FORMALDEHYDE AS A TRACER OF EXTRAGALACTIC MOLECULAR GAS. I.
PARA-H$_2$CO EMISSION FROM M82

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ABSTRACT

Using the IRAM 30 m telescope and the 15 m JCMT, we explore the value of paraformaldehyde (p-H$_2$CO) as a tracer of density and temperature of the molecular gas in external galaxies. The target of our observations are the lobes of the molecular ring around the center of the nearby prototypical starburst galaxy M82. It is shown that p-H$_2$CO provides one of the rare direct molecular thermometers. Reproducing the measured line intensities with a large velocity gradient (LVG) model, we find densities of $n_{H_2} \sim 7 \times 10^3$ cm$^{-3}$ and kinetic temperatures of $T_{kin} \sim 200$ K. The derived kinetic temperature is significantly higher than the dust temperature or the temperature deduced from ammonia (NH$_3$) lines, but our results agree well with the properties of the high-excitation component seen in CO. We also present the serendipitous discovery of the $4_2 \rightarrow 3_1$ line of methanol (CH$_3$OH) in the northeastern lobe, which shows— unlike CO and H$_2$CO—significantly different line intensities in the two lobes.

Subject headings: galaxies: individual (M82) --- galaxies: ISM --- galaxies: starburst --- ISM: molecules --- radio lines: ISM --- submillimeter

Online material: color figures

1. INTRODUCTION

Molecular gas is regarded as the fuel for star formation. Increasing evidence for nonstandard initial mass functions (e.g., Paumard et al. 2006; Klessen et al. 2007) and warm molecular gas in starburst galaxies (e.g., Rigopoulou et al. 2002; Mauersberger et al. 2003) suggest that its physical properties may influence the star formation rate and the properties of the next generation of stars. Unfortunately, the physical properties of the molecular gas in external galaxies, in particular the kinetic temperature, are often not well constrained. The easily thermalized and optically thick CO and H$_2$CO transitions could constitute a good temperature tracer, but the filling factor of extragalactic clouds is poorly constrained. Other commonly observed molecules like HCN and HCO$^+$ are good density tracers, but require an a priori knowledge of the kinetic temperature. The inversion lines of the symmetric top molecule ammonia (NH$_3$) are frequently used as the galactic “standard cloud thermometer.” However, in the disk of the Milky Way, the fractional abundance of NH$_3$ varies between $10^{-5}$ in hot cores (Mauersberger et al. 1987) and $10^{-3}$ in dark clouds (Benson & Myers 1983). Thus, ammonia may preferentially trace a specific component of the molecular gas and the assumption of an approximately constant fractional abundance on linear scales of a few 100 pc is likely not valid. Other symmetric or slightly asymmetric top molecules may therefore be more favorable for extragalactic line studies.

1.1. Formaldehyde as a Molecular Gas Tracer

In this paper, we investigate the diagnostic properties of paraformaldehyde (p-H$_2$CO) lines in extragalactic sources. Formaldehyde is formed on the surface of dust grains by successive hydrogenation of CO (Watanabe & Kouchi 2002), released into the gas phase by shocks or UV heating, and subsequently destroyed by gas-phase processes. Variations in fractional abundance rarely exceed one order of magnitude. Johnstone et al. (2003) found only little variation in a variety of galactic environments ranging from cool protostellar candidates to hot photon-dominated regions and infrared sources, with the latter showing the highest discrepancy, by a factor of 5–10. These higher abundances are likely caused by the release of H$_2$CO molecules from grain surfaces in regions of massive star formation. As another example for the level of variability in the abundance of formaldehyde versus that of ammonia in active environments, the H$_2$CO abundance is the same in the hot core and the compact ridge of Orion A, whereas the NH$_3$ abundance in the core is two orders of magnitude higher than that in the ridge (Charnley et al. 1992).

Paraformaldehyde, which is a subspecies of the slightly asymmetric top molecule H$_2$CO, has a rich millimeter and submillimeter spectrum of transitions. Since the relative populations of the $K_a$ ladders are generally governed by collisions, line ratios involving different $K_a$ ladders (interladder ratios) are generally good tracers of the kinetic temperature. With the temperature known, line ratios within a single $K_a$ ladder, the so-called intraladder ratios, whose populations are mainly determined by collisional excitation and radiative de-excitation, sensitively probe the gas density (Mangum & Wootten 1993). The $K$-doublet transitions of ortho-H$_2$CO in the centimeter range, $1_{10} \rightarrow 1_{11}$ at $\lambda = 6$ cm, and $2_{11} \rightarrow 2_{12}$ at $\lambda = 2$ cm, have been observed in a number of external galaxies since the 1970s (e.g., Gardner & Whiteoak 1974; Seaquist & Bell 1990). H$_2$CO lines in the millimeter range were detected in several galaxies including the LMC, M82, and NGC 253 since the 1990s (e.g., Baan et al. 1990; Johansson et al. 1994), but to date there are only three published studies of the

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1 Based on observations carried out with the IRAM 30 m telescope. IRAM is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain).
The target for our exploratory investigation is the nearby prototypical starburst galaxy M82. As the most prominent galaxy in the northern hemisphere with a nuclear starburst, M82 has been the target of numerous molecular line studies (e.g., Fuente et al. 2006; Seaquist et al. 2006). Most of the excitation studies focus on the central 1 kpc disk, where the molecular gas is concentrated in a circumnuclear ring around the center of the starburst (e.g., García-Burillo et al. 2002; Seaquist et al. 2006), with the more highly excited lines found at smaller radii (Fig. 1; see also Mao et al. 2000) for an overview of ring diameters. Note that the two lobes of the molecular ring in this highly inclined galaxy can be easily separated with single-dish telescopes and the observed molecular lines in the lobes have typical widths of only 100–150 km s$^{-1}$ (e.g., Seaquist et al. 1998; García-Burillo et al. 2002), thus greatly reducing the potential for line blending. The most comprehensive CO line studies to date (Mao et al. 2000; Ward et al. 2003) suggest that the broad database of CO and $^{13}$CO lines observed toward the molecular lobes of M82 cannot be fitted by a single-component large velocity gradient (LVG) model and that the majority of the molecular gas may actually be in a high-excitation state. The $^{12}$CO($1_{10} - 1_{11}$) transition at $\lambda = 6$ cm was detected toward the nucleus of M82 in absorption by Graham et al. (1978), whereas the $^{12}$CO($2_{11} - 2_{12}$) line at $\lambda = 2$ cm was observed in emission, which was interpreted as evidence for very dense ($10^6$ cm$^{-3}$) molecular gas in the circumnuclear ring (Baan et al. 1990). The latter study also reported the first detection of an $^{13}$CO emission line in the millimeter range in M82. A first simultaneous LVG excitation study toward M82 was performed by Hüttemeister et al. (1997, see also § 1.1) using an LVG model that included 16 ortho-$^{12}$CO levels of the $K_a = 1$ ladder.

