First detection of NH$_3$ ($1_0 \rightarrow 0_0$) from a low mass cloud core* **

On the low ammonia abundance of the $\rho$ OphA core

R. Liseau$^1$, B. Larsson$^1$, A. Brandeker$^1$, P. Bergman$^2$, P. Bernath$^3$, J.H. Black$^2$, R. Booth$^2$, V. Buat$^4$, C. Curry$^3$, P. Encrenaz$^5$, E. Falgarone$^6$, P. Feldman$^7$, M. Fich$^8$, H. Florén$^9$, U. Frisk$^8$, M. Gerin$^6$, E. Gregersen$^9$, J. Harju$^{10}$, T. Hasegawa$^{11}$, A. Hjalmarson$^2$, L. Johansson$^2$, S. Kwok$^{11}$, A. Lecacheux$^{12}$, T. Liljeström$^{13}$, K. Mattila$^{10}$, G. Mitchell$^{14}$, L. Nordh$^{15}$, M. Olberg$^2$, G. Olofsson$^1$, L. Pagani$^5$, R. Plume$^{11}$, I. Ristorcelli$^1$, A. Sandqvist$^1$, F.v. Schéele$^8$, G. Serra$^{16}$, N. Tothill$^{14}$, K. Volk$^{11}$, and C. Wilson$^9$

1. Introduction

The ammonia molecule (NH$_3$) has a complex energy level structure, which makes it a useful tool to probe regions of very different excitation conditions in a given source (see Ho & Townes 1983 who also provide an energy level diagram), and molecular clouds have routinely been observed from the ground in the inversion lines at about 1.3 cm, with critical densities of about 10$^{4}$ cm$^{-3}$. On the other hand, the rotational lines have much shorter lifetimes (minutes compared to months) and consequently much higher critical densities ($> 10^7$ cm$^{-3}$, see Table 2). Their wavelengths fall, however, into the submillimeter and far infrared regime and these lines are generally not accessible from the ground. Using the Kuiper Airborne Observatory (KAO), the submillimeter ground state line of ammonia of wavelength 524 µm, NH$_3$ ($J_K = 1_0 \rightarrow 0_0$), was first

Abstract. Odin has successfully observed the molecular core $\rho$ Oph A in the 572.5 GHz rotational ground state line of ammonia, NH$_3$ ($J_K = 1_0 \rightarrow 0_0$). The interpretation of this result makes use of complementary molecular line data obtained from the ground (C$^{17}$O and CH$_3$OH) as part of the Odin preparatory work. Comparison of these observations with theoretical model calculations of line excitation and transfer yields a quite ordinary abundance of methanol, $X$(CH$_3$OH)$= 3 \times 10^{-9}$. Unless NH$_3$ is not entirely segregated from C$^{17}$O and CH$_3$OH, ammonia is found to be significantly underabundant with respect to typical dense core values, viz. $X$(NH$_3$)$= 8 \times 10^{-10}$.

Key words. ISM: individual objects: $\rho$ Oph A– clouds – molecules – Stars: formation
Larsson et al., Nordh et al. and Olberg et al., this volume).

The cold and dense molecular core ρ Oph A is part of the ρ Ophiuchi cloud at the distance of 160 pc (Loren et al. 1990), which is a region of ongoing low mass star formation. In this Letter, we present Odin observations of ρ Oph A in the NH$_3$ 572.5 GHz rotational ground state transition. Compared to the KAO, the highly improved sensitivity of Odin permits the clear detection of this tenfold weaker line. These Odin observations were complemented with C$^{17}$O and CH$_3$OH data obtained with the Swedish ESO Submillimeter Telescope (SEST) in La Silla, Chile (see Table I), aimed at the determination of the average physical conditions of the ρ Oph A core and these are discussed in Sect. 4.1. The Odin observations and their results are presented in Sects. 2 and 3. The implications are discussed, together with our conclusions, in Sect. 4.2.

