1. INTRODUCTION

Detailed knowledge of the gaseous environment in the Galactic center (GC) is of vital importance in understanding the wide range of extraordinary phenomena that have recently taken place and are currently taking place there. For several decades many well-known atomic and molecular species have been used as probes to help characterize that environment. In the last decade, a newly discovered species, H$_3^+$, found in interstellar clouds 18 yr ago (Geballe & Oka 1996) and toward the GC one year later (Geballe et al. 1999), has proven to be a unique and valuable tool in this endeavor.

The simple chemistry of H$_3^+$, i.e., its production through ionization of H$_2$ (mainly either by cosmic rays or X-rays) followed by the rapid proton hop reaction H$_2$ + H$_+$ → H$_3^+$ + H and its destruction, in diffuse clouds by recombination with electrons H$_3^+$ + e$^-$ → H + H + H or H + H$_2$ and in dense clouds by reaction primarily with CO, allows one to reliably determine the product $\zeta L$, where $L$ is line of sight dimension of the cloud, and $\zeta$ is the ionization rate of H$_2$. In addition, column densities of H$_3^+$ in its low rotational levels are useful for measuring the temperature $T$ and number density $n$ of the gas (Oka & Epp 2004; Oka et al. 2005; Oka 2006).

Previous studies of H$_3^+$ in the GC have revealed the presence there of a vast amount of warm ($T \sim 250$ K) and diffuse ($n \lesssim 100$ cm$^{-3}$) gas (Oka et al. 2005; Goto et al. 2008) and an unusually high ionization rate, on the order of $\zeta \sim 10^{-15}$ s$^{-1}$. The presence of so much H$_3^+$ requires a drastic change in our understanding of the physical states and volume filling factors of the gas in the Central Molecular Zone (CMZ; Morris & Serabyn 1996; Lazio & Cordes 1998), the name given to the region of radius $\sim 200$ pc at the center. The high ionization rate required to account for the large column density of H$_3^+$ is potentially important for understanding the overall energetics of the GC. A high ionization fraction and an elevated gas temperature may help to explain the current low star-forming efficiency in the CMZ (Yusef-Zadeh et al. 2007; Yusef-Zadeh et al. 2007). Whatever its cause, the high gas kinetic temperature may help to explain the current low star-forming efficiency in the CMZ (Yusef-Zadeh et al. 2007; Yusef-Zadeh et al. 2007).
Of the previously studied 15 lines of sight within 3 pc of the Galactic plane and longitudinally distributed from the Central Cluster, within 1 pc of the central black hole, Sgr A*, to the Quintuplet Cluster 30 pc east of Sgr A* (l ≈ 0:18; Goto et al. 2008; T. Oka 2014, private communication), the one toward GCIRS 3, located only a few arcseconds from Sgr A* (Figure 1), is exceptional. While all 15 sightlines show prominent absorption by H$_3^+$ in its R(1, 1)$^f$ and R(3, 3)$^f$ lines, indicating high H$_3^+$ populations both in the lowest (J, K) = (1, 1) level and the (3, 3) metastable level 361 K above ground, the R(2, 2)$^f$ line is prominent only on the sightline toward GCIRS 3, over a velocity range centered near +50 km s$^{-1}$ (Goto et al. 2008). Since the (2, 2) level spontaneously decays to ground (1, 1) (Pan & Oka 1986) with a lifetime of 27 days (Neale et al. 1996), the density in the gas producing this absorption must be considerably higher than in other regions of the CMZ observed to date. This gas is likely to be in the form of a compact cloud, since the sightline toward GCIRS 1W, which is only 8′′ away from GCIRS 3 (0.33 pc, assuming equal radial distances of 8 kpc; Eisenhauer et al. 2003; Ghez et al. 2008), produces a much weaker R(2, 2)$^f$ absorption line.

In this paper, we present, analyze, and discuss new and improved spectra of H$_3^+$ toward GCIRS 3 and GCIRS 1W, as well as CO ro-vibrational transition spectra toward them and few other objects in the Central Cluster and the Quintuplet Cluster. The velocity resolution of the CO spectra is higher by factors of ~5–100 than previous studies of the CO fundamental band lines toward these objects (Geballe et al. 1989; Moneti et al. 2001; Moultaka et al. 2009). The ratio of the column densities N(CO)/N(H$_3^+$) is invariably much lower in diffuse clouds (n < 300 cm$^{-3}$) than dense clouds. Thus, observations of both species help to discriminate between dense and diffuse environments.

2. OBSERVATIONS

The observations consisted of high resolution infrared spectroscopy of several GC sources using spectrographs at the Very Large Telescope (VLT) at Paranal in Chile and the Subaru Telescope on Mauna Kea in Hawai‘i. A summary of the observations is given in Table 1.

2.1. CRIRES/VLT

Spectra of H$_3^+$ lines toward GCIRS 3 and GCIRS 1W were obtained using CRIRES (Käufl et al. 2004) at the VLT on several occasions in 2007 June and August in an open time program (079.C-0874). The CRIRES 0′/2 wide slit, oriented at position angle 113° so that GCIRS 3 and GCIRS 1W could be observed simultaneously, provided a velocity resolution of 3 km s$^{-1}$. The adaptive optics system MACAO (Bonnet et al. 2004) was used with a R = 13.5 mag star 17′′ distant from GCIRS 1W as the wavefront reference. The R(1, 1)$^f$ (3.71548 μm), R(2, 2)$^f$ (3.62047 μm), and R(3, 3)$^f$ (3.53366 μm) lines were observed separately using three grating settings.

Spectra of CO toward GCIRS 3, GCIRS 1W, GCIRS16 NE, GCIRS 21 (all members of the Central Cluster; Figure 1), and the Quintuplet Cluster source GCS 3-2 were obtained between 2006 October and 2007 September in service observing mode during science verification time for CRIRES (60.A-9057) as well as in the open time program (079.C-0874), using the same adaptive optics set-up as described above and an R = 15 mag star 8′′ away from GCS 3-2 as a wavefront reference for that object. The $^{12}$CO ν = 2–0 overtone band, which has been used by us previously (Oka et al. 2005) was observed for GCIRS16 NE, GCIRS 21, and GCS 3-2, but not for GCIRS 3 and GCIRS 1W, since those objects are faint in the K-band; for them the fundamental band ν = 1–0 was observed. For the overtone band, the spectral range 2.292–2.356 μm was covered in two grating settings, allowing measurements of all R-branch lines and the P(1)–P(4) lines. For the fundamental band, the spectral range 4.692–4.809 μm was observed in two grating settings covering the P(3) to P(15) lines of $^{12}$CO ν = 1–0 and the R(9)–R(0) and P(1)–P(4) lines of $^{13}$CO ν = 1–0. The $^{12}$CO ν = 1–0 lines are heavily saturated and have not been analyzed, unless otherwise...
### Summary of Observations

