

Submillimeter absorption from SH⁺, a new widespread interstellar radical, ¹³CH⁺ and HCl^{*}

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ABSTRACT

We have used the Atacama Pathfinder Experiment 12 m telescope (APEX) to carry out an absorption study of submillimeter wavelength rotational ground-state lines of H³⁵Cl, H³⁷Cl, ¹³CH⁺, and, for the first time, of the SH⁺ radical (sulfoniumylidene or sulfanylium). We detected the quartet of ground-state hyperfine structure lines of SH⁺ near 683 GHz with the CHAMP+ array receiver against the strong continuum source Sagittarius B2, which is located close to the center of our Galaxy. In addition to absorption from various kinematic components of Galactic center gas, we also see absorption at the radial velocities belonging to intervening spiral arms. This demonstrates that SH⁺ is a ubiquitous component of the diffuse interstellar medium. We do not find clear evidence for other SH⁺ lines we searched for, which is partially due to blending with lines from other molecules. In addition to SH⁺, we observed absorption from H³⁵Cl, H³⁷Cl, and ¹³CH⁺. The observed submillimeter absorption is compared in detail with absorption in 3 mm transitions of H¹³CO⁺ and *c*-C₃H₂ and the CO *J* = 1–0 and 3–2 transitions.

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

1. Introduction

1.1. (Sub)millimeter spectroscopy of diffuse interstellar clouds

Starting in the late 1930s, studies of molecular absorption toward diffuse and translucent clouds have traditionally been in the realm of optical and, later, ultraviolet (UV) and infrared (IR) spectroscopy. Over the last 15 years, observations at radio and (sub)mm wavelengths have greatly added to our knowledge of the chemistry of the diffuse interstellar medium (ISM) (see, e.g., the review of Snow & McCall 2006). Measurements toward strong continuum sources are a powerful means to detect spectral lines that have their lower level in (or near) the rotational ground state of a molecule and may be the only way to detect a number of species in low density environments or even at all. In particular, the large rotational constants of light hydrides, resulting in a rotational spectrum starting at submillimeter or far-infrared wavelengths, together with substantial electric dipole moments, make collisional excitation negligible compared to radiative decay. This leaves substantial population only in the lowest energy level, which can be split in the case of fine structure (fs) or hyperfine structure (hfs).

Two particularly fruitful avenues of research have emerged; first, choosing extragalactic sources with strong mm- and cm-wavelength continuum emission as background objects, Liszt and Lucas have studied the abundances of a variety of di-, tri-, and even polyatomic molecules toward up to 20 lines of sight with often surprising results (see, e.g., Liszt & Lucas 2002, and references therein). A second possibility is using as

a background the thermal continuum from star-forming regions, (mostly) free-free emission at cm- and longer mm-wavelengths and dust emission at shorter wavelengths. Particularly interesting lines of sight are those toward regions M and N in the Sagittarius B2 Giant Molecular Cloud (GMC), which allow sensitive absorption spectroscopy of the ISM surrounding the Galactic center (GC) near which they are located at a distance of ~8 kpc (Reid et al. 2009) as well as of intervening GMCs. For a long time, absorption between –120 kms⁻¹ and Sgr B2's local velocity range (>+50 kms⁻¹) has been observed in the HI 21 cm line (see Garwood & Dickey 1989, and references therein) as well as in (mostly) mm-wavelength lines from quite a number of molecules (see Linke et al. 1981; Nyman 1983; Greaves & Williams 1994, and references therein). Intervening spiral arm absorption toward other bright inner Galaxy (sub)mm continuum sources has been found as well, most prominently toward the central radio/(sub)mm source Sgr A^{*} and W49N (see, e.g., Liszt et al. 1977; Linke et al. 1981; Cox et al. 1988; Greaves & Williams 1994; Plume et al. 2004; Polehampton et al. 2005b).

At submillimeter wavelengths, numerous molecules have been detected in absorption via their ground-state transitions (until recently mostly) toward Sgr B2 (for summaries see Menten 2004; Lis et al. 2009). In particular, the 1₁₀–1₀₁ transition of ortho-H₂¹⁶O and -H₂¹⁸O was detected with the Submillimeter Wave Astronomy Satellite (Neufeld et al. 2000); this H₂¹⁶O line, near 557 GHz, is responsible for much of the Earth atmosphere's shorter-wavelength submillimeter opacity.

In fact, atmospheric absorption by the rotational spectrum of H₂O (and to a lesser extent of O₂) makes the ground-state lines of many light hydride species inaccessible from the ground. Using the Long Wavelength Spectrometer (LWS) aboard the

* This contribution is dedicated to the memory of John M. Brown, pioneer of submillimeter spectroscopy of free radicals.

Infrared Space Observatory (ISO), which covered frequencies >1.5 THz (wavelengths <200 μm), several hydroxyl isotopologues (Polehampton et al. 2003, 2005a) were detected, as well as CH_2 (Polehampton et al. 2005b), and *para*- H_2D^+ (Cernicharo et al. 2007). From the excellent high altitude site in the Atacama desert, recently OH^+ was found with the APEX telescope by Wyrowski et al. (2010a).

Very recently, a new era in submillimeter absorption spectroscopy started with operation of the High Frequency Instrument for the Far Infrared (HIFI, see de Graauw et al. 2010) aboard *Herschel* (Pilbratt et al. 2010). Utilizing the superb sensitivity of *Herschel*'s 3.5 m aperture combined with HIFI's high spectral resolution heterodyne receivers operating in a low thermal background space environment, revolutionized observations of light hydrides. (Mainly) in the framework of the guaranteed time key projects *Herschel* observations of EXtra-Ordinary Sources (HEXOS) (PI: Bergin) and PRobing InterStellar Molecules with Absorption line Studies (PRISMAS, PI: Gerin) observations were made of H_2O^+ , H_3O^+ , H_2O and its isotopologues, H_2Cl^+ , C_3 , CH , and CH^+ , as well as NH and NH_2 , while NH^+ has so far remained undetected (Ossenkopf et al. 2010; Schilke et al. 2010; Gerin et al. 2010; Wyrowski et al. 2010b; Neufeld et al. 2010a; Lis et al. 2010b; Melnick et al. 2010; Comito et al. 2010; Lis et al. 2010a; Phillips et al. 2010; Neufeld et al. 2010b; Sonnentrucker et al. 2010; Mookerjee et al. 2010; Qin et al. 2010; Falgarone et al. 2010; Persson et al. 2010).

High quality optical/UV observations, needed, e.g., for meaningful abundance determinations, mostly sample relatively nearby clouds since they require optically bright background stars, typically members of OB associations (with HD catalogue numbers) within a few kpc (see, e.g. Gredel 1997; Stahl et al. 2008, and references therein). In contrast, being much less affected by interstellar extinction, radio/submm and near infrared absorption observations, e.g. of the key H_3^+ molecular ion (Geballe & Oka 1996), are capable of probing diffuse clouds throughout the Milky Way.

1.2. Interstellar SH^+

The ionized hydride SH^+ (sulfoniumylidene or sulfanylium) potentially is a probe of comets, photon-dominated regions (PDRs), shocked interstellar gas and diffuse molecular clouds (Horani et al. 1985). Toward the latter, optical absorption measurements have shown for a very long time large abundances of another ionized molecule, methylidyne, CH^+ , the first interstellar molecule, detected by Dunham (1937) and identified by Douglas & Herzberg (1941). CH^+ 's abundance is orders of magnitude higher than predicted by otherwise successful models (see, e.g., van Dishoeck & Black 1986). This has been a long-standing puzzle to astrochemists, who invoked shock wave scenarios to overcome the formation reaction's endothermicity (Federman 1982).

Millar et al. (1986) and also Pineau des Forêts et al. (1986) have extended chemical models by including sulfur chemistry and predicted efficient SH^+ formation to occur in shocked diffuse clouds and that the abundance of SH^+ can approach that of CH^+ in moderate velocity magnetic shocks, but is negligible for a non-magnetic shock. This, in principle, could make the CH^+/SH^+ abundance ratio a good shock indicator.

Millar & Hobbs (1988) made sensitive searches of an optical wavelength electronic transition of SH^+ from the $A^3\Pi-X^3\Sigma(0,0)$ band at 3363.49 \AA toward the well-studied diffuse cloud in the direction of ζ Oph, which shows significant CH^+ absorption.

They were only able to put an upper limit on the SH^+ column density of $1 \times 10^{13} \text{ cm}^{-2}$, which is a factor of 3 lower than the measured CH^+ column density. Magnani & Salzer (1991) searched for this line and another one at 3366.08 \AA toward a sample of 13 stars with known diffuse molecular clouds in front of them and were only able to determine comparable 3σ upper limits on the SH^+ column density between 0.4 and $1 \times 10^{13} \text{ cm}^{-2}$ and upper limits on the $[\text{SH}^+/\text{CH}^+]$ abundance ratio between 0.12 and 2. An earlier search by Magnani & Salzer (1989) toward a sample of diffuse and high-latitude clouds resulted in a factor of a few coarser limits on the SH^+ abundance. High (Galactic) latitude clouds belong to the so-called translucent clouds.

Translucent clouds, which were recognized as a class by van Dishoeck & Black (1986) have physical properties in between those of diffuse and dense dark clouds. In particular, they have higher visual extinctions, A_V , (1–a few mag) than diffuse clouds (<1 mag) and, consequently, a higher ratio of molecular to atomic gas.

Other astrochemical interest in SH^+ derives from the fact that, given a possible formation route via doubly ionized sulfur (S^{+2}), it is predicted to be a diagnostic of X-ray dominated regions (XDRs) (Abel et al. 2008). Stäuber et al. (2007) report an observation of the $\text{SH}^+ N=1-0, J=0-1, F=0.5-1.5$ line near 346 GHz toward the high-mass young stellar object (YSO) AFGL 2591, which is surrounded by an XDR. Since this line is blended with a $^{34}\text{SO}_2$ line, they were only able to quote an upper limit to the SH^+ line's intensity. Again very recently, *Herschel*/HIFI observations led to the discovery of emission in the 526 GHz 1_2-0_1 transition of SH^+ toward the high-mass protostar W3 IRS 5 (Benz et al. 2010).

In Sect. 2 of this paper we review the laboratory spectroscopy picture for both SH^+ and $^{13}\text{CH}^+$. In Sect. 3 we describe our submillimeter observations. Our results and the analysis procedure used to determine primary parameters of the observed lines are presented in Sect. 4. In Sect. 5 we discuss the derived information in an astrochemical context.

2. Rest frequencies

2.1. Accurate SH^+ frequencies

Savage et al. (2004) performed the only measurements of SH^+ with microwave accuracy. They obtained rest frequencies for four hfs lines from the $X^3\Sigma^- N=1-0$ state, one near 346 and three near 526 GHz. A previous study by Hovde & Saykally (1987) employed laser magnetic resonance to record rotational spectra. Recently, Brown & Müller (2009) used these and further rovibrational (infrared) data on energy levels of SH^+ in and between the $v=0$ and 1 vibrational states of the $X^3\Sigma^-$ electronic ground state to perform a single, weighted least-squares fit in order to determine an improved set of molecular parameters for this molecule. They used their results to calculate the rotational spectrum of SH^+ in these vibrational levels up to the $N=4-3$ transition. The predictions presented in the catalog section¹ of the Cologne Database for Molecular Spectroscopy, CDMS, (Müller et al. 2001, 2005) are based on the data from Savage et al. (2004), on weighted averages of the experimental data from Hovde & Saykally (1987) extrapolated to zero field taken from the fit of Brown & Müller (2009) and all available infrared data (up to $v=4-3$). These predictions are essentially

¹ <http://www.astro.uni-koeln.de/cdms/entries/>, see also <http://www.astro.uni-koeln.de/cdms/catalog/>

Table 1. Spectroscopic data and beam-averaged continuum brightness temperature assumed for the LTE modeling of the absorption lines toward Sgr B2(M).

