O$^{18}$O and C$^{18}$O observations of $\rho$ Ophiuchi A***

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ABSTRACT

Context. Contrary to theoretical expectation, surprisingly low concentrations of molecular oxygen, O$_2$, have been found in the interstellar medium. Telluric absorption makes ground based O$_2$ observations essentially impossible and observations had to be done from space. Millimetre-wave telescopes on space platforms were necessarily small, which resulted in large, several arcminutes wide, beam patterns. Observations of the ($N_j = 1_1 - 1_0$) ground state transition of O$_2$ with the Odin satellite resulted in a $\geq5\sigma$ detection toward the dense core $\rho$ Oph A. At the frequency of the line, 119 GHz, the Odin telescope has a beam width of 10$''$, larger than the size of the dense core.

Aims. The precise nature of the emitting source and its exact location and extent are therefore unknown. The current investigation is intended to remedy this.

Methods. Although the Earth’s atmosphere is entirely opaque to low-lying O$_2$ transitions, it allows ground based observations of the much rarer $^{16}$O$^{18}$O in favourable conditions and at much higher angular resolution with larger telescopes. In addition, $\rho$ Oph A exhibits both multiple radial velocity systems and considerable velocity gradients. Extensive mapping of the region in the proxy C$^{18}$O ($J = 3-2$) line can be expected to help identify the O$_2$ source on the basis of its line shape and Doppler velocity. Line opacities were determined from observations of optically thin $^{13}$C$^{18}$O ($J = 3-2$). During several observing periods, two C$^{18}$O intensity maxima in $\rho$ Oph A were searched for O$^{18}$O in the ($2_1 - 0_0$) line at 234 GHz with the 12 m APEX telescope. These positions are associated also with peaks in the mm-continuum emission from dust.

Results. Our observations resulted in an upper limit on the integrated O$^{18}$O intensity of $\int T_A^* du < 0.01$ K km s$^{-1}$ (3$\sigma$) into the 26$''$ beam. Together with the C$^{18}$O data, this leads to a ratio of $N(C^{18}O)/N(O^{18}O) > 16$. Combining Odin’s O$_2$ with the present O$^{18}$O observations we infer an O$_2$ abundance $5 \times 10^{-7} < X(O_2) \leq 2.5 \times 10^{-6}$.

Conclusions. Examining the evidence, which is based primarily on observations in lines of O$^{18}$O and C$^{18}$O, leads us to conclude that the source of observed O$_2$ emission is most likely confined to the central regions of the $\rho$ Oph A core. In this limited area, implied O$_2$ abundances could thus be higher than inferred on the basis of Odin observations (5 $\times$ 10$^{-6}$) by up to two orders of magnitude.

Key words. ISM: abundances – ISM: molecules – ISM: lines and bands – ISM: clouds – ISM: individual objects: $\rho$ Oph A SM 1 – ISM: individual objects: $\rho$ Oph A SM 1N

1. Introduction

Oxygen is the most abundant of the astronomical metals (e.g., Asplund et al. 2009, and references therein). Consequently, in its molecular form, it was also expected to be very abundant in the UV-shielded regions inside molecular clouds (e.g., Black & Smith 1984; Bergin et al. 2000; Charnley et al. 2001; Roberts & Herbst 2002; Spaans & van Dishoeck 2001; Viti et al. 2001; Willacy et al. 2002; Quan et al. 2008) and to contribute significantly to the cooling, hence the energy balance, of dense clouds (Goldsmith & Langer 1978).

Because of the high O$_2$ content in the Earth’s atmosphere, astronomical O$_2$ sources cannot be observed from the ground.

* Based on observations with APEX, Llano Chajnantor, Chile.
** Data cubes of Figs. 3 and 4 are only available in electronic from at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J=A+A/510/A98

Dedicated space missions$^1$ came into operation near the beginning of the new millennium. Their unsuccessful searches (Goldsmith et al. 2000; Pagani et al. 2003) were highly disappointing and it was hard to understand that, in the interstellar medium (ISM), O$_2$ is an elusive species (see references cited above).

