APEX mapping of H30+ in the Sgr B2 region
Tak, F.F.S. van der; Belloche, A.; Schilke, P.; Güsten, R.; Philipp, S.; Comito, C.; Bergman, P.; Nyman, L.A.

Published in:
Astronomy & astrophysics

DOI:
10.1051/0004-6361:20065289

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2006

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Tak, F. F. S. V. D., Belloche, A., Schilke, P., Güsten, R., Philipp, S., Comito, C., Bergman, P., & Nyman, L. A. (2006). APEX mapping of H30+ in the Sgr B2 region. Astronomy & astrophysics, 454(2), L99-L102. https://doi.org/10.1051/0004-6361:20065289

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.
Astronomy & Astrophysics

LETTER TO THE EDITOR

APEX mapping of H$_3$O$^+$ in the Sgr B2 region

F. F. S. van der Tak$^{1,2}$, A. Belloche$^1$, P. Schilke$^1$, R. Güsten$^1$, S. Philipp$^1$, C. Comito$^1$, P. Bergman$^3$, and L.-Å.Nyman$^3$

1 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
2 National Institute for Space Research (SRON), Postbus 800, 9700 AV Groningen, The Netherlands
3 European Southern Observatory, Casilla 19001, Santiago, Chile

Received 27 March 2006 / Accepted 22 May 2006

ABSTRACT

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

Aims. Variations of $\zeta_{CR}$ 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 H$_3$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 H$^3$O 203 GHz line at the same positions.

Results. Strong H$_3$O$^+$ emission is detected over a ∼3 × 2 pc region, indicating an H$_3$O$^+$ column density of 10^{15}−10^{16}$ cm$^{-2}$ in an 18″ beam. The H$_2$O$^+$ abundance of ∼3 × 10^{8} and H$_3$O$^+$/$H_2$O ratio of ∼1/50 in the Sgr B2 envelope are consistent with models with $\zeta_{CR} \sim 4 \times 10^{-16}$ s$^{-1}$, 3× lower than derived from H$_2^+$ observations toward Sgr A, but 10× 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 ∼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 $\zeta_{CR}$ (Per diffuse cloud) (Le Petit et al. 2004). Even larger enhancements are found for the Galactic Center, where Oka et al. (2005) derive $\zeta_{CR} \sim 10^{-15}$ s$^{-1}$ from H$_2^+$ 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 $\zeta_{CR}$ 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 DCO$^+$/HCO$^+$ ratio is complicated by the uncertain D abundance, while comparing 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 (H$_3$O$^+$) a key ion in the oxygen chemistry of dense clouds. Its submillimeter rotation-inversion transitions may be used to measure $\zeta_{CR}$ and trace H$_2$O and 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 H$_3$O$^+$ emission toward Sgr B2 (OH)$^1$. Unfortunately, the atmospheric transmission from Mauna Kea is rarely good enough to observe H$_3$O$^+$, so mapping is not feasible.

The Chajnantor site greatly facilitates observation of the H$_3$O$^+$ J$_K = 3_2^−2_1^−$ line at 364.7974 GHz, which has an upper level energy of 139 K and an Einstein A-coefficient of 2.8 × 10^{-18}$ s$^{-1}$. The J$_K = 1^−1^−2^−$ line (ν = 307.1924 GHz, $E_u = 80$ K, A = 3.5 × 10^{-19}$ 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 H$_2$O 313–202 line at 203.4075 GHz ($E_u = 204$ K, A = 4.9 × 10^{-19}$ s$^{-1}$), the data are used to estimate $\zeta_{CR}$ 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 H$_2$O$^+$ (Goicoechea & Cernicharo 2001).

2. Observations

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

---

1 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).
APEX telescope (Güsten et al., this volume). 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 (Güsten 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 (Güsten et al., this volume). 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 ~0.1 K on 0.20 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 Genschナー et al. (1996).

3. Results

Emission in the H\(_2\)O\(^+\) 364 GHz line is detected over an (80 × 40″) region in Sgr B2 (Fig. 1). The facility 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 ~0.1 K on 0.20 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 Genschナー et al. (1996).

A distribution of velocity-integrated H\(_2\)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 K km s\(^{-1}\).

Fig. 1. Distribution of velocity-integrated H\(_2\)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 K km s\(^{-1}\).

