CO AND NEUTRAL GAS IN THE DISK OF THE SPIRAL GALAXY IC 342

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ABSTRACT

We present “on-the-fly,” fully sampled maps of CO(1–0) in the central 15′ of the spiral galaxy IC 342. In addition to the bright CO nuclear peak, there is a prominent CO 2′ × 5′ bar and an extensive CO disk. The bar and nucleus contain 30% of the total observed CO emission in IC 342. Beyond the bar the CO disk contains two spiral arms, which coincide with the two inner optical arms. The substantial inter-arm CO component within this region has a mean surface density of 8 $M_\odot$ pc$^{-2}$, close to the mean surface density of 10 $M_\odot$ pc$^{-2}$, that extends to a radius of 7′ (4 kpc). The total inferred H$_2$ mass is $7 \times 10^8$ $M_\odot$, which is 30% of the total H i mass. We combine the CO data with VLA H i maps to obtain a map of the total gas surface density (ΣH$_2$ + ΣH i) in IC 342. The gas surface density shows a centrally peaked disk, dominated by H$_2$ to a radius of 5′ (3 kpc). Spiral arms run continuously from the inner to outer galaxy, transitioning smoothly from predominantly molecular in the inner galaxy to predominantly atomic at large radii. On a global scale, the gas surface density is spatially correlated with optical spiral arm structure. On 1′ (600 pc) scales the disk displays bar and arm asymmetries, azimuthal displacements of CO and H i emission, and structure that becomes increasingly complex with increasing galactic radii. We find an excellent correlation between 21 cm radio continuum and the total gas surface density.

Key words: galaxies: individual (IC 342) — galaxies: ISM — galaxies: spiral — galaxies: structure — ISM: molecules

1. INTRODUCTION

When studying the distribution of molecular gas in spiral galaxies, one cannot detect cold H$_2$ directly, and one is therefore restricted to the use of a proxy, which is generally CO. Many studies have established that CO emission is strongest in the central regions of spiral galaxies (Morris & Lo 1978; Young & Scoville 1991, and references therein) and falls off, as does blue light, in a near exponential manner with galactocentric distance (Young & Scoville 1982). CO is present in early- as well as late-type spirals (Young et al. 1995) and is less abundant in dwarf or low-metallicity galaxies (Sage et al. 1992). All of these results are also believed to hold for H$_2$. The physical mechanisms governing the formation of molecular clouds and their relation to the atomic gas component are not well understood (for a recent review see Blitz & Williams 1999).

To date, few full images of CO emission in galaxies have been made. Radio telescopes typically have only a single detecting element, and images are constructed point by point with this single element. Most observing programs have tended to sparsely survey the outer disk regions (Young & Scoville 1982; Young et al. 1995), although there are fully sampled maps of the central regions of nearby galaxies, such as IC 342 (Sage & Solomon 1991), M31 (Dame et al. 1993; Neininger et al. 2000), M33 (Wilson & Scoville 1989), M51 (Rydbeck, Hjalmarson, & Rydbeck 1985; Garcia-Burillo, Guerin, & Cernicharo 1993), M81 (Brouillet et al. 1991), M101 (Kenney, Scoville, & Wilson 1991), NGC 253 (Scoville et al. 1985), NGC 2403 (Thornley & Wilson 1995), NGC 2903 (Jackson et al. 1991), NGC 5055 (Thornley & Mundy 1997b), NGC 6946 (Tacconi & Young 1989). Interferometric images tend to be limited in extent and relatively insensitive to cold, extended CO. Therefore, the detailed distribution of CO emission and the total neutral gas content in galaxies is at present poorly known. Understanding the CO distribution and its relation to the H i distribution is crucial to being able to answer questions such as: What is the structure of the total gas disk in a galaxy? Does the H i represent pre- or post-molecular phase gas?

In this project, we have taken advantage of the “on-the-fly” (OTF) observing mode at the NRAO 12 m telescope, where the telescope smoothly and repeatedly scans a large field. The OTF observing mode, as implemented at the 12 m telescope, minimizes many of the systematic errors associated with single-element imaging, allowing the construction of large, deep, fully sampled images. This mode is perfect for the imaging of extended, cold CO gas.

To initiate the OTF mapping in galaxies on the 12 m telescope, we chose to observe the nearby galaxy, IC 342. IC 342 is a nearly face-on normal Scd galaxy of a size and luminosity similar to the Milky Way, although a later
Deep, reliable imaging and sensitivity to cold, extended gas molecular gas largely confined to spiral arms? Does the CO galaxy look like the optical galaxy? How does CO fill in the align? How far out in the disk do we find molecular clouds?

To answer several fundamental questions about the azimuthal distribution of the molecular gas? Is the quarters of the optical extent de Vaucouleurs, de Vaucouleurs, & Corwin 1976). The maps are deep enough to detect cold, extended, interarm CO gas to levels of $I_{\text{CO}} \sim 0.2$ K km s$^{-1}$ and $N_{\text{H}_2} \sim 4 \times 10^{19}$ cm$^{-2}$. We use this primary tracer of the molecular gas phase and VLA H I maps (Crosthwaite, Turner, & Ho 2000, hereafter Paper I) in order to answer several fundamental questions about neutral gas distributed in this normal spiral galaxy. What is the azimuthal distribution of the molecular gas? Is the molecular gas largely confined to spiral arms? Does the CO galaxy look like the optical galaxy? How does CO fill in the H I central depression? How do the H I and CO spiral arms align? How far out in the disk do we find molecular clouds? Deep, reliable imaging and sensitivity to cold, extended gas is critical to our ability to answer these questions.

2. THE OBSERVATIONS AND DATA REDUCTION

The observations of CO(1–0) at 115 GHz were made at the NRAO 12 m telescope at Kitt Peak, 1995 February. Three nights of data resulted in the equivalent of 12 hours on source. $T_{\text{sys}}$ ranged from 600 to 900 K, SSB, during the observations. Calibration was by the chopper wheel method (Ulrich & Hass 1976). We converted $T^*_{\text{mb}}$ recorded by the telescope (Kutner & Ulrich 1981) to main beam temperature, $T_{\text{mb}} = T^*_{\text{mb}} / \eta^*$ using the main beam efficiency, $\eta^* = 0.84$ at 115 GHz (Mangum 2000). We report $T_{\text{mb}}$-values throughout this paper. The filter bank spectrometer was configured for 2 MHz channel widths with 128 total channels. The pointing center was $\alpha = 3^h 41^m 57^s 0$, $\delta = 67^\circ 56' 32''$ (B1950.0); coordinates have been switched to J2000.0 for this paper.

The OTF observing mode was used, which produces high-quality, fully sampled, large-scale maps by sampling on small timescales while smoothly and continuously scanning the map region. Deep integration times are achieved by averaging multiple maps (Mangum 1999). This method records telescope encoder positions as the field is scanned, which allows first-order pointing corrections to be made. OTF mapping has the advantage of reducing the effects of transients that impact map quality, such as pointing errors, variations in sky background, and weather changes. The beam size (FWHM) of the 12 m telescope at 115 GHz is 55°. Scanning rates of 15° s$^{-1}$ (the spectrum was sampled every 0.1 s) and scan row spacings of 18° were selected to ensure sampling better than Nyquist over the mapped region of 15° × 15°. A calibration and sky measurement was made every two rows, or roughly every 2 minutes, using a 30° azimuth slew off position. The rms noise level was reduced by averaging the eight individual OTF maps that were made.