Eventually, after more than 20 days of Odin-observing during three different runs, came a real break-through: for the very first time, O$_2$ was finally detected in the ISM (Larsson et al. 2007). The O$_2$ emitting object, $\rho$ Oph A, is a dense clump (Loren et al. 1990) in a region of active star formation (L1688). On the basis of theoretical model calculations, the detectability of this kind of source had earlier been predicted by Black & Smith (1984) and Maréchal et al. (1997a), where the latter authors made their specific prediction with regard to Odin.

Odin carries a 1.1 m telescope which is designed for observations in the submillimetre regime, between roughly 480 and 2500 GHz. It has successfully observed towards $\rho$ Oph A SM 1 (5$''$ beam) through the Odin $^1$H$_2$O line at 601 GHz in the first run, and towards $\rho$ Oph A (5$''$ beam) through the Odin $^1$H$_2$O line at 601 GHz in the second run.
580 GHz (0.5–0.6 mm). However, the O$_2$ discovery was made with a dedicated 119 GHz (2.5 mm) receiver aboard Odin, fixed-tuned to the frequency of the ground state O$_2$ ($N_J=1-1_0$) transition at 118750.343 MHz. At this frequency, the telescope beam size is 10′, larger than the angular dimension of the dense ρ Oph A core, which is about 4′ (FWHM of devolvedCS core, Liseau et al. 1995).

It follows that the true O$_2$ source is likely under-resolved, the consequence of which directly affects estimates of the abundance of O$_2$, i.e. $N(O_2)/N(H_2)$: depending on the adopted model, the Odin observations imply an abundance which is currently uncertain by two orders of magnitude (Liseau et al. 1995).

In Fig. 2 of Larsson et al. (2007), the Odin-O$_2$ line is compared to transitions of other molecular species in ρ Oph A. Whereas lines of H$_2$O and CO are optically very thick over large parts of the cloud and have self-absorbed profiles, the optically thin O$_2$ line displays a simple, Gaussian shape. This line shape is similar to that of the C$^{15}$O line (Pankonin & Walmsley 1978), displayed at the top of the figure and which most likely originates in the ρ Oph-PDR. If also the main source of O$_2$ emission, the abundance would indeed be very low.

However, the O$_2$ line shape is also similar to that of the C$^{13}$O (3–2) line, also shown in the figure. This suggests that the C$^{13}$O line can be used as a tracer of the molecular oxygen emission and we set out to map the 10′ Odin beam in the (3–2) transition of C$^{13}$O with the APEX beam of size 19′. It was expected that a detailed comparison of the line centre velocity with that of the O$_2$ line would help to narrow down the exact location of the O$_2$ emission, since two distinct velocity components are known to be present in ρ Oph A. This information is needed to understand, where, i.e. in what physical conditions, the majority of the O$_2$ molecules is excited: in the cold and dense dark cores (Di Francesco et al. 2004), in the extended warm Photon Dominated Region (PDR; Hollenbach et al. 2009) or in the hot shocked gas of the outflow from VLA 1623 (Liseau & Justtanont 2009)? With the C$^{13}$O proxy for O$_2$ emission, probable emission regions were identified, which were then observed for $^{16}$O$^{18}$O (2,−1,0).

There exists earlier work for this line and the ρ Oph cloud. Goldsmith et al. (1985) observed ρ Oph A in the same transition and with comparable beam size (26′′), albeit at an offset 11′ E and 61′′ N relative to the position of SM1N. They obtained $T_R < 120$ mK (1σ) over 0.34 km s$^{-1}$. At similar channel resolution (0.32 km s$^{-1}$) and toward essentially the same position, Lüdtke & Vanden Bout (1985) obtained an rms-noise value of $T_R < 17.5$ mK with a 12 m NRAO telescope (34′). These papers also present energy level diagrams. Observations made with the 10 m telescope of the Caltech Submillimeter Observatory (CSO) in July 1991 and for the position 16°23′25″, −24°15′49″ (B1950) resulted in an rms noise temperature of 16 mK in a 0.25 km s$^{-1}$ velocity bin and of 12 mK after binning to 0.50 km s$^{-1}$ (van Dishoeck, Keene, & Phillips, private communication).

