DYNAMICALLY INFLUENCED MOLECULAR CLOUDS IN THE NUCLEUS OF NGC 6946: VARIATIONS IN THE CO ISOTOPIC LINE RATIOS

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ABSTRACT

We present high-resolution (~5″) maps of the J = 1–0 transitions of 13CO and C18O toward the nucleus of NGC 6946 made with the Owens Valley Millimeter Array. The images are compared with existing 12CO (1–0) maps to investigate localized changes in gas properties across the nucleus. As compared with 12CO, both 13CO and C18O are more confined to the central ring of molecular gas associated with the nuclear star formation; that is, 12CO is stronger relative to 13CO and C18O away from the nucleus and along the spiral arms. The 12CO (1–0)/13CO (1–0) line ratio reaches very high values of greater than 40. We attribute the relative 13CO weakness to a rapid change in the interstellar medium (ISM) from dense star-forming cores in a central ring to diffuse, low-density molecular gas in and behind the molecular arms. This change is abrupt, occurring in less than a beam size (90 pc), about the size of a giant molecular cloud. Column densities determined from 12CO (1–0), C18O (1–0), and 1.4 mm dust continuum all indicate that the standard Galactic conversion factor, XCO, overestimates the amount of molecular gas in NGC 6946 by factors of ~3–5 toward the central ring and potentially even more so in the diffuse gas away from the central starburst. We suggest that the nuclear bar acts to create coherent regions of molecular clouds with distinct and different physical conditions. The 12CO (1–0)/13CO (1–0) line ratio in galactic nuclei can be a signpost of a dynamically evolving ISM.

Key words: galaxies: individual (NGC 6946) — galaxies: ISM — galaxies: nuclei — galaxies: starburst — radio lines: galaxies

1. INTRODUCTION

Molecular clouds in galactic centers may differ significantly from the molecular clouds we are familiar with from our own Galactic disk. Characteristics of the nuclear regions of galaxies—strong tidal forces, rapid rotational timescales, the propensity for molecular cloud interactions due to confined spaces and noncircular motions, the tendency toward extreme star formation events—can easily leave their imprints on the properties of giant molecular clouds (GMCs), and hence on star formation.

Some of the first indications that GMCs in starbursts are unusual came with the discovery of bright, high J transitions of CO and the detection of bright HCN (1–0) lines in nearby, actively star-forming nuclei, both indicative of warm, dense gas (e.g., Ho, Turner, & Martin 1987; Nguyen-Q-Rieu, Nakai, & Jackson 1989; Carlstrom et al. 1990; Turner, Martin, & Ho 1990; Scoville et al. 1991; Solomon, Downes & Radford 1992; Nguyen-Q-Rieu et al. 1992). In the more extreme starbursts of distant ultraluminous infrared galaxies, CO and HCN observations seem to indicate volume densities of greater than 10⁵–10⁶ cm⁻³ over kiloparsec scales (e.g., Scoville et al. 1991; Okumura et al. 1991; Downes & Solomon 1998; Solomon, Downes, & Radford 1992; Gao & Solomon 2003). The remarkably large amounts of high-density gas in these luminous galaxies likely are the cause of their high star formation rates.

Despite the certain presence of high-density molecular gas, these starbursts are often found to have low 12CO (2–1)/12CO (1–0) line ratios (Radford, Downes, & Solomon 1991; Papadopoulos & Ivison 2002) and high 12CO (1–0)/13CO (1–0) line ratios (Sage & Isbell 1991; Aalto et al. 1991, 1995; Casoli, Dupraz, & Combes 1992; Aalto et al. 1997; Taniguchi & Ohyama 1998; Taniguchi, Ohyama, & Sanders 1999), characteristic of low-density gas. The explanation for this apparent contradiction is not yet clear. Explanations for the anomalously high 12CO (1–0)/13CO (1–0) ratios tend to fall into two main categories: unusual physical conditions resulting in low CO opacities or abundance anomalies. If the CO isotopic ratios arise from diffuse, low-opacity gas, this might be an indicator of starburst feedback or dynamical cloud dispersal, either of which could result in a diffuse gaseous medium capable of inhibiting future star formation. If instead the explanation for the isotopic ratios is unusual abundances, then the presence of high 12CO (1–0)/13CO (1–0) might be a useful indicator of chemical evolution of gas in the presence of star formation.

In distant galaxies, distinguishing between these alternatives is difficult because of poor spatial resolution. In nearby galaxies interferometric imaging at resolutions of a few arcseconds allows us to resolve changes in physical and chemical conditions on the scale of individual GMCs (~50 pc). Observations of the starbursts in M82 and IC 342 have demonstrated that small-scale changes in isotopic line ratios are present and correlate with changes in gas properties (e.g., Turner & Hurt 1992; Wright et al. 1993; Neininger et al. 1998; Meier, Turner, & Hurt 2000; Weiss et al. 2001; Meier & Turner 2001). In this work we extend such studies to the nearby, spiral galaxy with active nuclear star formation NGC 6946.

NGC 6946 is a nearby (~5.2 Mpc), fairly face-on, barred spiral galaxy (Table 1). One of the brightest galaxies in the mid-infrared sky (Rieke & Lebofsky 1978), NGC 6946 is also
bright in CO (Ball et al. 1985; Sofue et al. 1988; Weliachew, Casoli, & Combes 1988; Regan & Vogel 1995; Sakamoto et al. 1999) and radio continuum (Turner & Ho 1983). NGC 6946 is currently the site of a moderate starburst that is 7–20 Myr old (Engargiola 1991). Belley & Roy (1992) find a flattened abundance gradient over the central 2.5 kpc, suggesting radial mixing of gas has occurred.

Here we compare interferometric 13CO (1–0) and C18O (1–0) observations with 12CO (1–0) with two main goals in mind: first, to obtain more reliable images of the true molecular column density in the nucleus; and second, to correlate the observed line ratios with other gas properties to determine what the isotopic ratios tell us about the structure of the molecular interstellar medium (ISM) in NGC 6946 and starbursts in general.

2. OBSERVATIONS

Aperture synthesis observations of the 13CO (1–0) and C18O (1–0) lines in NGC 6946 were made with the Owens Valley Radio Observatory (OVRO) Millimeter Interferometer between 1999 September 26 and 1999 November 28. Also obtained were 2.7 mm and 1.4 mm continuum measurements in a separate 1 GHz bandwidth filter. The interferometer consists of six 10.4 m antennas with cryogenically cooled SIS receivers (Padin et al. 1991; Scoville et al. 1994). System temperatures (single-sideband) ranged from 180 to 380 K at 2.7 mm. The transitions were observed simultaneously making use of OVRO’s multiple-line spectrometer capabilities, and hence share the same instrumental configurations, phase centers, and weather. The instrumental parameters are presented in Table 2.

Data were calibrated using the MMA software package. Phase calibration was done every 25 minutes using the calibrator 2037+511. Absolute flux calibration was done using Neptune for primary flux calibration and 3C273, 3C84, and 3C454.3 as secondary flux calibrators. Because of variability of the quasars, Neptune’s low elevation, and imprecise 2.7 mm brightness, the absolute flux calibration is estimated to be good to 10% for the 2.6 mm data (and 20% for the 1.4 mm continuum map). The data set was reduced using the NRAO AIPS data reduction package. The maps are naturally weighted and primary beam-corrected. In making the zeroth moment (integrated intensity) maps, a mask was generated to help minimize the inclusion of noise into the maps from nonsignal portions of these wide lines. The naturally weighted data set was smoothed to a resolution of 10", and all regions below 2 σ were blanked. This mask was then used on the full-resolution data set to blank out nonsignal portions. Only emission greater than 1.2 σ was included in making the integrated intensity maps. In making the line ratio maps, regions with emission below 3 σ in either map were blanked to avoid taking ratios of low signal-to-noise ratio (S/N) emission.

Lack of short baselines limits our sensitivity to structures on scales larger than ~40" at 2.7 mm (~20" for the 1.4 mm continuum map). To estimate the amount of extended flux the interferometer resolves out of the maps, spectra integrated over the single-dish beam size were compared with available single-dish spectra. For NGC 6946, Paglione et al. (2001) obtained an integrated intensity of 4.8 K km s$^{-1}$ for 13CO (1–0) (assuming $T_{\text{mb}} = 0.5$ for the FCRAO antenna). Convolving the interferometer channel maps to the 45" resolution of the single-dish and sampling the map at the same location yields a line intensity of 3.0 K km s$^{-1}$, or 63% of the flux. A similar analysis of C18O (1–0) based on a comparison with the 22" resolution spectra of Walsh et al. (2002) suggests that ~75% of the single-dish flux has been detected, consistent with the 13CO (1–0) value.

