Title
SPATIALLY RESOLVED CHEMISTRY IN NEARBY GALAXIES. III. DENSE MOLECULAR GAS IN THE INNER DISK OF THE LIRG IRAS 04296+2923

Permalink
https://escholarship.org/uc/item/0ft3f51h

Journal
ASTROPHYSICAL JOURNAL, 795(2)

ISSN
0004-637X

Authors
Meier, DS
Turner, JL
Beck, SC

Publication Date
2014-11-10

DOI
10.1088/0004-637X/795/2/107

Peer reviewed
SPATIALLY RESOLVED CHEMISTRY IN NEARBY GALAXIES III. DENSE MOLECULAR GAS IN THE INNER DISK OF THE LIRG IRAS 04296+2923

David S. Meier, Jean L. Turner, and Sara C. Beck

ABSTRACT

We present a survey of 3 mm molecular lines in IRAS 04296+2923, one of the brightest known molecular-line emitting galaxies, and one of the closest LIRGs. Data are from the Owens Valley and CARMA millimeter interferometers. Species detected at ≲ 4″ resolution include C^{18}O, HCN, HCO^+, HNC, CN, CH_3OH and, tentatively, HNCO. Along with existing CO, C^{13}O and radio continuum data, these lines constrain the chemical properties of the inner disk. Dense molecular gas in the nucleus fuels a star formation rate ≥ 10 M_⊙ yr^{-1} and is traced by lines of HCN, HCO^+, HNC, and CN. A correlation between HCN and star formation rate is observed on sub-kpc scales, consistent with global relations. Toward the nucleus, CN abundances are similar to those of HCN, indicating emission comes from a collection (~40-50) of moderate visual extinction, photon-dominated region clouds. The CO isotopic line ratios are unusual: CO(1-0)/C^{13}CO(1-0) and CO(1-0)/C^{18}O(1-0) line ratios are large toward the starburst, as is commonly observed in LIRGs, but farther out in the disk these ratios are remarkably low (< 3). C^{13}O/C^{18}O abundance ratios are lower than in Galactic clouds, possibly because the C^{18}O is enriched by massive star ejecta from the starburst. C^{13}O is underabundant relative to CO. Extended emission from CH_3OH indicates that dynamical shocks pervade both the nucleus and the inner disk. The unusual CO isotopologue ratios, the CO/HCN intensity ratio versus L_{IR}, the HCN/CN abundance ratio and the gas consumption time versus inflow rate, all indicate that the starburst in IRAS 04296+2923 is in an early stage of development.

Subject headings: astrochemistry — galaxies: individual (IRAS 04296+2923, 2MASX J04324860+2929578) — galaxies: ISM — galaxies: starburst — radio lines: galaxies

1. INTRODUCTION

Luminous infrared galaxies (LIRGs) and ultraluminous infrared galaxies (ULIRGs) represent the most active members of the star-forming galaxy population in the nearby universe. Often morphologically disturbed, with vast reservoirs of atomic and molecular gas (e.g., Sanders et al. 1988, 1991, Solomon et al. 1997), their high IR luminosities are driven by prodigious amounts of efficient star formation (e.g., Sanders & Mirabel 1996). LIRGs are important laboratories for the interplay of molecular gas and starbursts and their evolution over time. But locally LIRGs are rare (e.g., Soifer et al. 1987, Sanders et al. 2003), so there are few examples that are near enough that we can detect and resolve their chemical properties.

Despite being one of the nearest (29 Mpc; 140 pc = 1″) LIRGs, IRAS 04296+2923 (hereafter IRAS 04296) — located behind the dark cloud L1500 in Taurus — has remained poorly studied until recently (Meier et al. 2010). It was not so long ago that it was even identified as a galaxy (Strauss et al. 1992, Chamaux et al. 1993). Within 35 Mpc only the galaxies NGC 1068, NGC 1365, NGC 2146, NGC 4418 and NGC 7552 are as IR luminous as IRAS 04296, at ~ 10^{11} L_⊙ (Table 1). Sanders et al. 2003). IRAS 04296 is remarkable for the compactness of its starburst, with an estimated star formation rate of ~ 10 M_⊙ yr^{-1} originating within the central 2″ (< 280 pc), and ~ 25 M_⊙ yr^{-1} for the entire galaxy (Meier et al. 2010). CO mapping with the Owens Valley Millimeter Array (OVRO) revealed an extremely massive molecular gas disk of M(H_2) ≃ 6 × 10^9 M_⊙ within the central 45″ (Meier et al. 2010). No galaxy within 30 Mpc, observed in the Five Colleges Radio Astronomy Observatory (FCRAO) CO survey (Young et al. 1993), has as high a CO luminosity over that aperture. Toward the central region H_2 column densities are 1 × 10^{23} cm^{-2} averaged over 500 pc scales. IRAS 04296 is one of the most gas-rich systems in the nearby universe.

In many respects, IRAS 04296 appears to be “normal” bar-induced star formation taken to an extreme (Figure 1). Meier et al. 2010). Unlike many [U]/LIRGs, there are no obvious signs, morphological or kinematic, of a recent major merger. It is a symmetric, barred spiral galaxy with a pronounced outer “theta” ring. However, judging from the estimated gas inflow rates along the bar, IRAS 04296 is not in a stable configuration. The nuclear star formation rate is so large that the nuclear component is being consumed more rapidly than it can be replenished by the bar-driven inflow of ~ 5 M_⊙ yr^{-1}. This argues that IRAS 04296 is early in its LIRG state; the observed starburst can be maintained for the next 100 Myr (Meier et al. 2010).

IRAS 04296’s unusual CO brightness raises questions about the dense gas in this LIRG. How much dense gas is there in IRAS 04296, and where is it found? What
are the densities and temperatures of the gas clouds? What are the effects of the nuclear starburst on the dense gas? What are the effects of bar inflow on the dense gas? What does the dense gas and its chemistry reveal about the nuclear starburst in this LIRG? Here we use 3 mm aperture synthesis observations to address these questions in IRAS 04296. The target molecules are tracers of dense gas and probe a range of chemical conditions.

2. OBSERVATIONS

Aperture synthesis observations were obtained for IRAS 04296 in dense gas tracers at $\lambda = 3$ mm with the Combined Array for Research in Millimeter Astronomy (CARMA) [Woody et al. 2004]. Table I lists the molecular transitions surveyed along with their observational parameters. Observing parameters for data from the Owens Valley Millimeter Array (OVRO) [Scoville et al. 1994], consisting of transitions between 109-113 GHz are as reported in [Meier et al. 2010]. The CO(1–0) and $^{13}$CO(1–0) observations have a velocity resolution of 10.5 km s$^{-1}$. The lines presented here were observed simultaneously in wideband mode (128×31.25 MHz) giving a velocity resolution of $\sim 90$ km s$^{-1}$. The 88 - 97 GHz tuning was observed separately with the CARMA interferometer but had the same wideband 31.25 MHz channels ($v_{chan} \approx 100$ km s$^{-1}$). All detected lines are resolved spectrally (emission in at least 3 adjacent channels) toward the nucleus, but the low spectral resolution may imply some spectral 'beam dilution' toward the narrower line width disk.

The OVRO and CARMA data sets were calibrated using the MMA and MIRIAD software packages, respectively. Phase calibration was done by observing the quasar J0336+323 every 25 minutes (OVRO) and 0237+288 or 0530+135 every 20 minutes (CARMA). Absolute flux calibration was done using Uranus as primary flux calibrator and 3C273, 3C84 and 3C454.3 for secondary flux calibration (both OVRO and CARMA).

Uncertainties in absolute flux calibration are $\sim 10\%$ for both data sets. Mapmaking was done in MIRIAD and subsequent data analysis and manipulation was done with the NRAO AIPS package. All data were naturally weighted. Spatial resolutions are $\lesssim 4.5''$ for the high frequency (OVRO) tuning and $\lesssim 3.3''$ for the low frequency (CARMA) tuning. Integrated intensity images are moment 0 maps with all emission brighter than $1.3\sigma$ per channel included. Since the emission observed from these higher density tracers remain confined well inside the half power point of the array(s), corrections for the primary beam attenuation have not been applied. No single-dish observations of this galaxy exists for these transitions, so no estimate of the amount of resolved-out flux is possible; however, it is not expected that there is missing flux as it would require the existence of a uniform dense component extended on $\gtrsim 6$ kpc scales.

