings or arms at galactocentric distances of around 4 kpc (Menon & Ciotti 1970), 3 kpc (see, e.g., Oort 1977), and 250 pc (Scoville 1972; Kaifu, Kato, & Iguchi 1972; Cohen & Few 1976; Listz & Burton 1978; Bieging et al. 1981), respectively. Observations in H_2CO and H I by Gušten & Downes (1981) revealed a fourth blueshifted feature at velocities from −170 to −200 km s^{-1}. The small-scale structure in this gas suggested that it is located in the central 10 pc of the Galaxy, and they concluded that it is being ejected from the center. Liszt et al. (1983) and Serabyn et al. (1986) detected this gas in H I and CO emission and found that it peaked about 1′ from the Galactic center.

In this *Letter*, we present the spectrum and a high-resolution (8."5 × 4."0) opacity map of the −170 to −200 km s^{-1} blueshifted feature seen in $HCO^+(J = 1 \rightarrow 0)$ absorption in the central 30″. Our opacity map shows fine-scale structure in the HCO^+ absorption which avoids the position of Sgr A*. In another study, Pauls et al. (1992) find that the H_2CO absorption also avoids Sgr A*. We discuss the relation between this feature and the continuum sources Sgr A*, the bar, and the ionized streamers. We explore the possibility that this gas is in the central ionized cavity and is associated with the ionized gas bar.

2. OBSERVATIONS

Observations of the $HCO^+(J = 1 \rightarrow 0)$ transition at 89.18852 GHz were obtained with the Hat Creek millimeter interferometer[2] between 1988 April and 1990 April. A total of 10 configurations of the three 6.1 m antennae were obtained, with baselines out to 150 m EW and 180 m NS. The total integration time was 88 hr.

A 512 channel digital correlator (Urry, Thornton, & Hudson 1985) was used to obtain cross-correlation spectra over a total bandpass of 290 MHz with 1.25 MHz (4.2 km s^{-1}) spectral resolution. The spectra were Hanning-smoothed, giving a final spectral resolution of 8.4 km s^{-1}. The point source NRAO 530

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was used for phase calibration, and Mars and Uranus were observed both for calibration of the spectrometer passband as well as for the determination of the absolute flux scale using brightness temperatures from Ulich (1981). The absolute flux scale should be accurate to within 20%. System temperatures were measured periodically and were typically between 300 and 800 K SSB scaled above the atmosphere. The rms sensitivity in a single 4.2 km s^{-1} channel is 0.15 Jy beam^{-1}.

The visibility data of each channel were convolved onto a grid, mapped and CLEANed. Natural weighting was used, yielding a synthesized beam of 8".5 × 4".0, roughly north-south. In addition, an opacity map, averaged from −166.1 to −191.3 km s^{-1} (Δv = 25.2 km s^{-1}), was calculated using a continuum map made by averaging 80 CLEANed line-free channel maps. At points where the line flux values fell below a 2 σ cutoff (0.2 Jy beam^{-1}), a lower limit to the opacity was calculated by setting the line flux at that point equal to the cutoff. In addition, opacities were not calculated where the flux in the continuum map fell below this same cutoff of 0.2 Jy beam^{-1}. The maximum signal in the continuum map is 2.1 Jy beam^{-1}, yielding a dynamic range of 125.

3. RESULTS

Figure 1 shows the Hanning-smoothed spectrum from the peak of the continuum image at 89.18852 GHz across our entire bandpass, covering a velocity range of approximately ±400 km s^{-1}. The deep, broad absorption at 0 km s^{-1} is due to interstellar gas in the Galactic plane in circular orbits about the Galactic center. In addition, the spectrum contains a series of absorption features at blueshifted velocities corresponding to three previously identified galactic features discussed in § 1. The source of the apparent absorption feature at −400 km s^{-1} is unclear. A map of the signal in this channel contains numerous unresolved emission and absorption components and is not similar to any of the known features in the Galactic center region. For the results presented here, we have avoided including these channels in creating the continuum map. We focus the discussion of this *Letter* on the feature at velocities −170 to −200 km s^{-1}, denoted in the spectrum by an arrow.