The OTF data were reduced using the NRAO AIPS package. The eight OTF maps were co-added, gridded, and assembled into a cube of 15° × 15° × 128 spectral channels of 5.2 km s$^{-1}$ width. A linear baseline was removed in each spectrum. At this stage the background in the channel maps is uneven, with “stripes” running in the scanning direction due to sky brightness fluctuations between successive off positions. A linear baseline, established using pixels at the eastern and western map edges of each scanned row of each channel, was removed to reduce this “striping” and create a uniform background, in effect a spatial “destriping” of the sky brightness variations. The mean rms noise in the channels with no CO emission prior to destriping was 40 mK. The mean rms noise in the fully reduced, line-free channels of the complete co-added map is 34 mK. Destriping may remove some extended low-level emission at levels comparable to the rms noise, but this consequence is unavoidable with the present data. In terms of $I_{\text{CO}}$, at the map edges we will have at most two channels contributing to the missing emission, giving us an upper limit of 0.2 K km s$^{-1}$ ($< 1 \sigma$) for the amount lost.

The quality of the moment maps (integrated intensity and intensity-weighted mean velocity) was improved by using a mask to identify regions of noise within the individual channel maps before the sum. We convolved the cube twice the nominal beam size and used emission greater than 2 $\sigma$ in the convolved cube to construct a mask to clip out regions of noise in the original cube. This technique suppresses the contribution of isolated noise spikes more effectively than the standard AIPS windowing algorithms. The clipped cubes were used to construct the peak and integrated intensity as well as the velocity maps. Peak intensity ($T_{\text{peak}}$), integrated intensity ($I_{\text{CO}}$), mean velocity, and velocity dispersion maps were made from CO emission above 1 $\sigma$ in the masked, clipped, channel cube, after Hanning smoothing (three-channel width) in velocity and Gaussian smoothing (5° FWHM) in the spatial dimension.

The objective of these OTF observations was to map the H$_2$ content of IC 342. To do so we convert from $I_{\text{CO}}$ to $N_{\text{H}_2}$ using a “standard conversion factor,” $X_{\text{CO}}$ (Sovcillo & Sanders 1987; Young & Scoville 1991). A value for $X_{\text{CO}}$ calibrated from Milky Way molecular clouds is typically assumed for extragalactic work. The conversion factor, estimated to be accurate to a factor of 2 in the Milky Way disk (Solomon et al. 1987; Hunter et al. 1997) appears to underpredict $N_{\text{H}_2}$ in low-metallicity galaxies (Verter & Hodge

2 Available at http://www.tuc.nrao.edu/12meter/obsinfo.html.

3 Available at http://www.tuc.nrao.edu/12meter/obsinfo.html.
3. RESULTS: CO IMAGES OF IC 342, THE MOLECULAR GAS

3.1. CO Morphology

The CO(1–0) emission-line channel maps are displayed in Figure 1 for the channels with emission. The butterfly pattern characteristic of an inclined rotating disk is apparent. There are departures from the expected symmetric pattern for circular rotation about the line of nodes, at $P.A. = 37^\circ$. Emission in the 80 to $-11$ km s$^{-1}$ range shows an S-shaped pattern, indicating that the underlying mass distribution is slightly axially asymmetric. This is also seen on much larger size scales in H I (Paper I).

The map of CO integrated intensity, $I_{\text{CO}} = \int T_{\text{CO}} dv$, and the peak main beam brightness temperature, $T_{\text{CO}}$, are shown in Figure 2. $I_{\text{CO}}$ ranges from our detection limit of 0.2 K km s$^{-1}$ to the peak at the galaxy center of 51 K km s$^{-1}$. The total observed CO luminosity of IC 342 is $L_{\text{CO}} = 2.0 \times 10^{4}$ Jy km s$^{-1}$, from which we obtain a total H$_2$ mass for IC 342 of $M_{\text{H}_2(\text{total})} = 7 \times 10^{4} M_\odot$. This number is uncertain by a factor of $\sim 2$ because of $X_{\text{CO}}$ uncertainties. This is comparable to the Milky Way molecular mass of $M_{\text{H}_2(\text{total})} = 2 \times 10^{4} M_\odot$ (Scoville & Sanders 1987), consistent with findings that earlier Hubble-type spirals (The Milky Way: Sb) have more H$_2$ than later type spirals (IC 342: Scd) (Young & Knezek 1989). All the CO emission detected in Figure 2 is contained within the corotation radius, $R_{\text{CR}} = 7.2$ (4.2 kpc, Paper I).

The $I_{\text{CO}}$ and $T_{\text{CO}}$ maps show the same features: the nucleus, a bar oriented roughly north to south, and two asymmetrical arms north and south of the bar. These stronger emission features are part of a larger scale “crablike” or “boxy” pattern with a radius of 3’ (2.8 kpc) as outlined by the 4 K km s$^{-1}$ contour. These features lie within a weaker, patchy, extended disk.

The prominent bright nucleus corresponds to the nuclear “minispiral” (Lo et al. 1984; Ishizuki et al. 1990). CO peaks at $\alpha = 3^h46^m48^s3, \delta = 68^\circ54'55''$ with $I_{\text{CO}} = 51$ K km s$^{-1}$ and $T_{\text{CO}} = 0.73$ K. The CO peak is coincident with the dynamical center of the galaxy (Paper I). The mean nuclear surface density is $\Sigma_{\text{H}_2} = 160 M_\odot$ pc$^{-2}$ ($R < 0.3$ kpc), which is lower than the Milky Way mean nuclear value of $\Sigma_{\text{H}_2}$ (R < 0.4 kpc) ~ $400 M_\odot$ pc$^{-2}$ (Scoville & Sanders 1987). The total nuclear molecular mass in the central 55” (R < 0.5 kpc) is $3.6 \times 10^3 M_\odot$, in agreement with values found in the higher resolution study of Sage & Solomon (1991).

Outside the nucleus, the CO disk is dominated by a distinct CO bar (Sage & Solomon 1991, have a higher resolution image of the bar region). IC 342 is not a strongly barred spiral in optical appearance, although the inner near-infrared isophotes are decidedly “boxy” and “lenslike” (Levine, Hurt, & Turner 1994). The 4.7’ × 2.1’ (2.7 × 1.2 kpc) bar region outside the nucleus contains nearly a third of the total observed CO luminosity of IC 342. $L_{\text{CO}} = 5.8 \times 10^3$ Jy km s$^{-1}$ ($M_{\text{H}_2} = 2.1 \times 10^4 M_\odot$). Mean densities in the bar are $T_{\text{CO}} = 0.30$ K and $I_{\text{CO}} = 12$ K km s$^{-1}$, corresponding to a mean bar H$_2$ surface density of $\Sigma_{\text{H}_2} = 38 M_\odot$ pc$^{-2}$. The bar surface density in IC 342 is intermediate in value between the central (R < 0.4 kpc) surface density of 400 $M_\odot$ pc$^{-2}$ for the Galaxy (Scoville & Sanders 1987) and 6–12 $M_\odot$ pc$^{-2}$ for the Galactic molecular ring (4 < R < 6 kpc, Bronfman et al. 1988; Scoville & Sanders 1987).

