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Low upper limits on the O_2 abundance from the Odin satellite*

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Abstract. For the first time, a search has been conducted in our Galaxy for the 119 GHz transition connecting to the ground state of O_2, using the Odin satellite. Equipped with a sensitive 3 mm receiver (T_{sys}(SSB) = 600 K), Odin has reached unprecedented upper limits on the abundance of O_2, especially in cold dark clouds where the excited state levels involved in the 487 GHz transition are not expected to be significantly populated. Here we report upper limits for a dozen sources. In cold dark clouds we improve upon the published SWAS upper limits by more than an order of magnitude, reaching $N(O_2)/N(H_2) \leq 10^{-7}$ in half of the sources. While standard chemical models are definitively ruled out by these new limits, our results are compatible with several recent studies that derive lower O_2 abundances. Goldsmith et al. (2002) recently reported a SWAS tentative detection of the 487 GHz transition of O_2 in an outflow wing towards ρ Oph A in a combination of 7 beams covering approximately $10' \times 14'$. In a brief (1.3 hour integration time) and partial covering of the SWAS region (≈65% if we exclude their central position), we did not detect the corresponding 119 GHz line. Our 3 sigma upper limit on the O_2 column density is 7.3×10^{15} cm^{-2}. We presently cannot exclude the possibility that the SWAS signal lies mostly outside of the $9'$ Odin beam and has escaped our sensitive detector.

Key words. radio lines: ISM – ISM: molecules – Galaxy: abundances

1. Introduction

Oxygen, the third most abundant cosmic element, is a key species in the chemistry of the interstellar medium (ISM). Our knowledge of its prevalence and distribution depends on the ability to measure the abundance of the main oxygen-bearing species: O, CO, CO_2, OH, H_2O, CH_3OH and O_2. The task is difficult due to telluric blocking of CO_2, H_2O and O_2, in addition to important transitions of OH and O. Standard chemical

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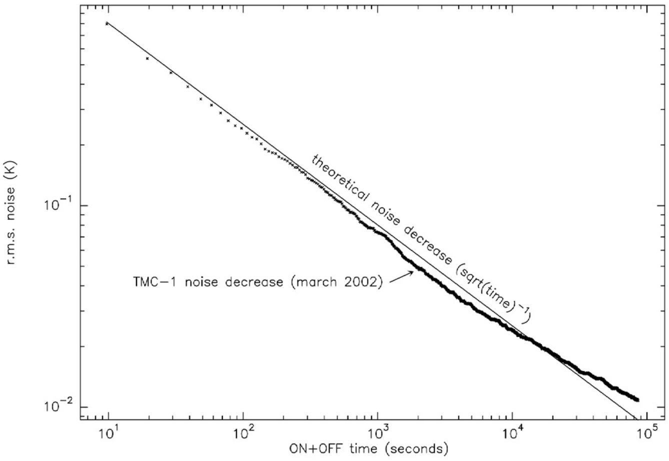

Fig. 1. Receiver stability. Over a period of 24 hours of integration, the noise keeps decreasing steadily.

