Spatially Resolved Chemistry in Nearby Galaxies I. The Center of IC 342

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ABSTRACT

We have imaged emission from the millimeter lines of eight molecules—C₂H, C³⁴S, N₂H⁺, CH₃OH, HNCO, HNC, HC₃N, and SO—in the central half kiloparsec of the nearby spiral galaxy IC 342. The 5″ (∼ 50 pc) resolution images were made with the Owens Valley Millimeter Array (OVRO). Using these and previously published CO and HCN images we obtain a picture of the chemistry within the nuclear region on the sizescales of individual giant molecular clouds. Bright emission is detected from all but SO. There are marked differences in morphology for the different molecules. A principal component analysis is performed to quantify similarities and differences among the images. This analysis reveals that while all molecules are to zeroth order correlated, that is, they are all found in dense molecular clouds, there are three distinct groups of molecules distinguished by the location of their emission within the nuclear region. N₂H⁺, C¹⁸O, HNC and HCN are widespread and bright, good overall tracers of dense molecular gas. C₂H and C³⁴S, tracers of Photo-Dissociation Region chemistry, originate exclusively from the central 50-100 pc region, where radiation fields are high. The third group of molecules, CH₃OH and HNCO, correlates well with the expected locations of bar-induced orbital shocks. The good correlation of HNCO with the established shock tracer molecule CH₃OH is evidence that this molecule, whose chemistry has been uncertain, is indeed produced by processing of grains. HC₃N is observed to correlate tightly with 3mm continuum emission, demonstrating that the young starbursts are the sites of the warmest and densest molecular gas. We compare our HNC images with the HCN images of Downes et al. (1992) to produce the first high resolution,
extragalactic HCN/HNC map: the HNC/HCN ratio is near unity across the nucleus
and the correlation of both of these gas tracers with the star formation is excellent. The
ratio exhibits no obvious correlation with gas temperature or star formation strength.

Subject headings: galaxies: individual(IC 342) — galaxies: starburst — galaxies: ISM
— radio lines: galaxies — astrochemistry

1. Introduction

The bright and abundant molecule CO has dominated the study of molecular clouds in external
galaxies. The millimeter-wave transitions of CO and its isotopomers are powerful probes of diffuse
molecular gas (eg. Young & Scoville 1991). However, emission from the optically thick and easily
excited CO tends to favor the warmer, radiatively lit and diffuse surface layers of clouds (eg.,
Turner, Hurt & Hudson 1993; Meier, Turner & Hurt 2000, hereafter MTH00). Since dense gas is
the component most closely connected to star formation (eg., Gao & Solomon 2004), to understand
the links between molecular clouds and star formation in different galactic environments, we need
to study tracer molecules appropriate to a cooler, dense component that may not be well traced by
CO.

Each molecular line traces a distinct regime of density and temperature within a molecular
cloud, while different molecules can trace different gas chemistries (see van Dishoeck & Blake 1998,
for a review of Galactic astrochemistry). Emission from high density tracers such as HCN, HCO$^+$
and CS show that large amounts of dense ($\gtrsim 10^4$ cm$^{-3}$) molecular gas are present in the centers
of galaxies (eg. Mauersberger & Henkel 1989; Mauersberger et al. 1989; Nguyen-Q-Rieu, Nakai, &
Jackson 1989; Nguyen-Q-Rieu et al. 1992; Solomon, Downes, & Radford 1992; Helfer & Blitz 1993),
and that the dense molecular interstellar medium (ISM) can vary significantly on scales of a few
tens of parsecs (eg. Downes et al. 1992; Brouillet & Schilke 1993; Helfer & Blitz 1997; Seaquist,
Frayer, & Frail 1997; Sorai et al. 2002).

Numerous molecules have been detected in nearby starbursts (eg., Henkel et al. 1987; Henkel,
Schilke & Mauersberger 1988; Nguyen-Q-Rieu et al. 1991; Mauersberger et al. 1991; Petuchowski
& Bennett 1992; Sage & Ziurys 1995; Mauersberger, Henkel & Chin 1995; Martín et al. 2003;
Usero et al. 2004; Wang et al. 2004). These studies find that the chemical differentiation seen
within Galactic molecular clouds survives to scales of hundreds of parsecs, and even to galaxy-wide
differences. However, most of these observations have been done with single dish telescopes, at
resolutions of $\sim 30''$, or a few hundred pc on the galaxy, and thus average many giant molecular
clouds (GMCs) together into one beam.

With millimeter interferometers it is now possible to resolve individual GMCs in the nearest
galaxies with sufficient sensitivity to allow the study of selected chemical species (eg., García-
Burillo et al. 2000, 2001, 2002). Because of the low ($\sim 50–100$ pc) physical resolution, extragalactic
observations are insensitive to small-scale (\(\sim\)tenths of pc) chemistry typically studied in the Galaxy, but such maps can resolve the chemical properties operating over the bulk of a GMC and between individual GMCs. These observations can provide insights regarding the extent to which distinct large-scale properties, such as starbursts, shocks, bars, spiral arms, tidal forces and AGN influence the chemistry of molecular clouds and how these influences are transmitted from the GMC-scale to the galaxy as a whole.

We have surveyed the nearby Scd galaxy, IC 342, in transitions from eight astrochemically important molecules. \(\text{C}_2\text{H}, \text{HNCO}, \text{HNC}, \text{HC}_3\text{N}, \text{N}_2\text{H}^+, \text{C}^{34}\text{S}, \text{CH}_3\text{OH},\) and SO were imaged at \(\sim 50\) pc resolution with the Owens Valley Millimeter Array (OVRO). These are the first published interferometer maps of these lines in an external galaxy. IC 342 is the nearest (\(D \sim 2\) Mpc)\(^1\), gas-rich spiral with active star formation in its nucleus (Becklin et al. 1980; Turner & Ho 1983), and the first galaxy to be mapped with millimeter interferometers (Lo et al. 1984). There is widespread resolvable molecular gas distributed in both dense clouds, with masses similar to SgrB2, and a diffuse medium about the size of the central molecular zone (Morris & Serabyn 1996) in the Milky Way. Detailed knowledge of the \(\text{H}_2\) column densities, excitation temperatures and densities in IC 342 exists from CO and its isotopomers as a basis for comparison with these new lines (Ishizuki et al. 1990; Downes et al. 1992; Turner & Hurt 1992; Wright et al. 1993; Turner, Hurt & Hudson 1993; MTH00; Meier & Turner 2001, hereafter MT01).

2. Observations

We observed eight lines at 3mm and one line at 1mm with OVRO between 1997 October 22 and 2001 April 07 (Table 1). The interferometer consisted of six 10.4 meter antennas with SIS receivers (Padin et al. 1991; Scoville et al. 1994). All transitions were observed in the C and L array configurations except for the SO, which was observed in L and H.

Table 1 lists the observed lines along with the observational parameters. The transitions were selected based on the criteria that (1) they are bright in SgrB2 (\(T_a\sim 1\) K in the Turner (1989) spectral line survey), (2) they sample a selection of different types of chemistry and (3) they maximize the number of species OVRO can observe simultaneously. Table 2 lists molecular parameters for the transitions. The nine spectral lines were observed in three sets of spectrometer configurations. \(\text{C}_2\text{H}, \text{HNCO}, \text{HNC}\) and \(\text{HC}_3\text{N}\) were observed as a group, as were \(\text{CH}_3\text{OH}, \text{C}^{34}\text{S}\) and \(\text{N}_2\text{H}^+\), and the two SO transitions were observed with \(\text{C}^{18}\text{O}\) (MT01). Each group has the same instrumental configuration, phase center, and weather. Data were calibrated using the MMA package. Phase calibration was done by observing the point source 0224+671 every 20 minutes. Absolute flux calibration is based on observations of Neptune or Uranus and with 3C273, 3C84, 3C454.3 and

\(^1\)Due to its location behind the Galactic plane, IC 342’s distance is still a matter of debate. Recent studies have argued for a distance of \(\sim 3\) Mpc (eg., Saha, Claver, & Hoessel 2002; Karachentsev et al. 2003), but we adopt the shorter distance to keep consistent with our previous work.
3C345 as supplementary flux calibrators. Based on the derived fluxes and flux histories of these secondary flux calibrators we estimate that the absolute fluxes are good to 10 - 15% for the 3 mm data and 20 - 25% for the 1 mm data (SO). The lines of SO(23 – 12) and SO(65 – 54) were not detected.

Both robustly weighted maps with resolutions of ∼ 5 – 6″ and uniformly weighted maps with ∼ 4″ resolution were produced. The maps are not primary beam corrected. Data reduction was done with the NRAO AIPS. In making the integrated intensity maps emission greater than 1.2σ was included. Continuum emission has not been subtracted from the maps since the 3 mm continuum peak is below 1σ.

The (u,v) coverages imply that emission on scales larger than ∼ 50″ is resolved out. To estimate the amount of extended flux missing from the images, each map was compared with its single-dish spectrum. Though somewhat uncertain due to the low S/N of some of the single-dish detections (Henkel, Schilke & Mauersberger 1988; Mauersberger & Henkel 1991b; Nguyen-Q-Rieu et al. 1991; Mauersberger, Henkel & Chin 1995; Hüttemeister et al. 1995a; Hüttemeister, Mauersberger & Henkel 1997), all species are consistent with no flux being resolved out, except possibly HC3N. This is consistent with what is found for 13CO and C18O (MTH00; MT01) towards IC 342, and is expected for these dense gas tracers. In the case of HC3N, the interferometer HC3N flux is ∼30 % of the claimed tentative detection by IRAM (Henkel, Schilke & Mauersberger 1988), but given its very high dipole moment it is not expected to be extended on ∼50 pc scales. This implies that the claimed single-dish brightness for HC3N was overestimated, and not that the interferometer resolves out significant flux.

3. IC 342 and its Molecules

3.1. A Sketch of the Nucleus of IC 342

We have a basic understanding of the small-scale molecular structure of IC 342’s nucleus from studies of CO, its isotopomers and HCN (Ishizuki et al. 1990; Turner & Hurt 1992; MTH00; MT01; Schulz et al. 2001; Mauersberger et al. 2003). A CO(1-0) map of IC 342 (Levine et al. 1994) is shown atop an HST image of the nucleus in Figure 1. Within the central 300 pc (30″) two molecular arms extend inward (Ishizuki et al. 1990), terminating in a central ring of dense gas (Downes et al. 1992). The total mass of molecular gas within the central kpc is ∼ 4 × 107 M⊙. Orbital timescales here are a few x 107 yrs. The gas is on pronounced oval orbits, with an estimated radial drift into the nuclear region due to tidal torquing of ∼ 0.1 M⊙ yr⁻¹ (Turner & Hurt 1992), which is also the approximate rate of current star formation in the radio/IR source. The central molecular ring surrounds a nuclear star cluster estimated to be 6-60 Myr in age (Böker et al. 1997). The star cluster coincides with a central “trough” of molecular gas, the hole in the molecular ring.

Five prominent GMCs with masses of ∼ 10⁶ M⊙ are found within the molecular ring and arms.
These clouds have masses slightly less than the Sgr B2 cloud in the Galactic Center. GMCs B and C (adopting the nomenclature of Downes et al. 1992) are located where the incoming molecular arms meet the ring. These clouds coincide with two young (∼ few Myr old) large star-forming regions. GMC B is near the dominant of the two IR/radio star-forming regions, which has a luminosity of $L_{OB} \sim 10^8 L_\odot$ (Becklin et al. 1980; Turner & Ho 1983) corresponding to an estimated 500 O stars. Cloud C appears somewhat warmer than B in the highest transitions of CO (Harris et al. 1991), but a careful analysis at high resolution in the lower transitions GMC B is actually the warmest location in the nucleus (MT01). GMC A is closest in projection to the nuclear star cluster and dynamical center. GMC A has similar CO(1-0) and HCN(1-0) properties to B and C, but much weaker star formation. GMC D, along the northern arm, is also not a site of strong star formation. In this region large gas streaming motions are observed (Turner & Hurt 1992) along the arms. The resulting shear could slow star formation, although there is some star formation indicated by Hα downstream from the molecular arms.

3.2. Overview of the Molecules of IC 342

Figure 2 displays the robustly-weighted integrated intensity maps for the seven detected lines plus smoothed maps of previously published $^{12}$CO(1-0) and $^{18}$O(1-0) (MT00; MT01). Each map is overlaid on a greyscale image of $^{12}$CO(1-0). Figure 3 displays the higher resolution uniformly weighted maps for the central ring region overlaid on the greyscale HCN(1-0) image of Downes et al. (1992). Figures 4 - 5 display spectra for six nuclear clouds. Spectra were generated by summing all the flux within a 6″ box centered on the GMC positions (Table 3). On each spectrum the expected line position of any other lines 0.1 K or brighter based on the spectrum of SgrB2 (Turner 1989) are indicated. Line intensities are listed in Table 3.

One might naively expect that the molecules would follow the basic CO distribution, since CO is a good overall tracer of molecular gas. Or perhaps one might expect to find emission peaks for these molecules preferentially at peaks of HCN peaks, since the molecules of our sample are high density tracers like HCN. Instead, dramatic variations in morphology are evident among the different transitions. Either the dense gas component of IC 342 has extreme variations in excitation among the GMCs, or there is widespread chemical differentiation across the nucleus. The morphology of the different astrochemical species provides evidence of changing chemical influences due to star formation, physical conditions, and dynamics across the nucleus (§5).