3. RESULTS: INTEGRATED INTENSITY MAPS AND ABUNDANCES

Figure 2 displays the integrated intensity maps of the detected transitions along with $^{12}$CO(1–0) and $^{13}$CO(1–0) from [Meier et al. 2010]. The CO(1–0) intensity map displays the overall structure of IRAS 04296. Two barred arms extend from the outer, low pitch angle spiral arms into the central region where the gas collects into a very bright nuclear feature, referred to as the ‘circum-nuclear zone’ (CNZ). The CNZ has a radius, corrected for inclination, $\sim 0.9$ kpc [Meier et al. 2010]. The CNZ region is also the site of an intense starburst which dominates the radio continuum and mid-infrared emission [Meier et al. 2010]. The compact core of the starburst traced with 6 cm radio continuum (marked in Figure 2 by a cross) is confined to the inner 3'' or $\sim 200$ pc radius. The centroid of this compact starburst is close to the center of the CNZ dense gas distribution, but appears shifted slightly ($\sim 1''$) southwest of the starburst. The CNZ is $\gtrsim 3.5$ kpc. CO(1–0) from Meier et al. 2010] and $^{13}$CO(1–0) peaks just southeast of the starburst. The CNZ is not significantly brighter than the arms in $^{13}$CO(1–0), remarkably different from CO(1–0), where it is more.

<p>| TABLE 1 |
| IRAS 04296+2923 BASIC DATA |</p>
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamical Center</td>
<td>04$^{h}2\text{''}48^{m}46^{s}65.1''</td>
</tr>
<tr>
<td>(kinematic) [J2000]</td>
<td>+29$^{\circ}2957.'45$ 1$'$.</td>
</tr>
<tr>
<td>2$\mu$m peak (2MASS)</td>
<td>04$^{h}32^{m}48^{s}.60 \pm 0.3$</td>
</tr>
<tr>
<td>[J2000]</td>
<td>+29$^{\circ}2957.'49$ 0'' 3</td>
</tr>
<tr>
<td>$V_{lsr}$</td>
<td>2086 km s$^{-1}$</td>
</tr>
<tr>
<td>Adopted Distance</td>
<td>29 Mpc</td>
</tr>
<tr>
<td>Position Angle</td>
<td>252$^\circ$</td>
</tr>
<tr>
<td>Inclination</td>
<td>50$^\circ$</td>
</tr>
<tr>
<td>$M_{H_2}$ (&lt; 3.5''$^b$)</td>
<td>4.3 $\times 10^5$ M$_\odot$</td>
</tr>
<tr>
<td>$\Sigma_{H_2}$ (&lt; 3.5''$^b$)</td>
<td>550 M$_\odot$ pc$^{-2}$</td>
</tr>
<tr>
<td>$M_{\mu}$ (&lt; 3.5''$^a$)</td>
<td>1.6 $\times 10^3$ M$_\odot$</td>
</tr>
<tr>
<td>$M_{\mu}$ (&lt; 30''$^c$)</td>
<td>5.9 $\times 10^3$ M$_\odot$</td>
</tr>
<tr>
<td>$M_{\mu}$ (&lt; 30''$^c$)</td>
<td>3.0 $\times 10^9$ M$_\odot$</td>
</tr>
<tr>
<td>$M_{\mu}$</td>
<td>1.38 $\times 10^9$ M$_\odot$</td>
</tr>
<tr>
<td>IRAS 12, 25, 60, 100$\mu$m</td>
<td>1.39, 5.90, 42.1, 48.3 Jy</td>
</tr>
<tr>
<td>$L_{IR}$</td>
<td>9.8 $\times 10^{10}$ L$_\odot$</td>
</tr>
</tbody>
</table>

References. — (1) Meier et al. (2010); (2) Sanders et al. (2003); (3) Chamaaux et al. (1995)

a Based on the best fitting rotation curve
b From $^{13}$CO(1–0).
c Assuming the standard CO conversion factor.
Dense Gas in IRAS 04296+2923

Fig. 1.— The J band near infrared image of IRAS 04296 from the Palomar 5 m with CO(1–0) integrated intensity in the bottom right corner (Meier et al. 2010). The black box marks the field of view covered in CO(1–0). Contours are 1, 2, 3, ... 10, 15, 20, ... 60 × 13.8 K km s$^{-1}$ for a beam size of 4.6′′ × 3.6′′; −14′′ (Meier et al. 2010). The scale bar in the upper left is 2.8 kpc (20″) long.

TABLE 2

<table>
<thead>
<tr>
<th>Transition</th>
<th>Dates</th>
<th>Frequency</th>
<th>$T_{sys}$</th>
<th>$\Delta V_{chan}$</th>
<th>Beam</th>
<th>K/Jy</th>
<th>Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(MMYY)</td>
<td>(GHz)</td>
<td>(K)</td>
<td>(km s$^{-1}$)</td>
<td>($'' \times''$)</td>
<td></td>
<td>(mJy bm$^{-1}$)</td>
</tr>
<tr>
<td>CARMA$^a$:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCN(1–0)</td>
<td>0808-1008</td>
<td>88.632</td>
<td>130-230</td>
<td>105.7</td>
<td>3.3 × 2.7; -90</td>
<td>17.5</td>
<td>2.9</td>
</tr>
<tr>
<td>HCO$^+$(1–0)</td>
<td>89.189</td>
<td>105.0</td>
<td>17.3</td>
<td>2.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HNC(1–0)</td>
<td>90.664</td>
<td>103.3</td>
<td>16.7</td>
<td>2.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C$^{34}$S(2–1)</td>
<td>96.413</td>
<td>97.17</td>
<td>14.8</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH$_3$OH(2$^k$–1$^k$)</td>
<td>96.741</td>
<td>96.84</td>
<td>14.7</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OVRO$^b$:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC$_2$N(12–11)</td>
<td>1103-0504</td>
<td>109.174</td>
<td>220-450</td>
<td>85.8</td>
<td>4.7 × 3.8; -15</td>
<td>5.91</td>
<td>4.0</td>
</tr>
<tr>
<td>C$^{18}$O(1–0)$^c$</td>
<td>109.782</td>
<td>85.3</td>
<td>5.86</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HNCO(0$^2$S–4$^2$P)</td>
<td>109.905</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CN(1–0; $\frac{3}{2}$ – $\frac{1}{2}$)</td>
<td>113.491</td>
<td>82.5</td>
<td>4.6 × 3.6; -14</td>
<td>5.71</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CN(1–0; $\frac{5}{2}$ – $\frac{3}{2}$)$^d$</td>
<td>113.191</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Phase Center: $\alpha = 04^h32^m48^s.6 \quad \delta = +29^\circ29'57.7''$ (J2000)

$^b$ Phase Center: $\alpha = 04^h32^m48^s.6 \quad \delta = +29^\circ29'58.9''$ (J2000)

$^c$ Partially blended

$^d$ Observed simultaneously with CN(1–0; $\frac{3}{2}$ – $\frac{1}{2}$)
than an order of magnitude stronger. This would be consistent with higher cloud temperatures in the CNZ, which would increase the intensity of optically thick CO. Along the arms, C$^{18}$O(1–0) brightnesses are comparable to $^{13}$CO(1–0). At the northern bar end $^{13}$CO(1–0) intensities increase slightly compared to C$^{18}$O. Peak brightnesses reach 0.10 K averaged over $\sim$0.5 kpc scales near the starburst and close to this along the northern arm. C$^{18}$O column densities are discussed in detail below (section 4.1).

HCO+(505 – 404) is tentatively detected ($\sim 3\sigma$) only in the western CNZ. For $T_{\text{ex}} = 30$ K, the HCO+ column densities peak at N(HCO+) $\lesssim 2.3 \times 10^{14}$ cm$^{-2}$. Increasing $T_{\text{ex}}$ to 50 K would raise the N(HCO+) limit to $4.1 \times 10^{14}$ cm$^{-2}$ (Table 4).

HCN(1–0), HCO+(1–0) and HNC(1–0) — All three of these dense gas tracers are bright and compact. HCN(1–0) is the brightest with antenna temperatures peaking at 0.94 K, while HCO+(1–0) and HNC(1–0) are $\sim 15\%$ and $\sim 50\%$ fainter, respectively. HCN(1–0) and HCO+(1–0) peak toward the starburst but extend beyond it to cover the entirety of the CNZ (Figure 3). The dense gas tracers have abundances ranging from $3.3 - 5.4 \times 10^{-9}$ here, assuming optically thin emission with HNC and HCO+ at the low end and HCN at the high end. For HNC and HCO+, abundances are higher than usual for single-dish measurements toward nearby star forming galaxies (Huettemeister et al. 1993, Nguyen-Q-Rieu et al. 1992), but typical of higher resolution interferometer values (Seagrist et al. 1998, Kolmo et al. 2001, Meier & Turner 2003, Knudsen et al. 2007, Meier & Turner 2012). Very weak emission is detected in HCN at two locations along the arms but clear emission is not detected in HCO+ and HNC. The CO/HCN contrast ratio between nucleus (7–9) and arms (6–9) is similar (section 4.2.1).