While the optical appearance of the inner disk of IC 342 (Buta & McCall 1999) is that of a symmetric, two-arm spiral, the CO appearance, particularly the CO bar and arm structure, is not as balanced nor as symmetric. The northern arm does not start at the northern end of the bar, but rather appears to connect to the eastern side of the bar, where the optical northern arm appears to originate. The northern arm extends for about 69’ (4 kpc), and the deconvolved width (FWHM) of the arm is 1.2’ (0.7 kpc), only slightly more than the beam width. At first glance, the southern arm seems to connect to the southern bar end and appears to wind in the wrong direction (counterclockwise). When one attempts to define a clockwise-wound southern arm, two alternatives present themselves. One can define a southern arm starting due west of the nucleus, which winds much closer to the CO bar than its northern counterpart, leading to the very asymmetric structure at the southern end of the bar. Or, a southern arm can be traced, again starting due west of the nucleus, extending to the south, then curving to the east at a location 2’ southwest of the bar end. The bright $I_{\text{CO}}$ patches, at $\alpha = 3^h46^m25^s1, \delta = 68^\circ34'38''$, $\alpha = 3^h46^m32^s0, \delta = 68^\circ1'33''$ and $\alpha = 3^h47^m0'4, \delta = 68^\circ1'14''$, trace this southern arm pattern. From a deconvolution of these southern arm patches, the arm width (FWHM) appears to be the same as that of the northern arm. We can try to use optical (Fig. 2c) or radio continuum (Fig. 2d) emission to define the arm structure. While the northern arm is clearly defined in all bands of Figure 2, the tracing of the southern arm is still ambiguous. Low resolution contributes somewhat to the appearance of the “wrong-way arm” visible in CO and to a lesser extent in the low-resolution optical image, in a region where the bar and southern arm are in close proximity. But, it is clear that there is significant asymmetry between the northern and southern arm and bar regions that is more pronounced in the CO.

Both the $I_{\text{CO}}$ and $T_{\text{CO}}$ maps show an extended interarm component. The mean brightnesses for the interarm gas are $T_{\text{CO}} = 0.12$ K and $I_{\text{CO}} = 2.4$ K km s$^{-1}$, corresponding to $\Sigma_{\text{H}_2} = 8 M_\odot$ pc$^{-2}$, which is comparable to the value for the Milky Way 4–6 kpc ring and a factor of 2 higher than the average Milky Way surface density for the extranuclear disk (2–10 kpc) (Bronfman et al. 1988). From a measure-
Fig. 1.—CO channel maps of IC 342. Each channel is labeled with the channel velocity (LSR). The beam size, 55”, is shown in the bottom left corner of the first channel. The gray scale ranges from −0.02 to 0.7 K. The 1 \( \sigma \) (rms) noise level in the maps is 0.034 K. Contours are at −0.136, −0.068 (dotted contours), 0.068, 0.136, 0.272, and 0.408 K.

The detection of a peak \( I_{\text{CO}} \) along each arm (at \( \alpha = 3^\circ 46^\prime 30^\prime \)\text{'} 6, \( \delta = 68^\circ 9'34'' \) for the northern arm and \( \alpha = 3^\circ 46^\prime 25^\prime \)\text{'} 1, \( \delta = 68^\circ 3'48'' \) for the southern arm) and at two “off-arm” locations separated from the peaks by one beam element (\( \alpha = 3^\circ 46^\prime 31^\prime \)\text{'} 3, \( \delta = 68^\circ 10'31'' \) and \( \alpha = 3^\circ 46^\prime 29^\prime \)\text{'} 5, \( \delta = 68^\circ 8'36'' \) for the northern arm; \( \alpha = 3^\circ 46^\prime 32^\prime \)\text{'} 7, \( \delta = 68^\circ 4'29'' \) and \( \alpha = 3^\circ 46^\prime 16^\prime \)\text{'} 3, \( \delta = 68^\circ 2'50'' \) for the southern arm) the maximum arm/interarm contrast is 2 for the southern arm, and 4 for the more well-defined northern arm, very similar to mean contrast values for unresolved molecular clouds seen in the Milky Way surveys (Scoville & Sanders 1987). Relative differences between the arm/
interarm contrast for the northern and southern arms suggest structural differences between the two arms. We note that we do not resolve the arm structure and higher resolution observations would probably yield very different arm/interarm contrast values. Mean values for the arm plus interarm disk (beyond the bar) emission are $T_{\text{CO}} = 0.15$ K and $I_{\text{CO}} = 3.5$ K km s$^{-1}$ or $H_2 = 10 M_\odot$ pc$^{-2}$.

We fail to detect CO beyond a radius of about 7’ (4 kpc). In the Milky Way Mead & Kutner (1988) detect molecular clouds at 13 kpc with a mean $T^*_c \sim 3$ K, a mean radius of 20 pc. Their map of the spatial distribution of these clouds indicates that, if observed at the distance to IC 342, only one cloud would be contained in a 55” beam. Taking beam dilution into account $I_{\text{CO}}$ for a cloud with the mean characteristics would be $\sim 0.1$ K km s$^{-1}$ (0.3 $M_\odot$ pc$^{-2}$). This gas would be below our detection threshold in IC 342, which is $I_{\text{CO}} \sim 0.2$ K km s$^{-1}$ (0.6 $M_\odot$ pc$^{-2}$). Our mapping of the CO disk of IC 342 is therefore sensitivity limited, and there may actually be H$_2$ at larger galactocentric radii.

3.2. CO Kinematics

The intensity-weighted velocity (“velocity centroid”) and velocity dispersion, $\sigma_{\text{CO}}$, maps for CO(1–0) in IC 342 are presented in Figures 3a and 3b. Both show the kinematic signatures for a weak bar, a slight “pinching” of the iso-velocity contours along the CO bar (Sanders & Tubbs 1980) and a “bar” shape in the $\sigma_{\text{CO}}$ map aligned with the “boxy” bar seen in $I_{\text{CO}}$. At the nucleus, $\sigma_{\text{CO}}$ peaks at 30 km s$^{-1}$, falling to values between 10 and 20 km s$^{-1}$ along the bar and arms falling to 5 km s$^{-1}$ at the edges of the CO disk emission (due to the low inclination of IC 342, the contribution from galactic rotation within the beam to the dispersions is a small effect, the rotation corrected velocity dispersion will be $\sim 2$ km s$^{-1}$ lower at the nucleus with negligible corrections farther out in the disk). Within the inner 1’ the mean value for both $\sigma_{\text{CO}}$ and $\sigma_{\text{H}}$ is 25 km s$^{-1}$, suggesting that both gas phases are well mixed. Outside the nucleus and bar region $\sigma_{\text{CO}}$ ($\sim$ 5 km s$^{-1}$) is half that of H I.
\( \sim 10 \text{ km s}^{-1} \), and can be compared with a value of \( \sim 5 \text{ km s}^{-1} \) (Knapp, Stark, & Wilson 1985; Malhotra 1994) and \( \sim 7 \text{ km s}^{-1} \) (Kulkarni & Heiles 1987), respectively, for a similar location \( (R \sim 4 \text{ kpc}) \) in the Galactic disk.

