Densitometry of Active Star Forming Galaxies

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Abstract. Attempting to distangle density and kinetic temperature of the star forming molecular gas in the central regions of galaxies, we have embarked on a project involving sensitive measurements of a variety of formaldehyde (H_2CO) and ammonia (NH_3) transitions. Preliminary results, based on observations from the Green Bank Telescope (GBT) and the Very Large Array (VLA) are summarized and an outline for the entire project is given.

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1. Introduction

To study the physical properties of the dense star forming molecular gas, abundant, high-dipole moment molecules are the best tracers. For this reason, emission line studies from linear molecules like CS, HCN, HCO^+ or HNC have been carried out toward a variety of nearby galaxies (e.g., Henkel *et al.* 1991; Gao & Solomon 2004a,b). However, simultaneous determinations of density and kinetic temperature suffer from a degeneracy. Observed line intensities can be fitted by both low densities and high kinetic temperatures and by high densities and low kinetic temperatures. To obtain a better understanding of the physical parameters of the dense star forming gas in the inner parts of active galaxies, we have therefore started a program based on spectra from the non-linear molecules H_2CO and NH_3, making use of recent drastic improvements with respect to attainable bandwidths and sensitivities.

2. The molecules

<u>H_2CO</u>: Formaldehyde (H_2CO) has proven to be a reliable density and kinetic temperature probe for galactic molecular clouds. Being a slightly asymmetric rotor, most rotational levels are split into two states. This splitting leads to two types of transitions, the high frequency (often mm-wave) $\Delta J = 1$ rotational and the lower frequency (often cm-wave) $\Delta J = 0$ K-doublet lines, which connect the two states of a split rotational level (J: total angular momentum quantum number, K: projection of J on the molecular axis). The K-doublet lines have a unique property. For $n(H_2) \lesssim 10^5 \, cm^{-3}$, the lower energy

states of the $J_{K_a K_c} = 1_{10} \rightarrow 1_{11}$ to $5_{14} \rightarrow 5_{15}$ K-doublet transitions become overpopulated due to a collisional selection effect (Evans *et al.* 1975) and are therefore seen in absorption even against the microwave background. At higher densities, the lines get thermalized and are seen in emission. Measurements of these K-doublet lines as well as of rotational lines within a K_a-ladder are good measures of density (if T_{kin} is known), with the collisional selection effect providing an important additional constraint. A comparison of ortho- or para-H_2CO lines from different K_a-ladders leads instead to a determination of kinetic temperature, which does not require any a priori knowledge of density.

<u>NH_3</u>: NH_3, a symmetric rotor, shows (like H_2CO) split rotational levels in the $K>0$ ladders. In this case it is due to the quantum mechanical tunneling of the nitrogen atom through the plane of the three hydrogen atoms. Most transitions connecting the two states of such inversion doublets are near $\lambda \sim 1\,\mathrm{cm}$ and cover a wide range of excitation. Metastable ($J{=}K$) levels of ortho- or para-NH_3 are connected via collisions. Thus their relative intensities provide good estimates of kinetic temperature, without requiring an a priori knowledge of the density. Complementing such data, non-metastable ($J{>}K$) transitions can be used to trace the infrared radiation field in star forming regions. For $n(H_2) \lesssim 10^7\,\mathrm{cm}^{-3}$, excitation temperatures remain low. However, in the presence of a strong infrared radiation field, level populations of the $(J,K) = (2,1)$ line (i.e., the line connecting the upper with the lower state in the $(2,1)$ inversion doublet) become inverted, providing a sensitive probe of the radiation environment (Morris *et al.* 1973).

## 3. Source selection and H_2CO measurements with the GBT

Our survey, initially using the Green Bank Telescope (GBT), includes 56 galaxies with $\delta > -40°$, $L_{\mathrm{IR}} > 10^9\,\mathrm{L}_\odot$, $L_{60\mu m} > 50\,\mathrm{Jy}$, and/or bright HCN and CO emission. The galaxies include nearby sources like NGC 253, IC 342, and M 82 at $D{\sim}3$–4 Mpc, but also much more distant (ultra)luminous infrared galaxies ((U)LIRGs) like Arp 220 or UGC 5101 at $D{\sim}70$ and 100 Mpc.