| Object      | UT Date       | Instrument/Telescope | Lines                  | Grating<sup>a</sup> | Spectral Resolution | Exp.<sup>b</sup> | Standard |
|-------------|---------------|----------------------|------------------------|----------------------|---------------------|---------------|----------|
| GCIRS 3/GCIRS 1W | 2006 Oct 11   | CRIRES/VLT           | 12CO v = 1–0          | 12/1/n               | R = 50000            | 1             | HR 6879  |
| GCIRS 3/GCIRS 1W | 2006 Oct 11   | CRIRES/VLT           | 12CO v = 1–0          | 12/1/i               | R = 50000            | 1             | HR 6879  |
| GCIRS 3/GCIRS 1W | 2007 Jun 9, Aug 4–5 | CRIRES/VLT           | H2 R(1, 1)            | 3739.4               | R = 100000           | 108           | HR 6879  |
| GCIRS 3/GCIRS 1W | 2007 Aug 5, 9, 10 | CRIRES/VLT           | H2 R(2, 2)            | 5646.1               | R = 100000           | 126           | HR 6879  |
| GCIRS 3/GCIRS 1W | 2007 Aug 10, 28 | CRIRES/VLT           | H2 R(3, 3)            | 5533.6               | R = 100000           | 108           | HR 6879  |
| GCIRS 16NE/GCIRS 21 | 2007 May 13   | CRIRES/VLT           | 12CO v = 2–0          | 2239.2               | R = 100000           | 40            | HR 6879  |
| GCIRS 16NE/GCIRS 21 | 2007 May 14   | CRIRES/VLT           | 12CO v = 2–0          | 2336.2               | R = 100000           | 40            | HR 6879  |
| GCS 3-2     | 2007 Sep 15   | CRIRES/VLT           | 12CO v = 2–0          | 2239.2               | R = 100000           | 16            | HR 6879  |
| GCS 3-2     | 2007 Sep 15   | CRIRES/VLT           | 12CO v = 2–0          | 2336.2               | R = 100000           | 16            | HR 6879  |
| GCS 3-2     | 2008 Jul 27   | CRIRES/VLT           | H2 v = 1–0 S(0)       | 2236.1               | R = 100000           | 80            | HR 6879  |
| GCS 3-2     | 2007 Oct 15   | CRIRES/VLT           | H2 v = 1–0 S(1)       | 2117.6               | R = 100000           | 40            | HR 6879  |
| GCS 3-2     | 2008 Aug 17   | CRIRES/VLT           | H2 v = 1–0 S(1)       | 2117.6               | R = 100000           | 40            | HR 6879  |
| GCS 3-2     | 2003 May 24   | IRC/SUBARU           | H2 v = 1–0 S(0)       | 4300/200              | R = 20000            | 60            | HR 7557, HR 7194 |

Notes.

<sup>a</sup> For CRIRES these are reference wavelength in nanometers, or grating setting name for 2006 observations only. For IRCs the entry is echelle and cross-disperser angle.

<sup>b</sup> Total integration time in minutes.

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noted. The 0′4 slit was used for GCIRS 3 and GCIRS 1W while the 0′2 slit was used for the other objects, resulting in velocity resolutions of 6 km s<sup>−1</sup> and 3 km s<sup>−1</sup>, respectively. The early-type star HR 6879 (B 9.5III, R = 1.85 mag) was observed before or after each GC object as a telluric standard.

Spectra of GCS 3-2 were also obtained by CRIRES in the intervals 2.200–2.255 μm and 2.087–2.133 μm to search for absorption from two quadruple transitions of H2, v = 1–0 S(0) and v = 1–0 S(1), in the same open time program. The 0′2 slit was employed, resulting in a velocity resolution of 3 km s<sup>−1</sup>.

Spectra were extracted from the CRIRES data using the crieres_spec_jitter recipe<sup>8</sup> on the ESO gasgano platform.<sup>9</sup> The results were consistent with the pre-processed CRIRES spectra provided by the observatory. In some cases the latter spectra were cosmetically better and were used for analysis. Custom-written IDL code was employed to divide spectra of the GC sources by the spectra of the telluric standard to remove atmospheric absorption lines. Wavelength calibration was obtained by cross-correlating the telluric absorption lines with model atmospheric transmission spectra computed using ATRAN (Lord 1992). The uncertainty in the wavelength calibration depends on the density of telluric lines and is typically less than one pixel (≤1 km s<sup>−1</sup>). The IRAF<sup>10</sup> <em>rv</em> package was used to convert the observed wavelengths to velocities with respect to the local standard of the rest utilizing the IAU definition of the Sun’s peculiar motion.

2.2. IRC/S Subaru

The spectrograph IRC/S at the Subaru Telescope was used to obtain a spectrum of GCS 3-2 in the vicinity of the H2 ν = 1–0 S(0) line on 2003 May 24 UT. The slit width was 0′15, resulting in a velocity resolution of 15 km s<sup>−1</sup>. The adaptive optics system was used employing the same wavefront reference as for the CRIRES observations of GCS 3-2. The slit was oriented east-west. HR 7557 (R = 0.77 mag, A7 V) and HR 7121 (R = 2.02 mag, B2.5 V) were observed as telluric standard stars. Reduction of the IRC/S data was performed in the similar manner as for the CRIRES data except that the IRAF aperture extraction package was used to extract the spectra.

3. RESULTS

3.1. H<sub>2</sub><sup>+</sup>

The spectra of the three H<sub>2</sub><sup>+</sup> lines toward GCIRS 3 and GCIRS 1W shown in Figure 2 together with the spectrum of the ν = 1–0 P(1) line of 12CO. The P(1) line was selected for comparison because it is least affected by nearby telluric absorption lines and interstellar 12CO lines, as discussed in Section 3.2. The systemic radial velocity of GCIRS 1W is +35 ± 20 km s<sup>−1</sup> (Paumard et al. 2006), measured by He I absorption line at 2.06 μm (Paumard et al. 2004). The radial velocity of GCIRS 3 is not known due to the absence of photospheric lines in its spectrum.

3.1.1. Negative Velocities

At negative velocities the spectra in Figure 2 are similar to those on the sightlines toward GCS 3-2 (Oka et al. 2005; located in the Quintuplet Cluster) and NHS 21, NHS 22, NHS 25, and NHS 42 (Goto et al. 2008; located between the Quintuplet and the Central Clusters). Our interpretation of them is similar to those authors. The three sharp absorption components at −53 km s<sup>−1</sup>, −32 km s<sup>−1</sup>, and 0 km s<sup>−1</sup>, conspicuous in both the H<sub>2</sub> R(1, 1)<sup>±</sup> and 12CO P(1) profiles, are due to relatively cold and dense gas in the lateral arms at 3 kpc and 4 kpc approaching the Sun, and to foreground spiral arms, respectively. The same sets of the absorption lines have been observed in CO J = 3–2 (Sutton et al. 1990; Moneti et al. 2001) and NH<sub>3</sub> (Serabyn & Güsten 1986) toward the GC. In common with the previously observed sightlines from the Central Cluster to 30 pc east, absorption by CO 2–0 band lines at negative velocities is almost entirely due to gas in these arms. In contrast, at negative velocities the H<sub>2</sub> R(1, 1)<sup>±</sup> spectrum shows a broad and structured absorption trough upon which the three sharp absorptions due to the arms are superimposed. No absorption in the R(2, 2)<sup>±</sup> line is present, indicating that the density of the gas producing the absorption troughs in the R(1, 1)<sup>±</sup> and R(3, 3)<sup>±</sup> line profiles is low. We therefore identify the absorption trough with diffuse gas in the CMZ, as in Oka et al. (2005).

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<sup>8</sup> CRIRES Pipeline User Manual VLT-MAN-ESO-19500-4406.