Fractional abundances ($X_{mol} \equiv N_{mol}/N_{H_2}$) are listed in Table 4, based on molecular parameters in Table 2. Column densities are determined assuming optically thin emission, and LTE:

$$N_{mol} = \left( \frac{3kQ_eE_u/kT_x}{8\pi^3\nu S_{ul}c^2g_u g_{T_u}} \right) I_{mol},$$  

(1)

where $S_{ul}$, $g$ and $E$ are the line strength, degeneracy and upper energy of each state, respectively, and $T_{ex}$ is the excitation temperature associated with the transition. Given that we have mapped
only one transition of each species, corrections for background radiation and opacity have been ignored. Column densities are sensitive to $T_{\text{ex}}$ through the partition function, $Q$, and the energy of the upper state. The asymmetric tops (HNCO and CH$_3$OH) are more sensitive to temperature changes than the linear rotors. Changes in gas density also affect excitation, particularly for molecules with high critical densities (HNC, N$_2$H$^+$ and HC$_3$N). Fortunately in IC 342 these properties have been at least partially constrained by observation. The kinetic temperature, $T_k$, determined from NH$_3$ is $\sim 50$ K (Ho, Martin, & Ruf 1982) which is similar to the derived dust temperature, 42 K (Becklin et al. 1980; Rickard & Harvey 1984). Modeling of the optically thick lines of CO(1-0), CO(2-1) and CO(3-2) indicate temperatures of 15-40 K (Ho, Turner, & Martin 1987; Eckart et al. 1990; Xie, Young, & Schloerb 1994); however, the optically thick CO lines may be biased toward the outer, radiation-warmed layers of the clouds (Turner, Hurt & Hudson 1993; MT01). We adopt $T_{\text{ex}} = 10$ K determined from C$^{18}$O interferometer maps (MT01) and single-dish H$_2$CO and CH$_3$OH measurements (Hüttemeister, Mauersberger & Henkel 1997) as the most suitable excitation temperature to use with the observed tracer species. Table 2 gives the factor by which the column densities would change if the assumed $T_{\text{ex}}$ was changed from 10 K to 50 K. Given the critical densities of the mapped species, $T_{\text{ex}}$ is very likely lower than $T_k$ (subthermal), so 50 K is considered a robust upper limit to the excitation temperature.

Fractional abundances require, in addition, an H$_2$ column density, N(H$_2$). N(H$_2$) is most easily obtained from the CO(1-0) brightness and an empirical Galactic conversion factor, $X_{\text{CO}}$. However, $X_{\text{CO}}$ overpredicts N(H$_2$) in nearby galaxy centers, including IC 342, by factors of a few (eg. MT01; Dahmen et al. 1998; Weiß et al. 2001; Meier & Turner 2004). A better measure of N(H$_2$) can be obtained from the C$^{18}$O. It is known to be optically thin and for the excitation temperatures observed, the intensities of the lower J transitions of C$^{18}$O are not strongly dependent on gas excitation (see MT01 for a detailed discussion of N(H$_2$) and its uncertainties in IC 342). Hence we adopt optically thin C$^{18}$O(1-0) and $[\text{H}_2/\text{C}^{18}\text{O}] = 2.9 \times 10^6$ ($[^{12}\text{CO}/\text{C}^{18}\text{O}] = 250$; Henkel & Mauersberger 1993) and $[\text{CO}/\text{H}_2] = 8.5 \times 10^{-5}$; Frerking, Langer & Wilson (1982)) when calculating the H$_2$ column densities, consistent with what is derived from the CO isotopomers. The lines observed in this study are also optically thin and have similar upper energy states, and thus their intensities vary with $T_{\text{ex}}$ in step with C$^{18}$O, providing at least partial compensation for changing physical conditions. Moreover, C$^{18}$O(1-0) has a higher critical density ($n_{\text{crit}} \simeq 2 \times 10^3$ cm$^{-3}$) than the optically thick CO, and should have more similar beam filling factors to the lines presented here. If the highest critical density species are strongly subthermal abundances may be somewhat overestimated. On the other hand, for these same high critical density species, it is expected that their emission will be more confined than C$^{18}$O and hence underestimated locally. Together with the compensating effect of C$^{18}$O(1-0) discussed above, we estimate that the column densities and fractional abundances are uncertain to at least a factor of three, although the relative column densities—that is, the relative spatial distributions within the nucleus—are probably more reliable.

We now introduce each of the different molecular species that have been mapped and discuss
their idiosyncrasies before we turn to the overall chemical picture in IC 342. Those who are already familiar with the molecules or are easily bored may skip to the next section.

$C_2H$ —Ethynyl: This is the $J = 3/2-1/2$ fine structure component of the $N = 1-0$ transition. $C_2H$ is confined to the central ring, with a peak antenna temperature of $T_{mb} = 0.27$ K (Table 3) at GMC A. Figure 3 shows that the $C_2H$ emission in GMC A does not originate from the main HCN peak but from its western side. $C_2H$ is also brightest on the inner, starburst lit, face of GMC C, and it follows the H$\alpha$ wisps (Figure 1) between GMCs A and C. $C_2H$ emission also appears in the central trough. The $C_2H$ spectrum appears preferentially blueshifted towards the central regions of IC 342, but this may be an artifact of the presence of the $F = 1-0$ hyperfine component. At GMC A the line is strong enough to separate the $F=1-0$ and $F=2-1$ hyperfine components. Their ratio is 2, the value expected for optically thin, LTE excitation. The $F=1-1$ component is not detected.

$C_2H$ fractional abundances in Galactic cores range from $1 - 60 \times 10^{-10}$ (Wootten et al. 1980; Huggins, Carlson, & Kinney 1984; Watt 1983) and reach $\sim 2 \times 10^{-8}$ (Turner, Terzieva & Herbst 1999; Lucas & Liszt 2000) in Galactic diffuse clouds. In IC 342, a peak abundance of $3 \times 10^{-8}$, similar to Galactic diffuse clouds, obtains towards GMC A. Upper limits towards the other major GMCs are an order of magnitude lower, more like Galactic dense cores.

$C^{34}S$ —Carbon Monosulfide: The $J = 2-1$ rotational transition of $C^{34}S$ expected to be optically thin. Like $C_2H$, $C^{34}S(2-1)$ emission is confined to the central ring region, and brightest towards GMC A ($T_{mb} = 0.16$ K). $C^{34}S$, however, lacks the eastern extension seen in $C_2H$. In general $C^{34}S(2-1)$ avoids the density peaks traced in the Downes et al. (1992) HCN(1-0) image, although $C^{34}S$ also has a high critical density. As with $C_2H$, the northern extension appears predominately on the inner face of GMC C, toward the nuclear star cluster. The $C^{34}S$ line at GMC A is rather broader than seen in the other observed transitions and appears blueshifted like $C_2H$ (Figure 4).

For an $^{32}S/^ {34}S$ isotopic abundance of 23 (eg. Wilson & Rood 1994, however see Chin et al. 1996) $X(C^{34}S) = 1 - 3 \times 10^{-10}$ in Galactic dense cores (eg. Wang et al. 1993; Morata et al. 1997; Lapinov et al. 1998) and diffuse/translucent clouds (Nyman 1984; Drdla, Knapp, & van Dishoeck 1989; Lucas & Liszt 2002). In IC 342, we find $X(C^{34}S) = 2 \times 10^{-9}$ towards GMC A. The upper limits elsewhere are consistent with the typical Galactic values.

Convoluting the $C^{34}S(2-1)$ interferometer data to the resolution of the single-dish map of the main CS isotopomer (Mauersberger et al. 1989), yields a morphology similar to that seen in the single-dish data except with a less prominent northern peak. The $CS(2-1)/C^{34}S(2-1)$ intensity ratio towards the central peak is $\sim 8$, while towards GMC C the intensity ratio increases to $\gtrsim 12$. Assuming a Galactic $^{32}S/^ {34}S$ abundance ratio of 23 implies a opacities of $\sim 2$ in the main isotope towards GMC A and slightly lower opacities towards GMC C. However recent observations suggest that in starburst nuclei $^{32}S/^ {34}S \sim 8 - 13$ (Wang et al. 2004; Martín et al. 2004). In this case, $C^{34}S(2-1)$ has low opacity everywhere in the nucleus.

$HNC$ —Hydrogen Isocyanide: The $J = 1-0$ line of the linear molecule HNC is the brightest of the observed lines with a peak antenna temperature of $T_{mb} = 0.62$ K, brighter even than $C^{18}O(1-0)$. 
HNC peaks at the starburst GMC B, and is bright at all other labeled GMCs with the possible exception of GMC E. The morphology of HNC(1-0) is similar to that of HCN(1-0) (Downes et al. 1992). HNC and HCN may be the best tracers of the dense gas distribution (§4). HCN(1-0) is similar to HNC(1-0) (Downes et al. 1992). HNC and HCN may be the best tracers of the dense gas distribution (§4). HCN emission, and presumably the dense gas, tends to arise on the clockwise (leading) side of the molecular arms when compared to $^{12}$CO(1-0), an effect also seen in CO isotopomers (Wright et al. 1993; MTH00; MT01). The HNC peak at GMC C is shifted closer to the nucleus than the $^{12}$CO(1-0). HNC(1-0) also peaks $\sim 5''$ due east of GMC D, a feature not obvious in the map of HCN(1-0) (Downes et al. 1992). This location is bright in several other lines, particularly $N_2H^+$, CH$_3$OH and HNCO. For the sake of reference, this location will be referred to as D’ and its position is given in Table 3.

HNC abundances are $5 - 10 \times 10^{-9}$ in Galactic dark clouds, and about an order of magnitude lower in clouds with massive star formation, including the Galactic Center (Wootten et al. 1978; Blake et al. 1987; Hirota et al. 1998; Nummelin et al. 2000), or diffuse and translucent clouds (Nyman & Millar 1989; Turner, Pirogov, & Minh 1997; Lucas & Liszt 2001). In IC 342 HNC abundances are fairly constant across the galaxy, and consistent with that found in the Galactic Center. Uncertain opacity effects could be important, although we view them as unlikely (§5.5).

$N_2H^+$ — Diazenylium: We observed the ground ($J = 1-0$) rotational state of this linear molecule. The hyperfine splitting is much smaller than the observed linewidths and is ignored. Emission from $N_2H^+$ is bright ($T_{mb} = 0.21$ K) and widespread, nearly matching HNC in extent. The higher resolution map shows that the $N_2H^+$ emission peaks between GMCs A and B, even though high resolution images of CO do not show any local maxima at this location (Schinnerer, Böker, & Meier 2003). This peak is also seen in the maps of HC$_3$N, HNCO and possibly HNC (Figure 3), and NH$_3$ (Ho et al. 1990), but no other lines. This cloud appears only in nitrogen-bearing species, and so we label it ‘N’ in Figure 3. On the larger scale, $N_2H^+$ is similar in morphology to NH$_3$, HNCO(4$_{04} - 3_{03}$), and CH$_3$OH($2_k - 1_k$). All are bright towards GMC D’.

$N_2H^+$ abundances in Galactic dense cores range are $10^{-10} - 10^{-9}$, with higher abundances in dark cores (Womack, Ziurys & Wyckoff 1992b; Benson, Caselli, & Myers 1998). In diffuse and translucent clouds, $N_2H^+$ has fractional abundances well below $10^{-11}$ (Womack, Ziurys & Wyckoff 1992b; Turner 1995; Lucas & Liszt 2001). In IC 342 we find $X(N_2H^+) = 2 \times 10^{-10}$ up to $6 \times 10^{-10}$ towards GMC D’. These abundances are up to an order of magnitude larger than the Galactic Center values.

HC$_3$N — Cyanoacetylene: We mapped the $J = 10-9$ rotational transition of HC$_3$N. This molecule has the largest electric dipole moment and the highest upper energy state of the sample (Table 2). HC$_3$N emission is confined to the two GMCs associated with the youngest starbursts, GMCs B and C, with peak $T_{mb} = 0.20$ K at GMC C, where the molecular arms intersect the central ring. As with HNC and HCN (Figure 3), the HC$_3$N peak towards GMC C is $\sim 1/2$ beamwidth closer to the nucleus than $^{12}$CO(1-0). HC$_3$N emits faintly at cloud N.

Abundances of HC$_3$N towards Galactic cores are $X$(HC$_3$N) $\sim$ few $\times 10^{-11}$ — few $\times 10^{-10}$, with the cold cores towards the high end (Morris et al. 1976; vanden Bout et al. 1983; Chung, Osamu,
& Masaki 1991). Translucent clouds have a similar range (Turner 1998). For IC 342, abundances peak towards GMCs C and D’ at $4 \times 10^{-9}$, somewhat higher than in cold Galactic clouds but much lower than the localized Galactic hot core values ($> 10^{-7}$; eg. de Vicente et al. 2000).

**HNCO —Isocyanic Acid:** We observed the K$^{-1} = 0$ transition of the J = 4-3 rotational state of the prolate, slightly asymmetric top, HNCO. HNCO emission is extended, with peaks at GMCs C, D’ and N, and brightest at D’ at $T_{mb} = 0.25$ K. HNCO emits only weakly towards the starburst (GMC B) and is undetected at GMC A. This transition of HNCO, which has no hyperfine structure, has the narrowest linewidth of the sample, barely resolved in the 14 km s$^{-1}$ wide channels. These line widths, narrow by extragalactic standards, are typical of Galactic GMCs with massive star formation, such as SgrB2. Evidently all galactic rotation has been resolved out at this spatial resolution and the velocity dispersion of individual clouds dominate.

Abundances of HNCO range from $X$(HNCO)$< \sim 1 \times 10^{-9}$ up to $3 \times 10^{-9}$ towards GMC D’. On ∼1-2 pc scales, Galactic massive dense cores have abundances of $10^{-9}$ increasing to $10^{-8}$ as the linewidth of the cloud increases (Zinchenko, Henkel & Mao 2000). In translucent clouds abundances are $(1-3 \times 10^{-9}$; Turner, Terzieva & Herbst 1999), and up to $> 2 \times 10^{-8}$ on sub-parsec sizescales (Wilson et al. 1996; Kuan & Snyder 1996). HNCO abundances in IC 342, averaged over 50 pc scales, are similar to those on ∼1 pc scales for massive cores in the Galaxy.

**CH$_3$OH —Methanol:** We observed the blended set of $2_1-1_1E$, $2_0-1_0E$, $2_0-1_0A^+$ and $2_{-1}-1_{-1}E$ low energy, thermal transitions of CH$_3$OH [hereafter designated the $2_k-1_k$ transition]. CH$_3$OH($2_k-1_k$) emission is as bright as C$^{18}$O(1-0) and nearly as extensive as 1$^2$CO(1-0)! The general morphology of CH$_3$OH is similar to C$^{18}$O(1-0) following the $^{12}$CO(1-0) emission but favoring the leading edges of the nuclear arms. The brightest methanol emission comes from GMCs C and D’, with peak $T_{mb} = 0.35$ K at GMC C. An additional CH$_3$OH peak is seen even north of GMCs D/D’, a position only detected in methanol, C$^{18}$O(1-0) and HNC(1-0). CH$_3$OH, like HNCO and N$_2$H$^+$, is bright towards GMC D’ and along the leading edge of the northern spiral arm. For a “hot gas” tracer, methanol is surprisingly weak near near the starburst at GMC B, actually appearing as a local minima. GMC A is also weak in methanol.

