SUBMILLIMETRE SPECTROSCOPY WITH ODIN

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Abstract

ODIN is a Swedish-international satellite for astronomy and aeronomy, with foreign partners being from Canada, Finland and France. ODIN will be launched in early 2001. To achieve its twofold objectives, ODIN will use its tunable heterodyne receivers to collect spectroscopic data in primarily the submm spectral domain of both astronomical objects and the atmosphere of the Earth.
ODIN's astronomical science focuses naturally on similar areas as HERSCHEL's, with a strong weight on the physics and chemistry of the star forming interstellar medium in our own and in other galaxies. First ranked observations will specifically address the key molecules H_2O and O_2. To achieve optimum sensitivity for the detection of molecular oxygen, a 119 GHz receiver will be flown on ODIN. The ground state lines of H_2O and of $H_2^{18}O$ will be observed as well as that of NH_3. In addition, transitions from other species and their isotopes (C, CO, CS etc.) are also admitted by the receiver bands.
The expected scientific capabilities of ODIN, resulting from the wide frequency coverage and the comparatively small beam size ($2'$ at submm wavelengths) will be discussed with respect to the achievements of SWAS and also be put into perspective to those foreseen for HERSCHEL.

Key words: Missions: ODIN – Submillimetre Astronomy: Heterodyne Spectroscopy – Molecules: O_2, H_2O, NH_3

1. The ODIN spacecraft

The space observatory ODIN[1] is a collaborative effort of astronomers and aeronomers from Sweden, Canada, Finland and France. ODIN features 3-axis stabilisation with reaction wheels, star trackers and gyros. The mass of the vessel is 250 kg, to which the payload contributes 80 kg. ODIN's height is 2.0 m and its width, once deployed, is 3.8 m. The power of 340 W will be delivered by the deployed fixed solar arrays. The launch on a Start-1 rocket from Svobodny, Russia, is foreseen for early 2001. ODIN will be on a solar synchronous orbit at an altitude of 620 km and with ascending node at 18:00 (Fig. 1). During ODIN's life of at least 2 years, communication at a rate of $> 720\,\mathrm{kbit\,s^{-1}}$ will be with Esrange, Sweden. The on-board storage capacity of the solid state memory exceeds 100 Mbyte.

[1] ODIN was successfully launched on February 20, 2001.

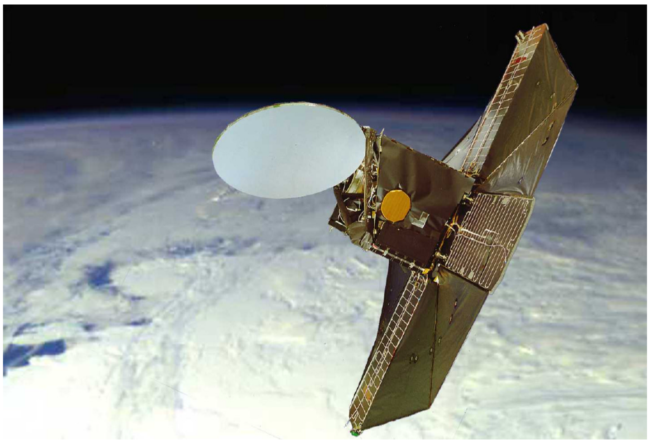

Figure 1. ODIN in its polar orbit at an altitude of 620 km.

1.1. The ODIN observatory

ODIN carries a 1.1 m offset Gregorian telescope, the surface accuracy of which is better than 10 μm rms (primary: 8 μm, secondary: 5 μm). When scanning the limb of the Earth the pointing stability will be $1\farcm2$ in aeronomy mode, whereas it is anticipated as $15''$ in astronomical mode (staring).

The front-ends consist of 4 tunable receivers in the submillimetre (480-580 GHz), using Schottky diode mixers, Stirling-cooled to 120 K, and having 17 GHz instantaneous bandwidth. The pre-flight system noise temperatures have been measured as 2300 K (SSB). In addition, for O_2 a dedicated, fixed at 119 GHz, Schottky receiver is operated with a system noise temperature of 500 K (SSB). ODIN is equipped with 2 digital hybrid autocorrelators (125 kHz - 1 MHz) and with 1 acousto-optical spectrometer (1 MHz) as back-ends, in addition to three 40 MHz wide filters for aeronomy. At 557 GHz, the highest attainable spectral resolution corresponds to $0.07\,\mathrm{km\,s^{-1}}$. Integration times of 15 min, including chopping, are expected to result in an S/N = 5 for a submillimetre source intensity

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of 1 K, at 1 MHz resolution. In the millimetre band, this is valid for 0.5 K and 150 kHz, respectively.