<sup>9</sup> http://www.eso.org/sci/data-processing/software/gasgano

<sup>10</sup> IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
It is noteworthy that at negative velocities the $R(3, 3)^J$ absorption profile, which contains no spiral arm components, matches the shape of the $R(1, 1)^J$ trough. This similarity is clearly seen in Figure 3 in which the spectra of the $R(3, 3)^J$ line, multiplied by a factor of 1.3 for each object, are superimposed on the spectra of the $R(1, 1)^J$ line. This likeness has been noted earlier (Oka et al. 2005; Goto et al. 2008), but has not previously been seen in such detail as in Figure 3. It provides conclusive evidence that the trough in the $R(1, 1)^J$ spectrum and the $R(3, 3)^J$ spectrum arise in the same warm and diffuse gas. Indeed, the accurate match indicates remarkably that although the gas that produces the absorption trough covers a wide range of velocities and presumably thus exists over a wide range of line of sight locations within the CMZ, its temperature is nearly constant.

At negative velocities the $R(3, 3)^J$ profiles, and in particular the one toward GCIRS 1W, also contain several weak and narrow absorption features. Some of these are close to the velocities of the foreground arms and might be interpreted as indicating the presence of warm gas in the spiral arms. We do not adopt this interpretation in view of the absence of such features in the $R(3, 3)^J$ spectra on other sightlines and because close examination reveals that the velocities of the absorption peaks are not exact matches to those of the spiral arms (as observed in the CO $P(1)$ and H$_3^+$ $R(1, 1)^J$ line profiles). It may be that they arise in compact and warm regions of the circumnuclear disk (CND; Genzel & Townes 1987), the chain of molecular clouds orbiting Sgr A* at $v \sim 100$ km s$^{-1}$ at a radius of 1.5 pc (Zhao et al. 2009).

3.1.2. Positive Velocities

At positive velocities the absorption profiles of the H$_3^+$ lines toward GCIRS 3 and GCIRS 1W are qualitatively different in two ways from those toward the other GC sources outside the Central Cluster shown in Oka et al. (2005) and Goto et al. (2008). First, absorption toward other GC stars is only present to about $+30$ km s$^{-1}$, whereas absorption extends to $+60$ km s$^{-1}$ toward GCIRS 1W and to $+80$ km s$^{-1}$ toward GCIRS 3, in both the $R(1, 1)^J$ and the $R(3, 3)^J$ lines (Figure 2). Note that these velocity extents are also present in the $^{13}$CO line in this figure. Second, the sightline toward GCIRS 3 also produces strong and broad absorption features toward GCIRS 3.
absorption at positive velocities in the $R(2, 2)'$ line (from +20 to +70 km s$^{-1}$, peaking at +52 km s$^{-1}$). The only other sightline for which this line has been seen strongly is toward 2MASS J17470898–2829561, which is apparently located within the Sgr B molecular cloud (Geballe & Oka 2010; Goto et al. 2011), far removed from the central few parsecs. The $R(3, 3)'$ profile toward GCIRS 3 has two absorption maxima, at +28 km s$^{-1}$ and +52 km s$^{-1}$, whereas the $R(2, 2)'$ profile has only a single maximum near +52 km s$^{-1}$.

Only a marginal detection of the $R(2, 2)'$ absorption near +40 km s$^{-1}$ is evident toward GCIRS 1W (Figure 2, right). Assuming that both GCIRS 1W and GCIRS 3 are members of the Central Cluster (see discussion below), the large differences in the H$_2$ and $^{13}$CO line profiles at positive velocities, on sightlines separated by 0.33 pc, suggests that the cloud (or clouds) producing the $R(2, 2)'$ absorption toward GCIRS 3 is compact, with linear dimension comparable to the sightline separation, and is located close to the Central Cluster.

3.1.3. Equivalent Widths and Column Densities

As noted previously, apart from velocities near those of the spiral arms (−62 → −45 km s$^{-1}$, −37 → −25 km s$^{-1}$, and −15 → +12 km s$^{-1}$) and at positive velocities for GCIRS 3, a nearly constant scaling factor of 1.3 exists between the $R(3, 3)'$ and $R(1, 1)'$ absorption profiles, as shown in Figure 3. To estimate the strengths of the $R(1, 1)'$ absorptions originating in the CMZ in the above velocity intervals, and thus to estimate the total column densities of H$_2$ in the CMZ, we assume the same factor also applies in the above velocity intervals, multiply the $R(3, 3)'$ line profiles by 1.3, and use them as surrogates for the $R(1, 1)'$ CMZ absorptions toward these objects. This appears to be a more accurate method than the one used by Oka et al. (2005), which did not include the velocity structure in the trough that is now evident in the $R(3, 3)'$ absorption profile observed by CRIRES.

The equivalent widths of those portions of the H$_2$ absorption lines arising in the CMZ, together with the corresponding column densities of the lower levels of the transitions, are listed in Table 2 over several sub-intervals covering the entire CMZ velocity range. The column densities were calculated using $N$(H$_2$)$_{\text{level}} = (3hc/8\pi^2\lambda)W_{\lambda}/|\mu|^2$, where $|\mu|^2$, the square of the dipole moment, is 0.0141 D$^2$, 0.0177 D$^2$, and 0.0191 D$^2$ for $^{12}$CO, $^{13}$CO, and C$^{18}$O, respectively.

### Table 2

| Object    | $v_{\text{LSR}}$ (km s$^{-1}$) | $W_{\lambda}$ (10$^{-6}$ μm) | $N(J, K)$ (10$^{14}$ cm$^{-2}$) |
|-----------|-------------------------------|-------------------------------|-------------------------------|
|           |                               | $R(1, 1)'$                   | $R(3, 3)'$                   | $R(2, 2)'$                   |
| GCIRS 3   | −180 → −109                   | 9.43 ± 1.59                  | 7.49 ± 1.10                  | <2.51                        |
|           | −109 → +1$^a$                 | 21.3 ± 2.5                   | 16.4 ± 1.7                   | <4.17                        |
|           | +1 → +38$^b$                  | 2.15 ± 1.06                  | 1.48 ± 1.01                  | <1.14                        |
|           | +38 → +51$^b$                 | 0.66 ± 0.34                  | 2.02 ± 0.36                  | 1.14 ± 0.40                  |
|           | +51 → +85$^b$                 | 2.30 ± 0.98                  | 5.51 ± 0.93                  | 3.98 ± 1.10                  |
| GCIRS 1W  | −180 → −109                   | 8.91 ± 1.22                  | 6.00 ± 0.96                  | <1.67                        |
|           | −109 → +1$^a$                 | 19.2 ± 1.9                   | 14.8 ± 1.5                   | <2.62                        |
|           | +1 → +38                     | 6.58 ± 0.65                  | 5.49 ± 0.50                  | 1.04 ± 0.81                  |
|           | +51 → +1                    | 1.71 ± 0.20                  | 1.36 ± 0.15                  | 0.76 ± 0.28                  |
|           | +51 → +64                    | 0.74 ± 0.19                  | 0.46 ± 0.15                  | 0.40 ± 0.24                  |

### Notes.

$^a$ Equivalent widths of $R(1, 1)'$ at the velocity range −109 → +1 km s$^{-1}$ are calculated by scaling $R(3, 3)'$ absorption lines at the same velocity interval by the factor of 1.3 so that $R(3, 3)'$ matches to the trough absorption of $R(1, 1)'$, in order to disentangle the absorptions in the CMZ from the foreground arm clouds.

$^b$ Equivalent widths of $R(1, 1)'$, $R(3, 3)'$, and $R(2, 2)'$ toward GCIRS 1W are subtracted to isolate the local absorption components of H$_2$ toward GCIRS 3.

