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Odin† Detection of O_2

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Abstract. We present the detection of molecular oxygen with Odin toward the dense molecular core ρ Oph A, which is part of a region of active star formation. The observed spectral line is the $(N_J = 1_1 - 1_0)$ ground state transition of O_2 at 119 GHz ($\lambda = 2.5$ mm). The line center is at the LSR velocity of a number of optically thin lines from other species in the region. The O_2 line also has a very similar, narrow, line width. Within the $10'$ beam, the line intensity is $\int T_{\rm A}\, {\rm d}v = 28$ mK km s^{-1}, which corresponds to $5\,\sigma$ of the rms noise. A standard LTE analysis results in an O_2 abundance of 5×10^{-8}, with an uncertainty of at least a factor of two. We show that standard methods, however, do not apply in this case, as the coupling of the Odin beam to the source structure needs to be accounted for. Preliminary model results indicate O_2 abundances to be higher by one order of magnitude than suggested by the standard case. This model predicts the 487 GHz line of O_2 to be easily detectable by the future Herschel-HIFI facility, but to be out of reach for observations on a shorter time scale with the Odin space observatory.

Keywords. abundances — ISM: clouds — ISM: molecules — lines and bands — stars: formation

1. Introduction

The energy balance of the interstellar medium (ISM) relies on a complex interaction of various heating and cooling processes, which of course also affect the chemistry being activated in the medium. This in turn regulates the amount of the major cooling species in the gas. Heating processes include mechanical and radiative energy input, whereas, in dense clouds, the cooling is dominated by molecules and dust particles, resulting in low equilibrium temperatures on short time scales. Whereas the coolant CO is readily observable from the ground, water and oxygen molecules need to be observed from space.

Odin is thus a mission in orbit around the Earth dedicated to the observation of H_2O and O_2. The millimeter/submillimeter (mm/submm) Odin facility is shared by aeronomers and astronomers on an equal time basis, and is described by Frisk *et al.* (2003) and Olberg *et al.* (2003). Odin's astronomy is reviewed by Hjalmarson *et al.* (2003). These articles are all collected in the special Odin edition of Astronomy & Astrophysics, which of course also contains numerous papers on initial results obtained with Odin. Energy level and excitation diagrams for the principal observable molecules can be found in Liseau (2001).

Prior to the launch of Odin in February 2001, it was already clear from the observations by the Submillimeter Wave Astronomy Satellite (SWAS) that H_2O was significantly less abundant in the ISM than was previously thought. Even more intriguing, perhaps, was the apparently total absence of O_2 (Goldsmith *et al.* 2000). However, a couple of years later, the tentative detection of the 487 GHz line (see Fig. 1) toward the dense molecular core ρ Oph A was announced by Goldsmith *et al.* (2002).