The derivation of molecular abundances requires knowledge of the H$_2$ column density. One of the widely exploited techniques to estimate $N$(H$_2$) is to use observations of C$^{13}$O, the transitions of which in many cases can be shown to be optically thin. We discovered, however, that in the dense core regions of ρ Oph A, this not to be the case everywhere and that appropriate opacity corrections using the C$^{13}$O line needed to be made.

This paper is organised as follows: in Sect. 2, our APEX observations of the ρ Oph A cloud in transitions of $^{16}$O$^{18}$O, C$^{13}$O and $^{13}$C$^{18}$O are described. Section 3 presents our results, which are discussed in Sect. 4. Finally, in Sect. 5 our main conclusions are briefly summarised.

2 Observations and data reductions

All observations have been made with the SIS receivers and spectrometers at the Atacama Pathfinder EXperiment (APEX). The 12 m APEX telescope is located at an altitude of about 5100 m on the Llano de Chajnantor in northern Chile. The telescope pointing is accurate to 3′′ (rms).

The Fast Fourier Transform Spectrometer (FFTS) was configured to have 8192 channels, which over a bandwidth of 1 GHz provides a resolution of 122 kHz, corresponding to 0.16 km s$^{-1}$ and 0.11 km s$^{-1}$ at 234 GHz and 329 GHz, respectively. As frontends for these frequencies, we used APEX1 of the Swedish Heterodyne Facility Instrument (SHFI, Vassiliev et al. 2008) and APEX2A (Risacher et al. 2006).

2.1 O$^{16}$O observations

The data have been collected during three different observing runs in 2008 and 2009. The frequency of the (2,−1,0) line can be derived from the data given by Steinbach & Gordy (1975) as 233946.179 MHz. At 234 GHz, the APEX beam has a half power beam width HPBW = 26′′5 and the main beam efficiency is $\eta_{mb} = 0.75$. The telescope was pointed toward RA = 16°26′27′′2 and Dec = −24°23′34″′ (J2000), a position which was initially chosen on the basis of, as it turned out, insufficiently sampled data (see Sect. 3.2). In addition, the strongest peak of doubly deuterated formaldehyde emission in the ρ Oph A core (Bergman et al., in preparation), which is situated 30′′ south of these coordinates, was also observed. These positions are close to the location of intense mm-dust-emission (cf. Fig. 3), i.e. the dense core SM1 (Motte et al. 1998). For the primary position, the total on-source integration time was 4.9 h and the average system temperature was $T_{sys} \sim 220$ K, whereas for the −30′′-position, these values were 6.5 h and 210 K, respectively.

2.2 C$^{13}$O and $^{13}$C$^{18}$O observations

The observations were collected during two observing runs in 2006 and 2007 at the APEX telescope. The observing mode was position switched raster mapping and the data were sampled according to the Nyquist criterion on a rectangular 10′′ grid, aligned with the equatorial coordinate system (200′′ × 200′′). At 329 GHz, the HPBW = 19′′ and the average system temperature was $T_{sys} = 200$ K. The efficiencies were $\eta_{mb} = 0.73$ and $\eta_{doon} = 0.85$ for point source and extended source calibrations, respectively.

In addition, an extended raster map of the outer regions of ρ Oph A was obtained on a coarser grid with 20′′ (full beam) spacings. The entire region observed is thus as large as Δα×Δδ = 10′ × 5′.