Galactic methanol abundances range from $10^{-10} - 10^{-8}$ depending on source size (eg. Kalenskii & Sobolev 1994; Kalenskii et al. 1997; Minier & Booth 2002). Diffuse and dark cloud CH$_3$OH abundances are $2 - 3 \times 10^{-9}$ (Friberg et al. 1988; Turner 1998), as determined from thermal transitions. CH$_3$OH abundances in the envelope of SgrB2 are $3 - 10 \times 10^{-9}$ (Nummelin et al. 2000). On smaller scales, methanol can be enhanced by factors of a few hundred over dark cloud values in shocks and outflows (eg. Menten et al. 1986; Bachiller & Perez Gutierrez 1997). In IC 342, the observed range is $3 - 8 \times 10^{-9}$, similar to the envelope of SgrB2. Multi-line single-dish CH$_3$OH data obtain $T_{ex} \simeq 5 - 10$ K averaged over 200 pc size scales (Hüttemeister, Mauersberger & Henkel 1997) suggesting that CH$_3$OH emission is not dominated by hot cores.

**Nondetections —SO:** We attempted to image two transitions of SO, the $(2_3 - 1_2)$ and $(6_5 - 5_4)$ transitions. Upper limits (2$\sigma$) of I$_{SO} < 1.5$ K km s$^{-1}$ for the $(2_3 - 1_2)$ line and I$_{SO} < 1.3$ K km s$^{-1}$
for the \((6_5 - 5_4)\) line are obtained. The SO abundance in Galactic dense cores is variable, ranging from \(X(\text{SO}) \sim 5 \times 10^{-11}\) up to \(1 \times 10^{-7}\), with enhancements seen towards dark clouds and hot cores (Gottlieb et al. 1978; Rydbeck et al. 1980; Blake et al. 1987), and in diffuse or translucent clouds \((2 - 30 \times 10^{-9}\); Turner 1995; Heithausen, Corneliussen, & Grossmann 1995; Lucas & Liszt 2002). In IC 342, the upper limits for SO of \(5 - 8 \times 10^{-9}\) are not strongly constraining.

Table 5 presents the limits for fainter transitions within the bandwidth of the spectrometer. We note that the broadening of \(\text{C}^{34}\text{S}(2-1)\) could be due to contamination from the \((5_{2,4} - 4_{2,3})E\) transition of acetaldehyde (\(\text{CH}_3\text{CHO}\)) at 96.426 GHz. The Turner (1989) 3 mm survey finds this transition to be \(\sim 1/5\) the brightness of \(\text{C}^{34}\text{S}(2-1)\) in Sgr B2. In IC 342, it would have to be comparable in brightness to \(\text{C}^{34}\text{S}(2-1)\) to explain the line width, which is unlikely. A 3\(\sigma\) feature is also seen in the \(\text{C}^{18}\text{O}(1-0)\) bandpass matching the frequency of the \((5_{1,4} - 4_{1,3})E\) transition of formamide (\(\text{NH}_2\text{CHO}\)) at 109.754 GHz. In the Turner (1989) survey of Sgr B2 this transition has a brightness \(1/5\) of the \(\text{C}^{18}\text{O}(1-0)\) line. Towards GMC E, where the feature is brightest, the observed ratio is \(\sim 1/3\). Therefore, it is possible that this feature is \(\text{NH}_2\text{CHO}\). \(\text{CH}_3\text{CHO}\) and \(\text{NH}_2\text{CHO}\) have yet to be detected in external galaxies. These deep interferometric observations suggest that these two aldehydes may be worth a dedicated search.

In the rest of the paper, we will omit the transition notations for the molecules to facilitate the exposition. The reader should be aware that the correlations that we investigate may be a function of the energy level and excitation, i.e., the specific transition, as well as the chemistry (§5).

### 4. Understanding the Molecular Maps: Principal Component Analysis

The maps give a picture of the astrochemistry of the molecular clouds in the nuclear region of IC 342. To begin to interpret these maps, we need to establish similarities and differences between the molecules. The correlations will reveal trends in what governs the chemistry, which in turn, can reveal the physical characteristics and forces within the galaxy that create these conditions.

To quantify the morphologies of the molecular maps and star formation, we apply a principal component analysis (PCA). PCA is a common technique (e.g. Murtagh & Heck 1987; Krzanowski 1988; Everitt & Dunn 2001; Wall & Jenkins 2003) used to reduce the dimensionality of a dataset. It is useful in identifying a small linear combination of datapoints that convey a significant percentage of the information of the whole dataset. The PCA simplifies the picture of molecular distribution, reducing a large amount of information to a few images, providing an excellent framework within which to study the complex variations in molecular properties in IC 342.

For a description of PCA applied to multi-transition molecular maps, see Ungerechts et al. (1997). Each pixel in each map is treated as a separate datapoint in an \(x \times y \times n\) dimensional space, where \(x\) and \(y\) are the number of pixels along the corresponding axis of the maps, and \(n\) is the number of maps included. The “cloud” of samples are then projected onto an axis such that the variance along that axis is a maximum. This projection corresponds to the first principal
component. The task is repeated, subject to the constraint that each successive projection is orthogonal to all previous projections. Each projection, the principal components or eigenvectors, will contain decreasing fractions of the total data variance (assuming there is some correlation in the maps). As long as the first few principal components contain a significant fraction of the variability in the data, the entire dataset can be adequately described by just these few principal components.

To calculate the principal components for IC 342, the line maps were convolved to the same geometry and beamsize (6″), normalized and mean-centered. Eleven maps, $^{12}\text{CO}(1-0)$, $^{18}\text{O}(1-0)$, HCN(1-0) (Downes et al. 1992) and 3 mm continuum (MT01), plus the seven detected transitions, were sampled at 1″ intervals over the central 32″ × 62″, making up a 20824 element dataspace. The algorithm used to calculate the principal components is essentially that of Murtagh & Heck (1987). The results are displayed in Tables 6 and 7, and Figures 6 and 7.

The correlation matrix resulting from the PCA (Table 6) indicates that all molecules are at least partially correlated. This is also represented by the most significant correlation, component PC1 (Figure 6a). HCN and HNC are the most tightly correlated of the molecules. $^{18}\text{O}$, N$_2$H$^+$, HCN and HNC have large projections onto PC1, but small projections onto PC2 and PC3 (and the PC2 and PC3 projections of $^{18}\text{O}$ and HNC have opposite signs). Since HNC is expected to trace the distribution of dense quiescent gas and $^{18}\text{O}$ the column density, it would appear that PC1 represents the density-weighted average column density map of IC 342. This also agrees with the general appearance of PC1. In fact the PC1 map is basically an average of the $^{18}\text{O}$ and HNC maps. PC1 accounts for 2/3 of the variance in the data, and all species have large projections on PC1. Variations in density-weighted column density therefore explain much of the overall morphology of the chemical species, as one might expect. Molecules are found in molecular clouds. The molecule N$_2$H$^+$ projects almost exclusively onto PC1. N$_2$H$^+$ in the Galaxy is considered a good “quiescent” gas tracer, and that also appears true in the nucleus of IC 342.

HNC, another molecule with a large PC1 projection, is the molecule most closely correlated with the 3 mm continuum. Of all of the detected transitions, HNC has the highest critical density, and is most heavily weighted toward regions of high density, and not just high column density. Thus the 3mm continuum is very closely associated with the dense gas. This extends the findings of Gao & Solomon (2004) based on their studies of global HCN fluxes in galaxies down to GMC sizescales. However, the correlation of dense gas with star formation, while excellent, is not perfect; we discuss this in §5.

The next principal component, PC2, characterizes the correlations remaining once density-weighted column density effects are taken into account. As shown in Figure 6b, PC2 distinguishes between molecules that peak at GMC A and those that are extended along the northern arm, particularly those peaking at GMC D$. HNCO and CH$_3$OH, which are found along the northern arm and are absent in GMC A, have the largest positive projections on PC2 and are well correlated. C$_2$H and C$_{34}$S have largest negative projections onto PC2, appearing almost exclusively at GMC A.
These groups are anticorrelated in the sense that clouds bright in C$_2$H and C$_{34}$S show little HNCO and CH$_3$OH emission and vice-versa. These differences suggest that these two groups—defined by the northern arm and GMC A locations—represent distinct types of chemistry. We discuss the chemistries of the GMC A vs. northern arm/GMC D' groups below. HC$_3$N, 3 mm continuum, and N$_2$H$^+$ are largely independent of PC2, indicating that their emission is not strongly influenced by the different chemical conditions of GMC A vs Northern arm/GMC D'.

PC3 is of less significance than the previous two correlations. PC3 distinguishes between GMC C (particularly between upstream [$^{12}$CO and C$_{34}$S] and downstream [HC$_3$N and 3 mm] species) and between GMCs C and D. PC3 thus hints at being connected with the distribution of massive star formation.

5. Spatially Resolved Chemistries in the Nucleus of IC 342

The large variations in spatial morphology observed for the different molecules across the central half kiloparsec of IC 342 are caused by either differences in emissivity (excitation) or abundances (chemistry). In this section we discuss the possible influences on the molecular emission that could lead to the observed variations.

5.1. Are Differences between the Molecular Species Due to Excitation?

The molecules of our sample have lower opacities, higher critical densities, and larger partition functions than CO, and so these lines are more sensitive to changes in excitation due to variations in density that can affect emissivity. Since we already know a fair amount about cloud conditions in IC 342 from the (1-0) and (2-1) lines of the CO isotopomers, we can investigate how important excitation is to the emissivities of these molecules. All of the detected lines have similar upper level energies and thus behave similarly to changes in excitation temperature, T$_{ex}$ (see Table 2). Significant variations in T$_{ex}$ as traced by C$^{18}$O are not seen, with a range of temperatures across the nucleus of 7-15 K, except for a small region towards the starburst (GMC B). Since the excitation properties are similar and most of the gas is at a relatively uniform excitation temperature anyway, T$_{ex}$ is not the major cause of the spatial differences between the molecules.

Critical density can also play a role in emissivity. The range of electric dipole moments for the observed species of $\mu_o = 0.8$ (C$_2$H) - 3.73 (HC$_3$N), corresponds to a factor of $\sim$20 in critical density (>1000 if one counts CO). The CO isotopomers indicate that volume densities of the GMCs are $\gtrsim 10^4$ cm$^{-3}$ (MT01). At this density, transitions with the highest critical density should have the most limited extent. However, we find that there are extended and confined species at both lower critical densities (CH$_3$OH vs. C$_2$H), intermediate critical densities (HNCO vs. C$_{34}$S) as well as the highest critical densities (N$_2$H$^+$ vs. HC$_3$N). We conclude that densities in the GMCs are $\sim 10^5$ cm$^{-3}$, high enough to (at least partially) excite all of the molecules everywhere across the nucleus.
except perhaps HC$_3$N and N$_2$H$^+$, which have the very highest critical densities.

Although variations in density and temperature are not the primary forces determining the appearance of the maps of Figure 2, there may be regions where they play a role. GMC A is genuinely different from the other GMCs, in spite of its similarity in CO and HCN. The first hints that GMC A was different came from the temperature map made using C$^{18}$O (MT01). GMC A is a localized ‘hot spot’, with $T_{\text{ex}} \simeq 15$ K, higher than the 10 K we adopt here. The species with intensities most sensitive to changes in $T_{\text{ex}}$, HNCO and CH$_3$OH, would be the most affected by a higher temperature; the observed weakness of HNCO and CH$_3$OH in GMC A could be due to depopulation of low-lying transitions. This effect is also possible for the localized maxima of CH$_3$OH towards GMC B. The second instance in which excitation appears to play a role is in HC$_3$N, which is closely confined to the starburst sites. This may indicate that the sites of the strongest star formation are the locations with the highest combined density and temperature.

Aside from these exceptions, variations in gas physical conditions do not appear to determine the widespread morphological changes seen in the chemical maps. Since the morphology of the maps are not explained completely in terms of changes in physical conditions, variation is the chemistry—relative molecular abundances—must be important.

5.2. Do the Maps Reflect Chemical Timescales?

One difference between molecular clouds of our Galactic disk and the clouds we observe in the nucleus of IC 342 is timescale. Dynamical timescales are shorter in galactic nuclei than they are in disks. Chemical models show that steady-state chemistry obtains after $10^6$–$10^7$ yrs, (eg., Herbst & Klemperer 1973; Prasad & Huntress 1980), and that abundances of molecules tend to fall into two categories. “Early-time” molecules, typically radicals and hydrocarbons — in general species descending from C or C$^+$ — are abundant early and get burned into CO and more complicated species as time passes. “Late-time” molecules, such as N$_2$H$^+$, NH$_3$ and SO, form from slower neutral-neutral reactions or are quickly destroyed by abundant C and C$^+$. Early-time species tend to peak by $\sim 10^5$ yrs, whereas late-time species reach their peak at steady state ($> 10^6$ yrs.) (eg., Graedel, Langer, & Frerking 1982; Watt 1983; Millar & Nejad 1985). In the disk of our Galaxy, these timescales are much shorter than the time between spiral arm passages, so that steady-state chemistry is expected in the absence of other disturbances.

In galactic centers, orbital timescales are short enough to rival chemical timescales. Based on the rotation curve in the nucleus of IC 342 (Turner & Hurt 1992), $\tau_{\text{GMC}} \lesssim 3$ Myr at the central ring, 7 Myr at 20″, and 10 Myr at the edge of the molecular arms. The arms seen in IC 342 are known to have strong non-circular and shearing motions, the expected response to a barred potential (Ishizuki et al. 1990; Turner & Hurt 1992; Schinnerer, Böker, & Meier 2003). It is likely that upon approaching/entering the arms, molecular clouds are either torn apart by the strong velocity gradients along the arm or are shocked due to cloud-cloud collisions, and this will happen
for a significant fraction of the orbit, or every $\sim \text{few} \times 10^5$ cm$^{-3}$. The “chemical clock” of the molecular clouds could well be reset after traversing the arms. Molecular clouds near the dynamical center of the galaxy may not be able to establish chemical equilibrium between arm passages; clouds farther out can potentially achieve equilibrium. A transition from early-time species to late-time species as galactocentric radius increases will then be manifested.

