ALMA observations of molecular absorption in four directions toward the Galactic bulge

H. Liszt¹ and M. Gerin²

1 National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
e-mail: hliszt@nrao.edu
2 LERMA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, École Normale Supérieure, 75005 Paris, France
e-mail: maryvonne.gerin@ens.fr

Received 22 September 2017 / Accepted 5 November 2017

ABSTRACT

Context. Alma Cycle 3 observations serendipitously showed strong absorption from diffuse molecular gas in the Galactic bulge at \(-200\ \text{km s}^{-1} < v < -140 \ \text{km s}^{-1}\) toward the compact extragalactic continuum source J1744-3116 at \((l, b) = -2.13\degree, -1.00\degree\). Aims. We aimed to test whether molecular gas in the bulge could also be detected toward the three other, sufficiently strong mm-wave continuum sources seen toward the bulge at \(|b| < 3\degree\).

Methods. We took absorption profiles of HCO\(^+\)(1\(^−\)0), HCN(1\(^−\)0), C\(_2\)H(1\(^−\)0), CS(2\(^−\)1) and H\(^{13}\)CO\(^+\)(1\(^−\)0) in ALMA Cycle 4 toward J1713-3418, J1717-3341, J1733-3722 and J1744-3116.

Results. Strong molecular absorption from disk gas at \(|v| \leq 30 \ \text{km s}^{-1}\) was detected in all directions, and absorption from the 3 kpc arm was newly detected toward J1717 and J1744. However, only the sightline toward J1744 is dominated by molecular gas overall and no other sightlines showed molecular absorption from gas deep inside the bulge. No molecular absorption was detected toward J1717 where H\(_1\) emission from the bulge was previously known. As observed in HCO\(^+\), HCN, C\(_2\)H and CS, the bulge gas toward J1744 at \(v < -135 \ \text{km s}^{-1}\) has chemistry and kinematics like that seen near the Sun and in the Milky Way disk generally. We measured isotopologic ratios \(N(\text{HCO}^+)/N(\text{H}^1\text{CO}^+)> 51 (3\sigma)\) for the bulge gas toward J1744 and 50 \(\pm 9\) and 64 \(\pm 4\) for the disk gas toward J1717 and J1744, respectively, all well above the value of 20–25 typical of the central molecular zone.

Conclusions. The kinematics and chemistry of the bulge gas observed toward J1744 more nearly resemble that of gas in the Milky Way disk than in the central molecular zone.

Key words. ISM: molecules – ISM: clouds – ISM: abundances

1. Introduction

In a recent paper (Gerin & Liszt 2017) we discussed the serendipitous discovery of strong molecular absorption at \(-210 \ \text{km s}^{-1} \leq v \leq -135 \ \text{km s}^{-1}\) toward the compact extragalactic continuum source J1744-3116 (aka B1744-312) at \(l, b = -2.13\degree, -1.00\degree\), along a line of sight passing through the inner portions of the Galactic bulge outside the central molecular zone (CMZ; Morris & Serabyn 1996). We extracted the run of IR K-band extinction with distance modulus from the 3D extinction maps of Schultheis et al. (2014) and showed that the K-band extinction in the bulge implied the existence of unseen gas, given the weakness of H\(_1\) emission at high negative velocities characteristic of the bulge. The H\(_2\) column density inferred from HCO\(^+\) absorption matched the amount of gas lacking in H\(_1\).

As we discussed, the quantity of molecular gas in the bulge outside the CMZ, at \(1.2\degree \leq |l| \leq 10\degree\) or galactocentric radius \(180 \ \text{pc} \leq R \leq 1500 \ \text{kpc}\) at the IAU standard distance \(R_0 = 8.5 \ \text{kpc}\), is rather uncertain. The total mass of H\(_1\) in the bulge is comparable to the mass of H\(_2\) in the CMZ, \(M(\text{H}_1) = 3 \times 10^7 \ M_\odot\) (Burton & Liszt 1978), raising the possibility that the mass of molecular gas in the bulge is yet larger.

Mm-wave absorption toward J1744 from a wider range of species was subsequently discussed by Riquelme et al. (2018) who pointed out some of the same similarities between the chemical composition of the bulge and disk gases that are noted here. In the present work we re-observed molecular absorption toward J1744 with more complete spectral coverage than in our earlier discussion, at much higher spectral resolution than in our earlier work or in Riquelme et al. (2018). We also searched for similar absorption toward the few (three) known, strong mm-wave continuum sources lying toward the bulge within 3\(^\circ\) of the Galactic plane. All of the newly-observed sightlines lie much further from the Galactic center than J1744, and none of them show molecular absorption at velocities characteristic of gas deep inside the bulge: we did find two weak features arising in the 3 kpc arm (Bania 1977, 1980; Dame & Thaddeus 2008).

