TWO NEW AND REMARKABLE SIGHTLINES THROUGH THE GALACTIC CENTER’S MOLECULAR GAS

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ABSTRACT

Until now, the known sources in the Galactic center with sufficiently smooth spectra and of sufficient brightness to be suitable for high-resolution infrared absorption spectroscopy of interstellar gas occupied a narrow range of longitudes, from the central cluster of hot stars to approximately 30 pc east of the center. In order to more fully characterize the gas within the r ∼ 180 pc central molecular zone, it is necessary to find additional such sources that cover a much wider longitudinal range of sightlines. We are in the process of identifying luminous dust-embedded objects suitable for spectroscopy within 1°/2 in longitude and 0°/1 in latitude of Sgr A* using the Spitzer GLIMPSE and the Two Micron All Sky Survey catalogs. Here we present spectra of H2 and CO toward two such objects, one located 140 pc west of Sgr A*, and the other located on a line of sight to the Sgr B molecular cloud complex 85 pc to the east of Sgr A*. The sightline to the west passes through two dense clouds of unusually high negative velocities and also appears to sample a portion of the expanding molecular ring. The spectra toward Sgr B reveal at least 10 absorption components covering over 200 km s−1 and by far the largest equivalent width ever observed in an interstellar H2 line; they appear to provide the first near-infrared view into that hotbed of star formation.

Key words: Galaxy: center – ISM: clouds – ISM: lines and bands – ISM: molecules

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1. INTRODUCTION

The Galactic center (GC) is a fascinating environment containing a multitude of extraordinary phenomena and extraordinary objects, not the least of which are three dense clusters of young and hot stars and a multi-million solar mass black hole, Sgr A*. Until recently, it was thought that the interstellar gas within the central few hundred parsecs of the Galaxy, usually referred to as the central molecular zone (hereafter CMZ), consists of three major components (Morris & Serabyn 1996; Lazio & Cordes 1998): ultra high temperature X-ray-emitting plasma; ionized gas at T ∼ 106–108 K responsible for the well-studied fine structure and radio recombination line emission; and cool and dense molecular clouds, which have also been observed in considerable detail at radio wavelengths. However, recent infrared spectroscopy of H2 and CO, and in particular of the key R(3,3)/ absorption line from a metastable state of H2 (Goto et al. 2002; Oka et al. 2005), has clearly revealed the presence of another component, which in terms of density (50–200 cm−3) has the characteristics of Galactic diffuse cloud material, but which is considerably warmer (200–300 K). At present, this warm dilute environment is unique to the GC; it has not been found in any other Galactic diffuse clouds surveyed in H2 (Geballe & Oka, unpublished). It appears to include gas associated with the r ∼ 180 pc expanding molecular ring (hereafter EMR; Kaifu et al. 1972; Scoville 1972), which has also been characterized as an expanding molecular shell (Sofue 1995), located at the outer edge of the CMZ.

Because of the unique properties of H2 (e.g., Geballe 2006), observations of it, combined with those of CO, are key to characterizing the physical conditions in the CMZ and the extent of the warm and diffuse component there. However, spectroscopy of H2 is difficult because its lines are weak owing to its low abundance. Until recently, there has been available as probes of the line of sight to the GC only a small number of hot stars in the Central cluster surrounding Sgr A* and in or near the Quintuplet cluster 30 pc to the east, which are both sufficiently bright for high-resolution spectroscopy and have smooth infrared spectra so that the H2 line profiles are uncontaminated by photospheric absorption lines in the background source.

Spectra of H2 toward these already-known sources (Oka et al. 2005; Goto et al. 2008) have shown that the warm and diffuse component is present on every sightline and also have shown that the H2 column lengths are substantial fractions of the radius of the CMZ. They thus suggest that the diffuse and warm environment in which the H2 is located takes up a large fraction of the volume in the central few hundred parsecs. If correct, this would strongly contradict the previous conceptual picture of GC gas, e.g., as illustrated in Lazio & Cordes (1998), in which a warm and diffuse component has not been included at all.