The origin of the map is the same as that of the Odin observations, i.e. the (0, 0) position is at RA = 16°26′24″6 and Dec = −24°23′54″′ (J2000). The same reference position as for the Odin observations (Larsson et al. 2007), viz. 15″ N relative to

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http://www.apex-telescope.org/
Fig. 1. The central part of the 1 GHz wide APEX spectrum centered on the frequency of the $^{16}\text{O}^{18}\text{O}(2_1-0_1)$ transition, 233.946179 GHz, and obtained toward RA =$16^h26^m27^s$ and Dec = $-24^\circ24'04"$ (J2000) in $\rho$ Oph A. The sampling is in 122 kHz wide channels ($\delta \nu = 0.16$ km s$^{-1}$).

Table 1. $^{18}$O-peaks of integrated intensity, $\int T^*_A dv$.

| $^{18}$O-peak Offset (arcsec) RA (J2000) Dec (J2000) Other ID |
|----------------|----------------|----------------|
| P1            | +35, +50       | 16:26:27.2     | -24:23:04 | N 1 |
| P2            | +45, +28       | 16:26:27.9     | -24:23:26 | N 5, SM 1N |
| P3            | +45, -13       | 16:26:27.9     | -24:24:07 | N 4, SM 1 |


to the map centre, was used here for calibration purposes. In addition to the $^{18}$O map, five positions were also observed in the (3−2) transition of the even rarer isotope $^{13}$C$^{18}$O (Table 2). Klapper et al. (2003) provide lab-frequencies for the (3−2) rotational transition of $^{18}$O and $^{13}$C$^{18}$O, i.e., 329.330.552 MHz and 314.119.660 MHz, respectively, and where the latter is a weighted mean value, with the $^{13}$C hyperfine structure being ignored.

3. Results

3.1. $^{18}$O

The $^{16}$O$^{18}$O(2−0) line was not detected toward any of the observed positions. Toward the position associated with P 2 (see Fig. 3 and Table 1), the noise level is $T_{\text{rms}} = 6.5$ mK (1$\sigma$) in a 0.62 km s$^{-1}$ bin. The result is similar for the observation of the position 30″ south (P 3), i.e., $T_{\text{rms}} = 8.2$ mK in a 0.16 km s$^{-1}$ bin (Fig. 1).

3.2. $^{18}$O and $^{13}$C$^{18}$O

Example spectra in three isotopes of CO (3−2) are shown in Fig. 2 toward two positions in the central region of the $\rho$ Oph A core. Further, Fig. 3 shows the inner, high-resolution, map of integrated intensity, $\int T^*_A dv$, of the $^{18}$O(3−2) line. Within a range of RA offsets +30″ to +50″, four distinct intensity peaks are discernable. In Table 1, these are designated P 1 through P 4 and their J2000 coordinates are given. The $^{18}$O line is very narrow, e.g. merely 1.0 km s$^{-1}$ (FWHM) at the inconspicuous (0, 0) position.

Fig. 2. (J = 3−2) spectra ($T_{\text{mb}}$ vs. $\nu_{\text{LSR}}$) of, from top to bottom, CO (black), $^{18}$O (red) and $^{13}$C$^{18}$O (blue) toward two positions in the $\rho$ Oph A core (cf. Fig. 3). For clarity, two of the spectra are offset by ±5 K and the $^{13}$C$^{18}$O spectra have been multiplied by a factor of twenty.

Fig. 3. $^{18}$O(3−2) integrated intensity, $\int T^*_A dv$, of the dark core $\rho$ Oph A. The map was obtained with APEX and observed positions are shown as crosses. The beam size at 329 GHz is shown in the lower right corner. Offsets are with respect to the origin, RA = $16^h26^m24^s$ and Dec = $-24^\circ23'54"$ (J2000). The position of the outflow driving Class 0 source VLA 1623 is shown by the star symbol. P 1-P 4 designate the clumps discussed in the text (Table 1). The beam size at 234 GHz is indicated by the dotted circles, at the observed $^{18}$O positions.
Fig. 4. A mosaic of maps of integrated C$^{18}$O(3−2) line intensity over 1.0 km s$^{-1}$ wide velocity intervals, from +1.0 to +5.0 km s$^{-1}$. The extended maps with 20$''$ spacing are shown. Two velocity components are identified in the ρ Oph A core, falling into the [2, 3] and [3, 4] bins, respectively. The lowest contour level corresponds to 4 K km s$^{-1}$ and increments are also by this amount.