The plan of this work is as follows: in Sect. 2 we describe the new and existing observational material that is discussed. In Sect. 3 we briefly summarize some properties of the observed sightlines and the disk gas that is present along them. In Sect. 4 we present new observational results leading to a better characterization of the bulge gas toward J1744: it has a chemistry and cloud structure comparable to that seen in HCO\(^+\), C\(_2\)H, HCN and CS in diffuse molecular gas near the Sun and, unlike material in the CMZ, is not enhanced in \(^{13}\)C. Section 5 is a summary and discussion.

2. Observations and data reduction

2.1. New ALMA absorption measurements

We observed the \(J = 1\rightarrow0\) lines of HCO\(^+\), H\(^{13}\)CO\(^+\), HCN and C\(_2\)H, and the \(J = 2\rightarrow1\) line of CS \(J = 2\rightarrow1\) in absorption...
Fig. 1. GASS H I and ALMA J = 1–0 HCO$^+$ profiles for the four sources observed here with ALMA.

Table 1. Observed and derived quantities.

<table>
<thead>
<tr>
<th>Source</th>
<th>l, b</th>
<th>$S_v$</th>
<th>$R_c$</th>
<th>$A_K$</th>
<th>$N$(H I)$_0$</th>
<th>$N$(H I)$_0$</th>
<th>$N$(H I)$_0$</th>
<th>$N$(H)</th>
<th>$f_{H_2}$</th>
<th>$N$(H)/$A_K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1713-3418</td>
<td>351.705, +2.787</td>
<td>0.93</td>
<td>1.23</td>
<td>0.40</td>
<td>0.43</td>
<td>(0.64)</td>
<td>0.18</td>
<td>(0.82)</td>
<td>(0.22)</td>
<td>&gt;1.53</td>
</tr>
<tr>
<td>J1717-3341</td>
<td>352.733, +2.391</td>
<td>0.49</td>
<td>1.08</td>
<td>0.66</td>
<td>0.54</td>
<td>0.78</td>
<td>0.53</td>
<td>1.31</td>
<td>0.40</td>
<td>1.98</td>
</tr>
<tr>
<td>J1733-3722</td>
<td>351.818, -2.889</td>
<td>0.60</td>
<td>1.21</td>
<td>0.60</td>
<td>0.56</td>
<td>(1.13)</td>
<td>0.11</td>
<td>(1.24)</td>
<td>(0.09)</td>
<td>&gt;1.12</td>
</tr>
<tr>
<td>J1744-3116</td>
<td>357.863, -0.997</td>
<td>0.33</td>
<td>0.32</td>
<td>1.46</td>
<td>0.90</td>
<td>1.20</td>
<td>1.93</td>
<td>3.13</td>
<td>0.62</td>
<td>2.14</td>
</tr>
</tbody>
</table>

Notes. (a) $R_c = R_0 \sin(|l|) / R_0 = 8500$ pc. (b) Values from Schultheis et al. (2014); $E(B - V)/A_K = 3.09$ (Schlafly & Finkbeiner 2011). (c) $N$(H I)$_0 = 1.823 \times 10^{18}$ cm$^{-2}$ $\int T_B vdv$. (d) N(H I)$_0$ from Eq. (1). (e) $N$(H$_2$) = $N$(HCO$^+$)$/3 \times 10^{-5}$, $N$(HCO$^+$) = $1.10 \times 10^{12}$ cm$^{-2}$ $\int T_{HCO^+} vdv$. (f) $f_{H_2} = 2N(H_2)/N(H I) + 2N(H_2))$. (g) Parenthesized quantities assume $N$(H)/$A_K = 2.06 \times 10^{12}$ cm$^{-2}$ mag$^{-1}$, the average for J1717 and J1744.

toward the four continuum sources listed in Table 1. The work was conducted under ALMA Cycle 4 project 2016.1.00132.S whose pipeline data products were delivered in 2017 February. The spectra discussed here were extracted from the continuum-subtracted pipeline-processed data cubes at the pixel of peak continuum flux in the continuum map made from each spectral window, and divided by the continuum flux in the continuum map at that pixel. Fluxes at 89.2 GHz ranged from 0.33 Jy for J1713 to 0.93 Jy for J1733. Each spectrum consisted of 1919 semi-independent channels spaced 61.13 kHz corresponding to 0.205 km s$^{-1}$ at the 89.189 GHz rest frequency of HCO$^+$ or 0.187 km s$^{-1}$ for CS(2−1) at 97.981 GHz: the channel spacing is half the spectral resolution. Velocities presented with the spectra are taken with respect to the kinematic definition of the Local Standard of Rest.

