Dense Gas Thermometry of Starburst Galaxies

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1 Scientific Justification

Studies of the distribution of CO emission in external galaxies have pointed to the presence of large quantities of dense molecular material, yielding a detailed picture of the molecular gas in many galaxies. CO, like many linear molecules, is limited as a probe of the physical conditions that give rise to star formation due to high optical depth and coupled sensitivity to kinetic temperature and volume density, making it impossible to disentangle changes in these physical conditions. Specific information about the individual physical conditions in these regions requires a molecular tracer which possesses singular sensitivity to either volume density or kinetic temperature.

Results from a survey of mainly nearby galaxies measured using the Green Bank Telescope (GBT; Mangum *et al.*, 2008, 2013a) and the Very Large Array (VLA; Mangum *et al.*, 2014) have shown that Formaldehyde (H_2CO) is a reliable and accurate density probe for extragalactic environments *where the kinetic temperature is known.* Our derivation of n(H_2) in a sample of starburst galaxies currently relies upon kinetic temperatures either assumed to be equivalent to the dust temperature, or derived from measurements of the NH_3 emission in these galaxies. Unknown, though, are the vaguarities of the relative abundance distributions of H_2CO and NH_3. As the NH_3 emission distribution is known to vary substantially in at least one starburst galaxy (M 82; Weiß *et al.*, 2001), while the H_2CO abundance in both galactic and extragalactic star formation regions is remarkably constant (Mangum *et al.*, 2013a), inconsistencies between the emission distribution of H_2CO and NH_3 could make their direct comparison problematic.

One can avoid issues of cospatiality between dense gas tracers by using the same molecule to effect all physical condition measurements. Using the unique sensitivities to kinetic temperature afforded by the excitation characteristics of several transitions of H_2CO, we propose to continue our characterization of the dense gas in galaxies by imaging the gas kinetic temperature in a representative pilot sample of three starburst systems: Arp 220, NGC 253, and NGC 4945. Imaging the kinetic temperature in starburst galaxies will allow us to measure the energetics that occur in these systems. Together with the known density, we will obtain the gas thermal pressure and its spatial variation. Furthermore, the kinetic temperature can be used to rigorously test predictions made by theoretical models and numerical simulations of merging galaxies.

1.1 Formaldehyde as a Volume Density and Kinetic Temperature Probe

Formaldehyde (H_2CO) is a proven tracer of the high density environs of molecular clouds. Because H_2CO is a slightly asymmetric rotor molecule, each rotational energy level is split by this asymmetry into two energy levels. This splitting leads to two basic types of transitions: the high-frequency $\Delta J = 1$, $\Delta K_{-1} = 0$, $\Delta K_{+1} = -1$ "P-branch" transitions and the lower-frequency $\Delta J = 0$, $\Delta K_{-1} = 0$, $\Delta K_{+1} = \pm 1$ "Q-branch" transitions, popularly known as the "K-doublet" transitions. The P-branch transitions are only observed in emission in regions where n(H_2) $\geq 10^4$ cm^{-3}. The K-doublet transitions are observed in absorption for n(H_2) $\lesssim 10^5$ cm^{-3} and in emission for n(H_2) $\geq 10^{5.0-6.0}$ cm^{-3}, driven by a collisional cooling effect (Evans *et al.* (1975)). Using the fact that H_2CO is a slightly asymmetric rotor molecule, one can compare appropriate energy levels to measure the volume density or kinetic temperature in star formation environments using the following formula:

Volume Density: Compare two ΔJ=0 or 1 transitions from the same K-ladder, with an assumed kinetic temperature. For example, the $\frac{2_{11}-2_{12}}{1_{10}-1_{11}}$, $\frac{2_{12}-1_{11}}{2_{11}-1_{10}}$, and $\frac{3_{13}-2_{12}}{3_{12}-2_{11}}$ ratios should be reliable monitors of the volume density (*e.g.* Mangum *et al.*, 2008, 2013a).

Kinetic Temperature: Compare the same ΔJ=1 transitions from different K-ladders within the same symmetry species (ortho or para; *e.g.* Mangum & Wootten, 1993). For example, the $\frac{3_{03}-2_{02}}{3_{22}-2_{21}}$, $\frac{3_{03}-2_{02}}{3_{21}-2_{20}}$, $\frac{5_{15}-4_{14}}{5_{33}-4_{32}}$, $\frac{5_{05}-4_{04}}{5_{24}-4_{23}}$, and $\frac{5_{24}-4_{23}}{5_{42}-4_{41}}$ ratios should be reliable monitors of the kinetic temperature.