Examination of the entire data set for C$^{18}$O(3−2) reveals the fact that, within the mapped region, maximum emission occurs at LSR-velocities +2.7 to +3.7 km s$^{-1}$. This velocity interval corresponds to that of the O$_2$ 119 GHz emission, viz. $v_{LSR}$ ∼ +2.5 to +3.5 km s$^{-1}$ (Larsson et al. 2007) and Fig. 6 here. ρ Oph A displays a complex velocity field and two distinct velocity components can be identified, giving rise to spectral line blending. These components are essentially confined within the LSR-velocity bins [+2, +3] and [+3, +4] (in km s$^{-1}$). Figure 4 presents a mosaic of the integrated line intensity in 1.0 km s$^{-1}$ wide bins. Experimenting also with different binnings demonstrates quite convincingly that the location of the O$_2$ emitting gas is most likely associated with the central core region of ρ Oph A.

4. Discussion

4.1. The dense clumps of ρ Oph A

The C$^{18}$O intensity maxima in Fig. 3 seem comparable in size with the APEX beam, which could indicate that the diameter of these clumps does not exceed 20$''$. From the comparison of their locations with those observed in the emission of the dust at 1.3 mm (Motte et al. 1998) and 850 μm (Johnstone et al. 2000) and of the quiescent gas in the N$_2$H$^+$ (1−0) line (Di Francesco et al. 2004), it becomes evident that P 4 lacks correspondence with features at 1.3 mm and N$_2$H$^+$ emission, but shows up weakly at 850 μm. P 1 likely is N1 (which is not seen in the dust maps), P 2 corresponds to N 5 (also prominent in the dust as SM 1N), and P 3 seems associated with N 4 and SM 1 (also 16264-2423 of Johnstone et al. 2000). Derived temperatures and densities for these clumps are of the order of 15−30 K and 0.2−5×10$^6$ cm$^{-3}$, respectively (e.g., André et al. 1993; Motte et al. 1998; Johnstone et al. 2000).

In summary, the evidence points toward the fact that also O$_2$ is concentrated in the dense dark core regions, where the molecules would be protected against photo-dissociation due to the intense UV field ($G_0$ of the order of 10$^2$) generated by the two B-stars, east and west of the cores, respectively (Liseau et al. 1999). The size of the O$_2$ emitting regions appears not to exceed one arcminute, so that a conservative estimate of the Odin beam filling would be about 0.01. If the emission originates in a core of size ∼ 20$''$ or smaller, the Odin beam filling factor would be reduced by yet another order of magnitude. The O$_2$ abundance would scale accordingly and could in this case be locally as high as a few times 10$^{-5}$, which would be comparable to the total abundance of oxygen in the gaseous phase (e.g., Liseau & Justtanont 2009).

4.1.1. Line optical depths

The ratio of the 13C$^{18}$O and 12C$^{18}$O line intensities can be used to estimate the optical depth in the rarer isotope line, $\tau_{13C^{18}O} \sim \ln(1 - r_{13})^{-1}$, where $r_{13} = T_{13C^{18}O}/T_{12C^{18}O}$. From the data presented in Table 2, it is clear that the C$^{18}$O(3−2) line could have significant opacity along several lines of sight, unless the relative abundance $12C^{18}O/13C^{18}O \ll 50$ (or the excitation temperatures for these species differ substantially).

Federman et al. (2003) determined a column density ratio $N(12CO)/N(13CO) = 125 \pm 23$ toward a line of sight designated ρ Oph A by them. However, their coordinates refer to $^5$ In addition, for their ρ Oph A line of sight, Federman et al. (2003) also give $N(12C^{16}O)/N(12C^{18}O) = 1100 \pm 600$. 