2.2. Other data

In Fig. 1 we compare our HCO$^+$ spectra with Galactic All-Sky Survey (GASS) III $\lambda$21 cm H I emission spectra (Kalberla & Haud 2015). For the sources J1717 and J1744 we use the H I absorption profiles of Dickey et al. (1983) to derive
an optical depth-corrected column density of atomic hydrogen as

\[ N(\text{H I}) = 1.823 \times 10^{18} \text{ cm}^{-2} \int \frac{\tau(v) T_B(v)}{1 - \exp(-\tau(v))} \, dv, \]  

(1)

where \( \tau \) and \( T_B \) are the optical depth and brightness temperature and the units of velocity are km s\(^{-1}\). In this work, \( N(\text{H}) \) is the column density of H-nuclei in neutral atomic and molecular form, \( N(\text{H}) = N(\text{H I}) + 2N(\text{H}_2) \).

We also use the CS and HCN absorption profiles for local clouds from Lucas & Liszt (2002) and Liszt & Lucas (2001), respectively, and the HCO\(^+\) and C\(_2\)H measurements of Lucas & Liszt (2000).

### 2.3. Extinction

We cite the 6\arcmin resolution dust-emission maps scaled to optical reddening \( E_{B-V} \) by Schlafly & Finkbeiner (2011) and the 3D IR extinction map of the Galactic bulge of Schultheis et al. (2014) at the same resolution, from which we cite values of the K-band extinction \( A_K \).

### 3. Disk gas toward the 4 targets

Profiles toward all sources are shown in Figs. 1–3 and some general properties of the sightlines are given in Table 1. All directions show strong molecular absorption from gas in the Galactic disk around zero velocity but only the sightline to J1744 passes inside galactocentric radius \( R = 1 \) kpc and only that sightline shows strong molecular absorption from gas deep inside the Galactic bulge.

The sightline to J1744 is also the only one for which the gas column density is dominated by molecular gas, mostly from the disk contribution around 0-velocity. The species-by-species chemistry of this gas is not a major focus of this work, but is shown in Sect. 4 along with a variety of other data that are used as a basis of comparison with the bulge gas. Chemistry of the disk gas toward J1744 was discussed for a broader range of species observed in a low spectral resolution spectral scan by Riquelme et al. (2018), whose conclusions agree with ours regarding the similarity of the disk and bulge diffuse molecular gas components.

Although some of the molecular gas must be quite close to the Sun, for instance material in the Heeschen Cloud.
the Sun has a rotation curve with \( \Theta \) quite shallow at the small longitudes of our sources: for a flat trajectory toward J1744, it is hard to place the disk gas in Galactic perspective. The line of sight velocity gradients due to Galactic rotation toward J1744 is shown in two parts in the upper panels, with different scaling. Regions over which the profiles were integrated are shown outlined, at the mean level within each region: see Table 2 for results.

Fig. 3. HCO\(^+\) and H\(^{13}\)CO\(^+\) absorption profiles for three of the sources observed here. The H\(^{13}\)CO\(^+\) are scaled upward as indicated and shown in blue over those of HCO\(^+\). Absorption toward J1744 is shown in two parts in the upper panels, with different scaling. Regions over which the profiles were integrated are shown outlined, at the mean level within each region: see Table 2 for results.

Table 2. \(^{12}\)C/\(^{13}\)C isotopic abundance ratios from HCO\(^+\).

<table>
<thead>
<tr>
<th>Source</th>
<th>Velocity range km s(^{-1})</th>
<th>( W_{\text{HCO}^+} ) km s(^{-1})</th>
<th>( W_{\text{H}^{13}\text{CO}^+} ) km s(^{-1})</th>
<th>( N(\text{HCO}^+) ) ( 10^{12} ) cm(^{-2})</th>
<th>( N(\text{HCO}^+)/N(\text{H}^{13}\text{CO}^+) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1744</td>
<td>-200...-180</td>
<td>0.890(0.014)</td>
<td>(0.017)</td>
<td>0.98(0.02)</td>
<td>( &gt; 17^9 )</td>
</tr>
<tr>
<td>J1744</td>
<td>-165...-135</td>
<td>3.301(0.019)</td>
<td>(0.021)</td>
<td>3.63(0.02)</td>
<td>( &gt; 51 )</td>
</tr>
<tr>
<td>J1744</td>
<td>-200...-135</td>
<td>4.191(0.024)</td>
<td>(0.027)</td>
<td>4.68(0.03)</td>
<td>( &gt; 51 )</td>
</tr>
<tr>
<td>J1713</td>
<td>-38...14</td>
<td>2.321(0.053)</td>
<td>(0.046)</td>
<td>2.55(0.06)</td>
<td>( &gt; 16 )</td>
</tr>
<tr>
<td>J1717</td>
<td>-25...10</td>
<td>7.002(0.027)</td>
<td>0.117(0.018)</td>
<td>7.70(0.03)</td>
<td>( 58 \pm 9 )</td>
</tr>
<tr>
<td>J1744</td>
<td>-33...13</td>
<td>21.852(0.056)</td>
<td>0.333(0.023)</td>
<td>24.03(0.06)</td>
<td>( 64 \pm 4 )</td>
</tr>
</tbody>
</table>

