

LETTER TO THE EDITOR

## APEX mapping of $\text{H}_3\text{O}^+$ in the Sgr B2 region

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### ABSTRACT

**Context.** The cosmic-ray ionization rate  $\zeta_{\text{CR}}$  of dense molecular clouds is a key parameter for their dynamics and chemistry.

**Aims.** Variations of  $\zeta_{\text{CR}}$  are well established, but it is unclear if these are related to source column density or to Galactic location.

**Methods.** Using the APEX telescope, we have mapped the 364 GHz line of  $\text{H}_3\text{O}^+$  in the Sgr B2 region and observed the 307 GHz line at selected positions. With the IRAM 30-m telescope we have observed the  $\text{H}_2^{18}\text{O}$  203 GHz line at the same positions.

**Results.** Strong  $\text{H}_3\text{O}^+$  emission is detected over a  $\sim 3 \times 2$  pc region, indicating an  $\text{H}_3\text{O}^+$  column density of  $10^{15}$ – $10^{16}$   $\text{cm}^{-2}$  in an 18'' beam. The  $\text{H}_3\text{O}^+$  abundance of  $\sim 3 \times 10^{-9}$  and  $\text{H}_3\text{O}^+/\text{H}_2\text{O}$  ratio of  $\sim 1/50$  in the Sgr B2 envelope are consistent with models with  $\zeta_{\text{CR}} \sim 4 \times 10^{-16}$   $\text{s}^{-1}$ ,  $3\times$  lower than derived from  $\text{H}_3^+$  observations toward Sgr A, but  $10\times$  that of local dense clouds.

**Conclusions.** The ionization rates of interstellar clouds thus seem to be to first order determined by the ambient cosmic-ray flux, while propagation effects cause a factor of  $\sim 3$  decrease from diffuse to dense clouds.

**Key words.** ISM: clouds – ISM: molecules – ISM: cosmic rays – molecular processes – astrochemistry

### 1. Introduction

The ionization rate of interstellar clouds is a key parameter for their dynamics and their chemistry (see Caselli & Walmsley 2001; Van der Tak 2006, for reviews). In dense star-forming regions, the bulk of the ionization is due to cosmic rays, at a rate of  $\zeta_{\text{CR}} \sim 3 \times 10^{-17}$   $\text{s}^{-1}$  as derived from  $\text{HCO}^+$  and CO emission line observations of the envelopes of young massive stars up to a few kpc from the Sun (Van der Tak & van Dishoeck 2000). This result is in good agreement with measurements of the local flux of low-energy cosmic rays with the Voyager and Pioneer spacecrafts (Webber 1998). However, mm-wave observations of  $\text{DCO}^+$  and  $\text{HCO}^+$  toward the nearby dark cloud LDN 1544 indicate a decrease of  $\zeta_{\text{CR}}$  by a factor  $\sim 10$  (Caselli et al. 2002), while observations of  $\text{H}_3^+$  absorption toward the  $\zeta$  Per diffuse cloud indicate an increase of similar magnitude (Le Petit et al. 2004). Even larger enhancements are found for the Galactic Center, where Oka et al. (2005) derive  $\zeta_{\text{CR}} \sim 10^{-15}$   $\text{s}^{-1}$  from  $\text{H}_3^+$  observations toward Sgr A. An enhanced ionization rate in the inner 250 pc of our Galaxy is expected from its strong X-ray and radio synchrotron emission, but this value is at the upper limit based on the observed temperatures of the Sgr B2 clouds (Güsten et al. 1985). It is unclear if these variations in  $\zeta_{\text{CR}}$  are due to propagation effects (absorption or scattering of cosmic rays) or to variations in the cosmic-ray flux with location in the Galaxy. To resolve this issue, an estimate of the ionization rate of dense gas in the Galactic Center is urgently needed. However, in the case of Sgr B2, using the  $\text{DCO}^+/\text{HCO}^+$  ratio is complicated by the uncertain D abundance, while comparing  $\text{HCO}^+$  with CO is difficult as the molecules may not trace the same gas (Jacq et al. 1999), which calls for other methods.

