Odin observations of H$_2$O in the Galactic Centre


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Abstract. The Odin satellite has been used to detect emission and absorption in the 557-GHz H$_2$O line in the Galactic Centre towards the Sgr A$^*$ Circumnuclear Disk (CND), and the Sgr A $+20$ km s$^{-1}$ and $+50$ km s$^{-1}$ molecular clouds. Strong broad H$_2$O emission lines have been detected in all three objects. Narrow H$_2$O absorption lines are present at all three positions and originate along the lines of sight in the 3-kpc Spiral Arm, the $−30$ km s$^{-1}$ Spiral Arm and the Local Sgr Spiral Arm. Broad H$_2$O absorption lines near $−130$ km s$^{-1}$ are also observed, originating in the Expanding Molecular Ring. A new molecular feature (the “High Positive Velocity Gas” - HPVG) has been identified in the positive velocity range of $±120$ to $+220$ km s$^{-1}$, seen definitely in absorption against the stronger dust continuum emission from the Circumnuclear Disk. The 548-GHz H$_2$O isotope line towards this source using Odin has not been detected at the 0.02 K (rms) level.

Key words. Galaxy: center – ISM: individual objects: Sgr A – ISM: molecules – ISM: clouds

1. Introduction

The central region of the Galaxy has been extensively studied at wavelengths between the near infrared and the radio portions of the spectrum (see reviews by Morris & Serabyn 1996; Mezger et al. 1996) as well as at γ-ray and X-ray wavelengths. The molecular clouds dominate the interstellar medium in the inner 500 pc ($1° = 150$ pc) of the Galaxy and the density of molecular clouds is far higher in this region than in any other part of the Galaxy. Although it represents less than 0.2% of the Galactic disk by volume, nearly 10% of the total Galactic molecular mass is found here. A dominant feature in this region is the inclined Expanding Molecular Ring (EMR, e.g. Güsten 1989). Another feature closer to the Centre is Sgr B2 which is the most prominent and massive concentration of molecular gas (GMC) and star formation in the entire Galaxy. Neufeld et al. (2000) have observed both H$_2$O and H$_2^{16}$O towards this source using the Submillimetre Wave Astronomy Satellite (SWAS). A dust ridge connects Sgr B2 to the regions closer to the Centre (Lis & Carlstrom 1994). The very central Sgr A Complex consists of a nonthermal shell component, Sgr A East, and a thermal
component, Sgr A West. The source Sgr A West, with its "mini-
spiral arms", consists of infalling gas (Killeen & Lo 1989) and
contains in its innermost regions the unique nonthermal radio
source Sgr A*, which is the manifestation of a 2.6 × 10^6 M⊙
black hole in the centre of the Milky Way system (Eckart &
Genzel 1996; Schödel et al. 2002).

The molecular complex associated with Sgr A consists pre-
dominantly of a molecular belt comprising the "+450 km s⁻¹
cloud" (M−0.02–0.07), the "+20 km s⁻¹ cloud" (M−0.13–
0.08), and the Circumnuclear Disk (CND) which surrounds
Sgr A West and has a rotational velocity of the order of
100 km s⁻¹ in the same direction as the rotation of the
Galaxy. These warm and high-density Galactic Centre molecu-
lar clouds are intimately entwined and interact with the contin-
uum complex described above (Sandqvist 1989 – H₂CO; Zytko
et al. 1990, 1996; Serabyn et al. 1994; Ojha et al. 2001 – C₁;

All these structures, together with many more, are parts of a mech-
anism complex involving shocks, magnetic fields and strong UV
radiation fields, and may thus function as prime candidates
for H₂O observations with the Odin satellite.

2. Observations

Odin is a submillimetre/millimetre wave spectroscopy astron-
omy and aeronomy satellite, launched on 20 February 2001
from Svalbard, Russia in far-eastern Siberia. It has a 1.1-m
high-precision telescope with a beam efficiency of about 90%
and beamwidths of 2.1 s and 9.5 s at submm and mm wave-
lengths, respectively. Its pointing uncertainty is <10″. There
are four cryo-cooled submm receivers tunable in the fre-
quency range of 486–580 GHz with a single sideband tem-
perature of ≈3000 K. A cryo-cooled HEMT receiver is tuned to
119 GHz and has a single sideband temperature of ≈600 K.