Transition	$F' - F''^a$	Position ^b (", ")	Frequency (MHz)	S	E_1 (K)	F_{eff}^c	B_{eff}^d	T_{cont}^e (K)	Reference ^f
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
<i>c</i> -C ₃ H ₂ 2 ₁₂ -1 ₀₁		2.6,-2.0	85338.893(14)	1.50	0.0 ^g	0.95	0.78	5.9	JPL, <i>h</i>
H ¹³ CO ⁺ 1-0		2.6,-2.0	86754.2884(46)	1.0	0.0	0.95	0.78	5.9	CDMS, <i>i</i>
CO 1-0		2.6,-2.0	115271.2018(5)	1.0	0.0	0.95	0.74	5.9	CDMS, <i>j</i>
CO 3-2		2.6,-2.0	345795.9899(5)	3.0	16.6	0.95	0.72	11.0	CDMS, <i>j</i>
SH ⁺ 1 ₀ -0 ₁	0.5-0.5	0,0	345843.591(128)	0.2289	0.0	0.95	0.72	11.0	CDMS, -
	0.5-1.5		345929.810(75)	0.5780	0.0				CDMS, <i>k</i>
H ³⁷ Cl 1-0	1.5-1.5	0,0	624964.374(100)	1.3333	0.0	0.95	0.41	33.8	JPL, <i>l</i>
	2.5-1.5		624977.821(100)	2.0	0.0				JPL, <i>l</i>
	0.5-1.5		624988.334(100)	0.6667	0.0				JPL, <i>l</i>
H ³⁵ Cl 1-0	1.5-1.5	0,0	625901.603(100)	1.3333	0.0	0.95	0.41	33.8	JPL, <i>l</i>
	2.5-1.5		625918.756(100)	2.0	0.0				JPL, <i>l</i>
	0.5-1.5		625932.007(100)	0.6667	0.0				JPL, <i>l</i>
SH ⁺ 1 ₁ -0 ₁	1.5-0.5	0,0	683336.08(51)	0.1890	0.0	0.95	0.41	30.0	CDMS, <i>m</i>
	0.5-0.5		683361.98(48)	0.3778	0.0				CDMS, -
	1.5-1.5		683422.31(50)	0.9441	0.0				CDMS, <i>m</i>
	0.5-1.5		683448.20(50)	0.1887	0.0				CDMS, <i>m</i>
¹³ CH ⁺ 1-0		0,0	830 216.096(22)	1.0	0.0	0.95	0.35	47.7	CDMS, <i>n</i>
SH ⁺ 2 ₁ -1 ₁	0.5-0.5	0,0	893047.60(95)	0.2889	32.8	0.95	0.35	43.5	CDMS, -
	0.5-1.5		893073.49(96)	0.1445	32.8				CDMS, -
	1.5-0.5		893107.92(105)	0.1444	32.8				CDMS, -
	1.5-1.5		893133.81(94)	0.7225	32.8				CDMS, -

Notes. ^(a) Hyperfine quantum numbers as far as appropriate. ^(b) Equatorial offset (J2000) with respect to Sgr B2(M). (0, 0) corresponds to $(\alpha, \delta)_{\text{J2000}} = 17^{\text{h}}47^{\text{m}}20^{\text{s}}.2, -28^{\circ}23'05''$. ^(c) Forward efficiency. ^(d) Main-beam efficiency. ^(e) The beam-averaged continuum brightness temperature was derived from the depth of the saturated absorption lines in the 3 mm wavelength range, and from a direct measurement of the baseline level at higher frequency. ^(f) Catalog used for rest frequency and reference for line measurement, see also Sect. 2. ^(g) Lower level is *ortho* ground state; it is 2.35 K above the zero level. ^(h) Vrtilek et al. (1987). ⁽ⁱ⁾ Schmid-Burgk et al. (2004). ^(j) Winnewisser et al. (1997). ^(k) Savage et al. (2004). ^(l) De Lucia et al. (1971). ^(m) Hovde & Saykally (1987); Brown & Müller (2009). ⁽ⁿ⁾ Amano (2010).

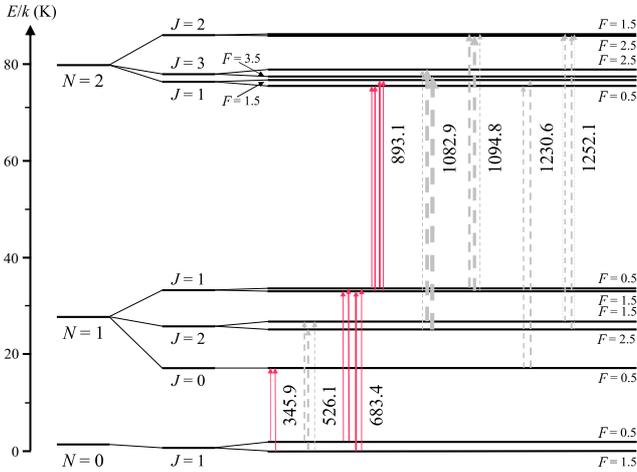


Fig. 1. Detail of the energy level diagram of SH⁺. The solid arrows mark transitions observed in the course of this work. The thickness of the arrows indicates the relative strengths of the transitions. The hyperfine splitting has been exaggerated slightly for clarity reasons.

identical to those in Brown & Müller (2009), in particular when the uncertainties are taken into account. The dipole moment of 1.285 D in the ground vibrational state has been taken from an ab initio calculation by Senekowitsch et al. (1985). The rest frequencies from the CDMS catalog are given in Table 1. Fig. 1 presents the lower part of the rotational energy level diagram of SH⁺.

2.2. The $J = 1-0$ transition of ¹³CH⁺

The X ¹Σ⁺ $J = 1-0$ rotational ground-state transition of the main isotopologue of methylidyne, ¹²CH⁺, near 835.2 GHz, cannot be observed from the ground for objects with Galactic radial velocities because of a strong telluric O₂ line approximately 1.1 GHz lower (Golubiatnikov & Krupnov 2003; Drouin et al. 2010). Observations of the $J = 1-0$ line of ¹³CH⁺ at an ~5 GHz lower frequency are however possible.

Falgarone et al. (2005) reported its detection toward the bright star-forming region G10.6-0.4 and evaluated from their observation the rest frequency as 830 132 ± 3 MHz. Two alternative values for the rest frequency, 830 107 ± 1 or 830 193 ± 4 MHz, remained viable due to ambiguities in ascribing the observed feature to LSR velocity components possibly associated with this source. These were discarded on the basis of the poor agreement with the prediction of Pearson & Drouin (2006) who had reported a transition frequency for $J = 1-0$ of ¹²CH⁺ and predicted the corresponding ¹³CH⁺ rest frequency as 830 134.3 MHz. This value was based on a combined analysis of their frequency and of optical CH⁺ data of four isotopologues employing an isotopically scaled Dunham analysis.

Our observations of ¹³CH⁺, however (see Sect. 3) indicate a rest frequency of around 830.2 GHz if we assume that this cation has an absorption profile similar to SH⁺, HCl, H¹³CO⁺, or *c*-C₃H₂.

Müller (2010) performed an analysis similar to the one published by Pearson & Drouin (2006) in order to evaluate rotational data for isotopologues of CH⁺ independently. Applying appropriate parameters which describe the breakdown of the Born-Oppenheimer approximation, he obtained a rest frequency for

$^{13}\text{CH}^+$ $J = 1-0$ compatible with the present observations. The reviewer of Müller (2010) pointed out new laboratory measurements of the $J = 1-0$ transitions of $^{12}\text{CH}^+$, $^{13}\text{CH}^+$, and $^{12}\text{CD}^+$ which were submitted subsequently by Amano (2010). Not only was the value for $^{13}\text{CH}^+$ in quite good agreement with the estimate from our observations, but it was also shown that the previously reported value for $^{12}\text{CH}^+$ was incorrect by several tens of megahertz. Including the data from Amano (2010) in his analysis, Müller (2010) calculated transition frequencies for several isotopologues of CH^+ which now should be quite reliable and which are in the CDMS catalog. The $^{13}\text{CH}^+$ $J = 1-0$ value is again given in Table 1.

The dipole moment of 1.683 D for CH^+ in the ground vibrational state has been taken from an ab initio calculation by Cheng et al. (2007); the change in dipole moment upon substitution of ^{12}C with ^{13}C is assumed to be small. A value of 1.7 D was used in the CDMS catalog (Müller et al. 2001, 2005).

2.3. HCl, $c\text{-C}_3\text{H}_2$, H^{13}CO^+ , and CO

The rest frequencies for the $J = 1-0$ transitions of both H^{35}Cl and H^{37}Cl , which have hfs, were taken from the JPL catalog² (Pickett et al. 1998). These frequencies were published by De Lucia et al. (1971). The dipole moment of H^{35}Cl for $v = 0$, $J = 1$ has been determined as 1.1086 (3) D by de Leluw & Dymanus (1973); the dipole moment of H^{37}Cl is expected to be only marginally different. See Table 1 for the frequencies of HCl and the other species considered.

The estimated accuracy for each of the three hyperfine components is 100 kHz, sufficient for the present analysis. It should be mentioned in this context that improved rest frequencies have been published by Klaus et al. (1998) and Cazzoli & Puzzarini (2004) employing Lamb-dip spectroscopy.

The $c\text{-C}_3\text{H}_2$ frequency data were also taken from the JPL catalog. The $2_{12}-1_{01}$ transition was measured by Vrtilek et al. (1987); the reported uncertainty is smaller than the value used in the JPL catalog.

The H^{13}CO^+ and CO rest frequencies were taken from the CDMS catalog (Müller et al. 2001, 2005). The rest frequency of the $J = 1-0$ transition of H^{13}CO^+ is from an astronomical observation by Schmid-Burgk et al. (2004); values for both CO transitions result from Lamb-dip measurements by Winnewisser et al. (1997).

3. Observations and data reduction

3.1. Overview

We have used the Atacama Pathfinder Experiment (APEX) 12 m telescope for observations of several sources in a number of sub-millimeter wavelength transitions of SH^+ whose accurate frequencies have recently been determined (see Sect. 2); these included the quartet of ground-state hfs lines near 683 GHz. Our observations, described in Sect. 3.2, led to the detection of these lines in absorption against Sgr B2(M) and (N). In addition to absorption from gas associated with the GC, we also find absorption at the radial velocities belonging to intervening spiral arms, which demonstrates that this species is widespread in the Galactic ISM.

For diverse reasons, our results for other SH^+ lines were not as clear as those obtained for the 683 GHz line, namely the

$N = 1-0$, $J = 0-1$ lines near 346 GHz, which are completely blended with the CO $J = 3-2$ line and our observations of the $N = 2-1$, $J = 1-1$ lines were inconclusive. We made, however, an unambiguous detection of absorption in the $J = 1-0$ transition of the $^{13}\text{CH}^+$ radical near 830 GHz, again from gas in the Sgr B2 region and from spiral arm clouds. Absorption in that line has previously been reported by Falgarone et al. (2005) toward G10.6+0.4, leading to an estimate of its rest frequency that is discussed in Sect. 2.2.

Finally, we took a wide bandwidth spectrum that covers the $J = 1-0$ transitions of both the H^{35}Cl and H^{37}Cl isotopologues of hydrochloric acid. The former had been observed by Zmuidzinas et al. (1995) toward a position midway between Sgr B2(M) and (N). Since their spectrum only covered the LSR velocity range between -10 and $+140$ km s⁻¹ it does not contain information for the spiral arm feature velocities. While we confirm the Sgr B2 velocity absorption, no clear absorption is found toward the latter in our more sensitive and wider bandwidth spectra. In Sect. 4.1.4, our upper limits for these diffuse lines of sight are compared with the tentative ultraviolet detection of HCl absorption toward ζ Oph by Federman et al. (1995).

3.2. APEX observations and data reduction

Our SH^+ observations were made on 2008 September 19 and 25 under good to very good weather conditions with the 12-m Atacama Pathfinder Experiment telescope, APEX³ (Güsten et al. 2006). The precipitable water vapor (PWV) content was between 0.3 and 0.7 mm throughout the observations.