CN(1–0; 3/2–1/2) and CN(1–0; 1/2–1/2) — CN(1–0; 3/2–1/2) is dominated by the CNZ. Faint emission is tentatively detected along the southeast arm and the northernmost clump, but not in the northwestern arm. Both fine structure components of CN(1–0) are clearly detected toward the CNZ. Hyperfine structure is not resolved due to the low spectral resolution of the data. The CN(3/2–1/2)/CN(1/2–1/2) intensity ratio is $1.8\pm0.5$ matching the optically thin theoretical value of 2, within uncertainties. For a $T_{\text{ex}} = 30$ K peak CN column densities are N(CN) = $9.0 \times 10^{14}$ cm$^{-2}$.

CH$_3$OH(2$_k$–1$_k$) — This line is composed of four transitions, (2$_{12} - 1_{11}$) E, (2$_{02} - 1_{01}$) A++, (2$_{02} - 1_{01}$) E, and (2$_{11} - 1_{10}$) E, which are blended in these spectra. We refer to the combined spectral feature as the $2k - 1k$ transition of methanol. Unlike the dense gas tracers, CH$_3$OH(2$_k$–1$_k$) does not peak exactly at the starburst, but slightly to the north. Emission is tentatively detected from the bar ends. CH$_3$OH abundances are $X$(CH$_3$OH) $\approx 2.3 \times 10^{-8}$ toward the CNZ and within 50% of this value at the ends of the bar. These abundances are quite large, reaching values comparable to the highest values seen on $\sim$50 pc scales toward strong bar shocks in nearby spirals (e.g., Meier & Turner 2003, 2012).

Non-detections — HC$_3$N(12–11) and C$^{34}$S(2–1) were searched for but not clearly detected anywhere across the field. There is tentative evidence for HC$_3$N(12–11) from the western CNZ but we do not consider it a detection. Upper limits for HC$_3$N(12–11)/HCN(1–0) and C$^{34}$S(2–1)/HCN(1–0) are $\lesssim 0.086$ and $< 0.064$ (2$\sigma$), respectively. Abundance limits (for $T_{\text{ex}} = 30$ K) are $\lesssim 5.6 \times 10^{-10}$ and $< 7.7 \times 10^{-10}$ for HC$_3$N and C$^{34}$S, respectively. For C$^{34}$S(2–1) this abundance is only weakly constraining, implying $X$(CS) $< 2 \times 10^{-8}$ for a $^{32}$S/$^{34}$S isotopic ratio of $\sim 24$ (e.g., Chin et al. 1996). Implied HC$_3$N abundance limits are $\sim 3 - 5$ times lower than toward IC 342 (Meier et al. 2011), but similar to abundances observed for M 82 and Maffei 2 (Aladro et al. 2011a, Meier & Turner 2012).

### TABLE 3

<table>
<thead>
<tr>
<th>Species</th>
<th>CNZ/Starburst</th>
<th>Northern Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(H$_2$)</td>
<td>$1.0 \times 10^{23a}$</td>
<td>$3.8 \times 10^{22e}$</td>
</tr>
<tr>
<td>HCN</td>
<td>$5.6 \times 10^{-9}$</td>
<td>$5.3 \times 10^{-10}$</td>
</tr>
<tr>
<td>HNC</td>
<td>$3.3 \times 10^{-9}$</td>
<td>$6.3 \times 10^{-10}$</td>
</tr>
<tr>
<td>CN</td>
<td>$9.0 \times 10^{-9}$</td>
<td>$&lt; 2.2 \times 10^{-9}$</td>
</tr>
<tr>
<td>HCO+</td>
<td>$3.4 \times 10^{-9}$</td>
<td>$&lt; 3.4 \times 10^{-10}$</td>
</tr>
<tr>
<td>C$^{34}$S</td>
<td>$&lt; 7.7 \times 10^{-10}$</td>
<td>$1.1 \times 10^{-9}$</td>
</tr>
<tr>
<td>HC$_3$N</td>
<td>$\lesssim 5.6 \times 10^{-10}$</td>
<td>$&lt; 3.4 \times 10^{-10}$</td>
</tr>
<tr>
<td>CH$_3$OH</td>
<td>$2.3 \times 10^{-8}$</td>
<td>$\sim 1.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>HNCO</td>
<td>$\lesssim 2.3 \times 10^{-9}$</td>
<td>$&lt; 1.7 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

a All upper limits are $2\sigma$.  
b Assumes an excitation temperature of 30 K for all transitions and optically thin emission.  
c Measured at $\alpha = 04^h32^m47^s.9$; $\delta = +29^\circ30'07''$ (J2000) and assumes an excitation temperature of 10 K for all transitions.  
d Based on the N(C$^{18}$O) value, a favored nuclear [CO/C$^{18}$O] isotopologue ratio of 200 (section 4.2.1) and CO/H$_2$ = 8.5 $\times 10^{-5}$ (Ferking et al. 1993).  
e As in d, except for the favored northern bar value of [CO/C$^{18}$O] isotopologue ratio of 225 (section 4.2.1).

4. DISCUSSION

4.1. $^{13}$CO and C$^{18}$O as Probes of CO Gas Opacity and Column

The CO isotopologues $^{13}$C$^{18}$O ($^{13}$CO$^+$) and $^{12}$C$^{18}$O ($^{12}$CO$^+$) are valuable probes of opacity and isotopic abundance when compared to the most abundant isotopologue, $^{12}$C$^{16}$O ($^{12}$CO$^+$). Under the LTE approximation, the isotopic ratios provide a direct constraint on gas opacity:

$$R_i \simeq \frac{(1 - e^{-12\tau})}{(1 - e^{-15\tau})}$$

where $^{12}\tau$ is the CO(1–0) optical depth and $^{15}\tau$ is the CO(1–0) isotopologue optical depth ($^{13}\tau$ and $^{18}\tau$) (e.g., Aalto et al. 1995). The lower opacity of the isotopologues also allow us to study the bulk of the molecular gas that is not sampled by optically thick CO. Furthermore, comparisons of the isotopologues with CO constrain gas opacity and isotopic abundance ratios and can reveal non-LTE gas excitation (e.g., Meier et al. 2008, Meier & Turner 2003). Typical values for the $R_{13}$ of CO(1–0)/$^{13}$CO(1–0) line intensity ratio range from $R_{13} \sim 4 - 7$ for Galactic disk clouds; this range reflects both opacity effects and isotopic abundance ratios varying from [CO/$^{13}$CO] $\sim 25 - 90$ within the Galaxy. The in-
Fig. 2.— Integrated intensity maps of the seven detected transitions, plus CO(1–0) in greyscale and $^{13}$CO(1–0). The latter two are from Meier et al. (2010). The beam of all transitions is displayed in the lower left of each panel, and the cross marks the location of the starburst (radio continuum peak; Meier et al. 2010). Top Left) CO(1–0). Contours are 1, 2, 3, ..., 10, 15, 20, ..., 60 $\times$ 13.8 K km s$^{-1}$ for a beam size of 4.6$''$ × 3.6$''$; $-14''$. Top Center) $^{13}$CO(1–0); contour levels are 7.3 K km s$^{-1}$ for the same beam size as CO(1–0). Beam sizes for the remaining transitions are as listed in Table 1. Top Right) C$^{18}$O(1–0). Contours as for $^{13}$CO(1–0). Middle Left) HCN(1–0). Contour levels are 13.1 K km s$^{-1}$. Middle Center) HCO$^+$(1–0). Contour levels are 17.3 K km s$^{-1}$. Middle Right) HNC(1–0). Contour levels 16.7 K km s$^{-1}$. Bottom Left) CN(1–0; $\frac{1}{2} - \frac{1}{2}$). Contours levels are 12.8 K km s$^{-1}$. Bottom Center) CN(1–0; $\frac{3}{2} - \frac{1}{2}$). Contours as for CN(1–0; $\frac{3}{2} - \frac{1}{2}$). Bottom Right) Combined intensity for the CH$_3$OH($2_2 - 1_2$) quadruplet of lines. Contours levels are 16.2 K km s$^{-1}$. The above contours correspond approximately to 2$\sigma$ increments for each transition except CO(1–0) (see Table 1).
ferred isotopic abundance ratio, \([\text{CO}/^{13}\text{CO}]\), has its lowest values in the Galactic center and increases with galacto-centric radius, reaching \(\sim 70\) at the solar circle and \(\gtrsim 120\) in the outer Galaxy (e.g., Wilson & Rood 1994; Milam et al. 2003; Wouterloot & Brand 1994). A similar gradient is observed in the Galaxy for \([\text{CO}/^{13}\text{CO}]\), with \([\text{CO}/^{13}\text{CO}]\) \(\sim 250\) at the Galactic center and \(\sim 500\) at the solar radius. This implies \([^{12}\text{CO}/^{13}\text{CO}]\) between 6 – 10 across the Galaxy. In external galaxies a wider range is seen, \(R_{13} \sim 3 – 30\), with the higher values tending to originate from LIRGs and ULIRGs (Aalto et al. 1991; Casoli et al. 1992; Aalto et al. 1995). Typical values for the \(R_{13} = \text{CO}(1-0)/^{13}\text{CO}(1-0)\) line intensity ratio are \(R_{13} \sim 15-100\). \(^{13}\text{CO}(1-0)/^{13}\text{C}^{18}\text{O}(1-0)\) intensity ratios, denoted \(R_{1318}\), tend to be lower than the Galactic \([^{13}\text{CO}/^{13}\text{C}^{18}\text{O}]\), having values of 3 – 6 (e.g., Aalto et al. 1993).

