STRUCTURE IN THE NEUTRAL HYDROGEN DISK OF THE SPIRAL GALAXY IC 342

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ABSTRACT

We present 38″ resolution Very Large Array 21 cm continuum and H I line emission observations of the spiral galaxy IC 342, at an adopted distance of 2 Mpc. Kinematic evidence exists for a m = 2 spiral density wave in the inner disk with a corotation radius located at 4 kpc and a possible four-arm pattern in the outer disk. On smaller scales, outside of the central depression in H I column density, H I is organized into a complex pattern of relatively short (∼ 2–5 kpc), interconnected, spiral arm segments. Numerous “holes” are distributed throughout the H I disk. By considering the effects of shear, structures that are not self-gravitating, such as holes and voids, cannot be long-term phenomena. The timescale, combined with the total energy required to evacuate holes, leads us to reject wind and supernovae origins for the large-scale pattern of H I holes in IC 342. Gravitational instabilities in the disk form on a timescale that is short compared with the rotation period of the disk. The pattern of H I spiral arm segments exists on a scale that is consistent with their being material arms that result from gravitational instabilities. The H I cavities are a natural remnant of the process.

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

1. INTRODUCTION

The gas disks of spiral galaxies have complicated morphologies with structure on many scales. The grand-design, two-arm spiral patterns seen both in optical light and in H I 21 cm line emission are generally attributed to the presence of a spiral density wave (SDW). Distinct density wave patterns can be seen in the H I disks of galaxies such as M51 (Rots et al. 1990). In contrast, a flocculent H I disk pattern may indicate that a process such as stochastic, self-propagating star formation driven by winds from previous generations of star formation, is taking place. In flocculent galaxies, H I lacks the distinct arm pattern and takes on the appearance of thick “ring” (given the commonly seen central depression in H I column density) as seen in NGC 4414 (Thornley & Mundt 1997). Intermediate between grand-design and flocculent galaxies, a pattern of multiple, well-organized, spiral arm segments could also be the result of strong self-gravity in a disk with high gas content, as shown in the simulations of NGC 1365 by Lindblad, Lindblad, & Athanassoula (1996). A spectrum of intermediate and combined arm patterns is seen, leading to the classification scheme of Elmegreen & Elmegreen (1987). On smaller scales than the grand design spirals, phenomena such as holes and bubbles appear. Heiles (1979, 1984) has convincingly shown that in the Milky Way, the H I distribution contains shells, bubbles, and holes that may be attributable to supernovae (SNe) and winds from the late evolutionary stages of massive stars.

H I is the best-known gas tracer. In gas-rich spiral galaxies, the H I disk can extend to radii several times that of the optical disk (Bosma 1981). In the Milky Way, H I mass dominates the total gas mass beyond the solar circle, and the atomic and molecular phases reach nearly equal mass proportions at 4 kpc (Kulkarni & Heiles 1987). Similar distributions of atomic gas are seen in other late-type galaxies. As such, H I is a less reliable tracer of total gas in the inner regions of a galaxy, particularly in the inner 1 to 2 kpc.

IC 342, a nearly face-on, normal Scd galaxy of a size and luminosity similar to the Milky Way, is an ideal candidate for studies of disk structure. Its relative proximity allows us to examine both large- and small-scale features in the disk. The galaxy has a large optical diameter (∼ 20″) on the sky and an even larger diameter H I disk (∼ 80″; Rogstad, Stostak, & Rots 1973). The optical morphology of IC 342 has several components: a bright nuclear region, an oval central lens, and two inner disk arms that rapidly break up into a multiarm pattern at increasing distance from the nucleus (Ables 1971; Elmegreen, Elmegreen, & Montenegro 1995). The optical structure of IC 342 is a less reliable tracer of total gas in the inner regions of a galaxy, particularly in the inner 1 to 2 kpc.

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The large-scale H I distribution is asymmetric (Rots 1979) and warped at radii beyond 16′ (Newton 1980a). Rots (1979) suggests that an interaction with the nearby irregular galaxy A0355 is the cause of the distorted velocity fields of both galaxies. Newton’s (1980a, 1980b) H I study indicates the presence of overall spiral structure that breaks up into multiple, clumpy, spiral arm segments. The inner gas disk (∼ 15″) is known to contain a substantial amount of molecular gas, strongly peaked at the nucleus (Morris & Lo 1978; Young & Scoville 1982; Sage & Solomon 1991; Crosthwaite et al. 2000).