Notes: \(^{12}\)N(\text{HCO}^+) = 1.10 \times 10^{12} \text{ cm}^{-2} \ W_{\text{HCO}^+}; \( N(\text{H}^{13}\text{CO}^+) = 1.135 \times 10^{12} \text{ cm}^{-2} \ W_{\text{H}^{13}\text{CO}^+}. \(^{10}\) All limits are 3\( \sigma \).

(Heeschen 1955) that is responsible for the H\(_{2}\) self-absorption toward J1744, it is hard to place the disk gas in Galactic perspective. The line of sight velocity gradients due to Galactic rotation are quite shallow at the small longitudes of our sources: for a flat rotation curve with \( \Theta(R) = 220 \text{ km s}^{-1} \), a location 5 kpc from the Sun has \( v \approx -10 \text{ km s}^{-1} \) toward J1744 or \( v \approx -40 \text{ km s}^{-1} \) toward the other sources. Moreover, much of the low-velocity absorption occurs at positive velocities that are inconsistent with rotation. Positive velocities could arise from a combination of random motions and streaming associated with spiral arms, although gas at \( v \gtrsim 30 \text{ km s}^{-1} \) most likely arises inside the Galactic disk.

The \( H_2 \) fraction falls monotonically with separation from the Galactic equator: only the line of sight toward J1744 at \( b = -1^\circ \) has a molecular fraction exceeding 50%. The optical depth corrections to \( N(\text{H}_1) \) in the two directions with measured H\(_{1}\) absorption profiles are 35–45% of the optically thin value, but these sightlines have relatively high H\(_2\) fractions and the correction to \( N(\text{H}_1) \) is smaller than 2\( N(\text{H}_2) \).

3.1. \(^{12}\)C/\(^{13}\)C in the disk gas

Profiles of the carbon isotopologues of HCO\(^+\) are shown in Fig. 3 and results for their profile integrals and ratios of column densities are given in Table 2. Column densities are derived from integrated optical depths in the limit of no rotational excitation above the cosmic microwave background, for a molecular dipole moment of 3.92 Debye (e.g. Ando et al. 2016). From this it follows that \( N(\text{HCO}^+) = 1.10 \times 10^{12} \text{ cm}^{-2} \int \tau \text{ d}e \) and \( N(\text{H}^{13}\text{CO}^+) = 1.135 \times 10^{12} \text{ cm}^{-2} \int \tau \text{ d}e \) in units of \( \text{ km s}^{-1} \), accounting for the lower line frequency of the heavier isotopologue. Error estimates for the integrated optical depths in Table 2 include effects associated with the appreciable optical depths in HCO\(^+\), which were estimated using the measured rms line/continuum ratios in absorption-free regions in channel-by-channel Monte Carlo simulations of the observed profile taken as the expectation value.

We have precise measurements of the carbon HCO\(^+\) isotopologues toward two sources: \( N(\text{HCO}^+)/N(\text{H}^{13}\text{CO}^+) = 58 \pm 9 \) toward J1717 and \( N(\text{HCO}^+)/N(\text{H}^{13}\text{CO}^+) = 64 \pm 4 \) toward J1744.
This is well below the solar isotopic abundance ratio 89, but typical for gas near the Sun observed in mm-wave absorption by Lucas & Liszt (1998). However, some of the disk gas observed here could be situated well inside the solar circle where the $^{12}$C/$^{13}$C ratio is known to be smaller (Milam et al. 2005), although still well above the very small values 20–25 characteristic of the CMZ (Wilson 1999; Riquelme et al. 2010).

### 3.2. H I spin temperature in the self-absorbed gas toward J1744

The line of sight to J1744 is the exceedingly rare case where H I absorption (Dickey et al. 1983) has been measured in a direction where the H I emission is self-absorbed. Earlier (Gerin & Liszt 2017) we showed that the H I self-absorption is coincident with CO $J = 1-0$ emission. Here we show how the combination of H I absorption and self-absorption can be used to derive an upper limit on the spin temperature of the H I self-absorbing but largely molecular gas.