Figure 3 presents the three isotopic line ratios, \(R_{13}\), \(R_{18}\), and \(R_{1318}\). All three exhibit the same trend that they are high toward the CNZ and lower along the arms. \(R_{13}\) is 16 ± 4 toward the CNZ but only 1.9 ± 0.4 at the north end of the northern arm (see Table 1 for position). Along the inner part of the bar arms \(R_{13} \sim 3-4\). Likewise \(R_{18} = 45 ± 10\) toward the CNZ and drops to 3.3 ± 0.7 by the end of the northern arm. The double rare isotopic ratio \(R_{1318}\), is fairly low everywhere across the mapped region, being 3.2 ± 0.7 toward the CNZ and falling to \(R_{1318} \sim 1.7 ± 0.5\) by the end of the northern bar. toward the starburst site, \(R_{1318} (R_{18})\) is 21±4 (94±30), even larger than seen elsewhere in the CNZ. However, \(R_{1318}\) is not significantly altered at the starburst (\(R_{1318} = 3.7±1.3\)).

The elevated \(R_{13}\) and \(R_{18}\) ratios in the CNZ are not unexpected, since this has long been seen in starburst regions (e.g., Aalto et al. 1991; Casoli et al. 1992). Common explanations for the elevated \(R_{13}\) and \(R_{18}\) include, 1) lowered gas opacity due to broader line widths that result in lower CO column densities per unit velocity, 2) non-LTE effects that raise CO brightness relative to the isotopologues, such as sub-thermal gas densities or PDR/externally heated clouds, or 3) anomalous isotopic abundances.

In contrast, the low isotopic line ratios seen toward the bar arm imply (for LTE) high opacities. The isotopic ratios approach unity in the limit of infinite opacity. For Galactic local ISM abundance ratios (e.g., Wilson & Rood 1994), \(^{18}\text{O} \gg 1\) would be required to explain the very low \(R_{1318}\) values seen along the bar arms. However, such an interpretation conflicts with the other two ratios. If gas opacity is high enough to explain \(R_{1318}\) then both \(R_{13}\) and \(R_{18}\) should exhibit ratios much closer to unity. The observed \(R_{13}\) and \(R_{18}\) along the northwestern arm, while lower than toward the nucleus, are still significantly above unity. Possible explanations for these unusual ratios for the nucleus and the bar arms are discussed below.

4.1.1. Low Opacity and Columns Toward the Circum-Nuclear Zone

The high ratios toward the CNZ are not extreme compared to other LIRGs and imply low opacity CO gas. A range of LTE solutions for gas opacity and isotopic abundance are possible. The optical depth of CO(1–0), \(^{12}\tau\), can range from \(\gtrsim 4.0\), (corresponding to \([\text{CO}/^{13}\text{CO}]\) \(\gtrsim 60\), and \([\text{CO}/^{13}\text{C}^{18}\text{O}]\) \(\gtrsim 200\) to \(\sim 8.0\), (for \([\text{CO}/^{13}\text{CO}]\) \(\lesssim 120\) and \([\text{CO}/^{13}\text{C}^{18}\text{O}]\) \(\lesssim 375\). Pushing \(^{12}\tau\) larger than 8.0 requires very large \([^{13}\text{CO}/^{13}\text{CO}]\) abundance ratios, greater than 120. These values would be consistent with the low nuclear processing levels observed for gas in the outermost parts of the Galaxy, based on the Wilson & Rood (1994) extrapolated gradient (there are indications that this gradient may be too shallow in the far-out Galaxy; Wouterloot & Brand 1994), and with values of \([^{12}\text{C}/^{13}\text{C}]\) \(\sim 100\) recently suggested for the centers of local starburst galaxies (Martin et al. 2010; Henkel et al. 2014). On the other hand, pushing \(^{12}\tau\) lower than 4.0 requires \([^{13}\text{CO}/^{13}\text{CO}]\) abundance ratios lower than seen anywhere in the Galaxy and lower than the fully massive star enriched values predicted from chemical evolution models (Henkel & Mauersberger 1993). Toward the starburst site, these constraints are even more dramatic if LTE applies (see below). Overall, low values of \(^{12}\tau\) are favored for the CNZ based on a comparison with the northern arm (section 4.1.2).

Low CO opacities in CO-bright nuclear starburst may seem surprising. Even \(^{13}\text{CO}\) has moderate, not low opacity in the more normal spirals, IC 342 and Maffei 2 (Wall & Jaffe 1990; Meier et al. 2000; Meier & Turner 2001; Meier et al. 2008). The presence of the starburst and its location at the center of a barred potential alters the situation somewhat: the CO line width of the nuclear emission is about twice the line widths of the bar ends. The broader line accounts for some of the increased CO intensity toward the nucleus, but not all. The C\(^{18}\text{O}\) peak brightness temperatures toward the CNZ and the northern arm differ by less than a factor of two.

Non-LTE effects can also be responsible for the high \(R_{13}\) and \(R_{18}\) values, especially toward the starburst. The CO(1–0)/HCN(1–0) and HCN(1–0)/HCO\(^{+}\)(1–0) line ratios over the CNZ argue that the gas is dense enough that sub-thermal CO emission can be neglected across the nucleus (section 4.2.2). However, the chemical data indicate that the nuclear molecular emission is may be partially influenced by photon-dominated regions (PDRs) (section 4.3). The radiation field from the starburst can heat the surfaces of the nearby clouds, preferentially exciting the optically thick \(^{12}\text{CO}\) transitions relative to the optically thin \(^{13}\text{CO}\) and \(^{13}\text{C}^{18}\text{O}\). The high radiation fields can also preferentially photo-dissociate the optically thinner species. Both mechanisms raise \(R_{13}\) and \(R_{18}\) relative to their values in quiescent conditions (e.g., Meier et al. 2000). Since \(^{13}\text{CO}\) is not highly opaque, there should be a much weaker influence on \(R_{1318}\). Non-LTE effects are able to explain the elevated ratios toward the starburst relative to the CNZ, but must be extreme to change the conclusion that the CNZ has modest \(^{12}\tau\).

So even accounting for non-LTE effects associated with the starburst, it appears that the observed nuclear CO isotopic line ratios imply quite low \(^{13}\text{CO}\) opacities \(^{13}\tau \ll 1\), \([^{13}\text{CO}/^{13}\text{CO}] \gtrsim 60\) and \([^{13}\text{CO}/^{13}\text{C}^{18}\text{O}] \gtrsim 200\). The isotopic abundances ratios are consistent with an ISM enriched in \(^{16}\text{O}\) from recent massive star ejecta. Moreover, a relatively lower abundance of \(^{13}\text{C}\) suggests less long term nuclear processing, since C is a primary and \(^{13}\text{C}\) is a (mostly) secondary nucleus (Henkel & Mauersberger 1993).

Adopting \([\text{CO}/^{13}\text{C}^{18}\text{O}] \sim 200\) and an excitation temper-
nature of 30 K along with a CO/H$_2$ abundance ratio of $8.5 \times 10^{-5}$ (Freking et al. 1982), we derive an H$_2$ column density of $N$(H$_2$) $\simeq 1.0 \times 10^{23}$ cm$^{-2}$ toward the CNZ. This is about a factor of two lower than predicted based on a Galactic conversion factor of 2.0 $\times$ 10$^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Hunter et al. 1997; Strong et al. 1988). The Galactic conversion factor can be accommodated either by adopting a nuclear excitation temperature of $\sim$50 K over $\sim$200 pc scales, or raising [CO/C$^{18}$O] to $\sim$340.

