**AMMONIA AS A TEMPERATURE PROBE**
**IN STAR FORMING REGIONS**

## Introduction

Molecules in the interstellar medium have been used as probes of some of the physical and chemical conditions in the medium. The radio spectra of these molecules, which are typically caused by the rotation of the molecule and its collision with hydrogen molecules, are especially good tools for this purpose. The radio spectral region is also rich in spectral lines of more than 100 molecular species.

Ammonia ($NH_3$) was the first polyatomic molecule discovered in interstellar space. This molecule has a rich rotation-inversion spectrum with a large number of transitions probing a wide range of excitation conditions. In molecular clouds these transitions are excited in collisions mainly with molecular hydrogen and their relative intensities reflect the kinetic temperature of the emitting medium.

Ammonia is, thus, an invaluable tool in measuring the physical conditions in molecular clouds. Temperature determinations from $NH_3$ have been used extensively in studies of star formation since ammonia emission has been found in regions of massive as well as low mass star formation. Such studies have proven useful in determining the conditions in molecular clouds that are necessary for star formation.

## Experiment

1. The first step in this experiment is to select the sources. These can be previously known sources of ammonia or some molecular cloud with no previous ammonia measurement. The nature of the sources can be determined depending on the level of complexity that the particular project requires.

2. One then needs to select a pointing source - preferably a source that is close to the source being observed. If planets are available then they may be used but water maser sources are probably a better choice.

3. Then one needs the frequencies of the (1,1) and (2,2) transitions of ammonia. A more detailed explanation of the above transitions and the nomenclature can be found in Ho and Townes (1983). The frequency of the (1,1) line is 23694.495 MHz and that of the (2,2) line is 23722.622 MHz.

4. The most efficient way to observe the ammonia line is by frequency switching (see Rohlfs and Wilson - page 205 and Umbrella manual). At this frequency the only other way of getting a spectrum is by position switching since there is no beamswitcher available. However, the frequency switching option works well in most cases.

5. Data is collected by integrating 5 minute spectra on a particular source position until a reasonable signal to noise ratio is obtained. This is done for both the (1,1) and the (2,2) line. Calibration can be done every 5 or 10 minutes depending on the sky conditions.

## Analysis

1. The first step in the analysis process is to extract the necessary information from the data. In the case of the (1,1) line we need the optical depth of the main component and the intensity of the main component. The optical depth is calculated from the ratio of the main component to the hyperfine component. The required equations for this calculation can be found in Ho and Townes (1983). The intensity of the main component can be found by fitting a gaussian line profile to the line. Both these calculations can also be done in the CLASS software, which is used at Haystack (See CLASS manual).