We define $T_B$ as the observed brightness temperature of the H I emission and $T_{B,bg}$ as the hypothetical brightness temperature in the absence of self-absorption: extrapolating across the self-absorption feature by Gaussian fitting of the H I emission gives $T_{B,fg} = 125.2$ K in the center of the H I self-absorption trough where $T_B = 71.1$ K. We also define the optical depth derived from the absorption profile of Dickey et al. (1983) as the sum of foreground and background contributions $\tau = \tau_{fg} + \tau_{bg}$ and define $T_{sp,fg}$ and $T_{sp,bg}$ as the spin temperatures of the foreground and background emitting gases, respectively. Then the two equations

$$ T_{B,fg} \exp(-\tau_{fg}) + T_{sp,fg}(1 - \exp(-\tau_{fg})) = T_B $$

and

$$ T_{B,bg} = T_{sp,fg}(1 - \exp(-\tau_{bg})) $$

can be solved for the spin temperatures of the foreground and background gases as functions of the value of $\tau_{fg}$. The minimum optical depth of the foreground gas is $\tau_{fg} = 0.58$ when $T_{sp,fg} = 2.73$ K. This can be compared with the total optical depth in the middle of the H I self-absorption trough, $\tau = 1.22$, and it implies a fairly high minimum spin temperature for the background gas seen in emission: $\tau_{bg} \leq 1.22 - 0.58 = 0.64$ and $T_{sp,fg} \geq 265$ K.

The implied spin temperature of the foreground self-absorbing gas increases as $\tau_{fg}$ increases above 0.58 and the maximum optical depth, $\tau_{fg} = \tau = 1.22$, corresponds to $T_{sp} = 48$ K that is typical of gas observed in H I absorption generally (Heiles & Troland 2003). Of course it is not realistic to assign all of the optical depth to any one component of the H I and an improved upper bound on the spin temperature of the self-absorbing gas follows from showing that the optical depth of the self-absorbing gas is below 1.22. To this end we decomposed the H I absorption profile of Dickey et al. (1983) as summarized in Table 3 and illustrated in Fig. 4. A kinematic component is found coincident with the self-absorption, having a center optical depth $\tau_{fg} = 0.686 \pm 0.081$ corresponding to $T_{sp,fg} = 16.2(\pm 8.0, -10.2)$ K. This result unfortunately spans the range of kinetic temperatures from dark (10 K) to diffuse (25 K) molecular gas and does not allow us to decide in which regime the foreground gas exists.

The precision of the present result is limited by the noise level in the rather old absorption profile of Dickey et al. (1983). This could be improved by taking a more sensitive and contemporary H I absorption profile toward J1744, and extended by taking H I absorption profiles toward other positions with apparent H I self-absorption, which is relatively common in sightlines through the Great Rift in the inner Galaxy. Further insight into the foreground gas toward J1744 could also be obtained by observing $^{13}$CO in emission, and by observing CO or $^{13}$CO in absorption.

### Table 3. Gaussian decomposition of disk H I absorption toward J1744.

<table>
<thead>
<tr>
<th>Comp</th>
<th>Center $v$ (km s$^{-1}$)</th>
<th>$\tau_0$</th>
<th>FWHM $v$ (km s$^{-1}$)</th>
<th>$W_{HI}$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-22.602</td>
<td>1.515</td>
<td>5.876</td>
<td>9.4763</td>
</tr>
<tr>
<td>2</td>
<td>0.127</td>
<td>0.109</td>
<td>0.260</td>
<td>0.515</td>
</tr>
<tr>
<td>3</td>
<td>-12.476</td>
<td>0.646</td>
<td>3.603</td>
<td>2.477</td>
</tr>
<tr>
<td>4</td>
<td>0.154</td>
<td>0.0928</td>
<td>0.411</td>
<td>0.290</td>
</tr>
<tr>
<td>5</td>
<td>0.127</td>
<td>0.967</td>
<td>17.369</td>
<td>17.874</td>
</tr>
<tr>
<td>6</td>
<td>0.579</td>
<td>0.0621</td>
<td>0.957</td>
<td>0.976</td>
</tr>
<tr>
<td>7</td>
<td>7.091</td>
<td>0.686</td>
<td>4.587</td>
<td>3.348</td>
</tr>
<tr>
<td>8</td>
<td>0.181</td>
<td>0.081</td>
<td>0.442</td>
<td>0.330</td>
</tr>
</tbody>
</table>

### 4. Gas inside the Galactic disk

This work shows more clearly the nuclear bulge gas at $v < -135$ km s$^{-1}$ toward J1744 that was discovered in our earlier work (Gerin & Liszt 2017; see also Riquelme et al. 2018) but otherwise we did not detect gas inside the Galactic disk except for weak features arising in the 3 kpc arm at $-90$ km s$^{-1}$ toward J1717 (Fig. 1) and at $v = +52$ km s$^{-1}$ toward J1744.
As discussed in Gerin & Liszt (2017), especially their Table 1 published emission measurements we have made in the vicinity of the continuum background targets used by Liszt & Lucas (2001) and Lucas & Liszt (2002) to study local gas in absorption. CS absorption is comparatively weak in the Galactic disk and HCO$^+$ absorption more ubiquitously than absorption in HCN or CS and the column densities of HCN and CS increase substantially for individual features having N(HCO$^+$) $\gtrsim 10^{12}$ cm$^{-2}$ or $W_{\text{HCO}^+}$ $\gtrsim 1$ km s$^{-1}$ (Liszt & Lucas 2001; Lucas & Liszt 2002).