Data regarding 12CO (1–0) have been kindly provided by S. Ishizuki (Sakamoto et al. 1999) for comparison with the isotopic line data. While the data were taken at the Nobeyama Radio Observatory Millimeter Array (NRO), not OVRO, this difference should not strongly affect the maps, since the NRO

| TABLE 1 |
| --- |
| NGC 6946 BASIC DATA |
| --- |
| Characteristic | NGC 6946 | Reference |
| Hubble class | SAB(rs)cd | 1 |
| Near-IR center: | | |
| α (J2000.0) | 20 34 52.34 ± 0.2 | 2 |
| δ (J2000.0) | +60 09 13.7 ± 0.2 | 2 |
| Radio continuum peak: | | |
| α (J2000.0) | 20 34 52.20 ± 0.2 | 3 |
| δ (J2000.0) | +60 09 14.2 ± 0.2 | 3 |
| Dynamical center: | | |
| α (J2000.0) | 20 34 52.29 ± 2 | 4 |
| δ (J2000.0) | +60 09 14.5 ± 2 | 4 |
| $V_{\text{LSR}}$ (km s$^{-1}$) | 50 | 4 |
| Adopted distance (Mpc) | 5 | 5 |
| ι (deg) | 40 | 6 |
| P.A. (deg) | 242 | 6 |
| $L_{\text{IR}}/C_{6}$ (J2000.0) | 1.5 x 10$^{9}$ | 7 |
| $T_{\text{D}}$ (K) | 40 | 7 |

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**NOTE.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

**REFERENCES.**—(1) de Vaucouleurs, de Vaucouleurs, & Corwin 1976; (2) measured from 2MASS images; (3) Turner & Ho 1983; Tsai et al. 2004; 2 cm peak; (4) this paper; (5) Tully & Fisher 1988; (6) Crosthwaite & Turner 2004; (7) Engargiola 1991.

| TABLE 2 |
| --- |
| OBSERVATIONAL DATA |
| --- |
| Transition | $v_0$ (GHz) | $T_{\text{sys}}$ (K) | $\Delta V_{\text{chan}}$ (km s$^{-1}$) | $\Delta v_{\text{band}}$ (MHz) | Beam (arcsec; deg) | Noise Level (mK/mJy beam$^{-1}$) |
| 13CO (1–0) | 110.20 | 240–380 | 10.88 | 128 | 5.4 x 4.2; 82 | 44/10 |
| C18O (1–0) | 109.78 | 240–380 | 10.92 | 128 | 5.5 x 4.4; 83 | 44/10 |
| 2.7 mm | 110.0 | 240–380 | ... | 1000 | 5.5 x 4.3; 89 | 3.8/0.9 |
| 1.4 mm | 221.9 | 700–1600 | ... | 1000 | 5.5 x 4.3; 89 | 3.7/5.5 |

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* Dates for observations of NGC 6946 were 1999 September 26–1999 November 28, with a phase center: $V_{\text{LSR}} = 50$ km s$^{-1}$.

b 13CO (1–0) line contamination has been removed.

Convolved to the resolution of 2.7 mm. 
array is similar in layout to OVRO with similar (u, v) coverage. In addition, the Ishizuki $^{12}$CO (1–0) map recovers 76% of the single-dish flux over the mapped region (Sakamoto et al. 1999), a significant fraction of the total flux and very similar to that found for the isotopomers. Moreover, the similarity of the NRO map and the BIMA $^{12}$CO (1–0) map, which is more sensitive to extended emission (Regan & Vogel 1995; Helfer et al. 2003), demonstrates that the observed distribution is not a strong function of the array used.

To simplify the nomenclature, we use “CO” to denote the main isotopomer, $^{12}$C$^{16}$O, “$^{13}$CO” to denote $^{13}$C$^{16}$O; and “$^{18}$CO” to denote $^{12}$C$^{18}$O. The integrated line intensity ratios,

![Figure 1](image_url)

**Fig. 1**—$^{13}$CO (1–0) channel maps for the nucleus of NGC 6946. LSR velocities are listed at the top of each panel. The contours are plotted in intervals of 20 mJy beam$^{-1}$ (or 0.09 K for the 5$''$4 × 4$''$2 beam), corresponding to 2$\sigma$. The beam is plotted in the bottom left of the first panel.
3. RESULTS

3.1. Morphology and Kinematics of the CO Emitting Gas

The $^{13}$CO channel maps for NGC 6946 are presented in Figure 1. Peak antenna temperatures obtained from the $^{13}$CO channels are ~0.82 K. Emission is present in channels from $V_{\text{LSR}} = -43$ to 164 km s$^{-1}$. Redshifted velocities are toward the southwest. No significant differences between CO and $^{13}$CO velocity dispersions or systemic velocities are seen. The morphology and kinematics (not shown) of C$^{18}$O, though limited by faintness, are consistent with the $^{13}$CO data. Integrated intensity maps of the three CO isotopomers are presented to the same resolution and scale in Figure 2. Integrated intensities of each transition are listed in Table 3 for the locations of the GMCs.

The CO emission within the central 1.3 kpc (50") of NGC 6946 is spatially asymmetric (Regan & Vogel 1995; Sakamoto et al. 1999). The CO integrated intensity peaks at the starburst and remains relatively bright along the northern arm. The southern arm is weaker. The optical spiral structure of NGC 6946 also reflects this asymmetry, although on a much larger scale, with a "heavy" northern arm (Arp 1966).

By contrast, $^{13}$CO emission is more symmetric and spatially confined to the center of the galaxy than is CO. The $^{13}$CO emission is suggestive of a central disklike structure with the starburst occurring at the southwestern edge of the disk. A secondary peak in CO at the northern end of the molecular bar is also bright in $^{13}$CO. Lower resolution studies of the CO showed extended barlike CO and hints of noncircular motion suggesting that it is a true bar (e.g., Sofue et al. 1988; Ishizuki et al. 1990b). From their high-resolution CO map, Regan & Vogel (1995) argued that it is difficult to distinguish between a nuclear bar and a continuation of spiral arms based on morphology alone. Elmegreen, Chromey, & Santos (1998) suggested the possibility of nested bars in NGC 6946.

In Table 1 we have listed the near-IR centroid of NGC 6946 as measured from 2MASS $J$, $H$, and $K$ images. The peak 2 cm continuum emission (Tsai et al. 2004) is located ~1" east-northeast of the near-IR center, although this emission is

![Figure 2](image).

### Table 3: Measured Intensities and Temperatures in NGC 6946

| GMC | $I^{12}$CO (1–0) | $I^{13}$CO (1–0) | $T^{13}$CO (1–0) | $I^{[13]}$CO (1–0) | $T^{[13]}$CO (1–0) |
|-----|----------------|----------------|----------------|----------------|----------------|
|     | (K km s$^{-1}$) | (K km s$^{-1}$) | (K)            | (K)            | (K)            |
| A   | 100 ± 16       | 64 ± 2         | 0.28 ± 0.05    | <3.6           | 0.13 ± 0.05    |
| B   | 120 ± 16       | 17 ± 2         | 0.59 ± 0.06    | 9.0 ± 1.8      | 0.17 ± 0.05    |
| C   | 87 ± 16        | 64 ± 2         | 0.29 ± 0.05    | 7.2 ± 1.8      | 0.15 ± 0.05    |
| D   | 74 ± 16        | 86 ± 2         | 0.50 ± 0.05    | 11 ± 1.8       | 0.20 ± 0.05    |
| E1  | 650 ± 65       | 64 ± 6         | 0.82 ± 0.08    | 31 ± 3         | 0.33 ± 0.05    |
| E2  | 590 ± 59       | 50 ± 5         | 0.59 ± 0.06    | 10 ± 1.8       | 0.22 ± 0.05    |
| F   | 300 ± 30       | 20 ± 2         | 0.32 ± 0.05    | 9.4 ± 1.8      | ~0.11          |
| G   | 300 ± 30       | 20 ± 2         | 0.45 ± 0.05    | <3.6           | 0.22 ± 0.05    |
| H   | 74 ± 16        | 36 ± 2         | 0.19 ± 0.05    | <3.6           | <0.11          |
| ARM | 270 ± 27       | 47 ± 2         | 0.14 ± 0.05    | <3.6           | <0.11          |

* Uncertainties are the larger of the map uncertainty or the absolute calibration uncertainties. Upper limits are 2σ.
* Positions are those labeled in Table 4 and Fig. 4a.
* Taken from the Sakamoto et al. 1999 data.
* The position of the “ARM” measurement corresponds to $\alpha = 20 34 51.20, \delta = +60 09 28.4$ (J2000.0).
extended. The dynamical center is, within the uncertainties, coincident with the near-IR peak, as one might expect if the near-IR emission traces the mass, whereas the $^{13}$CO peak is $\sim2''$ east-southeast of the near-IR peak.