The backend spectrometers consist of an acousto-optical spec-
trometer (AOS) with a total bandwidth of 1040 MHz and two
auto-correlators with bandwidths in the range of 100–800 MHz,
corresponding to velocity resolutions of 0.08–1.0 km s⁻¹. The
satellite is described in detail by Frisk et al. (2003) and the re-
ceiver calibration by Olberg et al. (2003).

Three positions towards Sgr A have so far been ob-
served with Odin, namely Sgr A* with the CND, the
+20 km s⁻¹ molecular cloud and the +50 km s⁻¹ molecular
cloud. The coordinates of the observed positions are given in
Table 1. Observations have been made in the spectral lines of
119-GHz O₂, 487-GHz O₂, 492-GHz C₁, 548-GHz H¹₃O,
557-GHz H¹₆O, and 576-GHz (J = 5 – 4) CO. However, only
the data for H¹₆O and H¹₃O have been fully calibrated and re-
duced so far and they are presented in Sect. 3. The data for the
other spectral lines will be presented in a subsequent paper.

Two observing methods have been employed with Odin.
One method is Dicke-switching against one of two sky horns
with beamwidths of 4.4′, displaced 42′ from the main beam.
Sgr A* CND was observed this way in the H¹₆O line dur-
ing October 2001. In order to improve the baselines, full-
orbit observations were made of an empty reference OFF-
position at α(1950.0) = 17°42′26″, δ(1950.0) = −28°35′04″
every second orbit (observing period of 60 min). The total

<table>
<thead>
<tr>
<th>α(1950.0)</th>
<th>δ(1950.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17°42′29″</td>
<td>−28°59′18″</td>
</tr>
<tr>
<td>17°42′29″</td>
<td>−29°02′18″</td>
</tr>
<tr>
<td>17°42′41″</td>
<td>−28°58′00″</td>
</tr>
</tbody>
</table>

Table 1. Observed positions in the Galactic Centre Sgr A region.

ON-position time for the H¹₆O line observations was eight or-
bits (480 min). The other observing method was total-power
position-switching to the above reference position with a duty
cycle of 120 s. This was used for H¹₃O observations of
+50 km s⁻¹ (27 orbits) and for H¹₆O observations of the Sgr A* CND-region (58 orbits) during April/May 2002. The AOS was used for all
the H₂O observations, which results in a velocity resolution
of 0.54 km s⁻¹ and a total velocity coverage of 560 km s⁻¹ in
the line profiles.

3. Results

Strong emission and absorption lines have been observed in
the H¹₆O line at all three Sgr A positions. However, no spectral
line features can be detected in the H¹₃O line down to the rms
noise limit of ≈0.02 K. The three 557-GHz H¹₆O line profiles
observed towards Sgr A* CND, the +20 km s⁻¹ cloud and the
+50 km s⁻¹ cloud, are presented in Figs. 1a–c, and the smooth
profile, (after 0.02 K r.m.s) profile of the 548-GHz H¹₃O line to-
wards Sgr A* CND is shown in Fig. 1d. This last profile gives
an indication of the high quality of the baselines in our broad-
band observations, which is important when judging the reality
of the many emission and absorption features in the H¹₆O pro-
files. The intensity scale has not been corrected for the main
beam efficiency (≈0.9) in these four profiles. Furthermore, no
baselines have been subtracted. The intensity thus includes
the presence of the background continuum emission, although
the uncertainty of this level is not yet determined. The rela-
tive continuum intensities for the H¹₆O observations conform
qualitatively to the continuum level expected from an inter-
polation to the H₂O frequency of the 800 and 350 μm maps by
Lis & Carlstrom (1994) and Dowell et al. (1999), respec-
tively. However, it seems that the continuum level obtained
with the Dicke-switching method (Fig. 1a) agrees better with
the interpolated results (see also Sect. 4) than the position-
switching method (Figs. 1b-d). For the sake of comparison
with other spectral lines, we have chosen the data from the
SEST C¹₃O (1 – 0) survey of the Galactic Centre by Lindqvist
et al. (1995). The C¹₃O profiles resulting for the three H₂O pro-
files of a convolution of the SEXT map spectra to a resolu-
tion of 2′ (corresponding to the Odin beam size) are shown in
Fig. 2.

4. Discussion

A Gaussian analysis has been performed on the Sgr A* CND
H¹₆O profile using four absorption components and two emis-
sion components (Fig. 3). The continuum emission was first
Fig. 1. The 557-GHz $^{16}$H$_2$O line profiles observed towards a) the Sgr A$^*$ Circumnuclear Disk, the b) +20 and c) +50 km s$^{-1}$ clouds, and d) the 548-GHz $^{18}$H$_2$O isotope line profile observed towards the Sgr A$^*$ Circumnuclear Disk.