These sources were observed with the GBT in the 6 cm $1_{10} \rightarrow 1_{11}$ and the 2 cm $2_{11} \rightarrow 2_{12}$ K-doublet transitions. Early results were published by Mangum *et al.* (2008). Up to now, both transitions have been detected in a total of 13 galaxies, almost tripling the number of previously known such sources. Furthermore, 26 galaxies were detected in at least one of the two transitions. As indicated in Sect. 2, emission in either transition of this study indicates high spatial densities ($n(H_2) > 10^5\,\mathrm{cm}^{-3}$) as, e.g., seen toward IRAS 15107+0724 (Fig. 1, left panel). Absorption in both H_2CO transitions as seen in NGC 253 hints at lower densities.

Analyzing these data with a Large Velocity Gradient (LVG) model and assuming $T_{\mathrm{kin}} = T_{\mathrm{dust}} \sim 30$–40 K (values for (U)LIRGs tend to be slightly higher), as the kinetic temperature of the gas, it turns out that apparently higher mean densities are found in the (U)LIRGs, while lower mean densities prevail in the less luminous targets.

4. Ammonia (NH_3) measurements with the GBT

Our assumption of $T_{\mathrm{dust}} = T_{\mathrm{gas}}$ may not be correct. In environments energetically dominated by photons, X-rays, cosmic rays or turbulent heating, gas temperatures may significantly surpass dust temperatures, at least if densities are not exorbitantly high. Therefore, T_{kin} values from the gas phase are an essential parameter, not only to estimate densities from H_2CO, but also to evaluate previously taken data from the abundant linear molecules mentioned in Sect. 1.
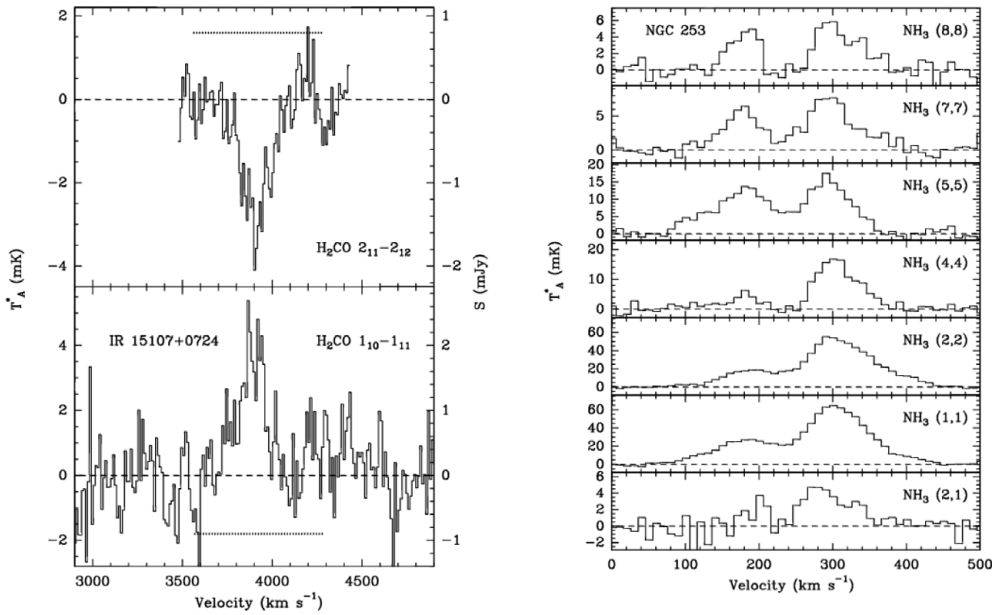
Figure 1. Left panel: 6 cm (lower spectrum) and 2 cm (upper spectrum) of H_2CO toward the ULIRG IRAS 15107+0724. Right panel: NH_3 lines observed toward the nearby starburst galaxy NGC 253. Note the detection of the non-metastable (2,1) inversion line.

