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DETECTION OF 1720 MHz HYDROXYL MASERS AT THE GALACTIC CENTER: EVIDENCE FOR SHOCK-EXCITED GAS AND MILLIGAUSS FIELDS

F. Yusef-Zadeh
Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208; zadeh@ossenu.astro.nwu.edu
D. A. Roberts
National Center for Supercomputing Applications, 405 N. Mathews Avenue, Urbana, IL 61801; droberts@sirius.astro.uiuc.edu
W. M. Goss and D. A. Frail
National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801; mgoss@aoc.nrao.edu, dfrail@aoc.nrao.edu
and
A. J. Green
School of Physics, University of Sydney, A28, Sydney, NSW 2006, Australia; agreen@physics.usyd.edu.au

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ABSTRACT

Radio observations of the Sgr A region have been carried out at the 1720 MHz transition of the OH molecule, using the Very Large Array and the Australia Telescope Compact Array. OH(1720 MHz) maser emission is detected at seven different positions within a few arcminutes of the Galactic center. Most of the masers are located to the southeast of Sgr A*, at the boundary of the Sgr A East nonthermal source with the M$-$0.02$-$0.07 molecular cloud. One maser is located within the circumnuclear disk (CND), and another may arise as the result of an expansion of Sgr A East into molecular gas to the northwest of Sgr A*. It is likely that these maser features are excited by the interaction of shocks in the Galactic center with adjacent molecular gas. Significant circular polarization is observed toward 10 distinct spectral components in the seven maser spots; if the V signal is due to Zeeman splitting, preliminary measurements of strong fields [local line-of-sight components of $\boldsymbol{B}$ ($B_{\rm LOS}$) are estimated to be between 2 and 4 mG] are inferred toward all sources. The direction of these magnetic fields is positive for all masers except the CND maser, which is negative. The potential for these maser features as a diagnostic of shocked gas in the Galactic center is discussed.

Subject headings: galaxies: ISM — Galaxy: center — ISM: individual (Sgr A East, Sgr A West) — ISM: magnetic fields

1. INTRODUCTION

The study of shocked gas and magnetic fields is important to our understanding of the nature of star formation and gas-dynamics in the Galactic center region. Because of the number of nonthermal and thermal features that coexist in this region, it is expected that shock activity increases at the boundary, where energetic features physically interact with each other. Shocks driven into the molecular gas clouds by the ram pressure of supernova remnants (SNRs) or winds are considered to be important in two prominent molecular features in the Galactic center: the circumnuclear disk (CND) and the Sgr A East molecular cloud. However, there is little direct evidence of such interaction in these clouds (Burton & Allen 1992; Pak, Jaffe, & Keller 1996). There is considerable evidence that the magnetic fields are strong near the Galactic center (see Genzel, Hollenbach, & Townes 1994; Morris 1994). Here again there are very few Zeeman measurements of the Galactic center that indicate positive detection of the magnetic fields with high signal-to-noise ratio (S/N) (Killeen, Lo, & Crutcher 1992; Plante, Lo, & Crutcher 1995; Marshall, Lasenby, & Yusef-Zadeh 1995).

Direct measurement of the shocked gas and of the magnetic field is quite difficult in the Galactic center region because of (1) the broad line widths of molecular clouds (Bally et al. 1988), (2) the large number of unrelated velocity features along the line of sight, and (3) an intense UV radiation field exciting the high-density H_2 in a photodissociation region (Sternberg & Dalgarno 1989; Pak et al. 1996), making it difficult to use the infrared lines as a shock diagnostic. Recently, the 1720 MHz transition of OH has come to be recognized as the source of an important class of masers for studying the interaction of shocks with molecular clouds (Frail, Goss, & Slysh 1994; Frail et al. 1996). Studies of SNRs in our Galaxy have shown shock-excited maser features in a number of objects that appear to be interacting with adjacent molecular clouds. The OH(1720 MHz) maser line traces molecular shocks at gas densities on the order of 10^3–10^5 cm^{-3} (Elitzur 1976). Their high surface brightness over a narrow line width makes their identification simple, and Zeeman splitting can, in principle, be measured with a high S/N.