Table 1: H_2CO Transition Properties

Trans	Freq (MHz)	E_{upper} (K)	Spec Window	Trans	Freq (GHz)	E_{upper} (K)	Spec Window
Band 6				Band 7			
$3_{03}-2_{02}$	218.222192	21.0	B6–1	$5_{15}-4_{14}$	351.768645	62.5	B7–1
$3_{22}-2_{21}$	218.475632	68.2	B6–2	$5_{05}-4_{04}$	362.736048	52.3	B7–2
$3_{21}-2_{20}$	218.760066	68.2	B6–3	$5_{24}-4_{23}$	363.945894	99.5	B7–2
				$5_{42}-4_{41}$	364.103249	240.7	B7–2
				$5_{41}-4_{40}$	364.103249	240.7	B7–2
				$5_{33}-4_{32}$	364.275141	158.4	B7–3
				$5_{32}-4_{31}$	364.288884	158.4	B7–3
				$5_{23}-4_{22}$	365.363428	99.7	B7–3

Figure 1 shows two representative examples of kinetic temperature-sensitive H_2CO transition ratios which exhibit the kinetic temperature measuring capabilities of formaldehyde. Both transition ratios measure T_K to better than 10% for $T_K \lesssim 100$ and 25% for higher T_K over a reasonable range of volume density and H_2CO column density. Clearly the measurement of these H_2CO transitions results in a very accurate *measurement* of the kinetic temperature in the dense material feeding starburst galaxies.

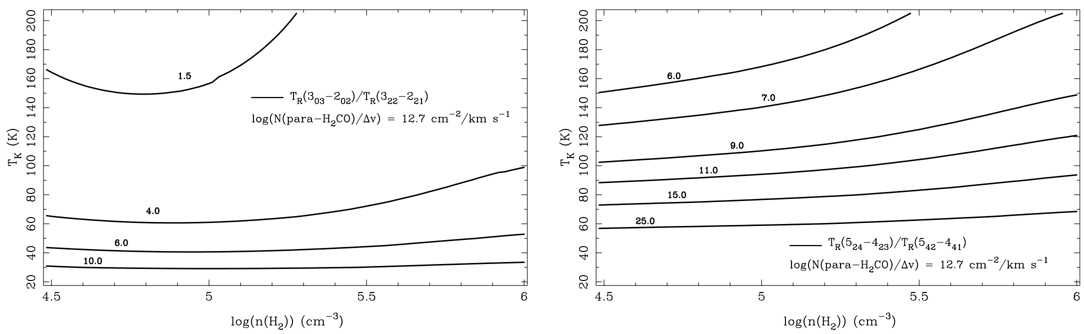

Figure 1: LVG-modelled kinetic temperature sensitivity for the H_2CO $\frac{3_{03}-2_{02}}{3_{22}-2_{21}}$ (left; sensitive to $T_K \lesssim 50$ K) and $\frac{5_{24}-4_{23}}{5_{42}-4_{41}}$ (right; sensitive to $T_K \lesssim 150$ K) transition ratios for the representative H_2CO column density indicated.

The Large Velocity Gradient (LVG) models presented above assume uniform (n,N,T_K). As it is likely that a range of kinetic temperatures which vary as functions of position and velocity are present in starburst galaxies, we require sensitivity to a range of kinetic temperatures. To effect this wide-ranging kinetic temperature sensitivity we have designed our experiment to sample a range of H_2CO excitation from $E_u =$ 21 to 241 K (see Table 1). This range of H_2CO excitation, combined with fortuitous placement of many of the H_2CO transitions within Bands 6 and 7, allows for simultaneous measurement of the three Band 6 and eight Band 7 transitions, for a total of 2 and 6 temperature-sensitive transition ratios. This measurement simultaneity also minimizes or eliminates many systematic errors in our kinetic temperature measurements. This experiment will allow us to spatially and spectrally characterize the dense gas kinetic temperature within starburst galaxies. Previous H_2CO measurements used in support of the technical justification for this proposal are summarized in Figure 2.

1.2 Starburst Galaxy Volume Density and Kinetic Temperature

Mangum *et al*. (2008, 2013a) have used the Green Bank Telescope (GBT) to survey the H_2CO emission and absorption toward 56 galaxies with δ(J2000) > -40 and $L_{IR} > 10^9 L_\odot$, of which 24 have been detected to-date. These 24 H_2CO-detected galaxies span a wide range in distance, from 3 (IC 342) to 158 (UCG 5101) Mpc, and L_{IR}, from $10^{10} L_\odot$ (M 83) to $2\times10^{12} L_\odot$ (Arp 220). High-resolution follow-up H_2CO measurements of 12 galaxies from our GBT H_2CO survey have been imaged using the VLA (Mangum *et al*., 2014), providing a measure of the *density structure* in these objects.