A closer view of the absorption in the bulge gas is presented in Fig. 5. This figure shows that absorption from CS and HCN is almost entirely concentrated in narrow-lined features having profile $FWHM \lesssim 1$ km s$^{-1}$. HCO$^+$ also shows these (and other) narrow features, although in HCO$^+$ they are superposed over a broad and presumably more nearly volume-filling component that also appears weakly in HCN at $v > -160$ km s$^{-1}$.

The appearance of so many narrow features, and so much kinematic substructure in the broader HCO$^+$ absorption is uncharacteristic of gas observed at small galactocentric radii. It likely arises because of the unusual circumstances under which the gas is being observed. The extremely large line of sight velocity gradient can kinematically separate gas parcels that are near each other in space and have little relative motion with respect to each other. In this way, spatial substructure is revealed that would otherwise remain hidden. If seen locally the same gas distribution would be narrower in velocity and the substructure seen toward J1744 would be blended together.

4.1.2. Chemical comparisons in the bulge gas

To illustrate the chemistry of the bulge gas, comparing HCN and CS column densities, we decomposed the line profiles of HCN and CS into gaussian components as shown in Tables 4 and 5. To account for the HCN components that are not apparent in CS (the feature at $-155.5$ km s$^{-1}$ we removed the gaussian fits in the CS profile and integrated the remainder CS profile over the range of the HCN components.

The results are presented in terms of HCN and CS column densities in Fig. 6 at left where we also include results for the local gas seen earlier at high Galactic latitude (Liszt & Lucas 2001; Lucas & Liszt 2002) and for the disk gas toward the four sightlines studied in this work. In fact, the HCN and CS column densities and their ratios in the bulge gas are very similar to those seen in local gas, with the exception of a high CS/HCN ratio in the feature at $-137$ km s$^{-1}$. Comparably high CS/HCN and CS/HCO$^+$ ratios are occasionally inferred from unpublished emission measurements we have made in the vicinity of the continuum background targets used by Liszt & Lucas (2001) and Lucas & Liszt (2002) to study local gas in absorption. CS absorption is comparatively weak in the Galactic disk gas toward J1733, and at $v < 0$ km s$^{-1}$ toward J1744. Similar conclusions regarding the similarity of disk and bulge gas are evident in the figures of Riquelme et al. (2018).

The hydrocarbon chemistry is illustrated at right in Fig. 6 where we compare C$_2$H and HCO$^+$ in the new data with

---

**Table 4. Gaussian decomposition of bulge HCO$^+$ absorption.**

<table>
<thead>
<tr>
<th>Comp</th>
<th>Center $V_{LSR}$ km s$^{-1}$</th>
<th>$\tau_0$</th>
<th>$FWHM$ $V_{LSR}$ km s$^{-1}$</th>
<th>$W_{HCO^+}$ km s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-192.6652</td>
<td>0.3406</td>
<td>0.3400</td>
<td>0.5480</td>
</tr>
<tr>
<td>2</td>
<td>-155.8931</td>
<td>0.2841</td>
<td>0.8530</td>
<td>0.4643</td>
</tr>
<tr>
<td>3</td>
<td>-155.5423</td>
<td>0.0084</td>
<td>0.0208</td>
<td>0.0048</td>
</tr>
<tr>
<td>4</td>
<td>-151.8292</td>
<td>0.1090</td>
<td>0.6582</td>
<td>0.0443</td>
</tr>
<tr>
<td>5</td>
<td>-136.7139</td>
<td>0.1040</td>
<td>0.0616</td>
<td>0.0054</td>
</tr>
<tr>
<td>6</td>
<td>-192.9346</td>
<td>0.1150</td>
<td>0.0426</td>
<td>0.0057</td>
</tr>
</tbody>
</table>