The 683 and 893 GHz lines were measured in the lower sideband (LSB) with the MPIfR-built CHAMP+ receiver array (Kasemann et al. 2006). CHAMP+ consists of two modules of 7 pixels each with one central pixel and the others forming a hexagon around it. The one module covers the 350 μm atmospheric window and the other the 450 μm window. Calibration was obtained using the chopper wheel technique, considering the different atmospheric opacities in the signal and image sidebands of the employed double sideband receivers. The image sideband was rejected to the 10 dB level. During the observations the single sideband system temperatures at 683 GHz were between 1700 and 2600 K. To ensure flat spectral baselines, the wobbling secondary was chopped with a frequency of 1.5 Hz and a throw of 240'' about the cross elevation axis. The wobbler was operated in symmetric mode, which means that the on source and off positions are interchanged between subsequent subsamples, which cancels any asymmetries in the optical paths. Such observations deliver a reliable estimate of the continuum level. We found, however, that the quality of the baseline deteriorated with increasing continuum flux density.

The radiation was analyzed with a new incarnation of the MPIfR Fast Fourier Transform spectrometer (FFTS) (Klein et al. 2006), which provided two 1.5 GHz wide modules set to 1024 frequency channels each. The resultant channel spacing was 1.46 MHz, corresponding to 0.49 and 0.70 km s⁻¹ at the highest and lowest frequency we observed (893 and 625 GHz, respectively). The FFTS modules were operated in series with an overlap of 300 MHz to provide a total coverage of 2.4 GHz bandwidth. To check the telescope pointing, drift scans were made across the continuum of Sgr B2(N). Pointing corrections were

³ This publication is based on data acquired with the Atacama Pathfinder Experiment (APEX). APEX is a collaboration between the Max-Planck-Institut für Radioastronomie, the European Southern Observatory, and the Onsala Space Observatory.

² Website: <http://spec.jpl.nasa.gov/ftp/pub/catalog/catdir.html>, see also <http://spec.jpl.nasa.gov/>

derived from these measurements. The pointing was found to be accurate to within $\approx 3''$, acceptable given the *FWHM* beam size, θ_B , which is $9''$ *FWHM* at 683 GHz.

The SH⁺ line near 346 GHz was observed with the 345 GHz atmospheric window module of the Swedish heterodyne facility instrument for the APEX telescope (Vassilev et al. 2008) with system temperatures between 320 and 370 K. Two facility FFTS backends with 1 GHz bandwidth and 8192 channels each were connected to the receiver with a slight overlap to reach a total bandwidth of 1.8 GHz. The beam width at the observing frequency is about $18''$. Pointing was again checked with continuum scans on Sgr B2(N).

Observations of the ¹³CH⁺ $J = 1-0$ lines near 830 GHz were performed using the CHAMP+ array on 2009, August 11 under extremely good weather conditions with a PWV content of 0.14 to 0.2 mm. Two 1.5 GHz FFTS modules were used with overlap to reach a total bandwidth of 2.4 GHz. Prior to the integration on Sgr B2, the telescope was pointed on the continuum of Sgr B2(N) and G10.62–0.38. For the line observations again the wobbler was used with a throw of $240''$ and a chopping frequency of 1.5 Hz.

Finally, observations of the H³⁵Cl and H³⁷Cl $J = 1-0$ transitions were made with CHAMP+'s lower frequency module in 2009 June under superb weather conditions.

4. Results and data analysis

During our three observing campaigns, we have gathered data that allow unambiguous identification of the SH⁺ and ¹³CH⁺ molecules toward Sgr B2. In addition, we have made observations of the $J = 1-0$ ground-state transition of both the H³⁵Cl and H³⁷Cl isotopologues of hydrogen chloride.

In absorption spectroscopy, the column density in a transition's lower energy level, N_1 , can be calculated from its observed optical depth, τ and line width $\Delta\nu$ if its excitation temperature, T_{ex} , is known:

$$N_1 = \frac{h}{8\pi^2} \frac{g_1}{S\mu^2} \left[1 - e^{-h\nu/kT_{\text{ex}}} \right]^{-1} \tau \Delta\nu, \quad (1)$$

where A_{ul} is the Einstein A coefficient; h and k are the Planck and Boltzmann constants, respectively, and $\nu = E_u - E_l$ the transition's rest frequency; E_u and E_l are its upper and lower energy levels, respectively.

The total column density, N_{tot} , is given by

$$N_{\text{tot}} = \frac{N_1}{g_1} e^{E_1/kT_{\text{rot}}} Q(T_{\text{rot}}), \quad (2)$$

where Q is the partition function for the rotation temperature, T_{rot} .

In the case of a line with a single absorption component, the optical depth and line width are usually determined by a Gaussian fit to the line profile and τ is calculated from the line to continuum intensity ratio:

$$\tau = -\ln(1 - |T_L|/T_C) \quad (3)$$

where T_L and T_C are the observed line and continuum brightness temperature, respectively.

Things are generally not so simple for the immensely line-rich Sgr B2 sources, for which practically the whole (sub)mm range contains a large number of lines from different species in each chosen frequency interval, many of them blended. To make things even more complex, many of the simpler species show

multiple absorption components originating from various spiral arms along the line of sight that are blended with each other and with spectral components from lines of other species at GC velocities. Lines showing hfs, such as SH⁺ are yet more difficult to analyze. To deal with this, we employ, as described by Belloche et al. (2008), the XCLASS⁴ program created and developed by Peter Schilke. XCLASS is an extension of the CLASS spectral line data reduction program that is part of the GILDAS⁵ software package developed by the Institute for Radio Astronomy at Millimeter Wavelengths (IRAM). Using XCLASS one may fit all lines in a spectrum simultaneously as described in Sect. 4.1.

For each species, XCLASS assumes that the level populations are described by a single excitation temperature, which we refer to as the rotation temperature, T_{rot} . Different species can have different rotation temperatures. Here we divide between two cases: First, the critical densities of all the lines in the frequency range of interest are lower than the density in the modeled emission region. Then we are dealing with local thermodynamic equilibrium (LTE), which applies, e.g., for the extremely line rich hot cores associated with Sgr B2(M) and (N). In particular in the latter, the complex molecules NH₂CH₂CN, C₂H₅OCHO, and C₃H₇CN along with the ¹³C isotopologues of vinyl cyanide have recently been identified using XCLASS with model temperatures of $\approx 100-150$ K (Belloche et al. 2008, 2009; Müller et al. 2008). In the second, very low density case, which applies for the absorption lines discussed in this paper, T_{rot} equals the temperature of the cosmic microwave background radiation, T_{CMB} , i.e. 2.728 K. While this might be a good assumption for clouds far from the strong Sgr B2 continuum sources, e.g., in the spiral arms, assuming $T_{\text{rot}} = T_{\text{CMB}}$ will underestimate column densities for molecules in the vicinity of Sgr B2(M) and (N).

4.1. Modeling of the absorption lines toward Sgr B2(M)

4.1.1. The model for the spiral arm and galactic center LSR velocity features

The SH⁺(1₁-0₁) spectra obtained with the CHAMP+ array consist of the superposition of a number of absorption components associated with the dense core Sgr B2(M) and several molecular clouds distributed along the line of sight with different systemic velocities (see, e.g., Greaves & Williams 1994).

The association of the absorption components' LSR velocities with Galactic spiral arms or kinematic features associated with the GC located along the line of sight is presented in Table 2. It is essentially based on the velocity interpretation of H₂CO and CS absorption by Whiteoak & Gardner (1979) and Greaves & Williams (1994), respectively, as well as the analyses of Sofue (2006) and Vallée (2008). Although in the GC direction absorption close to $V_{\text{lsr}} = 0$ could in principle come from any location on the line of sight, we favor a physical association with the GC since Gardner & Whiteoak (1981) found low values of the ¹²C/¹³C ratio (20–30) for this velocity range, consistent with a Galactic center origin.

The blending of these absorption components is further complicated by the hyperfine structure of the SH⁺ transition. To allow meaningful fitting, we used information derived from the absorption spectra of other molecules obtained as part of a complete line survey done with the IRAM 30 m telescope in the

⁴ <http://www.astro.uni-koeln.de/projects/schilke/XCLASS>

⁵ <http://www.iram.fr/IRAMFR/GILDAS/>

Table 2. Velocity ranges and $^{12}\text{C}/^{13}\text{C}$ isotopic ratios of the Galactic absorption components along the line of sight of Sgr B2(M).

Velocity range (1)	$^{12}\text{C}/^{13}\text{C}$ (2)	Location (3)
~62	20	Galactic Center, Sgr B2
39–25	40	Scutum/Crux arm
22–12	60	Sagittarius arm
8 – –9	20	Galactic Center
–13 – –50	40	3 kpc expanding ring
<–53	20	Galactic Center

3 mm atmospheric window toward both hot cores Sgr B2(M) and Sgr B2(N) (see [Belloche et al. 2008, 2009](#)).

The line survey was analysed with the XCLASS software (see Sect. 4)⁶. Each molecule identified in the survey was modeled with the following free parameters: source size, temperature, column density, linewidth, and velocity offset with respect to the systemic velocity of the source, 62 km s⁻¹ for Sgr B2(M). When several components were needed to reproduce the observed spectrum of a molecule, we fitted a set of parameters for each component. The combination of the predicted spectra of all identified molecules was done assuming that the emission adds up linearly (for more details, see [Belloche et al. 2008](#)).

To model the absorption lines observed toward Sgr B2(M), we assumed a beam-averaged continuum brightness temperature T_{cont} of 5.9 K in the 3 mm window, as derived from the saturated absorption spectra of HCN and CN (see Table 1). The modeling of the absorption components was done in the $T_{\text{rot}} = T_{\text{CMB}}$ approximation with a flag indicating that the absorption spectrum has to be computed against a background emission consisting of both the continuum emission and the contribution of the other molecules seen in emission, i.e. for each absorption component with the equation

$$T_{\nu} = (J_{\nu}(T_{\text{ex}}) - J_{\nu}(T_{\text{cont}})) (1 - e^{-\tau_{\nu}}) + T_{\nu}^{\text{em}} e^{-\tau_{\nu}}, \quad (4)$$

with T_{ex} the excitation temperature, T_{cont} the background brightness temperature, T_{ν}^{em} the emission line spectrum, and τ_{ν} the opacity of the line at frequency ν , for a beam filling factor of 1.

Table 2 also lists the $^{12}\text{C}/^{13}\text{C}$ isotopic ratios we assumed. The $^{12}\text{C}/^{13}\text{C}$ isotopic ratio of the Galactic Center components was fixed to 20 ([Müller et al. 2008](#)). This value is compatible with the Galactic gradient derived by [Milam et al. \(2005, Eq. \(5\)\)](#). Their equation was additionally employed to fix the ratio to 40 for the Scutum and Norma arm components, and 60 for the Sagittarius arm components, with the galactocentric distances of [Vallée \(2008\)](#). The $^{16}\text{O}/^{18}\text{O}$ isotopic ratio was taken from [Wilson & Rood \(1994\)](#): 250 for the GC components, 327 for the Scutum and Norma arm components, and 560 for the Sagittarius arm components.

We present, in Fig. 2d and e, the results of our modeling for $c\text{-C}_3\text{H}_2(2_{12}-1_{01})$ and $\text{H}^{13}\text{CO}^+(1-0)$, respectively. The model for $\text{H}^{13}\text{CO}^+(1-0)$ was obtained by fitting HCO^+ , H^{13}CO^+ , and HC^{18}O^+ simultaneously. The fit to the observed $\text{H}^{13}\text{CO}^+(1-0)$ spectrum consists of four components in emission (one for the main emission peak and three to reproduce the wings), one absorption component to mimic the self-absorption in Sgr B2(M)⁷

⁶ Where noted, for the components associated with Sgr B2 (around +62 km s⁻¹), a $T_{\text{rot}} > T_{\text{CMB}}$ was assumed.

⁷ Although the fits to the self-absorption features in Fig. 2d and e look relatively good, we emphasize that a uniform $T_{\text{rot}} = T_{\text{CMB}}$ model is not complex enough to provide reliable physical parameters to describe the self-absorption. The parameters listed for the self-absorption components in the following tables should therefore be viewed with caution.