The distance to IC 342 is fundamental to a discussion of masses and kinematic properties. McCall (1989) used new estimates for Galactic extinction and asymptotic B magnitude and an extinction-corrected, face-on diameter to arrive at a distance of 1.8 Mpc. Karachentsev & Tikhonov (1993) used photometry of the brightest red and blue supergiants to derive a distance of 2.1 Mpc. Krismer, Tully, & Gioia (1995) have assigned a distance of 3.6 ± 0.5 Mpc to the IC 342/Maffei group, but the group is so close that the size of the group itself is a significant fraction of its distance. We
will adopt a 2.0 Mpc value, or a linear scale of 0.58 kpc arcmin$^{-1}$.

This is the first of two papers in which we examine the large-scale gas disk of IC 342 at higher resolution than previously available. In this paper, we present images of the H I emission made with the Very Large Array (VLA). In a subsequent paper, we will examine the molecular disk as traced by CO and its relation to H I in IC 342 (Crosthwaite et al. 2000).

2. OBSERVATIONS

The 21 cm continuum and H I line observations were made in 1985 June and 1984 August using C and D array configurations, respectively. In each array, a full 8 hr track was taken for uv coverage. The phase center for the observations in B1950.0 coordinates was $\alpha = 3^\mathrm{h}41^\mathrm{m}57^s.3$ and $\delta = 67^\circ56^\prime29^\prime$ ($\alpha = 3^\mathrm{h}46^\mathrm{m}48^s.4$ and $\delta = 68^\circ05^\prime48^\prime$ [J2000]). The channel width for the line observations was 48.83 kHz (10.3 km s$^{-1}$), with 63 channels giving a total of 639 km s$^{-1}$ coverage. Absolute flux calibration was achieved by bootstrapping from 3C 48, which has a flux of $S(1419$ MHz) = 16.0 Jy, accurate to within 2%. The absolute positional uncertainty is determined by the positional uncertainty of the phase calibrator 0212+735 (B1950.0), known to less than 0.05.

The C and D array uv data were independently calibrated and then combined. A zero-spacing flux was extrapolated from the shortest $uv$ spacings for each channel and applied in the CLEANing process. The zero-spacing flux estimates were typically one-third of the total fluxes from Rots's (1979) single-dish observations of IC 342 covering a region 3 times larger than our primary-beam area. The continuum plus line emission cube was CLEANed with a natural weight (no taper) for improved sensitivity to the extended H I emission present in this galaxy. The FWHM beam size for the combined, naturally weighted C + D array data is 38" $\times$ 37", with position angle (P.A.) of 17°. The largest scale structure that can be imaged is limited by the lack of short spacings to $\sim 15''$, significantly less than the FWHM of the primary beam, which is 32'. The channel cube was corrected for primary-beam attenuation out to the 20% power point and blanked beyond. The rms noise in the channel maps is 1.2 mJy beam$^{-1}$. The observations can be converted from units of janskys per beam to a temperature scale using $T_0(K) = 434S_{H I}$(Jy beam$^{-1}$).

3. RESULTS

3.1. The 21 cm Continuum Map

The 21 cm continuum map shown in Figure 1 is an average of 25 line-free channels. The rms noise level, measured in an emission-free region 10' from the phase center, is 0.5 mJy beam$^{-1}$. The 21 cm continuum emission, consisting largely of synchrotron emission, displays clear spiral structure. A bar-like structure running from the southeast to the northwest through the nucleus is apparent at position angle of 135° and with a length of $\sim 3$ kpc (5'). Hummel & Gräve (1990) noted the apparent one-arm spiral structure of the continuum. In our continuum map, a two-arm spiral pattern (with one severely underdeveloped arm) can be seen, confused somewhat by the unresolved source west of the nucleus.

The bright, unresolved source northeast of the nucleus ($\alpha = 3^\mathrm{h}47^\mathrm{m}29^s, \delta = 68^\circ08^\prime24^\prime$ [J2000]) has a 21 cm continuum flux of $S(21$ cm) = 46 mJy. In a high-resolution 6 cm map, from the data of Turner & Ho (1983), it has the distinct double-lobed appearance of a radio galaxy. The same source is identified in Hummel & Gräve's (1990) continuum study as "discrete source 4." The steep spectral index ($x = -0.87$) they found is consistent with this identification.

The unresolved source seen west and slightly south of the nucleus ($\alpha = 3^\mathrm{h}46^\mathrm{m}22^s, \delta = 68^\circ05^\prime06^\prime$ [J2000]) has a 21 cm continuum flux of $S(21$ cm) = 10 mJy. This source was noted in the radio continuum studies of Baker et al. (1977) and Hummel & Gräve (1990), the latter assigning a rather flat spectral index of $-0.2$ to this source identified as "discrete source 2." The total power for this object is $L(21$ cm) = $4.8 \times 10^{18}$ W Hz$^{-1}$, or twice that of the supernova remnant (SNR) Cas A ($L(21$ cm) = $2.2 \times 10^{18}$ W Hz$^{-1}$), presenting the possibility that this is an IC 342 disk SNR. Hummel & Gräve (1990), however, suggest that this is a background core-jet source.