2. Odin observations and data reductions

Odin observed ρ Oph A in NH$_3$ on February 13–15, 2002, toward RA = 16°26′29″78 and Dec = −24°23′42″3 (J2000) with a 2′ FWHM circular beam. The pointing was accurate to 30″, with an rms-stability during these observations better than 5″ (ΔRA = ±4′′7 and ΔDec = ±1′′1). The data were obtained in a sky-switching mode (Olberg et al., this volume) by observing a total of 4500 s each ON-source and on blank sky, with 10 s integrations per individual scan. In addition, once per orbital revolution, an OFF-position (1° north) was observed, for a total integration time of 7000 s.

Shortly after launch, it was recognised that the 572 GHz Schottky receiver was not properly phase-locked. However, Odin ‘sees’ the Earth’s atmosphere during its revolution and a relatively weak telluric ozone line, O$_3$ ($J_K = 30_{4,26} → 30_{3,27}$) 572877.1486 MHz (Pickett et al. 1998), falls sufficiently close to the ammonia line, NH$_3$ ($J_K = 1_0 → 0_0$) 572498.0678 MHz, to allow monitoring of the receiver frequency. For large portions of the ρ Oph A observations, the O$_3$ line center frequency was within 0.3 of a spectrometer channel (AOS-channel width = 0.32 km s$^{-1}$) and we used these fiducial channels to restore the remaining data in frequency space (cf. Fig. 1). Data collected during revolution 5336 to 5339 were not used because of too-low mixer current. The reduction procedure is described by Larsson et al. (this volume).

3. Results

The $T_{mb}$ = 0.4 K line ($\eta_{mb} = 0.9$; Hjalmarson et al., this volume) of NH$_3$ (1$_0 → 0_0$) toward ρ Oph A is centered on $v_{LSR}$ = 3.2 ± 0.1 km s$^{-1}$. The width of the hyperfine components (Downes & Schawlow 1955) in Fig. 2 is 1.5 km s$^{-1}$ and some line broadening results from velocity smearing.

![Fig. 1. Gaussian fits to the weak telluric O$_3$ (30$_{4,26}$ → 30$_{3,27}$) line during the Odin observations of ρ Oph A determined the AOS channel of the line peak (channel width = 0.32 km s$^{-1}$). The adopted average channel values for the segments, during which the phase lock was stable, are indicated (see the text).](https://example.com/fig1.png)

In order to discuss the implications of this Odin observation we will first derive the physical characteristics of the source from ground based observations, specifically obtained for the Odin mission. The technical details of these SEST observations will be presented elsewhere.

4. Discussion and conclusions

4.1. Physical parameters of ρ Oph A

4.1.1. H$_2$ column density from C$^{17}$O ($J = 1 → 0$)

The SEST observations of ρ Oph A in the C$^{17}$O (1-0) line (46″ beam, $\eta_{mb} = 0.70$) revealed spectra with partially resolved hyperfine components. Their relative intensities reflect the ratios of their statistical weights (0.5, 1.0, 0.75), indicating that the levels are populated according to their thermodynamic equilibrium values and that the emission is most likely optically thin. The lines are relatively narrow, $\Delta v = (1.29 ± 0.05)$ km s$^{-1}$, with the main line centered on $v_{LSR} = (3.41 ± 0.02)$ km s$^{-1}$. From these observations, the beam averaged column density of molecular hydrogen can be estimated from the standard solution of the ‘radio’-equation of radiative transfer, i.e. $N(H_2) = 2.75 × 10^{12} \Phi(T_k) \int T_{mb} dv_z$ (cm$^{-2}$), where $\Phi(T_k) = 8\pi k^3 T_0^2 \exp(T_{10}/T_k) Q(T_k)/h^2 c^3 g_1 A_{10} [1 - J_0(T_{bg})/J_0(T_k)]$. $T_{10} = h\nu_{10}/k = 5.390$ K is the transition temperature, $Q(T_k) \sim k T_k/hB$ with $B = 56.1830$ GHz is the partition function, $g_1 = 3$ is the total statistical weight of the upper level $J = 1$, $A_{10} = 7.13 × 10^{-8}$ s$^{-1}$ (Chandra et al. 1990) is the spontaneous transition probability, $T_{bg} = 2.74$ K

and solely detected 20 years ago toward Orion OMC1 by Keene et al. 1983. Only recently have renewed attempts been made to observe this line with the spaceborne sub-millimeter telescope Odin (Frisk et al., Hjalmarson et al., Larsson et al., Nordh et al. and Olberg et al., this volume).