2. ODIN spectroscopy

2.1. Oxygen: O_2 (N_J): $(1_1 - 1_0)$ & $(3_3 - 1_2)$

As yet molecular oxygen has eluded observers and galactic upper limits to the O_2-abundance are $X(O_2) < 2.6 \times 10^{-7}\,(3\sigma)$ or higher as established by SWAS (Goldsmith et al. 2000) and PIROG 8 (Olofsson et al. 1998). This SWAS limit is based on observations in the 487 GHz line (Fig. 2), which will also be observed by ODIN. Furthermore, the dedicated 119 GHz receiver will permit the simultaneous observation of the ground state line, $(1_1 - 1_0)$. Under typical molecular cloud conditions, these transitions will most likely be thermalised and optically thin. With obvious notations, the flux ratio for an extended source is given by

$$\left(\frac{F_1}{F_2}\right)_{\rm ext} = \frac{I_1\Omega_1}{I_2\Omega_2} = \frac{h\nu_1\Omega_1 A_{11'} n_1}{h\nu_2\Omega_2 A_{22'} n_2} = \frac{\nu_2 A_{11'} g_1}{\nu_1 A_{22'} g_2}\, e^{\Delta E_{12}/kT} \quad (1)$$

where we have assumed that $\nu\Omega \propto \nu^{-1}$ and that the source has no gradients. We get $F_{118.8}/F_{487.3} = 1.3\, e^{20.7/T}$, i.e. for a cloud at 10 K the 119 GHz line is expected to become 10 times as strong as the 487 GHz transition. Compared to previous O_2 measurements, ODIN will thus potentially perform with significantly increased sensitivity. On the other hand, the sensitivity to pointlike sources is largely reduced for the 119 GHz transition, since then

$$\left(\frac{F_1}{F_2}\right)_{\rm point} = \frac{I_1\Omega_1 f_{\rm beam,\,1}}{I_2\Omega_2 f_{\rm beam,\,2}} = \left(\frac{\nu_1}{\nu_2}\right)^3 \frac{A_{11'} g_1}{A_{22'} g_2}\, e^{\Delta E_{12}/kT} \quad (2)$$

where we have assumed a source coupling $f_{\rm beam} \sim \Omega_{\rm source}/(\Omega_{\rm beam} + \Omega_{\rm source})$. Numerically, we get in this case $F_{118.8}/F_{487.3} = 0.005\, e^{20.7/T}$, i.e. the 487 GHz line would be 30 times stronger ($T = 10$ K). If eventually detected, these transitions will potentially probe the O_2 source size.

2.2. o-H_2O $(1_{10} - 1_{01})$ and o-NH_3 $(1_0 - 0_0)$

The ground state transition of NH_3, $J_K = (1_0 - 0_0)$, has previously been detected by the KAO (Keene et al. 1983). At typical temperatures in dark clouds, $T \ll 90$ K, the energy diagramme of ortho-ammonia (for K=0) is to first order approximated by a two-level system (Fig. 3). The intensity of the $(1_0 - 0_0)$ line can then be expressed as

$$T_{\rm R} = \frac{hc^3}{8\pi k\nu^2 \Delta v} X({\rm o-NH_3}) N({\rm H_2}) n({\rm H_2}) \gamma_{12} \times \quad (3)$$

$$\times \frac{\frac{\beta_{\rm e} n_{\rm crit}}{n({\rm H_2})}}{\frac{\beta_{\rm e} n_{\rm crit}}{n({\rm H_2})} + \frac{\gamma_{12}}{\gamma_{21}} + 1} \quad (4)$$

