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Water at z=2.286 ?

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Abstract. We have used the IRAM 30m telescope to search for rotational lines of water and molecular oxygen in the very distant galaxy IRAS 10214+4724 at a redshift of 2.286. We report the tentative detection of the $2_{11} \rightarrow 2_{02}$ para transition of H_2O at 752.0 GHz. This would be the first time that a thermal rotational line of water is detected. The ortho transitions $1_{10} \rightarrow 1_{01}$ and $4_{14} \rightarrow 3_{21}$ at 556.9 and 380.2 GHz are not detected with intensities at most twice that of the detected 752 GHz line. We cannot derive the water abundance since the line is likely optically thick. Assuming that the levels are thermalized at 100 K, the surface filling factor of the H_2O emitting cores with respect to the total galaxy size of 8 kpc is about $3\ 10^{-3}$.

We have also observed three lines of molecular oxygen towards the same source, but detected none. Relative to H_2, this implies an abundance ratio $[O_2]/[H_2] \leq 3\ 10^{-4}$.

Key words: Interstellar Medium: molecules; Galaxies : individual : IRAS10214+4724 ; Galaxies : interstellar matter ; Radio lines: molecular: interstellar

1. Introduction

Water and molecular oxygen are thought to be abundant in molecular clouds. Their abundance is expected to be a fraction of that of carbon monoxyde CO, which is by far the most abundant molecule after H_2. Indeed since the cosmic abundance of oxygen is larger than that of carbon (C/O = 0.4) carbon monoxyde, water and oxygen are predicted to be the main reservoirs of gas phase oxygen in molecular clouds. The detection of water and oxygen lines from the ground is however very difficult due to the presence of these molecules in the earth atmosphere. There are two tricks to search for water and oxygen, either to observe lines of isotopomers (HDO, $H_2{}^{18}O$, $^{16}O^{18}O$), or to choose objects distant high enough as to redshift lines at frequencies where the atmospheric transmission is good.

Despite intensive searches, oxygen has been detected neither in redshifted galaxies (Liszt 1985, Goldsmith and Young 1989, Combes et al 1991), nor in molecular clouds (Goldsmith et al 1985, Liszt and Vanden Bout 1985, Combes et al 1991). The best upper limit for the $[O_2]/[H_2]$ column density ratio is 10^{-6} for the galaxy NGC 6240 (Combes et al 1991). As for water, several rotational radio lines have been detected in star forming regions, but they are all masing (Cernicharo et al 1990, Neufeld and Melnick 1987, Menten et al 1990). Knacke and Larson (1991) have detected absorption lines of interstellar water at 2.66 μm towards BN-KL, and conclude that most of the water is frozen on the grains and that the gas phase abundance is about $10^{-6} - 10^{-5}$. The isotopic species HDO and $H_2{}^{18}O$ are detected in hot cores of molecular clouds (e.g. Henkel et al 1987, Jacq et al 1988, 1990). Although the derivation of the water abundance is not straightforward from these data, they yield an abundance ratio $[H_2O]/[H_2]$ "of the order of 10^{-5} or less". The fundamental line of $H_2^{18}O$ at 547 GHz was unsuccessfully searched for in dense clouds by Wannier et al (1991), corresponding to upper limits for the water abundance of $[H_2O]/[CO] \leq 0.003$, or $[H_2O] \leq 3\ 10^{-7}$. From the observed abundance of the precursor molecular ion H_3O^+, Wootten et al (1986,1991) and Phillips et al (1992) also find a low water abundance towards the same sources, namely $10^{-7} - 10^{-6}$. These numbers should be compared with the CO abundance which is about 10^{-4} in hot cores and more generally 10^{-5} - 10^{-4} (Irvine et al, 1987).

Chemical models of interstellar clouds predict a large range of oxygen and water abundances which includes the observed values. However, at steady state and with a cosmic C/O value, the predicted abundances are somewhat higher than the observed ones. Results of steady-state chemical models are very sensitive to the adopted C/O ratio (Langer and Graedel 1989). As for time dependent models, the water abundance presents a maximum of a few 10^{-6} at early times (about 10^5 yr) (Herbst and Leung 1989). More realistic models including different rates of cosmic rays ionisation (Pineau des Forêts et al, 1992) or mixing of gas at different densities and illumination (Chièze & Pineau des Forêts 1989) predict low water and oxygen gas phase abundances. Other effects are important in determining the water gas phase abundance : - at low temperatures water is frozen on the grains for clouds with extinction larger than 3 mag (Whittet and Duley 1991), - at high temperature in star forming clouds, the water abundance is increased due to desorption from grains and to formation in shock waves associated to winds, outflows, ionisation fronts. The model in which H_2O is formed in magnetic "C-type" shocks, has been widely studied; it is the only one to successfully predict the observed lines of H_2, CO and OI in BN-KL (Draine & Roberge 1982; Draine et al 1983).