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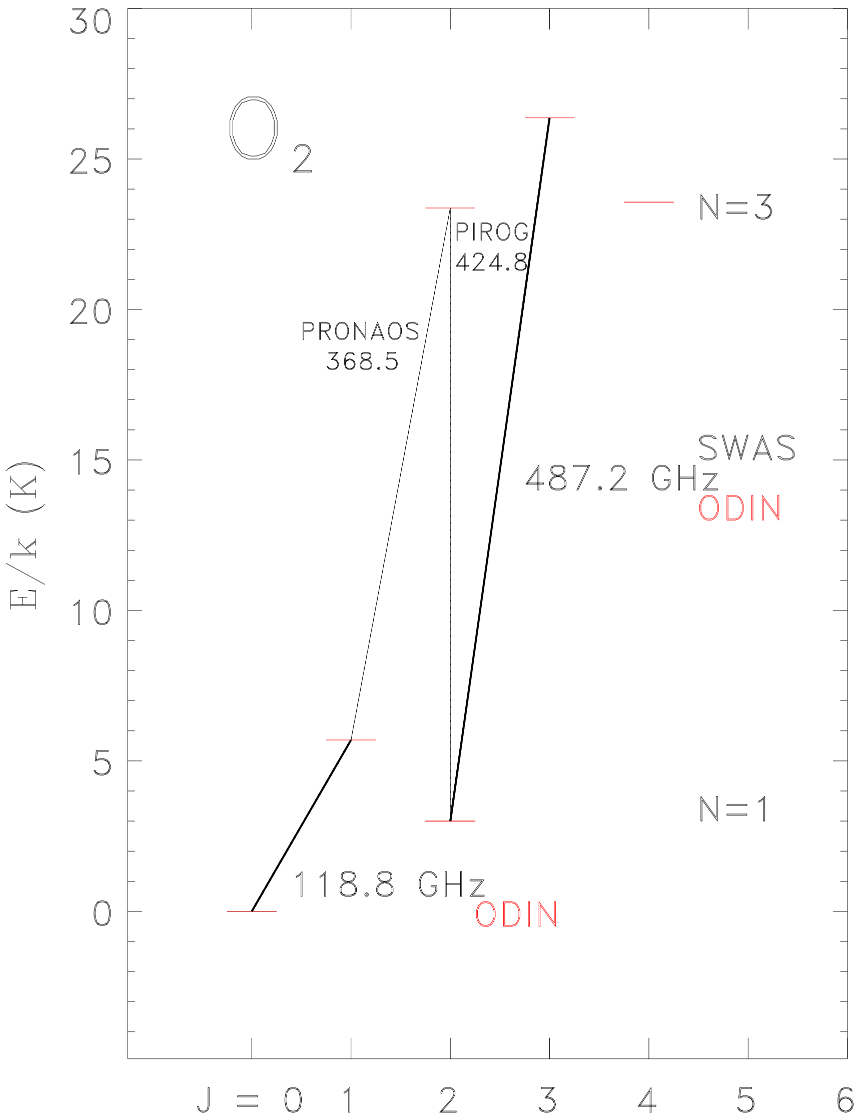

Figure 1. Rotational energy level diagram of O_2 for E_{upper}<30 K. Transitions accessible to various missions discussed in the text are also indicated (adopted from Liseau 2001).

The SWAS result was challenged by Pagani *et al.* (2003), who were unable to confirm the presence of oxygen in ρ Oph A based on observations with Odin in the ground state transition of O_2 at 119 GHz (Fig. 1). Taking into account the fact that this involved a different line at considerably lower angular resolution toward a somewhat different position, the status of the SWAS result was rendered inconclusive.

Besides the negative result for the dense cloud ρ Oph A, Pagani *et al.* (2003) also reported on unsuccessful observations of nearly a dozen galactic sources in the O_2 ($N_J = 1_1 - 1_0$) line at 119 GHz. Furthermore, Wilson *et al.* (2005) recently published an upper limit in this line toward an extragalactic object, *viz.* the Small Magellanic Cloud (SMC). Contrasting with these negative results, we report here the detection with Odin, at the 5 σ level, of the 119 GHz line of O_2 toward the dense cloud ρ Oph A.

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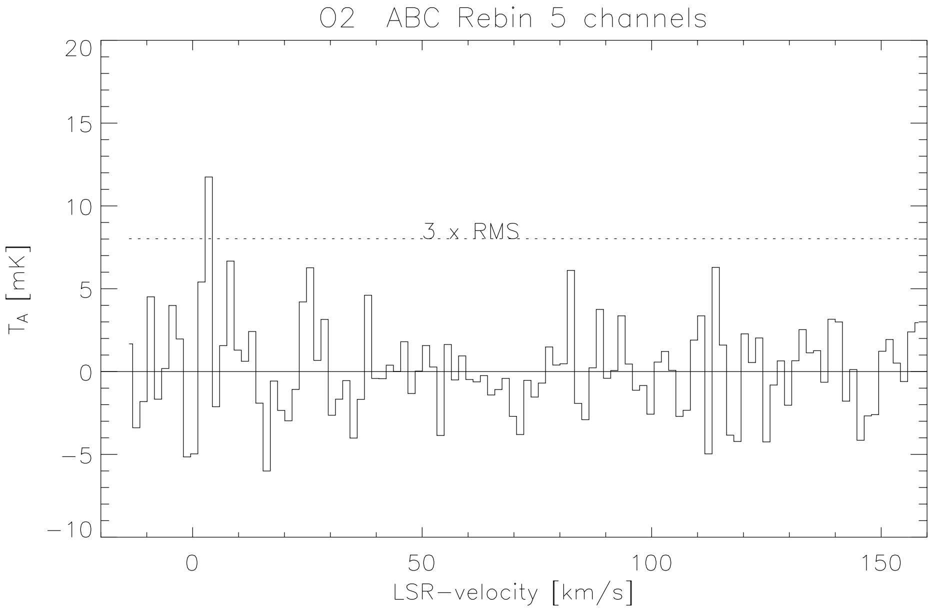