A rotation curve has been constructed from the CO maps, allowing us to trace the mass distribution in the center of IC 342, where \( \text{H} \alpha \) is weak or absent (Paper I). The Brantd model rotation curve parameters (Table 1) from a previous fit to the \( \text{H} \alpha \) data (Paper I) were applied to the CO kinematic data, resulting in the rotation curve of Figure 3c. An independent fit to the CO data alone, finds a slightly lower inclination, \( 27^\circ \) rather than \( 31^\circ \), but still within the \( \pm 6^\circ \) uncertainty in the \( \text{H} \alpha \) inclination determination. The independent fit finds a slightly different major-axis position angle, P.A. = \( 43^\circ \), than determined from the \( \text{H} \alpha \) data, \( 36^\circ \), significantly greater than the \( \pm 1^\circ \) uncertainty. This change in P.A. probably reflects the pinching of the isovelocity contours tracing noncircular orbits along the weak bar. We also note that fits to the rotation curve are dependent on the “turnover” radius where the circular velocity peaks, which is only weakly sampled in the CO data. The rotation curve is slowly rising from the center of IC 342, as found by Young & Scoville (1982) from their CO radial cross mapping. It connects smoothly with the higher resolution nuclear rotation curve of Turner & Hurt (1992). We note that the kink in the \( \text{H} \alpha \) rotation curve at \( R \sim 2' \) occurs in a region where the CO isovelocity contours show the largest deviation from purely circular motions and \( I_{\text{H}} \) is at a local minimum (the \( \text{H} \alpha \) “hole”). Intensity weighting of the velocity field in a region of uneven, low signal-to-noise, \( \text{H} \alpha \) emission and peculiar velocities may be responsible for the kink.

Velocity residuals (Fig. 3d), obtained by subtracting off the circular rotation velocity, trace the kinematic signatures of departures of the mass distribution from axisymmetry. The bipolar pattern of CO velocity residuals is consistent with what is seen inside corotation for other barred spirals (Canzian 1993; Sempere et al. 1995; Lindblad, Lindblad, & Athanassoula 1996; Canzian & Allen 1997) where this
TABLE 1
GLOBAL PROPERTIES OF IC 342

<table>
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<td>Position angle (deg)</td>
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<tr>
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<tr>
<td>MH (M⊙)</td>
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</tbody>
</table>

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds (J2000.0).

* Obtained from the NASA/IPAC Extragalactic Database.

* Dynamical center from Paper I.


* Brandt model fit from Paper I.

* Newton 1980, adjusted to a 2 Mpc distance.

4. THE TOTAL NEUTRAL GAS COMPONENT IN IC 342
4.1. Comparing the H I, H₂, and Optical Distributions

The fully sampled map of the CO in IC 342 allows us to combine it with the H I to produce a map of the total gas density in this galaxy. As noted over two decades ago by Morris & Lo (1978), Young & Scoville (1982), and more recently by Honna, Sofue, & Arimoto (1995), the CO and H I disks of IC 342 have distinctly different characteristics. CO emission fills the interior region of the H I map where the H I column density declines. CO falls off sharply with galactocentric distance, while H I is comparatively flat to radii ~20' (12 kpc). However a detailed comparison of the azimuthal structure of CO and H I has not been done before.

Figure 4 is a false color image of H I and CO emission in IC 342. The color balance of Figure 4 is set so that the regions of overlap of the H I (red) and CO (green) is yellow at a column density of 2 × NH₂ ~ NH ~ 10²¹ cm⁻². The CO bar region is enhanced by including a blue channel for NH₂ > 2 × 10²¹ cm⁻². The H I map of Figure 4 is only the inner portion of the total H I disk of IC 342, corresponding to the inner 30' of the VLA primary beam at 21 cm. The full H I disk extent is close to 90' (Rogstad et al. 1973; Rots 1979). The CO disk imaged here, ≤15' in extent, accounts

residuals pattern has been used to infer the presence of a spiral density wave. The CO velocity residuals pattern agrees with the H I residuals pattern (Paper I).
for about one-sixth of the total diameter of the full \textit{H\textsc{i}} disk, and only $\sim 3\%$ of the area. Neutral gas fills the disk of this galaxy at half-kiloparsec resolution; there are few locations in IC 342 with little or no gas for $R < 4.5$ kpc. There is a significant region where the CO and \textit{H\textsc{i}} are coextensive, between 4' and 6' (2 to 4 kpc).

Figure 5 shows a close-up of the central $15' \times 15'$ of IC 342, with the green CO and red \textit{H\textsc{i}} as for Figure 4, and a Digital Sky Survey image in the blue channel. This figure focuses on the region of CO/\textit{H\textsc{i}} overlap, roughly the area corresponding to the CO and optical disk. The stretch of the image is adjusted from Figure 4 to emphasize the overlap of the CO and \textit{H\textsc{i}} spiral arms, and while the H$_2$ and \textit{H\textsc{i}} distributions are not uniform the inner 15' (9 kpc) is in fact well-filled with neutral gas. Point sources in the blue channel are foreground Milky Way stars; extended blue sources are \textit{H\textsc{ii}} regions in IC 342. The bright CO nuclear peak coincides with the bright optical peak, as found by Young & Scoville (1982). The bar is more prominent in CO than in the optical, as can be seen from the green color. The faint optical “lens” or “boxy bar” is broader (convolved to the 55' resolution of the CO maps) than the CO bar, 2'6 versus 1'5, FWHM (1.5 vs. 0.9 kpc). The optical bar has P.A. $\sim -22^\circ$ and trails the CO bar (P.A. $\sim -13^\circ$). Prominent \textit{H\textsc{ii}} regions (extended blue regions) tend to lie along the CO arms, but there are also some \textit{H\textsc{ii}} regions present at \textit{H\textsc{i}} peaks beyond the CO disk. Examples can be seen in the \textit{H\textsc{i}} peak in the northeast corner of the map and to the southeast.

We now consider the molecular and atomic gas disks as components of the total neutral gas disk. A total gas surface density map, $\Sigma_{\text{gas}} = 1.36 (\Sigma_{\text{H\textsc{i}}} + \Sigma_{\text{H}_2})$ (corrected for inclination but not for missing $\Sigma_{\text{H}_2}$ due to undersampling $\sim 2 M_\odot$ pc$^{-2}$; Paper I), is presented in Figure 6. CO and \textit{H\textsc{i}} blend on kiloparsec size scales into a single global gas structure extending from the nucleus to the outer gas disk. The total gas mass, molecular and atomic, is $4 \times 10^9 M_\odot$ (Rots 1979, Paper I). The estimated dynamical mass of IC 342 is $10^{11} M_\odot$ (Paper I). Gas therefore makes up about 4% of the total mass of IC 342.

The azimuthally averaged $\Sigma_{\text{H}_2}, \Sigma_{\text{H\textsc{i}}}, \Sigma_{\text{gas}}$ as a function of galactic radius are shown in Figure 7. \textit{H\textsc{i}} and \textit{H}_2 attain equal surface densities, $6.5 M_\odot$ pc$^{-2}$, at 6' (3.5 kpc). \textit{H}_2 dominates the neutral gas distribution in the inner disk, rapidly fading into a predominantly \textit{H\textsc{i}} disk beyond. Young & Scoville (1982) found that the radial \textit{H}_2 distribution mimics the exponential distribution of the blue stellar disk (excluding the nucleus), implying a constant star formation rate per unit $\text{H}_2$. A least-squares fit of an exponential to our azimuthally averaged $I_{\text{CO}}$ between radii of 0' to 10' has a scale length of 2' (1.2 kpc), shorter than the scale length, 3', found by Young & Scoville (1982) fitted to their radial cross pointings with $R > 1.5'$.

Although CO fills in the central hole in the \textit{H\textsc{i}} disk (Morris & Lo 1978), in other respects these two gas tracers are more correlated than anticorrelated. In the region of CO/\textit{H\textsc{i}} overlap, the molecular spiral arms of the inner galaxy clearly connect to the \textit{H\textsc{i}} arms of the outer galaxy.