### Table 3

| Object    | $v_{\text{LSR}}$ (km s$^{-1}$) | $W_{\lambda}$ (10$^{-6}$ μm) | $N(J, K)$ (10$^{14}$ cm$^{-2}$) |
|-----------|-------------------------------|-------------------------------|-------------------------------|
|           |                               | $R(1, 1)'$                   | $R(3, 3)'$                   | $R(2, 2)'$                   |
| GCIRS 3   | −62 → −45                     | 2.95 ± 0.72                  | 1.35 ± 0.33                  |
|           | −37 → −25                     | 0.78 ± 0.51                  | 0.36 ± 0.23                  |
|           | −15 → +12                     | 6.57 ± 1.17                  | 3.01 ± 0.54                  |
| GCIRS 1W  | −62 → −45                     | 3.61 ± 0.57                  | 1.66 ± 0.26                  |
|           | −37 → −25                     | 1.88 ± 0.39                  | 0.86 ± 0.18                  |
|           | −15 → +12                     | 5.90 ± 0.94                  | 2.71 ± 0.43                  |

### Notes.

$^a$ After removal of CMZ trough component, assumed to be given by the $R(3, 3)'$ absorption profile scaled by 1.3.

3.2. CO

Velocity profiles of lines of the $^{13}$CO $v = 1$–0 fundamental band toward GCIRS 3, GCIRS 1W, and of lines of the $^{12}$CO $v = 2$–0 overtone band toward GCIRS 16NE, GCIRS 21, and GCS 3–2 are shown in Figures 4 and 5. In Figure 6 for each of these sources a profile of the $R(0)$ line from either the $1$–0 band of $^{12}$CO or from the $2$–0 band of $^{13}$CO is shown. In Figures 4 and 5 there are numerous gaps in the profiles due to strong telluric absorption lines. In addition some of the $^{13}$CO line profiles overlap with those of strong lines of the $^{12}$CO fundamental. The $^{13}$CO $v = 1$–0 $R(J)$ lines nearly coincide with the $^{13}$CO $v = 1$–0 $R(J+1)$ lines, with velocity offsets of 50–95 km s$^{-1}$. The $^{12}$CO $v = 1$–0 $P(J)$ lines nearly coincide with $^{18}$O $v = 1$–0 $P(J−1)$ lines with offsets of 18–30 km s$^{-1}$. However, in each case the contamination is relatively minor. $^{18}$O $v = 1$–0 $R(0)$ is the only observed transition that is not contaminated by lines of $^{12}$CO and $^{13}$CO; a simple comparison of the line depths of $^{18}$O $R(0)$
and $^{13}$CO $R(0)$ (the former shown at the bottom of Figure 4) indicates that C$^{18}$O abundance is less than one-fourth of that of $^{13}$CO. The ratio above should be taken as an upper limit, since $^{13}$CO $R(0)$ is expected to be more saturated than C$^{18}$O $R(0)$.

The measured equivalent widths and calculated column densities of the least contaminated $^{13}$CO $v = 1–0$ and $^{12}$CO $v = 2–0$ lines are listed in Tables 4 and 5. For the $H_2$ and $^{12}$CO $v = 2–0$ lines, the absorption strengths $\Delta I$ and optical depths $\tau$ are approximately proportional, because the maximum optical depths are 0.1–0.3. For the fundamental band of $^{13}$CO, however, the non-linear equations $\Delta I(\lambda) = I_0(1 - e^{-\tau(\lambda)})$ and $W_\lambda = \int \tau(\lambda) d\lambda$ must be used to relate the two, because the peak absorptions are as large as 80%. The column densities of CO were calculated using the same equation as for $H_2$, but with $|\mu|^2 = S/(2J + 1)((\mu_{1-0}/2-0)^2$, where the spectral strength $S$ is $J + 1$ for $R(J)$ lines and $J$ for $P(J)$ lines and $\mu_{1-0} = 0.1055$ D, $\mu_{2-0} = 6.53 \times 10^{-3}$ D are the dipole moments of $^{12}$CO $v = 1–0$ and $v = 2–0$ transitions, respectively (Zou & Varanasi 2002). The small differences between the transition dipole moments of $^{12}$CO $v = 1–0$ and $^{13}$CO $v = 1–0$ lines (Chackerian & Tipping 1983) were neglected. Population diagrams, from which temperatures can be estimated, are shown in Figure 7 in velocity intervals corresponding to the various cloud and gas environments.

At negative velocities the dominant CO absorbers on all sightlines to the Central Cluster are the spiral and lateral arms. An additional and weaker absorption at $-72$ km s$^{-1}$ is present toward GCIRS 1, GCIRS 3, and GCIRS 16NE. In all of these the highest rotational level observed at negative velocities is $J = 3$, and excitation temperatures range from 7 to 19 K (Table 6, and also Figure 7), depending on the line of sight and the line pair. It is likely that the population distribution is subthermal (Neufeld 2012). The total column densities of $^{13}$CO in the three foreground arms were determined by summing the level populations using the values in Table 5 and are about $8 \times 10^{16}$ cm$^{-2}$ toward each source. This is in reasonable agreement with the value of $1.1 \times 10^{17}$ cm$^{-2}$ of Moneti et al. (2001) based on lower resolution ($R = 2000$) spectroscopy of $^{13}$CO $v = 1–0$ over an extended region near Sgr A$^*$. At positive velocities, as in the case of $H_2^+$, it seems likely that most or all of the absorption by CO arises within the CMZ. At $0 < v < +38$ km s$^{-1}$ absorption toward GCIRS 1W, GCIRS 3, and GCIRS 16NE is observed only up to $J = 3$. At higher positive velocities, a weak and narrow $+45$ km s$^{-1}$ absorption is observed toward GCIRS 1W out to $J = 5$, and a similar $+43$ km s$^{-1}$ absorption is observed toward GCIRS 3 out to $J = 6$. Most strikingly, a strong and broad absorption centered near $+60$ km s$^{-1}$ is present toward GCIRS 3 also up to $J = 6$ for $^{13}$CO, and up to $J = 15$ for $^{12}$CO, but is not observed toward GCIRS 1W. The velocity range of this feature is similar to those of the positive velocity features seen toward GCIRS 3 in $H_2^+$ lines, indicating that the absorptions by each species probably originate in physically related gas components. The much higher velocity gas ($\pm 300$ km s$^{-1}$ or more) seen by Goicoechea et al.
Figure 5. Spectra of $^{12}$CO $v = 2–0$ $P(3)$–$P(1)$ and $R(0)$–$R(5)$ lines on sightlines to GCIRS 16NE, GCIRS 21, and GCS 3-2. Individual velocity components are shaded.

3.3. H$_2$

Figure 8 shows the spectra of GCS 3-2 obtained at the wavelengths of the H$_2$ $v = 1–0$ $S(0)$ and $S(1)$ lines, which in absorption originate from the two lowest lying rotational levels of the molecule. Neither line was detected. The radial velocities and widths of the expected absorption features are uncertain. From the spectrum of CO (bottom of the figure) one may assume that H$_2$ in foreground arms would produce three narrow absorptions, each of velocity width $\sim 6$ km s$^{-1}$. The upper limits on the equivalent widths of such absorption features in the observed spectrum are $2.3 \times 10^{-7}$ $\mu$m for each. For excitation temperatures of H$_2$ in the range 10–50 K typical of interstellar clouds, only the $J = 0$ level should be significantly populated. The corresponding upper limit on the H$_2$ column density is $N$(H$_2$) $< 7 \times 10^{21}$ cm$^{-2}$ for each arm. For a standard dust-to-gas ratio (Bohlin et al. 1978) and gaseous hydrogen fully molecular and not depleted by adsorption on grains each limit corresponds to $A_V < 7$ mag. The accuracies of the limits to the extinction derived from the H$_2$ measurements are highly uncertain, as are any implications, because the fractions of gas in the intervening arms that are in diffuse and dense clouds are not well constrained.