Page 4 of 7
Table 2. Observed positions of $^{13}$C$^{18}$O (3-2) and line opacities, $\tau_{\nu,C^{18}O}$.

<table>
<thead>
<tr>
<th>Offset (arcsec)</th>
<th>$v_{LSR}$ (km s$^{-1}$)</th>
<th>FWHM (km s$^{-1}$)</th>
<th>$T_{peak}(13C^{18}O)$ (K)</th>
<th>$T_{peak}(13C^{18}O)$ (K)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-$60, +80</td>
<td>2.86 ± 0.05</td>
<td>0.78 ± 0.12</td>
<td>10.5, 0.25</td>
<td>0.02</td>
<td>...</td>
</tr>
<tr>
<td>0, +60</td>
<td>3.13 ± 0.06</td>
<td>0.92 ± 0.14</td>
<td>8.1, 0.22</td>
<td>0.03</td>
<td>...</td>
</tr>
<tr>
<td>+30, +80</td>
<td>3.09 ± 0.05</td>
<td>1.11 ± 0.09</td>
<td>13.0, 0.38</td>
<td>0.03</td>
<td>P1</td>
</tr>
<tr>
<td>+30, 0</td>
<td>3.62 ± 0.02</td>
<td>1.02 ± 0.05</td>
<td>16.5, 0.71</td>
<td>0.04</td>
<td>P3</td>
</tr>
<tr>
<td>+60, −100</td>
<td>2.95 ± 0.06</td>
<td>1.17 ± 0.15</td>
<td>6.1, 0.23</td>
<td>0.04</td>
<td>2 lines?</td>
</tr>
</tbody>
</table>

Notes. Error on line ratios is estimated at 15–20%.

Table 3. Column densities of C$^{18}$O and O$^{16}$O.

<table>
<thead>
<tr>
<th>$T_X$</th>
<th>$A_{21}/21\gamma_2$</th>
<th>$N(C^{18}O)$</th>
<th>$A_{21,01}/21\gamma_{21,01}$</th>
<th>$N(O^{16}O)$</th>
<th>$N(O^{18}O)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>(cm$^{-2}$)</td>
<td>(cm$^{-2}$)</td>
<td></td>
<td>(cm$^{-2}$)</td>
<td>(cm$^{-2}$)</td>
</tr>
<tr>
<td>300</td>
<td>3.4 × 10$^4$</td>
<td>4.9 × 10$^5$</td>
<td>2.7 × 10$^2$</td>
<td>&lt;5.6 × 10$^5$</td>
<td>&gt;9</td>
</tr>
<tr>
<td>100</td>
<td>4.0 × 10$^4$</td>
<td>2.0 × 10$^5$</td>
<td>4.7 × 10$^2$</td>
<td>&lt;2.0 × 10$^5$</td>
<td>&gt;10</td>
</tr>
<tr>
<td>40</td>
<td>1.7 × 10$^5$</td>
<td>1.2 × 10$^5$</td>
<td>7.4 × 10$^2$</td>
<td>&lt;9.5 × 10$^4$</td>
<td>&gt;14</td>
</tr>
<tr>
<td>20</td>
<td>1.7 × 10$^5$</td>
<td>1.4 × 10$^5$</td>
<td>1.0 × 10$^3$</td>
<td>&lt;6.3 × 10$^4$</td>
<td>&gt;22</td>
</tr>
<tr>
<td>10</td>
<td>1.7 × 10$^5$</td>
<td>3.2 × 10$^5$</td>
<td>1.5 × 10$^3$</td>
<td>&lt;5.5 × 10$^4$</td>
<td>&gt;59</td>
</tr>
</tbody>
</table>

Notes. (a) Collision rate coefficient $\gamma(T)$ = 4.9 × 10$^{-11}$ (T/300 K)$^2$ cm$^3$ s$^{-1}$.