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**Fig. 5.—CO, \textit{H\textsc{i}}, and optical comparisons for IC 342.** Detail of the inner 15' of IC 342 in CO (green), \textit{H\textsc{i}} (red), and optical (blue). Regions of CO/\textit{H\textsc{i}} overlap appear in yellow, regions of CO/optical overlap in cyan and regions of \textit{H\textsc{i}}/optical in purple.
Fig. 6.—Neutral gas surface density of IC 342. The gray scale ranges from 0 to $130 M_\odot$ pc$^{-2}$, $\Sigma_{\text{gas}}$, with contours at 2, 5, 10, 20, 30, 40, 50, 70, and 100 $M_\odot$ pc$^{-2}$. Surface density has been corrected for inclination ($\cos 31^\circ$) and increased by a factor of 1.36 for He. No adjustment has been included for the missing flux contribution to the H i surface density (Paper I). The missing short spacing flux is below the first contour in the figure. Including an adjustment for the missing flux estimate, would increase $\Sigma_{\text{gas}}$ by $\sim 2 M_\odot$ pc$^{-2}$.

(Fig. 5). There is a continuous transition of the spiral arms from molecular to atomic. The CO spiral arm structure, which fades with increasing radius, continues as H i spiral arm structure. Most of the clumps of CO emission in the outer CO disk are seen to lie along H i arms, which better define the total gas pattern at these galactic radii. This is consistent with the idea that most disk CO emission comes from molecular clouds with surrounding H i envelopes (Allen, Atherton, & Tilanus 1986).

Changes in the $H_2$ and H i gas surface densities along the optical arms (Fig. 8a) are shown in Figure 8b. The transition from $H_2$ to H i along the outer spiral arms can be seen in the example of the northeastern arm. The $H_2$/H i relationship is more complex along the two inner arms. The optical arms do not appear to connect to the bar or lens. The same is true for the CO arms in Figure 2a, and this is reflected in the relative inner minima for the northern and southern CO arms. This raises the possibility that the bar and spiral arm structures have different pattern speeds and/or that the bar is too weak to drive the spiral arm pattern (Sellwood & Sparke 1988; Combes 1991). The maximum in the southern CO arm occurs at a position where that arm is in closest proximity to the southern end of the bar/lens, which enhances the appearance of a connection at that point. There is much less variation in $\Sigma_{\text{H}_2}$ along the inner arms than in $\Sigma_{\text{H}_2}$, whose profiles peak roughly midway along the arms. We follow two segments of the bifurcation that occurs at the western end of the northern arm in Figure 8 and note that surface densities are higher (factor of 2) for the spur that extends due west compared to the segment that continues without a change in pitch angle. The optical flux (convolved to 55" resolution) remains constant along the arms, within 10% of the mean for each arm.

4.2. Neutral Gas and the Nonthermal Continuum Disk

Now that we have a $\Sigma_{\text{gas}}$ image of IC 342 it is worthwhile considering a comparison with the nonthermal, 21 cm continuum, disk. Adler, Allen, & Lo (1991) report a relatively constant CO to 20 cm continuum ratio for galactic disks as evidence for cosmic rays being the primary heating source for molecular clouds. On the other hand, Helou & Bicay (1993) report a close correspondence with the gas density,
which carries a magnetic field \( n_{\text{gas}} \propto B^x \), where \( x \) is between 1/3 and 2/3, which in turn prevents electrons propagating along the magnetic field (the source of the nonthermal continuum) from escaping the gas disk. While not mutually exclusive, we can at least now test which is a better fit. This comparison is also interesting in that IC 342 looks very different in each of the emission tracers. We have already noted the somewhat regular appearance of the optical lens and inner two-arm pattern, the pronounced CO bar, the asymmetric inner CO arm pattern, and the apparent lack of corresponding structure in the central H I hole. By contrast, the 21 cm continuum has a distinctive one arm spiral appearance (Paper I) and, at first glance, does not look like either the CO or the H I maps alone, although localized correlations are present. Is the 21 cm continuum related to the H$_2$ component, or the H I component, or both?

The 21 cm continuum morphology (Paper I, Fig. 1) bears a close resemblance to the total gas surface density map, better than the \( I_{\text{CO}} \) map by itself. This is illustrated by the relatively flat ratio of \( \Sigma_{\text{gas}} / F_{21\text{cm}} \) beyond 2' (Fig. 9a). The correlation of \( \Sigma_{\text{gas}} \) and \( F_{21\text{cm}} \) is consistent with cosmic-ray propagation models of Bicay & Helou (1990) and Helou & Bicay (1993). In a comparison of \( \Sigma_{\text{H}_2} \) to 21 cm continuum (Fig. 9b) we reproduce the result reported by Adler et al. (1991) for IC 342. Inside 2 ', where H$_2$ dominates the total gas mass, we see a dip in the \( \Sigma_{\text{gas}} / F_{21\text{cm}} \) ratio, which may be due to a higher star formation efficiency (and consequently higher cosmic-ray production) per unit H$_2$ in the starburst nucleus of IC 342. It is less likely that this dip is due to an underestimate of the molecular material; if anything X$_{\text{CO}}$ is likely to overestimate \( N_{\text{H}_2} \) in the central regions (Meier et al. 2000). The uniform correlation of the neutral gas surface density and the 21 cm continuum suggests that the correspondence is a property of the neutral gas and its correlated properties (such as magnetic fields), and is not defined by properties peculiar to either the H I or H$_2$ alone.

4.3. Polar Maps of H I, CO, Radio Continuum and Optical: Azimuthal Variation in the Disk of IC 342

In order to examine the relationship between the neutral gas components, 21 cm continuum and optical emission in

![Fig. 7](image_url) Neutral gas surface density vs. \( R \) in IC 342. The surface densities, \( \log(\Sigma) \), are plotted as a function of galactic radius. All surface densities are corrected for inclination (\( \cos31^\circ \)). \( \Sigma_{\text{H}_2} \) is shown with (+1.58) and without a correction for the missing flux due to the lack of short baselines in the VLA observations (Paper I). \( \Sigma_{\text{gas}} \) includes this H I missing flux correction and has the surface density increased by 1.36 to account for the He contribution.

![Fig. 8](image_url) \( \Sigma_{\text{H}_2} \) and \( \Sigma_{\text{gas}} \) along arms in IC 342. (a) DSS image with the foreground stars removed to bring out the spiral arm features. Circles trace the inner northern and southern arms. The inner northern arm bifurcates at its western end. An additional outer arm is traced to the northeast. (b) \( \Sigma_{\text{H}_2} \) (solid line) and \( \Sigma_{\text{gas}} \) (dashed line) along the three arms at the positions indicated in the DSS image. The vertical-axis tick marks are in \( 5 \, M_\odot \, \text{pc}^{-2} \) increments and the 0 \( M_\odot \, \text{pc}^{-2} \) level for each of the arms is indicated by a dotted line. Inner radius positions are to the left, outer positions to the right. Each measured position is \( \sim 50^\circ \) apart. The bifurcation of the western end of the northern arm is traced along two paths, the northern path has the higher H$_2$ and H I surface densities.
greater detail, we produced polar maps which were corrected to a face-on inclination. A comparison of $I_{\text{CO}}$, Figure 10a, and $\Sigma_{\text{gas}}$, Figure 10b, shows that molecular gas surface density defines most of the structure in the inner 15' of IC 342. The comparisons to the radio continuum at 21 cm are interesting in light of the constant $I_{\text{CO}}$ to nonthermal radio continuum ratio seen on kiloparsec scales and a decoupling of the two on smaller size scales (Adler et al. 1991). Where does the decoupling occur? Does it also occur if the total gas surface density is taken into account (Helou & Bicay 1993)?

