Molecular gas in active environments

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Abstract. The question whether or not the initial mass function (IMF) is universal, i.e. the same in all kinds of environments, is subject to intense debate. A number of recent observations have been interpreted as evidence for a nonstandard IMF. Hydrodynamical simulations indicate that the kinetic temperature of the collapsing molecular gas is crucial for the shape of the resulting IMF. Unfortunately, the kinetic temperature of the molecular gas in external galaxies is often not well constrained. We demonstrate the diagnostic power of a selected set of paraformaldehyde lines as tracers of the kinetic temperature as well as the gas density in external galaxies using our non-LTE radiative transfer model. With this new observational tool, we have engaged in characterizing the properties of the dense molecular gas phase in a number of nearby starburst galaxies and near AGN. Our first results suggest the existence of a dense molecular gas phase in these active environments that is significantly warmer than the dust and much warmer than dense molecular gas found in the disk of our own Galaxy.

1. Introduction

Star formation and its feedback are among the most fundamental processes that shape the evolution of galaxies throughout the universe. In the disk of our own Galaxy, groups of stars form out of dense molecular gas that is cold ($T \sim 10 - 30 \text{ K}$) and the stellar initial mass function (IMF) can generally be described by a power-law with a Salpeter index ($\Gamma = 1.35$) for masses above a few solar masses. Whether this so-called “standard IMF” is universal is a matter of intense debate (see Bastian et al. 2010 for a review). Non-canonical, usually top-heavy, IMFs have been suggested for a range of objects, including the stellar disks in the Galactic Center (Bartko et al. 2010), disturbed galaxies (Habergham et al. 2010) and ultra-compact dwarf galaxies (Dabringhausen et al. 2009). In hydrodynamic simulations of the influence of star formation feedback and other environmental parameters on the IMF, the temperature of the collapsing molecular gas plays a key role in the fragmentation process, thus influencing the shape of the IMF (Klessen et al. 2007, Krumholz et al. 2010). Unfortunately, the temperature of the molecular gas outside of our own Galaxy is usually not well constrained. Observational evidence is growing, though, that a significant fraction of the molecular gas in starburst galaxies and near AGN may be warm, with kinetic temperatures of 100 K and more (Rigopoulou et al. 2002, Mauersberger et al. 2003, Krips et al. 2011), sufficient to yield a top-heavy IMF. Possible heating sources of the molecular gas, even down to the densest cores, include intense UV and X-ray radiation, cosmic rays and me-
Figure 1. The lowest energy levels of ortho- and paraformaldehyde, adapted from Mangum & Wootten 1993. The selected para-H$_2$CO transitions at 218 GHz and 146 GHz are marked by ellipses in red and blue, respectively.

Mechanical heating (Hocuk & Spaans 2010, Krumholz et al. 2010, Papadopoulos 2010, Meijerrink et al. 2011). In starburst galaxies, the conversion factor between the CO(1-0) line intensity and the H$_2$ column density has been found to be up to an order of magnitude smaller than the Galactic conversion factor (Downes & Solomon 1998). Thus, the properties of the molecular gas in active environments with strong feedback in form of shocks, intense radiation and/or cosmic ray emission seem to differ significantly from the properties of the molecular gas in the Galactic disk.

Given the important influence of the kinetic temperature of the star-forming molecular gas on the IMF, we have developed a new method for deriving the key properties of the dominant phase of the molecular gas in external galaxies. Here we present this new method and discuss the first results of our survey of nearby active environments.

2. Tracing the properties of extragalactic molecular gas

The diagnostic power of many commonly observed gas tracers like HCN or HCO$^+$ suffers from a degeneracy between the kinetic temperature and the gas density in the model analysis, i.e. the intensity ratios of the observed lines are good density tracers, but only if the kinetic temperature is known. The easily thermalized CO(1 $\rightarrow$ 0) and CO(2 $\rightarrow$ 1) transitions could act as a temperature tracer, but unfortunately, the filling factor of extragalactic clouds is not well constrained. In contrast, the rich millimeter and submillimeter spectrum of formaldehyde H$_2$CO (Fig. 1) offers tracers of both temperature and density: line ratios involving different $K_a$ ladders are sensitive to the kinetic temperature, whereas ratios of lines of the same $K_a$ ladder form excellent density tracers, once the temperature is derived (Mangum & Wootten 1993). On the
other hand, the spectrum of formaldehyde is not so rich that many different transition would be blended into one broad feature in extragalactic observations. In addition, the abundance of H$_2$CO has been found to change only within one order of magnitude in a variety of Galactic environments (Johnstone et al. 2003), whereas the abundance of ammonia, the “standard cloud thermometer”, can vary by three orders of magnitude (Benson & Myers 1983, Mauersberger et al. 1987).