4.1.2. Anomalous $^{13}$CO and C$^{18}$O Ratios Across the Bar Arms

toward the bar arms the isotopic line ratios are very low compared to what is typically observed for disks in other extragalactic systems (e.g., Paglione et al. 2001). Under LTE, low $R_{13}$ and $R_{18}$ imply large $^{12}\tau$ ($\sim$65 – 110). It is counter-intuitive that the northern arm would have gas opacity at least an order of magnitude greater than the CNZ, while its CO intensity is more than an order of magnitude fainter. For these high opacities, the observed $R_{1318}$ imply $^{13}$CO/C$^{18}$O $\sim$2.1, lower than favored for the CNZ and more than three times lower than found in either the local Galactic ISM or the Galactic center region.

Assuming LTE it is difficult to obtain a consistent solution for these line ratios. To simultaneously match the three ratios at the end of the northern arm we require [CO/$^{13}$CO] $\simeq$90 – 140 (unusually high) and [CO/C$^{18}$O] $\simeq$ 185 – 300, as $^{12}\tau$ ranges from 65 – 110. Given the strong bar here it is possible that radial inflow of relatively unprocessed outer disk gas could explain the high [CO/$^{13}$CO] ratio observed for the bar arms, however this explanation would imply that the [CO/C$^{18}$O] abundance ratio should also be raised, which is not observed. These [CO/$^{13}$CO] ratios suggest that stellar processing on the longer timescales typical of intermediate mass star life-times is rather low.

If we accept the high end of the opacity range for the CNZ and the low end of the range for the end of the northern arm (to minimize dramatic opacity differences) then the implied abundance ratios [CO/$^{13}$CO] and [CO/C$^{18}$O] would both decline with galacto-centric radius. This is at odds with the measured gradients in the Galaxy and chemical evolution models. To have [CO/$^{13}$CO] and [CO/C$^{18}$O] gradients in the right sense we are forced to favor low opacity for the CNZ and high opacity for the outer arms. But even this is not particularly satisfying because with high $^{12}\tau$ in the arms, [CO/C$^{18}$O] $\simeq$ 300. Moreover, if we adopt $T_{ex}$ $\simeq$ 10 K and this abundance the implied N(H$_2$) column is almost five times that obtained using the Galactic conversion factor. Such high conversion factors may be seen in low metallicity systems, but not in solar metallicity gas (e.g., Bolatto et al. 2013).

The anomalies in the ratios demand that we consider non-LTE effects. The PDRs that were discussed in the nuclear region are not relevant in the bar arms because strong star formation is absent. Two other non-LTE effects worth considering are, 1) sub-thermal excitation of the isotopologues and 2) $^{13}$CO chemical fractionation in the arm medium versus the CNZ. The second we dismiss because we observe $^{13}$CO/C$^{15}$O to be smaller than toward the CNZ. Since $^{18}$O is not expected to fractionate efficiently in the cold ISM, fractionation would act to raise the $^{13}$CO/C$^{15}$O abundance ratio relative to the nucleus, not lower it. Moreover, detailed studies find little evidence for $^{13}$CO fractionation actually being observed in the ISM (e.g., Milam et al. 2003).

Sub-thermal excitation is a viable explanation, especially since the clouds in the arms likely have lower densities than the nuclear disk. The large opacity of CO lowers its effective critical density relative to the CO iso-
topologies by the escape probability factor ($\beta \sim 1/{12}\tau$).
Therefore when gas densities drop below $n_H \lesssim 10^{3.5}$ cm$^{-3}$, the brightness temperatures of the CO isotopologues can drop relative to CO, inflating $R_{13}$ and $R_{18}$ (Meier & Turner 2001). This agrees with the observed behavior only if the true $R_{13}$ and $R_{18}$ are unity ($12\tau \to \infty$).

If we adopt the $12\tau \simeq 80$ solution for the end of the northern arm, the lowest that keeps the correct sense of the abundance gradient, then $[CO/^{13}CO] \simeq 110$ and $[CO/C^{18}O] \simeq 225$. For an excitation temperature of 10 K, the observed $^{13}$CO and C$^{18}$O intensities imply areal filling factors of $f_o \sim 0.03$. This is reasonable for the bright, extended molecular gas disk characteristic of IRAS 04296. Adopting the above abundances and temperature for the arm, $N$(H$_2$) $\simeq 3.8 \times 10^{22}$ cm$^{-2}$ at the outer end of the northern arm. This column is larger than that from a Galactic conversion factor but is not extreme; we will use it to estimate abundances toward the northern arm. Until $J = 2 - 1$ transitions are observed so the gas excitation can be directly measured, implied conversion factors must be regarded as suspect, but it is clear that the conversion factor for the CNZ is lower than in the arms (Meier et al. 2010), as it is in many galactic centers.

4.1.3. CO Isotopologues and Stellar Processing in IRAS 04296

We have seen that CO isotopic abundance ratios in IRAS 04296 are anomalous compared to the Galaxy and other local galaxies. The observations further show that the physical conditions of the molecular gas in the arms are very different from that observed in the CNZ. Taking into account gas columns, absolute abundance ratios and their variation with galacto-centric radius, we conclude that $12\tau \sim 4 - 6$, $[CO/^{13}CO] \simeq 60$ and $[CO/C^{18}O]$ $\simeq 200$ toward the CNZ. At the outer end of the bar arm these values have changed to $\sim 80$, 110, and 225, respectively. The $[CO/C^{18}O]$ ratios are fairly low, consistent with the inner Galaxy value and with enrichment from massive star ejecta over much of the inner $r \sim 3.5$ kpc. However, the inner disk $[CO/^{13}CO]$ values are like those $\gtrsim 10$ kpc out in the Galactic disk. Recent observations suggest high $^{12}$C to $^{13}$C isotopic abundance ratios of $[^{12}$C/$^{13}$C] $\sim 100$ may be common in other starburst nuclei (Martin et al. 2010; Henkel et al. 2014). Hence if $[CO/C^{18}O]$ can be a proxy of longer term nucleosynthetic processing, the underlying disk of IRAS 04296 and possibly other starbursts are less processed than most of the Galaxy.

Meier et al. (2010) concluded from the molecular gas and dynamical masses that IRAS 04296 must be experiencing one of its first major starburst episodes. The isotopic abundances agree with this initial burst scenario, but also show that the current burst is mature enough to have enriched the nuclear disk and potentially the inner bar with massive star ejecta. In this picture IRAS 04296’s evolutionary state parallels the Large Magellanic Cloud: a relatively unprocessed galaxy with a current burst of massive star formation. But the LMC appears to have a completely different abundance pattern, being somewhat enriched in $^{13}$CO, extremely depressed in C$^{18}$O (e.g., Wang et al. 2009), and with no sign of local isotopologue variation across the galaxy (Hughes et al. 2014, in prep.). Finding the metallicity of IRAS 04296 could help determine the stage of enrichment.

4.2. The Dense Molecular Gas Component in IRAS 04296

CO(1–0) is a good tracer for overall molecular gas morphology, but it is the dense gas from which stars form. We need to observe molecular species with higher critical densities than CO(1–0) to find the state and char-
acteristics of the star forming component of molecular gas. HCN(1–0) is an example of a dense gas probe that linearly correlates with star formation rate (SFR) \citep{Gao:2003}. Other dense gas probes include HCO$^+$, HNC, CS, HC$_3$N and CN. Here we investigate the nature of the dense gas as traced by these species and their connection with the SFR.

4.2.1. CO(1–0)/HCN(1–0) and the Dense Gas Fraction

Since CO(1–0) traces low density molecular gas and HCN(1–0) high density, the CO(1–0)/HCN(1–0) line ratio is a measure of the fraction of gas that is dense. The tight correlation observed between HCN(1–0) and the SFR \citep[section 4.2.3]{Meier:2012}, together with the compactness of nuclear star formation in IRAS 04296 \citep{Meier:2010}, suggests that the dense gas fraction ought to increase toward the starburst.

This is indeed seen across the CNZ, with CO(1–0)/HCN(1–0) decreasing from $\geq 12$ at the outer edge of the nuclear disk to $\sim 7$ at the starburst. Just southwest of the starburst the ratio even drops below six, at the low end of that found by \citep[single-dish][]{Meier:2008} surveys of nearby \citep[see][section 4.2.3]{Meier:2012}. Aalto et al. 1993, Gao & Solomon 2004, Baan et al. 2008. Even averaged over the inner 20$''$ diameter, close to single-dish sampling scales, the CO(1–0)/HCN(1–0) line ratio is $< 8$. We see that the fraction of dense molecular gas, $n_{H_2} \gtrsim 10^{4.5}$ cm$^{-3}$, in the CNZ is high near the nuclear starburst, and falls away from the starburst.

