FIRST EXTRAGALACTIC DETECTION OF SUBMILLIMETER CH ROTATIONAL LINES FROM THE HERSCHEL SPACE OBSERVATORY

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ABSTRACT

We present the first extragalactic detections of several CH rotational transitions in the far-infrared in four nearby galaxies, NGC 1068, Arp 220, M82, and NGC 253, using the Herschel Space Observatory. The CH lines in all four galaxies are a factor of 2–4 brighter than the adjacent HCN and HCO+ J = 6–5 lines (also detected in the same spectra). In the star-formation-dominated galaxies, M82, NGC 253, and Arp 220, the CH/CO abundance ratio is low (∼10−5), implying that the CH is primarily arising in diffuse and translucent gas where the chemistry is driven by UV radiation as found in the Milky Way interstellar matter. In NGC 1068, which has a luminous active galactic nucleus (AGN), the CH/CO ratio is an order of magnitude higher, suggesting that CH formation is driven by an X-ray-dominated region (XDR). Our XDR models show that both the CH and CO abundances in NGC 1068 can be explained by an XDR-driven chemistry for gas densities and molecular hydrogen column densities that are well constrained by the CO observations. We conclude that the CH/CO ratio may a good indicator of the presence of AGN in galaxies. We also discuss the feasibility of detecting CH in intermediate- to high-z galaxies with ALMA.

Key words: galaxies: ISM – galaxies: starburst – ISM: molecules – line: identification – techniques: spectroscopic

Online-only material: color figures

1. INTRODUCTION

The methylidyne radical CH has been studied extensively at visible wavelengths through its electronic transitions in diffuse Galactic gas (Federman et al. 1997; Sheffer et al. 2008). From these observations, CH was found to be a powerful tracer of the molecular hydrogen in diffuse and translucent gas. Because CH is a light molecule, its ground-state rotational transitions lie at submillimeter/far-infrared (FIR) wavelengths and are impossible to observe from the ground. Herschel made the first observations of the rotational transitions of CH arising in the FIR/submillimeter regime in Galactic star-forming regions (Gerin et al. 2010; Qin et al. 2010; Bruderer et al. 2010; Naylor et al. 2010). In this work we present the first extragalactic detections of CH in four prototypical galaxies dominated by starbursts or active galactic nuclei (AGNs): NGC 1068, Arp 220, M82, and NGC 253.

The CH molecule can be present in high- or low-density gas depending on the formation scenario. If the abundance of ionized carbon is substantial, CH formation is believed to be initiated by the radiative association of C+ with vibrationally excited molecular hydrogen, H2, in the outer layers of photon-dominated regions (PDRs), where the chemistry is dominated by UV radiation. The chemical network forming CH (described in Black & Dalgarno 1973) involves the following reactions:

\[
\begin{align*}
C^+ + H_2 & \rightarrow CH_2^+ + hv \\
CH_2^+ + H_2 & \rightarrow CH_3^+ + H \\
CH_3^+ + e^- & \rightarrow CH + H \\
CH_2^+ + e^- & \rightarrow CH + H_2.
\end{align*}
\]

(1)

CH can be formed in high-density gas via reactions described in Equation (1) or it can also be produced during CH+ synthesis in lower density material (∼50 cm−3) from MHD shocks (Draize & Katz 1986; Pineau des Forêts et al. 1986). In Galactic star-forming regions, CH is about a factor of 1–3 more abundant than CH+ (Godard et al. 2012). The most efficient reaction forming CH+ is C+ + H2 → CH+ + H, which has a high endothermic barrier of 4640 K. This reaction can form CH+ in a dense and highly illuminated PDR but is inefficient in the cold diffuse interstellar medium (ISM). The recent investigations by Godard et al. (2009, 2012; also see Falgarone et al. 2010) suggest that CH+ can be produced in the diffuse ISM via kinetic energy from turbulent dissipation. The CH+ molecule is also rapidly destroyed at high densities. By comparing CH/CH+ ratios with other galaxies we can determine whether these molecules are tracing similar environments and densities as the Milky Way (MW) or if their production is influenced by strong starbursts and AGN.

The CH energy-level diagram shown in Figure 1 is taken from Stacey et al. (1987). The rotational lines of CH in the submillimeter/FIR have a characteristic doublet pattern due to lambda doubling: the spin–orbit interaction of the unpaired π electron splits the rotational levels (J) into two ladders depending on the relative orientation between the electron’s spin and orbital angular momentum vectors. The rotational levels, J, in the individual ladders split into A-doublet states (denoted by + or −) from the relative orientations of the electron’s orbital momentum axis and the molecular rotational axis. The magnetic hyperfine interaction further splits the A-doublet states. The major rotational transitions at 560 μm, 203 μm, 180 μm, and 149 μm (highlighted by the red arrows in Figure 1) are accessible with Herschel. The 560 μm transition is the easiest to detect by both the SPIRE Fourier transform spectrometer (FTS) and the Heterodyne Instrument for the Far Infrared (HIFI) because of their high sensitivity at this
wavelength. This transition has six hyperfine components grouped near 532.8 GHz (1→1−, 2→1−, and 1→0−) and 536.8 GHz (2→1+, 1→1+, and 1→0+), very close in frequency to the HCN and HCO+ J = 6→5 lines and therefore can only be resolved by the higher resolution of HIFI.