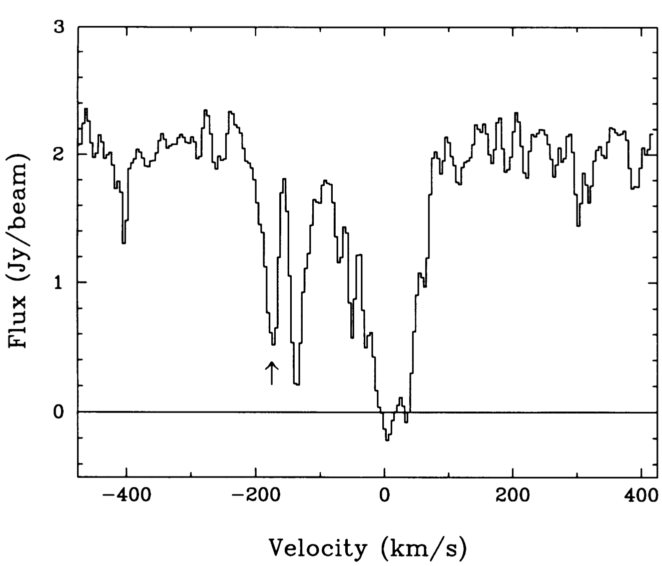

FIG. 1.—Hanning-smoothed spectrum in the direction of the peak of our continuum image at 89.18852 GHz. Zero velocity corresponds to the HCO^+ ($J = 1 \rightarrow 0$) transition. The high-velocity feature discussed in this *Letter* is indicated with an arrow.

In Figures 2*a* and 2*b*, we display the opacity map for the −185 km s^{-1} absorption feature, averaged over 25.2 km s^{-1}, along with the continuum map. The lowest contour of the continuum map (0.2 Jy beam^{-1}) traces the edge of the region over which opacities were calculated. The cross at the center of each map marks the 6 cm position of Sgr A* (Lo & Claussen 1983).

4. DISCUSSION

Güsten & Downes (1981), based on their H_2CO and H I observations, suggest that the −170 to −200 km s^{-1} molecular gas has at least a 10 pc extent and is being ejected from the Galactic center. The extended nature of this gas is supported by the observations of Liszt et al. (1983) and Serabyn et al. (1986) who find CO emission around −185 km s^{-1} extended over a few arcminutes and peaked ~1' from Sgr A*. Our data reveal fine-scale structure in the opacity on a scale of a few arc seconds, and, owing to this fine structure, we explore the possibility that the high-velocity gas is within the central parsec of the Galaxy.

The observed opacity map of the high-velocity gas, shown in Figure 2*a*, is optically thick in several places, particularly across the bar, but is not consistent with uniform opacity across the entire image. If the absorption were saturated (which we define as when the emission falls to below twice the noise) across the image, then we can only calculate a lower limit to the true opacity given by $\tau_{min} = -\ln (2\,\sigma/S_{cont})$. Since the continuum level varies across the map, this opacity limit varies with ln (S) and therefore, the opacity limit map will mimic the continuum. Figure 2*c* shows such a map and is a good model for the −135 km s^{-1} absorption, as expected. In contrast, the −175 km s^{-1} absorption map in Figure 2*a* exhibits a hole at the position of Sgr A* of similar size and shape as the synthesized beam, suggesting that Sgr A* is not being absorbed. To test this hypothesis, we constructed a model opacity map, which is displayed in Figure 2*d*, for gas that is optically thick everywhere except at the position of Sgr A* (assuming a flux of Sgr A* of 1 Jy; Wright et al. 1987). Comparison of our observation (Fig. 2*a*) with this model (Fig. 2*d*) shows that the observation is consistent with absorption by gas that is optically thick at all positions *except* at Sgr A*. Either Sgr A* is between the observer and the absorbing and emitting gas, or the absorbing gas is in front of both regions, but has structure such that the Sgr A* line of sight is not absorbed. We prefer the latter hypothesis owing to the unique nature of Sgr A*, its low proper motion (Backer & Sramek 1982, 1987), and its apparent dynamical association with the ionized gas structures (Serabyn & Lacy 1985; Aitken et al. 1991).