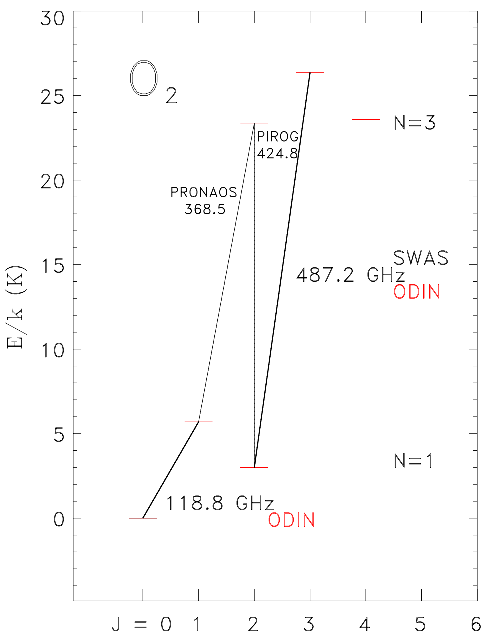

Figure 2. Energy level diagramme for O_2 with the transitions of various experiments indicated. The ODIN transitions can be observed simultaneously, potentially enhancing the ODIN sensitivity by an order of magnitude.

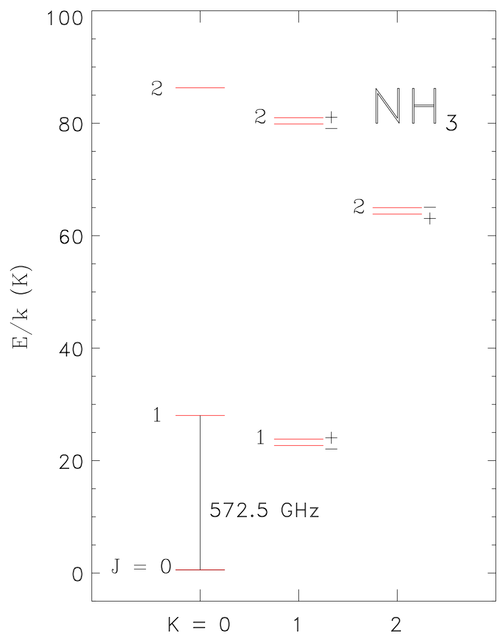

Figure 3. Low-lying energy levels of NH_3. K = multiples of 3, including K = 0, identify the ortho states. The energy levels of the familiar (1,1 - 1,1) and (2,2 - 2,2) inversion lines of the para-branches are also shown.

where $\beta_e \sim 1/\tau$ is a photon escape probability, $n_{crit} = A_{21}/\gamma_{21}(T)$ = a few times $10^7\,cm^{-3}$ is the critical density of the transition, Δv is approximately given by the width of the line, and the other symbols have their usual meaning. A linear growth is expected as long as the optical depth $\tau \lesssim 10^3$, making the line effectively optically thin. For standard conditions, viz. $n(H_2) = 10^4\,cm^{-3}$, $T = 20\,K$, $\Delta v = 1\,km\,s^{-1}$, $X(o-NH_3) = 10^{-7}$ and $N(H_2) = 10^{22}\,cm^{-2}$ ($A_V = 5$ mag), one finds a line peak intensity of $T_R = 0.5\,K$. According to Sect. 1.1, this would be easily detectable with ODIN.

Multi-transition calculations confirm this result, validating the 2-level approximation, since for e.g. the three lowest J-levels (K=0) the fractional population numbers are 0.931, 0.048 and $8.32\,10^{-6}$, respectively, and the opacity in the 572 GHz line $\tau = 245$. Apparently, this line behaves much like the 557 GHz o-H_2O line, ($J_{K_{-1,+1}} = (1_{10} - 1_{01})$), and could in cases, where the H_2O line is very weak or not detected, become a valuable substitute (cf. Fig. 7). For instance at 10 K, about one order of magnitude less ammonia would be required for the same signal strength (Fig. 4).