1.3. Line Selection

Having developed a comprehensive LVG code for ortho-$^{12}$CO (40 levels) and para-$^{12}$CO (41 levels, see § 4.1), we searched for the set of transition lines best suited for extragalactic observations while trying to minimize observational uncertainties. The usually small filling factor of extragalactic observations and the decreased sensitivity of ground-based receivers at high frequencies limits the choice to the strongest lines, usually corresponding to transitions between low excitation levels. Among the $^{12}$CO lines that can be observed with present-day receivers, the para-$^{12}$CO transitions $3_{03} \rightarrow 2_{02}, 3_{22} \rightarrow 2_{11},$ and $3_{21} \rightarrow 2_{20}$ stand out by being close in frequency and at the same time strong enough for extragalactic observations. With rest frequencies at 218.22, 218.48, and 218.76 GHz, all three lines can be observed simultaneously, if the receiver and spectrometer both offer a bandwidth of 1 GHz. That way, the observed interladder line ratio $H_2CO(3_{03} \rightarrow 2_{02})/H_2CO(3_{21} \rightarrow 2_{20}),$ which is a good temperature tracer, will be free from uncertainties related to pointing accuracy, calibration issues or different beamwidths. Due to the large line widths of extragalactic observations (≥100 km s$^{-1}$), the $H_2CO(3_{22} \rightarrow 2_{21})$ line may be blended with methanol emission (see § 5) and thus be of limited use for the LVG analysis. At the very high densities (10$^6$ cm$^{-3}$; Baan et al. 1990) and kinetic temperatures of 50–100 K inferred for $H_2CO$ in M82, our LVG code suggests a line ratio $H_2CO(3_{21} \rightarrow 2_{20})/H_2CO(5_{24} \rightarrow 4_{23})$ of the order of unity. This ratio sensitively traces the gas density. In addition, observing the $H_2CO(3_{23} \rightarrow 2_{22})$ line with the IRAM 30 m telescope and the para-$H_2CO(5_{24} \rightarrow 4_{23})$ line with the 15 m dish of the James Clerk Maxwell Telescope (JCMT) results in data with nearly the same beamwidth (11" vs. 13") and thus minimizes the uncertainty inherent in line ratios derived from observations consisting of single pointings. Using a spectrometer with a bandwidth of at least 900 MHz, the $H_2CO(5_{24} \rightarrow 4_{23})$ transition at 363.95 GHz can be observed simultaneously with the weaker and heavily blended para-$H_2CO$ transitions $5_{22} \rightarrow 4_{21}$ and $5_{41} \rightarrow 4_{40}$ at 364.10 GHz, as well as with the blended ortho-$H_2CO$ transitions $5_{13} \rightarrow 4_{12}$ and $5_{22} \rightarrow 4_{11}$ at 364.28 GHz and 364.29 GHz, respectively. The nondetection of the $H_2CO(5_{24} \rightarrow 4_{23})$ line (see § 3) hinted at a much lower gas density regime than previously assumed and necessitated the addition of the relatively strong para-$H_2CO(2_{02} \rightarrow 1_{01})$ line at 145.60 GHz to the selected transitions in order to be able to derive the density-sensitive intraladder line ratio $H_2CO(2_{02} \rightarrow 1_{01})/H_2CO(3_{03} \rightarrow 2_{02}).$

Here we present the results of our para-$H_2CO$ observations. To our knowledge, this is the first dedicated search for para-$H_2CO$ transition lines of the $K_a = 2$ ladder outside of the Galactic neighborhood (Milky Way and Magellanic Clouds). The distribution of the $H_2CO$ emission and its correlation to other tracers will be discussed in a forthcoming paper based on high-resolution (~4\') ortho-$H_2CO$ data recently obtained with the Very Large Array (VLA). After a description of the observations and the data reduction strategy in § 2, we present the observational results in § 3. In § 4, we describe our LVG code and the parameter space covered, before we discuss our results and compare them to other molecular excitation studies. Finally, we report the serendipitous detection of methanol emission in one of the lobes (§ 5). Our conclusions are summarized in § 6.

2. OBSERVATIONS AND DATA REDUCTION

For this study, we selected the para-$H_2CO$ transitions described in § 1.3 to be observed at nearly the same spatial resolution with the IRAM 30 m telescope and the 15 m JCMT. The parameters of the observations are summarized in Table 1.