Strong lines of water and oxygen lie in the submillimeter region, for example the fundamental ortho line of water at 556.9 GHz. Therefore, high redshift objects like the galaxy

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IRAS10214+4724 (z=2.286) offer the opportunity of observing these lines at millimeter frequencies where the sky transparency is good and the receivers more sensitive.

IRAS 10214+4724 is an extremely luminous infrared galaxy with a total luminosity of $10^{14}h^{-2}$ $L_\odot$ (Rowan-Robinson et al 1991), comparable to that radiated by the most luminous QSOs (H_0 = 100 $kms^{-1}Mpc^{-1}$, q_0 = 0.5). This luminosity is probably powered by star formation as well as by an active nucleus (Lawrence et al 1993). The dust temperature in this object is very high : around 80 K (Downes et al 1992). The detection of rotational CO lines (J=3-2, 4-3, 6-5) shows that this object has a huge content of molecular gas : about 10^{11} $M_\odot$ (Brown and van den Bout 1991,1992, Solomon et al 1992). The strength of the CO lines suggested that other molecules may be detectable in this source. Indeed Elbaz et al (1992) suggest that the metallicity in this object could be higher than solar, and the C/O ratio lower than the solar system value : molecular oxygen and water should then be abundant. We thus searched for three lines of water vapor and three lines of molecular oxygen. Table 1 gives the spectroscopic data for the observed lines, using data from De Lucia et al (1974), Chandra et al (1984), Black and Smith (1984) and Johns and Lepard (1975).

Table 1. Observed lines

Molecule	Line	Name	ν_{rest}	A_{ul}	
O_2	3_2–1_1	O2J1	368499	1.92E-9	
O_2	3_2–1_2	O2J2	424763	2.41E-8	
O_2	5_4–3_4	O2J4	773902	4.39E-8	
H_2O	$4_{1,4}$–$3_{2,1}$	H2OJ4	380197	2.9918E-5	ortho
H_2O	$1_{1,0}$–$1_{0,1}$	H2OJ1	556936	3.4580E-3	ortho
H_2O	$2_{1,1}$–$2_{0,2}$	H2OJ2	752033	7.0618E-3	para

ν_{rest} is the line frequency in MHz.
A_{ul} is the Einstein coefficient in s^{-1}.

2. Observations

We observed the galaxy IRAS 10214+4724 with the IRAM 30m telescope at Pico Veleta near Granada, Spain, during two observing sessions in November 1992 and January 1993. Table 2 lists the redshifted frequencies, the telescope characteristics at these frequencies, and the observational parameters.

We used simultaneously three SIS receivers, connected with either one of the two 512x1MHz filterbanks or an AOS. For each line, we used alternatively two or three of these backends in order to avoid systematic effects. The frequencies were calculated using a redshift of 2.2860 (Rowan-Robinson et al 1991). We observed with a wobbler switching procedure with a throw of 2' in azimuth. Chopper wheel calibrations on an ambient temperature load and on a cold load (in liquid nitrogen) were done at the beginning of each scan. Pointing was checked at least every two hours by broadband continuum observations of the nearby radio source 0923+392. The rms pointing errors were about 3". We checked the frequency tunings by observing molecular lines towards the molecular source Orion-IRc2 at the beginning of each observing session.

For each line, the data reduction procedure was the following : we excluded a few scans (less than 10%) with obviously bad baselines, then the scans were added and a linear baseline was removed, and the final spectrum was smoothed to the resolution given in Table 2. At the H2OJ2 frequency, the integrated spectrum for the November observations showed a marginally detected line. We thus observed the source again in January, shifting the central velocity by - 40 kms^{-1}. These new data also showed a weak line. The combined data have then been reduced independently by three of us. The three resulting spectra all showed a line, with an area ranging from 0.5 to 1.1 $Kkms^{-1}$. The line area given in Table 2, 0.8 $Kkms^{-1}$, is the average value for the three reductions. We have checked by several means the reliability of this line : keeping only one scan out of two, the line still shows up. Keeping only one kind of backend, the line also persists. This line could be due to incomplete cancellation of telluric line, either in the signal or in the image bands, although it is unlikely because the sky subtraction has been made with a wobbler throw of only 4 arcmin. Indeed, three ozone lines are expected in the image band, but they are due to molecules with an ^{18}O atom and are thus likely to be very weak. Two of these are expected outside the range covered by the detected line and are not seen; the third which is also the weakest is expected at the edge of the line. Therefore we are confident that the line is not an atmospheric artefact.