Figure 2. The 5 channels of the O_2 feature have been binned into 1 channel, corresponding to the integrated line intensity $\int T_A\,dv$ at the $5\,\sigma$ level. All other features in the entire useful spectral range over $180\,\mathrm{km\,s^{-1}}$ are below the $3\,\sigma$ leve, shown as the dashed horizontal line.

2. Odin O_2 Observations

The Odin observations of ρ Oph A were performed during 2002 and 2003 and the total on-source integration time was 78 hours. At 119 GHz, the half-power-beam-width of the 1.1 m telescope is $10'$. A digital autocorrelator of 100 MHz bandwidth and 125 kHz resolution was used as the backend. In Doppler-velocity units, this corresponds to $250\,\mathrm{km\,s^{-1}}$ and $0.3\,\mathrm{km\,s^{-1}}$, respectively. More exhaustive details regarding these observations and the subsequent complex data reductions are provided by Larsson *et al.* (2005).

In Figure 2, showing the final stage of this data reduction, the Odin 119 GHz spectrum is presented. At full spectral resolution, the O_2 line occupies five autocorrelator channels, which in the figure have been binned into one channel. This is equivalent to the integrated line intensity, $\int T_A\,dv_z = (28 \pm 5.5)\,\mathrm{mK\,km\,s^{-1}}$.

Other Gauss-fit parameters are: peak $T_A = (17.5 \pm 3.5)\,\mathrm{mK}$, line center velocity $v_{\rm LSR} = (3.0 \pm 1.0)\,\mathrm{km\,s^{-1}}$ and line width $\Delta v_{\rm FWHM} = (1.53 \pm 0.03)\,\mathrm{km\,s^{-1}}$. The velocity and width of the O_2 line are in agreement with that of the PDR recombination line emission observed by Pankonin & Walmsley (1978) with a $7\overset{'}{.}8$ beam, *i.e.* comparable to the spatial resolution of Odin. As also indicated by the $C^{18}O$ observations of Frerking *et al.* (1989) with a $2\overset{'}{.}3$ beam, the line parameters center velocity and width of optically thin species appears constant on various angular scales. The values of both parameters are significantly different for the 487 GHz line of Goldsmith *et al.* (2002).

The Odin observations at full spectral resolution, and the comparison with other molecular line data, will be presented by Larsson *et al.* (2005).

3. O_2 Abundance

Of general interest is the relative concentration of various forms of oxygen in the interstellar medium and in particular that of the molecular constituents. Below, we shall

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examine the derivation of the O_2 abundance in some detail, as widely used standard methods will encounter difficulties in this particular case, leading to erroneous results.

3.1. *Column Density of Oxygen*

The data for radiative ($A_{\rm ul}$) and collisional ($q_{\rm ul}$) de-excitation have been provided by Marechal *et al.* (1997) and by Bergman (1995 and private communication). The collisional excitation $N_J = 1_0$ to $N = J$, such as $(1_0 - 1_1)$, is forbidden and we assume that the collisional population of the 1_1 level occurs mainly via 3_2 and hence, the critical density for $O_2\,(N_J = 1_1 - 1_0)$, *viz.*

$$n_{\rm crit} = A_{11,10}/q_{32,11}(T_{\rm k}) \tag{3.1}$$

becomes $> 10^3\,{\rm cm^{-3}}$ but $< 10^4\,{\rm cm^{-3}}$ for $T_{\rm k} < 100\,{\rm K}$ and is likely lower than densities in the cloud. Local Thermodynamic Equilibrium (LTE) provides thus a reasonable assumption for the population of the lower levels. The weak $O_2\,(N_J = 1_1 - 1_0)$ line is most likely optically thin and can be expected to exhibit a nearly Gaussian shape, reflecting small scale stochastic motions in the cloud.