There are two ways that Sgr A* can be more distant than the absorbing gas and not be absorbed. The absorbing gas could cover the entire region, but have a patchy, or filamentary, structure such that the Sgr A* line of sight is not covered. Alternatively, the absorbing gas could be associated with the emitting gas which is spatially distinct from Sgr A* in high-resolution continuum images. While the extended nature of gas at these high velocities (Liszt et al. 1983; Serabyn et al. 1986) argues in favor of the former, the inferred complete absorption of the extended emission combined with the absence of absorption along the line of sight to Sgr A* which is separated by only 0.25 pc in projection, pushes us to consider the latter. This inference is additionally supported by the fact that gas with velocities around −200 to −170 km s^{-1} is seen in the bar in

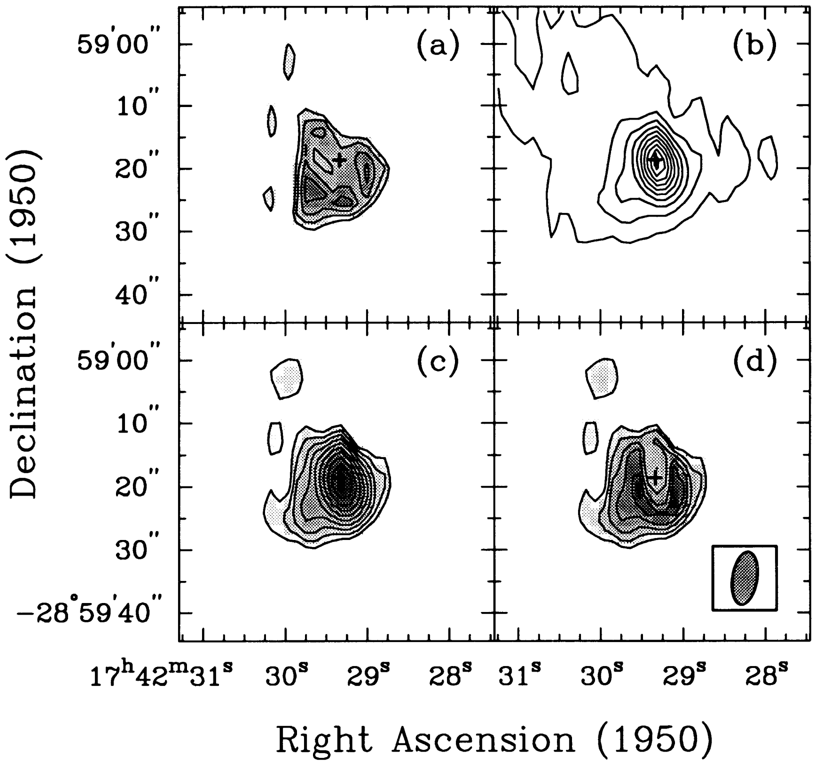

FIG. 2.—(*a*) Opacity map covering the velocity range −166.1 to −191.3 km s^{-1}. The contour levels correspond to optical depths of 0.5, 0.7, 0.9, 1.1, 1.3, 1.5, 1.7, 1.9, 2.1. At positions where the emission fell below 2 σ (0.2 Jy $beam^{-1}$), a lower limit to the opacity $\tau_{min} = -\ln(2\,\sigma/S_{cont})$ was calculated. In addition, no opacity was calculated where the continuum flux fell below the same 2 σ cutoff. (*b*) Continuum map made by averaging 80 line-free channels (Δv = 100 MHz). The contours are 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0 Jy $beam^{-1}$. Thus, the lowest contour corresponds to the outline of the region where opacities were calculated in Fig. 2*a*. (*c*) Model opacity map showing absorption that is optically thick (completely absorbed) across the entire map. Note that this map mimics the continuum map (Fig. 2*b*), since the lower limit calculated at all points τ_{min} varies as ln (S_{cont}). (*d*) Model opacity map showing absorption that is optically thick at all positions in the map *except* at the position of Sgr A*, where it is optically thin (no absorption). Note the similarity of this model map to the actual opacity map (Fig. 2*a*), supporting the suggestion that Sgr A* is not being absorbed by this HCO^+ gas. The resolution of the observations is displayed in the lower right-hand corner of this map.

the [Ne II] data (Serabyn et al. 1988) at positions about 6″ south and 5″ west of Sgr A*. These positions are very near the positions of peak HCO^+ opacity, suggesting that some high-velocity HCO^+ gas may be in the bar, taking part in the motions of the ionized gas.