The 1720 MHz transition of OH line received comparatively little attention in the Galactic center region until Yusef-Zadeh, Uchida, & Roberts (1995a) used the VLA to observe the supernova remnant G359.1$-$0.5, which had been shown by Uchida et al. (1992) to be surrounded by a ring of molecular gas. The ease with which such masers were detected, both along the edge of the SNR and where a nonthermal filament crossed the remnant, suggested that further searches for the OH(1720 MHz) maser line would be fruitful. In this Letter, we present the detection of 1720 MHz masers at the interface of two prominent continuum features, Sgr A East and Sgr West, with their corresponding molecular clouds.

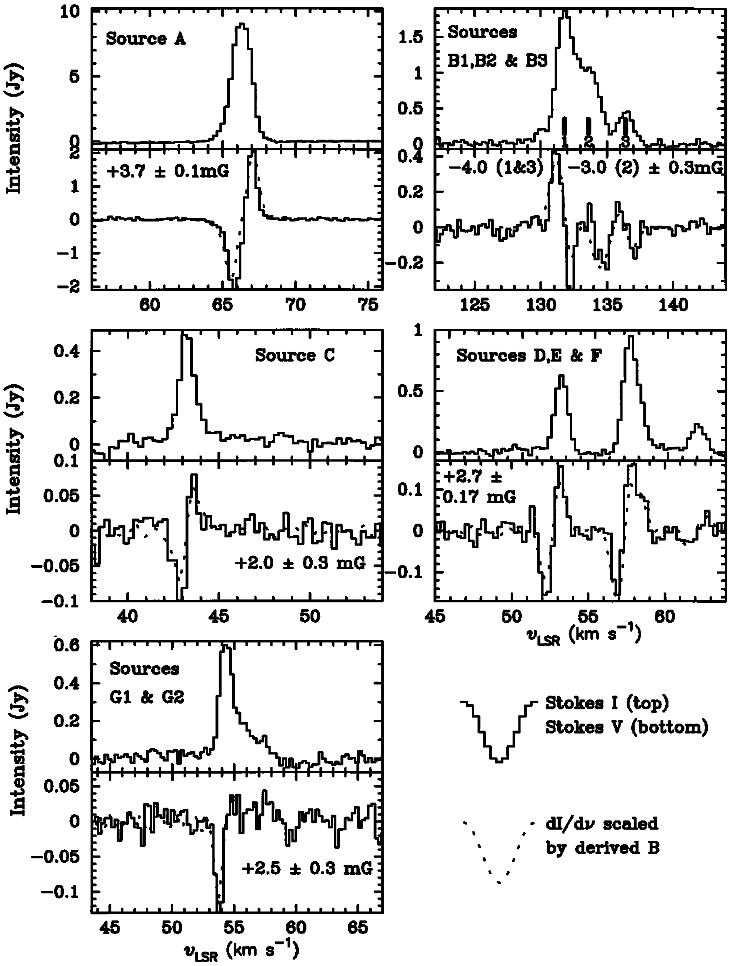

FIG. 1.—Profiles of Stokes I (*upper histograms*) and V (*lower histograms*) in the OH(1720 MHz) line for our maser detections. The dotted lines superposed on the V spectra are the derivatives of the I spectrum scaled by the magnetic fields listed in Table 1. For spectra containing more than one feature, the I spectrum is decomposed into several Gaussian components, and independent fields were fitted to each component.