In this work we present submillimeter observations of these CH lines and additionally CH+ lines from Herschel in four prototypical galaxies: Arp 220 (starburst/AGN), NGC 1068 (AGN Seyfert-2), M82 (starburst/no AGN), and NGC 253 (starburst/no AGN). These observations are presented in Section 2. The properties of molecular gas derived from CH are compared with CO observations to investigate where CH is arising in these galaxies and if its formation in these starburst/AGN-dominated galaxies differs from the MW (Sections 3 and 4). The feasibility of detecting CH in intermediate- to high-redshift galaxies with ALMA is discussed in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

The lowest spin-rotational (560 μm) transition of CH has six hyperfine components grouped at 532.8 and 536.8 GHz. We first detected them in the SPIRE-FTS spectrum of Arp 220 (Rangwala et al. 2011, hereafter R11), as shown in the left panel of Figure 2. In the FTS spectra, they are blended with the HCN and HCO+ J = 6→5 lines. The presence of CH was inferred from the line center of the blended feature and larger line widths than expected from the FTS resolution. The CH lines are resolved in the HIFI data presented here, unambiguously confirming their detection. We also detected the CH 203 μm transition, consisting of eight hyperfine components grouped around 1471 and 1477 GHz, in the same FTS spectra, as shown in the right panel of Figure 2.

We use data from Herschel-HIFI to measure the fluxes of the CH, CH+, HCN, and HCO+ lines in the four galaxies. These data come from our Open Time (OT) program (OT1-rangwal-1) and other programs (both OT and GTO) publicly available on the Herschel Science Archive (HSA). In our OT program we acquired follow-up observations with HIFI to resolve the CH 532/536 GHz lines from the HCN/HCO+ lines. Additionally, we obtained observations and integrated line fluxes (J. Fischer & E. Sturm 2013, private communication) for the CH 149 μm and CH 180 μm transitions detected in Arp 220 with the PACS spectrometer. The 149 μm line was detected in absorption. Due to blending with a strong water line, the 180 μm CH transition is not easily recoverable, and therefore its line flux is not reported. The summary of the observations and various programs is provided in Table 1.

For CH, we used the level-2 HIFI spectra that were reduced with HIPE version 9.0. A Gaussian function was fit to the spectral lines to determine the line width (FWHM) and integrated fluxes. All of the spectra were observed in HIFI band-1a, in which the baselines are well behaved. We analyzed both V- and H-polarization data separately and report the error-weighted
averages of the line widths (FWHM) and integrated fluxes in Table 2. The spectra for the CH 532 GHz lines and their Gaussian fits are shown in Figure 3 for the H (top panel) and V (bottom panel) polarizations. The HCN and HCO⁺ lines are also detected and are separated from the corresponding CH lines by about 1 and 1.7 GHz, respectively. Table 2 lists the rest frequencies, line-width FWHMs, line fluxes in Jy km s⁻¹ and W m⁻², source or beam size in arcseconds, and column densities for CH, HCN, and HCO⁺ calculated for their respective beam or source size (discussed in Section 3).

The observations of the CH⁺ 835 GHz line are available in the literature and on the Herschel Science Archive for the four galaxies presented in this work. For CH⁺, we use the line fluxes for NGC 1068 and Arp 220 published in Spinoglio et al. (2012, hereafter S12) and R11, respectively. For NGC 253 and M82, the HIFI CH⁺ observations are publicly available on HSA. We show these data and their fits in Figure 4. The CH⁺ appears in absorption in all of the galaxies except for NGC 1068, in which it is detected in emission (S12). The equivalent widths and corresponding column densities of CH⁺ are listed in Table 3.

3. ANALYSIS: COLUMN DENSITIES OF CH AND CH⁺

The column densities for the transitions of CH, HCN, HCO⁺ and CH⁺ are calculated assuming that the lines are optically

### Table 1

Observations of CH

| Galaxy  | Lines               | ObsID       | OD | t_int (s) | Program ID          |
|---------|---------------------|-------------|----|----------|---------------------|
| M 82    | CH 560, HCN 6-5     | 1342232963  | 925| 94       | OT1 (N. Rangwala)   |
| M 82    | CH 560, HCO⁺ 6-5    | 1342232964  | 925| 82       | OT1 (N. Rangwala)   |
| M82     | CH⁺ 359             | 1342246037  | 1106| 1995     | OT2 (E. Falgarone)  |
| NGC 1068| CH 560, HCN 6-5     | 1342247837  | 1154| 6891     | OT1 (N. Rangwala)   |
| NGC 1068| CH 560, HCO⁺ 6-5    | 1342237609  | 980| 7137     | OT1 (N. Rangwala)   |
| NGC 253 | CH 560, HCN 6-5     | 1342210772  | 568| 64       | KPCT (R. Guesten)   |
| NGC 253 | CH 560, HCO⁺ 6-5    | 1342210773  | 568| 40       | KPCT (R. Guesten)   |
| NGC 253 | CH⁺ 359             | 1342212138  | 595| 348      | KPCT (R. Guesten)   |
| Arp 220 | CH 560, HCN 6-5     | 1342262569  | 1357| 3453     | OT2 (P. Maloney)    |
| Arp 220-FTS| CH 560         | 1342190674  | 275| 10445    | KPCT (C. Wilson)    |
| Arp 220-FTS| CH 203       | 1342190674  | 275| 10445    | KPCT (C. Wilson)    |
| Arp 220-PACS| CH 149          | 1342191305  | 289| 3447     | KPCT (E. Strum)     |
| Arp 220-PACS| CH 180         | 1342191309  | 289| 3505     | KPCT (E. Strum)     |

**Note:** The CH⁺ observations for Arp 220 and NGC 1068 are published in Rangwala et al. (2011) and Spinoglio et al. (2012).