2.1. Observations with the IRAM 30 m Telescope

For the observations at 218 GHz, the IRAM 30 m telescope with the heterodyne receiver array HERA, consisting of nine
dual-polarization receivers arranged in the form of a center-filled square with a pixel separation of 24", was pointed toward the southwestern lobe (SW lobe) of M82 at α2000 = 09h55m49.4s, δ2000 = 69°40'43.1" during four nights in 2005 March/April. The derotator optical assembly was set to keep the pixel pattern stationary in equatorial coordinates at an angle of 20° clockwise relative to the axis of right ascension, so that the central row of pixels was aligned with the major axis of the molecular ring, with the two molecular lobes being covered by two adjacent pixels (Fig. 1) and the third pixel pointing at a position 24" southwest of the SW lobe. In this arrangement, the remaining pixels of the array pointed toward six positions 24" northwest and southeast of the major axis (Fig. 2). The spectra were obtained in a wobbler switching mode with a beam throw of 240" in azimuth. As back end, we used the WILMA autocorrelator, which provides a bandwidth of 1024 MHz (512 channels) in each of its two receiver channels, sufficient to cover simultaneously the para-H$_2$CO transitions (5 24 to 20), (3 22 to 21), and (3 21 to 20) transitions (see Table 1). Good winter weather conditions resulted in system temperatures during the four shifts varied from 200–400 K ($T_A$) and a pointing accuracy of 3" or better. The chopper wheel calibration was checked by observing the C$^{18}$O(2 1) line at 219.56 GHz toward the reference source CLIR 2688 and the relative stability of each tuning baseline was subtracted. The spectra at each position were then baseline were subtracted. The spectra at each position were then weighted according to their noise level, combined and smoothed for analysis using the GILDAS software package.

### Table 1

| Transition       | $\nu$ (GHz) | $\theta_a$ (arcsec) | rms $b$ (mK) |
|------------------|-------------|---------------------|---------------|
| H$_2$CO(201 $\rightarrow$ 100) p | 145.6029 | 17 | 1.9, 1.8 |
| H$_2$CO(301 $\rightarrow$ 200) p | 218.2222 | 11 | 2.7, 2.4 |
| H$_2$CO(321 $\rightarrow$ 210) p | 218.4756 | 11 | 2.7, 2.4 |
| H$_2$CO(322 $\rightarrow$ 211) p | 218.7601 | 11 | 2.7, 2.4 |
| H$_2$CO(212 $\rightarrow$ 101) p | 363.9459 | 13 | 5.4, N/A |
| H$_2$CO(222 $\rightarrow$ 111) p | 364.1032 | 13 | 5.4, N/A |
| H$_2$CO(312 $\rightarrow$ 211) o | 364.2751 | 13 | 5.4, N/A |
| H$_2$CO(323 $\rightarrow$ 212) o | 364.2899 | 13 | 5.4, N/A |

Note.—Para-H$_2$CO is indicated by the letter p, and ortho-H$_2$CO is indicated by the letter o.

$^a$ Half power beamwidth (FWHM).

$^b$ The rms in $T_A$ at 10 km s$^{-1}$ resolution at the positions of the SW lobe and the NE lobe, respectively.

### Figure 2

- Contours of the velocity-integrated SiO ($v = 0$, $J = 2 - 1$) emission superposed on a radio continuum emission image at 4.8 GHz, adapted from García-Burillo et al. (2001). Map offsets are relative to the dynamical center of the galaxy ($\alpha_{2000} = 09h55m51.9s$, $\delta_{2000} = 69°40'47.1"$). The large circle delimits the primary beam field of the SiO interferometric observations at 87 GHz (55°), while the synthesized beam is shown in the bottom left corner. The white square marks the position of SNR 441.95+57.5. The radio continuum filament is indicated by an arrow. The pointing positions observed with the HERA array and the beamwidth of 11" are marked by the gray and black solid circles, where the gray circles cover the molecular lobes in M82.

#### 2.2. Observations with the JCMT

During four shifts in 2004 December and 2005 January, the SW lobe of M82 was observed with the dual-mixer receiver B3 at the JCMT,$^2$ tuned to a rest frequency of 364.1 GHz and a velocity of 180 km s$^{-1}$. The observations were carried out in beam switching mode with a throw of 210". The DAS autocorrelator provided a bandwidth of 920 MHz with a spectral channel separation of 1.25 MHz in each of its two receiver channels, sufficient to cover simultaneously the para-H$_2$CO transitions (524 $\rightarrow$ 432), (541 $\rightarrow$ 432), and (542 $\rightarrow$ 431), as well as the ortho-H$_2$CO transitions (533 $\rightarrow$ 432) and (532 $\rightarrow$ 431) (see Table 1). The system temperatures during the four shifts varied from ~750 to ~1650 K and the uncertainty of the chopper wheel calibration was about 15%, as indicated by observations of the standard source IRC+10216. The temperature scale was converted to main-beam brightness temperature using a beam efficiency of $B_{eff} = 0.63$.

#### 2.3. Data Reduction

All data were reduced, converted to the main-beam temperature scale, and analyzed using the GILDAS software package CLASS. Each individual spectrum was inspected for bad channels, standing waves, or other baseline problems before a linear baseline was subtracted. The spectra at each position were then weighted according to their noise level, combined and smoothed to a common velocity resolution of 10 km s$^{-1}$. The data obtained at 218 GHz with the newly commissioned WILMA back end required special attention, because a large fraction of the individual spectra

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$^2$ Program ID M04BC10; the James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.
then fitted the lines in each individual spectrum using the multiple baseline quality. In order to guard against more subtle baseline ripples in certain sections of the bandpass. As a first step, we fixed the velocity and line width of all spectral features to the Gaussian lines displayed in Figure 3. The basic assumption that the Gaussian distribution and the resulting integrated intensities are summarized in Table 2. 

The 218 GHz spectrum of the SW lobe is reproduced well by the three H$_2$CO lines near this frequency. The central velocity is 132 km s$^{-1}$ (local standard of rest, hereafter LSR); the line width is 111 km s$^{-1}$. In the spectrum of the northeastern lobe (NE lobe), the central velocity is 301 km s$^{-1}$ (LSR) and the line width is 131 km s$^{-1}$. The apparent shift of the H$_2$CO(322→221) line relative to the central velocity indicates the presence of at least one additional emission line, which we identify as the methanol CH$_2$OH(4$_2$→3$_1$ E) transition at 218.44 GHz. The ratio of the fitted intensities of the highly blended lines H$_2$CO(322→221) and CH$_2$OH(4$_2$→3$_1$ E) can vary strongly with slight changes in the central velocity or the line width, which suggests that the fitting procedure is strongly influenced by the noise in the spectra. In addition, there might be faint HC$_3$N(24→23) emission at 218.33 GHz in the spectrum of the NE lobe. However, the effect of such an additional component on the other fitted Gaussians is well inside the observational errors and can be neglected. The integrated line intensities resulting from a simultaneous fit of all five emission lines are given in parentheses in Table 2. A simultaneous fit of all five lines to the spectrum of the SW lobe gives a stringent upper limit to the HC$_3$N(24→23) emission at this position.