To better evaluate the extent and physical nature of this newly discovered environment, sightlines providing a wider coverage of the CMZ are needed. It is therefore essential to find additional bright sources with featureless or nearly featureless spectra—either hot stars with few emission or absorption lines, or stars encased in dense shells of warm dust—in a more extended region of the GC.

2. FINDING NEW SIGHTLINES THROUGH THE CMZ

The CMZ is filled with bright infrared sources, but everywhere except at locations of the three clusters of luminous hot stars (the Central, Arches, and Quintuplet clusters) the overwhelming majority of them are red giants, whose complex photospheric absorption spectra make them unsuitable as probes of the interstellar medium. Until very recently, no smooth-spectrum objects in the line of sight to the CMZ but far from those clusters were known. We are using the Two Micron All Sky Survey (2MASS) Point Source Catalog (Skrutskie et al. 2006) and the Spitzer Space Telescope GLIMPSE Catalog (Ramirez et al. 2008) to identify bright objects in the direction of the...
levels of the ground vibrational state can help to locate the J of sight are unknown. Although we attempt to select for suitable sources, the locations of those sources along the line of sight are shown in Figure 1, have been found to be suitable for observations. They are likely to contain either young stellar objects or luminous evolved stars. Wavelength calibration was obtained from telluric transitions. Observations were made in stare/nod-along-slit mode. Data reduction was standard for near-infrared spectroscopy of point sources. Wavelength calibration was obtained from telluric absorption lines observed in the spectrum of HR 6409 and is accurate to better than 0.0005 μm. The 2.166 μm Br absorption line in HR 6409 was removed by interpolation prior to ratioping.

The 2.0–2.4 μm portions of the spectra of the two objects are shown in Figure 2. 2M1743 has a smooth and steeply rising spectrum, consistent with that of a dust-embedded star. The spectrum of 2M1747, which rises even more steeply, is also indicative of warm dust. However, while the spectrum of 2M1743 appears featureless at this resolution, that of 2M1747 shows several significant absorption features. These include the 2–0 and 3–1 band heads of CO, perhaps originating in the veiled photosphere of a cool and luminous star or in a dense and high-temperature circumstellar shell or disk of a young stellar object. In addition, absorption is present near the wavelength of the 2–0 CO band center (2.347 μm), indicating the presence of a large column density of low-temperature (interstellar) CO. Finally, a broad absorption band, centered at approximately 2.265 μm, is present. It has a full width at zero intensity of ~0.02 μm.
Figure 2. Medium-resolution 2.0–2.4 \(\mu\)m spectra of two sources identified as likely dust-embedded stars located close to the GC. Locations of spectral features are indicated and identified if known.

We are unable to identify this feature. Its wavelength range encompasses that of the triplet of neutral calcium lines seen in late-type stars (Kleinmann & Hall 1986); however, the feature is too broad and too strong relative to CO for that identification to be viable. It is possible that the absorption is produced in frozen grain mantles within molecular clouds along the line of sight. An absorption at 2.27 \(\mu\)m with a similar profile, possibly due to solid methanol, has been observed in some solar system objects (Cruikshank et al. 1998).