The “early-time” species $\text{C}_2\text{H}$ and $\text{HC}_3\text{N}$ are confined to the central ring region. However, other species such as HNC and CH$_3$OH (early-time if produced by gas-phase reactions, e.g. §5.4) are extended. $\text{N}_2\text{H}^+$, the most prominent late-time species detected, is actually brightest towards the central ring. Therefore, we conclude that time dependent chemistry is not the dominant effect causing the chemical differences between the clouds in IC 342. With the short orbital timescales it is likely that early-time chemistry is the relevant chemistry over the whole region, although in this context the brightness of the “late-time” molecule $\text{N}_2\text{H}^+$ is surprising. In the next section we show that photo-dissociation region (PDR) chemistry may also create the appearance of early-time chemistry in this region.

### 5.3. The Effects of a High Radiation Field: PDR Chemistry and the Cloud A

**Peakers C$_2$H and C$^{34}$S**

Photo-dissociation regions are widely believed to be responsible for many chemical properties of molecular clouds. IC 342 has active nuclear star formation, with $L_{\text{OB}} \sim 10^8 L_\odot$, and a slightly older (>10 Myr) nuclear star cluster. Clearly PDR chemistry will be important; however, is it a dominant driver of the chemistry in IC 342?

The observed molecules most affected by PDR chemistry are C$_2$H and the sulfur-bearing species such as C$^{34}$S. The spatial distributions of these molecules are distinct from the others (Figure 7), and it is likely that C$_2$H and C$^{34}$S emission trace the molecular clouds that are experiencing particularly high radiation fields. We discuss the chemistry and detailed distribution of each below.

#### 5.3.1. C$_2$H

The gas phase chemistry of C$_2$H follows two main pathways. One is dissociative recombination with hydrocarbon ions:

$$C_2H_2^+ + e^- \rightarrow C_2H + H,$$

$$C_2H_3^+ + e^- \rightarrow C_2H + 2H/H_2,$$

where C$_2$H$_2^+$ and C$_2$H$_3^+$ are built up from reactions of the form (e.g., Wootten et al. 1980; Watt et al. 1988; Sternberg & Dalgarno 1995; Turner, Herbst, & Terzieva 2000):

$$C^+ + CH_n \rightarrow C_2H_2^+ + H/H_2.$$
The second pathway involves the direct photodissociation of acetylene ($C_2H_2$), which also forms from reaction (3) (eg. Truong-Bach et al. 1987; Fuente et al. 1993; Heikkilä, Johansson & Olofsson 1999). $C_2H$ is destroyed primarily by photodissociation at $A_V$ ($\sim 1$ mag) and by reactions with $O$ and $C^+$ at $A_V \sim 5-6$ mag (eg., Wootten et al. 1980; Watt et al. 1988; Turner, Herbst, & Terzieva 2000). $C_2H$ should be abundant where $C^+$ and FUV photons are profuse. In the Galaxy, $C_2H$ abundances of $X_{C_2H} > 10^{-8}$ are observed in the diffuse ($A_V \sim 1 - 5$m) PDR gas (eg. Fuente et al. 1993; Heikkilä, Johansson & Olofsson 1999; Lucas & Liszt 2000).

In IC 342, $C_2H$ emission is confined to within 40 pc of the dynamical center, where the radiation field is high due to current star formation and to the 60 Myr nuclear star cluster. $C_2H$ is bright even in the central molecular “trough” coincident with the nuclear star cluster (Figure 3). Except in GMC A, $C_2H$ emission avoids the density peaks traced by HCN. In GMCs C and possibly B $C_2H$ emission peaks towards the side of the GMC facing the nuclear cluster. (This could also be true for GMC A, which is probably viewed “face-on” and therefore difficult to judge.) $C_2H$ appears to arise from cloud surfaces illuminated by the nuclear star cluster and not by the young IR/radio star-forming regions. The influence of the IR/radio star-forming regions may be localized and minimized because these young stars are still deeply embedded where their photons remain trapped. GMC A, which is the brightest in $C_2H$, is the closest cloud to the nuclear cluster. Apparently photons can penetrate GMC A more effectively than the other clouds. Perhaps GMC A is more diffuse than the other GMCs, in spite of its bright HCN emission.

5.3.2. Sulfur Bearing Molecules: $C^{64}S$

Reactions of $S$ and $S^+$ with hydrogen are endothermic so sulfur chemistry is not initiated through hydrides. For CS, formation is primarily via:

$$HCS^+ + e^- \rightarrow CS + H,$$  

where $HCS^+$ comes from:

$$S^+ + CH/C_2 \rightarrow CS^+ + H/C,$$  

(6)

and:

$$C^+ + SO \rightarrow CS^+ + O,$$  

(7)

followed by reactions with $H_2$. The reaction:

$$C + SO \rightarrow CS + O,$$  

(8)

can also be important in the formation of CS, particularly when there is a large SO abundance. At low $A_V$ reaction (6) is should dominate the formation of $CS^+$, while at large $A_V$ reaction (7) dominates. CS is destroyed by reactions with atomic O, $He^+$ ($H_3^+$, and $HCO^+$ also destroy CS.
but the products are rapidly recycled back into CS), and photodissociation. Photodissociation dominates the destruction at low $A_v$ (e.g. Drdla, Knapp, & van Dishoeck 1989; Turner 1996).

SO is considered a ‘late-time’ species built up through the neutral-neutral reaction,

$$S + OH \rightarrow SO + H,$$

and destroyed by reactions (7) and (8) in C/C$^+$-rich environments. In environments where carbon has yet to be locked into CO, SO tends to be burned into CS. Therefore the abundance ratio $[SO]/[CS] < 1$ at ‘early-times’, in regions of high C/O elemental abundance and low $A_v$ than it is at ‘late-times’, when $[SO]/[CS] \gtrsim 10$ (eg. Swade 1989; Bergin et al. 1997; Nilsson et al. 2000).

$C^{34}S$ peaks in the central trough and near GMC A. The CS abundance may be enhanced in these regions through the increase in $S^+$ associated with a high UV flux from the nuclear cluster. The CS abundance can be approximated as (e.g. Sternberg & Dalgarno 1995):

$$X_{CS} \sim \frac{k_{CH}X_{S^+}X_{CH} + k_{C_2}X_{S^+}X_{C_2}}{\left(\frac{G_0}{n_{H_2}}\right)k_\gamma(CS)}.$$  \(10\)

If S is undepleted and mostly ionized as expected at modest $A_v$, then for values of $k_{CH} \simeq 6.3 \times 10^{-9} \text{cm}^3 \text{s}^{-1}$, $k_{C_2} \simeq 8.1 \times 10^{-10} \text{cm}^3 \text{s}^{-1}$, $k_\gamma \simeq 2 \times 10^{-10} \exp(-2A_v) \text{ s}^{-1}$ and $[CH] \sim [C_2] \sim 10^{-8}$ (Drdla, Knapp, & van Dishoeck 1989), the observed CS (23$^*$C$^{34}S) abundances of few $\times 10^{-8}$ are obtained for $A_v \simeq 3$, when $G_0 = 320$ (Israel & Baas 2003) and $n_{H_2} = 10^4 \text{ cm}^{-3}$. This is consistent with the observed $C^{34}S$ morphology.

The SO/(23$^*$C$^{34}S) intensity ratio is everywhere less than 0.7 and less than 0.1 ($2\sigma$) towards GMC A. While not strongly constraining, this shows that SO is not enhanced in IC 342’s nucleus and is consistent with S molecule formation in a C/C$^+$-rich environment.

In the PCA analysis, $C^{34}S$ is the most anomalously distributed molecule of all (Figure 7), with the lowest correlation coefficients with any other molecule. We suggest that this may be due to the abundance distribution of ionized sulfur ($S^+$). In diffuse PDR cloud edges, sulfur should be relatively undepleted and ionized (eg. Lepp et al. 1988). The bright $C^{34}S$ emission toward GMC A and toward the edges of GMCs B and C is consistent with this model. If so, then the GMC A cloud is relatively well illuminated. In dense clouds, sulfur should be depleted onto the grains, and $C^{34}S$ comparatively faint. This is the case for the GMCs other than A and the edges of B and C towards the nuclear cluster. CS depletion in the denser regions of dark clouds is well established in the Galaxy, though on a much more local scale (eg. Bergin et al. 2001; Di Francesco et al. 2002).

5.4. Shocks and Gas-Grain Chemistry in IC 342: The Northern Arm Peakers

CH$_3$OH, HNCO

The pronounced spiral morphology in the nucleus of IC 342 indicates that shocks are likely to be present, both in the spiral arms and where the spiral arms meet the nuclear ring. Shocks can
influence the chemistry of molecular clouds by raising gas temperatures, but they also affect the chemistry by liberating molecules formed through the processing of grain mantles. Two molecules believed to be produced by grain processing are CH$_3$OH and HNCO.

5.4.1. CH$_3$OH

The gas phase chemistry of methanol is simple. The only formation mechanism is radiative association of CH$_3]^+$ + H$_2$O to form CH$_3$OH$_2]^+$ followed by dissociative recombination (Millar, Herbst & Charnley 1991; Turner 1998). This formation mechanism is too slow to produce methanol relative abundances greater than $X$(CH$_3$OH) $\sim$ 1 – 3 $\times$ 10$^{-9}$. (Lee, Bettens, & Herbst 1996). Abundances in Galactic star forming regions can reach up to $\sim$ 10$^{-7}$ (eg. Menten et al. 1986) and interstellar ice mantles are rich in methanol $X$(CH$_3$OH) $\sim$ 10$^{-6}$ (Schutte, Tielens & Sandford 1991). The high abundance of the methanol is thus believed to arise from hydrogenation of CO on grain surfaces. Methanol is expected to trace warm ($T_k$ $\sim$ 90 K) molecular gas where mantles have been evaporated.

In IC 342 methanol emission is widespread and bright and traces out the leading edges of the two molecular arms. If methanol were produced by the evaporation of grain mantles by warm molecular gas, then $T_k$ $\geq$ 90 K would be required. Instead, $T_k$ $\lesssim$ 50 K (§3.2) and $T_{ex}$(CH$_3$OH) $\sim$ 10 K are indicated (Hüttemeister, Mauersberger & Henkel 1997) for the nuclear region. Despite of the cool temperatures, the fractional abundance of CH$_3$OH is uniformly at or above $X$(CH$_3$OH) $\sim$ 3 $\times$ 10$^{-9}$ (Table 4). A second method of injecting a large amount of grain mantle material back into the ISM is through shock disruption of grains. Grain mantle material can be liberated either by the localized heating due to the shock or directly via grain disruption (eg. Sandell et al. 1994; Bachiller & Perez Gutierrez 1997; Bergin, Neufeld, & Melnick 1998). In mild shocks ($v_s$ $\lesssim$ 10 km s$^{-1}$) mantles of grains can be liberated without destroying the molecules in the process (eg., Bergin, Neufeld, & Melnick 1998). In order to be relevant for these observations the shocks must operate coherently over several tens of pcs in order to generate noticable enhancements on the observed scales. Shocks due to local phenomena such as outflows from massive stars likely do not influence enough of the molecular gas to explain the elevated abundances unless there are a very large number of them.

Large scale shocks due to orbital dynamics are the most plausible explanation for the bright methanol emission. The central region of IC 342 must have a barred potential to explain the overall molecular morphology. Non-circular orbital motions and highly supersonic changes in velocity direction are observed, particularly in the northern arm (eg. Turner & Hurt 1992). Orbital shocks associated with cloud-cloud collisions would be expected, although the exact nature of these shocks would depend on the strength and geometry of the magnetic fields. We expect shock processing of grains to be most important along the arms, at the intersections of the molecular arms and the central ring (the $x_1 - x_2$ orbital intersections: GMCs B and C) and at the bar ends where the molecular gas piles up and collides with the existing molecular gas in the arms (GMC D/D'). All of these locations are sites of bright methanol emission. While star formation at GMCs B
and C complicates the interpretation at the $x_1 - x_2$ orbital intersections, the enhanced methanol abundance towards GMC D/D’ is almost certainly due to shocks resulting from molecular gas from the southern arm, “spraying” off the central ring and colliding with the gas already present in the northern arm.

5.4.2. The Enigmatic HNCO

The chemistry of HNCO is poorly understood. The distribution in IC 342 and its correlation with other northern arm peakers such as methanol, give interesting insights on the chemistry of HNCO.

It has been proposed that the excited K ladders ($K_{-1} > 0$) of HNCO are excited by FIR radiation because their critical densities are prohibitively high for collisional excitation (e.g., Churchwell et al. 1986; Wilson et al. 1996; Blake et al. 1996). The situation is less clear for the $K_{-1}=0$ transitions observed here because the critical densities are lower. Rapid $b$-type transitions from $K_{-1} > 0$ to $K_{-1} = 0$ states can thermalize the level populations at the $330\mu m$ ($K_{-1} = 1 - 0$) and $110\mu m$ ($K_{-1} = 2 - 1$) radiation temperatures, but the lower critical densities make collisional excitation more relevant. In both Sgr B2 and OMC-1, the low lying $K_{-1} = 0$ transitions have higher column densities and lower rotational temperatures as compared to the excited K ladders (Churchwell et al. 1986; Blake et al. 1987). Derived abundances of HNCO($K_{-1}=0$) can be high, and emission much more widely distributed than found for the $K_{-1} \neq 0$.

In IC 342 HNCO is not well correlated with either molecular column density traced by $^{13}$CO, dense gas traced by HCN, or massive star-formation traced by 3 mm continuum. One would expect that if the dominant excitation mechanism for HNCO was FIR pumping, it would tend to be found near regions of active star formation and large gas column. That it is not arising from GMCs B and C argues against excitation mechanisms involving the FIR radiation field. We conclude that the 3 mm $K_{-1} = 0$ transitions of HNCO do not trace the FIR radiation field in IC 342. The HNCO emission appears to be governed by abundance variations rather than excitation.

Iglesias (1977) considered the possibility that HNCO is formed from electron recombination of H$_2$NCO$^+$, which has been produced by ion-molecule reactions between NCO$^+$ and H$_2$. He found that this model fell short of the observed abundances by an order of magnitude. Turner, Terzieva & Herbst (1999) suggest that the dominant formation mechanism is through:

$$CN + O_2 \rightarrow NCO + O,$$

$$NCO + H_2 \rightarrow HNCO + H,$$  \hspace{1cm} (11)

and destroyed predominately by reactions with H$_3^+$ and He$^+$. For abundances $X$(HNCO) $\sim 10^{-9}$ typical of the translucent clouds being studied, they argue that gas phase reactions alone appear necessary to explain the observed abundances. While the first reaction step is rapid, the second possesses a significant activation barrier ($\sim 1000$ K), and therefore the above reaction scheme may
be too slow at typical ISM temperatures. Additionally, O$_2$ is notoriously underabundant in the Galactic ISM (eg. Bergin et al. 2000; Goldsmith et al. 2000), hence the abundance of NCO is very poorly known. So as it stands, gas-phase chemistry alone may able to generate $[\text{HNCO}/\text{H}_2] \sim 10^{-10\text{--}9}$, but the matter remains unsettled.