In the SW lobe, the two H$_2$CO lines (303→202) and (202→101), detected with high signal-to-noise ratios, show a similar deviation from a Gaussian profile. They are skewed, with a blueshifted peak and a weaker red line wing. The peak at v ≈ 100 km s$^{-1}$ may originate from a gas component that has been identified previously in interferometric maps and may constitute the eastern part of the molecular supershell (Weiβ et al. 1999). To better account for these line profiles, we fitted two velocity components, a narrow one at ≈ 100 km s$^{-1}$ and a wide one, to each identified spectral line using the velocity and line width derived from the H$_2$CO(303→202) line (Table 2, Fig. 4). While the line profiles of the two strongest lines are fitted reliably by those two components, the result for the much weaker H$_2$CO(321→220) line may be dominated by noise.
We also inspected the spectra obtained with the other pixels of the HERA array in order to search for possible outflows. Filaments of SiO emission, another molecule related to dust chemistry and shocks, have been found at a distance as large as 24000 km from the central plane (Fig. 2). No significant H$_2$CO emission was found in any of these spectra above a noise level of $C^2_{24}$ mK (on the $T_{mb}$ scale). Note, however, that H$_2$CO filaments may be present in the halo at locations not covered by our observations.

In both 146 GHz spectra, the H$_2$CO($202 \rightarrow 101$) line at 145.60 GHz is partially blended with the HC$_3$N($16 \rightarrow 15$) line at 145.56 GHz, but the two lines can easily be separated given the constraints derived from the 218 GHz spectra (Table 2). We did not detect any H$_2$CO emission at 364 GHz from the SW lobe. The values given in Table 2 are 3 $\sigma$ upper limits, derived from the rms noise with the assumption that these lines have the same width and central velocity as those at 218 and 146 GHz.

4. DISCUSSION

4.1. The Physical Conditions of the Dense Molecular Gas

For the analysis of the derived integrated line intensities, we have developed a non-LTE code for para-H$_2$CO adopting the LVG approximation and choosing a spherically symmetric cloud geometry. The choice of a particular cloud geometry can affect the resulting gas densities. In the LVG approximation, the escape probability $\beta_{ij}$ for a photon of a transition $ij$ is $\beta_{ij} = \left[1 - \exp(-\tau_{ij})\right]^{-1}$ for a model with spherically symmetric geometry compared to $\beta_{ij} = \left[1 - \exp(-3\tau_{ij})\left(3\tau_{ij}\right)^{-1}\right]$ for a plane-parallel geometry. Thus, if a plane-parallel instead of a spherical cloud geometry is applied, photon trapping sets in at lower optical depths. In the optically thick case, the particle densities derived from the observed line ratios can be lower by up to half an order of magnitude (e.g., Ward et al. 2003). Our code is based on the collision rates with He by Green (1991), the collision rates with H$_2$ being approximated by a scaling factor of 1.37 (Schoier et al. 2005), and includes 41 para-H$_2$CO levels, up to 210 cm$^{-1}$ (300 K) above the ground state. We checked our code successfully by using the physical conditions derived in this study as input to the online version of RADEX, a program using a similar non-LTE code, and by comparing its output with our observed and derived line ratios and optical depths.

Fig. 3.—Observed spectra of the NE (left) and SW (right) lobes of M82. 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($322 \rightarrow 221$) line. The H$_2$CO($303 \rightarrow 202$) and the H$_2$CO($313 \rightarrow 212$) transitions are offset by 348.5 and 389.7 km s$^{-1}$, respectively, while the CH$_3$OH($4_2 \rightarrow 3_1 \ E$) line is offset by 49.4 km s$^{-1}$. In the 146 GHz spectra, the HC$_3$N($16 \rightarrow 15$) line is offset by 86.46 km s$^{-1}$ from the H$_2$CO($202 \rightarrow 101$) emission. Gaussian line profiles were fitted to every individual line assuming the same line width and velocity for all lines. All identified lines of a spectrum were fitted simultaneously with these constraints. The curves show the Gaussian fit to each individual line as well as the spectrum resulting from a superposition of all identified lines: $a = \text{H}_2\text{CO}(202 \rightarrow 101), b = \text{HC}_3\text{N}(16 \rightarrow 15), c = \text{H}_2\text{CO}(303 \rightarrow 202), d = \text{H}_2\text{CO}(313 \rightarrow 212), e = \text{CH}_3\text{OH}(4_2 \rightarrow 3_1 \ E), f = \text{H}_2\text{CO}(323 \rightarrow 222), g = \text{H}_2\text{CO}(323 \rightarrow 222) + \text{H}_2\text{CO}(533 \rightarrow 432) + \text{H}_2\text{CO}(532 \rightarrow 431), h = \text{H}_2\text{CO}(524 \rightarrow 423).$ [See the electronic edition of the Journal for a color version of this figure.]

3 See http://www.strw.leidenuniv.nl/~moldata.
the integrated intensities of molecular transitions like CO(2 → 1), HCO⁺(1 → 0), and HCO⁺(F = 2 → 1) (e.g., Seajusto et al. 1998; Weiß et al. 2001b; Garciá-Burillo et al. 2002) indicate that the NE and the SW lobes can be approximated by circular Gaussian distributions of 7′′–8′′ in diameter (FWHM). Here we adopt a Gaussian source distribution with a size of $\theta_s = 7.5''$, unless noted otherwise, and convolve all intensities to a common resolution of 17″. We calculated the expected line ratios for a large number of physical conditions, covering the parameter space for a kinetic temperature of $T_{\text{kin}} = 5–300$ K in steps of 5 K, a molecular gas density of $n_{\text{H}_2} = 3.0–6.0$ (cm$^{-3}$) in steps of 0.1, and a para-H$_2$CO column density per velocity interval of $N_{\text{H}_2\text{CO}}/\Delta v = 10.5–14.5$ (cm$^{-2}$ km$^{-1}$ s$^{-1}$) in steps of 0.1. The assumed ambient radiation field is the cosmic background radiation field ($T_{\text{bg}} = 2.73$ K). Since the H$_2$CO(322 → 221) line in the NE lobe is heavily blended with a nearby methanol line (see §5) and does not add significant constraints to the physical conditions, we do not include the line in our LVG analysis for either lobe.