The high proton affinity of water makes hydronium ( $\text{H}_3\text{O}^+$ ) a key ion in the oxygen chemistry of dense clouds. Its

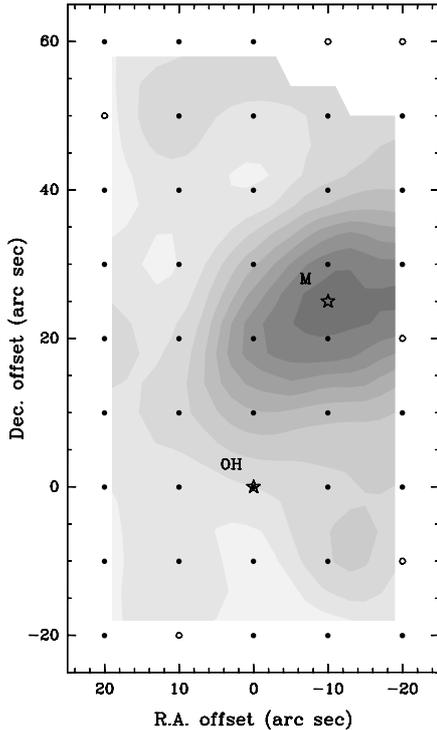
submillimeter rotation-inversion transitions may be used to measure  $\zeta_{\text{CR}}$  and trace  $\text{H}_2\text{O}$  and  $\text{O}_2$  which are unobservable from the ground. Pioneering work by Wootten et al. (1991) and Phillips et al. (1992) has demonstrated this potential with observations of strong  $\text{H}_3\text{O}^+$  emission toward Sgr B2 (OH)<sup>1</sup>. Unfortunately, the atmospheric transmission from Mauna Kea is rarely good enough to observe  $\text{H}_3\text{O}^+$ , so mapping is not feasible.

The Chajnantor site greatly facilitates observation of the  $\text{H}_3\text{O}^+$   $J_{\text{K}} = 3_2^+ - 2_2^-$  line at 364.7974 GHz, which has an upper level energy of 139 K and an Einstein A-coefficient of  $2.8 \times 10^{-4}$   $\text{s}^{-1}$ . The  $J_{\text{K}} = 1_1^- - 2_1^+$  line ( $\nu = 307.1924$  GHz,  $E_u = 80$  K,  $A = 3.5 \times 10^{-4}$   $\text{s}^{-1}$ ) is a probe of denser gas, because the emission competes with fast pure inversion decay, unlike for the 364 GHz line. This paper presents new observations of these lines toward the Sgr B2 region. Combined with observations of the  $\text{H}_2^{18}\text{O}$   $3_{13} - 2_{02}$  line at 203.4075 GHz ( $E_u = 204$  K,  $A = 4.9 \times 10^{-6}$   $\text{s}^{-1}$ ), the data are used to estimate  $\zeta_{\text{CR}}$  in the Sgr B2 region. Due to the high critical densities of the lines, our observations are not sensitive to the extended low-density envelope seen in absorption lines of water (Comito et al. 2003) and  $\text{H}_3\text{O}^+$  (Goicoechea & Cernicharo 2001).

### 2. Observations

In July 2005, we observed the 364 GHz line of  $\text{H}_3\text{O}^+$  towards selected sources in the Sgr B2 and Sgr A clouds using the

<sup>1</sup> This position between the Sgr B2 (M) and (S) cores was used for early line surveys of the Galactic Center (e.g., Cummins et al. 1986) but does not correspond to any object, not even the centroid of the OH masers (Gaume & Claussen 1990).



**Fig. 1.** Distribution of velocity-integrated  $\text{H}_3\text{O}^+$  364 GHz emission toward Sgr B2, observed with the APEX telescope. Filled dots indicate detections; open dots denote upper limits. The greyscale runs from 1.9 to 35.5 in steps of  $3.7 \text{ K km s}^{-1}$ .