2. OBSERVATIONS

Three separate observing runs were conducted toward the Galactic center with the Very Large Array (VLA) of the National Radio Astronomy Observatory[1] and the Australia Telescope Compact Array (ATCA).[2] The first set was made with the VLA in 1995 February in the compact DnC configuration. Details are given in Yusef-Zadeh et al. (1995a). The ATCA observations made in 1995 August, with the array in its long-baseline configuration (6 km), employed a single 4 MHz bandwidth and 1024 channels in each of two directions of linear polarization (see Frail et al. 1996 for further details). The velocity coverage was from −430 km s^{-1} to +230 km s^{-1}, with a velocity resolution (after Hanning smoothing) of 1.36 km s^{-1} and a synthesized beam of approximately 8″.

The confirmation of the maser candidates was carried out in 1996 January and February with the VLA in the CnD and C configurations. The observing mode employed is detailed in Frail et al. (1996). In short, the right (RCP) and left (LCP) hands of circular polarization were measured with a 195.3 kHz bandwidth and 128 channels, yielding a velocity resolution of 0.27 km s^{-1} (after Hanning smoothing), a synthesized beam of ~15″, and an rms noise in the final spectra of ~15 mJy beam^{-1}. Stokes I [=(RCP + LCP)/2] and V [=(RCP − LCP)/2] spectra were formed for each of the maser candidates. Figure 1 shows each of our detections while Table 1 contains the results of Gaussian fitting to their peaks and line profiles. We believe that these emitting features are masers because their narrow line widths (~1–3 km s^{-1}) are roughly an order of magnitude less than the line widths of molecular clouds in the Galactic center region (Bally et al. 1988). Furthermore, OH features distributed toward the strong continuum in the Galactic center are generally seen in absorption rather than emission (Killeen et al. 1992). It is unlikely that these 1720 MHz masers originate in compact H II regions since we also searched for main-line emission (1665 and 1667 MHz), a hallmark of such regions, but failed to detect any spectral features above 20 mJy.

All masers show significant signal in the Stokes V profiles. The coincidence, within our beam size, on the sky of the emission in RCP and LCP suggests the V signal is due to the Zeeman effect. Given our relatively low angular resolution (15″), it remains possible that the Zeeman effect gives rise to polarized features, and the inferred magnetic field by pairing up features is not always certain. Followup observations at

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[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc.

[2] The Australia Telescope National Facility is operated in association with the Division of Radioastrophysics by CSIRO.

TABLE 1

GAUSSIAN FITS FOR OH(1720 MHz) MASER FEATURES

Maser Designation	α_{1950}	δ_{1950}	S_p (Jy)	$V_{\rm LSR}$ (km s^{-1})	ΔV (km s^{-1})	$B_{\rm LOS}$ (mG)
Sgr A OH1720:A (66)	17 42 33.63	−29 00 09.6	9.55	+66.3	1.57	+3.7 ± 0.1
Sgr A OH1720:B1 (132)	17 42 29.96	−28 58 35.0	1.77	+131.8	1.46	−4.0 ± 0.3
Sgr A OH1720:B2 (134)	···	···	1.07	+133.6	2.01	−3.0 ± 0.3
Sgr A OH1720:B3 (136)	···	···	0.46	+136.4	1.25	−4.0 ± 0.3
Sgr A OH1720:C (43)	17 42 28.07	−28 58 32.3	0.46	+43.3	1.1	+2.0 ± 0.3
Sgr A OH1720:D (53)	17 42 32.51	−29 00 26.1	0.63	+52.7	1.1	+2.7 ± 0.2[a]
Sgr A OH1720:E (56)	17 42 32.65	−29 00 23.3	0.91	+57.5	1.3	+2.7 ± 0.2[a]
Sgr A OH1720:F (62)	17 42 32.48	−29 00 25.1	0.22	+62.1	1.1	+2.7 ± 0.2[a]
Sgr A OH1720:G1 (54)	17 42 30.77	−29 00 38.5	0.52	+54.3	1.0	+2.5 ± 0.3
Sgr A OH1720:G2 (56)	···	···	0.18	+55.5	3.2	(1.0)[b]

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Three components fitted simultaneously.