In Figure 10a, the polar map of $I_{\text{CO}}$, the molecular bar is readily apparent at the bottom of the plot, with the northern end at $\phi \approx 340^\circ$ extending to a radius of $3'$ (1.8 kpc) and the southern end at $\phi \approx 165^\circ$ extending to a radius of $4'$ (2.4 kpc). There is a pronounced asymmetry in the CO emission which is dominated by the emission at the southern end evident in these plots. The bar is less pronounced in the DSS optical map (convolved to 55' resolution, Figure 10c, and is more symmetrical than the CO bar. The bar is also apparent in the 21 cm continuum polar map, Figure 10d.

The northern spiral arm is clearly seen in the polar maps, beginning at the eastern side of the northern bar end at $\phi \approx 390^\circ$, $R \approx 2'$ (1.2 kpc) sloping up 100' in phase out to the border of the CO map at $R = 7'$. This same arm is well defined in both the DSS optical and the 21 cm continuum polar maps. The southern arm starts at the western side of the bar at $\phi \approx 200^\circ$, $R \approx 3'$ (1.8 kpc), and winds through 90' in phase out to the CO map border. The “wrong way” appearance of the false southern arm feature is caused by the comparatively weak southern arm CO emission and the strong, broad CO emission at the southern bar end. The two arm inner spiral pattern is also apparent in the optical polar map. The “one-arm” 21 cm continuum spiral is shown to be two different arm patterns with the stronger arm coincident with the northern CO arm, while the emission pattern of the southern continuum arm is weaker for $R < 4'$ (2.4 kpc). Bifurcation of the basic two-armed spiral pattern is indicated by V-shaped patterns and parallel patches of emission extended out in radius starting at $R \sim 4'$ (2.4 kpc).

While the global morphology on kiloparsec-sized scales is similar for the CO, H I, and stars, the emission patterns of the bar and arms are offset from one another. To quantify offsets between various emission patterns, slices through polar plots between $R = 1'$ and 6.5 in 0.5 increments were made and are presented in Figure 11.

The azimuthal profiles from 1' to 1.5' are dominated by the bar structure in IC 342. Inside of the corotation radius located at $\sim 7'$ (Paper I) gas flows counterclockwise (right to left in the plots) through the bar and spiral arm pattern. Along the bar CO peaks downstream from the optical bar peak and H I peaks downstream of CO. The displacement between CO and H I is $\phi \sim 40^\circ$ (2/3 of a beam at $R \sim 1'$ over 1 at $R \sim 2'$). The displacement between CO and the optical is less, $\phi \sim 30^\circ$. The clear bar pattern becomes less dominant in the $R \sim 2'$ slice as the inner spiral arm pattern begins to contribute to the profiles. CO, H I, and optical peaks at the ends of the bar tend to lie at the same azimuthal position in the $R \sim 2'$ slice. The 21 cm continuum emission roughly follows the CO emission profile. The asymmetry between the northern and southern ends of the bar can be seen in both the CO and 21 cm emission profiles at $R \sim 2.5$. There is a pronounced dip in all four images at $\phi \sim 100^\circ$, reflecting the paucity of stars and gas in the interarm region directly west of the nucleus at this radius.

The 3' to 4' profiles are dominated by the inner two arm spiral pattern. The bimodal pattern becomes less distinct by $R \sim 4'$. Interarm regions east and west of the nucleus at $\phi \sim 100^\circ$ and 300' are well defined by local minima in the profiles of the $R \sim 3'$ slice. Strong 21 cm continuum emis-

![Fig. 9](image-url)
Fig. 10.—Polar maps of the disk of IC 342. Polar maps of IC 342 have been corrected to a face-on view of the galaxy. North is located at $\phi = 0^\circ, 360^\circ$, and $\phi$ runs counterclockwise from north. White lines mark the position of the bar. Rotation of the galaxy is right to left in the maps. The gas, optical, and continuum maps were convolved to 55$''$ resolution, matching the CO beam. In each case the gray scale was selected to bring out features in the disk. (a) CO gray scale runs from $0$ to $20 \text{ K km s}^{-1}$. (b) $\Sigma_{\text{gas}}$ gray scale runs from $0$ to $100 \, M_\odot \text{ pc}^{-2}$. (c) DSS optical gray scale is uncalibrated. (d) 21 cm continuum gray scale runs from $0$ to $20 \text{ mJy}$. The strong 21 cm continuum sources located at $\phi \sim 50^\circ, 410^\circ, R \sim 4.5$ and $\phi \sim 260^\circ, R \sim 2.6$, have been identified as a background radio galaxy and a possible SNR in the disk of IC 342, respectively (Paper I).

sion is associated with the northern arm. The CO peaks are upstream of the optical arms by $\phi \sim 20^\circ$ (more than one beam element at these radii). The H I arms appear to coincide with the optical arms here. The CO at $R \sim 3'$ and $R \sim 3.5$ is much stronger in the southern arm than the northern. The 21 cm continuum emission begins to trace the total gas density rather than the CO exclusively. At $R \sim 4'$ and $R \sim 4.5'$ the northern arm becomes prominent. The H I in this arm roughly follows the optical, while the CO and 21 cm continuum peaks upstream from both.

At radii between 3.5 and 5.5, we identify distinct patches of interarm CO. CO peaks can be found coincident with major minima in the optical profile separated by one beam width from the optical peaks. Examples include the CO peaks at $\phi \sim 90^\circ$ in the 3.5 and 4' profiles and at $\phi \sim 245^\circ$ in the 4.5 and 5' profiles. These represent 5 $\sigma$ detections in the $I_{\text{CO}}$ map and are 3 $\sigma$ above the adjacent CO minima. The column densities corresponding to these locations are $\sim 6 \times 10^{20} \text{ cm}^{-2}$. They correspond to the patches of $I_{\text{CO}}$ located at $\alpha = 3^h47^m27^s, \delta = 68^\circ6'20''$ for the former two peaks and $\alpha = 3^h46^m5^s, \delta = 68^\circ3'30''$ for the latter two.

Beyond 4.5 the effects of the bifurcating spiral arm pattern become increasing apparent in the ragged azimuthal profiles. Clear but secondary CO arm patterns can be followed to progressively larger radii. The majority of CO peaks are coincident with optical and H I peaks, but the relative amplitudes vary considerably. The identification of upstream versus downstream features becomes impossible. The 21 cm continuum emission profile increasingly follows the H I profiles with increasing radii as H I begins to dominate the total gas surface density.