APEX telescope (Güsten et al., this volume)<sup>2</sup>. The front end was the facility APEX-2a receiver built at Onsala (Risacher et al., this volume); the back end was an FFT spectrometer built at the MPIfR providing 8192 channels over a bandwidth of 1.0 GHz (Klein et al., this volume). A map of Sgr B2 at  $10''$  spacing (Fig. 1) was made by integrating 1 min per point, which for system temperatures of 340–360 K gave a noise level of 0.2 K per  $0.8 \text{ km s}^{-1}$  channel. Deeper integrations (2–5 min) were made at the (N), (M) and (OH) positions. The line was also observed toward two positions in the Sgr A cloud, CGS 3–2 and GC IRS3, where strong  $\text{H}_3^+$  mid-infrared absorption suggests a high ionization rate (Oka et al. 2005). The non-detections at these positions probably reflect a lack of dense gas along these lines of sight. Follow-up observations of the 307 GHz line of  $\text{H}_3\text{O}^+$  were performed in November 2005. Since this line lies very close to a  $\text{CH}_3\text{OH}$  line, several local oscillator settings were used to verify the sideband origin of the detected features. In this case, the system temperature of 300 K resulted in an rms noise level of 90 mK on  $0.24 \text{ km s}^{-1}$  channels after 10.4 min of on-source integration.

All data were obtained using position switching with a throw of  $3'$  in Az. Test spectra taken at the Sgr B2 (OH) offset position indicate that the emission is  $<10\%$  of the strength at the target position. The beam size of APEX is  $\sim 18''$  at 364 GHz and  $\sim 21''$  at 307 GHz. Data at both frequencies were calibrated onto  $T_{\text{mb}}$  scale using forward and main beam efficiencies of 97% and 74%. From a comparison of calibrations using hot and cold loads and using a water vapour radiometer, we estimate the calibration uncertainty to be  $\approx 10\%$ . For reasonably strong lines

**Table 1.** Measured line parameters at selected positions with  $1\sigma$  errors in units of the last decimal in brackets. Upper limits are  $1\sigma$  limits on  $T_{\text{mb}}$  in K on  $1.0 \text{ km s}^{-1}$  channels.

Position	$\alpha(\text{J2000})$ hh mm ss	$\delta(\text{J2000})$ ° ' ''	$\int T_{\text{mb}} dV$ K $\text{km s}^{-1}$	$V_{\text{LSR}}$ $\text{km s}^{-1}$	$\Delta V$ $\text{km s}^{-1}$
$\text{H}_3\text{O}^+$ 364 GHz:					
Sgr B2 (M)	17:47:20.2	-28:23:05	42.0(13)	+62.0(6)	17.3(16)
Sgr B2 (OH)	17:47:20.8	-28:23:32	8.7(4)	+62.7(3)	15.3(8)
GCS 3-2	17:46:14.9	-28:49:43	<0.09	...	...
GC IRS3	17:45:39.6	-29:00:24	<0.10	...	...
$\text{H}_3\text{O}^+$ 307 GHz:					
Sgr B2 (M)			27.1(52)	+64.6(14)	16.6(21)
Sgr B2 (OH)			7.7(7)	+64.9(13)	24.0(22)
$\text{H}_2^{18}\text{O}$ 203 GHz:					
Sgr B2 (M)			20.5(3)	+63.3(1)	13.2(1)
Sgr B2 (OH)			<0.03	...	...

( $T_{\text{mb}} \geq 10 \times \text{rms}$ ), as is the case here, spectral rms has a negligible contribution to the intensity uncertainty.