The sizes of the clumps are comparable to the beam size, so that the main beam efficiency, $\eta_{bm}$ = 0.73, is used for the intensity calibration and we assume here a beam filling factor of unity. For the broad range of temperatures of 10 to 300 K, the corresponding column densities of C$^{18}$O are listed in Table 3.

4.4. Column densities

If local thermal equilibrium (LTE) is a good approximation for the level populations, the column density of all molecules of the species, $N$(mol) in cm$^{-2}$, can be estimated from the observed intensity of an optically thin line, viz.

$$N(\text{mol}) = \frac{\int T_A^* \, dv}{f_b \eta_{mb}} \times \Phi(T_k)$$

where

$$\Phi(T_k) = \left( \frac{2 \pi^{3/2}}{hcT_k} \right)^{3/2} \frac{T_k^2}{A_{21}} \frac{F(T_k) - F(T_{bg})}{Q(T_k)} \exp(T_a/T_k)$$

with cgs-units of K$^{-1}$ cm$^{-3}$ s. Here, $f_b$ is the beam filling factor for the source which may be smaller than the beam ($0 \leq f_b \leq 1$) and $\eta_{mb}$ is the main beam efficiency. $T_a = h \nu/k$ is the transition temperature, $T_{bg} = 2.725$ K is the temperature of the background radiation field, $F(T) = T_a/[\exp(T_a/T) - 1]$ is the quasi-Planck function, $T_a$ is the upper level energy in K, $Q(T_k)$ is the partition function and $g_a = (2J + 1)$ is the statistical weight of the upper level and the other symbols have their usual meaning.

4.4.1. C$^{18}$O and H$_2$ column densities

We limit the discussion to the central core region, where observed C$^{18}$O (3–2) line intensities of the +3 km s$^{-1}$ component are $T_A^* dv = 20$ K km s$^{-1}$. The upper level energy lies nearly 32 K above ground. The spontaneous transition probability for the transition is $A_{21} = 2.158 \times 10^{-6}$ s$^{-1}$, the transition temperature is $T_{eq} = 15.813$ K and the statistical weight of the upper level is $g_a = 7$. Using the collisional rate coefficients of Schinke et al. (1985) for collisions with para-H$_2$, yields critical densities, $n_{crit} = 0.32/\gamma_{21}(T_k)$, of about $2 \times 10^9$ to $3 \times 10^9$ cm$^{-3}$ for $T_k = 10$ K to 300 K, respectively (Table 3). Therefore, except perhaps for the very lowest temperatures, the condition of LTE should be fulfilled for the C$^{18}$O (3–2) transition (cf. Sect. 4.1).

4.2. O$^{18}$O column density and O$^{16}$O abundance

The $N_f = 2_1^1, 0_1^1$ transition has the largest Einstein coefficient of the low-lying O$^{18}$O transitions, viz. $A_{21,01} = 1.33 \times 10^{-7}$ s$^{-1}$ (Maréchal et al. 1997b). We adopt the coefficients for collisional de-excitation, $\gamma_{21,01}(T_k)$, which are based on the work by Bergman (1995) and which have been derived for collisions with H$_2$. For collisions with H$_2$, these were multiplied by 1.4. Values for temperatures other than 300 K were obtained by scaling with the square root of the temperature. From Table 3, it can be seen that critical densities for the $2_1^1, 0_1^1$ transition are rather low for a wide range of temperatures (<1500 cm$^{-3}$ above 10 K). In particular, for the dense core conditions of $\rho$ Oph A, where densities are in excess of $10^5$ cm$^{-3}$ (Sect. 4.1), LTE is certainly a valid assumption (see also Black & Smith 1984; Maréchal et al. 1997b). The temperature of the transition is $T_a = T_{eq} = 11.228$ K and the statistical weight of the upper level is $g_a = 3$.