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

| Position     | \(\alpha(J2000)\) | \(\delta(J2000)\) | \(T_{\text{mb}}dV\) | \(V_{\text{LSR}}\) | \(\Delta V\) |
|--------------|-------------------|-------------------|--------------------|-----------------|-------------|
|              | hh mm ss          | K km s\(^{-1}\)   | K km s\(^{-1}\)    | km s\(^{-1}\)   | km s\(^{-1}\) |
| Sgr B2 (M)   | 17:47:20:2.2      | 28:23:05          | 42.0(13)           | +62.0(6)        | 17.3(16)    |
| Sgr B2 (OH)  | 17:47:20:2.8      | 28:23:32          | 8.7(4)             | +62.7(3)        | 15.3(8)     |
| GC 3-2       | 17:46:14.9        | 28:49:43          | <0.09              | ...             | ...         |
| GC IRS3      | 17:45:39.6        | 29:00:24          | <0.10              | ...             | ...         |
| \(\text{H}_2\text{O}^+\) 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)           | ...             | ...         |
| \(\text{H}_2\text{O}\) 203 GHz: | | | | | |
| Sgr B2 (M)   | 20.5(3)           | +63.3(1)          | 13.2(1)            | ...             | ...         |
| Sgr B2 (OH)  | <0.03             | ...               | ...                | ...             | ...         |

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

Observations of the H\(_2\)\(^{18}\)O 203 GHz line were performed with the IRAM 30-m telescope\(^2\) 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 ∼0.1 K on 0.20 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 Genschナー et al. (1996).

---

\(^2\) 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.

---

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 Geográfico Nacional (Spain).
in the vicinity of Sgr B2 (N) are so confused that the H$_3^+$ 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 H$_3^+$ and H$_2$O

Figure 2 shows spectra of the two H$_3^+$ lines at the positions where 307 GHz observations have been made. At both positions, the intensities of the two H$_3^+$ lines are comparable. Since the lines are optically thin for any chemically reasonable H$_3^+$ abundance, the line ratio of unity indicates a high excitation temperature, $T_{ex} \geq 50$ K. Statistical equilibrium calculations using molecular data from Schöier et al. (2005)$^a$ indicate that at the conditions in the M core ($T = 200$ K, $n(H_2) = 10^{7}$ cm$^{-3}$), collisions can sustain $T_{ex} \approx 100$ K, consistent with the observed H$_3^+$ line ratio. However, the density ($10^6$ cm$^{-3}$) at the OH position is too low to thermalize the excitation at the kinetic temperature of 60 K. The observed H$_3^+$ line ratio therefore indicates that the H$_3$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 $T_d = 40$–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 $N(p-H_2O^+) = 1.83(\pm 0.27) \times 10^{15}$ cm$^{-2}$ for Sgr B2 (OH) and $6.81(\pm 0.101) \times 10^{15}$ cm$^{-2}$ for Sgr B2 (M). The total H$_3$O$^+$ column densities are twice these values, as the ortho/para ($a/p$) 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 H$_2$O, H$_3$O$^+$, and H$_2$ in the Sgr B2 region.

| Component | $N$(H$_2$O) | $N$(H$_3$O$^+$) | $N$(H$_2$) |
|-----------|-------------|----------------|-----------|
| Core (M)  | 35          | 13.6           | 4.4       |
| Envelope (OH) | 0.15$^b$   | 3.7            | 1.1       |
| Beam size (″) | 12          | 18             | 20        |

$^a$ From CSO 350 μm data assuming $T_d = 40$ K and $\kappa_0 = 0.07$ cm$^2$ g$^{-1}$ (Lis, priv. comm.). $^b$ From Cernicharo et al. (2006) assuming H$_2$O/H$_2 = 10^{-2}$.

---

5. Chemistry of H$_2$O and H$_3$O$^+$

Table 2 summarizes measurements of the H$_2$O and H$_3$O$^+$ column densities toward the Sgr B2 cores (represented by the M position) and the surrounding envelope (represented by the OH position). The H$_2$O/H$_2$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 H$_2$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 $\zeta_{CR}$ 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, $\zeta_{CR}$, and the abundances of CO, O, N$_2$ and H$_2$O, this model calculates the steady-state abundances of HCO$^+$, N$_2$H$^+$, and H$_3$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

---

$^a$ [http://www.strw.leidenuniv.nl/~moldata/radex.php](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 H$_3^+$, HCO$^+$ and N$_2$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 $n = 10^7$ cm$^{-3}$, while for the envelope, we use $T = 60$ K and $n = 10^6$ 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 N$_2$ abundances.