Gas-grain chemical models have no trouble producing large abundances of HNCO. Chemical models find that significant amounts of HNCO ($X(\text{HNCO}) \sim 10^{-6}$) are formed in ice mantles by reactions such as CO(g) + N(g) + H(g) $\rightarrow$ HNCO and C(g) + N(g) $\rightarrow$ CN(g); CN(g) + O(g) $\rightarrow$ NCO(g); NCO(g) + H(g) $\rightarrow$ HNCO (Hasegawa & Herbst 1993). HNCO can also be formed by reactions of NH$_3$ (and its daughter products) with CO (Hudson & Moore 2000). Observers of ice mantles have often ascribed the so-called 4.62 $\mu$m 'XCN' feature to the ion, OCN$^-$ (eg. Grim & Greenberg 1987; Demyk et al. 1998; Novozamsky, Schütte, & Keane 2001), which forms either from UV photolysis of CO + NH$_3$ (eg., Grim & Greenberg 1987; Schütte & Greenberg 1997) or by acid-base reactions between HNCO and NH$_3$ (eg., Keane et al. 2001). In either case, the presence of this feature has been taken as evidence that HNCO is an abundant constituent of interstellar ices (eg., van Dishoeck & Blake 1998; van Broekhuizen, Keane, & Schütte 2004). If so, then like SiO and CH$_3$OH it is reasonable to expect HNCO abundances may also be enhanced in shocked regions.

Observational evidence is mounting for a shock tracer interpretation for the production of HNCO. (1) In SgrB2 the K$_{-1}$=0 transitions peak locally at SgrB2(N), near warm dust, and likely IR excitation, whereas the lower critical density K$_{-1}$=0 transitions arise from the more extended envelope (eg., Churchwell et al. 1986; Kuan & Snyder 1996). The K$_{-1}$=0 emission is strong towards the north and west edges of SgrB2, near the CO 'hole' seen in the molecular disk (Kuan & Snyder 1996; Minh et al. 1998), a hole that may have been created in a cloud-cloud collision (eg., Hasegawa et al. 1994; Mehringer et al. 1995; Sato et al. 1998). (2) HNCO is distributed differently from C$^{18}$O and is significantly enhanced in another Galactic Center cloud known to have strong shocks, GMC G+1.6-0.025 (Mauersberger & Bronfman 1998; Hüttemeister et al. 1998). (3) A recent study of dense cores in the Galactic disk, find a tight correlation between HNCO (K$_{-1}$=0) and SiO, a well established shock tracer suggesting the same production mechanism (Zinchenko, Henkel & Mao 2000).

Towards the northern bar end in IC 342 (GMC D'), $X(\text{HNCO})$ can be well above $10^{-9}$ over $\sim$100 pc scales. It seems unlikely that gas-phase chemistry can dominate in this region. Localized shocks/mantle evaporation due to star formation such as in the SgrB2 or Orion Hot Core cannot provide the observed enhancement unless star formation is extreme and widespread here, which it is not. The PCA finds that HNCO has a morphology most similar to that of CH$_3$OH, which is expected to trace shocks. These extragalactic observations appear to suggest that HNCO is being liberated from grain mantles due to the action of large scale shocks.

If the shock interpretation for the 3mm HNCO emission is correct, it is somewhat surprising that the linewidth of HNCO seen towards GMC D' is quite narrow. However, every other line
peaking at GMC D’ is broadened by unresolved hyperfine structure except HNC(1-0), so HNCO’s linewidth may appear “artificially” narrow. The narrow linewidth may be evidence that the shocks are not strong. Strong shocks (v $\sim$ 100 km s$^{-1}$) are expected to destroy the molecules as they are released from the grains, and there are some suggestions of this in the Galaxy (Zinchenko, Henkel & Mao 2000). Large-scale shocks due to cloud-cloud collisions at orbital resonances appear optimal in this respect, because they are probably mild, correlated with magnetic fields, and operate coherently over many tens of parsecs.

5.5. An Extragalactic Map of the HCN/HNC Ratio

The HCN/HNC abundance ratio is also an astrochemical enigma. In thermodynamic equilibrium, HCN is highly favored over the rare HNC. However, in cold dark clouds in the Galaxy, HNC is observed to be of similar abundance to HCN, and up to a factor of three more abundant (Hirota et al. 1998). In hotter regions such as the Orion hot core, HNC is still present but HCN dominates, with $|\text{HCN}|/|\text{HNC}| \sim$100 (eg., Goldsmith et al. 1981; Churchwell, Nash, & Walmsley 1984; Schilke et al. 1992; Turner, Pirogov, & Minh 1997). This has been interpreted as a transition from a chemical pathway that forms HNC and HCN at roughly equal abundances at low temperatures to neutral-neutral reaction paths with a small activation energy ($E_a \sim$ 200 K) that takes over creating HCN at the expense of HNC in warmth (Schilke et al. 1992; Hirota et al. 1998). Hence a low HCN/HNC ratio has been considered a tracer of cool, quiescent gas.

From a theoretical perspective, the HCN/HNC abundance ratio is much cloudier. Standard model chemistry predicts a ratio of unity over a wide range of conditions (eg., Lee, Bettens, & Herbst 1996), but with considerable uncertainties in the reactions. Recent models have suggested that the reaction $\text{HCNH}^+ + e^- \rightarrow \text{HCN}/\text{HNC} + \text{H}$ either slightly favors HNC over HCN (Shiba et al. 1998) or is equally probable (Talbi & Herbst 1998). If so, in cold dark clouds where cosmic ray driven ion-molecule chemistry dominates, it may be possible to explain the low observed HCN/HNC ratios. However, the dependence of the ratio on temperature is still largely unexplained. Given the observational evidence that the HCN/HNC ratio increases with temperature, neutral-neutral reactions with small activation energies that would preferentially destroy HNC in high temperature gas have been sought. Two commonly suggested reactions include:

\[
\text{HNC} + \text{H} \rightarrow \text{HCN} + \text{H},
\]

and:

\[
\text{HNC} + \text{O} \rightarrow \text{NH} + \text{CO},
\]

(eg., Schilke et al. 1992). The first reaction is especially promising because it converts HNC directly into HCN, effecting the HCN/HNC ratio sensitively. However, theoretical calculations suggest that both reactions have activation energies too large to contribute at gas temperatures less than several hundred Kelvin (Talbi, Ellinger, & Herbst 1996). Other reactions such as:

\[
\text{N} + \text{CH}_2 \rightarrow \text{HCN} + \text{H},
\]
have been suggested (eg. Goldsmith et al. 1981; Turner, Pirogov, & Minh 1997), but are calculated to be exothermic enough to undergo isomerization upon relaxation, and therefore actually end up making equal amounts of HNC and HCN (Herbst, Terzieva, & Talbi 2000).

Observations of HCN and HNC in starburst and Seyfert galaxies often find HCN/HNC $\sim$ 1, typical of Galactic dark clouds (Hüttemeister et al. 1995b; Aalto et al. 2002). Moreover, no correlation is seen between high HCN/HNC ratios and any typical indicator of high gas temperature. It is not clear that these observations even support the notion that HCN/HNC is an indicator of temperature (eg., Aalto et al. 2002). However, it is difficult to interpret single dish ratios given the large physical size they subtend on the galaxy. It is in this context that we investigate the high resolution GMC-to-GMC changes in the HCN/HNC ratio in IC 342.

In Figure 8 and Table 8, we use our HNC data together with HCN data kindly provided by D. Downes (Downes et al. 1992) to present the first high resolution HCN/HNC line ratio map in an external galaxy. The HCN/HNC line ratio is $\sim$ 1 – 2, and fairly constant over the nuclear region. GMC A has the highest ratio of 2. While GMC A appears somewhat hotter than the ambient gas in IC 342 (MT01), it is not the hottest GMC (GMC B, $T_{ex}$ $\sim$ 20 K) nor is it near the present star formation and IR sources (GMCs B and C). In fact, starburst GMCs B and C are actually local minima of HCN/HNC. Finally, though the interpretation is limited somewhat by the smaller primary beam of the Plateau de Bure HCN(1-0) data, it does appear that there is a real trend for the HNC/HNC line ratio to decrease below unity as one goes to large distances from the center along the northern and southern spiral arms.

If we assume that HCN/HNC traces temperature and we use the Hirota et al. (1998) empirical Galactic dependence, then across the entire nuclear region this ratio would predict that $T_k$ is approximately constant at 22 - 27 K. This is low compared to the observed dust temperature, 42 K, and gas kinetic temperatures of $\sim$50 K in ammonia or the observed antenna temperature of the $^{12}$CO(2-1) transition (Turner, Hurt & Hudson 1993; Schinnerer, Böker, & Meier 2003). The explanation for the low HCN/HNC values could be that IC 342 has an abundant dense component that is significantly cooler and more uniform than the more diffuse component traced by CO. We consider this unlikely, since the CO, HNC, and HCN distributions are nearly coextensive. We consider a more likely the possibility that HCN/HNC is simply not a function of temperature.

We have assumed that the HCN(1-0)/HNC(1-0) line ratio reflects the abundance ratio. This is only true if the line opacities are small. For $\tau > 1$, HCN(1-0)/HNC(1-0)$\sim$1, independent of chemistry. Such an effect is most relevant where the line intensities are the highest, namely GMCs B and C. This is where the ratio approaches unity despite the proximity to HII regions. However single-dish observations of H$^{13}$CN(1-0) in IC 342 show that HCN(1-0)/H$^{13}$CN(1-0) $\simeq$ 30 (Schulz et al. 2001), close to what is expected for the $^{12}$C/$^{13}$C isotopic ratio in the nuclei of starburst galaxies (eg., Henkel & Mauersberger 1993; Wilson & Rood 1994), indicating low opacities. Future high resolution observations of H$^{13}$CN and HN$^{13}$C should provide information on this issue.
5.6. Quiescent Gas Tracer? $N_2H^+$

It has been suggested that $N_2H^+$ is a robust tracer of the dense, quiescent component of molecular gas (eg., Womack, Ziurys & Wyckoff 1992b). $N_2H^+$ abundances tend to be low in hot-cores, outflows and PDRs in the Galaxy. Hence, the extent and brightness of $N_2H^+$ in the nucleus of IC 342, with its active star formation, radiation, and shocks, is surprising. One might infer that dense gas is present in IC 342, but that this gas is largely sterile and quiescent with “dark cloud-like” chemical conditions. In this picture, shocks, winds and outflows associated with star formation are confined to small regions around each forming star, and the remaining dense gas is largely undisturbed. This would have interesting ramifications for the extremely luminous ($L_{IR} \sim 10^8 \text{ L}_\odot$) star forming GMCs, B and C, which are both strong sources of $N_2H^+$ emission.

Alternatively, there could be differences in the formation or destruction rates of $N_2H^+$. $N_2H^+$ is formed almost exclusively from the reaction:

$$N_2 + H_3^+ \rightarrow N_2H^+ + H_2,$$

and is destroyed primarily by dissociative recombination with electrons in diffuse gas, and the ion-neutral reactions with CO and O in dark clouds. Therefore, $N_2$ is cycled through $N_2H^+$, and if the abundance of $H_3^+$ and electrons can be assessed then $N_2H^+$ is a direct tracer of the (otherwise invisible) molecular nitrogen (eg. Womack, Ziurys & Wyckoff 1992a; Turner 1995; Benson, Caselli, & Myers 1998).

The $H_3^+$ abundance is formed from cosmic-ray ionization of $H_2$ and destroyed by reactions with $e^-$, CO and O. In steady-state:

$$X(H_3^+) = \frac{\zeta/n_{H_2}}{k_{H_3,CO}X(CO) + k_{H_3,e}X(e^-)},$$

where $\zeta$ is cosmic-ray ionization rate and the rate coefficients, $k$, are taken from Benson, Caselli, & Myers (1998) and Dalgarno & Lepp (1984), except for the dissociative recombination rate ($k_{H_3,e}$), which is taken from McCall et al. (2003). If we assume that $N_2H^+$ is formed by (15) then:

$$\frac{X(N_2)}{X(N_2H^+)} = \frac{k_{N2H,CO}X(CO) + k_{N2H,e}X(e^-)}{k_{H3,N2}X(N_2)X(H_3^+)},$$

or:

$$\frac{X(N_2)}{X(N_2H^+)} = \frac{[k_{N2H,CO}X(CO) + k_{N2H,e}X(e^-)][k_{H3,CO}X(O) + k_{H3,e}X(e^-)]}{k_{H3,N2}X(N_2)[\zeta/n_{H_2}]}.$$

In this steady-state chemical scheme, the abundance of $N_2H^+$ increases with (1) increasing $\zeta$, (2) decreasing density, (3) decreasing electron fraction, $X(e^-)$, or (4) increasing $N_2$, assuming that the CO and O abundances remain fairly constant across the nucleus. It seems unlikely that explanations (2) and (3) dominate in the nucleus of IC 342. We know the densities are high, at
least a few $\times 10^4$ cm$^{-3}$, and $X(e^-)$ could be as high as $\simeq 1.5 \times 10^{-5}$ based on the C$^+$ abundance determined by Crawford et al. (1985) and Eckart et al. (1990). The most likely alternatives for the bright, extensive $N_2H^+$ emission are therefore either a high cosmic-ray ionization rate or enhanced $N_2$ abundance.