To study the impact of the galactic potential on the molecular gas, we first investigate the kinematics of the nucleus. We use two methods to study the velocity field in NGC 6946. First, we fit the entire velocity field to a disk in circular rotation and use this to determine the azimuthally averaged rotation curve of the central region (Fig. 3a). Second, position-velocity (PV) diagrams are constructed along the major and minor axes (Fig. 4). The major-axis PV diagram should essentially trace out the same shape as the rotation curve (reflected through the origin), but it also provides additional information on the distribution of emission versus velocity. Comparison of the major-axis PV diagram in Figure 4b with the rotation curve of Figure 3a demonstrates this is true. The rotation curve increases steeply for $\sim7.5''$ then turns over and falls for $\sim5''$ before it reverses and continues to rise out to larger distances. The radius of turnover corresponds to the edge of the central ring. The same structure can be seen in the PV diagram. In Figure 4b the two emission peaks on either side of the center of the major-axis PV diagram hint that the disklike structure seen in the isotopomers does not extend all the way to the center of the galaxy and hence is ringlike (compare Fig. 4b with Fig. 5 of Sakamoto et al. 1999). The central ringlike structure may reflect the $x_2$ orbits of an inner Lindblad resonance (ILR) or possibly gas response to the small inner bar.

In the case of pure circular motion the PV diagram taken along the minor axis predicts emission only at zero velocity, since all motion would be in the plane of the sky at these locations. Deviations from this imply radial motions are present. In Figure 4c a large percentage of the emission over the central $5''$ radius is blueshifted on the southeast side of the galaxy and redshifted on the northwest side of the galaxy. Since the northern molecular arm is the near one (Elmegreen, Chromey & Santos 1998; Regan 2000), consistent with trailing spiral arms, these shifts imply that the gas is orbiting radially inward from both sides. Radial velocities peak at $|v_r| \sim 80$ km s$^{-1}$ at the center, decreasing as one moves away from the center of the galaxy. Strong radial motion is not obvious beyond a radius of $\sim7''$. Either the gas inflow strengthens as the nucleus is approached, or more likely the gas streamlines are turning progressively more radial with decreasing galactocentric distance.

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**Fig. 3.**—(a) Observed and fitted rotation curve of the central arcminute of NGC 6946. Circles mark the measured azimuthally averaged velocity vs. radius, and short vertical bars are the uncertainty. The fitted model (thick solid line) consists of two mass distributions corresponding to Brandt rotation curves (see text for details). The pattern speed appropriate for the nucleus, $\Omega_p = 66$ km s$^{-1}$ kpc$^{-1}$ (thin solid line) is taken from (Crosthwaite & Turner 2004), based on the large-scale disk velocity field traced by CO (1–0) and H I. $\Omega_L$ is the angular velocity of the gas and $\kappa$ is the epicyclic frequency. The intersections of $\Omega_p$ with the $\Omega_p - \kappa$ curve (dotted line) mark the locations of the ILR ($\sim 7.5''$) and OILR ($\sim 26''$) for this same pattern speed. (b) Observed azimuthally averaged molecular gas surface density, $\Sigma_0$ (dotted line), based on the $^{13}$CO column density derived in $\S$ 4.2 for the central 30''. The cumulative dynamical mass interior to a given radius based on the model rotation displayed in (a) is also shown (solid line). Given the rotation curve in (a) and the gas surface density, we calculate and display the Toomre Q parameter (dot-dashed line) for the central region of NGC 6946. The surface density axis is on the left-hand side, while the dynamical mass axis is on the right-hand side in units of $10^6 M_\odot$. Q uses the same axis as surface density but is unitless. All rotation curve data have been corrected for inclination.

**Fig. 4.**—PV diagrams of NGC 6946 taken from the $^{13}$CO (1–0) data. (a) $^{13}$CO (1–0) integrated intensity map of NGC 6946 contoured as in Fig. 2a. Fitted GMCs are labeled on the figure, as well as the locations at which the PV slices have been measured. The PV diagram for the major (b) and minor (c) axes. PV diagrams are contoured in steps of 3 $\sigma$. 

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The overall kinematics of NGC 6946’s nucleus can be explained either as noncircular motions in response to a barred potential or as a region of enhanced mass density in the nucleus. In the case of a barred potential noncircular motions “contaminate” the rotation curve, causing the observed rotation curve to develop breaks (e.g., Sakamoto et al. 1999). Radial inflow will raise the inferred circular velocities. If the radial flow dominates over a narrow radii around the molecular ring, the velocity peak at $700$ is explained. Therefore, the noncircular motion associated with a barred potential provides a good explanation for both the radial motions seen in the minor-axis PV diagram and the turnover in the rotation curve.

Alternatively, the rotation curve could be due to a compact nuclear mass distribution. This would affect the dynamics and the location of orbital resonances. In Figures 3a–3b the rotation curve of NGC 6946 is shown fitted with a two-component mass density distribution: one with a characteristic scale of $275$ pc ($1100$) and a peak velocity of $175$ km s$^{-1}$, roughly consistent with the size of the secondary nuclear bar (Elmegreen, Chromey, & Santos 1998), and the other with a scale of $5$ kpc ($2000$) that reaches the same peak velocity. This two-component mass distribution matches the observed velocity profile. If we (somewhat arbitrarily) assume the density wave pattern speed determined for the large-scale disk

![Figure 5](image-url)
of \(\omega_p \simeq 66 \text{ km s}^{-1} \text{kpc}^{-1}\) is the same for both, the “buckle” in the nuclear rotation curve corresponds to an inner ILR near the ring, at a radius of 7.5, and the location of the clumps at the ends of the molecular bar would correspond to an outer ILR, at a radius of 26.

Given the strong noncircular motions across the nuclear region, we favor a barred potential over a central mass for explaining the gas morphology and kinematics.

### 3.2. Properties of the Nuclear GMCs in NGC 6946

GMCs in NGC 6946 are identified from the 13CO data. The method of localizing and fitting the GMCs is the same as given in Meier & Turner (2001). Results are given in Table 4 and Figure 4a. Given a distance of 5.2 Mpc (1'' \(\simeq 25\) pc), only the larger GMCs are spatially resolvable (fitted sizes greater than one-half the FWHM of the beam size). GMCs that are off the central ring region (A, C, D, H, G) are the most isolated, and hence their fits are the most robust. GMCs away from the central ring generally have deconvolved sizes \(\sim 50–100\) pc in size, FWHM line widths of 25–40 km s\(^{-1}\) and predicted virial masses of \(\sim 10^7 M_\odot\). The central ring GMCs have implied virial masses of \(\sim 10^8 M_\odot\); however, while NGC 6946 is not highly inclined (\(i = 40^\circ\)), the GMCs that are centered along the central ring almost certainly have line widths contaminated by the steep rotational velocity gradient and noncircular motions present. The derived virial masses are consistent with the enclosed dynamical masses (§ 4.2).

### 3.3. The High and Variable Isotopic CO Line Ratios in NGC 6946

Figure 5 (and Table 5) shows the \(R_{13}\) and \(R_{18}\) isotopic line ratio maps for the nucleus of NGC 6946. Two unusual characteristics of the line ratios are evident: there are regions with very high values compared with the Galaxy, and the ratios vary rapidly across the nuclear region. Over the mapped regions, \(R_{13}\) reaches values greater than 25 along the northern arm. By comparison, Galactic disk molecular clouds generally have values of 6–7 (Polk et al. 1988). In almost all cases 13CO (C\(^18\)O for \(R_{18}\)) limits the region covered by the ratio map, which implies that blanked regions in Figure 5 have even higher \(R_{13}\), with values as high as 60 estimated for in these regions.