[b] Upper limit of 3 σ.

higher angular resolution are needed before this can be fully discounted. Nevertheless, here we assume that the V signal is due to the Zeeman effect, that the splitting is less than the Doppler line width, and that saturation effects are not important. The magnetic field is derived numerically using $V = C(dI/d\nu)$, where $C = 0.6536 B_{\rm LOS}$ Hz μG^{-1} (Roberts et al. 1993). The dotted lines in the lower panels of the spectra in Figure 1 are the derivatives of the respective I spectra, scaled by the derived local line-of-sight magnetic fields $B_{\rm LOS}$ listed in Table 1. We note that Elitzur (1996) has recently argued that the 1720 MHz OH masers discussed in this Letter are saturated; thus the inferred magnetic field strengths shown in Table 1 are preliminary and subject to further study.

3. RESULTS AND DISCUSSION

The locations of the newly discovered maser features are shown as crosses in Figure 2 (Plate L4), superposed on a $\lambda = 6$ cm continuum image of the Sgr A region from Pedlar et al. (1989). The peak emission comes from Sgr A*, the compact nonthermal source at the Galactic center. The 2′ spiral-shaped thermal structure Sgr A West can be seen, as well as the shell-like nonthermal feature Sgr A East that surrounds Sgr A*. All the masers are distributed either along the southeastern edge of Sgr A East or to the northwest of Sgr A West. We suggest below that the masers with velocities between +43 and +65 km s^{-1} (see Table 1) are physically associated with Sgr A East whereas the +134 km s^{-1} velocity feature is related to the thermal feature Sgr A West.

3.1. *Sgr A East and the M−0.02−0.07 Molecular Cloud*

The faint, partial shell to the east of Sgr A* is known as Sgr A East and is thought to be a supernova remnant located just behind the Galactic center (Yusef-Zadeh & Morris 1987; Pedlar et al. 1989). It should be noted, however, that Khokhlov & Melia (1996) and Mezger et al. (1989) have questioned the interpretation of Sgr A East as a standard SNR. The 1720 MHz masers in Figure 2 that have radial velocities between +52.7 and +66.3 km s^{-1} are located at the southeastern boundary of Sgr A East and the molecular cloud M−0.02−0.07 and lie on a line with a velocity gradient of ≈12 km s^{-1} arcmin^{-1}. These velocities are in rough agreement with the kinematics of this region as seen in H I absorption and CS line studies (Serabyn, Lacy, & Achtermann 1992; Lasenby, Yusef-Zadeh, & Lasenby 1989). Another maser, at $V_{\rm LSR} = +43$ km s^{-1}, located at the northwest boundary of Sgr A East has a velocity similar to that of masers located at the southeast boundary. The orientation and strength of the magnetic field of the +43 km s^{-1} feature are also similar to those masers observed to the southeast of Sgr A East. These striking kinematic and magnetic field similarities of this group of masers, all of which are located at the boundary of the nonthermal shell, strongly suggest that these masers are associated with the molecular cloud M−0.02−0.07. In this picture, the radial velocities of the masers to the southeast and northwest of Sgr A East are redshifted and blueshifted, respectively, with respect to the undisturbed +50 km s^{-1} M−0.02−0.07 molecular cloud.

The well-known +50 km s^{-1} giant molecular cloud M−0.02−0.07 has been interpreted by many to be interacting with the eastern half of the nonthermal Sgr A East (Zylka, Mezger, & Wink 1990; Lasenby et al. 1989; Mezger et al. 1989). The expansion of Sgr A East is considered to be responsible for inducing star formation, as evidenced by the chain of four compact H II regions (Ekers et al. 1983; Goss et al. 1985; Ho et al. 1985) (an alternative view is stated by Serabyn et al. 1992 on the origin of H II regions near Sgr A East). A north-south CS ridge is also seen at the eastern edge of Sgr A East, with a velocity gradient of ∼5–6 km s^{-1} arcmin^{-1} and a peak density of ≈10^6 cm^{-3} (Serabyn et al. 1992). The distribution of OH(1720 MHz) maser features with velocities near +50 km s^{-1} suggests that Sgr A East is surrounded by the molecular cloud M−0.02−0.07 not only to the southeast but also to the northwest. The +43 km s^{-1} maser is particularly interesting in that it provides the first evidence of molecular gas, as seen in emission, surrounding the western half of Sgr A East.