Observations of the  $\text{H}_2^{18}\text{O}$  203 GHz line were performed with the IRAM 30-m telescope<sup>3</sup> in February 2006. The facility receiver A230 was used as front end and the VESPA autocorrelator as backend. At this wavelength, the telescope has a beam size of  $12''$  and a main beam efficiency of 57%. System temperatures were 500–600 K and integration times 10–30 min, resulting in rms noise levels of  $\sim 0.1 \text{ K}$  on  $0.20 \text{ km s}^{-1}$  channels. The line was detected at the Sgr B2 (M) but not at the (OH) position. Calibration was verified to 10% on Sgr B2 (N) which was observed before by Gensheimer et al. (1996).

### 3. Results

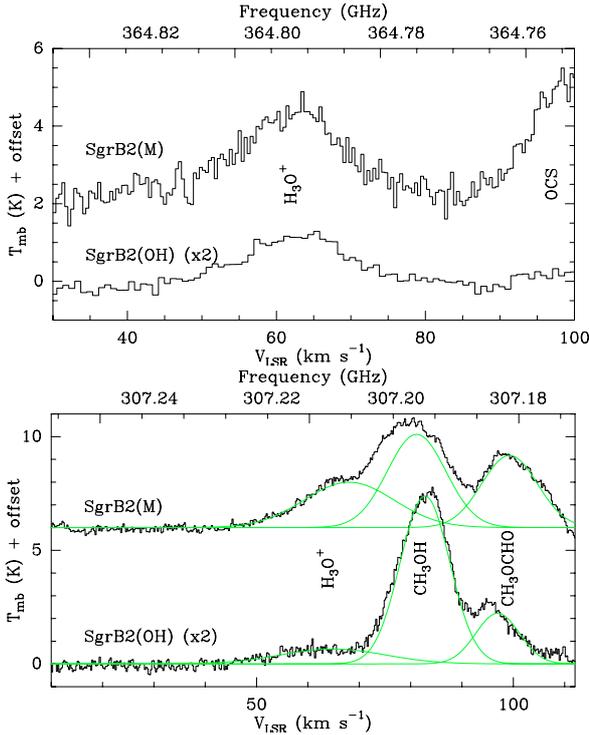
Emission in the  $\text{H}_3\text{O}^+$  364 GHz line is detected over an  $(80 \times 40)''$  region in Sgr B2 (Fig. 1), corresponding to  $(3.3 \times 1.6) \text{ pc}$  at a distance of 8.5 kpc. The overall distribution of  $\text{H}_3\text{O}^+$  364 GHz in the Sgr B2 region follows that of many other molecular lines when mapped at comparable resolution (e.g., Martín-Pintado et al. 1990; de Vicente et al. 1997). The distribution of  $\text{H}_3\text{O}^+$  also follows that of the (sub-)millimeter dust continuum emission (Lis et al. 1991), a common tracer of the  $\text{H}_2$  distribution. In contrast, the  $\text{H}_2\text{O}$  183.31 GHz emission is strongly peaked at the cores, dropping to  $\leq 10\%$  of its peak value at the (OH) position (Cernicharo et al. 2006). This behaviour does not necessarily reflect the  $\text{H}_2\text{O}$  column density distribution because of the maser nature of the 183 GHz line.

Table 1 lists the results of fitting Gaussian profiles to the spectra after subtracting a polynomial baseline. The 307 GHz line strength toward OH may be overestimated due to blending: fixing  $\Delta V$  to 15–16  $\text{km s}^{-1}$  reduces the line flux by 25–30%. The strength of this line agrees with the data of Phillips et al. (1992), while the 364 GHz line is a factor of 2 weaker. The steep emission gradient (Fig. 1) makes the measurement sensitive to pointing offsets. In the APEX data,  $\text{H}_3\text{O}^+$  and other lines peak at the M core, validating the pointing to  $<5''$ .

The 307 and 364 GHz spectra show many lines in addition to  $\text{H}_3\text{O}^+$ . While the Sgr B2 (OH) spectra show  $<10$  mostly weak ( $T_{\text{mb}} \lesssim 0.5 \text{ K}$ ) lines over the 1 GHz bandwidth, the Sgr B2 (M) spectrum shows  $>20$  features with  $T_{\text{mb}} \geq 1 \text{ K}$ . The spectra taken

<sup>2</sup> This paper is based on data acquired with the Atacama Pathfinder EXperiment, which is a collaboration between the Max-Planck-Institut für Radioastronomie, the European Southern Observatory, and the Onsala Space Observatory.