### Table 5

| GMC | \(^{12}\text{CO}(1\text{--}0) / ^{13}\text{CO}(1\text{--}0)\) | \(^{12}\text{CO}(1\text{--}0) / C^{18}\text{O}(1\text{--}0)\) | \(^{13}\text{CO}(1\text{--}0) / C^{18}\text{O}(1\text{--}0)\) |
|-----|----------------|----------------|----------------|
| A   | 16 ± 6         | >28            | >1.8           |
| B   | 7.1 ± 1        | 13 ± 3         | 1.9 ± 0.4     |
| C   | 14 ± 5         | 12 ± 5         | ~0.9          |
| D   | 8.6 ± 3        | 6.7 ± 2        | ~0.8          |
| E1  | 10 ± 2         | 21 ± 3         | 2.1 ± 0.3     |
| E2  | 12 ± 2         | 59 ± 12        | 5.0 ± 1       |
| F   | 15 ± 2         | 32 ± 7         | 2.1 ± 0.5     |
| G   | 15 ± 2         | >170           | >11           |
| H   | 21 ± 13        | >21            | >1            |
| ARM | 57 ± 25        | >75            | >1            |

Fig. 6.—Millimeter continuum maps of the nucleus of NGC 6946. (a) The 110 GHz (2.7 mm) continuum map for NGC 6946 overlaid on the HST P28 NICMOS image (Böker et al. 1999), smoothed to the same resolution. Contours are in steps of the 2 \(\sigma\) value of 2.0 mJy beam\(^{-1}\). This map has been corrected for 13CO (1--0) contamination. (b) The 222 GHz (1.4 mm) continuum emission from NGC 6946 overlaid on the 13CO (1--0) gray scale. Contours are in steps of the 2 \(\sigma\) value of 7 mJy beam\(^{-1}\).
blanked regions. The lower values of $R_{13}$ are $\sim$10 near the starburst, more consistent with what is typically seen in starburst nuclei (e.g., Aalto et al. 1991, 1995). The lowest isotopic line ratios ($R_{13} \approx 4$–5) are found $\sim$5° east of the main starburst, extending perpendicular to the main CO arms. Along the northern arm gas transitions from its lowest values of $R_{13}$ to $R_{13} \geq 25$ in one beamwidth ($\leq$100 pc). The transition from $R_{13} \sim 10$ regions dominating toward the starburst to $R_{13} \geq 25$ is even sharper, being unresolved by our beam. Evidently, just outside the central ring the molecular gas undergoes a sharp change in gas physical conditions.

To test whether the high isotopic ratio could be due to a larger amount of flux resolved out of the $^{13}$C transition versus the CO, we have taken 26% of the total CO flux (the percentage of the flux resolved out at CO) and distributed it uniformly over the central 30° × 60° and 38% of the $^{13}$CO and distributed it uniformly over the same region, and then recalculated $R_{13}$. This approximates what we would expect to see if the fluxes resolved

### Table 6

| GMC     | $X^{12}$CO/H$_2$ | $^{13}$N$_{H_2}$ | $X^{12}$CO/13CO | $^{12}$N$_{H_2}$ | $^{13}$N$_{H_2}$ | $^{12}$CO/13CO | $^{13}$CO/12CO | $^{12}$CO/13CO |
|---------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| A       | 2.0 ± 0.3        | 0.31 ± 0.1       | <0.37           | 6.8              | 6.7 ± 2          | >5.4             |
| B       | 2.4 ± 0.3        | 0.31 ± 0.1       | 0.96 ± 0.2      | 2.9 ± 0.5        | 2.5 ± 0.7        |
| C       | 1.7 ± 0.3        | 0.31 ± 0.1       | 0.72 ± 0.2      | <4.0             | 5.5 ± 2          | 2.4 ± 0.7        |
| D       | 1.5 ± 0.3        | 0.41 ± 0.1       | 1.1 ± 0.2       | 3.1              | 3.7 ± 1          | 1.4 ± 0.3        |
| E1      | 13 ± 1.3         | 3.1 ± 0.3        | 3.2 ± 0.2       | 4.2 ± 0.7        | 4.1 ± 0.7        |
| E2      | 12 ± 1.2         | 2.4 ± 0.3        | 1.0 ± 0.2       | 5.0 ± 0.8        | 12 ± 3           |
| F       | 6.0 ± 0.6        | 0.98 ± 0.1       | 0.96 ± 0.2      | 6.1 ± 1          | 6.3 ± 1          |
| G       | 6.0 ± 0.6        | 0.98 ± 0.1       | <0.37           | 6.6              | 6.1 ± 1          | >16              |
| H       | 1.5 ± 0.3        | 0.17 ± 0.1       | <0.37           | 1.6              | 8.8 ± 5          | >4.1             |
| ARM     | 5.4 ± 0.5        | 0.22 ± 0.1       | <0.37           | 25 ± 10          | >15              |

* None of the column densities have been corrected for resolved-out flux. To account for this $^{13}$N$_{H_2}$ (and presumably the $^{18}$N$_{H_2}$) should be divided by $\sim$0.63 and $X^{12}$N$_{H_2}$ should be divided by $\sim$0.76. Uncertainties reflect only the statistical uncertainties and not the potentially larger systematic uncertainties associated correct abundance ratio and $T_{ex}$ (see text). Upper limits are 2 $\sigma$.

b Based on the LTE assumption with $T_{ex} = 20$ K, and $^{12}$CO/$^{13}$CO = 40.

b Based on the LTE assumption with $T_{ex} = 10$ K, and $^{12}$CO/$^{13}$CO = 150.

d Based on the virial masses derived for the isolated GMCs (Table 4).

c Based on the position for “ARM” given in Table 3.

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**Fig. 7.** CO LVG models. (a) LVG models for the $R_{13}$ and $R_{13}$ line ratios for a “standard” abundance per velocity gradient determined by $^{12}$CO/H$_2$ = 8.5 × 10$^{-4}$, and $dN/dr$ = 3.0 km s$^{-1}$ pc$^{-1}$ and $^{12}$CO/$^{13}$CO = 40 and $^{12}$CO/$^{13}$CO = 150. The observed values toward E1 plus their ±$\sigma$ range of $R_{13}$ and $R_{13}$ are plotted (Table 5). The fact that the acceptable parameter space implied from $R_{13}$ is slightly lower than that implied by $R_{13}$, suggests that $^{13}$CO/$^{12}$CO has been slightly overestimated. The two curves coincide for an abundance ratio of $[CO/^{13}$CO] $\approx$ 60 and $[CO/^{13}$CO] $\approx$ 150. Also overlaid for reference is the location where the $^{12}$CO (1–0)/HCN (1–0) line ratio is unity, assuming $X_{HCN}/X_{CO} = 1.3 \times 10^{-7}/3$ km s$^{-1}$ (see text). The single-dish $^{12}$CO (3–2)/$^{13}$CO (1–0) line ratio is shown, along with an asterisk marking the derived kinetic temperature and density of (Walsh et al. 2002). Overlap of the large-scale CO (3–2)/CO (1–0) ratio with $R_{13}(E1)$ gives an estimate of the large-scale average excitation. On the other hand, the overlap between $R_{13}(E1)$ and $^{13}$CO (1–0)/HCN (1–0) gives an indication of the local ($\sim$5°) physical conditions toward E1. The $R_{13}$ = 30 contour is also displayed to show the constraint on the parameter space suitable for the molecular arm regions [labeled “$R_{13}(ARM)$”]. Since along the arms $R_{13} \geq 30$, acceptable densities are $n_{H_2} \leq 10^4$. (b) Same plot as in (a), except for a velocity gradient (abundance) 4 times larger (smaller). This gives an indication of the sensitivity of the models to changes in abundance per velocity gradient and may represent models more suitable to the large line width central molecular ring.
out of each map were distributed uniformly over the largest spatial scales. The newly calculated 2σ lower limit to $R_{13}$ at the arm locations become greater than 47. Therefore, the very high ratios in the arm region cannot be due to differentially resolved-out flux. Similar results are seen in $R_{14}$, when taking account its more limited coverage, providing further evidence for true changes in gas physical conditions and not just anomalies in $^{13}$CO. Typical values of the $^{13}$CO/$^{18}$O line ratio toward the high S/N regions is $\sim 2.5$.

Comparisons with interferometric HCN (1–0) data show that within the uncertainties the morphology of the $^{13}$CO and C$^{18}$O transitions match closely what is seen in the HCN (1–0) (Helfer & Blitz 1997). The HCN/CO ratio map of Helfer & Blitz (1997) correlates well with the inner structure of $R_{13}$. Both show a "saddle"-shaped distributed approximately perpendicular to the CO arms (Helfer & Blitz 1997). This suggests that density changes sensitively influence the isotopic line intensities.

3.4. Millimeter Continuum from Star-forming H II Regions in NGC 6946

Displayed in Figure 6 are the 2.7 mm continuum map of NGC 6946 overlaid on the HST $P_{\nu}$ image (Böker et al. 1999), convolved to the same beam size as the OVRO maps, and the 1.4 mm continuum map overlaid on the $^{13}$CO (1–0) integrated line intensity map. The 2.7 mm continuum is reliably detected at only one location, the north-northwest of GMC E1. Its position is within 1″ of the 2 cm continuum peak (Tsai et al. 2004). A Gaussian fit shows that the 2.7 mm source is slightly resolved with a size of $7″ \times 2″$ (P.A. $\approx 120°$) and a total flux of $S_{2.7 \text{mm}} = 8.3 \pm 1.0$ mJy. The full-resolution HST $P_{\nu}$ image, which is sensitive to weaker star formation than the millimeter continuum, also shows a secondary star-forming peak just east of the starburst, at the secondary HCN peak and the $R_{13}$ minima, as well as faint H II regions encircling the entire central ring (Böker et al. 1999). The total flux detected at 2 cm is 23 mJy (Turner & Ho 1983). The spectral index between 2 cm and 2.7 mm is $\alpha_{2.7 \text{mm}} \approx -0.51 \pm 0.07$. Hence, the starburst is a mixture of bremsstrahlung and synchrotron at 2 cm, which is consistent with the 6–2 cm spectral index (Turner & Ho 1983) and the distribution of compact sources (Tsai et al. 2004).