Fig. 1. Gaussian fits to the weak telluric O$_3$ (30$_{4,26}$ → 30$_{3,27}$) line during the Odin observations of ρ Oph A determined the AOS channel of the line peak (channel width = 0.32 km s$^{-1}$). The adopted average channel values for the segments, during which the phase lock was stable, are indicated (see the text).
Table 1. A- and E-state methanol (CH$_3$OH) observations toward $\rho$ Oph A with the 15 m SEST. $\eta_{mb}$ and beam-FWHM are, respectively, 0.73 and 52$''$ for the (2−1) and 0.67 and 35$''$ for the (3−2) transitions.

| Rotational transition | Frequency$^b$ (MHz) | $E_u/k$ (K) | $10^6 A_{ul}$ (s$^{-1}$) | $v_{LSR}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $T_{mb}$ (K) | $T_R$ (K) | $\tau_0$ | $T_{ex}$ (K) |
|----------------------|---------------------|-------------|-------------------------|-----------------------|------------------------|-------------|----------|--------|------------|
| $2_{1} - 1_{1}$ E    | 96739.39            | 12          | 2.48                    | 1.51 ± 0.05           | 0.9 ± 0.1              | 1.16        | −0.07    | −11.6  |            |
| $2_{0} - 1_{0}$ A    | 96741.42            | 7           | 2.38                    | 1.52 ± 0.04           | 1.3 ± 0.1              | 1.14        | 1.09     | 16.3   |            |
| $2_{0} - 1_{0}$ E    | 96744.58*           | 20          | 3.30                    | 3.36 ± 0.09           | 0.85 ± 0.31            | < 0.10      | 0.21     | 0.5    | 7.8        |
| $2_{1} - 1_{1}$ E    | 96755.51            | 28          | 2.48                    | …                     | …                     | ∼ 0.04$^c$  | 0.04     | 0.005  | 10.2       |
| $3_{1} - 2_{1}$ A$^+$| 143865.79           | 28          | 11.16                   | …                     | …                     | < 0.06      | 2.28     | 0.21   | 15.9       |
| $3_{0} - 2_{0}$ E    | 145093.75           | 27          | 11.93                   | 1.32 ± 0.14           | 0.5 ± 0.13             | 0.32        | 0.04     | 12.9   |            |
| $3_{1} - 2_{1}$ E    | 145097.47*          | 20          | 10.61                   | 3.33 ± 0.09           | 1.53 ± 0.09            | 1.72        | 0.12     | 18.4   |            |
| $3_{0} - 2_{0}$ A    | 145103.23           | 14          | 12.23                   | 1.52 ± 0.09           | 2.15 ± 0.15            | 2.28        | 0.21     | 15.9   |            |
| $3_{2} - 2_{2}$ A$^-$| 145124.41           | 52          | 6.50                    | < 0.06                | 0.002      | 0.0003    | 9.7     |        |            |
| $3_{2} - 2_{2}$ E (blend) | 145126.37         | 36          | 6.63                    | 1.28 ± 0.19           | 0.25 ± 0.06            | 0.071       | 0.009    | 11.6   |            |
| $3_{3} - 2_{2}$ E (blend) | 145126.37         | 40          | 6.63                    | 1.28 ± 0.19           | 0.25 ± 0.06            | 0.007       | 0.0004   | 10.8   |            |

Notes to the table:
$^a$ Average of data for two positions, spaced by 30’’ north-south.
$^b$ Rest frequencies were adopted from [Lovas 1992]. Tuning frequencies are identified with an asterisk.
$^c$ Low resolution spectrum (1.4 MHz). This spectrum includes also DCO$^+$ (2−1) at a level of $\int T_{mb} \, dv = 6.4 \, K \, km \, s^{-1}$.