Comparing the computed line ratios with our observational result (Table 3), we can significantly constrain the range of possible physical conditions in the molecular lobes of M82.\footnote{Splitting the observed H$_2$CO line profiles in the SW lobe into two velocity components (Table 2), the H$_2$CO(202 → 101)/H$_2$CO(303 → 203) line ratio suggests that the narrow component has a higher density than the wide component at a given abundance per velocity gradient and kinetic temperature. However, since the other line ratios are highly uncertain because of the low signal-to-noise ratio in the H$_2$CO(321 → 202) line, we do not treat the two velocity components separately in the following analysis.}

That in reality, the molecular gas is likely to be inhomogeneous in its properties such as temperature and density. However, given the limited number of measurements, we are constrained to consider only a one-component model, yielding the average properties of the molecular gas phase traced by H$_2$CO.

The observed integrated line intensity of extragalactic sources is usually only a small fraction of the intensity predicted by the LVG calculations. This fraction $F = T_{\text{obs}}/T_{\text{bg}}$, the so-called filling factor or dilution factor, is the product of several components $F = f_o f_r f_s$ and provides insights into the structure of the observed source. The beam filling factor $f_r = \theta^2/(\theta^2 + \theta_v^2)$ accounts for the fact that the source does not extend over the whole beam area. Assuming a source size of $\theta_s = 7.5''$, $f_o = 0.163$ for a beamwidth of $\theta_v = 17''$. At the distance of M82, at $D = 3.9$ Mpc (Sakai & Madore 1999), a $17''$ beam covers an area with a diameter of 320 pc. Thus, it is reasonable to assume that the observed emission does not originate from a single molecular cloud, but rather represents an ensemble of giant molecular clouds, a giant molecular association. The individual clouds are expected to have (much) smaller radii than the overall source size and (much) smaller line widths than the observed beam-averaged width. Measures of this small-scale structure are the area filling factor $f_a = C \Delta r / \Delta r_{\text{cloud}}$ and the velocity filling factor $f_v = \Delta v_{\text{cloud}} / \Delta v_{\text{line}}$, where $r$ and $\Delta r_{\text{cloud}}$ are the radius and velocity width of an individual cloud, $R_s$ is the radius of the source, $\Delta r_{\text{line}}$ is the observed line width, and $C$ is the total number of clouds in the beam. Since the latter two filling factors cannot be separated, we combine them into the small-scale dilution factor $F_{\text{sc}} = f_o f_r f_s$. Note that $F_{\text{sc}}$ represents the volume filling factor of the velocity cube and thus cannot be larger than unity.

Previous studies of H$_2$CO emission in starburst galaxies suggest total H$_2$CO abundances of the order of $~10^{-9}$ to $~10^{-8}$ (Hüttemeister et al. 1997; Wang et al. 2004; Martin et al. 2006b). In the high-temperature limit, the ortho- para-H$_2$CO ratio is $o/p = 3$. However, in starburst galaxies, $o/p$ may be closer to 1.

TABLE 3

| Line Intensity Ratio/Source, $\theta_s''$ | NE, 5° | NE, 7.5° | NE, 10° | SW, 5° | SW, 7.5° | SW, 10° |
|----------------------------------------|--------|---------|---------|--------|---------|---------|
| H$_2$CO(202 → 101)/H$_2$CO(303 → 203) | 2.88$^{+0.20}_{-0.11}$ | 2.61$^{+0.18}_{-0.20}$ | 2.36$^{+0.16}_{-0.18}$ | 2.84$^{+0.23}_{-0.26}$ | 2.58$^{+0.21}_{-0.24}$ | 2.33$^{+0.19}_{-0.21}$ |
| H$_2$CO(202 → 101)/H$_2$CO(321 → 202) | 11.91$^{+2.21}_{-1.12}$ | 10.79$^{+1.99}_{-2.81}$ | 9.75$^{+1.03}_{-2.54}$ | 11.26$^{+1.31}_{-2.31}$ | 10.20$^{+1.89}_{-3.04}$ | 9.22$^{+2.19}_{-2.71}$ |
| H$_2$CO(303 → 203)/H$_2$CO(321 → 202) | 4.13$^{+0.80}_{-1.12}$ | 4.13$^{+0.80}_{-1.12}$ | 4.13$^{+0.80}_{-1.12}$ | 3.96$^{+0.63}_{-1.21}$ | 3.96$^{+0.63}_{-1.21}$ | 3.96$^{+0.63}_{-1.21}$ |
| H$_2$CO(202 → 101)/H$_2$CO(324 → 203) | ... | ... | ... | >0.88 | >7.84 | >7.40 |

\footnote{Selected lobe, assumed source size $\theta_s$.}
or 2 (e.g., Hüttelmeister et al. 1997). Adopting a para-H$_2$CO abundance per velocity gradient of

\[ \Lambda = \frac{X_{\text{para-H}_2\text{CO}}}{\text{grad}(v)} = \frac{N_{\text{para-H}_2\text{CO}}/\Delta v}{n_{\text{H}_2}} = 1 \times 10^{-9} \text{ km}^{-1} \text{ s pc}^{-1} \]

we derive the physical conditions of the molecular gas in the lobes by comparing the observed line ratios (Table 3, \( \theta_4 = 7.5'' \)) with those calculated in the model parameter space. While interladder line ratios of formaldehyde are generally good tracers of the kinetic temperature and intraladder ratios sensitively trace the density at a given temperature (§1.1), we find that at moderate gas densities of \( \sim 10^4 \text{ cm}^{-3} \) and high kinetic temperatures of \( >100 \text{ K} \), the individual line ratios are not completely independent of the other model parameters and that a combination of the line ratios constrains the physical properties of the molecular gas even more tightly. Figure 5 shows the cuts through the parameter space where the different derived line ratios intersect. Also plotted are the uncertainties given in Table 3. We derive similar physical conditions for the two lobes, in particular a high kinetic temperature of \( \sim 200 \text{ K} \) and a moderate gas density of \( n_{\text{H}_2} \sim 7.4 \times 10^3 \text{ cm}^{-3} \) (Table 4). Under these conditions, the 146 GHz line is optically thick, while the optical depth of the 218 GHz lines is of the order of unity and the emission at 364 GHz is optically thin.