4. ANALYSIS AND DISCUSSION

As described in the previous sections, the observed H$_2^+$ and CO absorption lines toward GCIRS 3 and GCIRS 1W are most simply interpreted as arising in three distinct physical environments and thus at least three distinct locations along those lines of sight. The environments and likely locations are (1) cold and mostly dense clouds in the foreground spiral and lateral arms, containing both species, (2) warm and diffuse gas within the CMZ, containing H$_2^+$ and relatively little CO (undetected in the overtone band of $^{12}$CO nor in the fundamental band of $^{13}$CO), and (3) warm and dense compact clouds in the central few parsecs of the CMZ, containing both species. In the first three subsections we use the new data and previous work by us and others to constrain the physical conditions in each of these environments. In the fourth subsection, we briefly discuss possible explanations for the enhanced ionization rates in the CMZ’s extended diffuse gas and in the dense gas within the central few parsecs.

4.1. Foreground Gas

The spiral arm local to the solar neighborhood, and possibly other spiral arms between the Sun and the GC are likely contributors to the strong absorption by CO and H$_2^+$ near 0 km s$^{-1}$. The sharp absorption feature at $-53$ km s$^{-1}$ in both species are readily identifiable as originating in the 3 kpc arm, which was first recognized as a stream of neutral clouds by van Woerden et al. (1957) in the H$\alpha$ 21 cm line and then located radially by Oort et al. (1958) from the tangential point of the stream at longitude of 303$^\circ$. (For a recent image of it, see Dame & Thaddeus 2008.) Likewise, the absorption feature at $-32$ km s$^{-1}$ arises in the 4 kpc arm, first identified by Menon & Ciotti (1970) via the H$\alpha$ line.
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The Astrophysical Journal (Galactic coordinates indicated on the right). Dashed lines from left to right correspond to radial velocities of an unidentified contributor at $-72$ km s$^{-1}$, the 3 kpc expanding arm, the 4 kpc expanding arm, and clouds in more local arms as well as other clouds in circular orbits.

The weak absorption feature in CO at $-72$ km s$^{-1}$ is close in velocity to an H$\text{I}$ absorption feature at $-75$ km s$^{-1}$ observed toward Sgr A by Liszt et al. (1983), who did not identify the feature with any previously known cloud. A similar kinematic component was recorded in OH 1667-MHz absorption spectrum at $-80$ km s$^{-1}$ by Sandqvist (1970) on the same line of sight. It is unclear if the CO feature observed here is related to either of the above. Its presence only in low-$J$ levels, its small angular size, and the lack of absorption features at that velocity in the H$\text{I}$ line profiles suggest that it does not arise within the CMZ, but rather in a cold, compact, and presumably dense foreground cloud.

4.2. Warm and Diffuse Gas in the CMZ

4.2.1. Velocities, Densities and Temperatures

Warm and diffuse CMZ gas was discovered by Goto et al. (2002) and characterized by Oka et al. (2005), who identified it as a major constituent of the CMZ. It produces a broad and shallow swath of absorption in the $R(1, 1)^3$ and $R(3, 3)^1$ lines of H$\text{II}$, but no absorption in the $^{12}$CO $v = 2-0$ or $^{13}$CO $v = 1-0$ lines. It is found almost entirely at negative velocities (from $-180$ km s$^{-1}$ to $+20$ km s$^{-1}$); thus the gas producing it is moving outward from the center. The strength of this absorption, its presence toward stars located from the Central Cluster to as far east as the Quintuplet Cluster (Oka et al. 2005; Goto et al. 2008), and its velocity breadth suggest not only that it extends across all sightlines between the two clusters, but also that its column length is a significant fraction of the $\sim 200$ pc radius of the CMZ.

The highest negative velocities observed in H$\text{II}$, those in excess of $-100$ km s$^{-1}$, have also been observed in the absorption and emission lines at radio wavelengths of several molecular species, e.g., CO and CS (Bally et al. 1987). It seems likely that the H$\text{II}$ and the other molecules seen at these high velocities are physically associated. The radio lines have often been interpreted as arising near the outer edge of the CMZ (Kaifu et al. 1972; Scoville 1972; Sofue 1995), in a shell or ring-like structure (see Binney et al. 1991 for an alternative explanation). If the high-velocity H$\text{II}$ absorption also arises there, then H$\text{II}$ absorption at lower negative velocities forms interior to it. However, the lower negative velocity gas must still be distant radially from the central few tens of parsecs, as absorption by it is observed on all sightlines from the Central Cluster to the Quintuplet Cluster.

The temperature and density of the diffuse gas can be determined from the H$\text{II}$ level column density ratios $N(3, 3)/N(1, 1)$ and $N(3, 3)/N(2, 2)$ (Oka & Epp 2004). At low densities the former ratio is mainly temperature dependent and the latter is mainly density dependent. Figure 9 shows temperature and density as functions of these ratios. In the velocity range $-109$ km s$^{-1}$ to $+1$ km s$^{-1}$ the $1\sigma$ lower limits of $n(3, 3)/n(2, 2)$ toward the two Central Cluster sources are 3.7 and 5.4, which correspond to mean temperatures near 250 K and mean densities $n \lesssim 50$ cm$^{-3}$.

In Figure 2 the spectra of GCIRS 1W show warm and diffuse gas at positive velocities as high as +50 km s$^{-1}$ as evidenced by the weakness of the absorption in the $R(2, 2)^3$ line. This positive velocity diffuse gas, previously seen by Goto et al. (2008), is not clearly present on any other GC sightlines observed to date, although it may contribute to the absorption profiles seen toward GCIRS 3. Figure 9 shows that while this gas is diffuse it is somewhat higher density than the diffuse gas on other GC sightlines.

4.2.2. Ionization Rate

The simple chemistry of H$\text{II}$ in the diffuse interstellar medium allows one to determine the product $\zeta L$ from the equation (Oka et al. 2005; Oka 2006)

$$\zeta L = 2k_r N(H_2)^{\text{total}}(n_C/n_{\text{H}_2})_{SV} R_X/f(H_2),$$

(1)

where $k_r$ is the rate constant for the dissociative recombination of H$\text{II}$ on electrons, $(n_C/n_{\text{H}_2})_{SV}$ is the carbon to hydrogen ratio in diffuse clouds in the solar vicinity, $R_X$ is the factor increase of that ratio from the solar vicinity to the GC (due to higher metallicity in the GC), and $f(H_2) = 2m(H_2)/m_{\text{H}_2}$ is the fraction of hydrogen in molecular form. We use the value of $k_r$ at 230 K, $8.1 \times 10^{-8}$ cm$^3$ s$^{-1}$, calculated from Equation (7) of McCaughrean et al. (2004; note that the recent experiment by Petigura et al. 2011 implies a somewhat larger value), and $(n_C/n_{\text{H}_2})_{SV} = 1.6 \times 10^{-3}$ (Sofia et al. 2004). We use $R_X = 3$, which appears to be conservative lower limit (Sodroski et al. 1995; Arimoto
\( \zeta L > \left(7.8 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}\right) N(H_3^+)_{\text{total}}. \)

The total \( H_3^+ \) column densities in the warm and diffuse gas, calculated from the sum of \( N(1, 1) \) and \( N(3, 3) \) from \(-180 \text{ km s}^{-1} \) to \(+20 \text{ km s}^{-1} \) in Table 2 and \( N(1, 0) \) in Table 4 of Goto et al. (2008; after multiplying by 0.83 in the case of GCIRS 1W to adjust for the different velocity intervals), are \( 3.0 \times 10^{15} \text{ cm}^{-2} \) toward each source. The actual value may be several percent higher because the higher metastable levels such as (4, 4), (5, 5), (6, 6) (Oka & Epp 2004) and some unstable levels such as (2, 2), and (2, 1) may have non-negligible populations.