4. HIGH-RESOLUTION SPECTRA OF H\(^{3}\) AND CO

High-resolution spectra of both objects at the \(R(1,1)\) transition of H\(^{3}\) near 3.715 \(\mu\)m and covering a small portion of the 2–0 band of CO near 2.342 \(\mu\)m were obtained at the Gemini South telescope on Cerro Pachon in Chile on 2009 July 6. The observations used the echelle spectrograph, Phoenix, whose 0.34 width provides a resolving power of 50,000. In one setting, the spectral coverage corresponds to \(\Delta \lambda/\lambda = 0.0045\) on the instrument detector array. For the CO spectra, the echelle was centered at 2.342 \(\mu\)m, thereby covering the five lowest lying \(R\) branch transitions of the 2–0 band, i.e., \(R(0)–R(4)\). The separation of adjacent 2–0 rovibrational CO lines corresponds to a velocity range of 260 km s\(^{-1}\); thus if the absorption profile is broad, the baseline for defining the continuum level between CO lines is quite restricted. The other setting was centered on the wavelength of the H\(^{3}\) line, whose lower level is the ground state. Data reduction was similar to that described earlier, with HR 6070 (A0V) and HR 7254 (A2V) serving as standards for both wavelength intervals. Wavelength calibrations used telluric absorption lines, and the resultant velocity scales in Figures 3 and 4 are accurate to 2 km s\(^{-1}\).

4.1. 2MASS J17432173–2951430

Profiles of the H\(^{3}\) line and the CO \(R(0)–R(3)\) lines observed toward 2M1743 are shown in Figure 3. Absorption components of CO are present at LSR velocities of \(-60\) km s\(^{-1}\), \(-172\) km s\(^{-1}\), and \(-200\) km s\(^{-1}\). The \(-172\) km s\(^{-1}\) absorption profile is slightly asymmetric, indicating the presence of a second and weaker absorption redshifted by a few km s\(^{-1}\). The H\(^{3}\) \(R(1,1)\) spectrum also contains prominent absorption components, including the same three seen in CO, and a redshifted shoulder on the \(-172\) km s\(^{-1}\) absorption that is relatively stronger than in CO. A fourth prominent absorption in the H\(^{3}\) spectrum is magnified by a factor of 3. Noise can be judged by point-to-point fluctuations in flat regions of the spectra.

Figure 3. Spectra of the \(R(1,1)\) line of H\(^{3}\) and the four lowest lying transitions of the 2–0 \(R\) branch of CO toward 2MASS J17432173–2951430. Spectra are offset vertically. CO spectra are to the same scale; an opaque CO line would have depth unity. The H\(^{3}\) spectrum is magnified by a factor of 3. Noise can be judged by point-to-point fluctuations in flat regions of the spectra.

Figure 4. Spectra of the \(R(1,1)\) line of H\(^{3}\) and the four lowest lying transitions of the 2–0 \(R\) branch of CO toward 2MASS J17470898–2829561. CO spectra are to the same scale; an opaque CO line would have depth unity. The H\(^{3}\) spectrum is magnified by a factor of 4.
spectrum, which is not present in CO, is an apparent velocity doublet at 0 and $+8$ km s$^{-1}$. Finally, broad but weaker H$_2^+$ absorptions, which also have no counterparts in CO, are centered near $-27$ km s$^{-1}$ and $-75$ km s$^{-1}$.

The CO absorptions observed at $-60$ km s$^{-1}$, $-172$ km s$^{-1}$, and $-200$ km s$^{-1}$ are likely to be formed in dense clouds. Only the first four rotational levels are significantly populated. The overall CO excitation temperature is roughly 10 K, but it is quite possible that the kinetic temperature is higher and that the level populations are sub-thermal. A more thorough analysis will be provided in a subsequent paper. The component at $-60$ km s$^{-1}$ possibly arises in the 3 kpc arm. On sightlines much closer to the center the absorption ascribed to that spiral arm occurs near $-52$ km s$^{-1}$ (Oka et al. 2005). The other two CO components, at much higher velocity, do not correspond to foreground spiral arms. Because of their high velocities, it is likely that these features arise close to the GC. CO $J = 1–0$ spectra obtained by Oka et al. (1998) approximately along this sightline ($h = 358.954$, $b = -0.065$) have their strongest emission components at those two high negative velocities.