If the line width \( \Delta v_{\text{cloud}} \) of an individual cloud is dominated by its velocity gradient \( [\Delta v_{\text{cloud}} \approx 2r \text{ grad}(v)] \) and the clouds are close to virial equilibrium, a cloud gas density of \( n_{\text{H}_2} = 7.4 \times 10^3 \text{ cm}^{-3} \) suggests a velocity gradient of \( \text{grad}(v) \approx 1.0 \text{ km s}^{-1} \text{ pc}^{-1} \), which is in very good agreement with the velocity gradient deduced from high-resolution CO observations (Weiße et al. 2001b). In this case, the paraformaldehyde abundance is \( X_{\text{para-H}_2\text{CO}} \approx 1 \times 10^{-9} \) and the total formaldehyde abundance \( X_{\text{H}_2\text{CO}} \approx 2 \times 4 \times 10^{-9} \), depending on the ortho- to paraformaldehyde ratio. The mass of the molecular clouds within the beam of the telescope is

\[ \frac{M_{\text{mol}}}{M_\odot} = 6.828 \times 10^{-19} \frac{N_{\text{H}_2,\text{beam}}}{\text{cm}^{-2}} \left( \frac{D}{\text{Mpc}} \right)^2 \left( \frac{\theta_{\text{beam}}}{\text{arcsec}} \right)^2, \]

where \( N_{\text{H}_2,\text{beam}} = (X_{\text{H}_2\text{CO}}/\Delta v) \Delta v_{\text{line}} F \) is the beam-averaged H$_2$ column density. This equation includes a factor 1.6 to account for dust and other molecular and atomic species like helium. At a distance of \( D = 3.9 \text{ Mpc} \) (Sakai & Madore 1999), \( M_{\text{mol}} = 1.7 \times 10^8 M_\odot \) in the NE lobe and \( M_{\text{mol}} = 1.4 \times 10^8 M_\odot \) in the SW lobe.

The small-scale dilution factor \( F_{\text{sc}} = F f_{\text{sc}}^{-1} \) can be derived from our LVG calculations. Expressed in terms of cloud properties, it is

\[ F_{\text{sc}} = f_{\text{a}} f_{\text{s}} \frac{C r^2 \Delta v_{\text{cloud}}}{R^2 C \Delta v_{\text{line}}}. \]
Assuming again that the line width of an individual cloud is dominated by its velocity gradient,

$$Cr^3 = \frac{R^2 \Delta v_{\text{line}} F_{sc}}{2 \text{grad}(v)}$$

yielding $r = 34 C^{-1/3}$ pc in the NE lobe and $r = 33 C^{-1/3}$ pc in the SW lobe for a velocity gradient of $1 \text{ km s}^{-1} \text{ pc}^{-1}$. For comparison, the maximum radius of a cloud is given by the observed line width and the velocity gradient $r_{\text{max}} = \Delta v_{\text{line}}/[2 \text{grad}(v)] = 66$ pc and 56 pc in the NE and SW lobes, respectively.

The fraction of the volume that the molecular clouds occupy within the source is

$$\Phi = \frac{C(4/3) \pi r^3}{\pi R^2 l} = \frac{2 \Delta v_{\text{line}} F_{sc}}{3 \text{grad}(v) l} \frac{1}{l}$$

where $l \approx 350$ pc is the adopted line-of-sight extent of the emitting region. For a gradient of $1 \text{ km s}^{-1} \text{ pc}^{-1}$, $\Phi \approx (0.30)^3$, or about $30\%$ in each dimension of the data cube in both lobes. Thus, the observed volume could contain a small number of large clouds, whose diameters are comparable to the source size, or a large number of small clouds, but the presence of only a single cloud within the beam is ruled out.

The results for other choices of $\Lambda$ can be found in Tables 5 and 6. In the optically thin limit (see, e.g., models N1 and N2), the small-scale dilution factor reaches its maximum value of $F_{sc} = 1$ and the temperature-density plots are almost independent of the assumed H$_2$CO column density per velocity interval. Thus, there is a lower limit to the kinetic temperatures and an upper limit to the gas densities consistent with our observations. We do not find a solution (corresponding to the intersection of the curves for the line ratios) in the calculated parameter space for $T_{\text{kin}} \leq 140$ K (NE lobe) and $T_{\text{kin}} \leq 155$ K (SW lobe), respectively. The upper limit to the gas density is $n_{\text{H}_2} \sim 2.5 \times 10^4 \text{ cm}^{-3}$ in both lobes.

The assumed source size $\theta_0$ also has a significant influence on the derived parameters (Table 4). A larger source size results in a lower kinetic temperature, a higher H$_2$ density and a smaller small-scale dilution factor. But even if the H$_2$CO emitting region is as large as 0.08, the kinetic temperature in the lobes is $\sim 170$ K, which is much higher than the dust temperature of $T_{\text{dust}} = 48$ K (Colbert et al. 1999) or the commonly assumed kinetic temperatures of 30–100 K. To summarize, the dominant component of the molecular gas in the lobes of M82 seems to be in a warm phase of moderate density.