Along the arms HCN(1–0) is only tentatively detected in a few locations \citep[see Fig. 5]{Meier:2012}, so there are just a few isolated regions with elevated dense gas fractions. Given the much fainter CO(1–0) at these arm locations, they have CO(1–0)/HCN(1–0) limits that are comparable to or slightly higher than the starburst values. But the CO isotopologues are likely better tracers of gas column \citep[section 4.2.3]{Meier:2012}. If $^{13}$CO/HCN or $^{13}$CO/HCN is used to constrain the dense gas fraction then there is a pronounced decrease in the dense gas fraction between the CNZ and the bar arms, as expected given the lower star formation rate there.

4.2.2. Dense Gas Properties of the Circum-Nuclear Zone

Line ratios between HCN(1–0), HCO$^+$ (1–0), HNC(1–0) and CN(1–0): 3/2–1/2 depend on gas physical conditions as well as chemistry. The dominant physical and chemical processes controlling the line intensities of these transitions have been extensively discussed in Paper II \citep{Meier:2012} and the literature \citep[e.g.,][]{Aalto:2002, Graci-Cardio:2006, Meier:2007, Papadopoulos:2007, Baan:2008, Knips:2008, Loenen:2008, Kazandjian:2012}, so here we only briefly summarize.

The first-order physical parameter controlling these ratios is gas density. The critical density of HCO$^+$ (1–0) is nearly and order of magnitude lower than HCN(1–0), while HNC(1–0) has a critical density slightly lower than HCN(1–0). Therefore in the density range from $10^{4.5}$ to $10^{5.3}$ cm$^{-3}$, the HCN/HCO$^+$ depend on gas density, with HCO$^+$ favored at lower densities relative to HCN. Furthermore, HCO$^+$, being a molecular ion, has its abundance decreased in high density gas due to faster recombination with electrons \citep[e.g.,][]{Papadopoulos:2007}.

Together these two effects suggest that HCN should be significantly brighter than HCO$^+$ in high density gas. In normal gas phase chemistry the HCN/HNC intensity ratio is driven to unity through the mutual formation reaction HCN$^+$ $\rightarrow$ HNC/HCN + H \citep[e.g.,][]{Talbi:1998, Shibashita:1998}. In environments that are hot or have experienced strong shocks or PDR irradiation, HCN can be rapidly converted to HCN so this ratio can deviate significantly from unity \citep[e.g.,][]{Schilke:1992, Turner:1997}. Thus we expect HCN/HNC intensity ratios to be near unity over a wide range of high density gas conditions. Where deviating from unity we expect HCN to be strongly favored in hot, disturbed gas. This is generally consistent with what we observe toward the more moderate starbursts, IC 342 and Maffei 2 in Papers I and II \citep{Meier:2003, Meier:2012}. CN is expected to trace PDR gas and its chemistry is discussed in more detail in section 4.2.3. Finally it should be noted that high optical depth in these lines will act to hide any differences in the physical and chemical behavior, driving all the ratios to unity.

Ratios of these three transitions are displayed in Fig. 5. Both the HCN(1–0)/HCO$^+$ (1–0) and the HCN(1–0)/HNC(1–0) line ratios exhibit the same east - west gradient across the CNZ, with high values at the western side. HCN(1–0)/HCO$^+$ (1–0) ranges from 0.7 – 1.5 and HNC(1–0)/HNC(1–0) from 1.3 – 2.5. The nuclear starburst resides approximately in the middle of the observed ratio gradient in both cases, so no clear evidence is seen for a distinct component directly associated with the compact starburst. The fact that the HCN/HCO$^+$ intensity ratio is 1.0 toward the starburst suggests that densities are high enough to thermalize both transitions and that the opacities of both lines could be high. Large velocity gradient modeling of HCN \citep[see][]{Meier:2008, Meier:2010} and HCO$^+$ toward the starburst (not shown) imply that for a kinetic temperature of 40 K (the dust temperature, Table 1) densities are $\sim 2 \times 10^{5}$ cm$^{-3}$. The inferred HCN abundance (Table 1) is near that typically observed on large scales toward star forming clouds \citep[e.g.,][]{Blake:1987}, so HCN opacities, while probably $\gtrsim 1$, are unlikely to be extreme.

Both HCN/HCO$^+$ and HCN/HNC have the same sense of trend, rising toward the west across the CNZ. One possible model for these ratios is that the gas density is lower in the east away from the starburst, resulting in lower HCN/HCO$^+$ there, and warm PDR or shocked gas is more prevalent in the west near the starburst, favoring HCN emission and producing the high HCN/HNC line ratio there. The starburst and CO column density peak, is located at the inner terminus of the northwestern bar arm, suggesting the western side of the nucleus to be hotter / more energetic \citep{Meier:2010}. In this model the elevated HCN/HCO$^+$ is a better indicator of high gas density and HCN/HNC more reflective of high radiation fields. However opacity must also be considered. A second possible model is that line ratios near the starburst could instead be dominated by high HCN line opacity; if HCN is opaque but the two lower abundance species, HCO$^+$ and HNC, transition from optically thick to thin from west to east, following the decline in CO column, then the decline in HCO$^+$ and HNC brightness relative to HCN toward the east could be explained by their decline.
in opacity in this region. However this second model is less favored since HCN/HCO$^+$ (and HCN/HNC) on the western side are significantly above one, ratios naively inconsistent with high opacities.

4.2.3. HCN(1–0) and the Nuclear Star Formation Rate

Here we consider IRAS 04296, a spatially resolved LIRG, in the context of the global LIR versus HCN(1–0) relations (e.g., Gao & Solomon 2004; Garcia-Burillo et al. 2012). The total HCN(1–0) luminosity over the CNZ is $L_{\text{HCN}} = 7.4 \times 10^7$ K km s$^{-1}$ pc$^2$. This equates to $L_{\text{IR}/L_{\text{HCN}}} = 1300 L_\odot$ (K km s$^{-1}$ pc$^2$). This value is 1.5 times the global values of [U] LIRGs (Gao & Solomon 2003) with $L_{\text{IR}} \approx 10^{11} L_\odot$. However the IR fluxes from IRAS cover a much larger area than the HCN emission. If we adopt $L_{\text{IR}}(\text{CNZ}) \approx 0.5 L_{\text{IR}}(\text{tot})$ (Meier et al. 2010), then the observed nuclear value for IRAS 04296 is $L_{\text{IR}}(\text{tot})/L_{\text{HCN}} = 660$, which is 40% smaller than the global values. That the CNZ in IRAS 04296 is slightly IR underluminous normalized by the HCN compared to global averages is consistent with the determination focused tightly on the dense gas of the CNZ region.

Since HCN(1–0) is imaged at high resolution, a rough estimate is attempted to see if the correlation also persists within the galaxy. Meier et al. (2010) provide a detailed discussion of the rate, efficiency and distribution of star formation over the nucleus of IRAS 04296. However, the high frequency radio data does not sample the SFR on spatial scales comparable to HCN(1–0) and so we use a crude SFR proxy, the 20 cm radio continuum map. Figure 3 displays the 20 cm radio continuum (Meier et al. 2010) compared with HCN(1–0) at matched spatial resolution. There is a clear linear correlation between the two. Adopting a $q$ parameter value of 2.3 ($q = \log[L_{\text{IR}}(\text{tot})/L_{\text{HCN}}] - \log[L_{\text{IR}}(\text{tot})/L_{\text{HCN}}]$), typical of what is commonly observed for star forming galaxies (Condon 1992), the observed $L_{\text{IR}}/L_{\text{FCR}}$ ratio (with $L_{\text{IR}}$ being the total luminosity from 8 - 1000$\mu$m and $L_{\text{IR}}$ being the luminosity from 40 - 400$\mu$m; Sanders et al. 2003), and Gao & Solomon (2004)’s conversion between $L_{\text{IR}}$ and SFR allows the 20 cm radio map to be roughly converted to a resolved SFR map. The observed correlation between HCN(1–0) and 20 cm radio continuum intensity is:

$$I_{20}(\text{mJy bm}^{-1}) = [0.38 \pm 0.08]I_{\text{HCN}}(K \text{ km s}^{-1}) - [0.42 \pm 0.35]$$

For the above normalization, after converting intensities to fluxes and luminosities, we find:

$$\text{SFR}(M_\odot \text{ yr}^{-1}) = [1.4 \pm 0.3 \times 10^{-7}] \frac{L_{\text{HCN}}(K \text{ km s}^{-1} \text{ pc}^2)}{[0.02 \pm 0.02]}$$

The quoted errors are statistical only and do not include (potentially large) systematic errors associated with uncertainties in adopted $q$ and the conversion between $L_{\text{IR}}$ and SFR. Discounting the very small zero-point offset, we find a slightly lower normalization than the SFR($M_\odot$ yr$^{-1}) = (1.8 \times 10^{-7}) \frac{L_{\text{HCN}}(K \text{ km s}^{-1} \text{ pc}^2)}{\text{Gao & Solomon 2004}}$. Given the assumptions this is considered good agreement between the local and global values.