Fig. 2. The SEST C$^{18}$O (1–0) survey Odin-beam convolved profiles towards a) the Sgr A$^*$ Circumnuclear Disk, the b) +20 and c) +50 km s$^{-1}$ clouds.

subtracted out by fitting a linear baseline to the outermost channels on either side of the profile. The Gaussian analysis results are given in Table 2.

The first two components, I and II, both seen in emission, are believed to originate in the rapidly rotating CND. The northeastern part of the CND is receding and the southwestern part approaching, which gives the asymmetric, somewhat double-peaked line profile structure. The 2.1-arcmin beam of Odin encloses fully the CND and the resulting velocity structure of the profile is reminiscent of that seen in many other molecular lines (see e.g. HCO$^+$ (1 – 0) – Linke et al. 1981; HCO$^+$ (3 – 2) – Sandqvist et al. 1985; H$_2$CO (2 – 1) and CS (5 – 4) – Sandqvist 1989; CO (4 – 3) – White 1996).

Three narrow H$_2$O absorption components, seen at velocities near –5, –30 and –53 km s$^{-1}$, are observed at all three positions and are well-known Galactic spiral arm features, which were first identified in early 21-cm H$^1$ observations. They originate along the line of sight crossing the so-called Local Sgr, –30 km s$^{-1}$ and 3-kpc spiral arm structures.

From the two submillimetre continuum maps discussed in Sect. 3, we find that the 350 µm:800 µm flux ratios (on a 30$''$ scale) for all three positions are about 17–18 (corresponding to a spectral index of about 3.5). From the 800 µm map we estimate the flux densities on a 2$'$ scale to be 160, 300, and 250 Jy, for the Sgr A$^*$ CND, +20 and +50 km s$^{-1}$ cloud positions, respectively. At 557 GHz
Table 2. Gaussian components of the Sgr A* Circumnuclear Disk 557-GHz H$_2^{16}$O line profile.

<table>
<thead>
<tr>
<th>Velocity (km s$^{-1}$)</th>
<th>$T_A$ (K)</th>
<th>Halfwidth (km s$^{-1}$)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>+73.2</td>
<td>+0.32</td>
<td>88.5</td>
</tr>
<tr>
<td>II</td>
<td>-31.6</td>
<td>+0.24</td>
<td>47.9</td>
</tr>
<tr>
<td>III</td>
<td>-4.8</td>
<td>-0.24</td>
<td>13.4</td>
</tr>
<tr>
<td>IV</td>
<td>-30.2</td>
<td>-0.25</td>
<td>11.0</td>
</tr>
<tr>
<td>V</td>
<td>-53.5</td>
<td>-0.21</td>
<td>8.1</td>
</tr>
<tr>
<td>VI</td>
<td>-132.2</td>
<td>-0.09</td>
<td>60.0</td>
</tr>
</tbody>
</table>

Fig. 3. Gaussian analysis performed on the 557-GHz H$_2^{16}$O line profile observed towards the Sgr A* Circumnuclear Disk.

(538 $\mu$m) and with a conversion factor of 4100 Jy/K (based on a theoretical $\eta_a = 0.7$ for Odin) we estimate continuum levels of 0.16, 0.29, and 0.24 K in our three positions. In the +20 km s$^{-1}$ cloud profile the deepest absorption is about 0.4 K which is significantly deeper than our estimated continuum level of 0.29 K.

The three distinct and rather narrow absorption features (III, IV and V) are present in the spectra at all three positions (see Figs. 1a–c). The absorption feature (III) at $-5$ km s$^{-1}$ appears to be the strongest and, judged by the estimated continuum levels, this feature has an optical depth of at least one. The absorbing gas in these three features lies in front of the Galactic Centre region performed with the VLA by Karlsson et al. (2003).

Evidence for the existence of the HPVG in the Sgr A region, seen in other spectral lines, is scarce. The HPVG should not be confused with the molecular gas in the far side of the EMR whose velocity falls inside the same range but whose emission lines are narrower. Also, the HPVG is seen in absorption which places it in front of the Galactic Centre continuum sources and thus it cannot be part of the far side of the EMR.

Additional evidence for the HPVG may also be present in VLA OH absorption observations towards the Sgr A Complex by Karlsson et al. (2003).
Table 3. Abundances in the Local Sgr (III) and −30 km s$^{-1}$ (IV) and 3-kpc (V) Spiral Arm features.