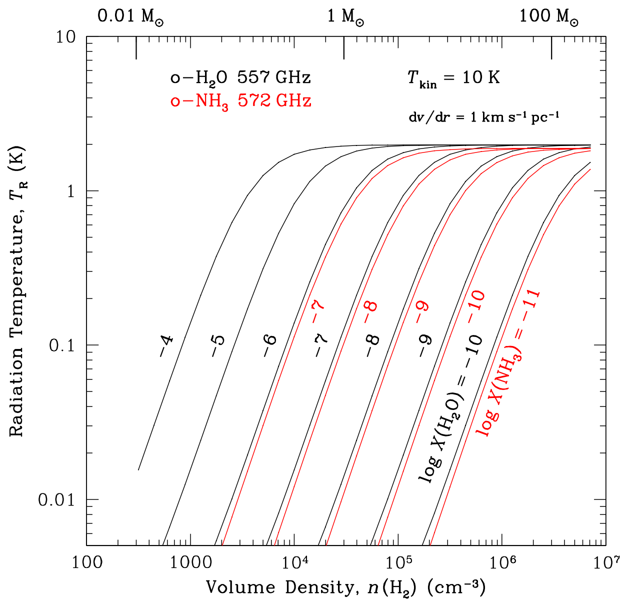

Figure 4. 557 GHz o-H_2O and 572 GHz o-NH_3 emission from cold cloud cores (total abundances are indicated, i.e. ortho/para = 3/1 has been assumed for H_2O and 1/2 for NH_3). An order of magnitude lower ammonia abundance produces a similar intensity as in the water line. The indicated masses (upper scale) are for core sizes of 0.1 pc.

In addition to ground state transitions, characteristic of gas of low excitation, ODIN is potentially able to observe also spectral lines from highly excited states of e.g.

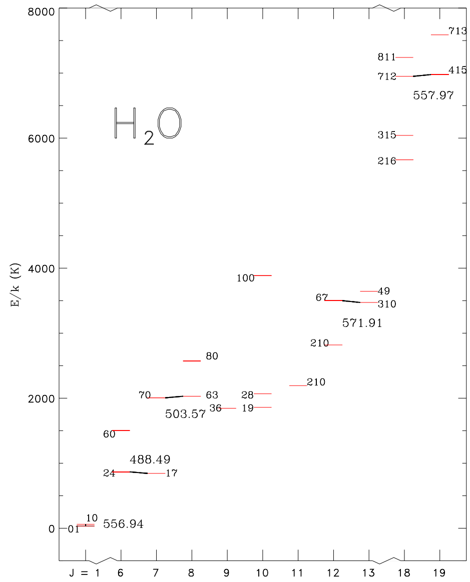

Figure 5. Transitions of highly excited H_2O, up to $E/k \sim 7\,000$ K, fall in the receiver bands of ODIN.

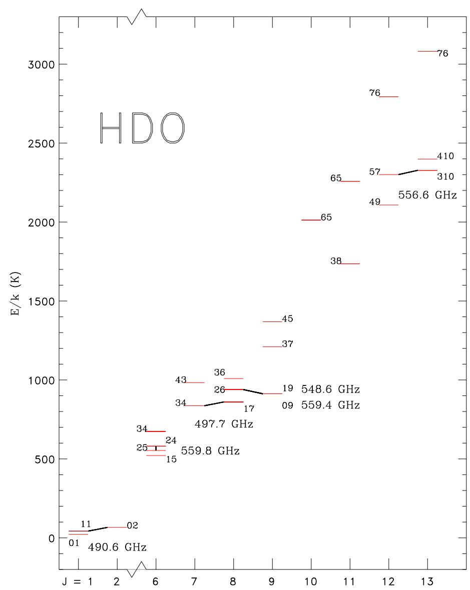

Figure 6. Similar to Fig. 6 but for HDO.

H_2O, up to $E/k \sim 7\,000$ K, and its deuterated form, HDO, up to $E/k \sim 2\,300$ K (Figs. 5 and 6).

3. ODIN astronomy

By its very nature ODIN is primarily a 'galactic' observing facility, addressing chemical and physical processes in the interstellar medium in the Galaxy, including star formation. This is reflected by the observing programme of ODIN, which in its initial phase can be grouped by astronomical topics according to: ISM and star formation 65.5%, galaxies and cosmology 16.5%, solar system 6.5%, spectral scans 6.0% and post-main-sequence evolution 5.5%, where the percentages are approximate numbers. Each topic is further divided into sub-fields. For instance, the field ISM AND STAR FORMATION is characterised mainly by surveys of Giant Molecular Clouds, including hot cores, of Dark Clouds, including cold cores, of High Velocity Flows, including shocks, of Cloud Edges, including PDRs, of High Latitude Clouds, including exotic chemistry regions, and of the Galactic Plane, including the Galactic Centre.

The expected scientific performance of ODIN can be put into perspective when considering the capabilities of related missions. For instance, at the frequency of the o-H_2O ($1_{10}-1_{01}$) line, i.e. 557 GHz, the circular 2.′2 ODIN beam is three times smaller than the elliptic beam of SWAS (Melnick et al. 2000), whereas that of HERSCHEL will measure merely 39″. The 80″ beam of the ISO-LWS for the $2_{12}-1_{01}$ line at 179.5 μm implies thus intermediate resolution, whereas HERSCHEL will eventually allow to observe objects in this line at 13″.