Figure 9 displays the $X(N_2)/X(N_2H^+)$ ratio as a function of electron fraction, for different values of $\zeta/n_{H_2}$ (see eq.[17]). It has been assumed that $X(O) \simeq X(CO) = 10^{-4}$. The maximum $N_2$ abundance possible is one half the total cosmic $N$ abundance, or $X(N_2) \sim 4 \times 10^{-5}$ (eg., Anders & Grevesse 1989). The brightness of the high density tracers suggest that $n_{H_2}$ is at least $10^{4-4.5}$ cm$^{-3}$, implying that $\zeta_{IC342} > 10^{-17}$ s$^{-1}$, at least the Galactic disk value. If some $N$ is not in $N_2H^+$ (and there is bright ammonia emission Ho et al. 1990) or $n_{H_2}$ is greater than $10^4$ cm$^{-3}$, then $\zeta$ is constrained to be higher than the Galactic rate. For $X(e^-) \gtrsim 10^{-7}$, the cosmic ray rate would have to be greater still. Therefore, to explain the bright and ubiquitous $N_2H^+$ emission it is likely that $\zeta > 10^{-17}$ s$^{-1}$ in the nucleus of IC 342.

5.7. The Warm and the Dense: HC$_3$N

HC$_3$N has the highest upper energy state and one of the highest critical densities of our sample. The most striking feature of the HC$_3$N(10-9) intensity distribution is how closely it follows the 3 mm continuum emission. We consider two possibilities for the bright HC$_3$N emission in regions where the millimeter continuum is high, (1) enhanced HC$_3$N abundance towards star-forming GMCs B and C (and possibly E) or (2) HC$_3$N is more highly excited by collisions with molecular hydrogen at the sites of the densest and warmest gas.

HC$_3$N formation is uncertain, but probably forms from the neutral-neutral reaction,

$$C_2H_2 + CN \rightarrow HC_3N + H,$$

and is destroyed by photodissociation and reactions with C$^+$ (eg. Sims et al. 1993; Fukuzawa & Osamura 1997; Turner, Lee & Herbst 1998). Since the central ring region has high abundances of $C_2H$ it is reasonable to expect this region will also have high abundances of $CN$ and $C_2H_2$, species that can maintain large abundances in PDRs. It is possible, therefore, that the high estimated HC$_3$N abundances follow from $CN$ and $C_2H_2$ abundances here. The weakness of HC$_3$N towards GMC A would then be attributed to increased destruction rates due to photodissociation and large C$^+$ abundances and more diffuse gas working in tandem.

The second possibility for the HC$_3$N morphology is excitation. HC$_3$N is the molecule most sensitive to decreases in $T_{ex}$ (decreases in density; Table 2). If there is an excitation gradient decreasing with distance from the starburst the abundances derived outside the central starburst region would be artificially low. Given the sensitivity of the derived HC$_3$N abundance to excitation, we do not at this stage overinterpret possible changes in HC$_3$N chemistry and conclude that decreasing excitation away from the starbursts is the simplest explanation of the HC$_3$N morphology.
If excitation is the answer then why isn’t HC$_3$N also bright at GMC A, since N$_2$H$^+$, HNC (and HCN) are bright there, species with critical densities nearly as high or higher than HC$_3$N? GMC A is actually one of the warmer GMCS (in CO), so chemical changes may be favored. However there is another possibility. Electrons could be responsible for some of the collisional excitation towards GMC A. In Table 2 the critical densities for electron collisions are compared with those for H$_2$ collisions. If $X(e^-)=X(C^+) \approx 1.5 \times 10^{-5}$ in the center of IC 342 (Crawford et al. 1985; Eckart et al. 1990), then electrons are of equal or greater importance as a collision partner for N$_2$H$^+$, HCN and HNC. For all other species, with the possible exception of C$^{34}$S(2-1), collisions with electrons are not relevant. The C$^+$ abundance is almost certainly lower than the above values everywhere except GMC A and the central trough given that the C$^+$ value was made with a large beam and likely is dominated by the more diffuse molecular cloud component associated with the PDRs. Evidently, in the regions with abundant C$^+$, HNC and HCN can be efficiently excited by electrons (Dickinson et al. 1977; Turner, Pirogov, & Minh 1997). This may have important consequences for densities derived from HCN in starburst galaxies dominated by PDR regions.

5.8. The Overall Chemistry of IC 342

When we consider all the observed molecular lines together a consistent picture of the structure of the ISM in IC 342 begins to emerge, which is summarized in the cartoon of Figure 10. Gas response to a barred potential has set up the molecular minispiral within the nucleus of IC 342. Energy dissipation from cloud collisions and star formation within the molecular arms, and angular momentum transfer from tidal torquing result in a gradual inward drift of molecular gas along the arms. Molecular gas piles up at the intersections of the arms and the central ring, where it triggers star formation at the rate of $\sim 0.1 \, M_\odot \, yr^{-1}$. In turn, the bar sets up density gradients both azimuthally along the molecular arms and radially. The molecular gas densities tend to be higher on the leading (counter-clockwise) edges of the molecular arms, becoming more diffuse behind the arms (Wright et al. 1993; MT01). Densities also tend to be higher as the gas approaches the nucleus, peaking near the $x_1 - x_2$ intersection. Compare the morphology of $^{12}$CO(1-0), $^{13}$CO(1-0), HNC and HC$_3$N in Figure 2 to see the density progression from diffuse to dense gas.

The sphere of influence of the nuclear bar extends not just to the physical conditions of the gas (density, temperature) but also to the chemistry. CH$_3$OH and HNCO delineate the locations of shocks associated with cloud-cloud collisions within spiral arms, following the theoretical expectations of the locations of shocks in a barred potential (eg. Athanassoula 1992). These molecules indicate that grain mantle liberation is important towards GMC D’ and possibly GMC C along the northern arm. The lack of the expected symmetry between the northern and southern arms appears to be due to a lower column density of dense gas towards the southwestern arm (Figure 6a). Outside of GMC A it may be that grain liberation influences the abundances of most of the observed species either directly (CH$_3$OH and HNCO) or indirectly due to injection of “invisible” N$_2$ and C$_2$H$_2$ (N$_2$H$^+$ and HC$_3$N). It is tempting to speculate that the prevalence of molecular arm
shocks explain why star formation is not pronounced along the spiral arms, but “waits” till the gas arrives in the central ring.

From \( \text{C}_2\text{H} \) and \( \text{C}^{34}\text{S} \), we learn that the faces of the molecular ring surrounding the central star forming complex are bright PDRs. The limited spatial extent of \( \text{C}_2\text{H} \) argues that the \( \text{C}^+ \) abundance is strongly enhanced in the central ring; the primary ionization sources are not distributed uniformly across the nucleus, nor does the ionization appear to penetrate deeply into most of the GMCs. This rules out more penetrative mechanisms such as cosmic-ray ionization (primary or secondary) or hard X-rays as the main source of enhanced \( \text{C}^+ \) ionization in IC 342. Photoionization from stars is likely to produce enhanced \( \text{C}^+ \) given the interstellar radiation field (ISRF) is \(~320\) times stronger than Galactic value (Israel & Baas 2003). This provides further support for previous studies which suggested that PDRs play an important role in the physical conditions of the central ring of IC 342 (Turner, Hurt & Hudson 1993; MTH00; Schulz et al. 2001). Synchrotron emission (Figure 3a; Turner & Ho 1983) indicates that supernovae have taken place in the nucleus, and one might expect the cosmic-ray ionization rate to be somewhat elevated here. The bright \( \text{N}_2\text{H}^+ \) emission alludes to such a possibility. Since the PCA analysis demonstrates that \( \text{N}_2\text{H}^+ \) and \( \text{C}^{18}\text{O} \) have similar morphologies, whatever process elevates the \( \text{N}_2\text{H}^+ \) abundance operates fairly uniformly across the entire region, as would be expected for cosmic-ray ionization.

From the morphology of \( \text{C}_2\text{H} \), the most likely source of ionizing radiation for the PDRs (see especially the inner face of GMC C) is the more mature (~60 Myr old) central, nuclear cluster and not the youngest (~few Myr) starbursts seen in radio and millimeter continuum towards GMCs B and C. Evidently, the young stars in these large HII regions have yet to break out of their natal cocoons and influence the large-scale chemistry of the nucleus. The HST composite image, the preferentially blueshifted \( \text{C}_2\text{H} \) and \( \text{C}^{34}\text{S} \) line profiles and the weak \( \text{C}_2\text{H} \) extension perpendicular to the major axis imply that this central star formation event is just beginning to break out along the galactic minor axis.

GMC A appears to be the molecular cloud most strongly penetrated by UV photons. GMC A is also the only GMC in the central ring that is not a site of strong current star formation. These results suggest that for some reason GMC A is on average more diffuse than the other two GMCs, and therefore more susceptible to UV radiation. The reason for this is unclear, but may be related to its location in the nucleus. Close to the dynamical center of the galaxy and at a position where it likely has just ‘whipped’ around from the \( x_1 \) orbital onto the \( x_2 \) orbital, tidal and shearing forces may be shredding Cloud A apart (note the broad \( \text{C}^{34}\text{S} \) line profile). In this condition, Cloud A is probably not inclined to collapse and form stars (until it collides with GMC B+E?).

It has been established that the chemistry of the two nearest prototypical starburst galaxies, M 82 and NGC 253, have different chemical makeups (eg. Mauersberger & Henkel 1991a; Henkel, Baan & Mauersberger 1991; Mauersberger & Henkel 1993). M 82 is bright in HCN, HNC, \( \text{C}_2\text{H} \), CN, \( \text{HCO}^+ \) and HCO, but notoriously weak in lines of SiO, \( \text{CH}_3\text{OH} \), \( \text{CH}_3\text{CN} \), HNCO and SO, as compared to NGC 253 (Mauersberger & Henkel 1993; Takano, Nakai & Kawaguchi 1995). In
IC 342, we see for the first time regions with M 82-like chemistry (GMC A), and regions of NGC 253-like chemistry (GMC D') in the same nucleus. Regions where grain disruption due to shocks occur are likely to manifest chemistries similar to NGC 253, whereas sites of PDRs manifest M 82-like chemistries. It is therefore tempting to conclude that the ISM in M 82 is dominated by GMC A-type molecular gas (PDRs) and is deficient in GMC D-type molecular gas (shock/grain process species) due to absence of strong nucleus-wide shocks compared to the barred galaxy, NGC 253. This lends support to similar conclusions reached by García-Burillo et al. (2000) and García-Burillo et al. (2002) for NGC 253 and M 82. It also illustrates that CH$_3$OH and HNCO hold the potential of being an much more useful shock tracers in external galaxies than the well established tracer, SiO, since the 3 mm transitions of these two molecules are much brighter than SiO (Nguyen-Q-Rieu et al. 1991; Sage & Ziurys 1995; Hüttemeister, Mauersberger & Henkel 1997). In IC 342 PDRs still remain largely confined to the central ring, but in M 82 they are clearly much more pervasive.

Finally, an intriguing result of this dataset is the apparent discovery of an isolated nitrogen-rich GMC. Its location between GMCs A and B suggests two possibilities. Firstly, it is seen at the location where gas going down the northern arm collides with the southern arm. This may then represent a location of N$_2$ injection (from grain disruption), which would explain the increased N$_2$H$^+$ abundance and HNCO, but not necessarily the HC$_3$N abundance (unless C$_2$H$_2$ is also injected). A second possibility is that this region is enriched in ejecta from young, massive stars, perhaps Wolf-Rayet stars. There is a young, massive cluster seen in the near-infrared (NIR) near this location (see Figure 3 of Schinnerer, Böker, & Meier 2003). There is evidence that massive star enrichment of $^{18}$O has taken place in the central trough vicinity (MT01). But why is the nitrogen enrichment seen in this one location when there are several other NIR bright clusters, including the much larger central cluster, which is not known to be enriched? Similar studies of other galaxies may shed light on this question.

6. Conclusions

We have detected emission from a number of molecules in the central region of IC 342 at resolution of 5'' using OVRO. Significant differences are seen in the spatial distributions of these molecules, and we have analyzed the causes of these differences. Main results include:

1. A principal component analysis of the maps of the seven detected molecules, $^{12}$CO(1-0), C$^{18}$O, HCN(1-0) and 3mm continuum, reveals that the maps all have some degree of correlation, and that the dominant common factor (PC1 axis) is the density-weighted mean column density. Molecules with the largest projections on PC1 are N$_2$H$^+$, C$^{18}$O, and HNC. These molecules, and primarily N$_2$H$^+$, give the best overall representation of the total molecular gas distribution.

2. Differences in excitation and critical density are not the dominant influences shaping the spatial differences among the different molecules in IC342, since the excitation energies of the transitions are similar, and cloud densities are high enough that most molecules are collisionally
excited.

3. The spatial differences among the molecular line emission are not driven by variations in chemical timescale: all clouds in this region are likely to have early-time chemistry due to the short orbital timescales of the nucleus.

4. The second principal component axis, PC2, splits into two anti-correlated groups of molecules: molecules that peak within the central 75 pc near GMC A and the nuclear star cluster, and those that peak up along the prominent northeastern arm, located 100-200 pc away from the nucleus.

5. The GMC A peakers, C$_2$H and C$^{34}$S, are enhanced in the center of IC 342 by high radiation fields. GMC A is a PDR cloud. The fact that these molecules tend to favor the parts of the clouds towards the center of IC 342 rather than toward the slightly off-center L\textsubscript{IR} $\sim$ 10$^8$ L$_\odot$ radio/IR source suggests that the source of the radiation field affecting the chemistry of GMC A is the $\sim$60 Myr central star cluster and not the actively star forming radio/IR sources.

6. Molecules that peak along the north-east arm of the molecular mini-spiral are HNCO and CH$_3$OH. Large scale shocks due to the changes in gas velocity at the arms of the nuclear minispiral are probably the cause of enhanced HNCO and CH$_3$OH here.

7. HCN and HNC are the best tracers of the dense gas and HC$_3$N of warm, dense gas. Their correlation with the 3mm continuum is excellent. The HCN/HNC ratio is 1-2 across the nuclear region, and appears to be unrelated to kinetic temperature.

8. The brightness and extent of emission from N$_2$H$^+$ suggests that the cosmic ray ionization rate is higher than $\zeta > 10^{-17}$ s$^{-1}$ in the nucleus of IC 342.