Because of these excellent diagnostic properties of formaldehyde, we selected three para-formaldehyde lines as molecular gas tracers in external galaxies: H$_2$CO(3$_03$ → 2$_02$) at 218.22 GHz, H$_2$CO(3$_21$ → 2$_20$) at 218.76 GHz and H$_2$CO(2$_02$ → 1$_01$) at 145.60 GHz. The paraformaldehyde lines at 218 GHz are particularly valuable from a diagnostic point of view. Within 1 GHz, i.e. usually within the same low frequency resolution spectrum, there are the three para-H$_2$CO transitions 3$_03$ → 2$_02$ (218.22 GHz), 3$_22$ → 2$_21$ (218.48 GHz) and 3$_21$ → 2$_20$ (218.76 GHz). While the H$_2$CO(3$_22$ → 2$_21$) line may be contaminated by methanol emission, the intensity ratio of the other two lines forms an excellent temperature tracer, without any uncertainty due to calibration issues, pointing errors or different beam widths. The set of diagnostic lines is completed by H$_2$CO(2$_02$ → 1$_01$) at 145.60 GHz, an easily detectable line that together with H$_2$CO(3$_03$ → 2$_02$) forms a sensitive density tracer.

3. The analysis of the diagnostic lines
As the upper levels of all the selected para-formaldehyde transitions lie below 70 K, the excitation conditions are similar for all lines. Therefore, it is reasonable to assume that the emission of all H$_2$CO lines originates from the same volume. This in turn implies that the lines have the same velocity profile, thus considerably reducing the number of free parameters in the derivation of the line intensities. If the line profiles are approximated by Gaussian curves, the velocity and width of all lines should be the same, leaving the peak intensity as the only free parameter. By thus fixing the velocity and the width of the common line profile with the help of a strong line, even the intensities of weak or slightly blended lines can be derived with high reliability.

When the ratios of the observed line intensities are compared with the predicted line ratios of a model, the physical properties of the gas like the kinetic temperature and the average gas density within the molecular cloud complexes can be derived. For the analysis of the para-H$_2$CO lines, we have developed a non-LTE model with a spherically symmetric cloud geometry and adopted the LVG approximation. The searched parameter space covers a kinetic temperature of $T_{\text{kin}} = 5$ to 300 K in steps of 5 K, a molecular gas density of log $n_{\text{H}_2} = 3.0$ to 6.0 (in cm$^{-3}$) in steps of 0.1 and a para-H$_2$CO column density per velocity interval of log $N_{\text{pH}_2\text{CO}}/\Delta v = 10.5$ to 14.5 (in cm$^{-2}$ km$^{-1}$ s) in steps of 0.1 (see Mühle et al. 2007 for details).

4. First results
The first targets in our survey of the molecular gas properties in active environments were the nearby galaxies M 82 and NGC 253, which are both regarded as prototypical starburst galaxies, with high infrared luminosities, super-star clusters and a prominent galactic wind. Both galaxies are viewed at a high inclination and their dense molecular gas is concentrated around the nucleus. In M 82, though, the fractional abundances of a number of molecules differ strongly from those derived for NGC 253 and other local starburst galaxies, which has been explained as M 82 being in an evolved state of a starburst (Takano et al. 2002, Wang et al. 2004). Note that the massive star cluster M 82 F is to date the best candidate to host a top-heavy IMF (Bastian et al. 2010).
Figure 2. Positions of observed H$_2$CO emission in M 82 superposed on a high-resolution maps of the integrated CO(2 → 1) intensity from Weiß et al. (2001). The diameter of the red circles corresponds to the width of the beam of the IRAM 30-m telescope at 218 GHz.