For the 13 galaxies from our GBT survey where both H_2CO $1_{10}-1_{11}$ and $2_{11}-2_{12}$ transitions were detected a LVG model has been used to derive, with an NH_3-derived kinetic temperature (Mangum *et al*., 2013b), the volume density and the H_2CO column density of the gas. This starburst galaxy K-doublet H_2CO survey has *measured* (for the first time) average volume densities in the range $10^{4.5}$ – $10^{5.7}$ cm^{-3}. The main conclusion drawn from these volume density measurements is that the correlation between L_{IR}

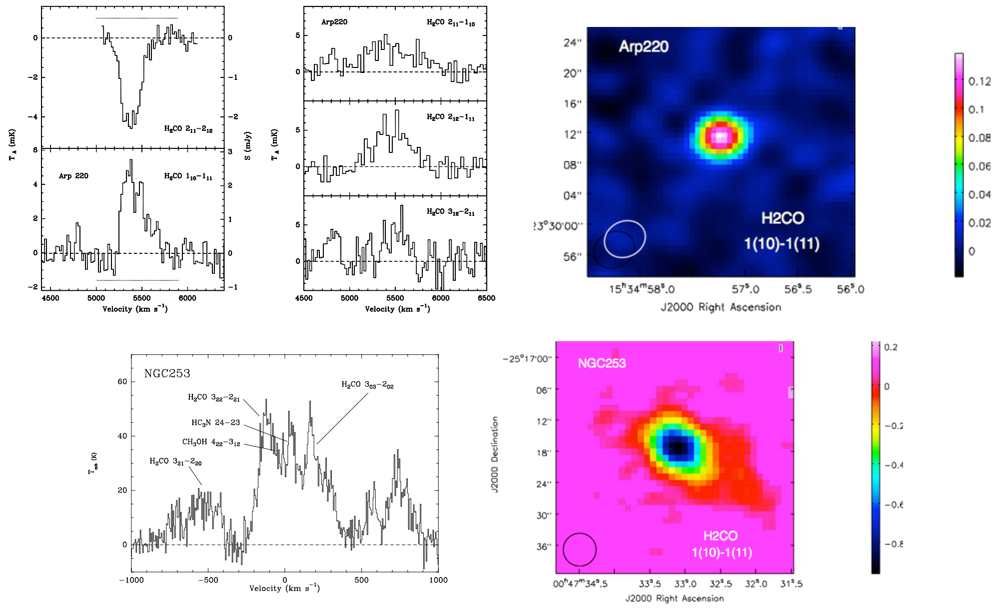

Figure 2: Top: GBT (left; θ_B = 51 and 153 arcsec), IRAM 30m (middle; θ_B = 11 to 20 arcsec), and VLA (right; θ_B = 6 arcsec with intensity scale Jy/beam*km/s) measurements of the H_2CO emission toward Arp 220. Bottom: IRAM 30m (left) and VLA (right) measurements of the H_2CO emission toward NGC 253. All of these H_2CO transitions have peak intensities > 4 mK.

and M_{dense} (the Schmidt-Kennicutt relation): (1) Is a measure of the dense gas mass reservoir available to form stars and (2) Is independent of the average density within the gas forming stars in all starburst galaxies. The conclusions of our study of the dense gas physical conditions in starburst galaxies are limited by an uncertain to poor understanding of the kinetic temperature in these systems. For example, within many of the starburst galaxies in our sample in which we have obtained NH_3 measurements, a range of T_K from 20 K to > 100 K spanning multiple galaxy components have been derived. This suggests that measurements of the dense gas kinetic temperature *structure* within starburst galaxies are essential to our understanding of the physical structure of these systems. *With the technique we have outlined in this proposal it will be possible, for the first time, to accurately measure the kinetic temperature structure within starburst galaxies.*

1.3 The Starburst Galaxies Arp 220, NGC 253, and NGC 4945

We have chosen three representative starburst systems within which to test our kinetic temperature imaging technique. All three systems are predicted to have detectable H_2CO emission at > 5 : 1 S/N (S(peak) > 4 mJy/beam) over 10's of pc to kpc spatial scales. The kinetic temperatures within these structures will be well-matched to the range of kinetic temperatures to which our experiment will be sensitive. H_2CO intensity predictions are detailed in the Technical Justifications for each of our Science Goals.