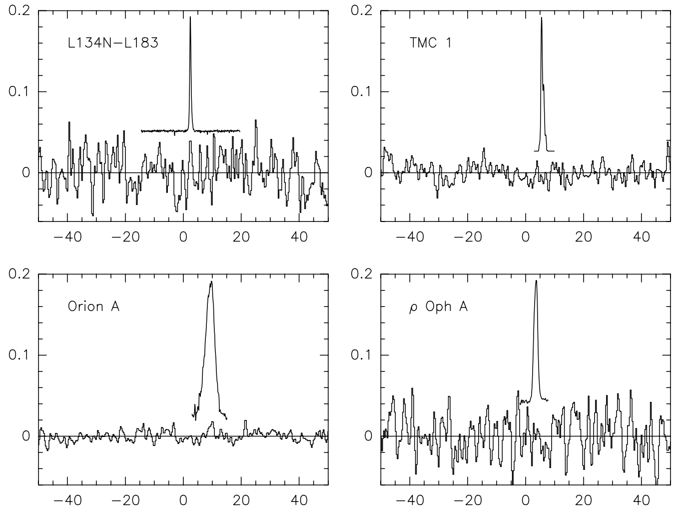

Fig. 2. O_2 spectra with unscaled $C^{18}O$ spectra. The noise peaks at source velocity are 1.5 σ (L134N) and 2.5 σ (Orion A). The horizontal axis is LSR velocity in km s^{-1}, the vertical axis, T_A in K (uncorrected for beam efficiency).

models predicted that the abundance of O_2 should be comparable to that of CO inside well-shielded cloud cores (e.g., Herbst & Klamperer 1973; Graedel et al. 1982; Maréchal et al. 1997). Consequently, O_2 was considered an important cooling species for clouds (Goldsmith & Langer 1978). It has been actively searched for from the ground (redshifted 119 GHz transition, e.g. Liszt 1985, 1992, Combes et al. 1996; $^{16}O^{18}O$ rare isotope transition at 1.3 mm, e.g. Goldsmith et al. 1985, Maréchal et al. 1997), from high above the troposphere by balloon (Olofsson et al. 1998), and most recently by satellite (SWAS, Goldsmith et al. 2000). None of these efforts has produced a convincing detection of O_2. SWAS reported the lowest upper limits yet: $N(O_2)/N(C^{18}O) \leq 1.5$ (3σ) and $N(O_2)/N(H_2) \leq 2.6\times10^{-7}$ (3σ) in sources with star-forming activity and $N(O_2)/N(H_2) \leq 3\times10^{-6}$ (3σ) in cold dark clouds (TMC-1 and L183/L134N). More recently, the SWAS team reported a possible detection of the 487 GHz O_2 line in the ρ Oph A outflow (Goldsmith et al. 2002) with $N(O_2)/N(H_2) \approx 10^{-5}$. Despite its diminished importance as a cloud coolant, O_2 still attracts interest because it provides strong constraints on chemical models.

Odin, a 1.1 m spaceborne millimeter and submillimeter telescope (Frisk et al. 2003; Olberg et al. 2003), is equipped with two receivers having O_2 search capabilities: a cryogenically cooled 3 mm HEMT preamplifier (fixed-) tuned to the 118.750343 GHz $(N_J: 1_1 - 1_0)$ transition of O_2 for which the beam diameter is 9′; and a submm receiver tunable to the 487 GHz O_2 line with a beamsize of 2.4′. Since the 119 GHz line is easy to thermalize, stronger than any of the submm transitions at temperatures below 100 K (Maréchal et al. 1997), and has an upper level only 5.7 K above the ground state, it is probably the best line to search for, especially in cold dark clouds. At 10 K, the 119 GHz line is 20 times stronger than the 487 GHz line. With a 119 GHz system temperature (T_{sys}(SSB) = 600 K) 8 times lower than that of SWAS, we gain 2 orders of magnitude in sensitivity in extended cold clouds and gain a factor of 40 even if the source is smaller than the SWAS beam.

In this paper, we present the observations in Sect. 2, the data reduction in Sect. 3, and discuss briefly the intriguing results in Sect. 4.

2. Observations

The first useful Odin observations were obtained towards Orion on 2001-08-19 and all reported sources but TMC-1 were subsequently observed until 2001-10-04. At that time, the phase-lock system became unstable and was lost after 2001-10-14. The phase-lock was recovered no later than 2002-03-09. Data taken towards TMC-1 (2002-03-23 to 2002-03-25) were correctly phase-locked. The absolute pointing uncertainty is within 30″, which is negligible for our beam size of 9′. In some sources, we allowed offsets up to 2′ to be included in the average, which still represents less than 25% error in pointing. The autocorrelator spectral sampling was 0.125 MHz (δv = 0.315 km s^{-1}) in a 100 MHz bandwidth for all sources except G0.26-0.01, for which we used 1 MHz (δv = 2.52 km s^{-1}) sampling (in a bandwidth of 800 MHz). The autocorrelator resolution is twice as wide as its sampling. In this Letter, we adopt $\eta_{MB} = 0.9$, as measured at 557 GHz towards Jupiter. Details of the calibration are presented by Olberg et al. (2003).