Fig. 2. The submm NH$_3$ ($J_K=1_0 - 0_0$) line (523.66$\mu$m) observed with Odin toward $\rho$ Oph A (histogram). At 572.5 GHz the Odin $T_{mb}$-scale is related to the flux density by $F_v/T_{mb} = 2600$ Jy/K. The quadrupole hyperfine lines in their equilibrium ratios are indicated, together with their total contribution.

is the temperature of the background radiation field and $J_v(T) = T_{10} / \exp(T_{10}/T) - 1$. The numerical constant, 2.75 $\times$ 10$^{12}$ s cm$^{-3}$ K$^{-1}$, assumes the relative abundance of C$^{17}$O (with respect to H$_2$), $X$(C$^{17}$O) = 3.6 $\times$ 10$^{-8}$, which is consistent with C$^{18}$O/C$^{17}$O = 4 in $\rho$ Oph A determined by [Encrenaz et al. 1973] (see also [Bensch et al. 2001] for $\rho$ Oph C).

The H$_2$ column density is not very sensitive to the assumed temperature: the function $\Phi(T_k)$ varies within a factor of less than three (2.65) for $T_k$ in the range 5 K to 50 K. For the observed line intensity $\int T_{mb} \, dv = 1.85 \pm 0.06 \, K \, km \, s^{-1}$, the H$_2$ column density is then in the range (0.5 − 1.3) $\times$ 10$^{23}$ cm$^{-2}$. On the arcminute scale, this translates to an average volume density of the order of $n$(H$_2$) = (0.4 − 1.0) $\times$ 10$^6$ cm$^{-3}$. These results are in accord with earlier molecular line observations (e.g. [Loren et al. 1990]).

4.1.2. Kinetic gas temperature from CH$_3$OH

The observed spectra of 11 CH$_3$OH lines (Table 1) for an energy level diagram, see [Nagai et al. 1979] are suggestive of gas of relatively low excitation (the A$^-$ (3$_2 - 2_2$) line with $E_u/k = 52$ K is not detected and the E (3$_2 - 2_2$), (3$_2 - 2_2$) blend, having $E_u/k \geq 36$ K, is weak, if detected at all). We use large velocity gradient models (LVG) of methanol to obtain estimates of the average conditions in the core by requiring acceptable models to be consistent with the C$^{17}$O observations.

We consider the rotational $J_k$ energy levels for both A- and E-type methanol in their ground torsional states. The level energies and frequencies were obtained from the JPL-catalogue [Pickett et al. 1998]. For the A-states we adopted the Einstein-A values from [Fei et al. 1988] whereas we calculated those of the E-states using the equations of [Lees 1973] with appropriate Hön-London factors for the a- and b-type transitions (e.g. [Zare 1980]). Rate coefficients for collisions with He were kindly provided by
D. Flower (see: Pottage et al. 2001, 2002) and were scaled for collisions with H$_2$ ($\times 1.37$).

The observed line spectrum (Table 1) is consistent with a model having $T_k = 20$ K, $N$(H$_2$) = 6.0 $\times$ 10$^{22}$ cm$^{-2}$, $n$(H$_2$) = 4.5 $\times$ 10$^5$ cm$^{-3}$, $dV/dr = 45$ km s$^{-1}$ pc$^{-1}$ (1.4 km s$^{-1}$ along 40$''$), and a methanol abundance of $X$(CH$_3$OH) = $X_A + X_E = (1.4 + 1.3) \times 10^{-9}$. The model yields thus a ratio $X_E/X_A = 0.89$, which can be compared to the equilibrium ratio of 0.67 at 20 K.