Because no infrared CO absorption is present at the velocities of the H$_2^+$ absorptions near $+8$ km s$^{-1}$, 0 km s$^{-1}$, $-27$ km s$^{-1}$, and $-75$ km s$^{-1}$, the clouds producing them must be diffuse. Only weak CO $J = 1–0$ line emission is present at those velocities. 2M1743 is located within a few parsecs of the Galactic plane and is approximately 140 pc west of the center (see Figure 1). If it is located somewhat behind the center, its sightline would cross the EMR where the gas is moving nearly in the plane of the sky (with very little Doppler shift). It is thus logical to associate the low-velocity doublet with the EMR and to place 2M1743 somewhat behind the EMR. Previous observations have demonstrated that the EMR contains diffuse gas (Oka et al. 2005; Goto et al. 2008). If the placement of 2M1743 is correct, its spectrum is evidence that the diffuse nature of the EMR’s gas is widespread, and is not limited to the sightlines close to the longitudes of the Central and Quintuplet clusters.

We have no specific identification for the H$_2^+$ features at $-27$ km s$^{-1}$ and $-75$ km s$^{-1}$. However, previously observed GC sightlines (Oka et al. 2005; Goto et al. 2008) showed a trough of absorption by diffuse gas from 0 km s$^{-1}$ to $-100$ km s$^{-1}$ and suggest that a significant fraction of the volume of the CMZ contains diffuse gas. If so, then the presence of H$_2^+$ absorption components in that velocity range would not be surprising.

### 4.2. 2MASS J17470898$-$2829561

Velocity profiles of the H$_2^+$ line and the CO $R(0)–R(3)$ lines toward 2M1747 are displayed in Figure 4. Both molecules absorb continuously over wide velocity ranges. Absorption by CO extends without interruption from $-100$ km s$^{-1}$ to $+100$ km s$^{-1}$, and the absorption by H$_2^+$ extends even further without a break, from $-130$ km s$^{-1}$ to $+100$ km s$^{-1}$. About a dozen discrete velocity components can be seen in both the H$_2^+$ and CO line profiles. Several, but not all of the components of the two molecules coincide, and thus the sightline appears to contain a combination of diffuse and dense clouds, but at present it is not possible to untangle the two contributions. The only clear indication of gas with a low excitation temperature similar to that seen in the CO toward 2M1743 is at $-43$ km s$^{-1}$, where the strongest absorption occurs in the $J = 0, 1$, and 2 levels and where the CO absorption depth noticeably decreases with increasing lower state energy. This absorption component may be a continuation of absorption by molecular gas in the 3 kpc arm, as discussed previously for 2M1743.

At $l = 0:548$, $b = -0:059$, 2M1747 is located approximately 85 pc east of the GC on the line of sight to the Sgr B giant molecular cloud complex, and is almost directly between Sgr B1 and Sgr B2 (see Figure 1). The CO $J = 1–0$ spectra of Oka et al. (1998) at this location show a strong and complex emission profile at positive velocities, not very different from those seen in the infrared CO and H$_2^+$ lines, but very little emission at negative velocities where both the infrared CO and H$_2^+$ absorptions also are strong.

Given the unprecedented large equivalent widths of the H$_2^+$ $R(1.1)'$ and interstellar CO lines (that of the H$_2^+$ line is roughly twice that previously reported for any other GC sightline), it seems beyond doubt that 2M1747 lies within Sgr B. To our knowledge, the absorption spectra in Figure 4 are the first near-infrared views into that complex and turbulent star-forming region.

### 5. CONCLUSION

The spectra presented here represent the beginning of a new phase of exploration of the CMZ using absorption spectroscopy of H$_2^+$ and CO along new sightlines, which has already yielded striking results. More detailed understanding of the gas on these two new sightlines, as well as on others that have been or are likely to be found, will require spectroscopy of additional transitions of H$_2^+$, in particular of the $R(2.2)'$ and $R(3,3)'$ lines, arising from higher energy levels than the $R(1,1)'$ line, and detailed comparison of the spectra of H$_2^+$ with infrared and millimeter spectra of CO and perhaps other molecular species.

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