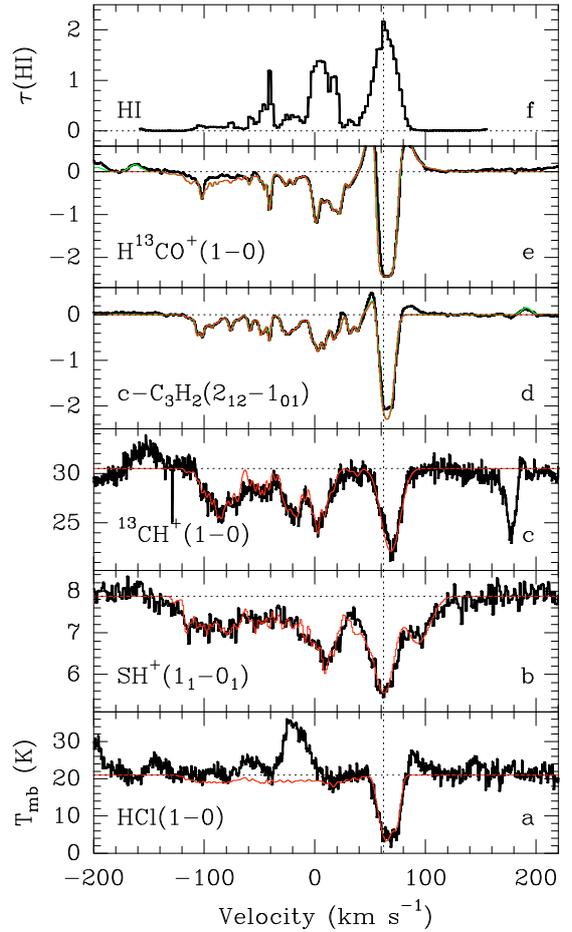


Fig. 2. From bottom to top, panels a) to e) show absorption spectra taken with the APEX telescope with the CHAMP+ receiver array. Spectra a) and b) were taken with the central pixel of CHAMP+ toward Sgr B2(M) (see Fig. 5). Spectrum b) was obtained toward a position ($-20.4'', 1.4''$) offset from Sgr B2(M) with the CHAMP+ pixel 2. a): H^{35}Cl 1–0 absorption spectrum. b): SH^+ 1_1-0_1 absorption spectrum. c): $^{13}\text{CH}^+$ 1–0 absorption spectrum. In panels a)–c), the red curve is the synthetic spectrum described in Sect. 4.1 and the horizontal dotted line shows the continuum level. d) and e): same as b) for the $c\text{-C}_3\text{H}_2$ $2_{12}-1_{01}$ and H^{13}CO^+ 1–0 transitions observed toward Sgr B2(M) with the IRAM 30 m telescope, respectively. Panel f) shows the optical depth of the 21 cm HI line vs. LSR velocity as derived by the procedure described in Sect. 5.1.2. In panels d) and e), the red curve is the synthetic spectrum of the molecule, the green curve is the predicted spectrum including in addition all molecules identified in our complete 3 mm line survey so far, and the horizontal dotted line indicates the zero level (after baseline removal because the observations were performed in position-switching mode with a far OFF position, which yields a very uncertain baseline level). In all panels, the spectra are plotted in main-beam brightness temperature scale, the vertical dotted line marks the systemic velocity of the source (62 km s⁻¹).

and 34 absorption components associated with the diffuse clouds along the line of sight, with linewidths varying between 3 and 8 km s⁻¹ and an excitation temperature arbitrarily fixed to 2.7 K. The parameters of the fit to H^{13}CO^+ are listed in Table 4. The model predicts too strong absorption for the $\text{H}^{13}\text{CO}^+(1-0)$ components with $v < -50$ km s⁻¹, while the corresponding $\text{HCO}^+(1-0)$ components are well fitted (not shown here). The disagreement must result either from an underestimate of the $^{12}\text{C}/^{13}\text{C}$ isotopic ratio or from contamination by emission lines that are not yet included in our complete model. It could in principle also

Table 3. Parameters of the best-fit LTE models of SH⁺, ¹³CH⁺, and c-C₃H₂, as well as the alternative LTE model of H¹³CO⁺ fitted with the same velocity components as c-C₃H₂.

n_c^a	V_{lsr}^b (km s ⁻¹)	ΔV^c (km s ⁻¹)	$\frac{^{12}\text{C}}{^{13}\text{C}}^d$	SH ⁺		¹³ CH ⁺		c-C ₃ H ₂		H ¹³ CO ⁺	
				N^e (cm ⁻²)	N^e (cm ⁻²)	R_{13}^f	R_{12}^g	N^e (cm ⁻²)	R^h	N^e (cm ⁻²)	R_{12}^i
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	—	—	—	—	—	—	—	2.4 × 10 ¹⁴	—	—	—
2	64.0	19.0	20	2.0 × 10 ¹⁴	1.8 × 10 ¹³	10.8	0.53	1.9 × 10 ¹⁴	1.0	1.4 × 10 ¹⁴	0.07
3	38.5	5.0	40	<2.8 × 10 ¹²	3.8 × 10 ¹¹	<7.4	<0.18	4.2 × 10 ¹²	<0.7	2.4 × 10 ¹¹	<0.29
4	32.0	5.0	40	<2.8 × 10 ¹²	<1.6 × 10 ¹¹	—	—	4.7 × 10 ¹²	<0.6	7.8 × 10 ¹¹	<0.09
5	22.0	5.0	60	1.1 × 10 ¹³	<1.6 × 10 ¹¹	>70.6	>1.15	4.1 × 10 ¹²	2.8	2.5 × 10 ¹²	0.07
6	17.0	5.0	60	2.1 × 10 ¹³	9.6 × 10 ¹¹	22.1	0.36	5.9 × 10 ¹²	3.6	2.0 × 10 ¹²	0.17
7	12.0	6.0	60	2.8 × 10 ¹³	1.4 × 10 ¹²	19.6	0.32	2.7 × 10 ¹²	10.5	1.8 × 10 ¹²	0.25
8	8.2	5.0	20	2.5 × 10 ¹³	2.1 × 10 ¹²	12.2	0.60	8.1 × 10 ¹²	3.2	6.0 × 10 ¹¹	2.06
9	2.5	5.0	20	1.8 × 10 ¹³	3.5 × 10 ¹²	5.2	0.26	9.7 × 10 ¹²	1.9	3.0 × 10 ¹²	0.30
10	-2.5	4.5	20	1.1 × 10 ¹³	1.9 × 10 ¹²	5.9	0.29	5.4 × 10 ¹²	2.1	1.2 × 10 ¹²	0.46
11	-8.7	5.0	20	1.6 × 10 ¹³	1.6 × 10 ¹²	9.7	0.48	1.4 × 10 ¹²	11.1	3.2 × 10 ¹¹	2.38
12	-15.5	6.0	40	8.4 × 10 ¹²	2.9 × 10 ¹²	2.9	0.07	3.2 × 10 ¹²	2.6	3.6 × 10 ¹¹	0.57
13	-20.0	5.0	40	8.4 × 10 ¹²	1.6 × 10 ¹²	5.3	0.13	2.7 × 10 ¹²	3.2	5.4 × 10 ¹¹	0.38
14	-25.0	6.0	40	8.4 × 10 ¹²	2.5 × 10 ¹²	3.3	0.08	5.6 × 10 ¹²	1.5	5.4 × 10 ¹¹	0.38
15	-29.5	4.0	40	8.4 × 10 ¹²	8.0 × 10 ¹¹	10.6	0.26	2.1 × 10 ¹²	3.9	3.3 × 10 ¹¹	0.63
16	-35.5	4.0	40	8.4 × 10 ¹²	4.8 × 10 ¹¹	17.7	0.43	2.7 × 10 ¹¹	31.5	1.5 × 10 ¹¹	1.38
17	-41.3	3.3	40	7.0 × 10 ¹²	7.3 × 10 ¹¹	9.6	0.24	4.5 × 10 ¹²	1.6	1.6 × 10 ¹²	0.11
18	-45.7	3.0	40	4.2 × 10 ¹²	8.0 × 10 ¹¹	5.3	0.13	2.6 × 10 ¹²	1.6	5.5 × 10 ¹¹	0.19
19	-49.0	3.0	40	4.2 × 10 ¹²	7.7 × 10 ¹¹	5.5	0.14	3.0 × 10 ¹²	1.4	2.9 × 10 ¹¹	0.36
20	-53.5	4.0	20	9.3 × 10 ¹²	9.2 × 10 ¹¹	10.0	0.49	1.2 × 10 ¹²	7.9	2.0 × 10 ¹¹	2.29
21	-58.7	4.0	20	<2.8 × 10 ¹²	7.0 × 10 ¹¹	<4.0	<0.20	3.2 × 10 ¹²	<0.9	6.6 × 10 ¹¹	<0.21
22	-69.8	6.0	20	9.9 × 10 ¹²	2.1 × 10 ¹²	4.8	0.23	1.6 × 10 ¹²	6.1	5.1 × 10 ¹¹	0.96
23	-76.0	4.5	20	9.0 × 10 ¹²	1.6 × 10 ¹²	5.7	0.28	3.3 × 10 ¹²	2.7	5.1 × 10 ¹¹	0.86
24	-80.1	4.0	20	7.0 × 10 ¹²	1.1 × 10 ¹²	6.3	0.31	4.8 × 10 ¹¹	14.6	2.4 × 10 ¹¹	1.43
25	-84.3	5.0	20	1.3 × 10 ¹³	2.5 × 10 ¹²	5.0	0.24	9.1 × 10 ¹¹	13.9	5.1 × 10 ¹¹	1.21
26	-88.5	4.0	20	<2.8 × 10 ¹²	1.8 × 10 ¹²	<1.6	<0.08	1.5 × 10 ¹²	<1.9	4.5 × 10 ¹¹	<0.31
27	-93.0	4.0	20	9.9 × 10 ¹²	1.4 × 10 ¹²	6.9	0.34	2.5 × 10 ¹²	4.0	6.0 × 10 ¹¹	0.80
28	-97.5	4.0	20	1.4 × 10 ¹³	1.1 × 10 ¹²	12.6	0.62	2.0 × 10 ¹²	6.9	6.0 × 10 ¹¹	1.15
29	-101.8	4.0	20	1.1 × 10 ¹³	9.6 × 10 ¹¹	11.8	0.58	4.3 × 10 ¹²	2.6	1.1 × 10 ¹²	0.48
30	-106.2	4.0	20	1.1 × 10 ¹³	4.5 × 10 ¹¹	25.2	1.24	4.1 × 10 ¹²	2.8	6.0 × 10 ¹¹	0.92
31	-111.6	4.0	20	8.4 × 10 ¹²	<1.6 × 10 ¹¹	>53.0	> 2.60	8.6 × 10 ¹¹	9.8	5.4 × 10 ¹¹	0.76
32	-116.0	4.0	20	1.4 × 10 ¹³	<1.6 × 10 ¹¹	> 88.3	> 4.33	4.3 × 10 ¹¹	32.8	4.2 × 10 ¹¹	1.64

Notes. All components have a rotation temperature of 2.7 K except components $n_c = 1$ and 2 of c-C₃H₂ which have 15.0 and 3.0 K, respectively, and component $n_c = 2$ of H¹³CO⁺ which has 3.1 K. The emission components of the H¹³CO⁺ model are the same as in Table 4 and are not listed here. ^(a) Component number. ^(b) LSR velocity, the same for all four molecules except for 1 component of ¹³CH⁺ (2: 68.7 km s⁻¹), 2 components of c-C₃H₂ (1: 61.0 km s⁻¹, 2: 65.0 km s⁻¹), and 1 component of H¹³CO⁺ (2: 64.5 km s⁻¹). ^(c) Linewidth (*FWHM*), the same for all four molecules except for 2 components of c-C₃H₂ (1: 15.0 km s⁻¹, 2: 11.0 km s⁻¹) and for 1 component of H¹³CO⁺ (2: 12.0 km s⁻¹). ^(d) Assumed ¹²C/¹³C isotopic ratio for HCO⁺ and CH⁺. ^(e) Column density. ^(f) Column density ratio SH⁺/¹³CH⁺. ^(g) Column density ratio SH⁺/¹²CH⁺. ^(h) Column density ratio SH⁺/c-C₃H₂. ⁽ⁱ⁾ Column density ratio SH⁺/HCO⁺.

result from larger excitation temperatures for HCO⁺ compared to H¹³CO⁺.