Table 2. Observation characteristics

	O2J1	O2J2	O2J4	H2OJ4	H2OJ1	H2OJ2
ν_{obs}	112142	129264	235515	115702	169487	228860
T_{sys}(K)	260	370	770	550	540	440
HPBW	22	18	12	22	15	12
η_{mb}	0.59	0.59	0.45	0.59	0.55	0.45
t_{int}	1314	472	473	381	522	1179
σ(mK)	0.9	1.7	2.9	3.2	2.2	1.8
dV	16.04	18.55	23.77	20.7	28.3	10.48
$\int T_{mb}dV$	$\leq$ 0.2	$\leq$0.4	$\leq$0.7	$\leq$ 0.7	$\leq$0.5	0.8

ν_{obs} is the observing frequency in MHz.
HPBW is the Half Power Beam Width in arcsec.
t_{int} is the integration time in minutes.
dV is the velocity resolution, in kms^{-1} of the spectrum used to compute the rms noise level (main-beam scale) σ.
Upper limits are given at the 1σ level.

3. Results and discussion

3.1. Water lines

We have detected none of the oxygen lines, but we report a tentative detection of the $2_{1,1}$-$2_{0,2}$ para line of water vapor, shown on Fig 1. Fig 2 shows the spectrum we obtained at the O2J1 frequency with a comparable integration time.

The feature seen in the 229 GHz spectrum is centered at about 40 kms^{-1} while the CO lines detected at the IRAM 30m telescope have a slightly negative velocity (Solomon et al 1992). We do not think that these differences are significant since the detection of the water line is a 3σ one. Assuming that the line is real, we can derive a lower limit of the water abundance in the galaxy IRAS 10214+4724, in the optically thin case. For a high redshift object, this calculation is not as easy as for nearby clouds. Gordon et al (1992) have detailed the subtleties involved in the determination of luminosities and masses from the measured quantities.

Assuming that the H_2O line is optically thin and that the emission is thermal (which is likely because of the large value of the Einstein coefficient, see Table 1), we can write the relationship between the integrated area $W = \int T_b dv$ of a given

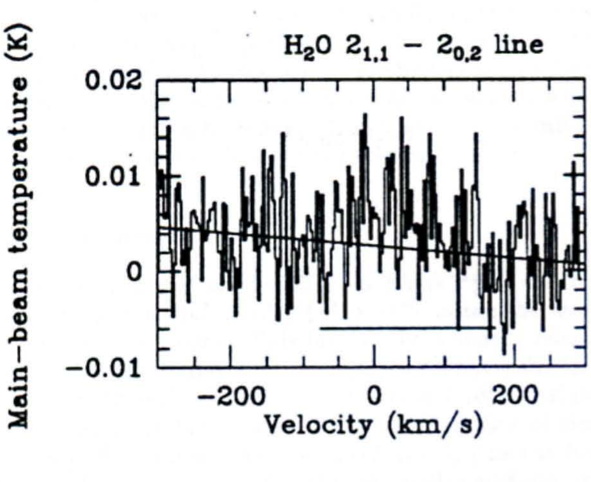

Fig. 1a. Raw spectrum of the $2_{1,1}$-$2_{0,2}$ para line of H_2O at 752.0 GHz redshifted to 228.86 GHz towards the galaxy IRAS10214+4724 ($RA(1950) = 10h21min31.1s$, $DEC(1950) = 47°24'23"$). About 10 percent of the original spectra have been dropped because of bad baselines.The linear baseline and line window are shown.