Continuum emission is also detected at 1.4 mm toward GMC E1. The source at 1.4 mm has a size similar to that found at 2.7 mm. The total flux at 1.4 mm is 21 ± 4 mJy. The 2.7–1.4 mm spectral index implied by this flux is $\alpha_{2.7 \text{mm}} = +1.4 \pm 0.5$. The rising spectral index suggests that dust emission begins to contribute at 1.4 mm. Assuming for simplicity that all of the 2.7 mm flux is a mixture of thermal free-free emission with a spectral index of $\alpha = -0.1$ and dust emission with a spectral index of $\alpha = +3.5$, which slightly overestimates the free-free emission since some 2.7 mm may still be synchrotron, we derive free-free fluxes of $\sim 7.0$ mJy at 2.7 and $\sim 6.5$ mJy at 1.4 mm, and dust fluxes of 1.2 mJy at 2.7 mm and 14 ± 5 mJy at 1.4 mm. The dust flux is confined within the $\sim 6″$ associated with GMC E1. The molecular mass implied by the dust emission is discussed in § 4.2.

Using the 2.7 mm continuum to constrain the number of ionizing photons, (and hence massive stars), a Lyman continuum rate of $N_{\text{LyC}} = 2.1 \pm 0.2 \times 10^{52}$ s$^{-1}$, or 2800 "effective" O7 V stars is obtained (assuming $T_{\star} = 8000$ K; e.g., Mezger & Henderson 1967; Vacca, Garmany, & Shull 1996). This is a factor of 2 higher than is estimated from BRγ data by Engelbracht et al. (1996). High extinction is probably the explanation for the difference, given that the H$_2$ column densities are at least $\sim 1–3 \times 10^{22}$ cm$^{-2}$ ($A_V \sim 6–17$; Table 6).

4. DISCUSSION

4.1. Physical Conditions of the Molecular Clouds in NGC 6946

To relate the observed intensities and line ratios to physical properties of the clouds, $n_{H_2}$ and $T_k$, a sample of large velocity gradient (LGV) radiative transfer models were run (e.g., Goldreich & Kwan 1974; Scoville & Solomon 1974; de Jong, Dalgaro, & Chu 1975). For very opaque lines, LVG models can be unreliable, but for the lower opacity $^{13}$CO and C$^{18}$O transitions, LGV models are expected to yield reasonable results. The LGV model used is the same basic model discussed in Meier, Turner, & Hutt (2000), expanded to cover $n_{H_2} = 10^1–10^6$ cm$^{-3}$, $T_k = 1.5–150$ K, and $X_{\text{CO}}/dv/dr = 10^{-3}–10^{-7}$. A [CO/H$_2$] abundance of $8.5 \times 10^{-5}$ (Ferking et al. 1982) and a velocity gradient of 3 km s$^{-1}$ pc$^{-1}$ was adopted as the standard case. A wide range of $^{13}$CO and C$^{18}$O relative abundances and velocity gradients were tested. Figure 7a displays the results assuming [CO/$^{13}$CO] $\approx 40$ and [CO/$^{18}$O] $\approx 150$, typical values for starburst nuclei (Henkel & Mauersberger 1993; Wilson & Rood 1994; Wilson 1999). Only ratios are used to constrain parameter space, so the derived solutions are independent of filling factors, as long as they are the same for both transitions.

In addition to the CO LGV models, a set of HCN LGV models were run. The first 12 $J$ transitions were included since collision coefficients are available only for those (Green & Thaddeus 1974). We do not extend the models to densities larger than $10^5$ cm$^{-3}$ to avoid significant populations in $J_{\text{max}}$; our derived densities are lower than this anyway. An HCN abundance, [HCN/H$_2$] = $1.5 \times 10^{-8}$, consistent with galactic HCN abundances (e.g., Irvine, Goldsmith, & Hjalmarson 1987; Paglione et al. 1998), and a velocity gradient of 3 km s$^{-1}$ pc$^{-1}$ was assumed. From the observed ratios $R_{13}$, $R_{18}$, and $^{13}$CO/HCN, physical conditions for the starburst region E1 were estimated.

Since both the $^{13}$CO and C$^{18}$O lines are optically thin (§ 4.2), $R_{13}$ and $R_{18}$ should provide similar constraints on gas density, $n_{H_2}$, and kinetic temperature, $T_k$, with any differences ascribed to inaccuracies in the adopted $[^{13}$CO/$^{18}$O] abundance ratio. Both $R_{13}$ and $R_{18}$ predict $n_{H_2} \sim 10^{2.5}–10^4$ cm$^{-3}$ and $T_k \sim 10–40$ K ranging to $n_{H_2} \sim 10^4$ cm$^{-3}$ and $T_k \sim 100–150$ K. $R_{13}$ predicts a slightly lower range in $n_{H_2}$, $T_k$ than does $R_{18}$. This suggests that the adopted [CO/$^{13}$CO] abundance ratio is slightly overestimated. The solution ranges agree if the [CO/$^{18}$O] abundance ratio is lowered from 3.75 (150/40) to $\sim 2.5$ (150/60).

Further constraints on $n_{H_2}$ and $T_k$ can be obtained by adding the $^{13}$CO/HCN line ratio, from HCN observations of Helfer & Blitz (1997) at a nearly identical beam size. Toward GMC E1, $^{13}$CO/HCN $\approx 1.0 \pm 0.2$. The similarity in intensity of the $^{13}$CO and HCN lines immediately argue for high densities ($n_{H_2} \approx 10^4$), as required to thermalize HCN. The best fit, including HCN, is $n_{H_2} \approx 10^{12}$ cm$^{-3}$ and $T_k \approx 90$ K. The single-dish value of a characteristic $\Delta v$ line ratio, CO (3–2)/CO (1–0) is 0.71 ± 0.2 (Walsh et al. 2002). Using this line ratio with $R_{13}$ or $R_{18}$ favors $n_{H_2} \sim 10^4$ cm$^{-3}$ and $T_k \sim 30$ K, consistent with the $n_{H_2} \sim 10^{14}$ cm$^{-3}$, $T_k \sim 40$ K obtained by Walsh et al. (2002). The fact that the high-resolution interferometer data toward the starburst favors warmer, denser solutions than those obtained from single-dish data suggests that the molecular
clouds are cooler and less dense outside the central starbursting ring and that this lower excitation, diffuse molecular component dilutes the single-dish ratios.

In the case of the high R13 ratio arm regions, for [CO/13CO] = 40 and R13 > 40, no portion of parameter space in the standard model is acceptable. Assuming LVG is applicable, we are forced to conclude that the 13CO relative abundance is lower than the assumed value of [CO/13CO] = 40, and densities are n_H2 ≤ 10^2 cm^-3. At these low densities 13CO emission is strongly subthermal, and R13 and R18 are approximately independent of T_k. These constraints can be loosened somewhat by raising X_CO/uv significantly (Fig. 7b), but it is unclear how the velocity gradients could be stronger along the arms than in the high line width, central ring region (Table 4). Single-dish observations of the higher J transitions CO (2–1)/CO (1–0), CO (3–2)/CO (2–1) and CO (4–3)/CO (3–2) line ratios all decrease up the northern arm (Wall et al. 1993; Nieten et al. 1999; Israel & Baas 2001; Walsh et al. 2002). While not extremely low, these ratios do suggest that even the higher opacity (less subthermal) CO transitions may not be highly excited.

In summary, the LVG solutions for n_H2 and T_k based on single-dish ratios (~22'' beam) are lower than our interferometer solutions because the large single-dish beam size averages the low density, lower temperature spiral arm gas with the warmer, denser molecular gas associated with the starburst. The bright, compact starburst gas dominates the interferometer maps. On the basis of the incompatibility of the line ratios with the CO line intensity, it has been argued that the nuclear ISM in NGC 6946 requires at least two distinct components with distinct physical conditions (Paglione et al. 2001; Israel & Baas 2001). Our interferometer images confirm this conclusion and resolves the spatial distribution of each component.