The fit to c-C₃H₂ was done with velocity and linewidth parameters slightly different from HCO⁺, although we tried to stay as close as possible to the components identified in HCO⁺. The parameters of the fit to c-C₃H₂ are listed in Table 3. The model consists of one component in emission (we did not attempt to model the possible wing emission in this case), one absorption component to mimic the self-absorption, and 30 absorption components associated with the diffuse clouds, with an excitation temperature of 2.7 K and linewidths varying between 3 and 6 km s⁻¹.

4.1.2. Modeling the SH⁺ absorption

Since we considered c-C₃H₂ a priori to be a better diffuse gas tracer than ¹³HCO⁺ (but see Sect. 5) and because of the added uncertainty of assigning a ¹²C/¹³C ratio to each absorption

components, we decided to model the SH⁺ absorption spectrum based on the parameters derived for c-C₃H₂, i.e. we used the same number of absorption components with the same velocities and line widths, except for the component physically associated with Sgr B2(M) itself. Again, we fixed the excitation temperature of each component to 2.7 K. Since the observations were done in wobbler mode, we trusted the baseline level and derived the level of continuum emission directly from the observed spectra shown in Fig. 5. To compute the synthetic spectra, we assumed that the physical parameters of the absorbing components are uniform across the CHAMP+ field of view and therefore we used the same set of parameters for all pixels. The resulting synthetic spectra are overlaid on the observed spectra in Fig. 5. The agreement is quite good in general, which gives us some more confidence in the way we estimated the continuum level. However, significant deviations are seen for pixels 1, 3, and 4. As mentioned in Sect. 3, the baseline quality of the CHAMP+ array drops with increasing level of continuum emission and

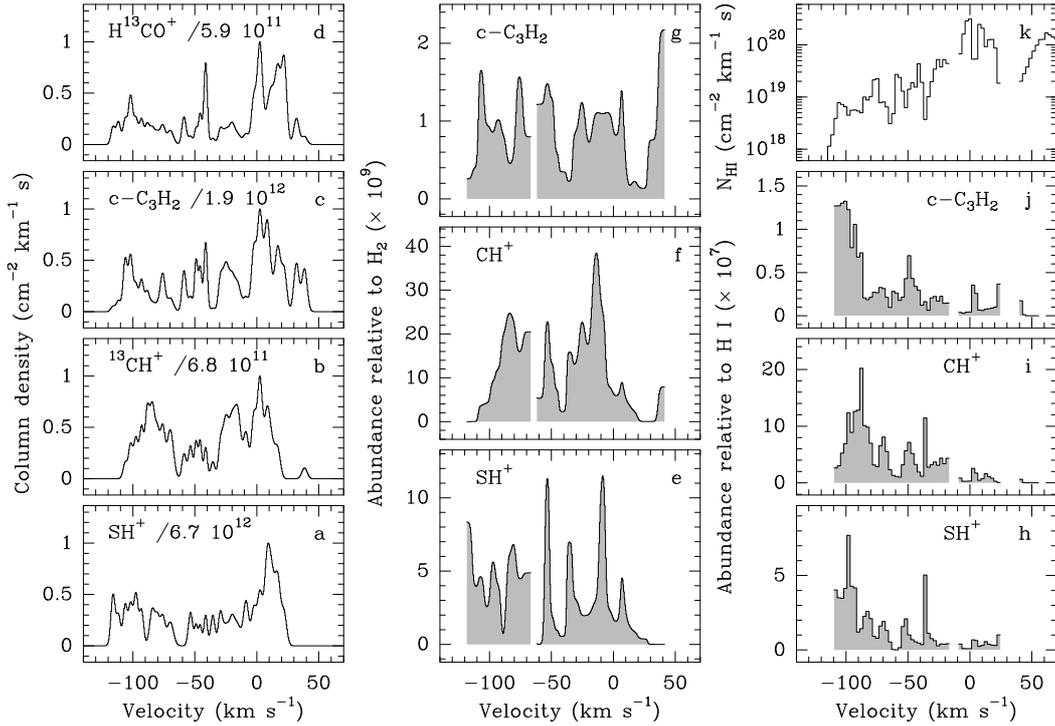


Fig. 3. a)–d) Column density profiles computed by adding the Gaussian velocity absorption components listed in Table 3. The components with upper limit were not included. e)–g) Abundance profiles relative to H_2 . The H_2 column density was computed from the HCO^+ column density assuming an HCO^+ abundance of 5×10^{-9} . h)–j) Abundance profiles relative to H I . k) The H I column density was computed from comparing an H I absorption with an H I emission profile (see text).

line contamination from the hot molecular core associated with Sgr B2(M). Pixel 4 is the most affected, and we believe that the poor quality of the fit is mainly due to this problem. As far as the northern pixels 1 and 3 are concerned, the main absorption component is much stronger than the one predicted by our simple model. This may be due to spatial variations of the SH^+ column density across the Sgr B2 molecular cloud since the cloud is far from being uniform (in particular, the hot, dense core Sgr B2(N) is located $\sim 50''$ to the north of Sgr B2(M)). If the variations from pixel to pixel can be trusted, then we can estimate the variations of the SH^+ column densities in the spiral arm diffuse clouds over the footprint of CHAMP^+ by modeling each pixel separately. This exercise yields column density variations typically on the order of a factor 2, but in some cases up to a factor 5. However, given the low signal-to-noise ratio, the unknown baseline quality, and the line blending, these numbers are very uncertain and it is unlikely that they really reflect the spatial variations of the SH^+ column density.

The parameters used to fit the SH^+ 1_1-0_1 absorption spectrum are listed in Table 3 and the fit to the spectrum obtained with pixel 2 is plotted again in Fig. 2b for a direct comparison with HCl , $^{13}\text{CH}^+$, $c\text{-C}_3\text{H}_2$, and H^{13}CO^+ . Although the decision to fix the linewidths and velocities to those derived from $c\text{-C}_3\text{H}_2$ helps a lot to constrain the SH^+ model, the hyperfine structure of SH^+ and the limited signal-to-noise ratio of the observed spectra do not allow to find a unique solution. Using the somewhat different set of velocity and linewidth parameters derived from HCO^+ , we were able to find a synthetic spectrum for SH^+ as good as the SH^+ model derived from $c\text{-C}_3\text{H}_2$ (the parameters of this alternative model are listed in Table 4). Therefore, the SH^+ model described in Table 3 should be considered as a possible model rather than the best-fit model. Nevertheless, if we assume that $c\text{-C}_3\text{H}_2$ and SH^+ trace the same diffuse clouds,

then it makes sense to compare the column densities listed in Table 3. Column 10 lists the column density ratio $\text{SH}^+ / c\text{-C}_3\text{H}_2$. It varies by nearly two orders of magnitude, from <0.6 to ~ 33 . As a caveat, we remind that the SH^+ model assumes no contamination from emission lines of other molecules. If there are contaminating emission lines, then the column densities derived for the SH^+ components contaminated by these emission lines are lower limits.

Unfortunately, the SH^+ 1_0-0_1 line at 345.9 GHz is heavily blended with the spiral arm components of the $\text{CO } 3-2$ line seen in absorption (see Fig. 6a). The $T_{\text{rot}} = T_{\text{CMB}}$ model derived for the 1_1-0_1 line predicts 1_0-0_1 spiral arm components in absorption that are relatively consistent with the observed spectrum dominated by the $\text{CO } 3-2$ features, except around 62 km s^{-1} , the systemic velocity of Sgr B2(M). At 893 GHz, there is no clear evidence for the SH^+ 2_1-1_1 line (see Fig. 7). Our $T_{\text{rot}} = T_{\text{CMB}}$ model predicts no significant absorption for this higher energy transition (see red spectrum in Fig. 7). On the other hand, this transition could partly contribute to the broad feature detected in emission between 58 and 125 km s^{-1} (although the higher velocity half of that feature is uncertain due to the limited baseline quality). An additional model component in emission is indeed permitted by the 893 GHz spectrum and can even solve the disagreement at 62 km s^{-1} between the synthetic and observed spectra of the 1_0-0_1 transition. If this emission component has a size smaller than $\sim 20''$, then the $T_{\text{rot}} = T_{\text{CMB}}$ synthetic spectrum of the $(-20.4'', +1.4'')$ CHAMP^+ pixel at 683 GHz (shown in Fig. 2) will be unaffected and still provide a good fit to the observations. However, the fit to the spectrum of the central pixel at 683 GHz (see Fig. 5) will be worse, and a more elaborate radiative transfer modeling would be needed to find a consistent fit for this potential emission component.

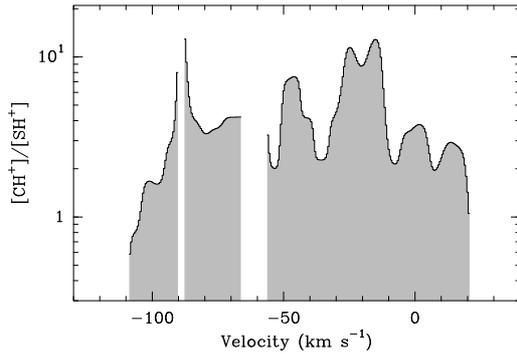


Fig. 4. Ratio of the column density profiles of CH⁺ and SH⁺ shown in Fig. 3.

4.1.3. The ¹³CH⁺ absorption

The ¹³CH⁺ 1–0 transition detected in absorption toward Sgr B2(M) was also modeled in the $T_{\text{rot}} = T_{\text{CMB}}$ approximation (see Fig. 2c). We used the SH⁺ model as a reference, keeping the velocity offsets and linewidths unchanged. The resulting fit, shown in red in this figure, is in good agreement with the observed spectrum, although it could certainly be somewhat better if the line widths were taken as free parameters for the fitting.

The column densities resulting from this fit are listed in Table 3, as well as the SH⁺/¹³CH⁺ and the SH⁺/¹²CH⁺ column density ratio. The latter varies significantly from component to component, from 0.07 to 1.2, if we exclude components 31 and 32 in Table 3 at whose velocity the signal-to-noise ratio in the SH⁺ spectrum is very low and which are not detected in the ¹³CH⁺ absorption at all.

The ¹³CH⁺ 1–0 spectrum shows an absorption feature at +172.6 km s⁻¹. Although absorption in CO is detected at this velocity in our 3 mm line survey in the CO 1–0 and ¹³CO 1–0 lines (see Fig. 6), this component is neither detected in H¹³CO⁺ 1–0, *c*-C₃H₂ 2₁₂–1₀₁, nor in SH⁺ 1₁–0₁ (see Fig. 2). Features at this velocity are usually attributed to the Expanding Molecular Ring (EMR, e.g. Morris & Serabyn 1996) but +172.6 km s⁻¹ would refer to the far side of the ring, hence no absorption is expected and it is possibly more likely that this feature is an as yet unidentified (U) absorption line.

We also list in Table 3 the parameters of an alternative H¹³CO⁺ $T_{\text{rot}} = T_{\text{CMB}}$ model fitted with the same velocity components as *c*-C₃H₂ (i.e. same linewidths and LSR velocities). This model is less good than the one that we described above and that we showed in Fig. 2e, but it can be used to roughly estimate the SH⁺/HCO⁺ column density ratio (Col. 12 of Table 3). This ratio varies by about one order of magnitude, from 0.07 to 2.38.

4.1.4. Modeling the HCl absorption only from the Sgr B2 region

The HCl and H³⁷Cl transitions detected in absorption toward Sgr B2(M) were also modeled in the $T_{\text{rot}} = T_{\text{CMB}}$ approximation (see Fig. 8). We used the SH⁺ model as a reference, keeping the velocity offsets and linewidths unchanged, except for the main absorption component associated with Sgr B2(M) itself. The resulting fit is shown in red in Fig. 8 and the fit parameters are listed in Table 5. Only the main absorption component is clearly detected for both isotopologues. For all other velocity components but one, we used a column density of 2.8×10^{12} cm⁻², represented by the red line in Fig. 8, to get a rough estimate of the column density upper limits. Only one additional velocity component ($n_c = 6$; ~ 17 km s⁻¹) marginally shows absorption in the

main isotopologue HCl at 2.8 times this value. Due to the compact hyperfine structure, the line width of the main absorption component (8 km s⁻¹) is somewhat uncertain, but our modeling suggests that it is significantly smaller than for the other species. Finally, for Sgr B2(M) we derive an isotopic [H³⁵Cl/H³⁷Cl] ratio of ~ 4 , consistent with the terrestrial value.