### Table 2

Line Fluxes and Column Densities

| Galaxy  | Molecule/Transition | ν_rest (GHz) | Line Width km s⁻¹ | Flux (Jy km s⁻¹) | Flux (×10⁻¹⁷ W m⁻²) | Size a (") | N⁺ (cm⁻²) |
|---------|---------------------|--------------|------------------|-----------------|---------------------|-----------|-----------|
| M82     | CH 560              | 532.730      | 265 ± 18         | 3414 ± 170      | 6.10 ± 0.30         | 43.5      | 1.38E+13  |
| M82     | CH 560              | 536.760      | 240 ± 18         | 2829 ± 267      | 5.10 ± 0.48         | 43.5      | 1.12E+13  |
| NGC 1068| HCN 6-5             | 531.716      | 255 ± 7          | 635 ± 22        | 1.10 ± 0.04         | 4.0       | 2.95E+14  |
| NGC 1068| HCN 6-5             | 531.716      | 235 ± 5          | 725 ± 21        | 1.30 ± 0.04         | 4.0       | 3.88E+14  |
| NGC 253 | CH 560              | 532.730      | 225 ± 8          | 6052 ± 242      | 11.00 ± 0.43        | 43.5      | 2.49E+13  |
| NGC 253 | CH 560              | 536.760      | 190 ± 18         | 4928 ± 235      | 8.80 ± 0.42         | 43.5      | 1.94E+13  |
| NGC 253 | HCN 6-5             | 531.716      | 275 ± 18         | 3187 ± 259      | 5.70 ± 0.46         | 43.5      | 8.06E+11  |
| NGC 253 | HCN 6-5             | 535.062      | 127 ± 8          | 1972 ± 147      | 3.50 ± 0.26         | 43.5      | 2.84E+11  |
| Arp220  | CH 560              | 532.730      | 470 ± 20         | 986 ± 54        | 1.80 ± 0.09         | 1.3       | 4.57E+15  |
| Arp220  | HCN 6-5             | 531.716      | 227 ± 25         | 230 ± 32        | 0.41 ± 0.06         | 1.3       | 6.49E+13  |
| Arp220-FTS| CH 560b        | 536.760      | ...             | 1025 ± 114      | 1.80 ± 0.20         | 1.3       | 4.43E+15  |
| Arp220-FTS| CH 203       | 1470.660     | ...             | 1506 ± 482      | 7.40 ± 2.40         | 1.3       | 1.13E+15  |
| Arp220-FTS| CH 180        | 1477.620     | ...             | 1507 ± 500      | 7.40 ± 2.50         | 1.3       | 1.15E+15  |
| Arp220-PACS| CH 149       | 2010.45      | 272             | -5268 ± 260     | -34.7 ± 1.7         | 1.3       | 1.00E+15  |

**Notes:**
- a The Size column refers to FTS beam size for M 82 and NGC 253, and source size for Arp 220 and NGC 1068.
- b blended with HCO⁺ 6-5.
- c The column densities listed here are lower limits as they calculated under the assumption of optically thin lines.

Uncertainties on N are directly proportional to the uncertainties in the line flux.

### Table 3

CH⁺ Column Densities

| Galaxy  | WJ μm | N_col (cm⁻²) | XCH₁₀₁₂ / XCH⁺ | Reference a |
|---------|-------|--------------|----------------|-------------|
| Arp 220 | 0.19  | 1.6 × 10¹³  | 560            | Rangwala et al. (2011) |
| NGC 1068| ...  | 3.0 × 10¹³  | 23             | Spinoglio et al. (2012) |
| NGC 253 | 0.14  | ≥1.2 × 10¹³ | ≤4             | This Work    |
| M82     | 0.074 | ≥6.3 × 10¹² | ≤4             | This Work    |

**Note:** a References for CH⁺ data.
- b No WJ is reported because the CH⁺ line was detected in emission.

which is detected in emission (S12). The equivalent widths and corresponding column densities of CH⁺ are listed in Table 3.
thin. A more accurate way to measure column density would be to use a non-local thermodynamic equilibrium (non-LTE) radiative transfer modeling technique (e.g., see, R11; Kamenetzky et al. 2012). However, this requires observations of several rotational transitions as well as the knowledge of collisional cross sections (or critical densities) with H$_2$. Since neither are available, an optically thin assumption will give a robust lower limit on the column density.