The observed integrated intensity of the optically thin 119 GHz line, formed in LTE, is then given by

$$\begin{aligned} I_{119}^{\rm obs} &= \int T_{\rm A}\,{\rm d}v_{\rm z} \approx f_{\rm b}\,\eta_{\rm mb}\int T_{\rm R}\,{\rm d}v_{\rm z} \\ &= f_{\rm b}\,\eta_{\rm mb}\left(\frac{hc}{2\pi^{1/3}k}\right)^3 \frac{A_{11,10}}{T_{11,10}^2}\left[1-\frac{J_\nu(T_{\rm bg})}{J_\nu(T_{\rm k})}\right]\frac{g_{11}\,{\rm e}^{-T_{11,10}/T_{\rm k}}}{Q(T_{\rm k})}\,X(O_2)\,N(H_2) \end{aligned} \tag{3.2}$$

where $f_{\rm b}$ is the beam filling factor, $\eta_{\rm mb}$ is the main beam efficiency and $T_{\rm R}$ is the radiation temperature of the source. In LTE, the only dependence is on the temperature, which for our present purposes is well represented by a power law, *i.e.* for the 119 GHz transition, the function $\Phi(T_{\rm k})$ is given by

$$\begin{aligned} \Phi(T_{\rm k}) &= \left(\frac{hc}{2\pi^{1/3}k}\right)^3 \frac{A_{11,10}}{T_{11,10}^2}\left[1-\frac{J_\nu(T_{\rm bg})}{J_\nu(T_{\rm k})}\right]\frac{g_{11}\,{\rm e}^{-T_{11,10}/T_{\rm k}}}{Q(T_{\rm k})} \\ &= 2.5\times10^{-11}\,T_{\rm k}^{-0.67}, \qquad T_{\rm k} > T_{11,10} \end{aligned} \tag{3.3}$$

in units of ${\rm K\,cm^3\,s^{-1}}$. In the above equations, the temperature of the background radiation field is $T_{\rm bg} = 2.734\,{\rm K}$, the statistical weight of the upper level is $g_{11} = 2J + 1 = 3$, the temperature of the transition is $T_{11,10} = 5.70\,{\rm K}$, the quasi-Planck function is $J_\nu(T) = T_{11,10}/[\exp(T_{11,10}) - 1]$ and the partition function is approximated by $Q(T_{\rm k}) \approx kT_{\rm k}/hB$, where the rotational constant is $B = 43100.460\,{\rm MHz}$.

Expressing the line intensity in ${\rm K\,km\,s^{-1}}$, the column density of O_2 is then simply found from

$$N(O_2) \geqslant 4\times10^{15}\,T_{\rm k}^{0.67}\,I_{119}^{\rm obs} \qquad ({\rm cm^{-2}}) \tag{3.4}$$

On the scale of the Odin beam, temperatures have variously been estimated from gas tracers (*e.g.*, CO; Loren *et al.* 1983) and multi-wavelength measurements of the dust emission (*e.g.*, Ristorcelli *et al.* 2005), yielding an average of about 30 K and, hence, $N(O_2) \geqslant 1\times10^{15}\,{\rm cm^{-2}}$. As can be seen from Eq. 3.4, the column density of O_2 is not very sensitive to the temperature and, *e.g.*, an uncertainty of $\pm10\,{\rm K}$ would amount to a change in $N(O_2)$ by no more than 20%. The critical parameter for the determination of $X(O_2)$ is obviously $N(H_2)$.