In Table 3, the results for C$^{18}$O and O$^{18}$O are compared. The ratio $N(C^{18}O)/N(O^{18}O)$ exceeds unity and increases with decreasing temperature. This ratio could correspond to about half the value of that of the CO/O$_2$ ratio (Black & Smith 1984). For three cold cores (10 and 15 K), Fuente et al. (1993) determined CO/O$_2 > 3$–7, limits consistent with, but considerably smaller, than the values displayed in Table 3. The effects of a varying C/O ratio in the ISM at column densities (values of the visual extinction $A_V$) as high as those found in $\rho$ Oph A were explicitly considered in the models by Maréchal et al. (1997a; see their Fig. 10). For the O$_2$ 119 GHz line, the integrated intensity is $>10$ km s$^{-1}$ for $C/O < 0.4$ when $A_V > 20$ mag. In contrast, for similar extinction, the intensity is $<100$ mK km s$^{-1}$ for $C/O > 1$. Future observations will likely be able to follow any variation
of this ratio in different regions of the ISM (see below and also Black & Smith 1984).

In the dense cold (\(<100 \text{ K}\)) regions of the \(\rho\) Oph A core, the column density of \(^{18}\text{O}\) is lower than \(10^{15} \text{ cm}^{-2}\) (Table 3) and, hence, the abundance relative to \(\text{H}_2\), \(X(\text{O}^{18}\text{O})<10^{-4}\). Consequently, for the range of 10 to 40 K and a standard elemental isotopic ratio, the abundance of the primary species of molecular oxygen, \(X(\text{O}_2)\sim 500/2 \times X(\text{O}^{18}\text{O})\) (Wannier 1980), should be limited to \(<5 \times 10^{-7}-2 \times 10^{-6}\), consistent with the Odin result (Larsson et al. 2007). We can conclude, therefore, that in the \(\rho\) Oph A core, the molecular oxygen abundance is bounded by \(5 \times 10^{-3} \leq X(\text{O}_2) < 2.5 \times 10^{-2}\); where the beam averaged \(\text{O}_2\) column density is \(10^{15} \text{ cm}^{-2}\). If reflecting the fraction of the Odin beam\(^6\) that is filled by the \(\text{O}_2\) source, its implied size is \(\leq 600''/\sqrt{250} = 38''\). This could be well-matched to the 3.5 m telescope of the Herschel Space Observatory\(^7\), the beam widths of which are \(44''\) at 487 GHz, the frequency of the \(\text{O}_2 (N_2 = 3_2-1_2)\) transition, and \(28''\) at 773 GHz for the \((5_1-3_1)\) line (Fig. 5).

4.3. Nature, location and extent of the \(\text{O}_2\) source

4.3.1. Oxygen in the cold ISM

The capital letter designation of the cores was introduced by Loren et al. (1990) for the location of emission peaks in lines of DCO\(^+\) in the \(\rho\) Oph cloud. Depending on the details of the considered models of the deuteration process, they derived kinetic gas temperatures inside the cores which were always low, in the range 18–23 K, whereas temperatures in the outer layers were considerably higher.

\(^6\) Odin observations resulted in a column density of oxygen \(N(\text{O}_2) = 1 \times 10^{15} \text{ cm}^{-2}\) (Larsson et al. 2007). If \(\Omega(\text{O}_2) = \Omega(\text{C}^{18}\text{O})\), the beam filling of the \(\text{O}_2\) source is \(10^{-3}\) to \(10^{-2}\), i.e. the beam corrected \(N(\text{O}_2)\) is \(10^{17} - 10^{18} \text{ cm}^{-2}\). If \(N(\text{O}^{18}\text{O})/N(\text{O}_2) = 1/250\), then the expected column density of isotopic oxygen is likely within \(0.4 \times 10^{15}\) to \(4 \times 10^{15} \text{ cm}^{-2}\) for a source size about 20'' to 60''.

\(^7\) http://herschel.esac.esa.int/
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