3. Data reduction

Our first concern was to establish the exact center frequency of the O_2 receiver band at all times and heck its stability. The Local Oscillator phase-lock reference signal is not thermally controlled and is thus allowed to drift somewhat around its standard frequency. The receiver tuning is checked by measuring the telluric O_2 line position in the backend during the 40% of each orbit Odin spends pointing at Earth's atmosphere. The tuning was extremely stable from mid-August to the 4th

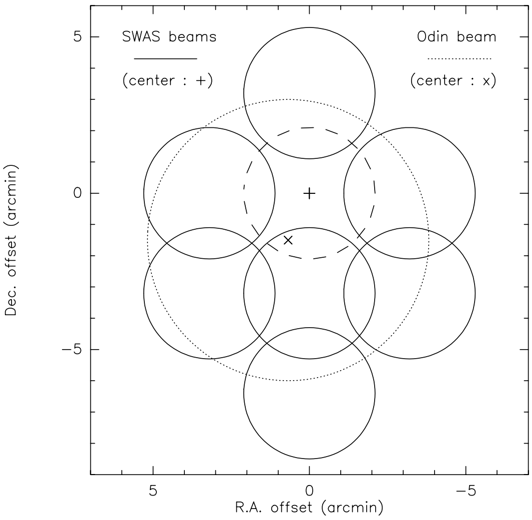

Fig. 3. The SWAS and Odin beams towards ρ Oph A. The dashed circle represents the SWAS central beam, not taken into account in their detection (Goldsmith et al. 2002).

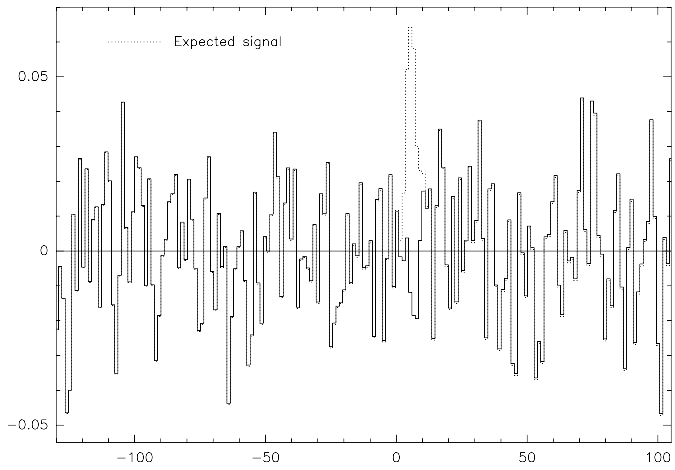

Fig. 4. Smoothed ρ Oph A O_2 spectrum, with the signal expected at 119 GHz from the SWAS O_2 column density estimate superimposed. Axes are the same as in Fig. 2.

of October 2001, with high and low resolution data requiring corrections of 4.85 ± 0.1 MHz and −0.3 to −0.1 MHz, respectively. In March 2002, the high resolution data correction was 0.12 MHz.

The observing mode ("Dicke" switching against blank sky with a 4.4° *FWHM* reference beam, off-axis by 20°) gives reasonably good baselines at high resolution but rather bad ones for large bandwidth. For the large-bandwidth G0.26-0.01 observation, the baselines were improved by subtracting a Dicke-switched off-source observation (+30′ in declination, with no $C^{18}O$ emission). After long integrations in high resolution mode, a sinusoidal ripple of low amplitude (a few mK) could sometimes be seen and was removed with a sinusoidal baseline fit.