4.2. Summary of modeling

To visualize the results of our modeling presented in Tables 3 and 4, we show, in Fig. 3, the column densities and abundances that we derived for the species considered as functions of LSR velocity. Figure 4 presents the CH⁺ to SH⁺ abundance ratio vs. LSR velocity.

5. Discussion

5.1. Column densities and abundances

5.1.1. Caveats

We would like to precede our discussion of the SH⁺, ¹³CH⁺, and HCl abundances in the spiral arm clouds with some cautionary notes. First, the assignment of velocity features to Galactocentric distance is by no means clear-cut. For example, Sofue (2006), from a careful analysis of the longitude-velocity diagram of the GC region, assigns certain velocity features to peculiar components of the complex Galactic center velocity field, namely the GC molecular ring and the GC expanding ring, both within a Galactocentric radius, R , of 600 pc of the GC. In addition to several spiral arms, he invokes expanding rings at $R = 3$ and 4 kpc. Some of Sofue’s conclusions are at variance from the LSR velocity-location assignment we present in Sect. 4.1. Second, SH⁺ and ¹³CH⁺ may in principle be associated with predominantly atomic or molecular diffuse clouds. For meaningful abundance calculations, it is thus necessary to have values for both the atomic hydrogen column density, $N(\text{HI})$, and the molecular hydrogen column density, $N(\text{H}_2)$. Actually, the clouds from which we see absorption may have complex structure, e.g., a Giant Molecular Cloud region and a diffuse atomic envelope (see Sect. 5.2) and/or we may be dealing with more than one cloud along each line of sight. Certainly, the HI spin temperatures are in the range of values found for diffuse clouds and significantly higher than the canonical GMC temperatures values of 20–30 K.

Two final, more technical caveats relate to the way we derive column densities. For the 3 mm Sgr B2(M) spectra for H¹³CO⁺ and *c*-C₃H₂ we have constructed full XCLASS models considering all the absorption from these molecules *plus* emission from them and all other molecules. In contrast, for the submillimeter spectra, we have not done this. While even the 3 mm spectra may be contaminated by emission features inadequately treated by the model, for the submm absorption spectra this is a much greater source of uncertainty for line assignments and intensity predictions, making, strictly speaking all the column densities we determine lower limits. We do at present not feel confident to construct a comprehensive model for the submm spectra. Similarly, if, as discussed in Sect. 4, excitation by the ambient radiation field is non-negligible, then $T_{\text{rot}} > T_{\text{CMB}}$, which would make our column densities underestimates.

Finally, our XCLASS-based method makes it difficult to derive statistical errors and, thus, upper limits rigorously in a χ^2 sense. Rather, upper limits are determined by assuming a column density, calculating a model spectrum and then “eye-balling” whether it is consistent with the data.

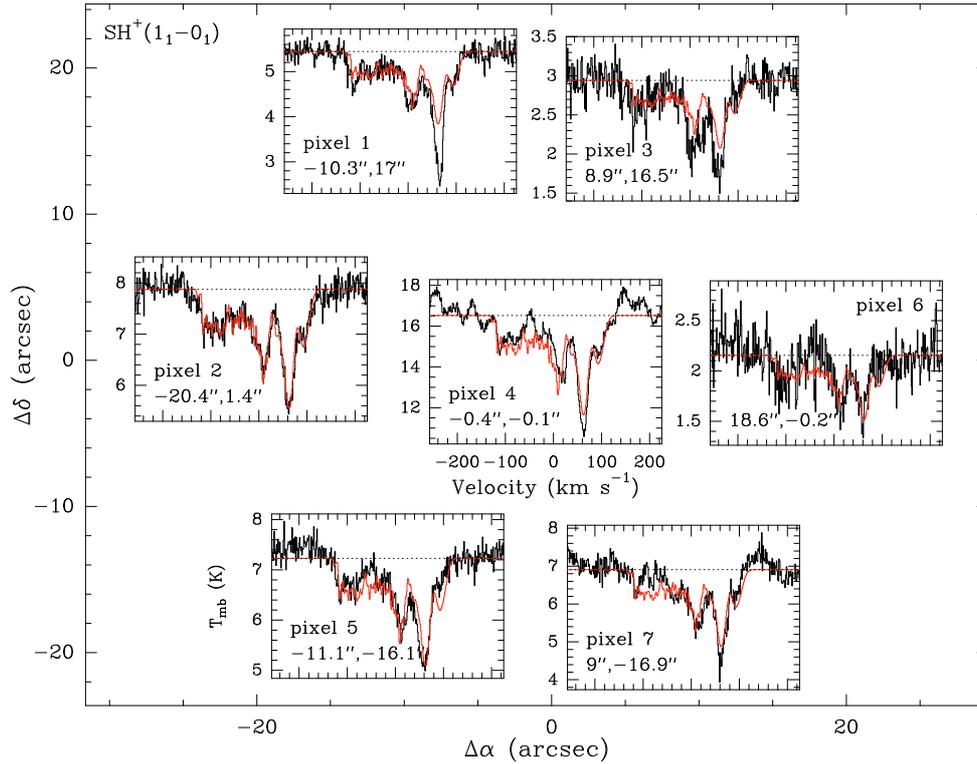


Fig. 5. SH^+ absorption spectra obtained toward Sgr B2(M) with the 7-pixel array CHAMP+ at the APEX telescope. The equatorial offset position of each pixel relative to Sgr B2(M) is given in the bottom left corner of each panel. In each panel, the dotted line shows the continuum level as measured over the emission/absorption-free channels, and the red curve is the spectrum predicted by the $T_{\text{rot}} = T_{\text{CMB}}$ model described in Sect. 4.1. All spectra are plotted in main-beam brightness temperature scale.

5.1.2. Atomic and molecular hydrogen column densities

The column density of atomic hydrogen, $N(\text{HI})$, can be calculated from measurements of the 21 cm HI line's optical depth, $\tau(\text{HI})$, at the intervening clouds' velocities (e.g., Garwood & Dickey 1989) and a determination of their spin temperatures, T_s , as described by Lazareff (1975). The method invokes a combination of interferometric observations to, first, directly determine the optical depths of the absorption components and, second, single dish observations to measure the (optically thick) line's brightness temperature. As described in a forthcoming paper, we have performed the necessary single dish observations with the Effelsberg 100 m telescope and obtained an optical depth spectrum ($\tau(\text{HI})$ vs. V_{lsr}) measured toward Sgr B2(M) with the NRAO Very Large Array from Lang (pers. comm.). We note our values for $N(\text{HI})$ are generally lower than those derived by Vastel et al. (2002). This is partially due to their assumption of $T_s = 150$ K for all velocity components.

A determination of $N(\text{H}_2)$ is more difficult, as selection of a “universal” trace molecule for molecular hydrogen is not straightforward. For meaningful modeling, such a molecule's lines would be required to be subthermally excited, meaning that their relative level populations be determined by T_{CMB} . This means, for example that, due to their small dipole moments and resulting low critical densities, isotopologues of CO are not suited. A possible choice for an H_2 tracer, which we adopt here, might be HCO^+ . Lucas & Liszt (1996) from their study of this molecule's 89 GHz $J = 1-0$ ground-state transition, conclude its abundance (relative to H_2) to be “ $\sim 3-6 \times 10^{-9}$ across a very broad range of extinction”, meaning between hydrogen column densities ~ 0.1 and $4 \times 10^{20} \text{ cm}^{-2}$. These authors base this finding, first, on the very tight correlation between the HCO^+ and

the OH column densities and, second, on the fact that OH has the same abundance (10^{-7}) in diffuse as in dense dark clouds. While their own absorption data only sample hydrogen column densities within the range quoted above, they find that the correlation holds at >10 times higher values than its upper boundary. Here we adopt 5×10^{-9} for the HCO^+/H_2 abundance ratio. This value is of the same magnitude as that listed by van Dishoeck et al. (1993) for (high column density) regions of low and high mass star formation.

Since HCO^+ absorption toward Sgr B2 is optically thick even for the non-Sgr B2 region velocity features, we use, as described in Sect. 4.1, H^{13}CO^+ spectra and obtain the main-isotope's column density by scaling with the appropriate $^{12}\text{C}/^{13}\text{C}$ ratios given in Col. 4 of Table 3.

Our estimates for $N(\text{HI})$ and $N(\text{H}_2)$ for the absorption components are listed in Table 6. For simplicity's sake and motivated by our optical depth fitting of the HI data and also to allow comparison with other studies, we have grouped the velocity components into seven intervals. The HI and H_2 column densities and HI spin temperatures were derived as described above from HI and H^{13}CO^+ data fixed to values compatible with the values given in the table. The column densities of SH^+ and CH^+ , presented in Table 7, were obtained by summing over the individual velocity components in Table 3 and multiplying the CH^+ column densities by the $^{12}\text{C}/^{13}\text{C}$ ratios given for each component in that table.

5.2. The origin of the $^{13}\text{CH}^+$ and SH^+ absorption

Since it is a priori not clear whether the observed SH^+ , CH^+ and HCl molecules are only associated with either atomic or

Table 4. Parameters of the best-fit LTE model of H¹³CO⁺ and the LTE model of SH⁺ fitted with the same velocity components as H¹³CO⁺.

H ¹³ CO ⁺					SH ⁺	
n_c^a	V_{lsr}^b	ΔV^c	N^d	$\frac{^{12}\text{C}}{^{13}\text{C}}^e$	N^d	R_{12}^f
(1)	(km s ⁻¹) (2)	(km s ⁻¹) (3)	(cm ⁻²) (4)	(5)	(cm ⁻²) (6)	(7)
1	62.0	12.0	3.75×10^{14}	20	–	–
2	80.0	20.0	5.00×10^{13}	20	–	–
3	104.0	20.0	4.00×10^{12}	20	–	–
4	51.0	12.0	4.00×10^{13}	20	–	–
5	64.5	12.0	1.36×10^{14}	20	1.97×10^{14}	0.07
6	35.0	7.0	4.82×10^{11}	40	$<2.82 \times 10^{12}$	<0.14
7	30.0	5.0	7.83×10^{11}	40	$<2.82 \times 10^{12}$	<0.09
8	25.5	3.0	3.01×10^{11}	40	$<2.82 \times 10^{12}$	<0.23
9	22.0	5.0	2.53×10^{12}	60	8.45×10^{12}	0.05
10	17.0	5.0	2.05×10^{12}	60	2.25×10^{13}	0.18
11	12.0	6.0	1.81×10^{12}	60	2.82×10^{13}	0.25
12	7.6	4.5	1.20×10^{12}	20	2.54×10^{13}	1.03
13	1.1	6.2	4.15×10^{12}	20	1.69×10^{13}	0.20
14	-5.5	7.0	6.02×10^{11}	20	1.97×10^{13}	1.61
15	-13.5	5.0	3.01×10^{11}	40	1.55×10^{13}	1.26
16	-19.5	5.0	6.62×10^{11}	40	8.45×10^{12}	0.31
17	-26.3	5.0	7.22×10^{11}	40	8.45×10^{12}	0.29
18	-31.0	5.0	2.17×10^{11}	40	8.45×10^{12}	0.96
19	-36.5	4.0	1.20×10^{11}	40	8.45×10^{12}	1.72
20	-41.0	3.3	1.57×10^{12}	40	7.04×10^{12}	0.11
21	-45.7	3.0	6.02×10^{11}	40	4.23×10^{12}	0.17
22	-49.5	3.0	3.01×10^{11}	40	4.23×10^{12}	0.34
23	-54.0	4.0	1.99×10^{11}	20	9.30×10^{12}	2.29
24	-59.3	4.0	5.72×10^{11}	20	$<2.82 \times 10^{12}$	<0.24
25	-66.0	5.0	4.21×10^{11}	20	$<2.82 \times 10^{12}$	<0.33
26	-72.0	5.0	4.21×10^{11}	20	9.86×10^{12}	1.15
27	-76.3	4.0	4.21×10^{11}	20	8.45×10^{12}	0.98
28	-80.1	4.0	2.71×10^{11}	20	7.04×10^{12}	1.27
29	-84.3	5.0	5.12×10^{11}	20	1.27×10^{13}	1.21
30	-88.5	3.5	4.21×10^{11}	20	$<2.82 \times 10^{12}$	<0.33
31	-92.6	3.5	5.42×10^{11}	20	8.45×10^{12}	0.76
32	-97.2	4.0	6.62×10^{11}	20	1.41×10^{13}	1.04
33	-102.2	5.0	1.57×10^{12}	20	1.69×10^{13}	0.53
34	-108.0	4.0	3.61×10^{11}	20	1.13×10^{13}	1.53
35	-112.0	4.0	4.82×10^{11}	20	8.45×10^{12}	0.86
36	-116.0	4.0	3.61×10^{11}	20	1.41×10^{13}	1.91
37	-120.0	4.0	1.20×10^{11}	20	5.63×10^{12}	2.29
38	-123.7	4.0	1.20×10^{11}	20	5.63×10^{12}	2.29
39	-130.4	8.0	1.99×10^{11}	20	7.04×10^{12}	1.74