Under this assumption, the column density of an emission line is given by $N_i = (F_i/(A_i h v_i)) \times 4\pi/\Omega$, where $N_i$ is the column density in the upper state, $F_i$ is the line flux in W m$^{-2}$, $A_i$ is the Einstein coefficient, $h$ is the Planck constant,
three transitions. We calculated an excitation temperature of
MW star-forming regions do not have detections of the other
object in which all four transitions have been detected. Even the
were detected in the PACS spectra. This makes Arp 220 the only

\[ T \sim \] about

function and derive a total CH column density in Arp 220 of
primarily the cold gas.

\[ \text{LTE. This value is comparable to the kinetic temperature of 50 K} \]

The values of upper-level degeneracies are obtained from the Splatalog
database [www.spatalogue.net].

\[ \gamma_i \text{ is the frequency of the line in Hz, and } \Omega \text{ is the beam or source solid angle in steradians. The total column density of a} \]
\[ \text{molecule is } N_{\text{mol}} = Z(T_{\text{ex}}) \times (N_j/g_i) \times \exp(-T_{\text{ex}}/T_i), \text{ where} \]
\[ T_{\text{ex}} \text{ is an excitation temperature in K, } Z(T_{\text{ex}}) \text{ is the partition function at } T_{\text{ex}}, \text{ and } g_i \text{ is the degeneracy of level } i. \]

Except for the CH 149 \(\mu\)m line in Arp 220, all other CH, HCN, and HCO⁺ lines appear in emission in all of the galaxies, and their column densities for individual transitions estimated according to the above relation are listed in Table 2.

The column density relation for an optically thin absorption line is given by
\[ \frac{W_i}{\lambda i} = 8.85 \times 10^{-11} N_j \lambda_j f_i (\text{Spitzer 1968}), \]
where \(W_i\) is the equivalent width, \(N_j\) is the column density in the \(j\)th level, and \(f_i\) is the oscillator strength. The unit of the constant in the above equation is cm. The column densities of CH⁺ lines that appear in absorption are listed in Table 3. In the cases of NGC 253 and M82, there is an overlapping emission line, which may be partially filling in the absorption. Thus, their column densities in Table 3 are listed as a lower limit.

A complete determination of the total CH column density would require all four major rotational transitions or an estimate of \(T_{\text{ex}}\). In all of the galaxies except Arp 220, we only detect the 560 \(\mu\)m transition. Arp 220, being the brightest nearby ULIRG and an important template for high-z galaxies, had much deeper observations from every instrument on Herschel. The signal-to-noise ratio in the FTS spectra was high enough to detect the 203 \(\mu\)m transition (hyperfine lines grouped around 1471 and 1477 GHz), while the 149 \(\mu\)m (in absorption) and 180 \(\mu\)m lines were detected in the PACS spectra. This makes Arp 220 the only object in which all four transitions have been detected. Even the MW star-forming regions do not have detections of the other three transitions. We calculated an excitation temperature of
\[ \text{Arp 220 to the relative populations in the upper states of the 560 } \mu \text{m and 203 } \mu \text{m transitions, assuming LTE. This value is comparable to the kinetic temperature of 50 K derived from low-}J \text{ transitions of CO and CI, which are tracing primarily the cold gas.} \]

Using this excitation temperature we calculate a partition function and derive a total CH column density in Arp 220 of about \(\sim 1.8 \times 10^{16} \text{ cm}^{-2}\). This is only a factor of two higher than the column density of the ground state 560 \(\mu\)m transition (\(\sim 9 \times 10^{15} \text{ cm}^{-2}\)). If the overall excitation of the CH levels is very subthermal, i.e., if \(T_{\text{ex}}\) for the upper and lower levels of the 560 \(\mu\)m line is small compared to \(E_i/k\), it is possible for most of the column density to be in the ground level, in which case the above estimate would be a significant underestimate of the true column density. However, this is a very unlikely scenario for several reasons. The upper level of the 203 \(\mu\)m transition lies much further above ground (\(\sim 100 \text{ K compared with } \sim 25 \text{ K}\) than the upper level of the 560 \(\mu\)m line. We would therefore generally expect that, if the levels are not in LTE, the excitation temperature characterizing these relative level populations (41 K) will be comparable to or lower than that of the 560 \(\mu\)m line. Additionally, in Arp 220, the 149 \(\mu\)m CH line is detected in absorption and therefore gives us a direct measurement of the column density in the ground state. The column density derived from the CH 149 \(\mu\)m absorption line is about \(\sim 10^{15} \text{ cm}^{-2}\), almost an order of magnitude lower than that of the 560 \(\mu\)m emission line, confirming that the column density in the ground state is not large compared to the column density derived from the excited-state transitions seen in emission. In fact, the ground-state column density is so low compared to that seen in emission that it is likely that there is some emission partially filling in the absorption. However, for the true ground-state column density to be much larger than our estimate of the total column density, nearly all of the absorption would need to be filled in by emission, while also leaving an absorption column that is coincidently within an order of magnitude of the column density estimated from the emission lines. This is a highly improbable scenario. Both of the above arguments suggest that in Arp 220 the true CH column density does not significantly differ from the lower limit derived from the 560 \(\mu\)m emission line.

For the other three galaxies, the 203 \(\mu\)m transition is not available, and hence we cannot estimate \(T_{\text{ex}}\). However, additional information from the HCN and HCO⁺ \(J = 6\)–5 lines detected in the same spectra as CH can be used to put reasonable constraints on \(T_{\text{ex}}\). The HCN and HCO⁺ 6–5 lines arise from levels much further above the ground (\(\sim 90 \text{ K}\)) than the CH 560 \(\mu\)m line and have much larger A-coefficients (by about an order of magnitude). If the collisional excitation rate coefficients are similar for the three species, then the critical densities for the HCN and HCO⁺ lines will be correspondingly larger than for the CH line, and we would expect that the excitation temperatures of the HCN and HCO⁺ \(J = 6\)–5 lines will be substantially lower than for the CH 560 \(\mu\)m line (unless the line optical depths are large enough that radiative trapping become significant, which is very unlikely for these species). There are no collision rates available in the literature for CH. However, those for OH, which has a very similar electronic structure, are available and are comparable in magnitude to those for the HCN and HCO⁺ lines.