The stability of the receiver is clearly demonstrated in the decrease of the rms noise versus time shown in Fig. 1. Some of our observational results are displayed in Fig. 2.

4. Results and discussion

4.1. Analysis

Table 1 gives the list of sources with their final noise limit, the $C^{18}O$ (J: 1 – 0) integrated intensity convolved in a 9′ Gaussian beam taken from literature, and the final O_2 relative abundance upper limit (3 σ). To derive O_2 column density upper limits, we assumed that the 119 GHz transition is thermalized (LTE), since the upper energy level is only 5.7 K and the spontaneous transition probability is $A_{\rm ul} = 4.46 \times 10^{-9}$ s^{-1}, one order of magnitude lower than that of $C^{18}O$ (see Goldsmith et al. 2000). Though the upper state cannot for quantum mechanical reasons be directly collisionally excited (Bergman 1995), the line should be thermalized above densities $\approx 10^3$ cm^{-3}, which is satisfied by all of the observed clouds. To estimate the O_2 integrated intensity upper limit, we took $I \leq 3\sigma\,\sqrt{\delta v \Delta v}$ where Δv is the $C^{18}O$ linewidth.The $C^{18}O$ (J: 1 – 0) line is rather easy to thermalize and is relatively insensitive to the density and temperature ranges spanned by the observed sources. For a 9′ beam size, depletion and saturation effects should be of limited importance. To derive $N(C^{18}O)$ we also assumed LTE and we took $N(C^{18}O)/N(H_2) = 1.7 \times 10^{-7}$ (Frerking et al. 1982) for local clouds and modulated this value as a function of Galactocentric distance following the $^{16}O/^{18}O$ variation described by Wilson & Rood (1994). The $C^{18}O$ data are all in the T_R^* scale as defined by Kutner & Ulich (1981), which is the most appropriate for extended sources.

4.2. ρ Oph A

In a recent paper (Goldsmith et al. 2002), the SWAS team reported a possible detection of 487 GHz O_2 in the red wing of the ρ Oph A outflow. Their tentative detection was made by adding 7 different SWAS positions surrounding, but excluding, the source itself (cf. our Fig. 3). Our larger beam, with a slightly different target position (ρ Oph A-VLA) covers about 65% of the SWAS-mapped region, not including their central beam. With the same assumptions as in Goldsmith et al. (2002), we find a 3 σ upper limit of $N(O_2) \leq 6.7 \times 10^{15}$ cm^{-2}, corresponding to $X(O_2) \leq 4.4 \times 10^{-6}$, a factor of 3 below their estimate ($N(O_2) = 2.3 \times 10^{16}$ cm^{-2}, $X(O_2) = 1.5 \times 10^{-5}$). Using their estimated O_2 column density, we have computed the expected Gaussian line at 119 GHz and overlaid it on our spectrum in Fig. 4 (the Gaussian line has been combined with our own noise spectrum to simulate real observing conditions). A clear signal should have been detected if O_2 is evenly distributed among the SWAS mapped region. Because the Odin beam does not completely cover that region, we cannot exclude the possibility that most of the emission lies outside our beam and thus escaped detection at 119 GHz. Further Odin observations are underway to settle this point.

Table 1. Derived upper limits on O_2 column density relative to H_2. The 1 channel rms noise is given in the T_A scale, but all computations have been done assuming a 90% coupling to the main beam. Resolution is 0.3 km^{-1} except for G0.26-0.01 (2.5 km^{-1}). 6.8(14) means 6.8×10^{14}. The "Ref." column provides references for the $C^{18}O$ data.