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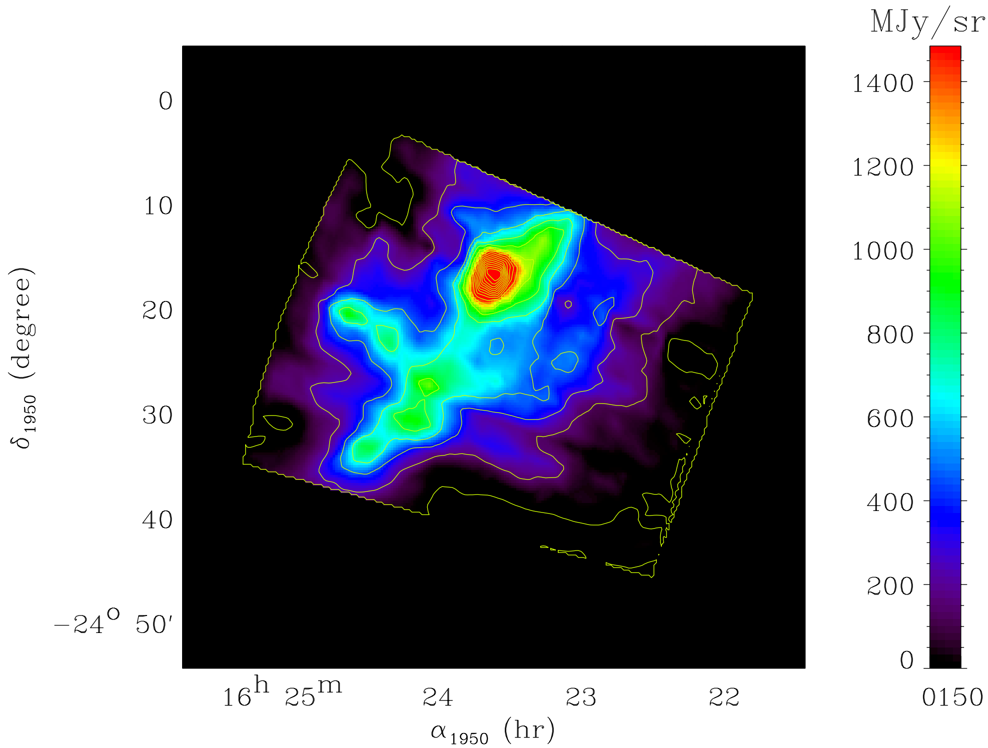

Figure 3. Continuum observations of the ρ Oph cloud at 200 μm with the 2′ beam of the balloon-borne submm-telescope PRONAOS (Ristorcelli *et al.* 2005). ρ Oph A is the hot spot above the center of the figure. Intensities, I_ν, are given in MJy sr^{-1} (see the scale bar to the right). In addition to the 200 μm-map shown here, full 40′ × 40′ maps have also been obtained at 260, 360 and 580 μm.

3.2. *Column Density of Hydrogen*

To find the oxygen abundance, $X(O_2) = N(O_2)/N(H_2)$, we need to specify the column density of hydrogen, H_2 (see: Eq. 3.2). Based on the $C^{18}O$ maps of Tachihara *et al.* (2000), Pagani *et al.* (2003) estimated for Odin O_2 observations with a 10′ beam the H_2-column to be $N(H_2) = 4 \times 10^{22}$ cm^{-2}. This is higher than values recently obtained from [C I] observations by Kulesa *et al.* (2005) on a much smaller, *i.e.* 3.′5, scale, *viz.* $(2-3) \times 10^{22}$ cm^{-2} and those derived from submm dust continuum observations by Ristorcelli *et al.* (2005), *viz.* 1×10^{22} cm^{-2} for the 10′ Odin beam. The earlier map of the LTE column density of $C^{18}O$ by Wilking & Lada (1983) would indicate a one order of magnitude higher $N(H_2)$. This is also the value obtained, on smaller angular scales, by Kamegai *et al.* (2003) from a large [C I] map of the ρ Oph cloud.

Various assumptions come into these estimates, such as the abundance of $C^{18}O$ or the opacity of the dust grains, leading to a considerable spread in $N(H_2)$. For the moment, we shall adopt a weighted average of 2×10^{22} cm^{-2}, a value which is associated with an uncertainty of at least a factor of two.