Figure 3. Observed spectra of the NE (left) and the SW lobe (right) of M 82. Each spectrum is labeled with the frequency the receiver was tuned to. Thus, the velocity scale of the 218.48 GHz spectra refers to the H$_2$CO(3$_{22}$ → 2$_{21}$) line. The H$_2$CO(3$_{03}$ → 2$_{02}$) and the H$_2$CO(3$_{21}$ → 2$_{20}$) transitions are offset by 348 km s$^{-1}$ and −390 km s$^{-1}$, respectively, while the CH$_3$OH(4$_2$ → 3$_1$ E) line is offset by 49 km s$^{-1}$. In the 146 GHz spectra, the HC$_3$N(16 → 15) line is offset by 86 km s$^{-1}$ from the H$_2$CO(2$_{02}$ → 1$_{01}$) emission. The curves show the Gaussian fit to each individual line as well as the spectrum resulting from a superposition of all identified lines: a = H$_2$CO(2$_{02}$ → 1$_{01}$), b = HC$_3$N(16 → 15), c = H$_2$CO(3$_{21}$ → 2$_{20}$), d = H$_2$CO(3$_{22}$ → 2$_{21}$), e = CH$_3$OH(4$_2$ → 3$_1$ E), f = H$_2$CO(3$_{03}$ → 2$_{02}$).
Figure 4. Results of our LVG analysis for the SW lobe of M 82 shown as cuts through the 3-D parameter space ($T_{\text{kin}}$ in K, $n(H_2)$ in cm$^{-3}$, $N_{\text{pH}_2\text{CO}}/\Delta v$ in cm$^{-2}$ km$^{-1}$ s) along a plane of constant para-$H_2$CO column density per velocity interval (left) and of constant kinetic temperature (right). The lines represent the following line ratios: $H_2$CO($3_{03} \rightarrow 2_{02}$)/$H_2$CO($3_{21} \rightarrow 2_{20}$) (red), $H_2$CO($2_{02} \rightarrow 1_{01}$)/$H_2$CO($3_{03} \rightarrow 2_{02}$) (blue), $H_2$CO($2_{02} \rightarrow 1_{01}$)/$H_2$CO($3_{21} \rightarrow 2_{20}$) (green). The corresponding thin lines outline the uncertainties of each line ratio. The adopted source size is $\theta_s = 7''5$ and the assumed para-$H_2$CO abundance per velocity gradient is $\Lambda = 1 \times 10^{-9}$ km$^{-1}$ s pc.

In M 82, we observed the two lobes of the circumnuclear ring with the IRAM 30-m telescope both at 218 GHz and at 146 GHz to an rms noise level of 2 – 3 mK and 2 mK, respectively, at a velocity resolution of 10 km s$^{-1}$ (Fig. 2). All $H_2$CO transitions have been detected at both pointing positions (Fig. 3). At 145.60 GHz, the $H_2$CO($2_{02} \rightarrow 1_{01}$) line is slightly blended with the HC$_3$N($16 \rightarrow 15$) line. However, by applying the constraints discussed above when fitting Gaussian curves to the line profile, it is possible to derive the intensities of these lines with high confidence. In the 218.48 GHz spectrum of the northeastern (NE) lobe, the central line seems to be shifted compared to the frequency of that line in the southwestern (SW) lobe. This is most likely due to methanol emission from the NE lobe (see Mühle et al. 2007 for details).

The intensity ratios derived from the observed $H_2$CO lines are remarkably similar for the two lobes. Comparing these values to our LVG model, we derive a kinetic temperature of $T_{\text{kin}} \sim 200$ K and a gas density of $n(H_2) \sim 7 \cdot 10^3$ cm$^{-3}$ for a para-$H_2$CO abundance per velocity gradient of $X_{\text{pH}_2\text{CO}}/\text{grad}(v) = 1 \cdot 10^{-9}$ km$^{-1}$ s pc, and an assumed source size of $\theta_s = 7''5$ (Fig. 4). The mass of the molecular gas in the lobes is $\sim 3 \cdot 10^8 M_\odot$. These values are in very good agreement with the high-excitation molecular gas component of other recent molecular line studies, which also suggest that this component may constitute more than half of the total molecular gas mass in M 82 (Mao et al. 2000, Ward et al. 2003).

In NGC 253, we observed six positions along the major axis of the circumnuclear disk at 218 GHz and at 146 GHz with the IRAM 30-m telescope (Fig. 5). In all spectra, the rms noise level at a velocity resolution of 10 km s$^{-1}$ is a few milliKelvin. The $H_2$CO($2_{02} \rightarrow 1_{01}$) line at 145.60 GHz, again slightly blended with the HC$_3$N($16 \rightarrow 15$) line, has been detected at all pointing positions. The three $H_2$CO lines at 218 GHz have been detected towards the inner four positions, but not at the outermost positions, most likely due to the decrease of $H_2$CO emission towards the edge of the circumnuclear disk. As an example, the spectra observed towards the nucleus (offset (0/0) in Fig. 5) are shown in Fig. 6.