The environment of the Sgr A East region is reminiscent of the W28 region, where an expanding SNR is interacting with a molecular cloud (Frail et al. 1994). Thus the OH(1720 MHz) maser emission from the boundary of Sgr A East and M−0.02−0.07 can be understood as arising from the expansion of the Sgr A East SNR, which drives a shock into the M−0.02−0.07 molecular cloud, compressing the gas and exciting the OH maser emission. This is also consistent with the interpretation that the expanding SNR is also responsible for compressing M−0.02−0.07 into a sheetlike geometry, as seen along the north-south CS ridge at the boundary of the Sgr A East shell. A C-type shock from the expansion of the SNR may be responsible for collisionally pumping the OH(1720 MHz) maser (see Elitzur, Hollenbach, & McKee

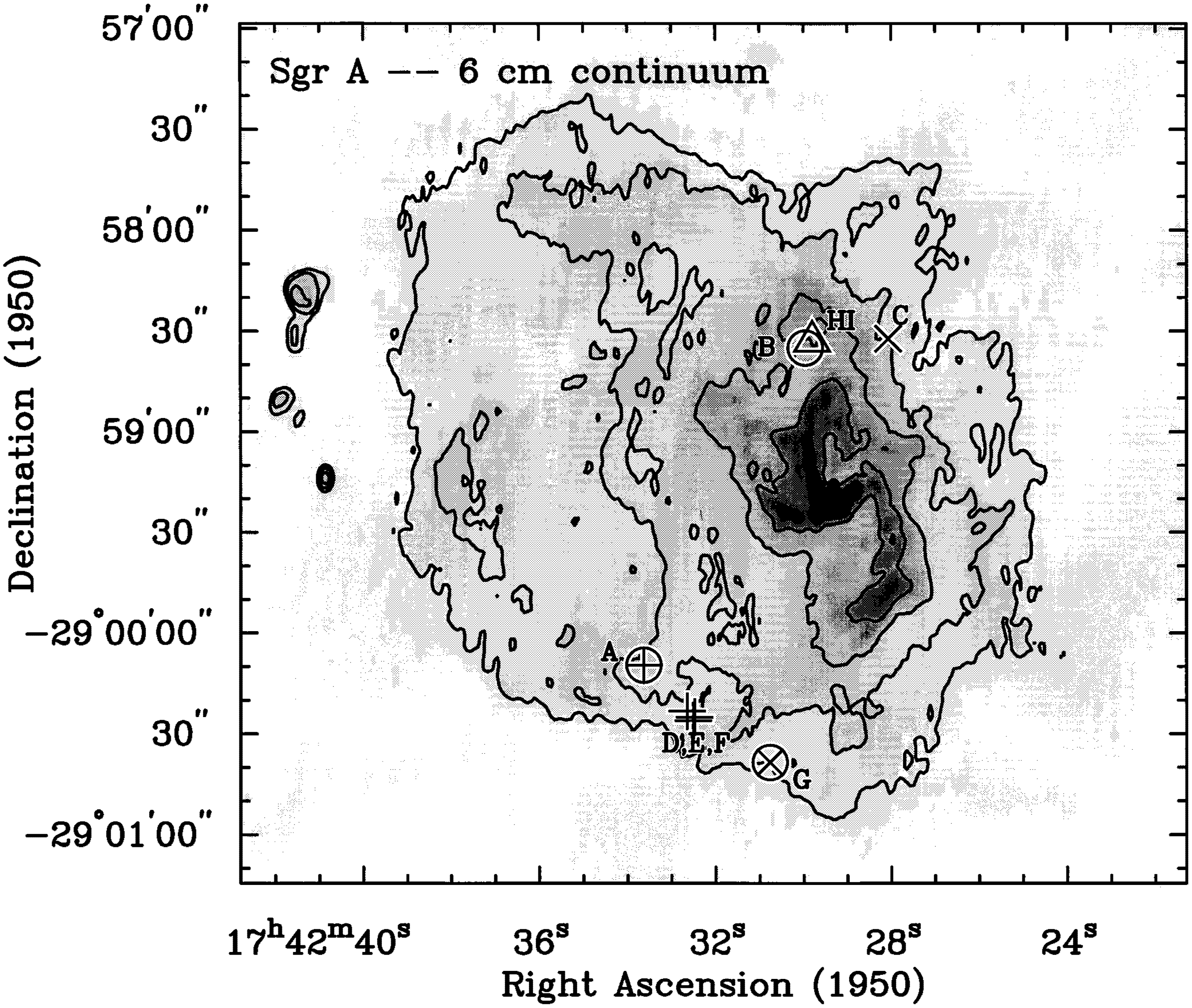

FIG. 2.—Continuum image of the Sgr A region at λ = 6 cm from Pedlar et al. (1989) with a spatial resolution of 3".7 × 3".2, showing the location of the OH(1720 MHz) maser features. The individual A, B, C, and G masers are designated by a circled plus sign, circle, cross, and circled cross, respectively. The three plus signs show the location (from east to west) of the D, E, and F masers. The position of the H I Zeeman splitting measurements at +130 km s^{-1} by Plante et al. (1995) is also shown (*triangle*).

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1989). A substantial magnetic field of +3.7 ± 0.1 mG is inferred from the detection of a Zeeman signal. This large field strength suggests that the shock must also have compressed the gas and the field lines.

3.2. *The Circumnuclear Disk*

Also shown in Figure 2, due north of Sgr A*, is the location of the high-velocity maser feature, which consists of at least three different velocity components near +134 km s^{-1}. This maser line coincides with a region of weakly emitting ionized gas between the eastern and northern arms of Sgr A West. High-resolution