<sup>3</sup> IRAM is an international institute for millimeter-wave astronomy, co-funded by the Centre National de la Recherche Scientifique (France), the Max-Planck-Gesellschaft (Germany) and the Instituto Geografico Nacional (Spain).



**Fig. 2.** Spectra of the  $\text{H}_3\text{O}^+$  364 GHz line (top) and 307 GHz line (bottom) toward the Sgr B2 (M) and Sgr B2 (OH) positions.

in the vicinity of Sgr B2 (N) are so confused that the  $\text{H}_3\text{O}^+$  line parameters cannot be reliably extracted. Identification and interpretation of these other lines will be done elsewhere in the framework of a spectral line survey program (Belloche et al., in prep.).

#### 4. Column densities of $\text{H}_3\text{O}^+$ and $\text{H}_2\text{O}$

Figure 2 shows spectra of the two  $\text{H}_3\text{O}^+$  lines at the positions where 307 GHz observations have been made. At both positions, the intensities of the two  $\text{H}_3\text{O}^+$  lines are comparable. Since the lines are optically thin for any chemically reasonable  $\text{H}_3\text{O}^+$  abundance, the line ratio of  $\sim$ unity indicates a high excitation temperature,  $T_{\text{ex}} \gtrsim 50$  K. Statistical equilibrium calculations using molecular data from Schöier et al. (2005)<sup>4</sup> indicate that at the conditions in the M core ( $T = 200$  K,  $n(\text{H}_2) = 10^7 \text{ cm}^{-3}$ ), collisions can sustain  $T_{\text{ex}} \approx 100$  K, consistent with the observed  $\text{H}_3\text{O}^+$  line ratio. However, the density ( $10^6 \text{ cm}^{-3}$ ) at the OH position is too low to thermalize the excitation at the kinetic temperature of 60 K. The observed  $\text{H}_3\text{O}^+$  line ratio therefore indicates that the  $\text{H}_3\text{O}^+$  excitation is driven by far-infrared pumping by the strong dust continuum radiation in the Sgr B2 region, as found before by Phillips et al. (1992). Models with  $T_d = 40\text{--}80$  K reproduce the observed line ratio. Far-infrared pumping is also expected to play a major role toward (M), due to its high infrared luminosity, and is therefore included in the model.

For these excitation conditions, the observed line strengths imply  $N(\text{p-}\text{H}_3\text{O}^+) = 1.83(\pm 0.27) \times 10^{15} \text{ cm}^{-2}$  for Sgr B2 (OH) and  $6.81(\pm 1.01) \times 10^{15} \text{ cm}^{-2}$  for Sgr B2 (M). The total  $\text{H}_3\text{O}^+$  column densities are twice these values, as the ortho/para ( $o/p$ ) ratio tends to unity at high temperatures ( $\gtrsim 100$  K). These estimates have uncertainties of a factor of  $\sim 2$  due to the uncertain excitation and the difference in estimated values from the

**Table 2.** Column densities of  $\text{H}_2\text{O}$ ,  $\text{H}_3\text{O}^+$ , and  $\text{H}_2$  in the Sgr B2 region.

Component	$N(\text{H}_2\text{O})$ $10^{18} \text{ cm}^{-2}$	$N(\text{H}_3\text{O}^+)$ $10^{15} \text{ cm}^{-2}$	$N(\text{H}_2)^a$ $10^{24} \text{ cm}^{-2}$
Core (M)	35	13.6	4.4
Envelope (OH)	0.15 <sup>b</sup>	3.7	1.1
Beam size (")	12	18	20