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Table 1. Observational Data

| Transition                  | Dates (MMYY) | Frequency (GHz) | $T_{\text{sys}}$ (K) | $\Delta V_{\text{chan}}$ (km s$^{-1}$) | $\Delta \nu_{\text{band}}$ (MHz) | Beam ($^{\prime\prime} \times^{\prime\prime}$) $^{(o)}$ | Noise (mK/mJy bm$^{-1}$) |
|-----------------------------|--------------|-----------------|----------------------|----------------------------------------|----------------------------------|------------------------------------------------------------|--------------------------|
| C$_2$H(1 − 0; 3/2 − 1/2)$^a$| 0900-1000    | 87.317          | 350-690              | 13.73                                  | 128                              | $5.5 \times 4.9; -41^o$                                      | 53/8.9                   |
| HNCO(4$_{04}$ − 3$_{03}$)$^a$| 0900-1000    | 87.925          | 420-780              | 13.64                                  | 128                              | $5.9 \times 5.1; -36^o$                                      | 39/7.4                   |
| HNC(1 − 0)$^a$             | 0900-1000    | 90.664          | 430-930              | 13.23                                  | 128                              | $5.9 \times 5.1; -39^o$                                      | 26/5.2                   |
| HC$_3$N(10 − 9)$^a$        | 0900-1000    | 90.979          | 400-890              | 13.18                                  | 128                              | $5.9 \times 5.1; -44^o$                                      | 24/4.8                   |
| N$_2$H$^+$(1 − 0)$^a$      | 0101-0401    | 93.174          | 380-440              | 12.87                                  | 128                              | $6.2 \times 5.1; -59^o$                                      | 29/6.4                   |
| C$^{34}$S(2 − 1)$^a$       | 0101-0401    | 96.413          | 370-450              | 12.44                                  | 128                              | $6.6 \times 5.6; -63^o$                                      | 24/6.8                   |
| CH$_3$OH(2$_k$ − 1$_k$)$^a$| 0101-0401    | 96.741          | 420-480              | 12.40                                  | 240                              | $6.0 \times 4.8; -65^o$                                      | 35/7.6                   |
| SO(2$_3$ − 1$_2$)$^b$      | 1097-1297    | 109.252         | 410-480              | 10.98                                  | 128                              | $5.0 \times 4.3; -21^{ac}$                                  | 41/8.6                   |
| SO(6$_5$ − 5$_4$)$^b$      | 1097-1297    | 219.949         | 410-1020             | 5.45                                   | 128                              | $5.0 \times 4.3; -21^{od}$                                  | 52/44                    |

$^a$Phase Center #1: $\alpha = 03^h41^m57.0^s \delta = +67^\circ56'30.0''$ (B1950); $v_{\text{lsr}} = 35$ km s$^{-1}$

$^b$Phase Center #1: $\alpha = 03^h41^m57.0^s \delta = +67^\circ56'26.0''$ (B1950); $v_{\text{lsr}} = 35$ km s$^{-1}$

$^c$Maps generated with a 50 k$\lambda$ taper.

$^d$Map convolved to the same resolution as the 3 mm SO transition.
Table 2. Molecule and Column Density Parameters

| Molecular Transition | µ (Dby) | A/B/C (GHz) | $S_{ul}gKgI$ | $E_u$ (K) | $H_2n_{cr}/e_{cr}$ | $N(50)$ | $T_{min}$ | $N_{min}$ |
|----------------------|---------|-------------|--------------|------------|---------------------|---------|----------|-----------|
| C$_2$H:(1 − 0; $\frac{3}{2}$ − $\frac{1}{2}$) | 0.8 | $\cdots$/43.675/$\cdots$ | 1 | 4.19 | 5.13/6.06 | 3.01 | 4.80 | 0.66 |
| HNCO(4$_04$ − 3$_03$) | 1.60 | 912.711/11.071/10.911 | 4 | 10.55 | 5.43/6.03 | 4.81 | 7.03 | 0.92 |
| HNC(1 − 0) | 3.05 | $\cdots$/45.332/$\cdots$ | 1 | 4.35 | 6.39/5.69 | 2.94 | 4.98 | 0.70 |
| HC$_3$N(10 − 9) | 3.72 | $\cdots$/4.5491/$\cdots$ | 10 | 24.02 | 5.86/6.69 | 0.723 | 24.0 | 0.59 |
| N$_2$H$^+$ (1 − 0) | 3.40 | $\cdots$/46.587/$\cdots$ | 1 | 4.47 | 5.63/5.67 | 3.00 | 5.12 | 0.75 |
| C$_3$S(2 − 1) | 1.96 | $\cdots$/24.104/$\cdots$ | 2 | 6.94 | 5.65/5.99 | 2.56 | 7.29 | 0.61 |
| CH$_3$OH(2$_k$ − 1$_k$) | 0.89 | 127.484/24.680/23.770 | 4.3,4$^e$ | 6.98 | 4.83/6.21 | 5.96 | 4.65 | 0.65 |
| SO(2$_3$ − 1$_2$) | 1.55 | $\cdots$/21.523/$\cdots$ | 1.51 | 21.06 | 5.27/6.10 | 0.901 | 21.4 | 0.68 |
| SO(6$_5$ − 5$_4$) | 1.55 | $\cdots$/21.523/$\cdots$ | 5.91 | 34.99 | 6.55/7.30 | 0.296 | 35.3 | 0.28 |

Note. — Data from the JPL Molecular Spectroscopy Catalog (Pickett et al. 1998) and references within. Collisional coefficients are HNC, C$_2$H (HCN; Green & Thaddeus 1974), C$_3$S, HC$_3$N (Green & Chapman 1978), N$_2$H$^+$ (Green 1975), CH$_3$OH (Pottage, Flower, & Davis 2004), HNCO (Green 1986) and SO (Green 1994).

$^a$The critical density of the transitions neglecting opacity effects ($H_2n_{cr} \simeq \frac{\lambda_{ul}}{C_{ul}}$) and $e_{cr}$ based on the formalism of (Dickinson et al. 1977), with $[e^-] = [C^+] \simeq 1.5 \times 10^{-5}$.

$^b$The ratio by which the derived column densities change when the $T_{ex}$ is changed from 10 K → 50 K.

$^c$The $T_{ex}$ at which derived (LTE) column densities are a minimum.

$^d$The ratio by which the derived column densities change when the $T_{ex}$ is changed from 10 K → $T_{min}$.

$^e$S$_{ul}gKgI$ for the three blended 2$_1$ − 1$_1$E, 2$_0$ − 1$_0$E, and 2$_0$ − 1$_0$A+ transitions (eg., Turner 1991).
| GMC<sup>a</sup> | Molecule | \( T_b \) \( (K) \) | \( I_{mol} \) \( (K \ km \ s^{-1}) \) | \( \Delta v \) \( (km \ s^{-1}) \) | \( v_o \) \( (km \ s^{-1}) \) |
|---|---|---|---|---|---|
| A | \( \text{C}_2\text{H} \) | 0.27±0.05 | 15±2 | 75±8.5 | 19±3.6 |
|  | \( \text{HNC} \) | 0.50±0.07 | 22±3 | 40±2.2 | 24±1.0 |
|  | \( \text{HNCO} \) | ≤0.078 | ≤3.6 | … | … |
|  | \( \text{HC}_3\text{N} \) | 0.069±0.02 | 4.1±0.8 | … | … |
|  | \( \text{N}_2\text{H}^+ \) | 0.18±0.03 | 8.9±1 | 38±5.7 | 26±2.4 |
|  | \( \text{CH}_3\text{OH} \) | 0.16±0.04 | 6.4±0.9 | 40±6.7 | 24±2.9 |
|  | \( \text{C}^{34}\text{S} \) | 0.089±0.02 | 8.5±1 | 120±38 | -5.3±16 |
| B | \( \text{C}_2\text{H} \) | 0.21±0.05 | 8.3±2 | 43±7.3 | 4.8±3.1 |
|  | \( \text{HNC} \) | 0.62±0.09 | 31±5 | 30±1.2 | 24±0.6 |
|  | \( \text{HNCO} \) | ≤0.11 | 5.3±1 | … | … |
|  | \( \text{HC}_3\text{N} \) | 0.088±0.02 | 5.4±0.9 | 20±9.5 | 19±4.3 |
|  | \( \text{N}_2\text{H}^+ \) | 0.19±0.03 | 7.1±1 | 23±3.8 | 23±1.5 |
|  | \( \text{CH}_3\text{OH} \) | 0.15±0.04 | 4.5±0.9 | 25±5.0 | 18±2.2 |
|  | \( \text{C}^{34}\text{S} \) | ≤0.053 | 3.6±0.9 | … | … |
| C | \( \text{C}_2\text{H} \) | ≤0.11 | 7.2±2 | 30±9 | 33±3.8 |
|  | \( \text{HNC} \) | 0.47±0.07 | 23±3 | 40±2.7 | 46±1.1 |
|  | \( \text{HNCO} \) | 0.23±0.04 | 8.4±1 | 30±6.5 | 49±2.7 |
|  | \( \text{HC}_3\text{N} \) | 0.20±0.03 | 8.4±1 | 30±5.8 | 52±2.5 |
|  | \( \text{N}_2\text{H}^+ \) | 0.18±0.03 | 7.6±1 | 35±6.2 | 48±2.6 |
|  | \( \text{CH}_3\text{OH} \) | 0.35±0.05 | 15±2 | 32±2.8 | 48±1.2 |
|  | \( \text{C}^{34}\text{S} \) | 0.078±0.02 | 3.6±0.9 | … | … |
| D | \( \text{C}_2\text{H} \) | ≤0.11 | ≤1.5 | … | … |
|  | \( \text{HNC} \) | 0.15±0.03 | 8.4±1 | 47±7.8 | 47±3.3 |
|  | \( \text{HNCO} \) | 0.16±0.04 | 3.9±1 | 28±5.8 | 54±7.5 |
|  | \( \text{HC}_3\text{N} \) | ≤0.048 | ≤1.5 | 25±25 | 46±13 |
|  | \( \text{N}_2\text{H}^+ \) | 0.11±0.03 | 3.2±0.8 | 35±8.3 | 48±3.5 |
|  | \( \text{CH}_3\text{OH} \) | 0.12±0.04 | 4.1±0.9 | 38±6.2 | 52±2.7 |
|  | \( \text{C}^{34}\text{S} \) | ≤0.048 | ≤1.8 | … | … |
| D' | \( \text{C}_2\text{H} \) | ≤0.11 | ≤1.5 | … | … |
|  | \( \text{HNC} \) | 0.17±0.03 | 6.7±1 | 37±5 | 50±2 |
|  | \( \text{HNCO} \) | 0.25±0.04 | 7.2±0.8 | 27±3 | 56±2 |
|  | \( \text{HC}_3\text{N} \) | ≤0.04 | ≤1.1 | 26±14 | 53±6 |
|  | \( \text{N}_2\text{H}^+ \) | 0.13±0.02 | 5.5±1 | 40±6 | 54±3 |
|  | \( \text{CH}_3\text{OH} \) | 0.26±0.03 | 8.6±1 | 31±3 | 52±1 |
|  | \( \text{C}^{34}\text{S} \) | < 0.11 | < 1.5 | … | … |
| GMC<sup>a</sup> | Molecule | $T_b$<sup>(K)</sup> | $I_{mol}$<sup>(K km s<sup>-1</sup>)</sup> | $\Delta v$<sup>(km s<sup>-1</sup>)</sup> | $v_o$<sup>(km s<sup>-1</sup>)</sup> |
|----------------|----------|------------------|------------------|------------------|------------------|
| E              | C$_2$H   | $\lesssim 0.11$  | 6.0±2            | 47±11            | 1.0±4.6          |
|                | HNC      | 0.46±0.07        | 18±3             | 35±2.2           | 18±0.9           |
|                | HNCO     | 0.25±0.04        | 5.8±1            | 22±3.3           | 15±1.8           |
|                | HC$_3$N  | 0.084±0.02       | 3.6±0.8          | 37±14            | 11±5.8           |
|                | N$_2$H$^+$| 0.21±0.03        | 6.7±1            | 28±4.8           | 19±2.0           |
|                | CH$_3$OH | 0.16±0.04        | 7.3±1            | 30±5             | 15±2.1           |
|                | C$_{34}$S| 0.089±0.02       | 2.7±0.9          | 25±5.5           | 4.6±2.5          |

Note. — $T_b$ is the main-beam brightness temperature in units of Kelvins based on the resolutions given in Table 1. $I_{mol}$ is the peak integrated intensity in units of K km s$^{-1}$ for the same resolution. Uncertainties are based on the larger of the RMS noise or an estimated $\approx 15\%$ absolute calibration errors for the temperatures and intensities, and 1σ from the least-squared gaussian fits for the velocity information. Upper limits represent 2σ values.

<sup>a</sup>Peaks are based on the C$^{18}$O data. See MT01 for coordinates, except for D’ which has coordinates $\alpha = 03^h 46^m 49^s.8$, $\delta = +68^\circ 05' 59.2''$ (J2000).
Table 4. Molecular Abundances in IC 342

| GMC | N(H₂)  | C₂H  | HNC  | HNCO | HC₃N | N₂H⁺ | CH₃OH | C³⁴S  | SO² |
|-----|--------|------|------|------|------|------|-------|-------|-----|
| A   | 2.3    | 3(8) | 2(9) | <1(9)| ≤1(9)| 5(10)| 5(9)  | 2(9)  | <7(9)|     |
| B   | 2.8    | 1(8) | 2(9) | 2(9) | 1(9) | 3(10)| 3(9)  | 6(10) | <6(9)|     |
| C   | 3.2    | 1(8) | 1(9) | 2(9) | 2(9) | 3(10)| 8(9)  | 5(10) | <5(9)|     |
| D   | 1.7    | <4(9)| 8(10)| 2(9) | <6(10)| 2(10)| 4(9)  | ≤5(10)| <8(9)|     |
| D'  | 2.0    | <3(9)| 8(10)| 3(9) | ≤3(9)| 5(10)| 8(9)  | <4(10)| <8(9)|     |
| E   | 5.5    | ~7(9)| 9(10)| 1(9) | 1(9) | 2(10)| 4(9)  | ~3(10)| <5(9)|     |

Note. — Format for entries are a(b)= a×10⁻ᵇ, except N(H₂) which is in units of ×10²² cm⁻². Each molecule is based on the assumptions of optically thin line emission with Tₓ also 10 K. Upper limits are 2σ. Uncertainties are dominated by systematics and are at least a factor of 3 (see text for discussion of uncertainties). H₂ column densities are based on C¹⁸O(1-0) emission sampled at 6” resolution. Tₓ = 10 K and an abundance of [H₂/C¹⁸O] = 2.94×10⁶ are adopted (§3.2).

