NH_3 AND H_2O EMISSION IN OUR GALAXY

D. M. RANK

Physics Department, University of California, Berkeley, Calif., U.S.A.

In 1968 NH_3 molecules were discovered in gas clouds near the center of our Galaxy. The NH_3 molecules showed emission lines in transitions arising from metastable $J=K$ rotational states. NH_3 has many transitions at about 1.25 cm; hence, a great deal can be learned about the gas clouds. In particular, 1–1, 2–2, 3–3, 4–4 have excitation temperatures of 24 K, 65 K, 125 K, 203 K respectively. Thus, one can determine temperatures very accurately by comparing line strengths to statistical theory. NH_3 is particularly useful as an interstellar thermometer since all of these lines can be detected by a single radio telescope with essentially the same beam size. Generally, a telescope measures the antenna temperature T_A of an object which is related to the brightness temperature T_B of an object by $T_A = \Omega_s/\Omega_A \, T_{Bj}$; $\Omega_s/\Omega_A \leqslant 1$. $T_A = T_B$ when $\Omega_s \geqslant \Omega_A$, where Ω_A is the solid angle of the antenna pattern and Ω_s is the solid angle of the source as seen from the antenna. If measurements can be made with the same telescope, T_B for different spectral lines will be simply related to the T_A for the lines and one does not have the complication of source size and geometry. The brightness temperature T_{BJK} of a spectral line from a rotational state specified by the quantum numbers (J, K) can be simply related to the optical depth of the line τ_ν and the excitation temperature of the molecule T_{exc},

$$T_{BJK} = T_{\text{exc}}\left(1 - e^{-\tau_\nu}\right). \tag{1}$$

For $\tau_\nu \ll 1$ we can expand and integrate Equation (1),

$$\begin{aligned} \int T_{BJK}\,\mathrm{d}\nu &= \int T_{\text{exc}}\tau_\nu\,\mathrm{d}\nu \\ &= T_{\text{exc}}L \int \gamma_\nu\,\mathrm{d}\nu\,, \end{aligned}$$

where γ_ν is the line strength which can be determined from simple theory. The result is

$$\int T_{BJK}\,\mathrm{d}\nu = \left\{\frac{8\pi^3}{3ck}\,|\mu_{JK}|^2\,\nu^2_{JKg(2J+1)}\right\} NL \exp\left(-W_{JK}/kT_{\text{exc}}\right) \tag{2}$$

where the quantity in brackets is the product of the matrix element, frequency, statistical weight, and other constants of the transition, NL is the column density of the molecules in the line of sight, W_{JK} is the energy of the rotational state and k is the Boltzmann constant.

Taking the ratio of the brightness temperature for two lines (which, provided they have very nearly the same frequency, is just the ratio of their antenna temperatures) NL cancels, and Equation (2) can be solved for T_{exc}. For the gas cloud near the center

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of our Galaxy $T_A(22)/T_B(11)=0.34$, which implies that the temperature there is about 25 K ± a few Kelvin.

In order to observe a spectral line in emission, there must be excitation of the molecules which will keep them out of equilibrium with the background 3 K radiation. The radiative lifetime of NH_3 at 1.25 cm is a few $\times 10^6$ sec and the induced transition rate of stimulated emission by the background radio frequency radiation corresponds to 10^{-6} sec^{-1}. Hence, if collisions are exciting the molecules, they must occur more rapidly than 10^{-6} sec^{-1}. This means the gas density in the cloud must be $\geqslant 10^3$ cm^{-3}. The strength of the NH_3 lines indicate that the NH_3 density is about 10^{-4} of that or 10^{-1} cm^{-3}. The bulk of the remaining gas is most probably molecular hydrogen.

Another useful property of NH_3 which can be related to temperature studies of interstellar gas is that there are two different spin states for the molecule which divide the rotational states of the molecule into two independent groups – ortho NH_3 where the rotational quantum number K is a multiple of 3, and para NH_3 where K is not a multiple of 3. Conversion from one form of NH_3 to the other requires a time greater than 10^6 yr in interstellar gases by collisions. Collisions, however, can bring molecules with the same spin state into equilibrium in a time of about 10^7 sec. Thus, the distribution of population in the rotational states of ortho NH_3 or para NH_3 reflect the present temperature of the gas while the relative population of para NH_3 to ortho NH_3 reflects the temperature history of the gas. A demonstration of this effect has been observed in a gas cloud which is in the central region of our Galaxy though not coincident with the true dynamical center. The present cloud temperature is about 40 to 50 K and the ortho to para NH_3 ratio indicate that the temperature has changed by about 40 to 50 K in a complicated fashion during the last few million years. The column densities of $NH_3 \simeq 10^{16}$ cm^{-2} in most of the clouds where it has been detected. NH_3 promises to be very useful as a probe to measure conditions inside interstellar dust clouds since it has proved to be rather well behaved and understandable on a simple physical basis. This is not true of OH and many of the more recently discovered molecules in the interstellar medium. Nearly all of them have some sort of anomalous excitation which makes the interpretation of their spectra difficult.

Water vapor emission was also discovered by our Berkeley group soon after the detection of NH_3 lines. The water vapor emission line at 1.3 cm comes from $6_{16} \rightarrow 5_{23}$ in H_2O. These levels are not metastable and, hence, it is somewhat surprising that they are observed in the interstellar medium. In fact, the 6_{16} level can decay by infrared emission in about 1 sec, whereas the microwave radiation lifetime of the level is 10^8 sec. Strong line emission from such unstable levels requires a very special excitation process in a tenuous gas cloud. Further observations demonstrated antenna temperatures on the order of a few thousand degrees and line widths which were considerably narrower than usual thermal or turbulent width. The water vapor is undergoing stimulated emission or maser action much like that observed in the OH molecule. It would seem that OH and H_2O should be connected by interstellar chemistry and be found in fairly similar regions. In fact, most OH sources of emission also show water vapor emission. The situation is very complicated and as yet no complete and convincing explanation has come forth. Also, as one might guess, there have been no cases of 'normal' H_2O absorption from the Galaxy because the transition is a very highly excited one. Hence, no column densities have been measured. Recent long base line interferometry has determined that the emitting regions are $<0.003''$ for most of the H_2O sources. This means that the radiation is apparently coming from regions a few tens of astronomical units in size.

DISCUSSION

Sullivan: At the Maryland Point Observatory of the Naval Research Laboratory we have monitored the 1.35 cm H_2O line emission in ten galactic sources over the period January, 1969 to June, 1970. The main observational results to date are: (a) all of the features in the H_2O profiles are variable in intensity with a time scale of several weeks and most are also variable in width and central radial velocity; (b) velocity shifts of as much as 1.5 km sec^{-1} have been observed, but no system or periodicities are yet apparant in these shifts; (c) as a general rule, the half width of a feature decreases as the intensity increases; (d) no circular polarization greater than 5% has been detected in any H_2O source and strong linear polarization is found only in the Orion Nebula; (e) for the Orion source, there definitely exists a positive correlation between percentage linear polarization (varying from 5% to 30%) and intensity of a feature.

Although there is a strong correlation between the positions and radial velocity ranges of the OH and H_2O line emission, it is clear that the masers involved are quite different. For the case of OH one observes strong linear or circular polarization in almost all features, while variations in intensity of OH features are only slight and of a longer time scale.