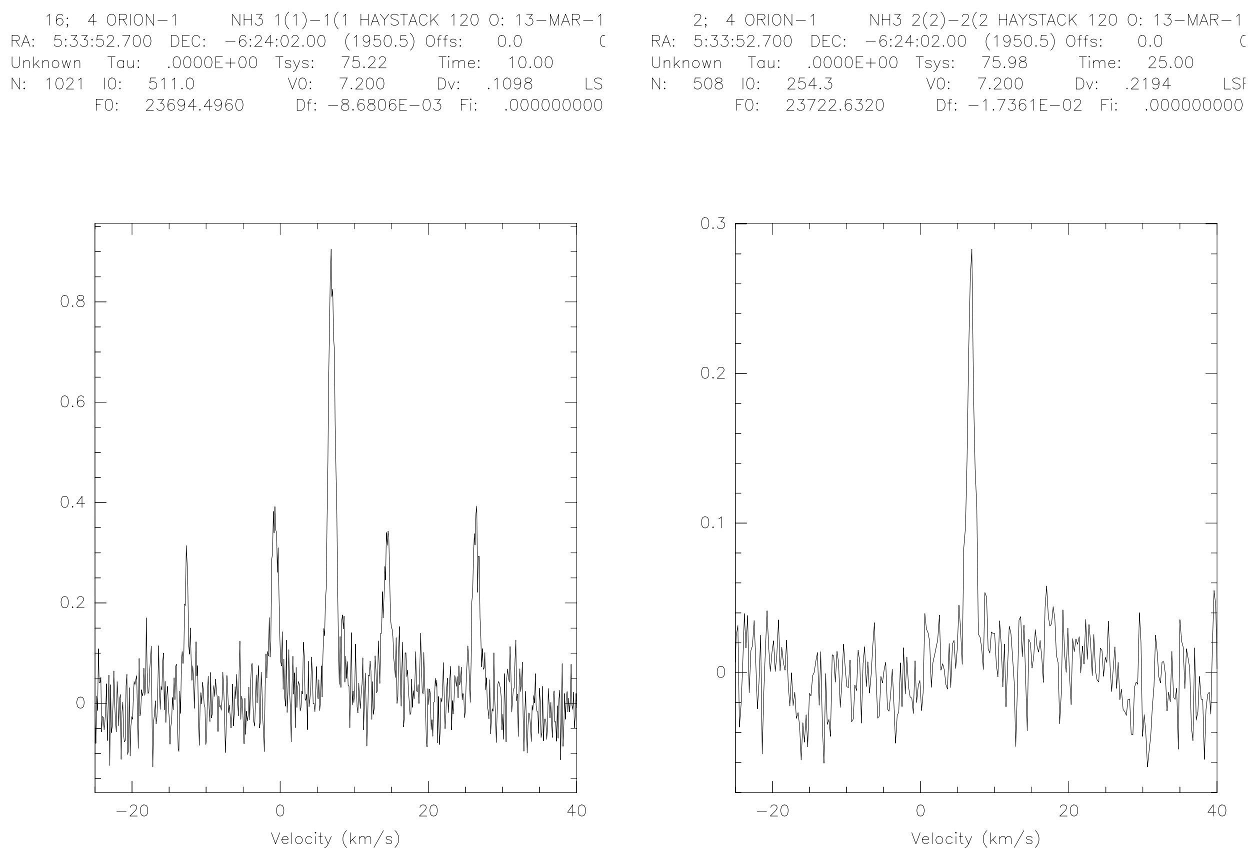


Fig. 1.— Example of the ammonia (1,1) and (2,2) lines toward a source in the Orion molecular cloud taken with Haystack.

2. The next step is to get the intensity of the (2,2) line. This can be done by fitting a gaussian line profile to the line. In most sources the hyperfine structure of the (2,2) line is too weak to observe.

3. The ratio of the (1,1) and (2,2) lines and the optical depth can then be used to calculate the rotational temperature and kinetic temperature. The appendix at the end of the document has a brief discussion on the various temperatures.

4. Once the temperatures are calculated one can turn to the scientific questions that can be addressed. For example, why is ammonia a good temperature probe? Do the kinetic temperatures (in a larger sampling of data) correlate with the star formation properties of the cloud? How do the linewidths of the ammonia lines correlate with the star formation?

**References**


Tools of Radio Astronomy by Rohlfs and Wilson 1996 (second edition, Springer)

Ho, P. T. P. & Townes, C. H. "Interstellar Ammonia", 1983, *Ann. Rev. Astr. Astrophys.*, **21**, 239.

Mangum, J. G., Wootten, A., & Mundy, L. G. "Synthesis Imaging of the DR 21 (OH) Cluster. II. Thermal Ammonia and Water Maser Emission", 1992, *Ap. J.* , **388**, 467. (Appendices)

Danby et al. 1988, *MNRAS*, **235**, 229.


**Appendix**

1. Mangum et al. call the rotational temperature as excitation temperature.

2. Collision rate coefficients to use in eqn A20: C(2,2;2,1) = 1.7e-11 cm3s-1 C(2,2;1,1) = 3.0e-11 cm3s-1

These values are for a temperature of 15K but it does not change drastically for a temperature of 25 K. They are obtained from Danby et al. 1988, MNRAS, 235, 229.

3. Use the collision rate C(2,2;1,1) in the expression for n(H2) in Ho and Townes also. The rate quoted in that paper is out of date.

4. $T_a$ = antenna temperature - the "raw" quantity measured by the radio telescope (beware - people tend to use different notation for this!). This is the temperature that is corrected for the system noise (with the system temperature measurement). It is directly correlated to the power generated at the receiver input terminals by the source.