Notes. All components have a rotation temperature of 2.7 K except components $n_c = 1$ to 4 of H¹³CO⁺ which have 20.0 K and $n_c = 5$ of H¹³CO⁺ which has 3.1 K. ^(a) Component number. ^(b) LSR velocity, the same for both molecules except for one component of SH⁺ (5: 64.0 km s⁻¹). ^(c) Linewidth (*FWHM*), the same for both molecules except for one component of SH⁺ (5: 19.0 km s⁻¹). ^(d) Column density. ^(e) Assumed isotopic ratio H¹²CO⁺/H¹³CO⁺. ^(f) Column density ratio SH⁺/HCO⁺.

molecular gas or both, when calculating abundance ratios, we might want to refer to the total column density of hydrogen nuclei, $N(\text{H}) \equiv N(\text{HI}) + 2 N(\text{H}_2)$. Inspecting Table 6, we find that over all velocity ranges showing absorption, $N(\text{H}_2)$ greatly exceeds $N(\text{HI})$, by factors between 13 and 133, approaching the value for Sgr B2 (138). This means that the absorbing medium is dominated by GMC gas. This is reinforced by the densities derived by Greaves et al. (1992) from LVG modeling of the two lowest rotational lines of CS, which, between 0.4 and 2×10^4 cm⁻³, are actually even higher than values in most of a GMC's volume.

Both the total hydrogen nuclei column density, $N(\text{H})$, and the H₂/HI ratio are much larger than the values found in translucent and diffuse clouds. Gredel et al. (1992) in their study of the archetypical translucent cloud toward HD 210121 find

$N(\text{H}_2) = 8 \times 10^{20}$ cm⁻² and $N(\text{HI}) = 1\text{--}5 \times 10^{20}$ cm⁻² for the molecular and atomic hydrogen absorption column densities, respectively. In comparison, the classic diffuse cloud line of sight toward ζ Oph has comparable HI and H₂ column densities of $\approx 5 \times 10^{20}$ cm⁻² or a column density of hydrogen nuclei of $N(\text{H}) = 1.5 \times 10^{21}$ cm⁻² (van Dishoeck & Black 1986).

As discussed above, the absorbing material is dominated by GMCs. There is, however, nothing that does imply that the observed quantities of CH⁺ and SH⁺ are associated with gas within a GMC, although little is known about the abundance of both species in such objects. Model calculations predict significant column densities in lower- A_V portions of dense ($>10^5$ cm⁻³) PDRs illuminated by intense ultraviolet fields (Sternberg & Dalgarno 1995). Even more extreme conditions (XDRs) are required to produce significant amounts of SH⁺ in dense regions

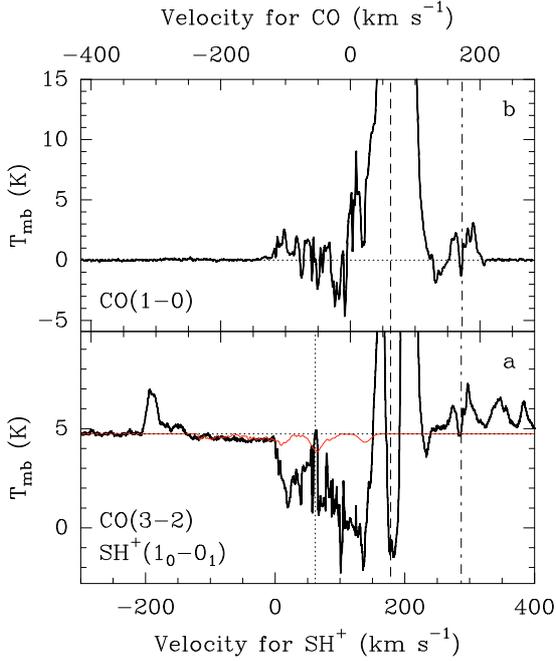


Fig. 6. **a)** Spectrum obtained toward Sgr B2(M) at the frequency of the $\text{SH}^+ 1_0-0_1$ line with the APEX telescope in main beam brightness temperature. The red curve is the synthetic spectrum described in Sect. 4.1, the horizontal dotted line shows the continuum level, and the vertical dotted line marks the systemic velocity of the source (62 km s^{-1}). The strong absorption lines are spiral arm components of CO 3–2. The lower axis gives the LSR velocity for SH^+ , while the upper axis refers to CO, with the same labeling as in panel **b)**. **b)** CO(1–0) spectrum obtained toward Sgr B2 as part of our line survey with the IRAM 30 m telescope. The horizontal dotted line indicates the zero level (after baseline removal because the observations were performed in position-switching mode with a far OFF position, which yields a very uncertain baseline level). In both panels, the dashed line marks the systemic velocity of the source in CO 3–2 and the dot-dashed line indicates the CO velocity $+172.6 \text{ km s}^{-1}$ at which an extra absorption component appears in the $^{13}\text{CH}^+$ spectrum (see discussion in Sect. 4.1.3.)

Table 5. Parameters of the best-fit LTE model of HCl and H^{37}Cl .

Molecule	$n_c^{(a)}$	$V_{\text{lsr}}^{(b)}$ (km s^{-1})	$\Delta V^{(c)}$ (km s^{-1})	$N^{(d)}$ (cm^{-2})
(1)	(2)	(3)	(4)	(4)
HCl	2	65.0	8.0	1.90×10^{14}
	6	17.0	5.0	7.60×10^{12}
H^{37}Cl	2	65.0	8.0	4.75×10^{13}

Notes. ^(a) Same component numbering as in Table 3. ^(b) LSR velocity. ^(c) Linewidth. ^(d) Column density.

(Abel et al. 2008). However, both dense P and XDRs have small volume filling factors, making them unlikely absorbers. These findings point to an (at least) two component picture for most of the absorption components, i.e., a diffuse envelope traced by HI, CH^+ and SH^+ absorption plus a denser core region, a view that is also invoked by Vastel et al. (2002) to explain the absorption they observed with ISO in the C^+ and O^0 fine structure transitions.

In Fig. 9 we plot CH^+ column density vs. hydrogen column density, $N(\text{HI})$ as defined above, for the seven velocity ranges in Table 6 (coded A–G). For each CH^+ column density entry two data points are plotted, both taken from the table. The left one (open squares) assumes that the CH^+ is only associated with

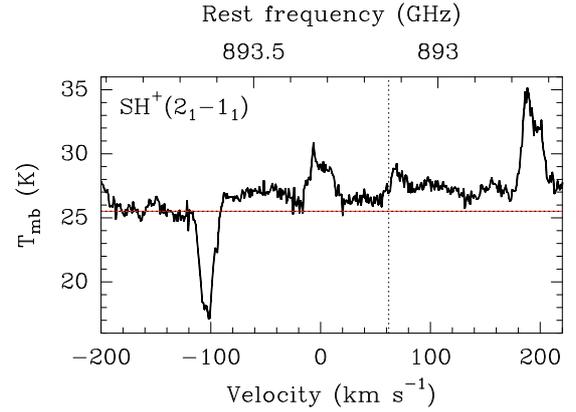


Fig. 7. Spectrum obtained toward Sgr B2(M) at the frequency of $\text{SH}^+ 2_1-1_1$ with the APEX telescope in main beam brightness temperature. The red curve is the synthetic spectrum described in Sect. 4.1, i.e., showing no detectable emission, the horizontal dotted line shows the continuum level, and the vertical dotted line marks the systemic velocity of the source (62 km s^{-1}). The absorption line appearing at $\sim -105 \text{ km s}^{-1}$ is the $J_{K_a K_c} = 1_{11}-0_{00}$ ground-state line of HDO at $893\,638.7 \text{ MHz}$ (Comito et al. 2003).

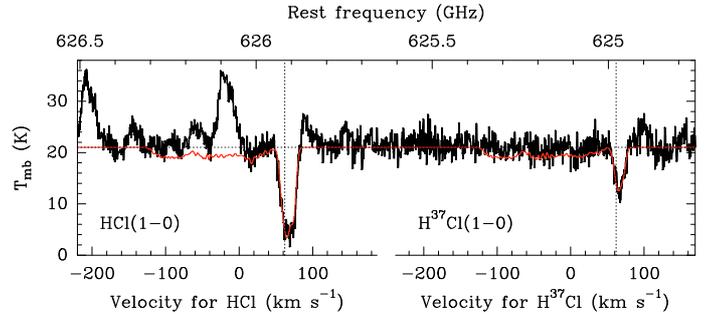


Fig. 8. Spectrum obtained toward Sgr B2(M) around 625 GHz with the APEX telescope in main beam brightness temperature. The red curve is the synthetic spectrum described in Sect. 4.1, the horizontal dotted line shows the continuum level, and the left and right vertical dotted lines mark the systemic velocity of the source (62 km s^{-1}) for HCl and H^{37}Cl , respectively. The strong emission close to the HCl line is likely due to a SO_2 line at $626\,087.3 \text{ MHz}$.

atomic hydrogen, whereas the right one (filled squares) assumes it is only associated with molecular hydrogen or, essentially, all the hydrogen since $N(\text{H}_2) \gg N(\text{HI})$ for all velocities. We also plot (as circles) data for the two classic diffuse clouds against $\zeta \text{ Oph}$ and $\zeta \text{ Per}$. For these, $N(\text{H}_2) \approx N(\text{HI}) \approx 5 \times 10^{20} \text{ cm}^{-2}$. In addition, we present data for the translucent cloud toward HD 210121 where, again, two points assuming that the CH^+ is only associated with atomic (left) or molecular gas (right) are plotted. All values for the latter three sources, $N(\text{H}_2)$, $N(\text{HI})$, and $N(\text{CH}^+)$, are taken from de Vries & van Dishoeck (1988). The circles represent the absorption data Gredel (1997) determined toward a sample of southern OB associations. For these lines of sight, which have higher extinctions, between 0.36 and 4.2 mag, (mostly) corresponding to translucent clouds, we cannot discriminate between atomic and molecular hydrogen columns as Gredel lists $N(\text{CH}^+)$ vs. A_V , which contains contributions from both. To convert his A_V values to hydrogen column densities we use the results of the classic study of Bohlin et al. (1978), who found for low values of visual extinction ($0.02 < A_V < 0.6$) a linear relation between A_V and hydrogen column density, which as first argued by Dickman (1978), also holds for significantly higher A_V values. It is consistent with a relation derived from

Table 6. HI and H₂ column densities of the absorption components.