Arp 220: Past studies of the molecular emission in the young merger system Arp 220 have noted the existence of two spatial/velocity components, associated with two nuclei embedded within a circumnuclear ring or disk (Scoville *et al.*, 1997; Downes & Solomon, 1998). Greve *et al.* (2007) point to a dichotomy in the relative excitation of HCN and CO within the two nuclei, with the western/eastern component possessing lower/higher volume densities. Recent Herschel-SPIRE measurements of high-excitation transitions from molecular species including CO and HCN (Rangwala *et al.*, 2011) have measured a warm gas component within Arp 220. As all of these measurements failed to spatially and/or spectrally resolve the source(s) of the purported low/high density or hot gas, the origin of these physical structures remains poorly defined.

NGC 253: The early-stage starburst NGC 253 has been imaged in numerous molecular tracers (see summary in Mangum *et al.* (2013b)). Most of these measurements are able to spectrally, and in the case of imaging measurements spatially resolve the dense gas emission into two distinct velocity components: a north-east (NE) component at $v \simeq 180\,\mathrm{km\,s^{-1}}$ and a south-west (SW) component at $v \simeq 300\,\mathrm{km\,s^{-1}}$. NH_3 single-dish ((1,1) through (9,9) transitions Mangum *et al.*, 2013b) and VLA imaging ((3,3) Lebrón *et al.*, 2011) arise from dense gas structures $\lesssim 30''$ in extent with a range of kinetic temperatures from 38 to > 150 K. The spatial structure associated with these multiple kinetic temperature components is unknown.

NGC 4945: The dense gas in the relatively nearby (d $\simeq$ 3.8 Mpc) and evolved starburst galaxy NGC 4945 has been measured in CO and its isotopomers (Chou *et al.*, 2007), HCN, HCO^+, and HNC 1−0 (Cunningham & Whiteoak, 2005). These single-dish maps and interferometric images reveal dense gas structures with sizes ranging from 10 to 30″, including a compact ring-like structure. Other than assuming that the peak brightness temperature measured in CO $2-1$ of ~ 30 K is a proxy for the kinetic temperature in the dense gas, there are no bona-fide dense gas kinetic temperature measurements toward NGC 4945.

The existence of a warm, dense gas phase may have far-reaching consequences for our understanding of star formation and galaxy evolution in local and high-redshift starburst galaxies. According to hydrodynamical simulations, star formation from even moderately warm gas ($T_K \sim 100$ K) results in a top-heavy initial mass function (IMF; Klessen *et al.*, 2007). As noted by Krumholz *et al.* (2010); Hocuk & Spaans (2011), simultaneous measurements of temperature and density yield a measure of the local Jeans mass ($M_J \sim T^{3/2}\rho^{-1/2}$), which sets the fragmentation scale of gravitationally unstable gas clouds. Furthermore, combined temperature and density data allow one assess the equation of state as $T(\rho) \sim \rho^{\gamma-1}$, *i.e.*, $P \sim \rho T \sim \rho^{\gamma}$ for the polytropic exponent γ. Both M_J and γ have been found in numerical simulations to be essential thermodynamic elements in what shapes both the slope and characteristic mass of the IMF. Furthermore, recent theoretical studies of the environment in starburst galaxies suggest that PDR or CRDR (photon or cosmic ray dominated regions) could enhance the average kinetic temperature to extremely high values ($T_K > 80$ K in CRDRs; *e.g.* Papadopoulos, 2010). Also, the contribution due to mechanical heating (Meijerink *et al.*, 2011), such as that produced by supernovae within an environment where the star formation rate is $\gtrsim 100\,M_\odot\,yr^{-1}$ (*i.e.*, Arp 220), is clearly an important potential source of heating in starburst galaxies.

1.4 The MasTER Collaboration

All of the investigators on this proposal are part of the MasTER (Molecules as Tools for Extragalactic Research) collaboration. This collaboration coordinates theoretical and observational efforts with the specific aim to address issues of star formation and AGN activity in extragalactic environments.

2 Potential for Publicity

The results of these measurements will produce a detailed image of the kinetic temperature structure on ~ 120 pc scales within the Arp 220 merger and on ~ 40 pc scales within the NGC 253 young starburst and the NGC 4945 evolved starburst galaxies. The general public can relate to how environment affects the star formation process in galaxies, or how the "cradle" influences the type of "offspring" produced in galaxies.

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