The derived value of $\zeta_{CR}$ for Sgr B2 (OH) is 10x higher than the value for dense gas in the Solar neighbourhood (Sect. 1), but 3x lower than indicated by 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, $\zeta_{CR}$ is 3x 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 H$_2$O $364$ GHz and H$_3$^+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 H$_2$O and H$_3$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.

Acknowledgements. The authors thank the APEX staff for making the H$_2$O$^+$ observations possible, José Cernicharo and Juan Pardo for communicating their 183 GHz results in advance of publication, Clemens Thum, Nuria Marcelino and Stéphane Leon for arranging the H$_2$O observations on short notice, and Darek Lis and Malcolm Walmsley for useful comments on the manuscript.

References

Caselli, P., Walmsley, C., Zucconi, A., et al. 2002, ApJ, 565, 344
Caselli, P., & Walmsley, C. M. 2001, in Origin and Evolution of Young Stellar Clusters, ed. T. Montmerle, & P. André, 67
Cernicharo, J., Goicoechea, J. R., Pardo, J., & Asensio-Ramos, A. 2006, ApJ, in press [arXiv:astro-ph/0601336]
Comito, C., Schilke, P., Gerin, M., et al. 2003, A&A, 402, 635
Cummins, S., Linke, R., & Thaddeus, P. 1986, ApJS, 60, 819
de Boisanger, C., Helmich, F. P., & van Dishoeck, E. F. 1996, A&A, 310, 315
de Vicente, P., Martin-Pontado, J., & Wilson, T. L. 1997, A&A, 320, 957
Gaume, R. A., & Claussen, M. J. 1990, ApJ, 351, 538
Gensheimer, P. D., Mauersberger, R., & Wilson, T. L. 1996, A&A, 314, 281
Geppert, W. D., Thomas, R., Semaniak, J., et al. 2004, ApJ, 609, 459
Goicoechea, J. R., & Cernicharo, J. 2001, ApJ, 554, L213
Goicoechea, J. R., Rodríguez-Fernández, N. J., & Cernicharo, J. 2004, ApJ, 600, 214
Güsten, R., Walmsley, C. M., Ungerechts, H., & Churchwell, E. 1985, A&A, 142, 381
Jacq, T., Baudry, A., Walmsley, C. M., & Caselli, P. 1999, A&A, 347, 957
Le Petit, F., Roueff, E., & Herbst, E. 2004, A&A, 417, 993
Le Teuff, Y., Millar, T., & Markwick, A. J. 2000, A&AS, 146, 157
Lis, D. C., Carlstrom, J. E., & Keene, J. 1991, ApJ, 380, 429
Martin-Pontado, J., de Vicente, P., Wilson, T. L., & Johnston, K. J. 1990, A&A, 236, 193
McCall, B. J., Huneycutt, A. J., Saykally, R. J., et al. 2003, Nature, 422, 500
Nummelin, A., Bergman, P., Hjalmarson, Å, et al. 2000, ApJS, 128, 213
Oka, T., Geballe, T. R., Goto, M., Usuda, T., & McCall, B. J. 2005, ApJ, 632, 882
Padoan, P., & Scalo. J. 2005, ApJ, 624, L97
Phillips, T., van Dishoeck, E., & Keene, J. 1992, ApJ, 399, 533
Schöier, F. L., van der Tak, F. F. S., van Dishoeck, E. F., & Black, J. H. 2005, A&A, 432, 369
van der Tak, F. F. S., & van Dishoeck, E. F. 2000, A&A, 358, L79
van der Tak, F. F. S. 2006, Phil. Trans. R. Soc. Lond. A, in press [arXiv:astro-ph/0602346]
Van der Tak, F. F. S., Walmsley, C. M., Herpin, F., & Ceccarelli, C. 2006, A&A, 447, 1011
Webber, W. R. 1998, ApJ, 506, 329
Wilson, T. L., & Rood, R. 1994, ARA&A, 32, 191
Wootten, A., Turner, B., Mangum, J., et al. 1991, ApJ, 380, L79