H I absorption studies also show atomic H I gas at this location with similar radial velocity (Plante et al. 1995). These observations are consistent with the picture that the H I gas, the ionized gas (Yusef-Zadeh, Zhao, & Goss 1995b), and the 1720 MHz masing gas all arise from the same region and are all associated with each other.

The magnetic field of the +134 km s^{-1} maser feature has a strength of −4 mG (for components 1 and 3), which is the strongest field detected at the Galactic center. In addition, the magnetic field is oriented differently from the rest of the Sgr A East masers. The polarization and kinematic characteristics of the +134 km s^{-1} feature indicate that the components of this high-velocity feature are distinct from the rest of the masers associated with the Sgr A East shell. We argue below that the +134 km s^{-1} feature is physically associated with the CND.

The CND, which consists of an inclined disk of orbiting gas, is traced by the distribution of HCN (1–0) and [O I] line emission (Güsten et al. 1987; Jackson et al. 1993) and extends from 1.5 to ~7 pc from the Galactic center. Within the inner edge of the CND, the ionized gas associated with Sgr A West dominates this region. The maser feature is located where there is a gap in the distribution of the highest density gas traced by HCN emission. The CND is known to orbit the Galactic center with a rotational velocity of about +110 km s^{-1}, but at the maser's location the kinematics of HCN and [O I] gas deviates from circular geometry (Jackson et al. 1993). H110α observations also indicate an elongated feature at velocities ranging up to +144 km s^{-1} near the position where the 1720 MHz maser is noted at +134 km s^{-1}. The ionized feature, known as the Northwestern Streamers, extends beyond the CND, and its kinematics is also inconsistent with circular motion around the Galactic center (Yusef-Zadeh & Morris 1987; Yusef-Zadeh et al. 1995b).