3.3. *O_2 Abundance: Extended Source*

Applying the estimates of temperature and H_2-column density to the O_2 observations with Odin yield an oxygen abundance $X(O_2) \approx 5 \times 10^{-8}$, if we assume that both $\eta_{\rm mb}$ and $f_{\rm b}$ are close to unity. The corresponding rotational O_2 spectrum between 100 μm and 1 cm is displayed in Figure 4. From this we infer that Odin is not capable of detecting

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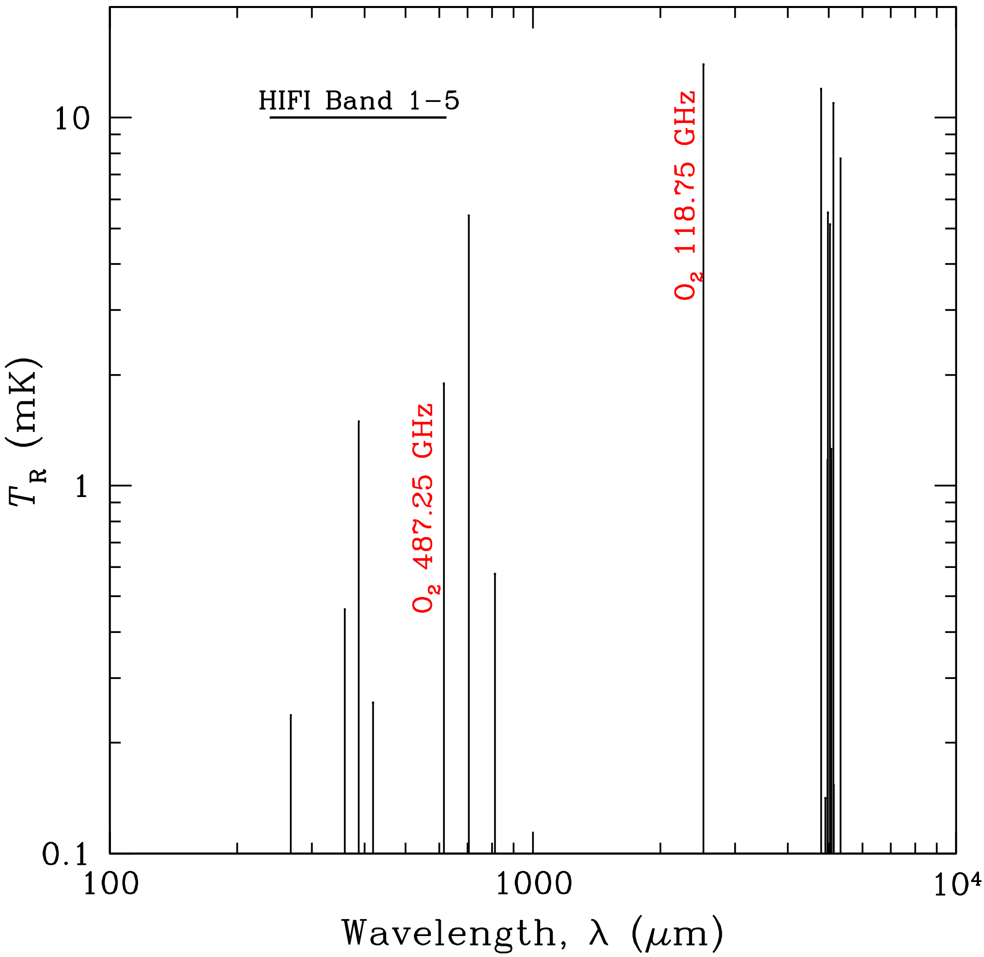

Figure 4. Theoretical (LVG) O_2 spectrum between 100 μm and 1 cm for ρ Oph A, based on the Odin observations in the O_2 ($N_J = 1_1 - 1_0$) line of ρ Oph A. The uniform source is assumed to fill the 10′ beam. The bar shows the frequency coverage of Herschel-HIFI, admitting the 487 GHz ($3_3 - 1_2$) line at its low-frequency end (see also Fig. 1), whereas the stronger 425 GHz ($3_2 - 1_2$) line falls unfortunately outside the HIFI band.

from ρ Oph A the other, in principle accessible, O_2 line, *i.e.* the ($3_3 - 1_2$) line at 487 GHz (2.′3 beam). It is also clear that the detection of the 487 GHz line with Herschel-HIFI† (45″ beam) would require the O_2 source to be significantly more compact than 10′.