Source	α_{2000}	δ_{2000}	O_2 rms (K)	$\int T_r^*(C^{18}O)dv$ (K km s^{-1})	$\Delta v(C^{18}O)$ (km s^{-1})	T_{kin} (K)	$N(O_2)$ (cm^{-2})	$N(C^{18}O)$ (cm^{-2})	$X(O_2)$	Ref.
TMC1 – NH_3	$4^h41^m16^s$	25°48′44″	0.010	1.6	1.1	10	≤6.8(14)	1.5(15)	≤7.7(−8)	1
OrionA	$5^h35^m14^s.36$	−5°22′30″	0.006	2.7	3.8	50	≤1.9(15)	3.6(15)	≤8.9(−8)	2
NGC2071	$5^h47^m4^s.1$	0°21′42″.8	0.026	2.86	1.8	20	≤2.6(15)	2.8(15)	≤1.5(−7)	3
L134N – NH_3	$15^h54^m08^s.52$	−2°52′48″	0.024	1.16	0.6	10	≤1.1(15)	1.1(15)	≤1.7(−7)	4
ρOphA	$16^h26^m26^s.4$	−24°24′30″.5	0.027	5.17	1.53	30	≤3.4(15)	6.2(15)	≤9.3(−8)	5
IRAS16293	$16^h32^m22^s.8$	−24°28′35″	0.017	2.07	0.94	30	≤1.7(15)	2.5(15)	≤1.2(−7)	5
NGC6334I	$17^h20^m53^s.38$	−35°47′1″.5	0.017	30.[a]	4.0	50	≤5.0(15)	[d]	≤7.1(−8)[e]	6–8
(G0.26 – 0.01)[c]	$17^h46^m11^s$	−28°42′39″	0.021	11.75	(164.0)[c]	20?	≤5.6(16)	1.2(16)	≤7.6(−7)	9, 10
M17SW	$18^h20^m23^s.11$	−16°12′47″.2	0.024	2.84	4.3	50	≤7.3(15)	3.0(15)	≤5.7(−7)	11
S68FIRS1	$18^h29^m50^s.3$	1°15′18″.6	0.016	2.63	1.4	25	≤1.6(15)	2.8(15)	≤9.7(−8)	12
G34.3 + 0.2	$18^h53^m18^s.34$	1°14′58″.4	0.021	[b]	6.0	30	≤5.2(15)	[d]	≤5.2(−8)	13–16

(a) Core only: 2′ × 3′; (b) No extended $C^{18}O$ measurements available; (c) *Line of sight towards* G0.26-0.01, containing many clouds over a large velocity range; (d) From ^{13}CO, $N(H_2) \approx 10^{23}$ cm^{-3}; (e) $\leq 1.7 \times 10^{-7}$ $C^{18}O$ core only.
Refs.: (1) Onishi et al. (1996), (2) Dutrey et al. (1996), (3) Aoyama et al. (2001), (4) Pagani et al. (2001), (5) Tachihara et al. (2000), (6) Kraemer & Jackson (1999), (7) Schwartz et al. (1989), (8) Dickel et al. (1977), (9) Dahmen et al. (1997), (10) Dahmen et al. (1998), (11) Ando et al. (2002), (12) McMullin et al. (2000), (13) Churchwell et al. (1992), (14) Matthews et al. (1987), (15) Little et al. (1994), (16) Kim et al. (2001).

4.3. The absence of O_2

Odin has improved upon the SWAS upper limits by a factor of a few in star-forming regions, and by factors of 20 and 40 for L134N and TMC-1, respectively, yet still has not detected O_2. It is now well established (since the work of Olofsson et al. 1998) that standard, steady state, chemical models are ruled out by this absence of O_2. In the meantime, more sophisticated models have been developed which can accomodate O_2 abundances compatible with these new upper limits. Goldsmith et al. (2000) and Bergin et al. (2000) discuss those models which appeared up to the time of the SWAS observations. More recent work includes Casu et al. (2001), Spaan & van Dishoeck (2001), Viti et al. (2001), Roberts & Herbst (2002), and Willacy et al. (2002). All propose different reasons for O_2 to be rare, and much work remains to be done to test which model(s) best represent reality (and also predict the observed abundances of other molecules). The detection of O_2 in one or more sources, even at a low level, would greatly help in this task.

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