HCO$^+$, which has a critical density lower than HCN’s, shows a statistically identical relationship. Krumholz & Thompson (2004) suggest that the slope and normalization of the SFR vs. molecular gas tracer relationship should differ between species that are fully thermalized and those that are not. The fact that we do not see a difference is further evidence that the molecular gas localized to the starburst in IRAS 04296 has a density high enough to excite both HCN(1–0) and HCO$^+$(1–0) equally well over much of the CNZ and that both may have moderate opacity. This finding is consistent with other observations of dense gas tracers in nearby, resolved star-forming galaxies (Zhang et al. 2014).

4.2.4. PDRs and the Nuclear Starburst in IRAS 04296

The interaction of UV photons from the starburst’s massive stars with the molecular gas is expected to result in PDRs with distinctive chemical properties (e.g., Tielens & Hollenbach 1985; Sternberg & Dalgarno 1995). Given the strong nuclear star formation in IRAS 04296, does it show signs of radiative feedback from the starburst in the gas chemistry?

CN is expected to be abundant in PDRs. It forms from reactions between CH and N, with CH forming directly from H$_2$ and PDR-abundant C$^+$ (Sternberg & Dalgarno 1995). CN(1–0); 3/2–1/2 and HCN(1–0) have similar critical densities, so the HCN(1–0)/CN(1–0;3/2-1/2) (hereafter HCN(1–0)/CN(1–0)) line ratio is considered to be an excellent tracer of dense PDRs (e.g., Sternberg & Dalgarno 1995; Boger & Sternberg 2003).

Toward the starburst in IRAS 04296 the HCN(1–0)/CN(1–0) line ratio reaches 2.4, which for LTE corresponds to an [HCN/CN] abundance ratio of $>0.6$ and a CN abundance of 9.0$\times$10$^{-9}$. (The abundance ratio is a lower limit because of the potentially large HCN opacity, whereas it is shown in section 3 that CN is optically thin.) According to the models of Boger & Sternberg (2003), the above conditions are consistent with molecular gas at $A_V \approx 4 - 5$ mag and a range of densities and radiation fields, $\chi$. In the range $A_V \sim 4 - 6$ the predicted column number ratio changes dramatically (Boger & Sternberg 2003), so the implied $A_V$ is not strongly sensitive to the optical depth of HCN as long as it is $<10$. Moderate densities ($\leq 10^4$ cm$^{-3}$) and radiation fields ($\chi < 10^7$), where $\chi$ is the normalized Draine solar neighborhood radiation field at 1000 A are slightly favored since as density and $\chi$ increase, peak CN abundances drop below 10$^{-8}$ as ionization is pushed deeper into the cloud. Molecular gas at $A_V \approx 4 - 5$ corresponds roughly to the transition between PDR and dark cloud conditions. So the starburst ISM traced by CN and HCN in IRAS 04296 appears to be influenced by PDRs, but not strongly. Furthermore, the fact that the HCN(1–0)/HNC(1–0) ratio $> 1$ over the CNZ favors PDR conditions. Localized chemical effects associated with X-ray dominated regions such as from a buried AGN are not pronounced (e.g., Meierink et al. 2007).

To explain the total observed CN column density when $n_H \leq 10^4$ cm$^{-3}$ and $\chi \lesssim 10^3$ with $A_V \sim 4 - 5$ gas requires $\sim 45$ PDR clouds along the line-of-sight. Using the same observed ratio Boger & Sternberg (2003) and Fuente et al. (2005) estimate somewhat higher $\chi$’s for the giant PDR in M 82, but fewer (10 - 20) numbers of PDRs.
Fig. 5.— The intensity ratios for dense gas tracers. Top Left) CO(1–0)/HCN(1–0) line ratio. Contours are 5, 7.5 (bold contour), 10, 13.3, and 20. The grayscale ranges from 0 to 15. In all planes darker grayscale corresponds to higher ratios. Top Right) The HCN(1–0)/CN(3/2–1/2) line ratio. Contours are 1.25, 1.5, 2.0 (bold contour), and 3.0, with grayscale ranging from 0 to 3. Bottom Left) HCN(1–0)/HCO(1–0) line ratio. Contours are 0.563, 0.75, 1.0 (bold contour), 1.5 and 3.0. The grayscale ranges from 0 to 1.5. Bottom Right) HCN(1–0)/HNC(1–0) line ratio. Contours are 0.75, 1.0, 1.33 (bold contour), 2.0 and 4.0. The grayscale ranges from 0 to 2.5. In all planes the cross marks the location of the starburst (peak of the cm radio continuum Meier et al. 2010). The beam for the ratios is displayed in the bottom left.
clumps. The number of clumps estimated here is 2 - 4 times larger than for M 82, the same factor by which the SFR is larger.

However it is hard to explain why HCN(1–0)/CN(1–0) decreases toward the outer CNZ in the context of PDR gas. This implies that the abundance of the PDR tracer CN relative to HCN increases with distance from the starburst, contrary to expectation. One possible explanation is that the ionization remains high over the entire CNZ, via the weaker extended star formation component or elevated cosmic ray ionization rate and the gas away from the starburst being on average somewhat more diffuse. This model of more diffuse gas in the outer CNZ, away from the starburst, is also consistent with the lower HCN(1–0)/CO(1–0) ratio there, since diffuse clouds have lower total dense gas fractions.

4.3. Gas-Grain Chemistry Across IRAS 04296

CH$_3$OH and HNCO have no efficient gas-phase pathway but are easily formed on grain mantles. Large gas-phase abundances of these species require mantle disruption, either by evaporation or shocks. CH$_3$OH is observed to peak just north of the starburst. Here CH$_3$OH abundances reach $1.8 \times 10^{-8}$ (Table 1). HNCO is tentatively detected toward the CNZ, with an abundance of $\sim 2.3 \times 10^{-9}$. Both are highly elevated relative to abundances in quiescent molecular clouds in the Galaxy (Kalenskii et al. 1993; Minier & Booth 2002) and comparable to the abundances observed on GMC scales toward the strongest shock regions in nearby galaxies (e.g., Meier & Turner 2005, 2012).

Since the SFR is large toward the starburst, we investigate whether the nuclear CH$_3$OH intensity can be explained by large collections of compact sources such as proto-stellar outflows or hot cores (e.g., Usero et al. 2006). We estimate the CH$_3$OH intensity produced from molecular outflows by taking the size and CH$_3$OH brightness of the proto-typical molecular outflow, L1157 (Bachiller & Pérez-Gutiérrez 1997). At the distance of IRAS 04296, we estimate a single such outflow will contribute an intensity, $I(CH_3OH)_{\text{out}} \sim 1.3 \times 10^{-9}$ K km s$^{-1}$. To reproduce the observed intensity (Figure 2), we require $3.2 \times 10^9$ such outflows, or 290 outflows pc$^{-2}$. The surface density of outflows predicted from a Salpeter IMF ($M_\text{out} = 100 M_\odot; M_\text{out} = 0.1 M_\odot$), a lifetime of $10^{-4}$ yr and a SFR of $12 M_\odot$ yr$^{-1}$ (Meier et al. 2011), is 3.1 outflows pc$^{-2}$, two orders of magnitude too low to explain the observed methanol emission. The situation is even more untenable for HNCO (Rodríguez-Fernández et al. 2010). Nor can hot molecular cores, which are roughly as common as outflows but an order of magnitude smaller in angular size, match the observed abundances.

Therefore we conclude that only (large-scale) shocks are capable of explaining the observed abundances and that CH$_3$OH provides a mapping of those shocks across the galaxy. This agrees with what is seen in local starburst galaxies (Meier & Turner 2005, 2012). Clearly the CNZ is a site of strong dynamical shocks. That the CH$_3$OH peaks off of the starburst could reflect shocks associated with the intersection of the inner molecular arms with the CNZ, as is observed in nearby bars (Meier & Turner 2005, 2012). It is also possible that the weakness of CH$_3$OH at the starburst is due to depopulation of the low lying energy states or to direct photodissociation.