4.2. CO as a Tracer of Molecular Gas Mass: The Conversion Factor in the Nucleus of NGC 6946

One might expect that the unusual and varying cloud conditions in NGC 6946’s nucleus will have an affect the CO conversion factor, X_CO, which is based on Galactic clouds that have relatively uniform properties. Therefore, we consider in detail an estimate of the conversion factor suitable to the nucleus of NGC 6946. To obtain a robust estimate of the amount of molecular gas, column densities derived from the optically thick CO integrated intensity and X_CO are compared with four independent estimates of the column density: from the optically thin 13CO and C18O lines, from the virial theorem, and from dust.

Table 6 records the column densities derived from CO and a Galactic conversion factor of X_CO = 2.0 × 10^20 cm^-2 (K km s^-1)^{-1} (Strong et al. 1988; Hunter et al. 1997). Column densities are derived from the isotopomers using

\[ N(\text{H}_2)_{13\text{CO}} = 2.42 × 10^{14} \text{cm}^{-2} \left( \frac{[\text{H}_2]/[\text{CO}]}{[\text{H}_2]/[\text{CO}]} \right) \left( \frac{e^{(E_s/T_{ex})}}{e^{(E_s/T_{ex})}} - 1 \right) \text{I}_{13\text{CO}} \text{ (K km s}^{-1}) \]

where E_s is 5.29 K (5.27 K) for 13CO (C18O), and abundances listed in Table 6. Excitation temperatures of 13T_ex = 20 K and 18T_ex = 10 K were adopted, taking into account the fact that the isotopomers are likely increasing subthermal at the relevant densities (§ 4.1). Derived column densities vary approximately linearly with the chosen T_ex, so uncertainties in N_H2 scale with T_ex. Non-LTE effects such as temperature gradients may explain some portion of the high observed R13 ratio (e.g., Meier, Turner, & Hurt 2000), although we doubt the uncertainties are high enough here (see below). Taking into account uncertainties in T_ex and abundances, we expect that column densities of N_H2 derived from isotopomers are accurate to about a factor of 2.

For molecular clouds with density profiles given by ρ ∝ R^-1, the virial mass is \( M_v = 189 (\Delta v_{1/2} \text{ km s}^{-1})^2 (R/\text{pc}) \), (e.g., MacLaren, Richardson, & Wolfendale 1988), where R is the radius of the cloud, and Δv_{1/2} is the FWHM of the line width (following Meier & Turner 2001). The radius of the clouds is assumed to be 0.7(ab^{1/2}), where a and b are the FWHM fitted sizes of the major and minor axes. Virial cloud masses are displayed in Table 6. Virial masses are always much larger than those found by any other method, even for GMCs far away from the central high line width molecular ring. In general, the virial estimates of column densities are much greater even than the column densities estimated from CO (e.g., Meier & Turner 2001). This confirms that GMC line widths are not virial across the nucleus and are dominated by rotational and noncircular motion.

For clouds that are entirely molecular and have a constant gas-to-dust ratio of 100 by mass, the gas mass is related to the 1.4 mm dust continuum flux by (e.g., Hildebrand 1983)

\[ M_{\text{gas}}(1.4 \text{ mm}) = 310 \, M_\odot \left( \frac{S_{4 \text{mm}} \text{ mJy}}{D \text{ Mpc}} \right)^2 \left( \frac{\kappa_{\nu}}{\text{cm}^2 \text{ g}^{-1}} \right) \left( \frac{e^{10.56/T_d} - 1}{D^2} \right), \]

where \( \kappa_{\nu} \) is the dust absorption coefficient at this frequency, \( S_{4 \text{mm}} \) is the 1.4 mm flux, D is the distance, and \( T_d \) is the dust temperature. \( T_d = 40 \text{ K} \) is assumed for the nucleus of NGC 6946 (Engargiola 1991), although the \( T_d \) suitable for the 1.4 mm emission could be lower. The dust opacity, \( \kappa_{\nu} \), at 220 GHz is taken to be 3 × 10^{-3} cm^2 g^{-1}, but is uncertain to a factor of 4 (Pollack et al. 1994). Dust masses determined from millimeter continuum are only linearly dependent on \( T_d \), so dust opacity dominates the uncertainty in the mass. The derived total molecular gas mass of GMC E1 based on its dust emission, is \( M_{\text{gas}}(M_\odot) \approx 1.2 \pm 0.4 \times 10^7 M_\odot \). The mass is consistent with the 13CO mass. If one instead uses the dust extinction toward the starburst derived from the NIR, \( A_V \geq 10.4 \) (Engelbracht et al. 1996), assumes the starburst is in the center of the GMC, and applies the Galactic conversion between \( N(\text{H}_2) \) and \( A_V \) (Bohlin, Savage, & Drake 1978), a column density of \( N(\text{H}_2) \sim 2 \times 10^{22} \text{ cm}^{-2} \) estimated, within a factor of 50% of the value obtained from 13CO.

Column densities obtained from 13CO and C18O are lower than what is implied by CO: values estimated from 13CO are low by a factor of 5 ± 2, and those from C18O are low by a factor of 3 ± 2. The agreement between the 13CO and C18O masses is generally good in the high S/N regions, with the exception of E2. The slight difference between the magnitude of X_CO between 13CO and C18O can be explained in one of two ways. Either 13CO is optically thick, with opacities, 13T_ex ~ 5/3, or the relative isotopic abundances that we have assumed are incorrect (§ 4.1). It is unlikely that the isotopomers are optically thick; even at E1, an opacity of 13T_ex ~ 0.1 is estimated given the observed line width; along the northern arm even CO may not be very optically thick in this region (assuming CO is optically thin one obtains column densities less than a factor of 2 higher than the 13CO value). The more likely explanation is that...
and derives conversion factors of 6946 sation factor. Regan (2000) has undertaken a detailed, multicolor masses agree with the values obtained from the isotopomers averages than seen anywhere in the Galaxy. Moreover, the dust peaks represent density peaks (§ 4.1), and in general far–IR fluxes are more tightly correlated with HCN than they are with CO (Gao & Solomon 2003).

4.4. Causes of High \( R_{13} \) in NGC 6946: Low-Density and CO and C\(^{18}\)O Abundance Enhancements

A number of possible explanations for the simultaneously very bright CO and weak 13CO has been suggested in the literature, primarily in the context of strong starbursts associated with distant mergers. Two main classes of possibilities are envisioned for generating high \( R_{13} \) ratios in NGC 6946. A first class of possibilities requires unusual isotopic abundances. This might occur through the inflow of metal-poor disk gas from the outer disk, isotope-selective fractionation or photodissociation, or chemical evolution due to pollution from in situ nuclear star formation (Casoli, Dupraz, & Combos 1992; Henkel & Mauersberger 1993; Taniguchi & Ohyama 1998; Taniguchi, Ohyama, & Sanders 1999). The second class of possibilities involve changes in physical conditions of the molecular gas, which lower the CO opacity. This could be caused by unusually high average gas temperatures, unusually low average gas densities, or unusually high cloud velocity dispersions (Aalto et al. 1991, 1995; Glenn & Hunter 2001; Paglione et al. 2001). Previous work has been limited by lack of spatial resolution, and it is clear from these ratio maps that the cloud properties vary rapidly across the nucleus. The high spatial resolution (≤100 pc) of these images (and also IC 342; see Meier, Turner, & Hurt 2000; Meier & Turner 2001) and this nearby galaxy allow for a clearer understanding of what molecular traits are most closely connected to the high \( R_{13} \) gas.

4.4.1. High \( R_{13} \) from Opacity Effects

We first discuss models that account for the anomalously high \( R_{13} \) with changes in line opacity due to variations in physical conditions, such as \( n_{\text{H}_2}, T_\text{e} \), or velocity dispersion. The most direct way to raise \( R_{13} \) (or \( R_{12} \)) is to decrease the opacity of each line. The first way to do this is to raise \( T_\text{e} \). As \( T_\text{e} \) increases, the optically thinner low \( J \) transitions of 13CO (and C\(^{18}\)O) depopulate, lowering their opacities and brightness temperatures, while the brightness temperature of the optically thick CO line increases. So long as the 13CO opacity is not greater than unity, \( R_{13} \) will increase as \( T_\text{e} \) increases. In NGC 6946 this is probably not the primary mechanism for enhanced \( R_{13} \) since the regions with the highest \( R_{13} \) are not found near the star-forming regions, where the gas should be warmest (Fig. 8a). However, changes in \( T_\text{e} \) cannot be ruled out completely until the gas temperature distribution is determined from high-resolution, multiline analysis.