For three of our four galaxies, observations of the HCN \(J = 1\)–0 transition are available in the literature. We have used these to calculate an excitation temperature for the populations of \(J = 6\) relative to \(J = 1\). These numbers range from 13 to 16 K, and (noting again that we expect these numbers to be in general be lower than for the 560 \(\mu\)m transition) argue against a very small \(T_{\text{ex}}\) for the 560 \(\mu\)m line and therefore against a very large ground-state column density. Also, in all four galaxies the CH 560 \(\mu\)m line is substantially brighter than the HCN/HCO⁺ \(J = 6\)–5 lines. Given that their abundances (relative to H2) are comparable to the abundance of CH (\(\sim (2\)–4) \(\times 10^{-8}\)), it would

\[ 8 \text{ in the limit in which the excitation is very subthermal, i.e., nearly all of the column is in the ground state, it is possible for the excitation temperature of a transition, which describes the relative populations of the upper and lower levels, to approach the gas kinetic temperature, even though the excitation temperatures of these levels defined with respect to the ground level are much lower, and may approach the temperature of the microwave background (assuming no other radiation background is more important). However, this only occurs when the fractional populations in these levels are negligibly small, meaning that the lines would be unobservable.} \]

\[ 9 \text{ In fact, for this argument to be invalid, the collision rates for CH would have to be anomalously small compared to typical collisional rate coefficients.} \]
be very surprising for the CH 560 $\mu$m line to be much brighter than HCN/HCO+ lines if the CH line has a very low excitation temperature. On the basis of these arguments, we make the reasonable assumption that the excitation temperature in the other galaxies is not very different from Arp 220 and use the CH 560 $\mu$m line as a proxy for the total CH column density, modulo a factor of two. Note that the CO-derived temperatures for the cold molecular gas range from about 1550 K in these galaxies (R11; S12; Kamenetzky et al. 2012).

4. CH FORMATION, EXCITATION, AND CH/CH$^*$ RATIO

4.1. Comparing CH and CO Column Densities

The optical observations of CH in the MW show that it primarily arises in the diffuse molecular ($n_H = 100–500$ cm$^{-3}$ and $T = 30–100$ K) and translucent regions ($n_H = 500–5000$ cm$^{-3}$ and $T = 15–50$ K) (see review by Snow & McCall 2006). A translucent cloud is a transition region between diffuse and (fully) shielded molecular gas where the incident UV radiation is becoming attenuated and the C$^+$ is transitioning to C and CO. In these regions, CH is a very reliable tracer of molecular hydrogen. Sheffer et al. (2008) compiled observations of CH, CO, and H$_2$ for many Galactic lines of sight. Their results show unambiguously that CO, CH, and H$_2$ are tightly correlated. However, as expected, there are breaks in these correlations at the boundaries of the diffuse/translucent and translucent/shielded regions where the abundances of CH and CO change significantly. The CH/CO ratio is much higher (10$^{-1}$–10$^{-3}$) in the translucent regions and starts dropping off dramatically when approaching the shielded and fully molecular regions (CH/CO $\sim 10^{-4}$) where the carbon is almost entirely in CO and the lack of C$^+$ halts the formation of CH; see Equation (1). In Sheffer et al. (2008), the break in the CH/CO ratio occurs around an H$_2$ column density of 5 $\times$ 10$^{20}$ cm$^{-2}$. More recently, Qin et al. (2010) used HIFI observations of the hyperfine components of the 560 $\mu$m line to reach even larger molecular hydrogen column densities: up to 10$^{23}$ cm$^{-2}$ toward the Sagittarius B2 star-forming region. This allowed them to probe the interior of fully molecular clouds. They found that the linear relationship between CH and H$_2$ found in diffuse and translucent clouds does not continue in the denser clouds (or at higher visual extinction). The CH column density curve flattens around an H$_2$ column density of $\sim 2 \times 10^{21}$ cm$^{-2}$, again implying that CH formation declines in denser shielded regions. To understand where CH arises in our sample of four galaxies, we compare CO and CH column densities in this section; the CH formation and its abundance could be different from our Galaxy because the molecular ISM of our sample galaxies are significantly influenced by starburst and AGN activity.

Because the rotational lines of CO are bright and easy to observe in galaxies, its emission has been widely used as a tracer of molecular gas mass in galaxies. By comparing the H$_2$ column densities derived from CH and CO we can also assess whether the CH rotational line transition at 560 $\mu$m can be used as a mass tracer in addition to CO. It will be particularly useful to have an additional molecular hydrogen tracer for measuring gas mass and excitation conditions of redshifted star-forming galaxies. This comparison will also allow us to investigate whether CH is arising in the translucent or shielded interiors of fully molecular clouds in these galaxies.