It is tempting to attribute the emission offsets along the bar and inner spiral arms to the same mechanisms used to explain similar offsets in the spiral arms of M51 (Tilanus et al. 1988; Tilanus & Allen 1989), M33 (Wilson & Scoville 1991), and M101 (Smith et al. 2000). The formation of massive stars generates a UV interstellar radiation field that dissociates $H_2$, seen as an increase in the downstream H I column density relative to the CO. If we assume circular orbits and a 24 km s$^{-1}$ kpc$^{-1}$ pattern speed for the inner arm pattern (Paper I), the time it takes for gas to move from the CO arm to the downstream H I peak is $\sim 7$–9 Myr. This is the main-sequence lifetime for $\sim 20 M_\odot$ stars, which would be the largest contributor to the UV radiation if they are in fact formed from spiral arm molecular gas (Condon & Yin 1990). Photodissociation of $H_2$ by UV would increase $\Sigma_{\text{H}_2}$ over the lifetime of the massive stars. However, we do not definitely locate ongoing star formation with this data set. With 1$'$ resolution we can only suggest that location and timescale of the CO and H I displacements point to massive star formation origin for what is presum-
Fig. 11.—Azimuthal slices through the disk of IC 342. These plots show selected cuts through polar maps of $I_{\text{CO}}$, $I_{\text{HI}}$, the optical and 21 cm continuum emission. All were convolved to 55" resolution and corrected to a face-on view of the galaxy. North is located at $\phi = 0^\circ$, $360^\circ$, and $\phi$ runs counterclockwise from north. Rotation of the galaxy is right to left in the plots. In each case, the emission has been divided by the peak emission found in the slices, so the various curves represent fractions relative to the highest level found in all the slices. Slices were taken in increments of between radii of 1' to 6.5', which azimuthal coverage in CO is incomplete. There are roughly six independent beam elements spread across 360° in azimuth at $R \approx 1'$, changing linearly to 40 independent beams at $R \approx 6'$. The strong 21 cm continuum sources (Paper I), a radio galaxy background source located at $\phi \approx 50^\circ$, $410^\circ$, and $R \approx 4.5'$ and a possible SNR in the disk of IC 342 at $R \approx 260'$, $R \approx 2.6'$ were blanked (set to 0 emission) prior to producing the azimuthal 21 cm continuum plots. The normalized 1 $\sigma$ noise level in $I_{\text{CO}}$, varies linearly from 0.033 to 0.016 in the 1' to 6.5' slice plots. The normalized 1 $\sigma$ noise level in the $I_{\text{HI}}$ data is almost constant, 0.017, for this region of the H I map. For the 21 cm continuum data the normalized 1 $\sigma$ noise level is constant, 0.03.

4.4. Individual Velocity-related H I/H$_2$ Structures

A direct comparison of CO and H I channel maps permits the identification of individual CO/H I features in velocity space whose associations may be ambiguous in integrated intensity maps. The H I (Paper I) and the CO were regridded to a 10.3 km s$^{-1}$ channel width. The resulting H I channel maps are shown in gray scale with superposed CO contours in Figure 12.

The continuity of the H I and CO gas structures is apparent in these maps. Hydrogen gas extends continuously from the outer primarily atomic disk to the inner primarily molecular disk. The high velocities of the gas in the nuclear "minispiral" can be seen, even in these low-resolution CO
maps, beginning in the 104 km s\(^{-1}\) channel and extending to the \(-30\) km s\(^{-1}\) channel.

In the region of CO/H\(\text{I}\) overlap, individual CO peaks are coincident with H\(\text{I}\) peaks in the same channel maps. Some of the CO/H\(\text{I}\) peaks are relatively isolated in the progression of peaks across the channel maps, which suggests a giant molecular association (GMA), although higher resolution might reveal these to be numerous individual clouds contained within our 55" beam. An example is in the 21 km s\(^{-1}\) channel at \(\alpha = 3^h 47^m 12.5^s, \delta = 68^\circ 132^\prime\) in the southeast at galactocentric radius \(R \sim 3\) kpc (5'). The cloud has dimensions 550 pc \(\times\) 1000 pc (0.9' \(\times\) 1.7'), although it may not be resolved along the shorter axis. \(N_{\text{H}1}\) in the cloud is \(2.1 \times 10^{20}\) cm\(^{-2}\), and \(N_{\text{H}2}\) is \(2.3 \times 10^{20}\) cm\(^{-2}\). The total H\(\text{I}\) mass of the cloud is \(1.3 \times 10^6\) \(M_\odot\), and the total H\(\text{2}\) mass \(2.2 \times 10^6\) \(M_\odot\). Wilson & Scoville (1991) found similar association between CO and H\(\text{I}\) for molecular clouds in M33. GMAs of similar size and mass (\(\sim 400\) pc and \(\sim 10^7\) \(M_\odot\)) were found in arms of the grand design spiral galaxies M51 (Lo et al. 1987; Rand & Kulkarni 1990) and M100 (Rand 1995) and in the disks of the flocculent spirals NGC 4414 (Sakamoto 1996; Thornley & Mundy 1997b) and NGC 5055 (Thornley & Mundy 1997a).

5. DO WE DETECT A THRESHOLD FOR MOLECULAR CLOUD FORMATION IN IC 342?

At this point we consider questions that result from the finite size of the CO disk embedded in a much larger H\(\text{I}\) disk. We know we have detected the bulk of the CO in the region where it is the dominant gas tracer (\(>95\%), assuming the worst case scenario of an inner 14' disk filled with CO just below our detection limit, 0.2 K km s\(^{-1}\)). Does the outer edge of our CO map represent a real threshold for the formation of molecular clouds? Does some com-
combination of low $T_{ex}$, a low filling factor for molecular clouds in the beam, or declining metallicity at large galactic radii, combine to create a detection limit rather than a real threshold?

It seems unlikely that the fall off in CO emission is due to a sudden fall in $T_{ex}$ for CO, although we cannot rule out this possibility with the present observations. The 21 cm continuum disk (Paper I) extends 2' in radius beyond our observed CO disk and from Figure 9a this nonthermal continuum, a measure of the cosmic ray density, is constant relative to $\Sigma_{gas}$. Cosmic ray heating may be sufficient to maintain molecular clouds at $T_k \sim 10$ K (Goldsmith & Langer 1978; Adler et al. 1991; Hunter et al. 1997) past the radius at which we last detect CO. By analogy, $T_{ex}$ for Galactic molecular clouds at large galactocentric radii is not found to differ much from their counterparts at lesser radii (Mead & Kutner 1988).

Could declining metallicity create a situation where CO no longer traces $H_2$? We argue against this possibility since the efficient formation of $H_2$ requires dust grains, therefore any radial fall off in metallicity would probably affect CO and $H_2$ in tandem since other formation mechanisms for $H_2$ are less efficient (Tielens & Hollenbach 1985; Hollenbach, Takahashi, & Tielens 1991; Abgrall et al. 1992; Sternberg & Dargarno 1995). While IC 342 has a metallicity gradient (Vila-Costas & Edmunds 1992) the metallicity is still nearly solar, 0.8 $Z_\odot$ at 7' (4 kpc); not enough of a decline to have a profound effect on $X_{CO}$. Also, the scale length for the decline in metallicity is 6' (compared with 2' for the CO emission); too shallow to be related to the decline in CO emission. The possibility exists that the metallicity falls off abruptly at the edge of the optical disk, but this occurs at a radius of 12' (7 kpc; Buta & McCall 1999), nearly twice the radius of our observed CO disk.
FIG. 12.—H I/CO channel map comparisons for IC 342. CO channel maps were regridded to the velocity width of the H I channel maps (Paper I). H I (21 cm) emission is shown in gray scale ranging from 0 to 0.09 mJy beam$^{-1}$ with a 38' beam. CO is shown in dark contours 0.048, 0.096, 0.192, 0.288, and 0.48 K, reflecting the improved rms noise level in the broader channels (0.024 K). The 6 K km s$^{-1}$ contour from the CO integrated intensity map is shown in light gray in order to indicate the position of the CO bar.

There is a very real possibility that the edge of our CO disk is primarily due to a decline in the filling factor of the molecular gas which pushes CO emission in a 1' beam below our detection limit. Wouterloot et al. (1990) found evidence for molecular gas in the Milky Way at Galactocentric radii $>20$ kpc. We have already determined that we would not detect the type of molecular clouds found at 13 kpc in the Milky Way (Mead & Kutner 1988) if they were observed at the distance of IC 342. But why would $\Sigma_{H_2}$ fall off at a faster rate than $\Sigma_{\text{gas}}$ over a region of the disk where
there is still ample gas available to form molecular clouds? Elmegreen (1989) has proposed that the fraction of a gas cloud that is in molecular form is a function of the metallicity, external radiation field, cloud size and external pressure. The metallicity, radiation field, the mean molecular cloud size, are probably not changing abruptly at the edge of the observed CO disk in IC 342. We would like to know how the gas pressure changes at the radial limits of the CO disk in order to evaluate its role in creating an edge.