5. To convert this antenna temperature into a "main beam brightness temperature" ($T_b$) we divide it by the beam efficiency. In doing so we take into account the fraction of the power that actually gets into the telescope beam. The brightness temperature is defined as the Rayleigh-Jeans temperature of an equivalent black body which will give the same power per unit area per unit frequency interval as the celestial source. Since our source is extended we are making some assumptions here. We are assuming that the source has a constant brightness temperature across the beam and that it just fills the beam. For a more detailed explanation on how to deal with clumpy sources look at "Tools of Radio Astronomy" by Rohlfs and Wilson, p 188-196.

6. From the observed emission line several temperatures can be derived. The first value is the excitation temperature $T_{ex}$(1,1) which describes the relative population of the (1,1) levels - i.e. the population of the parity + level to the parity - level (Fig 2 in Ho and Townes 1983, ARAA 21, 239-270). This relationship can be mathematically expressed as:

$$\frac{N_+}{N_-} = \frac{g_+}{g_-} exp(\frac{-h\nu}{kT_{ex}})$$

Here $g_+$ and $g_-$ are statistical weights of the two levels - in this case they're equal and hence the ratio is 1. Now, obviously, this value of $T_{ex}$ will be different for the (1,1) and the (2,2) levels. However, one assumption that is made in Local Thermodynamic Equilibrium (LTE) is that these are equal.

7. Now, in order to calculate $T_{ex}$ from the measured quantities, we can equate the brightness temperature to the excitation temperature as follows:

$$T_b = (J_\nu(T_{ex}) - J_\nu(T_{bg}))(1 - e^{-\tau})$$

Here

$T_{bg}$ = cosmic background = 2.7K
$\tau$ = optical depth
$J_\nu(T)$ is given by $(h\nu/k)/(e^{h\nu/kT} - 1)$

If we assume $h\nu/kT$ is small, then the denominator can be expanded out and $J_\nu(T) = T$. So,

$$T_b = (T_{ex} - T_{bg})(1 - e^{-\tau}).$$

And furthermore, if $\tau$ is small, then

$$T_b = (T_{ex} - T_{bg})\tau.$$

This is what CLASS is trying to give you when it does the $NH_3$ fit. However, since CLASS does not know what your beam efficiency is, it is really giving you a $T_a$. So, you have to take the CLASS number and divide by the beam efficiency to get your excitation temperature.

8. The next quantity we are interested in is the rotational temperature, $T_{rot}$. This temperature describes the relative population between the (1,1) and the (2,2) levels. Now, you can derive this equation by starting out with a Boltzmann equation for each level. Mangum, Wooten, and Mundy (1988, Ap.J. 388, 467-488) do this in detail - but make sure you realize - in their equations, what they call $T_{ex}$ is actually $T_{rot}$. So, finally,

$$T_{rot}(2,2;1,1) = -41.5\left[ln\left(\frac{-0.283\delta v(2,2)}{\tau(1,1,m)\delta v(1,1)}ln(1 - \frac{T_b(2,2,m)}{T_b(1,1,m)}(1 - e^{-\tau(1,1,m)}))\right)\right]^{-1}$$

Here $T_b(1,1,m)$ and $T_b(2,2,m)$ correspond to the peak brightness temperatures of the main components of the (1,1) and (2,2) lines. The $\delta v$'s are the linewidths of the two transitions. Everything else should be obvious.

9. The final temperature we can estimate is the kinetic temperature of the gas. This temperature is related to the velocity field in the cloud. In the case of ammonia, radiative transitions between the states we consider (called metastable states) are forbidden. So the only allowed transitions are collisional - hence the populations of the metastable levels are directly related to $T_K$. We can thus obtain $T_K$ from $T_{rot}$ (which describes the relative populations of the metastable states) using the following equation:

$$T_{rot}(2,2;1,1)\left(1 + (\frac{T_K}{41.5})ln\left[1 + \frac{C(2,2;2,1)}{C(2,2;1,1)}\right]\right) - T_K = 0$$

Here C(2,2;2,1) and C(2,2;1,1) are the collision rates for a particular temperature. Its a bit circular since we have to assume a $T_K$ to get an appropriate collision rate...but that's the way it is!