Based on [Ne II] and hydrogen recombination line observations, the minispiral is modeled as gas that originated in the molecular ring and has been ionized as it falls in toward the dynamical center of the Galaxy (Serabyn et al. 1988). In this model, the ionized gas was molecular at one time and therefore may still contain molecules. Recent measurements of the 63 μm line of [O I] (Jackson et al. 1992) have shown that there is neutral material within the inner radius of the molecular ring, indicating that the central cavity is not completely ionized. Additionally, high-resolution maps (1″ resolution) of the 12.4 μm dust emission from the Galactic center (Gezari & Yusef-Zadeh 1991; Aitken et al. 1991) show that the dust emission reproduces most of the minispiral and is therefore well mixed with the ionized gas. This dust may provide both shielding from the far-ultraviolet (FUV) photons for the survival of molecules in the gas streamers, as well as a source of molecules. If we associate the source of the FUV radiation with Sgr A*, then Sgr A* must be behind, but above in projection, both the ionized gas and the molecules.

In the models of Serabyn et al. (1988) the closest approach of the infalling gas to the central mass concentration is 0.2 pc. The total luminosity of the Galactic center is between 6×10^6 and 2×10^7 $L_\odot$ (Becklin, Gatley, & Werner 1982; Davidson et al. 1992). Assuming that approximately half that radiation will be emitted at FUV wavelengths (Hollenbach 1990), the FUV flux at a distance of 0.2 pc is $G_0 = 2 - 5 \times 10^6$ expressed in units of the interstellar radiation field (1.6×10^{-3} ergs cm^{-2} s^{-1}; Tielens & Hollenbach 1985).

The main production mechanism for HCO^+ in dense gas is via the reaction

$$H_3^+ + CO \rightarrow HCO^+ + H_2$$

(Elitzur 1983), which requires the presence of CO. To shield CO from destruction by a UV field of strength G_0 = 2–5 × 10^6 requires a column density of shielding material of 10^{22} cm (van Dishoeck & Black 1988; Tielens & Hollenbach 1985; Bohlin, Savage, & Drake 1978).

The density in the molecular ring is $\approx 10^5$ cm^{-3} (Genzel et al. 1985; Harris et al. 1985), while the electron density in the dense clumps of ionized gas is 5×10^4 cm^{-3} (Lo & Claussen 1983). At a density of 10^5 cm^{-3}, the minimum thickness of shielding material required to protect CO from destruction is 10^{17} cm, or less than 1″ for R_0 = 8.5 kpc. Inspection of the map of Lo & Claussen (1983) reveals that, with 1″ resolution, the ionized filaments are well resolved, with thicknesses of the order of a few arcseconds. Since the calculation above for the amount of dust needed for sufficient shielding was done for the distance of closest approach to the ionizing source, the required thickness will decrease at larger distances. Thus, it may be possible for molecules to exist quite near the source of UV radiation in the Galactic center. Clearly, further observations of this high-velocity molecular gas in both emission and absorption, which we have initiated, are needed to develop a more complete model.

5. CONCLUSIONS

The high-resolution (8$''$.5 × 4$''$) HCO^+ opacity structure of high-velocity blueshifted gas (-200 to -172 km s^{-1}) seen in the direction of the Galactic center appears deficient in the direction of Sgr A* relative to that at the surrounding positions. The HCO^+ peak opacity positions coincide with the positions of [Ne II] emission at these velocities (Serabyn et al. 1988), suggesting that at least some of this molecular gas is mixed with the ionized gas in the central parsec, particularly in the bar. Simple calculations show that, although the far-ultraviolet flux from the central luminosity source is quite high ($\approx 10^7$ $L_{\odot}$), shielding by dust, found to exist in the ionized minispiral (Aitken et al. 1991; Gezari and Yusef-Zadeh 1991), may be sufficient for the survival of molecules very close (0.2 pc) to the ionizing source.

Future studies of the molecular gas in the central parsec should yield important information about the kinematics of this gas. We are obtaining high-resolution observations of molecules seen in emission, such as CO, which will not be limited to the areas of significant continuum, and will allow a more detailed investigation of the geometry and physical conditions of this unusual gas.

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