We estimated the H$_2$ column densities ($N$(H$_2$)) from the observations of CH and CO column densities ($N$(CH) and $N$(CO)). The $N$(CO) for the four galaxies were derived from non-LTE radiative transfer modeling of the observed CO rotational lines from $J = 1–0$ to $J = 13–12$. The mid- to high-$J$ lines were observed with the SPIRE-FTS, and the low-$J$ measurements are ground-based observations obtained from the literature. The CO spectral line energy distributions (SLEDs) were modeled using a custom version of RADEX (van der Tak et al. 2007), combined with a likelihood code. For a given set of input parameters ($T_{\text{kin}}$, $n_H$, and $N$(CO)), the code starts from an optically thin case to generate the initial guess for the level populations then iterates until a self-consistent solution is achieved such that the optical depths of the lines are stable from one iteration to the next. This code can reliably converge for optical depths up to 100. Model CO SLEDs are produced for a wide range in gas parameters ($T_{\text{kin}}$, $n_H$, $N$(CO)) and compared to the observed SLEDs to generate likelihood distributions of $T_{\text{kin}}$, $n_H$, and $N$(CO). Using multiple CO transitions, this code provides a robust determination of the CO column density without requiring an assumption of LTE. The observations, modeling, and results for Arp 220, NGC 1068, and M82 are published by R11, S12 (see also Hailey-Dunsheath et al. 2012), and Kamenetzky et al. (2012). In the cases of the starburst galaxies Arp 220 and M82, the low-$J$ lines (up to $J = 3–2$) trace cold molecular gas ($T_{\text{kin}}$: 15–50 K), which dominates the mass of the molecular gas, whereas the mid-high-$J$ lines trace warm molecular gas ($T_{\text{kin}}$: 450–1300 K), which dominates the luminosity of the molecular gas. In NGC 1068, which is a Seyfert-2 galaxy, the high-$J$ CO transitions originate in the compact circumnuclear disk and are almost entirely excited by the X-ray radiation from the central AGN. The results for NGC 253 are in preparation; the same procedure as described above was used to derive the column densities for cold and warm CO. Note that in each galaxy the same source size was used to estimate both $N$(CH) and $N$(CO).

The summed cold and warm $N$(CO) is converted to $N$(H$_2$) by using a CO/H$_2$ abundance ratio of 1 $\times$ 10$^{-4}$ (Sheffer et al. 2008) found in the MW clouds. For converting CH column densities to $N$(H$_2$), we use two values of the CH/H$_2$ abundance ratio: (1) 3.5 $\times$ 10$^{-8}$ derived from UV observations of CH and H$_2$ (Sheffer et al. 2008) and (2) 2 $\times$ 10$^{-8}$ derived from the Herschel-HIFI observations of the 560 $\mu$m CH line in Sgr B2 (M) (Qin et al. 2010). The latter probes a larger H$_2$ column density (deeper into the cloud and higher densities), up to 1 $\times$ 10$^{23}$ cm$^{-2}$. Note that $N$(H$_2$) cannot be measured directly in dense clouds, and in Qin et al. (2010) it was derived from $^{13}$CO column densities. These two assumed abundances define the $N$(H$_2$) range in Table 4.

The H$_2$ column densities as derived from CO and CH are in reasonably good agreement for NGC 1068, implying that both CH and CO are arising in the dense molecular gas with a CH/CO ratio of $\sim 10^{-4}$. This is in contrast to the MW, where the CH is primarily in the diffuse/translucent gas, and its abundance relative to CO drops significantly in the dense regions to less than $10^{-4}$ (see Figure 9 of Sheffer et al. 2008). This implies that the formation of CH in NGC 1068 is driven by an X-ray-dominated region (XDR) powered by the luminous AGN. The CH/CO ratios in the other three galaxies are much lower: about 4 $\times$ 10$^{-5}$ in Arp 220 and 2 $\times$ 10$^{-5}$ in M82 and NGC 253. If the formation of CH is as in the MW, we would expect a low CH/CO ratio when observing the total line-of-sight molecular hydrogen column density because it will be dominated by the shielded fully molecular gas where the local CH abundance is very low. Both M82 and NGC 253 have low CH/CO ratios, suggesting that the CH arises in translucent regions in these
galaxies and also that the translucent regions contain about 10% of the molecular gas mass. In Arp 220 this ratio is also lower but not as low as in M82 and NGC 253. There are many factors that make the interpretation for Arp 220 more complex. The dust optical depth in Arp 220 is much higher, such that our assumption of optically thin lines could underestimate the CH dust optical depth in Arp 220, but not as low as in M82 and NGC 253. There are many factors affecting the results only at column densities of molecular gas. The kinetic temperature of the gas in NGC 1068 were obtained from non-LTE radiative transfer modeling of high-J CO observations from Herschel SPIRE-FTS (S12; Hailey-Dunsheath et al. 2012). It was found that the high-J lines tracing the molecular gas in the central region (∼4") of NGC 1068 were excited by an AGN, and the gas density and kinetic temperature were constrained to lie between 104.5–106.5 cm$^{-3}$ and 170–570 K, respectively. This shows that both CH and CO observations can be reproduced for similar excitation conditions, suggesting that the CH and CO are most likely coming from the compact nuclear region of NGC 1068 and tracing the same gas. This also explains why the hydrogen columns derived from CH and CO are in good agreement in this case. This is the only object in our sample for which CH formation can be unambiguously explained by an XDR. This, combined with a large difference (∼1 order of magnitude) in X-ray-source (AGN) is assumed to be 50 pc. The physical and chemical state of the gas is calculated using an iterative scheme; radiative transfer of cooling radiation is handled with an escape probability treatment, including the effects of dust trapping of line photons.