### 4.2. Comparison with Other Excitation Studies

Numerous previous studies have used molecular lines to derive the physical properties of the molecular gas in M82. Frequently, the small number of lines available to constrain the free parameters has led to the adoption of a kinetic temperature of $T_{\text{kin}} \sim 50$ K, similar to the dust temperature $T_{\text{dust}} = 48$ K (Colbert et al. 1999). This assumption is supported by the results of early analyses of the low-$J$ CO lines (e.g., Wild et al. 1992) and, more recently, by the ammonia study of Weiß et al. (2001a, see below).

The most comprehensive database exists for CO and $^{13}$CO lines, which have been searched for up to $J = 7 \rightarrow 6$ (Mao et al. 2000) and $J = 6 \rightarrow 5$ (Ward et al. 2003), respectively. Based on this large collection of CO lines, Mao et al. (2000) confirm that a one-component LVG model cannot fit all the observed line intensities simultaneously. Thus, in order to derive the properties of the high-excitation component, they restrict their LVG analysis to the high-$J$ excitation lines in the submillimeter range, i.e., CO(7 $\rightarrow$ 6), CO(4 $\rightarrow$ 3), CO(3 $\rightarrow$ 2), and $^{13}$CO(3 $\rightarrow$ 2). In the most recent multiline CO study, Ward et al. (2003) analyze the CO and $^{13}$CO emission at all available transitions using a two-component plane-parallel LVG model. The physical properties of the high-excitation molecular gas phase derived from these comprehensive excitation studies are compared to our results in Table 7. Considering that our investigation is completely independent of the other studies, the results are remarkably similar. The physical properties derived from our H$_2$CO data and our LVG model adopting a spherically symmetric cloud morphology lie well within the range of values found for the high-excitation component of the two-component LVG model by Ward et al.
(2003). In fact, our kinetic temperature is only 20–40 K higher than their median value, which is influenced by the limited temperature range considered, and their median density is lower by only a factor of ~2 if the effect of using a plane-parallel model versus a spherically symmetric one is taken into account. The most striking difference between our results and the values derived by Mao et al. (2000) is their lower kinetic temperature. A possible explanation for this discrepancy is a small contribution of the cooler low-excitation component to the submillimeter CO line emission that would lower the average kinetic temperature of the one-component model.

The presence of a warm gas component in nearby starburst galaxies with $T_{\text{kin}} = 50–440$ K was also inferred from the detection of highly excited NH$_3$ lines (Mauersberger et al. 2003). In this study, M82 was the notable exception in not showing evidence for a warm molecular gas component in its NH$_3$ emission. The ammonia inversion lines detected toward M82 suggest a rotational temperature of only 29 K and thus a kinetic temperature of only ~60 K in the SW lobe of M82 (Weiβ et al. 2001a). In contrast, Rigopoulou et al. (2002) find a warm molecular gas component with $T_{\text{kin}} \sim 150$ K in a sample of starburst and Seyfert galaxies including M82 by analyzing IR rotational H$_2$ emission lines. Possible mechanisms that could heat a large fraction of the molecular gas to temperatures of ~150 K include shocks, strong UV and/or X-ray irradiation (photon or X-ray dominated regions; e.g., Rigopoulou et al. 2002; Fuente et al. 2005), as well as the more uniform cosmic-ray heating (Bradford et al. 2003), in short processes that are likely to be found in an active environment such as a starburst.

A comparison of the H$_2$CO line widths and the derived molecular gas mass with the values derived from the CO studies suggests that the H$_2$CO lines trace approximately the same gas as traced by the ubiquitous CO lines (Table 7). According to our data, each lobe contains warm molecular gas of about $M_{\text{mol}} \sim 1.5 \times 10^8 M_\odot$, which is in good agreement with the estimate by Mao et al. (2000) of $M_{\text{mol}} \sim (1–10) \times 10^8 M_\odot$ and the mass of

| Model | $T_{\text{kin}}$ (K) | log $n(H_2)$ (cm$^{-3}$) | log $N_{\text{H}_2}$ (cm$^{-2}$ km$^{-1}$ s$^{-1}$) | $A$ (10$^{-9}$ km$^{-1}$ s pc) | $\tau_{146}^{a}$ | $\tau_{218.2}^{b}$ | $\tau_{218.8}^{a}$ | $\tau_{218.8}^{b}$ | $\tau_{364}^{a}$ | $F_v^{abc}$ | $F_{v}^{ace}$ | $\int T_{\text{mb}} dV$ (K km s$^{-1}$) |
|-------|-----------------|------------------------|---------------------------------|-------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| T1    | 150             | 4.24                  | 12.73                           | 0.100             | 0.78           | 0.22           | 0.09           | 0.06           | 0.02           | 0.059          | 0.36           | 0.53           |
| T2    | 175             | 4.02                  | 13.18                           | 0.469             | 2.41           | 0.79           | 0.29           | 0.18           | 0.006          | 0.027          | 0.16           | 0.54           |
| T3    | 200             | 3.79                  | 13.47                           | 1.55              | 4.72           | 1.81           | 0.53           | 0.33           | 0.008          | 0.020          | 0.12           | 0.55           |
| T4    | 225             | 3.64                  | 13.61                           | 3.03              | 6.24           | 2.23           | 0.58           | 0.34           | 0.007          | 0.023          | 0.14           | 0.55           |
| T5    | 250             | 3.52                  | 13.75                           | 5.51              | 9.52           | 4.02           | 0.84           | 0.51           | 0.001          | 0.017          | 0.11           | 0.54           |
| T6    | 275             | 3.40                  | 13.88                           | 9.81              | 11.96          | 5.24           | 0.95           | 0.59           | 0.010          | 0.016          | 0.10           | 0.55           |
| T7    | 300             | 3.28                  | 13.99                           | 16.65             | 15.07          | 6.82           | 1.11           | 0.67           | 0.011          | 0.016          | 0.10           | 0.55           |
| T8    | 300             | 3.28                  | 13.99                           | 16.65             | 15.07          | 6.82           | 1.11           | 0.67           | 0.011          | 0.016          | 0.10           | 0.55           |
| N1    | 142             | 4.38                  | 12.00                           | 0.0135            | 0.15           | 0.04           | 0.19           | 0.13           | 0.0007         | 0.202          | 1.24           | N/A           |
| N2    | 146             | 4.31                  | 12.50                           | 0.0503            | 0.49           | 0.14           | 0.06           | 0.04           | 0.002          | 0.078          | 0.48           | 0.52           |
| N3    | 159             | 4.13                  | 13.00                           | 0.2407            | 1.54           | 0.46           | 0.19           | 0.12           | 0.004          | 0.036          | 0.22           | 0.53           |
| N4    | 206             | 3.76                  | 13.75                           | 1.7842            | 4.68           | 1.81           | 0.53           | 0.33           | 0.008          | 0.020          | 0.12           | 0.55           |
| N5    | 298             | 3.28                  | 14.00                           | 17.0392           | 15.04          | 6.80           | 1.11           | 0.67           | 0.017          | 0.023          | 0.14           | 0.55           |