A second way of lowering the opacity of the molecular gas is dynamical. Broadening the line width of the molecular gas spreads the total column density over a larger line width, reducing the opacity at a given velocity, hence raising \( R_{13} \) (Aalto et al. 1995). It is clear from Figure 8b that there is no correlation between \( R_{13} \) and \( \Delta v \) locally in NGC 6946. In fact, the locations of the highest line width are found toward the central ring, but these areas tend to have the lowest \( R_{13} \) (Table 5). Moreover, if, in general, changes in line width
dominated, one would expect a correlation between $R_{13}$ and galaxy inclination, which is not seen (Sage & Isbell 1991; Paglione et al. 2001). It is unlikely, therefore, that broadened line widths are the reason for the high $R_{13}$.

Alternatively, $R_{13}$ can be increased by reducing the gas density. Because of radiative trapping, the critical density of CO is much lower than for $^{13}$CO or C$^{18}$O. The critical density for the $^{13}$CO line is $n_{cr} \approx 2 \times 10^3$ cm$^{-3}$, compared with $2 \times 10^3/n_{12}$cm$^{-3}$ for CO. Line intensities drop rapidly when the gas density is below the critical density. At densities of a few hundred per cubic centimeter CO is still bright, but $^{13}$CO and C$^{18}$O are subthermally excited and faint. Moreover, at such low densities intensities of the dense gas tracers such as HCN ($n_{cr} \approx 10^5 r_{HCN}$ cm$^{-3}$) decrease dramatically. This scenario explains well the overall structure of $R_{13}$ in NGC 6946 and in IC 342 (Meier, Turner, & Hurt 2000; Meier & Turner 2001). In fact, in galaxies with gas densities of $\sim 10^3$ cm$^{-3}$ the isotopomers become powerful density probes (note that the $R_{13}$ contours are approximately horizontal in Figure 7 at densities below $\sim 10^4$ cm$^{-3}$). This also provides a natural explanation for the “underluminosity” of $^{13}$CO versus “overluminous” CO typically seen in distant starbursts (Taniguchi & Ohyama 1998).

4.4.2. High $R_{13}$ from Abundance Variations

The second major class of models that produce enhanced $R_{13}$ are caused by changing molecular abundances. The CO opacity can be lowered by decreasing the overall [CO/H$_2$] abundance. This is unlikely given the active star formation history and high metallicity of the nucleus (3 Z$_{\odot}$; Belley & Roy 1992). Moreover, since CO is optically thick, [CO/H$_2$] must be decreased by a large amount before a strong effect is seen in $R_{13}$. Decreasing the isotopic abundances equates directly to changes in $R_{13}$ because of their low opacity; so changes in the relative isotopic abundances have a much more direct impact on $R_{13}$. Several methods of changing the isotopic abundances are considered in turn.

One way to raise the [CO/$^{13}$CO] abundance ratio is from the inflow of $^{13}$CO-poor molecular gas from the galactic disk. In the Galaxy the [CO/$^{13}$CO] abundance ratio increases with galactocentric distance (e.g., Wilson & Rood 1994; Wilson 1999). Driving $^{13}$CO-poor gas into the nucleus could raise the average [CO/$^{13}$CO]. NGC 6946 is a barred galaxy, and bars promote radial gas flow, which also tends to smooth out radial abundance variations (e.g., Alloin et al. 1981; Friedli, Benz, & Kennicutt 1994). Flat abundance profiles over the central 2.5 kpc of NGC 6946 are already established for N and O (Belley & Roy 1992). Therefore, it is possible that the average [CO/$^{13}$CO] abundance ratio over the region is slightly high compared with Galactic ratios (as suggested by the LVG analysis). However, the abundance ratio should be well mixed over the whole nuclear region, while in fact, in both NGC 6946 and IC 342, nuclear $R_{13}$ values are significantly larger than those found in the disk (Paglione et al. 2001). So even if gas inflow is important, it still requires that the molecular gas undergo a change in physical conditions as it enters the nuclear region to explain the increase in $R_{13}$. In addition, [CO/C$^{18}$O] increases with Galactocentric distance with a slope steeper than [CO/$^{13}$CO]. Hence, if inflow alone were the determining factor, the $^{13}$CO/C$^{18}$O ratio would be expected to be driven to even higher values, more typical of galactic disks, $\leq 5$. In fact, the opposite is seen.

Isotopic abundances can also be changed by chemical fractionation and/or isotope-selective photodissociation. Chemical fractionation imparts a chemical formation bias toward $^{13}$CO over CO when gas is cold and ion-molecule chemistry dominates (significantly below 35 K; e.g., Langer et al. 1980, 1984), while isotope-selective photodissociation lowers the isotopomer abundances relative to the main isotopomer because of decreased self-shielding (e.g., van Dishoeck & Black 1988). It is questionable whether chemical fractionation is relevant here since the molecular gas is mostly 35 K or warmer (§ 4.1). Moreover, $R_{13}$ does not correlate with star formation (Fig. 8a). The locations of the highest $R_{13}$ are well away from the starburst site, where the gas is presumably cooler. Likewise for isotope-selective photodissociation. We dismiss both possibilities as controlling factors of the global $R_{13}$ morphology. But we note that if the low $R_{13}$ and $R_{18}$ seen toward the eastern edge of the central ring are typical of physical conditions in the central ring in the absence of strong star formation, then the slightly higher ratios observed locally toward the starburst western edge of the ring could result from localized selective photodissociation of $^{13}$CO and C$^{18}$O.

A final possibility for $R_{13}$ enhancement due to variable molecular abundances is enrichment resulting from ejecta from massive stars. Though still somewhat uncertain, massive stars are predicted to pollute the nuclear ISM with $^{12}$C and potentially $^{18}$O, primarily early on in a starburst, with $^{13}$C following
later as intermediate mass stars evolve off the main sequence (e.g., Wilson & Matteucci 1992; Henkel & Mauersberger 1993; Prantzos, Aubert, & Audouze 1996; Romano & Matteucci 2003). Enhancement of 12C and 18O at the expense of 13C in young systems is expected if the starburst IMF is biased to massive stars (as suggested for NGC 6946, Engelbracht et al. 1996). If the newly generated 12C and 18O is incorporated back into CO rapidly then CO and C18O will be enhanced relative to 13CO, raising R13, leaving R18 relatively unaffected and lowering the 13CO/C18O ratio. A combination of low opacity in the isotopomers and a relatively low 13CO/C18O ratio implies that [13CO/C18O] > 2–3 in the nucleus of NGC 6946. As discussed in § 4.1, this provides some evidence that more applicable isotopic abundances are [CO/13CO] ~ 60 and [CO/C18O] ~ 150, and [13CO/C18O] ~ 2.5. The [13CO/C18O] abundance ratio is significantly lower than the solar value of ~6, the Galactic center value of ~10 and typical nearby galaxy nuclear values of ~4. Thus, it is possible that the somewhat low [13CO/C18O] value combined with the absence of a tight spatial correlation with the starburst indicates that the entire nuclear region is modestly enriched in CO and C18O as compared with 13CO. Orbital timescales are 8 Myr for the central ring and 28 Myr at the edge of the field of view, much shorter than the lifetime of intermediate-mass stars but comparable to the estimated starburst age of 7–20 Myr (Engelbracht et al. 1996). If the ejecta can immediately return to the ambient ISM, then interstellar enrichments probably has had time to spatially mix, providing an explanation for the globally 13CO/C18O line ratio. Abundances anomalies may, therefore, explain the globally low CO/C18O and 13CO/C18O ratios, but not their spatial variation.

In summary, from the close connection between R13 and HCN intensities, combined with the overall inadequacies of all other explanations, it appears that the most likely explanation for the distribution of large R13 and R18 gas in the nucleus of NGC 6946 is a significant and coherent decrease in gas density as one moves away from the central ring, causing the isotopomers to become subthermal and faint relative to the main species, which remains thermal, opaque, and bright. Operating in tandem with higher temperatures or anomalous abundances that are peculiar to the nuclear environment, a small reduction in opacity at low gas densities can increase R13 substantially. The molecular arms in the inner 300 pc region appear to consist of a warm, low-density gas that abruptly transitions to warmer, dense gas in the central ring. So the observed R13 is likely best considered a probe of the mixing fraction of dense, low R13 gas and diffuse, high R13 gas (Aalto et al. 1995; Sakamoto et al. 1997). HCN (1–0) emission probes the hotter, high-density cores embedded inside the diffuse medium. Since there is no global correlation between R13 and HCN (3–2)/HCN (1–0) (Paglione et al. 2001), a tracer of the density of the dense gas component, R13 does not appear strongly sensitive to the exact density of the dense component.