Any beam effects of significance are not evidenced by the CH$_3$OH data (35$''$ and 52$''$ beam sizes), suggestive of emission regions not exceeding half an arcminute. Even the strongest methanol lines have only modest optical depths (max $\tau_0 \leq 0.2$) and the excitation of these lines is only mildly subthermal, giving confidence to our temperature determination. Much higher temperatures (say 50 K) are not consistent with the methanol observations. $T_k$ is also equal to the temperature of the cold dust component evidenced by ISO-LWS observations (Liseau et al. 1999).

**4.2. NH$_3$ ($J = 1 - 0$) emission from $\rho$ Oph A**

The model of the previous sections represents the basis for our analysis of the Odin ammonia line observations, where we varied only the NH$_3$ abundance. Using the equations of Poynter & Kakar 1975 (and their ‘15 parameter exponential fit’) we computed the level energies and Einstein-A values, with the dipole moment from Cohen & Poynter 1974. The collisional rate coefficients were adopted from Danby et al. 1988.

The observation with Odin (Table 2) can be fit with an ortho-ammonia abundance of, formally, $X_o$(NH$_3$) = 4.25 $\times$ 10$^{-10}$, corresponding to a beam averaged column density $N_o$(NH$_3$) = 2.6 $\times$ 10$^{13}$ cm$^{-2}$. $\rho$ Oph A has been mapped in the (1$_1$-1$_1$) and (2$_2$-2$_2$) inversion lines of NH$_3$ with the 100 m Effelsberg antenna (43$''$ beam) by Zeng et al. 1984. Their Fig. 2 displays the spectra toward one position, and the values scaled to the Odin beam size are given in our Table 2 together with our model for an ortho-to-para ratio of unity. According to Zeng et al. 1984 extended ammonia emission on the 90$''$ scale is also observed. Fortuitously perhaps, a 43$''$ source (~45$''$ SE) is also consistent with the (2$_2$-2$_2$) and (3$_3$-3$_3$) observations by Wootten et al. 1994 with the VLA (6$''$ beam). The observed and model values are, respectively, 11.5 K and 11.8 K for (2$_2$-2$_2$) and 2.2 K and 2.0 K for (3$_3$-3$_3$), which is slightly masing. No data are given for their (1$_1$-1$_1$) observations, the model value of which is 45.2 K. However, Wootten et al. 1994 used their (11-11) measurement (in combination with 2$_2$-2$_2$) to estimate $X_p$(NH$_3$) $\sim$ 3 $\times$ 10$^{-10}$. Albeit referring to a much smaller angular scale, this is in reasonable agreement with our ad hoc assumption of equal amounts of ortho- and para-NH$_3$.

We thus estimate a total ammonia abundance of the order of $X$(NH$_3$) $\sim$ 8.5 $\times$ 10$^{-10}$ in the $\rho$ Oph A core. This value is significantly lower than the 10$^{-8}$ to 10$^{-7}$ generally quoted for molecular clouds (and cannot be explained by an erroneous ortho-to-para ratio) and contrasts with our value of $X$(CH$_3$OH), which appears entirely ‘normal’ (e.g., van Dishoeck et al. 1993). Although the uniqueness of the present model may be debatable (e.g., gradients in velocity, temperature and density are known to exist over the 2$''$ Odin beam), these results are certainly significant. Smaller velocity gradients, higher temperatures and/or densities would result in even lower $X$(NH$_3$). At the other extreme, ‘normal’ abundances would require the line to be thermalized ($\tau > 10^3$), e.g., at the unrealistically low value of $T_k = 6$ K, unless the NH$_3$ source is point-like. With this caveat in mind, we conclude that the $\rho$ Oph A core likely has a very low NH$_3$ abundance.