With the GBT we can observe up to four NH_3 inversion lines simultaneously. Two optimized observing configurations allow for measurements of the metastable (1,1) to (7,7) and the non-metastable (2,1) transitions (the (8,8) and (9,9) lines were also measured in exceptional cases). The (7,7) line is ∼535 K above the ground state. 19 of the 26 galaxies detected in H_2CO have already been targeted, detecting at least the (1,1) and (2,2) lines in 12 objects (e.g., Fig. 1, right panel). For the first time, extragalactic ammonia has been detected in a non-metastable inversion doublet. The (2,1) line is seen toward five sources. Derived T_{kin} values surpass T_{dust} values in many sources, in particular in those with high infrared luminosities. As a consequence, the correlation between density and L_{IR}, suggested in Sect. 2 by assuming $T_{dust} = T_{kin}$, does not hold any more. Densities of the bulk of the molecular gas cover the rather small range $10^{4.5}$ cm^{-3} < $n(H_2)$ < $10^{5.5}$ cm^{-3}. This implies that *the Schmidt-Kennicutt relation between L_{IR} and M_{dense}, the mass of the dense gas, is (1) an indication of the dense gas mass reservoir available to form stars*, and *(2) is not directly dependent upon a higher average density driving the star formation process in the most luminous starburst galaxies.*

5. Occam's Razor and High Resolution Measurements

Using the simplest possible interpretation, we have so far relied on beam averaged quantities. While such an approach is reasonable for first order estimates, it ignores the potential impact of masers, distorting the picture outlined above. This holds in particular for H_2CO, where Baan *et al.* (1986) proposed 6 cm maser emission in the case of Arp 220, but also for NH_3, where Ott *et al.* (2005) and Lebrón *et al.* (2011) discuss tentatively detected extragalactic (3,3) and (6,6) masers.

With our LVG codes, all data could be successfully simulated without having to adopt population inversion. However, GBT data alone do not provide a tool to discriminate safely between quasi-thermal and maser emission. With the VLA, it will be possible, (1)

to reject or to confirm the presence of masers in individual sources and (2) to reveal spatial fine structure. First data are presently being collected.

6. Outline

While the project is still far from completion, the steps necessary to derive the densities and kinetic temperatures in the nuclear regions of active galaxies are quite clear. There are seven major steps:

- Measurements of the 6 and 2 cm H_2CO lines with the GBT
- Observations of eight NH_3 transitions with the GBT
- Follow-up measurements of the galaxies detected in H_2CO with the VLA
- Follow-up measurements of the galaxies detected in NH_3 with the VLA
- Measurements of rotational H_2CO lines to determine densities with IRAM/ALMA
- Determinations of kinetic temperatures through H_2CO observations with ALMA
- Apply the gained knowledge on kinetic temperatures also to data from other molecules

While the first four steps have already been explained above, we have also carried out IRAM 30-m measurements of rotational transitions of H_2CO toward a couple of galaxies. It is worthwhile to note that H_2CO is particularly useful, because its fractional abundance in molecular clouds does not vary strongly (e.g., Johnstone *et al.* 2003), so that H_2CO traces a representative fraction of the entire dense molecular gas phase. In view of this unique advantage, which is not shared by NH_3, it would be highly desirable to also determine kinetic temperatures from H_2CO for a large number of galaxies. This has not been done so far. While Mühle *et al.* (2007) presented a pioneering study of M 82, observing the $K_a = 0$ and 2 triplet near 218 GHz, extreme sensitivities are required for almost all other targets. The Atacama Large Millimeter/Submillimeter Array (ALMA) has the required collecting area to perform such measurements. We then would have reliable density and kinetic temperature estimates from a single tracer, which samples rather evenly the molecular gas phase. Using the resulting kinetic temperatures, density estimates could then also be deduced from other molecules like those mentioned earlier (see Sect. 1). Note, however, that $n(H_2)$ and T_{kin} derived from just one very representative species, namely H_2CO, would likely continue to provide the most valuable estimates of these important physical parameters.

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