One of the prime objectives of the STAR FORMATION programme of ODIN is to search for protostellar infall, exploiting the full diagnostic power of the water and/or ammonia lines in combination with the high sensitivity and high resolving power of the ODIN spectrometers: for low-mass objects, spectral signatures are expected to be narrow and lines to be weak. The observations by SWAS made the second point particularly clear.

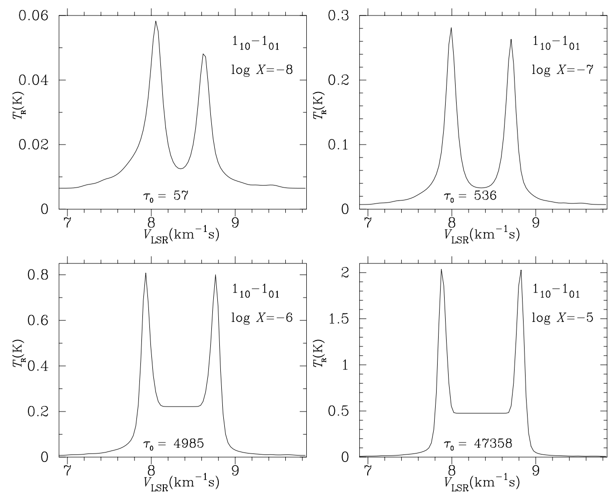

Figure 7. Theoretical line profiles of the H_2O-line at 557 GHz for an infall model of B 335 (but see Wilner et al. 2000) as seen by ODIN (Hartstein & Liseau 1998). Reasonable expectation values of the water abundance prior to SWAS are depicted in the lower two panels, whereas the upper right panel is consistent with the observed 3σ limit (Ashby et al. 2000). The upper left panel expresses the corresponding ODIN sensitivity (same t_{int}). Intensities in the temperature scale are expressed in K.

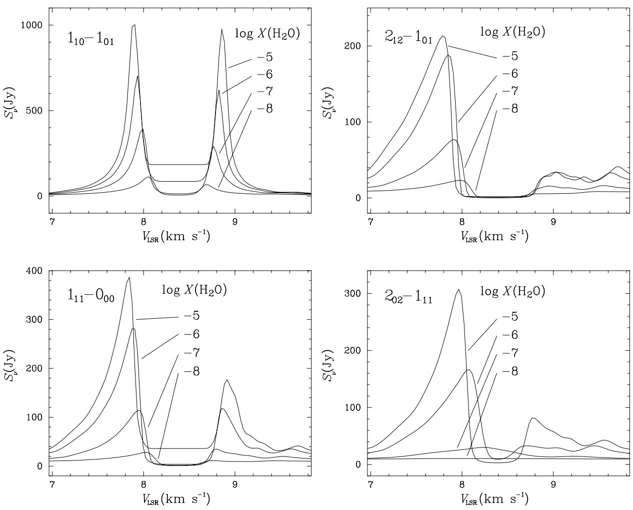

Figure 8. Water lines for various H_2O-abundances of the infall model of B 335, computed for future observations with HERSCHEL (Hartstein & Liseau 1998). The upper panels show the two ground state lines of o-H_2O, whereas the lower panels depict the corresponding para-lines (o/p=3 for both H_2O and H_2). Flux densities are given in Jy.

We have computed H_2O model spectra for an infall scenario of a low mass object, both for observations with ODIN and with HERSCHEL (HIFI) as shown in Figs. 7 and 8, respectively. Whereas both SWAS and ODIN are sensitive only to H_2O in its ortho-state, HERSCHEL being able to observe also para-lines will potentially resolve any ortho-to-para ambiguity for the water molecules (although H_2 would still need independent observations).

For the protostar search and as a preparatory program for ODIN, Larsson & Liseau 2001 have observed, in both celestial hemispheres, a very large sample of dark cloud cores and/or globules. Small maps were obtained in both CS (J=2-1) and CS (3-2) and the stronger sources were also observed in the optically thin $C^{34}S$ transitions. In addition, many sources were mapped in CN (J=1-0) and CN (2-1). The majority of these cores had previously also been observed in the $(1,1-1,1)$ inversion lines of ammonia, and partially also in the $(2,2-2,2)$ lines. From the combined results we have reason to believe that where SWAS and H_2O have been only partially successful, ODIN and NH_3 should have a better chance to succeed.

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