We thus obtain \( \zeta L > 2.3 \times 10^7 \text{ cm} \text{ s}^{-1} \), which is similar to the lower limit found toward GCS 3-2 (Oka et al. 2005) and toward other stars from Sgr A* to 30 pc east (Goto et al. 2008). The limit is more than an order of magnitude higher than values in diffuse clouds in the Galactic disk \((0.5-1.9) \times 10^6 \text{ cm} \text{ s}^{-1} \) (McCall et al. 2002; Indriolo & McCall 2012), gives \( L > 200 \text{ pc} \), which is comparable to the radius of the CMZ. Since it is unlikely that the warm and diffuse gas fills the entirety of the foreground CMZ, \( \zeta \) is probably considerably greater than its average value in Galactic diffuse clouds.

This conclusion is strengthened by the likelihood that \( f(H_2) \) is considerably less than unity in the warm and diffuse gas in the CMZ. No information about \( f(H_2) \) on Central Cluster sightlines...
Table 5

Level Column Densities of CO

| vLSR (km s⁻¹) | ¹²CO v = 1–0 | P(4) | P(3) | P(2) | P(1) | NCO (10¹⁵ cm⁻²) |
|---------------|--------------|------|------|------|------|----------------|
|               | R(0) | R(1) | R(2) | R(3) | R(4) | R(5) | R(6) |
| GCIRS 3       | −82 → −65  | ...  | ...  | ...  | ...  | 1.17  | 1.29  | 0.80  | 1.70  | ...  | ...  | ...  | ...  |
|               | −65 → −45  | ...  | ...  | ...  | ...  | 8.30  | 6.83  | 6.77  | 1.86  | ...  | ...  | ...  | ...  |
|               | −37 → −25  | ...  | ...  | ...  | ...  | 4.34  | 4.71  | 5.64  | ...  | ...  | ...  | ...  | ...  |
|               | −15 → +12  | ...  | ...  | ...  | 2.19 | 9.71  | 24.50 | 14.97 | ...  | ...  | ...  | ...  | ...  |
|               | +12 → +38  | ...  | ...  | ...  | 5.72 | 9.57  | 5.13  | 9.76  | 5.67  | 2.08 | ...  | ...  | ...  | ...  |
|               | +38 → +51  | ...  | ...  | ...  | 5.34 | 7.58  | 3.95  | 8.71  | 3.82  | 2.62 | ...  | ...  | ...  | ...  |
|               | +51 → +85  | ...  | ...  | ...  | 1.62 | 3.51  | 2.56  | ...  | 4.58  | 2.03 | 1.52 | 1.44 | 1.41 | ...  |
| GCIRS 1W      | −82 → −65  | ...  | ...  | ...  | ...  | 9.03  | 6.71  | 6.69  | 2.69  | ...  | ...  | ...  | ...  | ...  |
|               | −65 → −45  | ...  | ...  | ...  | ...  | 2.72  | 3.82  | 3.59  | ...  | ...  | ...  | ...  | ...  | ...  |
|               | −37 → −25  | ...  | ...  | ...  | ...  | 2.09  | 10.25 | 22.69 | 15.01 | ...  | 6.08 | 3.64 | ...  | ...  |
|               | −15 → +12  | 3.36 | 2.01 | 6.04 | 8.31 | 3.55  | 8.71  | 3.82  | 2.62  | ...  | ...  | ...  | ...  | ...  |
|               | +12 → +38  | ...  | ...  | ...  | 1.65 | 3.38  | 1.90  | 3.38  | 1.90  | 0.43 | ...  | ...  | ...  | ...  |
|               | +38 → +51  | ...  | ...  | ...  | 0.85 | 2.50  | 1.46  | 0.25  | 1.67  | 1.37 | ...  | ...  | ...  | ...  |
|               | +51 → +64  | ...  | 1.67 | 3.20 | 1.19 | 2.28  | ...  | 1.35 | 0.46  | ...  | ...  | ...  | ...  | ...  |
| GCIRS 16NE    | −82 → −65  | ...  | ...  | ...  | ...  | 0.81  | 1.55  | 0.51  | 0.99  | ...  | ...  | ...  | ...  | ...  |
|               | −65 → −45  | 0.84 | 0.82 | 4.97 | 7.58 | 3.89  | 6.13  | 2.42  | 0.73  | ...  | ...  | ...  | ...  | ...  |
|               | −37 → −25  | 0.48 | ...  | 1.16 | 2.74 | 1.54  | 1.74  | 1.10  | ...  | ...  | ...  | ...  | ...  | ...  |
|               | −15 → +12  | 1.86 | 2.85 | 6.30 | 14.02 | 5.76 | 9.36  | 8.43  | 2.79 | 0.72 | 0.47 | ...  | ...  | ...  |
|               | +12 → +38  | 1.06 | 2.01 | 6.04 | 8.31 | 3.55  | 8.71  | 3.82  | 2.62  | ...  | ...  | ...  | ...  | ...  |
|               | +38 → +51  | 0.85 | 2.50 | 1.46 | 0.25 | 1.67  | 1.37  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
|               | +51 → +64  | 0.56 | 1.65 | 1.05 | 0.23 | 1.45  | 1.29  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| GCIRS 21      | −82 → −65  | ...  | ...  | ...  | ...  | 3.86  | 8.04  | 4.07  | 4.23  | 2.20 | ...  | ...  | ...  | ...  |
|               | −65 → −45  | 1.15 | 1.29 | ...  | ...  | 1.62  | 1.99  | 1.99  | 1.01  | ...  | ...  | ...  | ...  | ...  |
|               | −37 → −25  | 4.17 | 4.37 | 5.37 | 16.15 | 7.83 | 10.12 | 7.91  | 4.79 | 3.20 | ...  | ...  | ...  | ...  |
|               | −15 → +12  | 1.02 | 2.02 | 2.20 | 2.76 | 1.10  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
|               | +12 → +38  | 0.32 | 0.25 | 0.51 | 0.68 | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
|               | +38 → +51  | ...  | ...  | ...  | ...  | 0.66  | 1.41  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
|               | +51 → +64  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| GCS 3-2       | −98 → −75  | 0.47 | 1.89 | 2.20 | 1.32 | 2.51  | 1.70  | 0.72  | 0.22  | ...  | ...  | ...  | ...  | ...  |
|               | −75 → −65  | ...  | ...  | ...  | ...  | 0.31  | 0.51  | 0.20  | ...  | ...  | ...  | ...  | ...  | ...  |
|               | −65 → −45  | ...  | ...  | 2.86 | 5.97 | 4.02  | 6.23  | 2.80  | 0.42  | ...  | ...  | ...  | ...  | ...  |
|               | −37 → −25  | ...  | ...  | 2.55 | 2.08 | 2.52  | 0.68  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
|               | −15 → +12  | 1.02 | 2.02 | 2.20 | 2.76 | 1.10  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
|               | +12 → +21  | 0.32 | 0.25 | 0.51 | 0.68 | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |

Table 6

Total Column Density of ¹²CO and Excitation Temperature in Foreground Arms

| ¹²CO | NCO (10¹⁷ cm⁻²) | Tex (K) | NCO (10¹⁷ cm⁻²) | Tex (K) | NCO (10¹⁷ cm⁻²) | Tex (K) |
|------|----------------|---------|----------------|---------|----------------|---------|
| GCIRS 16NE | 16.6 ± 0.9 | 11.4 ± 0.6 | 6.2 ± 0.5 | 12.3 ± 1.0 | 30.6 ± 1.3 | 14.6 ± 0.5 |
| GCIRS 21 | 13.8 ± 1.7 | 8.4 ± 1.3 | 9.5 ± 1.7 | 19.1 ± 3.2 | 42.6 ± 3.4 | 17.4 ± 1.2 |
| GCS 3-2 | 13.6 ± 0.8 | 8.0 ± 0.4 | 5.4 ± 0.4 | 6.1 ± 0.4 | 6.2 ± 0.9 | 7.2 ± 0.8 |
| Average | 14.7 ± 0.7 | 9.4 ± 0.7 | 7.0 ± 0.6 | 12.5 ± 3.8 | 26.5 ± 1.2 | 13.1 ± 0.7 |

Note. Uncertainties listed are from fitting only.
is available. Elsewhere in the CMZ recent Herschel observations have revealed strong H$_2$O$^+$ line emission toward Sgr B2 (Schilke et al. 2010) with a complex velocity profile strikingly similar to that found for H$^+_3$ toward 2MASS J17470898–2829561 (Geballe & Oka 2010), at a projected distance of only 17 pc from Sgr B2. This similarity indicates that the two sightlines pass through the same clouds. Models suggest that H$_2$O$^+$ can only exist in regions where $f$(H$_2$) is less than 0.1, since H$_2$O$^+$ would be quickly destroyed through the reaction H$_2$O$^+$ + H$_2$ → H$_3$O$^+$ (Gerin et al. 2010). If $f$(H$_2$) smaller than 0.1 is appropriate for the sightlines toward the Central Cluster and Quintuplet sources the ionization rates there may exceed 10$^{-14}$ s$^{-1}$. It would be
The presence of high temperature gas in the interior of the CND, as originally proposed by Geballe et al. (1989). The locations of the stars in the Central Cluster are compared to an HCN $J = 4–3$ map of Montero-Castaño et al. (2009) in Figure 1. GCIRS 3 coincides with an extension of the northwest portion of the CND to the east–southeast (i.e., into the interior of the CND) termed “clump I” by Montero-Castaño et al. (2009), while the line of sight to GCIRS 1W is clear. Clump I is close to Sgr A*, and thus far from the inner edge of the CND. In order to determine if this extension is related to the CND, HCN $J = 4–3$ spectra were extracted along the line connecting clump H (in the main portion of the CND as seen in Figure 1) and clump I. The spectra are shown in Figure 10. The radial velocity at the line peak smoothly changes from $+60 \, \text{km s}^{-1}$ to $+50 \, \text{km s}^{-1}$ from clump H to the position of GCIRS 3 at the western extension of clump I, as well as steadily decreasing in intensity. Emission at this velocity disappears just beyond clump I; the intensity peak there is due to emission at $-30 \, \text{km s}^{-1}$. This shift in radial velocity of the peak is also visible in the velocity-integrated map of HCN $J = 4–3$ in Figure 11. Thus the western extension of clump I, which intersects the line of sight to GCIRS 3, is physically connected to clump H of the CND, rather than to the source of emission peak at clump I at $-30 \, \text{km s}^{-1}$, which likely is situated in the background.

The H$_2$ $R(2, 2)'$ absorption line toward GCIRS 3 is compared to HCN $J = 4–3$ emission line extracted at the position of GCIRS 3 in Figure 12. The line profiles match almost perfectly in terms of their line center velocities and widths. We conclude that the $+60 \, \text{km s}^{-1}$ absorption observed toward GCIRS 3 in $^{13}$CO and H$_2$ occurs in the western extension of clump I, which is a part of the CND. The extension was not resolved by the $4.6' \times 3.0'$ synthesized beam of the Submillimeter Array (SMA; Montero-Castaño et al. 2009); thus its linear dimension is less than 0.2 pc.

It is not surprising that this gas, observed by us up to $J = 6$ in $^{13}$CO, is warm. The presence of high temperature gas in the CND, although not specifically on this sightline, has been known from millimeter wave spectroscopy $^{12}$CO populated up to $J = 7$.

### Table 7

| Total Column Densities of $^{13}$CO and Excitation Temperature of Galactic Center Clouds at Positive Velocities |
|---|
| | $N_{^{13}CO}$ (10$^{16}$ cm$^{-2}$) | $T_{ex}$ (K) | $N_{CO}$ (10$^{16}$ cm$^{-2}$) | $T_{ex}$ (K) |
| GCIRS 3 | 0.8 ± 0.1 | 9.8 ± 1.1 | ... | ... |
| GCIRS 3 (warm) | 1.0 ± 0.2 | 50.8 ± 6.4 | 6.0 ± 0.6 | 52.8 ± 5.4 |
| GCIRS 1W | 3.2 ± 0.1 | 18.4 ± 0.7 | ... | ... |

**Note.** Uncertainties listed are from fitting only.
Figure 10. HCN $J = 4–3$ emission lines (Montero-Castaño et al. 2009) extracted from the apertures between clumps H and I shown in Figure 1. The velocity of the peak line emission is marked by a dotted line (originally published in Goto et al. 2013).

(A color version of this figure is available in the online journal.)

Figure 11. HCN $J = 4–3$ maps (Montero-Castaño et al. 2009) integrated over the velocity intervals $-40$ to $-25$ km s$^{-1}$ (left) and $+20$ to $+80$ km s$^{-1}$ (right). The locations of clump H, I, and GCIRS 3 are shown by crosses.

(A color version of this figure is available in the online journal.)

Figure 12. Comparison of H$_3^+$ R(2, 2)$^j$ absorption toward GCIRS 3 (black) to HCN $J = 4–3$ emission line (Montero-Castaño et al. 2009) extracted at the location of GCIRS 3 (blue, scaled to R(2, 2)$^j$; originally published in Goto et al. 2013).

(A color version of this figure is available in the online journal.)

Mills et al. (2013) recently argued, however, that in the CND the effective critical density of HCN is reduced by radiative pumping in the mid-infrared in the CND, $\sim 10^4$–$10^5$ cm$^{-3}$. Our H$_3^+$ spectroscopy seems to be more consistent with the latter values.

The mass of the $+60$ km s$^{-1}$ cloud may be crudely estimated assuming a diameter given by the separation of GCIRS 1W and GCIRS 3 and the gas density derived from H$_3^+$ spectroscopy, $\sim 10^4$ cm$^{-3}$. We obtain $M \sim 4 M_\odot$. We are unable to identify the material producing the $+45$ km s$^{-1}$ feature toward GCIRS 1W and GCIRS 3 with any known cloud and do not attempt to estimate its mass.