²In determining SO upper limits, a linewidth of 30 km s⁻¹ has been assumed.
Table 5. Other Selected Transitions

| Molecule   | Transition | \( \nu \) (GHz) | \( T_{mb} \) (mJy/bm) | GMC |
|------------|------------|----------------|----------------------|-----|
| HC\(_5\)N  | 33-32      | 87.8636        | 22\(\pm\)7           | B   |
| HC\(_5\)N  | 35-34      | 93.1881        | <13                   | ... |
| HCC\(^{13}\)CN | 10-9   | 90.6018        | <10                   | ... |
| C\(_2\)S   | 7\(_7\) - 6\(_6\) | 90.6864         | <10                   | ... |
| \(^{13}\)C\(^{34}\)S | 2-1   | 90.9260        | 13\(\pm\)5            | C   |
| CH\(_3\)CHO | 5\(_{24}\) - 4\(_{23}\) E | 96.4256         | \(\leq\)16              | a   |
| HCOOCH\(_3\) | 8\(_{45}\) - 8\(_{36}\) A | 96.7092         | <16                   | ... |
| NH\(_2\)CHO | 5\(_{14}\) - 4\(_{13}\) | 109.7535       | 22\(\pm\)8\(^b\)       | E   |
| H\(_2\)^{15}\)CO | 3\(_{12}\) - 2\(_{11}\) | 219.9085       | <90                   | ... |
| C\(^{15}\)N | 2 \(- 1; \frac{5}{2} - \frac{3}{2}; F = 3 - 2\) | 219.734        | <90                   | ... |
| ...        | ...        | 93.132(4)      | 15\(\pm\)6            | B,C |
| ...        | ...        | 96.431(4)      | 19\(\pm\)7\(^a\)       | B,C |
| ...        | ...        | 96.466(4)      | 14\(\pm\)7            | B,C,E |
| ...        | ...        | 109.221(4)     | 20\(\pm\)9            | B,E |
| ...        | ...        | 109.819(4)     | 20\(\pm\)8            | D   |
| ...        | ...        | 109.839(4)     | 22\(\pm\)8            | D   |

Note. — Upper limits are 2\(\sigma\).

\(^a\)Blended with C\(^{34}\)S(2-1).

\(^b\)Blended with SO\(_2\)(17\(_{513}\) − 18\(_{414}\)).
Table 6. PCA Correlation Matrix

| Maps  | $^{12}\text{CO}$ | $^{18}\text{CO}$ | 3MM | $^{2}\text{H}$ | $^{34}\text{S}$ | $^{3}\text{CH}_{3}\text{OH}$ | $^{3}\text{HC}_{3}\text{N}$ | HCN | HNC | HNCO | $^{2}\text{H}^{+}$ |
|-------|------------------|------------------|-----|---------------|---------------|-----------------|-----------------|-----|-----|------|-----------------|
| $^{12}\text{CO}$ | 1.0 | | | | | | | | | | |
| $^{18}\text{CO}$ | 0.82 | 1.0 | | | | | | | | | |
| 3MM | 0.65 | 0.76 | 1.0 | | | | | | | | |
| $^{2}\text{H}$ | 0.53 | 0.62 | 0.76 | 1.0 | | | | | | | |
| $^{34}\text{S}$ | 0.38 | 0.39 | 0.48 | 0.50 | 1.0 | | | | | | |
| $^{3}\text{CH}_{3}\text{OH}$ | 0.75 | 0.80 | 0.67 | 0.49 | 0.21 | 1.0 | | | | | |
| $^{3}\text{HC}_{3}\text{N}$ | 0.60 | 0.71 | 0.85 | 0.57 | 0.30 | 0.68 | 1.0 | | | | |
| HCN$^a$ | 0.65 | 0.75 | 0.90 | 0.74 | 0.49 | 0.64 | 0.77 | 1.0 | | | |
| HNC | 0.76 | 0.85 | 0.94 | 0.79 | 0.49 | 0.72 | 0.81 | 0.91 | 1.0 | | |
| HNCO | 0.67 | 0.75 | 0.58 | 0.42 | 0.19 | 0.78 | 0.57 | 0.57 | 0.66 | 1.0 | |
| $^{2}\text{H}^{+}$ | 0.73 | 0.81 | 0.75 | 0.59 | 0.42 | 0.71 | 0.68 | 0.74 | 0.82 | 0.69 | 1.0 |

$^a$Data from (Downes et al. 1992). The data was taken at the Plateau de Bure Interferometer and hence has a slightly smaller primary beam.
| PCA Comp.     | 1   | 2    | 3    | 4   | 5    | 6    | 7    |
|--------------|-----|------|------|-----|------|------|------|
| $^{12}$CO    | 0.30| 0.19 | 0.36 | 0.075| -0.69| 0.084| 0.27 |
| C$^{18}$O    | 0.33| 0.16 | 0.17 | 0.063| -0.14| -0.039| 0.009|
| 3MM          | 0.33| -0.18| -0.30| -0.12| 0.032| 0.032| 0.080|
| C$_2$H       | 0.28| -0.37| -0.16| 0.75 | 0.064| 0.13  | -0.25 |
| C$^{34}$S    | 0.18| -0.62| 0.62 | -0.33| 0.20 | 0.21  | 0.070 |
| CH$_3$OH     | 0.30| 0.38 | 0.076| 0.003| 0.021| 0.44  | -0.56 |
| HC$_3$N      | 0.30| 0.026| -0.44| -0.54| 0.034| 0.21  | -0.16 |
| HCN          | 0.33| -0.19| -0.23| -0.038| 0.024| -0.082| 0.43  |
| HNC          | 0.35| -0.11| -0.13| -0.058| -0.074| -0.10 | 0.18  |
| HNCO         | 0.27| 0.43 | 0.21 | 0.11 | 0.67 | 0.10  | 0.39  |
| N$_2$H$^+$   | 0.32| 0.078| 0.15 | -0.089| 0.090| -0.81 | -0.39 |
| Egnv. %      | 70  | 10   | 5.8  | 3.4  | 2.7  | 2.4  | 1.8  |
Table 8. Selected Intensities Ratios

| Location | $\frac{HCN(1-0)}{HNC(1-0)}^a$ | $SO_{23+CS}^b$ | $<0.15$ | $<0.43$ | $<0.43$ | $<0.70$ | $<0.72$ |
|----------|--------------------------------|----------------|---------|---------|---------|---------|---------|
| A        | 2.2±0.4                        |                |         |         |         |         |         |
| B        | 1.5±0.3                        |                |         |         |         |         |         |
| C        | 1.6±0.3                        |                |         |         |         |         |         |
| D        | ~0.99                          |                |         |         |         |         |         |
| D'       | ~1.2                           |                |         |         |         |         |         |
| E        | 1.6±0.3                        |                |         |         |         |         |         |

Note. — The measurements of the HCN/HCN ratio is based on the resolution of HNC(1-0) given in Table 1. The uncertainties reflect the larger of the absolute calibration uncertainty or the map noise. Upper limits are 2$\sigma$.

$^a$The HCN(1-0) is kindly provided by Downes et al. (1992).

$^b$The SO/CS abundance ratio based on the most constraining of the SO upper limits.
Fig. 1.— A color HST composite of IC 342’s nucleus. Green/Blue is F555 (V band) and red is Hα + continuum. The blue contours are $^{12}\text{CO}(1-0)$ and the yellow contours are 3 mm (see MT01).
Fig. 2.— The integrated intensities of nine tracer molecules observed towards the nucleus of IC 342. Each map is contoured in steps of the 2σ times the RMS intensity in each map, except for $^{12}$CO(1-0). (a) The $^{12}$CO(1-0) transition smoothed to 5$''$ × 4.7$''$ resolution and contoured in steps of 7.7 K km s$^{-1}$. Locations of five major GMCs (Downes et al. 1992) are displayed. (b) The C$^{18}$O(1-0) transition contoured in steps of 1.4 K km s$^{-1}$ for 6$''$0 resolution, (c) the HNC(1-0) transition in steps of 1.5 K km s$^{-1}$, (d) the HC$_3$N(10-9) transition in steps of 1.5 K km s$^{-1}$, (e) the C$_2$H N(J,K)= 1(3,2)-0(1,1) transition in steps of 3.0 K km s$^{-1}$, (f) the C$^{34}$S(2-1) transition in steps of 1.8 K km s$^{-1}$, (g) the N$_2$H$^+$ (1-0) transition in steps of 1.6 K km s$^{-1}$, (h) the HNCO(4$_{04}$ - 3$_{03}$) transition in steps of 2.1 K km s$^{-1}$, and (i) the CH$_3$OH($2_k-1_k$) transition in steps of 1.8 K km s$^{-1}$. The greyscale seen in all frames is of $^{12}$CO(1-0) at full resolution (2.7$''$ × 2.2$''$; see MTH00) for comparison.
Fig. 3.— Integrated intensities of the seven tracer molecules observed in the central portion of IC 342’s nucleus, weighted to optimize spatial resolution at the expense of sensitivity. Each map is contoured at $\sim 2\sigma$ times the RMS noise level in each map except for 6 cm synchrotron. Each transition is overlaid the greyscale image of HCN(1-0) kindly provided by D. Downes (Downes et al. 1992). The HCN(1-0) greyscale ranges from 10 - 82 K km s$^{-1}$ for a resolution of 2.′′8x2.′′7; pa = -180. The location of the potential nitrogen core is labelled by “N” in the corresponding panels. (a) The 3mm continuum emission (black contours; MT01) in steps of 1 mJy beam$^{-1}$ for a resolution of 3.′′3x3.′′0; -44.3$^\circ$, together with the 6 cm synchrotron flux (white contours) at the same resolution and contour increment. The 6 cm synchrotron emission is obtained by assuming the 3 mm continuum emission (MT01) is all thermal free-free and extrapolating this flux to 6 cm, and removing it from the 6 cm continuum flux of Turner & Ho (1983). (b) C$_2$H N(J,F)= 1(3,2)-0(1,1) transition in steps of 3.6 K km s$^{-1}$ for 4.′′5x4.′′0; -21.7$^\circ$ resolution. (c) C$^{34}$S(2-1) transition in steps of 3.1 K km s$^{-1}$ for 5.′′0x4.′′3; -51.7$^\circ$ resolution. (d) HC$_3$N(10-9) transition in steps of 2.8 K km s$^{-1}$ for 4.′′6x4.′′1; -30.2$^\circ$ resolution. (e) HNC(1-0) transition in steps of 3.3 K km s$^{-1}$ for 4.′′5x4.′′0; -24.6$^\circ$ resolution. (f) N$_2$H$^+$ (1-0) transition in steps of 2.9 K km s$^{-1}$ for 4.′′7x4.′′1; -37.3$^\circ$ resolution. (g) HNCO(404 - 303) transition in steps of 4.2 K km s$^{-1}$ for 4.′′7x4.′′0; -22.3$^\circ$ resolution. (h) CH$_3$OH(2$_k$ - 1$_k$) transition in steps of 2.5 K km s$^{-1}$ for 4.′′6x4.′′0; -51.7$^\circ$ resolution.
Fig. 4.— Spectra from five of the observed transition sampled at the locations of the five major GMCs (e.g. Downes et al. 1992). Spectra are summed of a 6” box centered on the fitted locations of each GMC. Positions for each GMC are taken from high resolution C$^{18}$O observations (Table 3 of MT01). GMC A is at the far left of the each set of spectra, extending to GMC E is at the far right. Note that the sampled locations do not necessarily align precisely with the peaks of the tracer molecules. In the first plane of the each set, any spectral line $T_{mb} > 0.1$ K in the Turner (1989) SgrB2 line survey that falls within the observed bandwidth is labeled. For the remaining four panels these lines are marked by tick marks shifted in velocity to match IC 342’s 12CO(1-0) velocity at that location. In all cases the zero velocity corresponds to $v_{LSR} = 35$ km s$^{-1}$ of the transition(the brightest component if there is unresolved hyperfine structure). Also included in the first plane is the 1σ errorbar, determined from the RMS in an individual linefree channel.
Fig. 5.— Same as in Figure 4 except for the five remaining transitions.
Fig. 6.— The maps of the first three principle components of the molecular distribution.
Fig. 7.— The projections of each species on the first three principle components.  

a) Each transitions projected onto the plane defined by the first and second principle components.  
b) Each transitions projected onto the plane defined by the second and third principle components.  
The figure is plotted in such a way that b) may be visualized as looking down the x-axis of a) from the right.
Fig. 8.— The HCN(1-0)/HNC(1-0) line ratio.  a) The HNC(1-0) integrated intensity map in contours of 2.5 K km s$^{-1}$ for the beamsize given in Table (1).  b) The HCN(1-0)/HNC(1-0) line ratio map towards IC 342. Contours are 0.5, 1.0, 1.5 and 2.0, with HCN/HNC = 1.0 contour in bold.  c) The HCN(1-0) integrated intensity map of Downes et al. (1992), convolved to the same resolution, plotted on the same scale and with the same contours.
Fig. 9.— The $N_2/N_2H^+$ abundance ratio as a function of various physical parameters, based on the basic, steady-state chemical model described in section 5.5. The hashed out regions of $X(e^-) < 2 \times 10^{-9}$ and $N_2/N_2H^+ > 9 \times 10^4$ are forbidden because the ISM is assumed to be neutral ($X(e^-) > X(HCO^+) + X(N_2H^+)$) and that the maximum $N_2$ abundance is one half of the cosmic $N$ abundance, respectively. The observed $X(C^+) (\simeq X(e^-))$ abundance is also marked (thin dashed line). However this value likely applies to the diffuse molecular gas component not the dense GMC component traced in $N_2H^+$. The set of thick contours mark the $N_2/N_2H^+ - X(e^-)$ values for different values of the cosmic ionization rate per molecular gas density, $[\zeta/n_{H_2}]$. Assuming $n_{H_2} > 10^4 \, \text{cm}^{-3}$, expected for the excitation of bright $N_2H^+$, $\log(\zeta/n_{H_2}) \lesssim 10^{21}$ corresponds to a Galactic cosmic ionization rate. For such an ionization rate, $X(e^-) < 10^{-7}$ and $N_2 \gtrsim 1 \times 10^{-5}$. If $n_{H_2} \gtrsim 5 \times 10^{-4} \, \text{cm}^{-3}$ in the $N_2H^+$ emitting regions then $\zeta_{IC342}$ must be larger than the Galactic disk value.
Fig. 10.— Schematic of the chemical and physical structure of the nucleus of IC 342.