<table>
<thead>
<tr>
<th>Position</th>
<th>Feature</th>
<th>I(C$^{18}$O) (K km s$^{-1}$)</th>
<th>N(C$^{18}$O) (cm$^{-2}$)</th>
<th>N(H$_2$) (cm$^{-2}$)</th>
<th>N[H$_2$O] (cm$^{-2}$)</th>
<th>X [H$_2$O]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sgr A* CND</td>
<td>III</td>
<td>2.10</td>
<td>2.1 × 10$^{14}$</td>
<td>1.0 × 10$^{22}$</td>
<td>&gt;2 × 10$^{13}$</td>
<td>&gt;2 × 10$^{9}$</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>0.18</td>
<td>1.8 × 10$^{14}$</td>
<td>9.0 × 10$^{20}$</td>
<td>&gt;9 × 10$^{12}$</td>
<td>&gt;1 × 10$^{8}$</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>0.65</td>
<td>6.5 × 10$^{14}$</td>
<td>3.2 × 10$^{21}$</td>
<td>&gt;8 × 10$^{12}$</td>
<td>&gt;2 × 10$^{9}$</td>
</tr>
<tr>
<td>+20 km s$^{-1}$ cloud</td>
<td>III</td>
<td>1.00</td>
<td>1.0 × 10$^{15}$</td>
<td>5.0 × 10$^{21}$</td>
<td>&gt;1 × 10$^{13}$</td>
<td>&gt;2 × 10$^{9}$</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>0.34</td>
<td>3.4 × 10$^{14}$</td>
<td>1.7 × 10$^{21}$</td>
<td>&gt;1 × 10$^{13}$</td>
<td>&gt;6 × 10$^{9}$</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>0.96</td>
<td>9.6 × 10$^{14}$</td>
<td>4.8 × 10$^{21}$</td>
<td>&gt;2 × 10$^{13}$</td>
<td>&gt;4 × 10$^{9}$</td>
</tr>
<tr>
<td>+50 km s$^{-1}$ cloud</td>
<td>III</td>
<td>1.10</td>
<td>1.1 × 10$^{15}$</td>
<td>5.5 × 10$^{21}$</td>
<td>&gt;2 × 10$^{13}$</td>
<td>&gt;4 × 10$^{9}$</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>0.64</td>
<td>6.4 × 10$^{14}$</td>
<td>3.2 × 10$^{21}$</td>
<td>&gt;1 × 10$^{13}$</td>
<td>&gt;3 × 10$^{9}$</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>0.81</td>
<td>8.1 × 10$^{14}$</td>
<td>4.0 × 10$^{21}$</td>
<td>&gt;6 × 10$^{12}$</td>
<td>&gt;2 × 10$^{9}$</td>
</tr>
</tbody>
</table>

Although 58 Odin orbits were dedicated to observing the H$^{18}$O line towards the Sgr A* CND position, no spectral line was detected (see Fig. 1d). Our non-detection of H$^{18}$O towards Sgr A* CND provides an upper limit on the H$_2$O abundance in the narrow absorption features. Given the rms noise of 23 mK in the H$^{18}$O spectrum and the estimated continuum level of 0.16 K we find that a 10 km s$^{-1}$ wide absorption feature of optical depth 0.08 should have been detected at the 3σ level. Using this limit and adopting a 16O/18O ratio of 500 for this local absorbing cloud (Wilson & Rood 1994) and an excitation temperature of 15 K, we obtain an H$_2$O column density of 5 × 10$^{14}$ cm$^{-2}$. Hence, for the Local Sgr Arm absorption, the 3σ upper limit of the H$_2$O abundance becomes 5 × 10$^{8}$, using the H$_2$ column density of 1.0 × 10$^{22}$ in Table 3, while the lower limit was found to be 2 × 10$^{-9}$. The average H$_2$O abundance estimated for the foreground gas towards Sgr B2 by Neufeld et al. (2000) is 6 × 10$^{-7}$, which is about an order of magnitude higher than our range towards Sgr A. On the other hand, our range is in better agreement with H$_2$O abundances found in giant molecular cloud cores by Snell et al. (2000) and in a local diffuse molecular cloud by Neufeld et al. (2002).

In September/October of 2002, Odin again observed the Galactic Centre region in the H$_2$O line, this time pointing at the +20 and +50 km s$^{-1}$ cloud positions. These observations have not yet been calibrated and reduced. They will be reported in a future paper.

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References