4.3.3. Ionization Rate

For dense clouds, in which electrons are scarce and proton hop reactions from H$_3^+$ to CO are the main destruction channel...
for H$_2^+$, we use the analog to Equation (1),
\[
\zeta L = k_L N(H_2^+)_{\text{total}}(n_{CO}/n_{H_2})_{\text{SV}} R_X, \tag{2}
\]
where the Langevin rate constant for CO, $k_L = 2 \times 10^{-9}$ cm$^{-3}$ s$^{-1}$ (Anicich & Huntress 1986), replaces $k_L$ in Equation (1). For the CO to H$_2$ ratio we use $8 \times 10^{-4}$, the value measured by in the dense cloud in front of NGC 2024 IRS 2 by Lacy et al. (1994), and then multiply by the lower limit $R_X = 3$ in view of the higher metallicity in the GC, as discussed earlier. Using the observed total H$_2^+$ column density for the +60 km s$^{-1}$ cloud toward GCIRS 3, 6 $\times$ 10$^{14}$ cm$^{-2}$ (the sum of the column densities in the bottom two rows in Table 2), and multiplying by 1.5 to account for destruction of H$_2^+$ by other dense cloud species, most notably O, we obtain $\zeta L > 1.5 \times 10^3$ cm s$^{-1}$. If the path length through the +60 km s$^{-1}$ cloud is 0.3 pc, $\zeta > 1.6 \times 10^{-15}$ s$^{-1}$. As in the case of the diffuse CMZ gas, this lower limit is significantly greater than mean values for dense or diffuse clouds outside of the GC.

### 4.4. High Ionization Rates in the CMZ

The sources of the enhanced ionization rates in the CMZ ($\zeta > 1 \times 10^{-15}$ s$^{-1}$ found here and also by Oka et al. (2005) and Goto et al. (2008) in the widely distributed diffuse gas, and $\zeta > 1.6 \times 10^{-15}$ s$^{-1}$ found here for the dense +60 km s$^{-1}$ cloud associated with the CND are not clearly identified. Both increased cosmic ray particle fluxes, arising from the relatively high concentration of supernova remnants in the GC, and enhanced photoionization by ultraviolet and X-ray photons from the nearby hot and luminous stars, supernova remnants, accretion disks of black holes, and ultra-hot diffuse gas are possible contributors (Crocker et al. 2011; Munro et al. 2009; Yusef-Zadeh et al. 2007).

In the CMZ, ionization of hydrogen due to UV radiation would be strongly influenced by the distribution of gas and dust. For gas densities of 100 cm$^{-3}$ or more, mean free paths for UV photons are small fractions of a parsec. The situation is different for X-rays. The X-ray photoionization cross section per hydrogen atom is $\sim 10^{-22}$ cm$^2$ per hydrogen atom at 1 keV (Wilms et al. 2000). In diffuse gas the mean free path of a 1 keV X-ray photon is a few tens of parsecs. X-ray images of the GC reveal an extended diffuse component and a plethora of point sources with no individual source or group of sources that are dominant (Baganoff et al. 2003; Munro et al. 2009). Thus it would not be surprising if the ionization rate, even if enhanced due to X-rays, or due to cosmic ray particles, were roughly constant on widely spaced sightlines through the extended warm and diffuse gas in the CMZ, as seems to be the case (Oka et al. 2005; Goto et al. 2008, 2011).

On the other hand, the high ionization rate measured in the +60 km s$^{-1}$ cloud, which is located close to the Central Cluster and to Sgr A*, might be attributed in part to recent flames of local X-ray sources such as Sgr A* itself, or possibly to UV ionization from the multitude of hot stars in the nearby Central Cluster. For more detailed discussion of ionization rates in the central few pc of the Galaxy, see Goto et al. (2013), who estimated X-ray and cosmic ray ionization rates based on X-ray and $\gamma$-ray observations near Sgr A*.

### 5. CONCLUSION

The basic physical properties of the gas in the CMZ of the Galaxy have been quantified on sightlines toward infrared stars in the Central Cluster that are within a few tenths of a parsec of Sgr A*, using new infrared absorption spectra of H$_2^+$ and CO. Two types of gaseous environments within the CMZ have been identified on these sightlines: (1) warm (200 K < $T <$ 300 K) and diffuse ($n \leq 100$ cm$^{-3}$) gas with velocities in the range $-180$ km s$^{-1}$ to $+20$ km s$^{-1}$ occupying a significant fraction of the outer portion of the CMZ; (2) warm ($T \sim 300$ K) and dense ($n \geq 10^4$ cm$^{-3}$) gas probably belonging to an inward extension of the 1.5 pc radius CND that is on the line of sight to GCIRS 3. In addition, cold dense and diffuse gas located in foreground spiral and lateral arms has been observed on these sightlines.

From the observed total column densities of H$_2^+$, products of ionization rate $\zeta$ and pathlength $L$ have been determined to be $\zeta L > 2.5 \times 10^3$ cm s$^{-1}$ and $\zeta L > 1.5 \times 10^3$ cm s$^{-1}$, respectively, for the above diffuse and dense CMZ gas. Although separation of $\zeta$ and $L$ is difficult, the large values of their products indicate ionization rates ($\zeta > 10^{-15}$ s$^{-1}$) in both environments, and large path lengths ($L > 30$ pc) in the diffuse gas of the CMZ.

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### REFERENCES

An, D., Ramirez, S. V., Sellgren, K., et al. 2011, ApJ, 736, 133
Anicich, V. G., & Huntress, W. T. Jr. 1986, ApJL, 62, 553
Arimoto, N., Sofue, Y., & Tsujimoto, T. 1996, PASJ, 48, 275
Baganoff, F. K., Maeda, Y., Morris, M., et al. 2003, ApJ, 591, 891
Bally, J., Stark, A. A., Wilson, R. W., & Henkel, C. 1987, ApJL, 65, 13
Bariko, H., Martins, F., Trippe, S., et al. 2010, ApJ, 708, 834
Binney, J., Gerhard, O. E., Stark, A. A., Bally, J., & Uchida, K. I. 1991, MNRAS, 252, 210
Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Bonnet, H., Abturer, R., Baker, A., et al. 2004, Msngr, 117, 17
Bradford, C. M., Stacey, G. J., Nikola, T., et al. 2005, ApJ, 623, 866
Brown, R. L., & Liszt, H. S. 1984, ARA&A, 22, 223
Chackerian, C. Jr., & Tipping, R. H. 1983, JMoSp, 99, 431
Chiappini, C., Matteucci, F., & Romano, D. 2001, ApJ, 554, 1044
Christopher, M. H., Scoville, N. Z., Stolovy, S. R., & Yun, M. S. 2005, ApJ, 622, 346
Colin, A. L., & Ho, P. T. P. 2000, ApJ, 533, 245
Crocker, R. M., Jones, D. I., Aharonian, F., et al. 2011, MNRAS, 413, 763
Dame, T. M., & Thaddeus, P. 2008, ApJL, 683, L143
Eisenhauer, F., Schödel, R., Genzel, R., et al. 2003, ApJL, 597, L121
Esteban, C., García-Rojas, J., Peimbert, M., et al. 2005, ApJL, 618, L95
Geballe, T. R., Baas, F., & Wade, R. 1989, A&A, 208, 208
Geballe, T. R., McCauley, J. B., Kinkle, K. H., & Oka, T. 1999, ApJ, 510, 251
Geballe, T. R., & Oka, T. 1996, Natur, 384, 334
Geballe, T. R., & Oka, T. 2010, ApJL, 709, L70
Genzel, R., & Townes, C. H. 1987, ARA&A, 25, 377
Gerin, M., de Luca, M., Black, J., et al. 2010, A&A, 518, L110
Ghez, A. M., Salim, S., Weinberg, N. M., et al. 2008, ApJ, 689, 1044

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