The line intensity ratios vary significantly along the major axis of the molecular disk in NGC 253, an indication for different physical properties of the dense molecular gas across the
Figure 5. Positions of observed H$_2$CO emission in NGC 253 superposed on a high-resolution map of the integrated CO($2 \rightarrow 1$) intensity from Sakamoto et al. (2006). The diameter of the red circles corresponds to the width of the beam of the IRAM 30-m telescope at 218 GHz. The beam width of the interferometric CO($2 \rightarrow 1$) observations is shown in the lower left corner.

NGC 253 – nucleus

Figure 6. Observed spectra of the nucleus of NGC253 (offset (0/0) in Fig. 5). Like in Fig. 3, each spectrum is labeled with the frequency the receiver was tuned to. The velocity scale of the 218.48 GHz spectrum refers to the H$_2$CO($3_{22} \rightarrow 2_{21}$) line. The H$_2$CO($3_{03} \rightarrow 2_{02}$) and the H$_2$CO($3_{21} \rightarrow 2_{20}$) transitions are offset by 348 km s$^{-1}$ and −390 km s$^{-1}$, respectively, while the CH$_3$OH($4_2 \rightarrow 3_1 E$) and the HC$_3$N($24 \rightarrow 23$) lines are offset by 49 km s$^{-1}$ and 207 km s$^{-1}$, respectively. In the 146 GHz spectrum, the HC$_3$N($16 \rightarrow 15$) line is offset by 86 km s$^{-1}$ from the H$_2$CO($2_{02} \rightarrow 1_{01}$) emission. The curves show the Gaussian fits to each individual line as well as the spectrum resulting from a superposition of all identified lines: a = H$_2$CO($2_{02} \rightarrow 1_{01}$), b = HC$_3$N($16 \rightarrow 15$), c = H$_2$CO($3_{21} \rightarrow 2_{20}$), d = H$_2$CO($3_{22} \rightarrow 2_{21}$), e = CH$_3$OH($4_2 \rightarrow 3_1 E$), f = H$_2$CO($3_{03} \rightarrow 2_{02}$), g = HC$_3$N($24 \rightarrow 23$). Note the strong HC$_3$N emission in the nucleus of NGC 253 compared to its small contribution to the spectra of M 82 (Fig. 3).
galactic core region. Unlike in M 82, there is strong HC$_3$N emission at both 146 GHz and at 218 GHz, most pronounced at the nucleus (Fig. 6). A preliminary LVG analysis of the line ratios derived for the different positions in NGC 253 yields kinetic temperatures of $T_{\text{kin}} \sim 70 \ldots 150$ K and gas densities of $n_{\text{H}_2} \sim 10^4$ cm$^{-3}$ for a para-H$_2$CO abundance per velocity gradient of $X_{\text{para-H}_2CO}/\text{grad}(v) = 1 \cdot 10^{-9}$ km$^{-1}$ s pc, and an assumed source size of $\theta_s = 10^\prime$.

Thus, in both starburst galaxies, the dense molecular gas component traced by the para-formaldehyde lines is considerably warmer than the bulk of the dense molecular gas in our Galaxy and probably warm enough to give rise to a top-heavy IMF should this gas be turned into stars.

5. Conclusions and outlook
Selected H$_2$CO lines can be powerful diagnostic tools for the derivation of key properties of the molecular gas in external galaxies. Para-H$_2$CO lines up to $K_a = 2$ can be detected in nearby starburst galaxies, providing a direct measure the the kinetic temperature of the molecular gas within one spectrum. The first results of our survey support the view that a considerable fraction of the dense molecular gas in starburst galaxies is significantly warmer than the dense molecular gas in quiescent galaxies, possibly giving rise to a nonstandard IMF in active environments.

However, the survey of the properties of dense molecular gas in active extragalactic environments is still in an early phase and many questions about the extent of the warm gas phase and the environments where it can be found are still to be investigated. The boost in sensitivity that ALMA will provide will make the para-H$_2$CO lines readily detectable in a variety of external galaxies. At the same time, ALMA will offer an unprecedented angular resolution, which will allow us to resolve the distribution and temperature gradients of the warm molecular gas phase in nearby galaxies and to relate them to the different possible heating sources.

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