To estimate the macroscopic, total, midplane gas pressure, $P_{\text{ism}}$, Elmegreen (1989) derived

$$P_{\text{ism}} = \frac{\pi}{2} G \Sigma_{\text{gas}} \left( \Sigma_{\text{gas}} + \Sigma_{\text{stars}} \frac{\sigma_{\text{gas}}}{\sigma_{\text{stars}}} \right)$$

from numerical solutions to equations of hydrostatic equilibrium for a combined gas and stellar disk (where the $\Sigma$ and $\sigma$ are the surface densities and velocity dispersions of the gas and stars). We can obtain a lower limit to $P_{\text{ism}}$ from sum of the $H_2$ and HI gas surface densities ($P_{\text{ism}} \times \Sigma_{\text{ISM}}^2$), ignoring the contribution from the thicker stellar disk): at $6'(3.5$ kpc), $\Sigma_{\text{gas}} = 17 M\odot$ pc$^{-2}$, $P_{\text{ism}} = 9 \times 10^3$ cm$^{-3}$ K; at $7'(4.1$ kpc, the edge of the CO disk) $\Sigma_{\text{gas}} = 12 M\odot$ pc$^{-2}$, $P_{\text{ism}} = 5 \times 10^3$ cm$^{-3}$ K. We can obtain an estimate of how $P_{\text{ism}}$ might change once the stellar contribution is taken into account, by using Galactic values for $\Sigma_{\text{ism}}$ and $\sigma_{\text{ism}}$ at equivalent radii (probably safe due to the similarity of $\sigma_{\text{CO}}$ in the Galaxy and IC 342 at the same galactocentric radius of 4 kpc, 7 km s$^{-1}$). Using the Galactic midplane total mass densities from Malhotra (1994) at 3.5 and 4.1 kpc and a stellar scale height of 320 pc (Bahcall & Soneira 1980), we obtain $P_{\text{ism}} \sim 5 \times 10^4$ cm$^{-3}$ K at $6'(R = 3.5$ kpc, $\Sigma_{\text{stars}} \sim 190 M\odot$ pc$^{-2}$, $\sigma_{\text{stars}} = 29$ km s$^{-1}$) and $P_{\text{ism}} \sim 3 \times 10^4$ cm$^{-3}$ K at $7'(R = 4.0$ kpc, $\Sigma_{\text{stars}} = 160 M\odot$ pc$^{-2}$, $\sigma_{\text{stars}} = 26$ km s$^{-1}$). For reference, $P_{\text{ism}}$ at the solar circle is $1.4 \times 10^5$ cm$^{-3}$ K (Elmegreen 1989). Between 6' and 7' both $P_{\text{ism}}$ and $\Sigma_{HI}$ decline by 40%, while $\Sigma_{\text{gas}}$ declines by 30%. The above are suggestive of connection between $P_{\text{ism}}$ and the fraction of the gas that is in molecular form. Given the uncertainties involved in the calculation, we can only state that the filling factor for CO probably falls with declining $\Sigma_{\text{gas}}$ and that it may fall at a faster rate if $P_{\text{ism}}$ is a factor.

How far out in the disk of IC 342 do we expect to be able to find molecular clouds? There are solely theoretical reasons to expect molecular gas at radii beyond our CO detection limit. According to Elmegreen & Parravano (1994), there exists a minimum pressure, $P_{\text{min}}$, below which only warm equilibrium states are possible. Thus molecular clouds are not formed where the pressure becomes too low to facilitate the formation of cold, dense clouds. Along narrow outer gas arm segments at large radii ($R \sim 18'$, 10 kpc) $P_{\text{ism}} \sim 5 \times 10^3$ cm$^{-3}$ K which is close to $P_{\text{ism}}$ values (once the stellar contribution is factored in) at the edge of the CO disk. By the Elmegreen & Parravano (1994) model, the pressure is high enough for molecular clouds to form there. These are locations to look for CO and star formation tracers with deeper integrations.

A strong compression event, such as the passage of a spiral density wave (SDW), can promote the creation of star forming molecular clouds by creating strongly self-gravitating structures temporarily under high external pressures. An outer Lindblad resonance (OLR) for an $m = 2$ mode SDW is located at $12'$ (7 kpc), but there is some evidence for an additional $m = 4$ mode SDW beyond this radius in the outer H I disk (Paper I). Some level of molecular cloud and star formation might be anticipated out to the termination radii (OLR) for any SDWs operating in the gas disk.

6. CONCLUSIONS

Molecular gas in IC 342 as traced by our 12 Meter CO(1–0) OTF maps is concentrated in the inner $14'$, coincident with the optical disk. The CO disk is embedded in a much larger ($1:5$) H I disk. The CO disk displays several prominent features: a bright nucleus, a bar, two inner spiral arms, and a clumpy disk filled with interarm emission. For a Galactic $X_{CO}$ we estimate an average nuclear $H_2$ surface density of $160 M\odot$ pc$^{-2}$, 38 $M\odot$ pc$^{-2}$ for the bar and 20 $M\odot$ pc$^{-2}$ along the 2 inner CO spiral arms.

The observed $H_2$ is 30% of the total H I mass in IC 342 and gas ($H_2 + H I$) represents about 4% of the total dynamical mass. On kiloparsec-size scales, the gas disk is seen to transition from a predominantly molecular hydrogen state in the inner disk to a predominantly atomic one at large radii. The two gas phases, H I and $H_2$, have equivalent azimuthally averaged surface densities, $\sim 7 M\odot$ pc$^{-2}$, at 6'(3.5 kpc). In this region, CO and H I are correlated rather than anticorrelated. Along the spiral arms, large H I/H 2 structures of mass $M_{\text{clump}} \sim 5 \times 10^4 M\odot$ are seen in individual channel maps. These may be GMAs with H I envelopes.

While the neutral gas, optical and 21 cm continuum disks have a similar global morphology, on smaller scales a great deal of complex structure is seen. The bar and the two inner spiral arms are all asymmetric. Azimuthal structure in the disk becomes increasing more complex with increasing galactic radii. A pattern of downstream displacement of H I from CO in the inner disk suggests the H I is photo-dissociated $H_2$.

There is an excellent spatial correlation between the 21 cm continuum and the total gas surface density with a scatter $< 10%$. Outside of $R > 2'$ the ratio of $\Sigma_{\text{gas}}/F_{21cm}$ is relatively flat, consistent with models of nonthermal emission from cosmic rays, produced in the late stages of massive star formation, diffusing through a gas disk. The decline in $\Sigma_{\text{gas}}/F_{21cm}$ in the central region may indicate a higher SF efficiency relative to the disk.

Indications are that we do not detect a radial limit for molecular gas in our map of CO in IC 342. While the bulk of the CO emission from IC 342 has probably been observed within the $14'$ region of our map, we note that the total gas disk is much more extensive than this ($\sim 90'$). However, molecular clouds present beyond our observed CO disk are restricted to surface densities of less than $1 M\odot$ pc$^{-2}$ averaged over a $55'(0.6$ kpc) beam. Based on the CO/H I correlations of the inner disk, we would expect $H_2$ present in the outer disk at the peaks in the H I distribution.

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