Label	Velocity range ^a (km s ⁻¹)	N_{HI}/T_s^b (cm ⁻² K ⁻¹)	T_s^c (K)	N_{HI}^d (cm ⁻²)	$N_{\text{H}_2}^e$ (cm ⁻²)	Abs. comp. ^f
(1)	(2)	(3)	(4)	(5)	(6)	(7)
A	95.3–38.6	$9.0(1.8) \times 10^{19}$	43(5)	$3.9(0.9) \times 10^{21}$	5.4×10^{23}	[2]
B	23.2–12.9	$1.5(0.5) \times 10^{19}$	65(10)	$1.0(0.4) \times 10^{21}$	5.5×10^{22}	[5, 6]
C	-12.9–-33.5	$8.5(2.0) \times 10^{18}$	93(10)	$7.9(2.0) \times 10^{20}$	1.4×10^{22}	[12, 13, 14, 15]
D	-36.1–-51.5	$1.6(0.4) \times 10^{19}$	20(3)	$3.1(0.9) \times 10^{20}$	2.0×10^{22}	[17, 18, 19]
E	-54.1–-64.4	$3.0(1.0) \times 10^{18}$	55(6)	$1.7(0.6) \times 10^{20}$	2.6×10^{21}	[21]
F	-69.6–-85.0	$2.6(0.7) \times 10^{18}$	80(8)	$2.1(0.6) \times 10^{20}$	7.1×10^{21}	[22, 23, 24, 25]
G	-90.2–-123.7	$2.8(0.7) \times 10^{18}$	43(7)	$1.2(0.4) \times 10^{20}$	1.6×10^{22}	[27, 28, 29, 30, 31, 32]

Notes. The numbers in parentheses are the uncertainties. ^(a) Velocity range over which the HI column density is computed. ^(b) Ratio of HI column density to spin temperature, obtained from the VLA data. ^(c) HI spin temperature derived from the Effelsberg data. ^(d) HI column density. ^(e) H₂ column density derived from the H¹³CO⁺ column densities assuming the isotopic ratios listed in Col. 4 of Table 3 and an HCO⁺ abundance of 5×10^{-9} relative to H₂. ^(f) List of the absorption components used to compute the H₂ column densities, with the same numbering as in Col. 1 of Table 3.

modeling of x-ray data (Güver & Özel 2009): $N(\text{H}(\text{cm}^{-2})) \approx 2 \times 10^{21} A_V(\text{mag})$.

5.2.1. Comparison with individual diffuse clouds

While we advocate above a diffuse cloud origin of the CH⁺ absorption, we note that, apart from one velocity range (B, 12.9–23.2 km s⁻¹), our CH⁺ column densities are much higher than found in diffuse clouds and mostly higher than in the translucent cloud sample. However, the velocity ranges over which the values were determined, are mostly much larger than the line widths found in diffuse or translucent clouds (and even GMCs). For this reason, we plot in the lower panel of Fig. 9 the average column densities that a cloud with “typical” line width ΔV_{typ} would have. This means we have divided for each of the velocity intervals A–G, both, CH⁺ and hydrogen column densities by the ratio of the width of the velocity interval and ΔV_{typ} . We chose ΔV_{typ} to be 4.3 km s⁻¹ FWHM, which is the mean of the sample of diffuse lines of sight for which Crane et al. (1995) present high spectral resolution CH⁺ data⁸. This value is consistent with that discussed by Gredel (1997) for his translucent cloud sample. The thus calculated values correspond to a “typical” cloud with averaged properties.

Inspecting the CH⁺ column densities for these typical clouds we find values very similar to those found in diffuse and translucent clouds. We note that the ratio of molecular to atomic hydrogen column densities is in most cases higher than that found in translucent and much higher than in diffuse molecular clouds. The reason for this is almost certainly sight line superposition of the CH⁺-containing diffuse/translucent and denser molecular clouds, as discussed above.

5.3. Comparison – SH⁺ and other S-bearing species and the CH⁺/SH⁺ ratio

The values we derive for the SH⁺ column density, $N(\text{SH}^+)$, for the non-Sgr B2 region velocity ranges go up to 7×10^{13} cm⁻² (see Table 7). Considering again the differences in line widths, these values are comparable with the upper limits found for optical SH⁺ absorption from diffuse and translucent clouds (i.e. 1×10^{13} cm⁻²; see Sect. 1.2).

⁸ The Doppler parameter, b , listed by this and numerous other optical absorption studies and FWHM line width are related via $\Delta V_{1/2} = 2\sqrt{\ln 2} b \approx 1.665 b$.

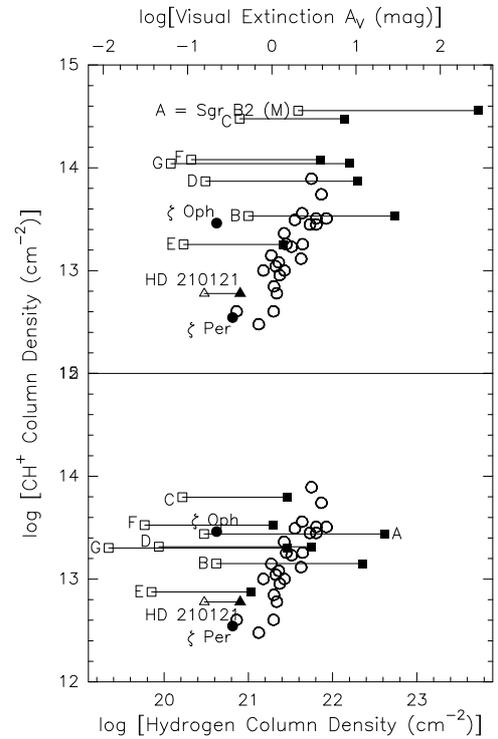


Fig. 9. CH⁺ column density versus hydrogen column density. The ordinate gives the CH⁺ column density for the seven different velocity intervals listed in Table 7. The capital letters designate the entries in table (top to bottom). The open circles represent data taken from the diffuse/translucent cloud sample of Gredel (1997). The squares connected by lines mark the CH⁺ column densities determined in this work. For the open squares it is assumed that all the absorption is from atomic gas; the abscissa corresponds to the HI column density (Table 6), whereas for the filled squares it is assumed that all the absorption is from molecular gas; the abscissa corresponds to the H₂ column density (Table 6). For the upper panel, column densities were calculated from the absorption over the whole velocity range of each interval, whereas in the lower panel average column densities normalized to a typical line width of 4.3 km s⁻¹ were used (see text).

The column densities of other sulfur bearing species in the velocity ranges of Table 7 have been determined by Greaves et al. (1992), who studied CS, and Tieftrunk et al. (1994) (SO, H₂S, and SO₂). Comparing with our values for SH⁺ (Table 6), we find [SH⁺/CS] abundance ratios between 0.5 and 3, [SH⁺/SO] between 1.6 and >55, and [SH⁺/SO₂] > 2. For the

Table 7. Column densities of the absorption components and abundances relative to H.

Velocity range (km s ⁻¹)	SH ⁺		CH ⁺		SO		H ₂ S		SO ₂		CS	
	<i>N</i> (cm ⁻²)	<i>X_H</i> (3)	<i>N</i> (cm ⁻²)	<i>X_H</i> (5)	<i>N</i> (cm ⁻²)	<i>X_H</i> (7)	<i>N</i> (cm ⁻²)	<i>X_H</i> (9)	<i>N</i> (cm ⁻²)	<i>X_H</i> (11)	<i>N</i> (cm ⁻²)	<i>X_H</i> (13)
95.3–38.6	2.0(14)	1.8(-10)	3.6(14)	3.3(-10)	–	–	–	–	–	–	–	–
23.2–12.9	3.2(13)	2.9(-10)	5.7(13)	5.2(-10)	–	–	–	–	–	–	–	–
-12.9–-33.5	3.4(13)	1.2(-9)	3.1(14)	1.1(-8)	3.6(12)	1.0(-10)	1.5(13)	5.2(-10)	<2.1(13)	<7.3(-10)	1.6(13)	5.5(-10)
-36.1–-51.5	1.5(13)	3.9(-10)	9.2(13)	2.3(-9)	9.4(12)	2.0(-10)	4.8(13)	1.2(-9)	<1.1(13)	<2.7(-10)	2.8(13)	7.1(-10)
-54.1–-64.4	–	–	1.4(13)	2.6(-9)	–	–	–	–	–	–	–	–
-69.6–-85.0	3.9(13)	2.7(-9)	1.5(14)	1.0(-8)	<7.0(11)	<5.0(-11)	<4.2(12)	<2.9(-10)	<3.7(12)	<2.6(-10)	1.3(13)	9.1(-10)
-90.2–-123.7	6.9(13)	2.2(-9)	7.9(13)	2.5(-9)	5.1(12)	2.0(-10)	<4.5(12)	<1.4(-10)	1.9(13)	6.1(-10)	4.4(13)	1.4(-9)

Notes. *N* is the column density of molecule *Y* and *X_H* the column density ratio $[Y]/([H_1]+2 \times [H_2])$. The column densities of SO, H₂S, and SO₂ are from Tieftrunk et al. (1994) and those of CS are from Greaves et al. (1992). The velocity ranges are the same as in Table 6. The list of absorption components used to compute the SH⁺ and CH⁺ column densities is given in Table 6. The components for which the column density is an upper limit in Table 3 were ignored. *x(y)* means $x \times 10^y$.

[SH⁺/H₂S] ratio we find values >2, except for the -33.2 to -50.1 km s⁻¹ velocity range, for which we find the low ratio of 0.3. We note that the velocity of this absorption places it in the Norma spiral arm. From Table 6 we see that this range has the highest H₂ column density and the highest H₂/HI ratio of all the (non-Sgr B2 region) absorption components and resembles most closely a GMC or GMC core. This reinforces SH⁺'s nature as a tracer of more diffuse gas whose abundance drops in denser environments.

As discussed by Tieftrunk et al. (1994), SH⁺ and H₂S are chemically related, as H₃S⁺, from which the latter forms via dissociative recombination is formed by the reaction



With respect to chemical models (Millar et al. 1986; Pineau des Forêts et al. 1986), it is also worth noting that, as can be seen from Table 7, the SH⁺/CH⁺ ratio, [SH⁺/CH⁺], which is 0.56 for Sgr B2(M) only varies between 0.11 and 0.26 for all but one of the non-Sgr B2 absorption features. These values are consistent with the upper limits on this ratio (0.12–2) for diffuse and translucent lines of sight (see Sect. 1.2). The component with the higher ratio, ≈0.9 is in the -90.2 to -123.7 km s⁻¹ range, which corresponds to peculiar velocity gas associated with the GC. Interestingly, this velocity range has also by far the highest SiO column density measured for the various velocity components by Greaves et al. (1996). These two findings may have a common (shock-wave) origin as an increased SiO abundance is commonly ascribed to shock chemistry (Schilke et al. 1997).

5.4. Limits on HCl absorption in the diffuse material

The HCl column density, *N*(HCl), we derive for the gas associated with Sgr B2(M) (see Table 5) is in good agreement, i.e. 16% higher, with the value derived by Zmuidzinas et al. (1995).

For the velocity components corresponding to the diffuse lines of sight we derive an upper limit on the HCl column density, *N*(HCl), of 8.4×10^{12} cm⁻² (see Table 5 and Fig. 8 in Sect. 4.1.4). Since *N*(H) ranges from $0.5\text{--}2.4 \times 10^{22}$ cm⁻² we calculate an HCl to hydrogen nuclei abundance ratio [HCl/H] of $0.6\text{--}3 \times 10^{-10}$. Our upper limit is much coarser than the $(2.7 \pm 1.0) \times 10^{11}$ cm⁻² Federman et al. (1995) determine for *N*(HCl) from an UV absorption line toward ζ Oph.

6. Conclusions

We have reported submillimeter wavelength absorption from rotational ground-state transitions of ¹³CH⁺, H³⁵Cl, H³⁷Cl, and, for the first time, of the SH⁺ molecule toward the strong Galactic center continuum source Sgr B2(M). From ¹³CH⁺ and SH⁺ we detect absorption at the systemic LSR velocity of Sgr B2(M) and in addition over a wide range of lower velocities belonging to intervening material. For the intervening clouds we have derived molecular hydrogen column densities from optically thin H¹³CO emission and atomic column densities from HI 21 cm line data. For all the clouds we find that the former is larger than the latter by factors between 15 and 130. If we “scale” the observed velocity ranges of the individual clouds to the line widths of single diffuse and translucent molecular clouds in the Solar neighborhood, we find similar ¹³CH⁺ column densities in both types of clouds. Most likely the reason for this is that the observed ¹³CH⁺ is indeed mostly associated with atomic material surrounding molecular material. The [SH⁺/CH⁺] ratio is consistent with upper limits from optical data. Our upper limits on the

HCl column density in the absorption components not associated with Sgr B2 are consistent with but coarser than measurements of UV absorption from this molecule.

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