**Notes.** N(HCN) $= 8.06 \times 10^{12}$ cm$^{-2}$.

**Table 5. Gaussian decomposition of bulge HCN absorption.**

<table>
<thead>
<tr>
<th>Comp</th>
<th>Center $V_{LSR}$ km s$^{-1}$</th>
<th>$\tau_0$</th>
<th>$FWHM$ $V_{LSR}$ km s$^{-1}$</th>
<th>$W_{HCN^+}$ km s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-192.6652</td>
<td>0.3406</td>
<td>0.3400</td>
<td>0.5480</td>
</tr>
<tr>
<td>2</td>
<td>-155.8931</td>
<td>0.2841</td>
<td>0.8530</td>
<td>0.4643</td>
</tr>
<tr>
<td>3</td>
<td>-155.5423</td>
<td>0.0084</td>
<td>0.0208</td>
<td>0.0048</td>
</tr>
<tr>
<td>4</td>
<td>-151.8292</td>
<td>0.1090</td>
<td>0.6582</td>
<td>0.0443</td>
</tr>
<tr>
<td>5</td>
<td>-136.7139</td>
<td>0.1040</td>
<td>0.0616</td>
<td>0.0054</td>
</tr>
<tr>
<td>6</td>
<td>-192.9346</td>
<td>0.1150</td>
<td>0.0426</td>
<td>0.0057</td>
</tr>
</tbody>
</table>

**Notes.** N(HCN) $= 1.89 \times 10^{12}$ cm$^{-2}$.
that shown earlier by Lucas & Liszt (2000). The bulge gas toward J1744 is at the lower edge of the range of $C_2$ abundance ratios but still within a factor two of the regression line through the older data.

4.2. $^{12}$C/$^{13}$C in the bulge gas seen toward J1744

HCO$^+$ and $^{13}$CO$^+$ profiles are shown in more detail for three sources in Fig. 3. The profiles toward J1744 are shown in two parts corresponding to gas in the nuclear bulge at $v < -135$ km s$^{-1}$ and Galactic disk material at $v > -40$ km s$^{-1}$, separately scaled. Figure 3 shows various velocity intervals over which the profiles were integrated to determine column densities, as given in Table 2.

For the gas in the nuclear bulge observed at $v < -135$ km s$^{-1}$ toward J1744 (Table 2) we have only a weak limit $^{12}$C/$^{13}$C > 17 for the sub-interval $v < -190$ km s$^{-1}$, but $^{12}$C/$^{13}$C > 51 overall and separately over the sub-interval $-165 < v < -135$ km s$^{-1}$. Apparently, this gas is not enhanced in $^{13}$C, which is very different from the values $^{12}$C/$^{13}$C $\approx 20-25$ seen in the CMZ (Wilson 1999; Riquelme et al. 2010). This could be disk gas that entered the bulge recently, or gas resident in the bulge that has never been averted beyond the values characteristic of the disk in the inner Galaxy.

4.3. Inner-Galaxy gas along the line of sight to J1717

As shown in Fig. 1, H I emission from the bulge is present toward J1717 at $-200$ km s$^{-1} < v < -140$ km s$^{-1}$; this was modeled as part of the tilted H I inner-galaxy gas distribution by Burton & Liszt (1978). The H I column density $N$(HI) = $4.6 \times 10^{19}$ cm$^{-2}$ is comparable to that seen toward J1744 at $-165$ km s$^{-1} < v < -135$ km s$^{-1}$, $N$(HI) = $6.1 \times 10^{19}$ cm$^{-2}$ (Gerin & Liszt 2017), but the bulge gas toward J1717 is not dominated by H$_2$; the $3\sigma$ limit on 2$N$(H$_2$) found by integrating the HCO$^+$ profile is 2$N$(H$_2$) $\leq 5.0 \times 10^{19}$ cm$^{-2}$.

As also shown in Fig. 1, a strong H I feature corresponding to the 3 kpc arm (Bania 1977, 1980; Dame & Thaddeus 2008) is present toward J1717 at $v \approx -90$ km s$^{-1}$. HCO$^+$ absorption is also present toward J1717 over the range $-125$ km s$^{-1} < v < -75$ km s$^{-1}$ but the gas is only weakly molecular; we find $N$(H I) = $2.0 \times 10^{20}$ cm$^{-2}$ and 2$N$(H$_2$) = $6.4 \pm 1.8 \times 10^{19}$ cm$^{-2}$, or $f_{H_2}$ = 0.24.

4.4. The far-side 3 kpc arm toward J1744

As seen in Fig. 1 there is a weak wing of H I emission at $v \approx 40$ km s$^{-1}$ toward J1744, and weak HCO$^+$ absorption as well. Integrating over the velocity range 40–60 km s$^{-1}$ we find $N$(H I) = $8.0 \times 10^{19}$ cm$^{-2}$, 2$N$(H$_2$) = $7.3 \pm 1.2 \times 10^{19}$ cm$^{-2}$, i.e., the gas is s48% molecular.