4.5. High R13: Bars as Redistributors of Gas Physical Conditions?

We find that the two gas components with distinctly different properties (nH, and Td) that are required to explain the single-dish line ratios in NGC 6946 are also found in distinctly different parts of the nucleus. Molecular gas with high R13 tends to be located along and upstream of the arms. The correlation of gas properties with position along a molecular bar was first noted by Wright et al. (1993) in IC 342. Similar features are now seen here in NGC 6946, Maffei 2 (Meier, Turner, & Hurt 2004), as well as the much larger scale bars, UGC 2855 and NGC 7479 (Hüttemeister, Aalto, & Wall 1999; Hüttemeister et al. 2000). The morphology of R13 in barred galaxies such as NGC 6946 suggests that changes in R13 are connected to the dynamics, but not through dynamical changes in line width. It must result instead from a mechanism capable of dispersing the molecular gas into spatially distinct regions of low-density, diffuse emission and high-density cloud cores, correlated with position across the bar. The theoretically predicted “spray regions” in barred potentials (Athanassoula 1992) provide a natural explanation for the presence and locations of the extended, low-density gas component inferred from the regions of high R13. Dense gas is associated with the central x1-type orbits and the cuspy ends of the x1-type orbits, while the remaining molecular gas is “scattered” off the x2 orbits, putting the diffuse gas at and upstream of the molecular arms (as illustrated in Fig. 9). In the case of IC 342, which has a higher column density (and density) in the arms, 13CO and C18O extend further along the arms than in NGC 6946. In fact, in IC 342, the densities are such that one can trace the density progression across the molecular arm from the upstream side up to the (shocked) leading edge (Wright et al. 1993; Meier & Turner 2001). Evidently, bars acting to disperse molecular gas into distinct regions with different physical conditions may be a common phenomena. This dynamical interpretation further supports the notion that the large R13 seen in distant mergers reflect changes in gas physical conditions associated with the large-scale dynamical redistribution of molecular gas, although in this case the redistribution would not be from a barred potential, but from the action of the merger directly.

4.6. High R13: Comparisons with Distant Galaxies and ULIRGs

The resolved structure of NGC 6946 appears to be a similar but more modest version of the structure inferred for the ISM of ULIRGs (e.g., Solomon et al. 1997; Downes & Solomon 1998). The diffuse arms in NGC 6946 appear to be cooler, lower column density analogues of the low-density, high filling-factor CO gas common in ULIRGs, while the starburst regions that are bright in HCN and 13CO in NGC 6946 are the more modest counterparts of the “extreme starbursts” seen in ULIRGs (Downes & Solomon 1998).

The ratio of CO to HCN luminosity is ~4–7 in ULIRGs as compared with ~30–70 in the disk of our Galaxy and normal galaxies (e.g., Solomon, Downes & Radford 1992; Sorai et al. 2002). The low absolute CO/HCN ratio in ULIRGs argues strongly that the fraction of the mass in the dense component is much higher than in more modest starbursts such as NGC 6946 (Solomon, Downes, & Radford 1992). However, this exacerbates the problem of explaining the high observed R13. Just requiring a large filling-factor, diffuse component along with low filling-factor embedded dense cores, like that seen in NGC 6946, is not enough to simultaneously explain both the low CO/HCN and high R13 ratios in ULIRGs for any reasonable [CO/13CO] abundance. Evidently, one must also require that 13CO/HCN be significantly lower than the unity observed for NGC 6946’s dense component. This can be achieved by a large opacity in the HCN (1–0) transition.

The relative opacity of lines with similar frequencies and upper energy levels (as is the case for the J = 1–0 transitions of CO, 13CO, C18O, and HCN) depend primarily on their relative abundances and transition line strengths (proportional to the dipole moment squared, |μ|^2). In gas with densities high
enough to thermalize HCN (and consequently CO and $^{13}$CO; e.g., Kohno, Kawabe, & Vila-Vilaró 1999)

$$
\frac{\tau_{\text{HCN}}}{\tau_{\text{CO}}} \approx \left( \frac{\text{HCN}}{^{13}\text{CO}} \right) \left( \frac{\mu_{\text{HCN}}}{\mu_{\text{CO}}} \right)^2 \sim 10,
$$
given expected HCN abundances. Hence, the opacity of HCN can significantly exceed the opacity of $^{13}$CO in warm, dense regions (e.g., Aalto et al. 1997). For example, based on our LVG models ($\S$ 4.1), for $T_K = 150$ K, $n_H = 10^5$, $[^{13}\text{CO}/\Delta n] = 10^{-6.4}$ and $[^{13}\text{CO}/\Delta n] = 10^{-8.3}$, $^{13}$CO (1–0)/HCN (1–0) $\approx 0.3$. This value can be decreased even more if one lowers the [CO/$^{13}$CO] abundance below that adopted for NGC 6946 (stronger isotope-selective photodissociation?). For the localized dense cores, CO and HCN can be bright because of high opacity, while the optically thin $^{13}$CO remains relatively faint. Assuming these dense cores are embedded in a low-density medium with a much larger filling factor, then it becomes possible to simultaneously explain low beam-averaged CO/HCN and CO (2–1)/CO (1–0) line ratios, while maintaining high beam-averaged $R_{13}$ ratios. Given the fairly high excitation required, it makes sense that this would be seen primarily in the “extreme starburst” cores associated with ULIRGs.

5. CONCLUSIONS

Aperture synthesis maps of $^{13}$CO and $^{18}$O in the nucleus of NGC 6946 are presented. The gas morphology and kinematics are consistent with molecular gas moving in response to a barred potential. The emission from $^{13}$CO and $^{18}$O is more symmetric and confined to the central ring of molecular material than is CO. Because of this, $R_{13}$ (ratio of integrated intensity, $^{12}$CO/$^{13}$CO, $J = 1–0$ for both) and $R_{18}$ ($^{12}$CO/$^{18}$O, $J = 1–0$) increase dramatically moving away from the central starburst, particularly along and to the trailing side of the CO bright northern molecular arm. $R_{13}$ reaches measured values as high as 30, more than 3 times higher than Galactic values, and upper limits significantly higher yet in some parts of this region. The transition between low $R_{13}$ gas and high $R_{13}$ gas is very sharp once the central ring is left, indicating a very rapid change in physical conditions.

If $^{13}$CO and $^{18}$O accurately trace the amount of molecular gas present, the standard conversion factor, $X_{\text{CO}}$, in NGC 6946 must be lower than the Galactic value. Column densities inferred from $^{13}$CO, $^{18}$O, and 1.4 mm dust continuum emission imply that $X_{\text{CO}}$ (6946) is about one-third to one-fifth the Galactic value at the sites of the GMCs, for a typical value of $X_{\text{CO}} = 0.5 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$. Toward the diffuse gas component along the northern arm, the conversion factor is likely a factor of 2–3 lower yet. Star formation as traced by 2.7 mm continuum and $P_{\text{irr}}$ more closely follows total gas surface density (or perhaps density) traced by the isotopomers rather than the optically thick CO intensity. The total gas mass in the central 175 kpc radius of NGC 6946 is $\sim 1 \times 10^8 M_\odot$, and the star formation efficiency on 100 pc size scales is a few percent.

Both gas moving with large radial velocities ($v_r \approx 80$ km s$^{-1}$) and bright HCN (1–0) emission imply that molecular gas has piled up along the central ring. LVG models find best-fit

![Fig. 9.—Left: Basic flow patterns of molecular gas in a barred potential (e.g., Athanassoula 1992). Right: Schematic showing the distribution of components with different physical conditions in response to that barred potential. The densest gas, bright primarily in HCN and $^{18}$O emission, is confined to the intersection regions of the $x_1$ and $x_2$ regions, explaining the sort of “saddle” region seen in $R_{13}$ and CO/HCN (Helfer & Blitz 1997). $^{13}$CO is seen primarily toward the central ringlike region, as well as at the cuspy ends of the bar. CO, on the other hand, remains bright over much of the entire region, tracing the distribution of the low-density gas. The locations of the extended, low-density gas component inferred from the regions of high $R_{13}$ correspond to the theoretically predicted “spray regions” in barred potentials.](image-url)
densities of $n_{H_2} \sim 10^{4.2}$ cm$^{-3}$ toward the central molecular ring and densities below $n_{H_2} \lesssim 10^2$ cm$^{-3}$ along the northern arm. Corresponding kinetic temperatures are $T_k \sim 90$ K for the central starburst and $T_k \lesssim 40$ K for northern arm. The morphology of the isotopomers are very similar to the high critical density tracer HCN (1−0), demonstrating that density changes are a key physical condition governing the local changes in $R_{13}$. Together with the fact that $R_{13}$ is correlated with position relative to the bar, this suggests that the bar potential acts to disperse the molecular gas into coherent regions with different physical conditions. Here in NGC 6946 the high $R_{13}$ line ratio values are a signpost of a dynamically evolving ISM. Applying these findings regarding the ISM structure of NGC 6946 to other more distant starbursts can successfully explain some of their observed molecular properties, hinting that similar processes may be at work there too.

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