**Table 2. Model results for NH$_3$ observations toward $\rho$ Oph A**

| Transition | $T_{mb}$ (K) | $T_k$ (K) | $\tau_p$ (K) | $\tau_o$ (K) | $A_{ul}/A_{oil}$ (cm$^{-3}$) | $n_v$(H$_2$)$^b$ |
|------------|--------------|------------|---------------|---------------|-----------------------------|----------------|
| o-(1$_1$-0$_1$) | 0.40 | 0.41 | 4.6 | 6.5 | 1.59 $\times$ 10$^{-3}$ | 3.6 $\times$ 10$^2$ |
| p-(1$_1$-0$_1$)$^c$ | > 0.38 | 0.88 | 0.10 | 11.8 | 1.69 $\times$ 10$^{-7}$ | 2.0 $\times$ 10$^2$ |
| p-(2$_2$-2$_2$)$^c$ | > 0.18 | 0.23 | 0.012 | 21.7 | 2.26 $\times$ 10$^{-7}$ | 2.0 $\times$ 10$^2$ |
| o-(3$_3$-3$_3$) | ... | 0.04 | < 0.005 | < 5.2 | 2.59 $\times$ 10$^{-7}$ | 2.2 $\times$ 10$^2$ |

Notes to the table:

$^a$ Ortho-to-para of unity is assumed ($X_o/X_p = 1$).

$^b$ Values of the critical density, $n_v$(H$_2$) = $A_{ul}/A_{oil}$($T_k$), for 20 K.

$^c$ Data estimated from Fig. 2 of Zeng et al. 1984 and scaled to the Odin beam size, i.e. multiplied by (43/120)$^2$.

**References**

Bensch F., Pak I., Wouterloot J.G.A., Klapper G., Winnewisser G., 2001, ApJ, 562, L185

Chandra S., Maheshwari V.U., Sharma A.K., 1996, A&AS, 117, 557

Cohen E.A., Poynter R.L., 1974, J. Mol. Spec., 53, 131

Danby G., Flower D.R., Valiron P., Schilke P., Walmsley C.M., 1988, MNRAS, 235, 229

Encrenaz P., Wannier P.G., Jefferts K.B., Penzias A.A., Wilson R.W., 1973, ApJ, 186, L77

Ho P.T.T., Townes C.H., 1983, ARAA, 21, 239

Keene J., Blake G.A., Phillips T.G., 1983, ApJ, 271, L27

Lees R.M., 1973, ApJ, 184, 763

Liseau R., White G.J., Larsson B., et al., 1999, A&A, 344, 342

Loren R.B., Wootten A., Wilking B.A., 1990, ApJ, 365, 269

Lovas F.J., 1992, J. Phys. Chem. Ref. Data, 21, 181

Nagai T., Kaifu N., Nagane K., Akabane K., 1979, PASJ, 31, 317

Pei C.C., Zeng Q., Gou Q.Q., 1988, A&AS, 76, 35

Pickett H.M., Poynter R.L., Cohen E.A., Delitsky M.L., Pearson J.C., and Muller H.S.P., 1998, "Submillimeter, Millimeter, and Microwave Spectral Line Catalog," J. Quant. Spectrosc. & Rad. Transfer 60, 883

Pottage J.T., Flower D.R., Davis S.L., 2001, J. Phys. B, 34, 3313

Pottage J.T., Flower D.R., Davis S.L., 2002, J. Phys. B, 35, 2541

Poynter R.L., Kakar R.K., 1975, ApJS, 29, 87
Townes C.H, Schawlow A.L., 1955, Microwave Spectroscopy, Dover Publications, Inc.
van Dishoeck E.F., Blake G.A., Draine B.T., Lunine J.I., 1993, in: Levy E.H. & Lunine J.I. (eds.), Protostars and Planets III, University of Arizona Press, p. 163
Wootten A., André P., Despois D., Sargent A., 1994, in: Clemens D.P. & Barvainis R. (eds.), Clouds, Cores and Low Mass Stars, ASP 65, 294
Zare R.N., 1986, Angular Momentum, John Wiley & Sons
Zeng Q., Batra W., Wilson T.L., 1984, A&A, 141, 127