Figure 5 shows contours for N(CH) and the N(CH)/N(CH+) ratio generated by our XDR code for a range of densities and column densities of molecular gas. The kinetic temperature of the gas is overplotted in blue contours. The shaded regions encompass the 2σ range of molecular hydrogen column density and gas density derived from CO (listed in Table 3) in Arp 220 and NGC 1068. The hard X-ray photons are capable of penetrating much larger column densities than the UV photons in PDRs, so CH may form through a similar process as described in Equation (1), even deep in molecular clouds. In addition, however, the radiative association reaction C + H → CH + hν and the neutral-neutral reaction C + H$_2$ → CH + H, which has a substantial activation barrier, may play a role or even dominate. The last reaction dominates the formation rate in the NGC 1068 portion of Figure 5 (i.e., attenuating columns of about 10$^{22}$ cm$^{-2}$), while radiative association with contributions from the sequence of Equation (1) are more important for the Arp 220 parameters. CH$^+$ formation occurs largely through charge exchange with H$^+$ and C*, i.e., H$^+$ + CH → CH$^+$ + H or else through ion-molecule reactions such as H$_3^+$ + C → CH$^+$ + H$_2$. Our models show that the CH abundance is much larger in an XDR compared to the MW value. This is in agreement with Meijerink et al. (2007), who also find the CH abundance relative to other molecules to be significantly greater in XDRs compared to PDRs.

4.2. CH Production in XDR Models

To investigate the origin of CH in NGC 1068 and Arp 220, along with the CH/CH$^+$ ratio discrepancy, we have generated XDR models using an updated version of the code described in Maloney et al. (1996). We assume a hard X-ray (1–100 keV) luminosity of 10$^{44}$ erg s$^{-1}$, as would be expected for an object of Arp 220’s luminosity if a large fraction of the bolometric luminosity (∼$L_{\text{FIR}}$) were produced by an AGN. These models are generated for an object with the properties (such as hydrogen column and X-ray luminosity) of Arp 220, but the results can be applied to other galaxies because they scale almost linearly with the X-ray luminosity and XDR column density. A power-law index $\alpha = 0.7$ is assumed. Unlike the models in Maloney et al. (1996), we assume a sharp lower energy cutoff of the incident spectrum at 1 keV such that everything except for hard X-rays have already been filtered out by intervening gas closer to the AGN. This assumption affects the results only at column densities ≤10$^{22}$ cm$^{-2}$. We assume an XDR column density that ranges from 1 × 10$^{20}$–3 × 10$^{24}$ cm$^{-2}$; note that this column also attenuates the X-ray flux. The upper limit of this range is based on the column density derived for Arp 220 using CO observations (R11). The distance between the XDR and the

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**Table 4**

| Galaxy | $L_{\text{FIR}}$ ($L_{\odot}$) | X(CH/CO)$^a$ | $N(\text{H}_2)$$_{\text{CH+}}$ (cm$^{-2}$) | $N(\text{H}_2)$$_{\text{CO}}$ (cm$^{-2}$) | References$^c$ |
|--------|----------------|-------------|----------------|----------------|--------------|
| Arp 220 | 1.8 × 10$^{12}$ | 4.5 × 10$^{-5}$ | (4.0 – 7.1) × 10$^{23}$ | 2.0$^{+0.0}_{-0.0}$ × 10$^{24}$ | Rangwala et al. (2011) |
| NGC 1068 | 2 × 10$^{11}$ | 1 × 10$^{-4}$ | (1.8 – 3.2) × 10$^{22}$ | 4.4$^{+0.6}_{-0.9}$ × 10$^{22}$ | Spinoglio et al. (2012) |
| NGC 253 | 2 × 10$^{10}$ | 2 × 10$^{-5}$ | (1.3 – 2.2) × 10$^{21}$ | 2.3$^{+0.7}_{-0.9}$ × 10$^{22}$ | This work |
| M 82 | 5.6 × 10$^{10}$ | 2 × 10$^{-5}$ | (0.7 – 1.3) × 10$^{21}$ | 1.2$^{+1.8}_{-0.6}$ × 10$^{22}$ | This work |

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**Notes.**

$^a$ Derived using the CH 560 μm line.

$^b$ See text in Section 4.1 for explanation of ranges.

$^c$ References for CO measurements.
NGC 1068 derived from CO observations in Rangwala et al. (2011) and Hailey-Dunsheath et al. (2012), respectively. The red and green lines are the observed values.

The relative abundance of CH/CO between NGC 1068 and the three starburst galaxies suggests that the CH/CO ratio could potentially serve as an AGN diagnostic. Note that for the above analysis we are using a lower limit on the total CH column density. The total CO column density is robustly determined from non-LTE modeling of multiple CO transitions. Thus, a lower limit on the total CH column density will give a lower limit on the CH/CO ratio. As mentioned in Section 3, at a kinetic temperature of $\sim$50 K (as measured in CO cold molecular gas) the total CH column density is underestimated only by a factor of two. In NGC 1068, where the CH appears to be arising in a warmer CND, the CH column density will likely be underestimated by a larger factor driving the CH/CO ratio even higher.