5. Summary

Following up on the serendipitous detection of molecular absorption at velocities characteristic of the Galactic bulge toward J1744-3116 ($l = -2.13^\circ$, $b = -1.00^\circ$), we observed molecular absorption toward three other quasars seen against the bulge in the fourth longitude quadrant, although at much larger
longitude separation from the center and higher Galactic latitude (Table 1). We also reobserved the absorption toward J1744 with higher spectral resolution and broader spectral coverage, to better characterize the bulge gas. The species and transitions observed were HCO\(^+\) (1–0), HCN(1–0), C\(_2\)H(1–0), CS(2–1) and H\(^{13}\)CO\(^+\) (1–0), all in the frequency range 87–98 GHz. Line profiles are shown in Figs. 1–3 and general properties of the sightlines are summarized in Table 1.

5.1 Absorption arising inside the Galactic disk

The 3 kpc arm appeared in HCO\(^+\) absorption at \(-90\) km s\(^{-1}\) toward J1717-3341 and we inferred a molecular hydrogen fraction 0.24. We also detected a weak molecular absorption feature at \(+52\) km s\(^{-1}\) toward J1744 from the far-side 3 kpc arm and inferred a higher molecular fraction, 0.48, in this case. No molecular absorption was observed from the bulge gas at \(-200\) km s\(^{-1}\) \(\leq v \leq -140\) km s\(^{-1}\) toward J1717, corresponding to the H I emission that was modeled as part of the tilted H I inner-galaxy gas distribution by Burton & Liszt (1978).

Absorption from CS and HCN in the bulge gas toward J1744 consists of several narrow lines with FWHM of 1 km s\(^{-1}\) or less (Tables 4 and 5 and Fig. 5). In HCO\(^+\) the narrow lines seen in CS and HCN (and other lines not seen in CS or HCN) are superimposed on a broader, more continuous absorption, indicating that HCO\(^+\) is more widespread and more broadly distributed in space, as is the case with diffuse molecular gas observed near the Sun and more generally in the Galactic disk. The appearance of narrow lines is untypical of gas that is observed inside the Galactic disk, but the proliferation of so many features, and substructure in the HCO\(^+\) profile, may be ascribed to the very large line of sight velocity gradient due to the viewing geometry. This can cause a velocity separation of gas parcels that are relatively close, and have little relative motion with respect to each other.

Comparing CS with HCN and C\(_2\)H with HCO\(^+\) (Fig. 6) we showed that their chemistries in the bulge gas observed toward J1744 at \(v < -135\) km s\(^{-1}\) resemble those seen in absorption in local and disk diffuse molecular gas. We set a limit \(N(\text{HCO}^+)/N(\text{H}_{13}\text{CO}^+) > 51\) (3\(\sigma\)) for the bulge gas toward J1744 (Table 2), showing that it is not enriched in \(^{13}\)C as is material in the central molecular zone within 200 pc of Sgr A*. The bulge gas seen toward J1744 just outside the CMZ is very clearly differentiated from gas in the CMZ, and similar to disk gas in every aspect we examined.

5.2 Molecular gas in the Galactic disk

All of the sightlines showed molecular absorption from disk gas at \(|v| \leq 40\) km s\(^{-1}\) in HCO\(^+\), C\(_2\)H and HCN, and two showed absorption in disk gas from CS (2–1). Toward J1717 and J1744 we measured isotopic abundance ratios \(N(\text{HCO}^+)/N(\text{H}_{13}\text{CO}^+) = 58 \pm 9\) and 64 \(\pm 4\), respectively. These are smaller than the solar abundance ratio 89, but comparable to values seen previously in J3mm absorption from local diffuse molecular gas. Chemical abundances in the disk gas are shown in Fig. 6: they are generally like that seen previously for diffuse molecular gas seen at high Galactic latitude near the Sun, with some peculiarities: high C\(_2\)H/HCO\(^+\) ratios toward J1744 and small CS/HCN ratios toward J1733 and at \(v < 0\) km s\(^{-1}\) toward J1744.

Acknowledgements. This paper makes use of the following ALMA data: ADS/JAO.ALMA#2016.1.0032.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work was supported by the French program “Physique et Chimie du Milieu Interstellaire” (PCMI) funded by the Conseil National de la Recherche Scientifique (CNRS) and Centre National d’Etudes Spatiales (CNES). H.S.L. is grateful to the hospitality of the ITU-R, the Hotel Bel Esperance in Geneva, the JAO in Santiago and L’Hotel in Montreux during the completion of this manuscript. We thank Chinshin Chang at the ALMA JAO for producing the imaging scripts for this project and shepherding it through the data reduction process and we thank the referee for a close reading of the manuscript.

References