Note.—For the $T$ models a kinetic temperature was specified, while the $N$ models used a specific para-H$_2$CO column density per velocity interval as an input parameter.

- $^{a}$ Evaluated at the nearest grid point.
- $^{b}$ Dilution factor $F = T_{\text{mb}}/T_{\text{mb}}$ in a 17" beam; the 218 GHz data are scaled to a 17" beam assuming a source size of $\theta_s = 7.5\arcsec$.
- $^{c}$ Small-scale dilution factor $F_{\text{sc}} = F_{\text{f}} F_{\text{v}}$.
- $^{d}$ Calculated integrated intensity of the H$_2$CO(321 $\rightarrow$ 230) line.
the molecular ring of $M_{\text{mol}} \sim 2.0 \times 10^8 M_\odot$ derived by Ward et al. (2003) from the integrated intensity of their CO(6 → 5) map. Having modeled the physical conditions and the conversion factor $X_{\text{CO}}$ at 18 positions along the circumnuclear ring as traced by high-resolution low-J CO maps, Wei et al. (2001b) find a molecular gas mass of $M_{\text{mol}} \sim 2.5 \times 10^8 M_\odot$ in the ring, whereas applying the standard conversion factor $X_{\text{CO}} = 1.6 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ to their data leads to a total mass of $M_{\text{mol}} \sim 7.1 \times 10^8 M_\odot$.

In contrast to the results of the CO and H$_2$CO investigations, the observed ammonia inversion lines seem to arise from cold, probably well-shielded regions within the ISM (Mauersberger et al. 2003). The physical properties derived in our analysis and the CO studies suggest that the majority of the gas is in a warm state of comparatively low density ($n_{\text{H}_2} \sim 5 \times 10^3$ cm$^{-3}$), which fits well with the idea that M82 is in an advanced phase of a star-burst. In such an environment, ammonia is easily photodissociated outside of the few remaining well-shielded regions (Fuente et al.

| Parameter/Study | Our Data | Ward/Range | Mao |
|-----------------|----------|------------|-----|
| $\theta_x$ (arcsec) | 17 | 24.4 | 22 |
| $\Delta v_{\text{line}}$ (km s$^{-1}$) | 180/160 | >50/50 | 60–130 |
| $T_{\text{kin}}$ (K) | 191/209 | 0.3–100 | >50 |
| $n_{\text{H}_2}$ (10$^3$ cm$^{-3}$) | 0.3 | 2.0–7.9 |
| $N_{\text{H}_2}$ (10$^{21}$ cm$^{-2}$) | 131/111 | 180/160 | 180/160 |
| $M_{\text{mol}}$ (10$^8$ $M_\odot$) | 2.0 | 10$^8$ $M_\odot$ |

* High-excitation component of a two-component LVG model assuming a plane-parallel geometry, using all available CO and 13CO lines; for a spherical model, $n_{\text{H}_2}$ ~5 times larger, $N_{\text{H}_2}$ ~2 times larger and $T_{\text{kin}}$ better constrained and slightly lower (Ward et al. 2003).
* Median likelihood of possible values, not a self-consistent solution.
* Full range of possible values (95% confidence interval).
* One-component LVG model assuming a spherically symmetric cloud geometry, using only the high-excitation lines CO(7 → 6), CO(4 → 3), CO(3 → 2), and 13CO(3 → 2) (Mao et al. 2000).
* FWHM, derived from CO(2 → 1) and CO(1 → 0) spectra.
* Using the average CO column density derived from the integrated CO(6 → 5) intensity map.
* Scaled to a distance of $D = 3.9$ Mpc, assumed to be the total mass.
2. Our line ratio analysis using an LVG model with spherical cloud symmetry suggests the presence of warm ($T_{\text{kin}} \sim 200$ K), moderately dense ($n_{\text{H}_2} \sim 7 \times 10^5$ cm$^{-3}$) molecular gas in the lobes near the center of the starburst activity. The ratio of column density to volume density and the small-scale filling factor may indicate that the observed molecular gas forms large complexes of comparatively low-density molecular gas, possibly extended envelopes around a few remaining well-shielded cores.

3. The physical properties of the molecular gas derived from our H$_2$CO data are in very good agreement with parameters of the high-excitation component in the lobes of M82 found in recent comprehensive CO studies, but differ from the results of a multilane NH$_3$ investigation. Thus, the para-H$_2$CO lines seem to trace the probably dominant high-excitation component of the molecular gas in M82 very well, while the NH$_3$ emission might originate predominantly from cold cloud cores.

4. The total mass of the molecular gas observed in the lobes is a few times $10^8 M_\odot$, similar to the mass determinations of other molecular line studies.

5. The selected para-H$_2$CO transitions are good tracers of the molecular gas in starburst galaxies, even if a large fraction of the gas is in a warm phase ($T_{\text{kin}} \sim 150$ K) of moderate density ($n_{\text{H}_2} \lesssim 10^4$ cm$^{-3}$).

6. We find strong evidence for CH$_3$OH($J=2 \rightarrow 1$) emission in the spectrum of the NE lobe at 218 GHz and also estimate the intensity of this emission line in the SW lobe. We thus confirm the detection of methanol in M82 by Martín et al. (2006b) with measurements of another transition line that are consistent with the earlier findings.

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