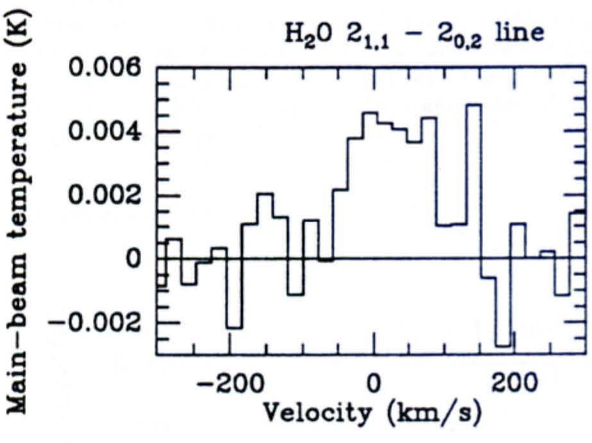

Fig. 1b. Reduced spectrum. The velocity resolution is 20.96 kms^{-1} and the rms noise 1.8 mK. The spectrum shown here is the average of three independent data reductions (see Sect. 2).

line (u→l) at zero redshift and the total column density of molecules N_{TOT}:

$$W = f(T)\frac{A_{ul}hc^3}{8\pi k\nu_{ul}^2}N_u$$

$$N_{TOT} = ZN_u(g_u s_I)^{-1}exp(E_u/kT)$$

where A_{ul} is the Einstein coefficient of the (u—l) line, given in Table 1, ν_{ul} its rest frequency, and E_u and g_u the energy and statistical weight of the upper level. The factor s_I is the nuclear spin statistical weight and is equal to 3/4 for ortho states and 1/4 for para states. The factor $f(T)$, which is close to 1, is equal to :

$$f(T) = \frac{B_\nu(T) - B_{\nu_{obs}}(T_{bg})}{B_\nu(T)}$$

defining $B_\nu(T) = h\nu/k\frac{1}{e^{h\nu/kT}-1}$, with T the kinetic temperature of the source and T_{bg} the background temperature. At a kinetic temperature of 100 K (note that the upper and lower energy levels of the line are at 133 and 98 K respectively) and for an ortho to para ratio of 3, we find :

$$N_{TOT} = 4.17\ 10^{12}\int T_b dV(\mathrm{cm^{-2}/Kkms^{-1}})$$

For a high redshift object, the observed line area, $\int T_{mb}dv$, differs from the velocity integrated brightness temperature emitted by the source for two reasons :

- beam dilution which affects the measured signal by a factor Ω_s/Ω_b for a source size Ω_s much smaller than the beam size Ω_b,
- antenna temperatures are defined as equivalent black body temperatures in the Rayleigh-Jeans limit, and vary with redshift as $T(z) = T(0)(1+z)$. The velocity widths of the channels are computed at the 30m telescope from $dV = -(c/\nu_{obs})d\nu_{obs}$, they thus correspond to the rest Doppler velocities in the source (see the discussion in Gordon et al 1992).

We deduce the following relationship :

$$I(H_2O) = \int T_{mb}dV = \int T_b dV(\Omega_s/\Omega_b)(1+z)^{-1} \qquad (1)$$

We calculate the mass of water in the beam $M(H_2O)$ as $M(H_2O) = N(H_2O)m(H_2O)\Omega_s D_A^2$ where $m(H_2O)$ is the mass of a water molecule, $N(H_2O)$ the column density of water molecules and D_A the angular size distance to the source. D_A is related to the luminosity distance D_L by $D_A = D_L/(1+z)^2$. The luminosity distance is equal to :

$$D_L = cH_0^{-1}q_0^{-2}(zq_0 + (q_0-1)((2q_0z+1)^{1/2}-1)) \qquad (2)$$

Using (1) and (2), and with $H_0 = 100$ kms^{-1}Mpc^{-1}, $q_0 = 0.5$, and defining X as $X = N(H_2O)/\int T_b dV$, we obtain

$$M(H_2O) = m(H_2O)XI(H_2O)\Omega_b D_L^2(1+z)^{-3}.$$

At z =2.286, D_L = 8.8 Gpc, and with $\Omega_b = 1.133(HPBW)^2$ for a gaussian beam = 163 square arcsec at 228 GHz, we deduce the mass of water vapor in the beam : $M(H_2O) = 1.2\ 10^{-9}XI(H_2O) = 4000$ to $6000\ h^{-2}$ $M_\odot$ assuming excitation temperatures of 100 K or 50 K.

If the lines were optically thin, the levels thermalized and the ortho to para ratio was three, the abundance of H_2O relative to H_2 would be about $N(H_2O)/N(H_2) = 6\ 10^{-9}$. This value seems very low compared to the various determinations made in the interstellar medium. However, it is clear that this is only a lower limit because the water lines are very likely optically thick (T. Phillips, private communication).