<sup>a</sup> From CSO 350  $\mu\text{m}$  data assuming  $T_d = 40$  K and  $\kappa_v = 0.07 \text{ cm}^2 \text{ g}^{-1}$  (Lis, priv. comm.). <sup>b</sup> From Cernicharo et al. (2006) assuming  $\text{H}_2\text{O}/\text{H}_2 = 10^{-7}$ .

two lines. Since the lines are optically thin and the source sizes cannot be constrained, the derived column densities are beam averages. For the Sgr A sources, assuming  $\Delta V = 10 \text{ km s}^{-1}$ ,  $T_{\text{ex}} = 100$  K and  $o/p = 1$ , the observed limit on the line flux of  $\approx 1 \text{ K km s}^{-1}$  corresponds to  $N(\text{H}_3\text{O}^+) < 6 \times 10^{13} \text{ cm}^{-2}$ .

Dividing the above column density estimates by  $N(\text{H}_2)$  values based on (sub-)millimeter dust continuum mapping (Table 2) provides estimates of the column-averaged abundance in the two sources:  $N(\text{H}_3\text{O}^+)/N(\text{H}_2) = 3.1 \times 10^{-9}$  in Sgr B2 (M) and  $3.4 \times 10^{-9}$  in Sgr B2 (OH). These estimates of the  $\text{H}_3\text{O}^+$  column density and abundance are higher than previous values by Phillips et al. (1992) which were derived from the  $\text{H}_3\text{O}^+$  396 GHz line assuming a density of  $10^5 \text{ cm}^{-3}$  for the Sgr B2 envelope, a value which likely is an order of magnitude too low (Goicoechea et al. 2004).

To estimate the  $\text{H}_2\text{O}$  column density from the IRAM observations, we adopt the same excitation conditions as for  $\text{H}_3\text{O}^+$ . To convert p- $\text{H}_2^{18}\text{O}$  into  $\text{H}_2\text{O}$ , we adopt  $o/p = 3$  as applicable for warm gas and  $^{16}\text{O}/^{18}\text{O} = 250$  as applicable for the Galactic Center (Wilson & Rood 1994). For the Sgr B2 (M) position, we estimate  $N(\text{H}_2\text{O}) = 3.5 \times 10^{19} \text{ cm}^{-2}$ , while the upper limit at the (OH) position implies  $N(\text{H}_2\text{O}) < 1.7 \times 10^{18} \text{ cm}^{-2}$  ( $1\sigma$ ). Within the uncertainty of a factor of two, our estimate of  $N(\text{H}_2\text{O})$  at the M position is consistent with radiative transfer modelling of the  $\text{H}_2^{18}\text{O}$  203 GHz line towards the N core (Comito et al. 2003). The  $\text{H}_2\text{O}$  column densities imply abundances of  $1.2 \times 10^{-5}$  and  $< 1.7 \times 10^{-6}$  at the (M) and (OH) positions, respectively, consistent with the estimates of  $\sim 10^{-5}$  and  $\sim 10^{-7}$  from observations of the  $\text{H}_2\text{O}$  183 GHz line (Cernicharo et al. 2006).

#### 5. Chemistry of $\text{H}_2\text{O}$ and $\text{H}_3\text{O}^+$

Table 2 summarizes measurements of the  $\text{H}_2\text{O}$  and  $\text{H}_3\text{O}^+$  column densities toward the Sgr B2 cores (represented by the M position) and the surrounding envelope (represented by the OH position). The  $\text{H}_3\text{O}^+/\text{H}_2\text{O}$  ratio is seen to be  $\sim 1/50$  in the envelope, or about 20 times the value in local clouds (Phillips et al. 1992), but drops by  $\sim 100$  toward the cores. This drop is more than expected from enhanced recombination at higher densities, and may be due to ongoing injection of  $\text{H}_2\text{O}$  into the gas phase by evaporation of icy grain mantles, which also causes the rich (sub-)millimeter spectra of the (M) and (N) cores.