This maser also appears to be located in a region of the CND with unusual magnetic field properties. H I observations reveal Zeeman splitting of the +130 km s^{-1} absorbing line located within a few arcseconds of the +134 km s^{-1} maser feature. The magnetic field strength inferred from the H I data is estimated to be about −3.0 ± 0.5 mG near the location of the OH(1720 MHz) maser (Plante et al. 1995). The strength and the orientation of the magnetic field based on H I and the OH(1720 MHz) maser emission are quite consistent with each other. The agreement between these two very different measurements is remarkable in that the physical conditions (e.g., the size and density) of the OH(1720 MHz) masing gas and the thermal H I gas are quite different from each other. Far-IR polarization observations of this region are also noted for their field orientation (Hildebrand & Davidson 1994). The geometry of the magnetic field is inferred from far-IR polarization measurements (Hildebrand & Davidson 1994) as showing a distribution that is quite similar to mid-IR polarization measurements along the northern arm (Aitken et al. 1991). This geometry differs from that predicted by an axisymmetric model in which the CND magnetic field is dominated by circular motion (Hildebrand & Davidson 1994).

These peculiar kinematic, morphological, and magnetic characteristics of the molecular gas of the CND and the OH(1720 MHz) maser gas in the same region strongly indicate that these features are related to each other. Because of the location of Sgr A East, behind the Galactic center, it is difficult to interpret the excitation of the +134 km s^{-1} feature as being driven by the supernova shock. Thus we suggest that the maser feature is excited by a shock resulting from an interaction between the gas in the CND and a distinct cloud having a peculiar motion in the Galactic center. This peculiar-moving redshifted cloud is likely to follow an orbit that becomes highly blueshifted as it approaches the Galactic center. In this picture, the highly blueshifted molecular and atomic gas clouds (e.g., H_2CO, HCO^+, H I, and OH) distributed close to Sgr A* (Marr et al. 1992; Pauls et al. 1993; Yusef-Zadeh et al. 1995b; Yusef-Zadeh 1994; Zhao, Goss, & Ho 1995), as well as the redshifted [O I] (Jackson et al. 1993) and OH(1720 MHz) gas clouds distributed closer to the CND, are likely to be part of a coherent feature orbiting the Galactic center. The +134 km s^{-1} maser is considered to be part of a cloud that is an extension of the neutral gas observed between the northern and eastern arms (Jackson et al. 1993; Yusef-Zadeh et al. 1995b; Telesco, Davidson, & Werner 1996). The molecular species closer to the Galactic center have velocities ranging between −150 and −180 km s^{-1} whereas clouds closer to the CND have velocities ranging from +70 to +140 km s^{-1}. These two velocity features could be part of the orbiting cloud whose interaction with the CND has resulted in the +134 km s^{-1} OH maser feature.

4. SUMMARY

We have detected OH(1720 MHz) masers near the boundary of the Sgr A East shell and the CND at the Galactic center. Based on kinematic, morphological, and magnetic field studies, we have been able to distinguish masers associated with the Sgr A East shell and with the CND and have presented the first evidence for molecular gas emission from the western half of the Sgr A East shell. A strong magnetic field, ranging between −4 ± 0.3 and +3.7 ± 0.1 mG, is inferred from the detection of Zeeman signals from almost all of the detected masers. These observations reveal for the first time regions where gas is presently being shocked at the Galactic center. We believe that the expansion of the Sgr A East shell is responsible for driving a shock into the M−0.02−0.07 molecular cloud, compressing the gas and exciting the OH(1720 MHz) masers. A readily identifiable shock to account for the maser emission from the CND is not present, but we suggest that an interaction may be taking place between the gas in the CND and a distinct cloud having a peculiar motion in the Galactic center. Future high-resolution OH(1720 MHz) and 2.122 μm H_2 observations make it potentially important to map the distribution of the shocked gas and the magnetic field in M−0.02−0.07 and in the CND. In addition, proper-motion studies of the maser spots have the potential to distinguish the infall and outflow models of the gas clouds at the Galactic center.

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