3.4. *O_2 Abundance: Compact Source*

The value of $X(O_2)$ derived above is based on an analytical model of the line excitation, where one has made the implicit assumption that the emitting region is an isothermal and homogeneous plane-parallel slab of gas. These idealized conditions would have to apply on an angular scale of 10′, corresponding to a physical length scale of half a parsec at the distance of the ρ Oph A cloud. This picture is inconsistent, however, with observations on smaller scales of the gas and the dust (see, *e.g.*, Ashby *et al.* 2000 and Johnstone *et al.* 2000, respectively), which show ρ Oph A to have a centrally condensed core structure. In

† `http://www.sron.nl/divisions/lea/hifi/`

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other words, strong gradients in temperature, density and velocity field are known to be present inside the Odin O_2 beam. In addition, UV-radiation illuminates and heats the core preferentially only from one side (Liseau *et al.* 1999).

Modeling the complex structure of this core is in progress. Preliminary results suggest that the line formation region of O_2 119 GHz is relatively compact, with a size of 22″. Consequently, the implied abundance is relatively high, $X(\mathrm{O_2}) = 6 \times 10^{-7}$, and the observed weakness of the line is due to substantial beam dilution (roughly $\theta^2_{\rm source}/\theta^2_{\rm beam} = 10^{-3}$). Predictions of this model for the O_2 487 GHz line are for Odin (2′.3 beam) a peak antenna temperature of 22 mK and for Herschel-HIFI (45″ beam) 0.2 K. Whereas the observation of the former would imply prohibitive integration times, the latter would be a matter of only minutes. We look impatiently forward to the launch of Herschel in the 2007/08 time frame.

4. Possible Implications

The weak detection of O_2 by Odin will likely not add to the present discussion of the energy balance of the ISM, as the role of a coolant of importance had already been altered before. For instance, the total cooling in the O_2 lines of the spectrum of Figure 4 amounts to a mere $7 \times 10^{-5}\, L_\odot$.

It is conceivable, though, that this detection eventually will lead to an increased understanding of the O_2 chemistry of the dense and cold ISM and that chemistry models may benefit from the Odin achievement.

5. Conclusions

In summary, we briefly conclude the following:

(i) Very deep integrations (3.5 mK rms) with Odin in the 119 GHz ground state line of O_2 toward the dense cloud core ρ Oph A resulted in a 5 σ detection of the line.

(ii) Standard analysis of an optically thin line formed in LTE leads to the beam-averaged column density of molecular oxygen for ρ Oph A, *viz.* $N(\mathrm{O_2}) = 1 \times 10^{15}\,\mathrm{cm^{-2}}$.

(iii) Estimates of the oxygen abundance need to rely on assumptions regarding the source size and structure with respect to the 10′ beam of Odin at 119 GHz. This results in $X(\mathrm{O_2}) = 5 \times 10^{-8}$ for a homogeneous extended source and $X(\mathrm{O_2}) = 6 \times 10^{-7}$ for a more realistic source structure, respectively.

(iv) This issue will most likely become resolved by observations with the future Herschel-HIFI, for which we predict an O_2 intensity of a few tenths of a Kelvin at 487 GHz.

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Discussion

van Dishoeck: (1) For the high O_2 abundance of 6×10^{-7}, would the $^{16}O^{18}O$ 234 GHz line be strong enough to detect from the ground? Large single dish telescopes have beam sizes comparable to, or smaller than 22″. (2) Have you looked at any other positions in ρ Oph with Odin?

Liseau: (1) This would seem to be a good suggestion (A rough estimate for APEX yields a few mK, *i.e.* very tough to unfeasible indeed). (2) Odin is at this very moment mapping cores in the ρ Oph main cloud.

Cernicharo: The O_2 line at 119 GHz is a magnetic dipole transition. Hence, we could expect to have $T_{ex} \sim T_k$. Why, then, there is a difference of factor 7 between LTE and LVG calculations? Why do you need LVG? What collisional rates to you use?

Liseau: The critical density of the transition is of the order of the average density of the core ρ Oph A. Thermalization normally occurs at densities beyond an order of magnitude higher than n_{crit}. We therefore solved the statistical equilibrium equations, checking the assumption of LTE. The difference in $X(O_2)$ is dominated by the alternate choice of N(H), however.