Toward the end of both bar arms we tentatively ($\sim 4\sigma$ in the north and $\sim 3\sigma$ in the south) detect CH$_3$OH emission. CH$_3$OH abundances toward these locations are comparable to those seen toward the CNZ. CH$_3$OH is similarly enhanced at the end of nuclear bar of the nearby starburst Maffei 2, suggesting that the structure of the (large-scale) bar here resembles the nuclear bar in Maffei 2 (Meier & Turner 2012). Shocks have been proposed as a deterrent to star formation along the arms, allowing gas to drift into the nuclear starburst region (Meier et al. 2010). CH$_3$OH emission is not detected elsewhere in the inner bar arms, but limits on its abundance ($< 1.8 \times 10^{-8}$) are inconclusive. So the observations do not rule out the existence of such strong shocks along the inner arms.

The tentative detection of HNCO toward the nuclear disk permits a limit to be placed on the HNCO($5_{05} - 4_{04}$)/CH$_3$OH($2_2 - 1_1$) line ratio. As discussed in Meier & Turner (2012), the HNCO/CH$_3$OH line ratio is sensitive to the physical conditions present in the shocked gas. This ratio is sensitive both to photodissociation and gas density. HNCO is both more rapidly photodissociated (e.g., Martin et al. 2003) and the observed transition has a slightly higher critical density than CH$_3$OH. Toward the nuclear disk HNCO/CH$_3$OH $\sim 0.25$, while toward the northern bar arm, HNCO/CH$_3$OH $< 0.20$. These ratios are small compared to those observed on small scales in the moderate star formation rate nuclear bars, IC 342 and Maffei 2 (0.9 - 1.1; Meier & Turner 2003, 2012), but comparable to the limits in M 82 (Martin et al. 2006; Aladro et al. 2011b). Hence the low HNCO/CH$_3$OH ratio suggests that either densities are on average lower or shocked gas is more strongly penetrated by UV radiation in the IRAS 04296 CNZ than in the nuclear bars of normal spiral galaxies. The brightness of the dense gas tracers toward the CNZ argues against the former explanation and the strong starburst favors the latter. However the latter is in some tension with the modest implied PDR penetration ($\sim 1.2\%$). Away from the starburst, at the end of the bar, lower gas density may be the reason for the low HNCO/CH$_3$OH intensity ratio.

4.4. IRAS 04296 Nuclear Physical Conditions Compared to Nearby Starbursts

Extensive recent work has focused on the dense gas properties of nearby, strong starbursts (e.g., Henkel et al. 1991; Nguyen-O-Rieu et al. 1992; Solomon, Downes & Radford 1992; Kohno et al. 2001b; Aalto et al. 2003; Gao & Solomon 2004; Graciá-Carpio et al. 2004; Pérez-Beaupuits et al. 2007; Imanishi et al. 2007; Krüps et al. 2008; Bussmann et al. 2008; Baan et al. 2008; Graciá-Carpio et al. 2008; Juneau et al. 2009; Bovet et al. 2009; Jiang et al. 2011; García-Burillo et al. 2012). Here we place the dense gas properties of IRAS 04296 in the context of these studies.

The CNZ intensity ratios, CO/HCN $\sim 7$, HCN/HCO$^+$ $\sim 1.0$, HCN/HNC $\sim 1.3$, and HCN/CN $\sim 2.0$ fall well within the range found for other luminous starburst galaxies. The CO/HCN ratio lies at the low end of the range, and the HCN/CN ratio lies at the high end of the range, while HCN/HCO$^+$ and HCN/HNC are more typi-
Dense Gas in IRAS 04296+2923

1. We confirm that IRAS 04296 is one of the brightest molecular line-emitting galaxies in the sky. We detect significant emission in CO(1–0), 13CO(1–0), C18O(1–0), HCN(1–0), HNC(1–0), HCO+(1–0), CN(1–0; 3/2–1/2), CN(1–0; 1/2–1/2), and CH3OH. Gas properties in IRAS 04296 are similar to those in the starburst galaxy NGC 253, although IRAS 04296 is more gas-rich.

2. Emission from the dense gas tracers, HCO+, HNC, and CN, is primarily confined to the inner $R \sim 500$ pc ($5''$) circum-nuclear zone (CNZ), and requires densities of $n \gtrsim 2 \times 10^4$ cm$^{-3}$ here. It is within this component that the starburst is located. The CO/HCN ratio in IRAS 04296 is $\sim 6$–8 for the inner $R < 500$ pc region, and $\gtrsim 12$ in most locations within the arms. This ratio traces the fraction of molecular gas that is dense, indicating nearly a factor of two higher dense-gas fraction in the nucleus as compared to the arms (though two locations in the arms have CO/HCN ratios comparable to the nucleus).

3. The three CO isotopic lines, which trace less dense gas, are detected across the central $R \sim 5$–6 kpc ($\sim 40''$) diameter. $R_{13}$, the CO(1–0)/13CO(1–0) line ratio, = $16 \pm 4$ in the CNZ ($R < 500$ pc) of IRAS 04296 and falls to the very low value of $1.9 \pm 0.4$ by the outer end of the bar. The higher-than-Galactic $R_{13}$ in the CNZ is consistent with observations of other actively star-forming galaxies. 12CO(1–0)/13CO(1–0), $R_{18}$, follows the same pattern with $R_{18} = 45 \pm 10$ in the nuclear starburst–CNZ and falling to $3.3 \pm 0.7$ toward the outer disk. This trend is likely due to either lower opacities in CO due to kinematics or to higher excitation temperature in the CNZ, which removes molecules from the lowest CO rotational levels.

4. The intensity ratio 13CO(1–0)/C18O(1–0) or $R_{1318}$ is low, $R_{1318} = 3.2 \pm 0.8$, in the CNZ, and even lower in the outer bar, with $R_{1318} \lesssim 2$. Interpretation of this unprecedentedly low ratio in terms of very high CO opacities conflicts with the high observed CO(1–0)/13CO(1–0). We can obtain barely consistent solutions for the CO isotopic ratios if we adopt $[CO]/[13CO] \sim 60$ toward the nucleus of IRAS 04296, increasing to 110 at the bar ends, and $[CO]/[C^{18}O] \sim 200 \sim 225$. These values may indicate a relative lack of long term stellar processing in IRAS 04296 as compared to the Galaxy. For the implied isotopic abundance ratios, optically thin C18O(1–0) emission predicts a nuclear conversion factor $\sim 0.5$ times that of the Galactic disk. The implied conversion factor in the bar arms is approximately equal (or slightly larger) than in the Galactic disk, consistent with that found in [Meier et al. 2010].

5. The observed global value of $L_{1R}/L_{HCN} \approx 1300$ L$_\odot$ (K km s$^{-1}$ pc$^2$) obtained for IRAS 04296 is nearly a factor of 1.5 times the standard global value for the IR to HCN luminosity ratio obtained by [Gao & Solomon 2004]. Excluding the non-CNZ IR luminosity, we obtain a value for the CNZ alone of $L_{1R}/L_{HCN} \approx 600$ L$_\odot$ (K km s$^{-1}$ pc$^2$) for IRAS 04296. From this we estimate a star formation rate relation SFR(M$_\odot$ yr$^{-1}$) = $1.4 \pm 0.3 \times 10^{-7}$ L$_{HCN}$, similar given the large systematic uncertainties, to that obtained by Gao & Solomon.

From LTE analysis we find that the CN abundance is $\sim 1.6$ times the abundance of HCN, if HCN is optically thin. If HCN is optically thick then HCN
6. Bright emission from the CH$_3$OH molecule indicates that grain chemistry is important on large scales in IRAS 04296. We are unable to reproduce the emission from models of collections of compact sources, and conclude that only a widespread mechanism such as shocks along spiral arms can explain the observed brightnesses of these species. A tentative detection of CH$_3$OH at a galactocentric radius of $\sim 2$ kpc is presented. The CH$_3$OH abundance in this region are comparable to those found in the CNZ.

7. All lines of evidence, including the unusual CO isotopologue ratios and CO/HCN vs. $L_\text{IR}$, indicate that the starburst in IRAS 04296 is very young, which is consistent with previous suggestions based on bar-fueling of the starburst (Meier et al. 2010).

DSM acknowledges support from the NSF under grant AST-1009620. We thank the anonymous referee for a thorough and helpful review. Support for CARMA construction was derived from the states of California, Illinois, and Maryland, the James S. McDonnell Foundation, the Gordon and Betty Moore Foundation, the Kenneth T. and Eileen L. Norris Foundation, the University of Chicago, the Associates of the California Institute of Technology, and the National Science Foundation. Ongoing CARMA development and operations are supported by the National Science Foundation under a cooperative agreement, and by the CARMA partner universities.

Facilities: CMA, OVRO

REFERENCES

Kohno, K., Matsushita, S., Vila-Vilaró, B., et al. 2001, The Central Kiloparsec of Starbursts and AGN: The La Palma Connection, 249, 672