We can however estimate the filling factor of the H_2O emitting cores with respect to the galaxy size of 2 arcsec. If the lines are thermalized at 100 K the expected brightness temperature at the source level is 83 K, thus the redshifted one would be 25 K. If the H_2O cloud were uniformly spread over 2 arcsec, we would have seen a brightness temperature of 0.7 K. The surface filling factor is therefore 1/350 = 3 10^{-3}. This does not take into account the velocity structure of the source and is therefore a lower limit of the true filling factor. Doing the same estimate for the CO(6-5) line, the expected brightness temperature over two arcsec is 0.2 K, and the surface filling factor 1/54 = 2 10^{-2}. As expected, the H_2O emitting cores are smaller than the CO emitting clouds, but nevertheless the surface filling factor of warm and dense cores is surprisingly high for a whole galaxy.

With these characteristics for the H_2O source, the expected brightness temperature of the H2OJ1 line is 87 K, if thermalized at 100 K and optically thick. Observed in a beam of 15 arcsec with the same dilution factor, we expect a peak temperature of 1.3 mK. Since our rms noise is 1.2 mK, it is not surprising that this line is not detected.

3.2. Line luminosities

The luminosity of an H_2O line, in $\mathrm{Kkms^{-1}pc^2}$, can be written as $L'(H_2O) = \Omega_b I(H_2O) D_L^2 (1+z)^{-3}$, using the notations of Solomon et al (1992). This luminosity is simply related to the mass calculated above by $M(H_2O) = m(H_2O) X L'(H_2O)$. For the H2OJ2 line, we find $L'(H2OJ2) = 7\ 10^9 h^{-2}$ $\mathrm{Kkms^{-1}pc^2}$, about half the luminosity of the CO(6-5) line of similar frequency. This shows that the H_2O $2_{1,1}$-$2_{0,2}$ line is bright and should be easily detected in the interstellar medium, when submillimeter telescopes are available.

For the H2OJ1 line, $L'(H2OJ1) \leq 6\ 10^9 h^{-2}$ $\mathrm{Kkms^{-1}pc^2}$. Note that the H2OJ1 and H2OJ2 lines were observed in our Galaxy by the COBE satellite and not detected (Wright et al 1991).

We have also observed the 4_{14}–3_{21} line at 380GHz, which is expected to be masing (Cooke & Elitzur 1985, Deguchi and Rieu 1990), since the upper level is a backbone (de Jong 1973). However, no signal was detected ; at the 1σ level the line area is lower than 0.7 $\mathrm{Kkms^{-1}}$, and the line luminosity $L'(H2OJ4) \leq 1.9\ 10^{10}$ $\mathrm{Kkms^{-1}pc^2}$.

3.3. Molecular oxygen

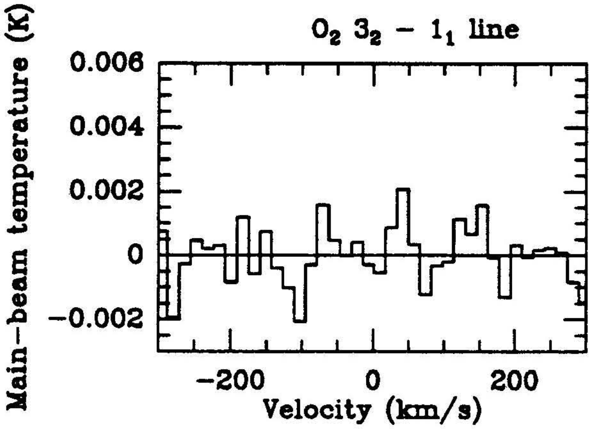

Fig. 2. Spectrum of the 3_2-1_1 line of O_2 at 368.5 GHz towards the galaxy IRAS10214+4724, the line is redshifted to 112.142 GHz. The integration time is 1314 minutes, the velocity resolution is 16.04 $\mathrm{kms^{-1}}$ and the rms noise is 0.5 mK.

None of the three lines of molecular oxygen was detected. We have achieved very low noise levels for the O2J1 and O2J2 lines. With the same calculations as for H_2O (assuming thermal emission at 100 K and optically thin lines), and using the 1σ upper limits, we conclude that $M(O_2) \leq 5\ 10^8$ $M_\odot$, and $[O_2]/[H_2] \leq 3\ 10^{-4}$. Observations of the redshifted 118 GHz line in nearby galaxies provide much more stringent upper limits (Combes et al 1991).

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