The situation is more complex in Arp 220. R11 found using CO observations that the density of the molecular gas was constrained very tightly around $10^3$ cm$^{-3}$. Therefore, the molecular gas as traced by CO emission cannot arise in an XDR because at such low gas densities the high ionization fractions result in rapid chemical destruction of the CO. A non-ionizing source, such as mechanical energy from stellar winds and supernovae, could explain the total observed CO luminosity in Arp 220. If CH and CO originate from the same molecular component, then the CH column density and formation also cannot be explained by an XDR with a density of $10^3$. Figure 5 shows that in the XDR models the expected column density of CH would be an order of magnitude higher than observed given the density and column density constraints of Arp 220. A lower CH/CO ratio implies that the CH in Arp 220 is arising in the translucent regions similarly to M82 and NGC 253. We note that the H$_2$ column densities derived from CH and CO differ by a factor between 3 and 6, which would imply that 15$\%$–30$\%$ of the molecular mass is in the diffuse-translucent phase. This mass fraction is higher than expected, but the assumed CH/H$_2$ abundance used in converting the CH column density into an H$_2$ column density has a large uncertainty.

The very high CH/CH$^+$ ratio in Arp 220, compared to the MW and other galaxies, also cannot be reproduced by an XDR at low gas densities. This leads us to consider another possibility: the unresolved CH$^+$ line observed in Arp 220 is also a mixture of emission and absorption, as seen in the CH 149 $\mu$m line, which would make its true column density higher, and hence the actual CH/CH$^+$ ratio could be as much as an order of magnitude lower than the observed value of 560. This is a very reasonable possibility for Arp 220 because other molecular lines have been observed in emission as well as absorption (e.g., HCN).

In conclusion, in NGC 1068 the formation of CH and CO in the molecular gas is consistent with an XDR, suggesting that the CH/CO ratio could potentially be a powerful AGN diagnostic tool. The other three galaxies have much smaller CH/CO ratios, suggesting that CH is tracing the molecular gas in translucent regions and its formation mechanisms are similar to the MW.

4.3. CH Excitation: Radiation versus Collisions

In the MW, the CH rotational lines tracing the diffuse ISM are believed to be radiatively excited by the cosmic microwave background radiation (Gerin et al. 2010; Bruderer et al. 2010). In our sample of galaxies, the dust radiation field can be much more intense than in the MW. For example, in Arp 220, the dust optical depths are high, and the dust temperature is $\sim$67 K. At this temperature, the radiative pumping rate ($B_{J'}$) is $\sim 10^{-4}$ s$^{-1}$ assuming a blackbody and no geometric dilution. In comparison, the collision rate of CH (with H$_2$) is $\sim 10^{-7}$ s$^{-1}$ for a gas density of $\sim 10^3$ cm$^{-3}$ (determined from CO modeling in our previous work) and an assumed collision cross section of $\sim 10^{-15}$ cm$^2$ (e.g., Bertojo et al. 1976); the collision cross sections for CH are not available in the literature, and the value used here is an approximation. Plausible corrections for optical depth and geometric dilution are unlikely to substantially reduce the large gap between the radiative and collisional excitation rates. Thus, we believe that the CH is most likely excited by radiation in Arp 220. Similar gas densities ($\sim 10^3$ cm$^{-3}$) in M82 and NGC 253 and the large difference in the radiative and collision rates suggest that CH is most likely also radiatively excited in these galaxies. In NGC 1068, the gas density in the CND is much higher ($\sim 10^6$ cm$^{-3}$), and the dust optical depths are much lower in Arp 220. The optical depth is lower in M82 and NGC 253 also, but not likely enough to disfavor radiative excitation. For optically thin dust emission, the background radiation field...
is dominated by the cosmic microwave background radiation, and collisional excitation/de-excitation are more important than radiative excitation.

5. DETECTING CH IN HIGH-z GALAXIES

Our observations of CH in four nearby galaxies suggest that the CH/CO ratio can potentially be used as an AGN diagnostic. This is also supported by the models of Meijerink et al. (2007), in which the CH abundance is significantly enhanced relative to other molecules in interstellar media of galaxies with AGN. However, more observations are needed to establish the CH/CO ratio as an AGN diagnostic. This would be extremely useful for probing AGN activity in high-z galaxies, for which determining the presence of an AGN and its influence on the excitation of the molecular ISM is challenging. In addition, determining whether CH is coming from diffuse or dense gas will allow us to determine mass fraction and excitation of the diffuse and dense molecular gas in high-z galaxies. With the ALMA observatory, CH observations can be made for galaxies with redshift \( z \gtrsim 0.1 \). The large bandwidth of ALMA will allow simultaneous measurements of HCN and HCO\(^+\) lines, enabling the determination of other line ratios, such as CH/HCN, CH/HCO\(^+\) and HCN/HCO\(^+\), which can also provide additional AGN diagnostics (Meijerink et al. 2007). Furthermore, for galaxies at \( z = 3–5 \), multiple CH rotational transitions are accessible with ALMA, increasing the accuracy of the measurements of molecular mass and excitation conditions, such as kinetic temperature and gas density. However, theoretical calculations of CH collisional cross sections are needed for non-LTE radiative transfer modeling. A CH and CO line survey for an adequate sample can be easily accomplished with only a few hours of integration time with ALMA, which will allow us to determine whether (1) CH is arising in the diffuse, translucent, or dense molecular gas, (2) it is tracing gas of different temperature and density compared to CO, and (3) it can be used as a potential AGN-diagnostic line.

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