To estimate the cosmic-ray ionization rate  $\zeta_{\text{CR}}$  in the Sgr B2 region from our observations, we have used the chemical model of Van der Tak & van Dishoeck (2000). Given estimates of temperature, density,  $\zeta_{\text{CR}}$ , and the abundances of CO, O,  $\text{N}_2$  and  $\text{H}_2\text{O}$ , this model calculates the steady-state abundances of  $\text{HCO}^+$ ,  $\text{N}_2\text{H}^+$  and  $\text{H}_3\text{O}^+$ , as well as the total electron fraction. The model neglects metals such as Mg, Fe and S as electron sources and PAHs as electron sinks; including these species may change the calculated electron fraction by 2–3 depending on

<sup>4</sup> <http://www.strw.leidenuniv.nl/~moldata/radex.php>

their abundance. The reaction rates in the model have been updated to follow the UMIST99 values (Le Teuff et al. 2000), except for the dissociative recombination reactions of  $\text{H}_3^+$ ,  $\text{HCO}^+$  and  $\text{N}_2\text{H}^+$  where the values of McCall et al. (2003), de Boisanger et al. (1996) and Geppert et al. (2004) are used. For the cores, we adopt  $T = 200$  K and  $n = 10^7 \text{ cm}^{-3}$ , while for the envelope, we use  $T = 60$  K and  $n = 10^6 \text{ cm}^{-3}$  (see Goicoechea et al. 2004). The CO abundance of  $5 \times 10^{-5}$  is from the SEST line survey (Nummelin et al. 2000), the O abundance of  $1.5 \times 10^{-4}$  is based on the ISO-LWS line survey (Goicoechea et al. 2004), and we assume equal CO and  $\text{N}_2$  abundances.

The model reproduces the observed  $\text{H}_3\text{O}^+/\text{H}_2\text{O}$  ratio in the Sgr B2 envelope for  $\zeta_{\text{CR}} \sim 4 \times 10^{-16} \text{ s}^{-1}$ . The uncertainty is a factor of 2 from the observed  $\text{H}_3\text{O}^+/\text{H}_2\text{O}$  ratio, and another factor of 2 through the assumed CO,  $\text{N}_2$  and O abundances. For Sgr B2 (M), the model indicates a  $\sim 10\times$  lower  $\zeta_{\text{CR}}$ , which we consider a lower limit because the chemistry may not be in steady state. The time scale to equilibrate the  $\text{H}_2\text{O}/\text{H}_3\text{O}^+$  ratio is  $t_{\text{ion}} \sim 30(n_e)^{-0.5} \text{ yr}$  (Van der Tak et al. 2006) which for the model electron density of  $n_e = 0.01 \text{ cm}^{-3}$  equals 300 yr.

The derived value of  $\zeta_{\text{CR}}$  for Sgr B2 (OH) is  $10\times$  higher than the value for dense gas in the Solar neighbourhood (Sect. 1), but  $3\times$  lower than indicated by  $\text{H}_3^+$  observations of the Sgr A region (Oka et al. 2005). We conclude that the ionization rates of dense molecular clouds are mainly determined by their location in the Galaxy through variations in the cosmic-ray flux by a factor of  $\sim 10$ . As a second order effect,  $\zeta_{\text{CR}}$  is  $3\times$  lower in dense molecular clouds than in diffuse clouds, presumably due to cosmic-ray scattering (Padoan & Scalo 2005).

In the future, large-scale mapping of the Sagittarius molecular clouds in the  $\text{H}_3\text{O}^+$  364 GHz and  $\text{H}_2^{18}\text{O}$  203 GHz lines, combined with constraints on the temperature and density structure of the clouds, will provide more detailed understanding of the nature of the interaction between cosmic rays and molecular gas. The IRAM and APEX telescopes are well suited to carry out such observations, especially if equipped with heterodyne array receivers. Observations of  $\text{H}_2\text{O}$  and  $\text{H}_3\text{O}^+$  ground-state lines with the *Heterodyne Instrument for the Far-Infrared* (HIFI) on the *Herschel Space Observatory* will allow us to extend these studies to regions of lower column density.

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