The unresolved source seen to the northwest, near the edge of the primary beam at $\alpha = 3^\mathrm{h}45^\mathrm{m}23^s, \delta = 68^\circ17^\prime00^\prime$ (J2000) has a 21 cm continuum flux of $S(21$ cm) = 26 mJy. Hummel & Gräve (1990) derived a spectral index, $x = -0.8$, for this source consistent with an identification of this as a background galaxy. It is less likely that this source is within IC 342 since it would have a rather large total-power output, $\sim 6$ times that of Cas A.

3.2. The H I Channel Maps

Because both IC 342 and its phase calibrator, 0212+735, are located at low Galactic latitudes ($b = 10^\circ6$ and $b = 12^\circ0$, respectively), contributions from Galactic absorption and undersampled Galactic emission are possible (Weaver & Williams 1974). Both the bandpass spectrum for 0212+735 and the spectrum at the location of the continuum peak in IC 342 were examined, and both show Galactic absorption. In order to produce unbiased integrated intensity and velocity moment maps, and to prevent the unrealistic negative-emission "hole" that occurs when a continuum image, unaffected by Galactic absorption, is subtracted from the affected channels, we correct for this absorption assuming a uniform foreground screen model, following Hurt, Turner, & Ho (1996). The correction is small, typically less than 10%, and affects only channels in the $-54$ to 8 km s$^{-1}$ range. After applying the correction to the CLEANed channels and performing continuum subtraction, 24 of the channels contained line emission.

We present gray scale and contour images of the 24 channels with line emission in Figure 2. The "butterfly" pattern characteristic of an inclined rotating disk is formed from the lumpy patchwork of H I emission. H I emission extending into the nucleus can be seen in the 11 to 70 km s$^{-1}$ channels. The $-54$ to 8 km s$^{-1}$ channels show a pattern of low-level diffuse emission outside of the normal butterfly pattern as compared with the corresponding redshifted channels. Because this diffuse emission is at anomalous velocities for its line-of-sight position in the rotating inclined disk of IC 342 and is at the velocities expected for Galactic H I, we assume it is Galactic H I emission. The positive-negative nature of the anomalous emission pattern and the negative

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1 VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.
bowl surrounding the source in the affected channels are indicative of undersampled diffuse emission.

3.3. The H\textsc{i} Integrated Intensity Map

The integrated intensity map is presented in Figure 3. In order to produce the moment maps, the channel maps were convolved to twice the beam size, and the emission greater than 4 $\sigma$ was used as a mask to isolate the emission in the channel maps to the butterfly pattern. Additional clipping removed the undersampled Galactic emission. A primary-beam correction was applied. The channel cube was Hanning smoothed in velocity across three channels, and the emission greater than 1.2 $\sigma$ (1.3 mJy beam$^{-1}$) was used to produce the integrated intensity map.

The observed average H\textsc{i} column density, $N_{\text{H}\textsc{i}}$, in the entire map is $4.7 \times 10^{20}$ cm$^{-2}$, based on a total flux of $S_{\text{H}\textsc{i}} = 2.2 \times 10^{3}$ Jy km s$^{-1}$. The total H\textsc{i} mass imaged in this map is $M_{\text{H}\textsc{i}} = 2.1 \times 10^9 M_\odot$, compared with $3.0 \times 10^9 M_\odot$ found by Rogstad et al. (1973), $2.6 \times 10^9 M_\odot$ by Newton (1980a), and $4.6 \times 10^9 M_\odot$ from single-dish observations by Rots (1979) (all corrected for distance).

Considerable deviations from the mean column density are apparent in the numerous structures seen in the disk of IC 342. The peak observed column density is $2.2 \times 10^{21}$ cm$^{-2}$. The arm-interarm contrast varies from 2 to 6, with typical arm column densities on the order of $1.6 \times 10^{21}$ cm$^{-2}$. There is also considerable column density variation for the numerous "holes" seen in the disk. Values range from $2.4 \times 10^{20}$ cm$^{-2}$ down to column densities a factor of 100 smaller. Typical hole column densities are $1.6 \times 10^{20}$ cm$^{-2}$, with regions immediately surrounding the holes at $1.2 \times 10^{21}$ cm$^{-2}$.
To more accurately determine a mean H I column density for IC 342, we need to estimate the amount of missing flux that could not be fully recovered by our estimate of the zero-spacing flux. We do this by comparing our map with Rots’s (1979) single-dish observations. When convolved to the same 10.8 beam size, comparison of our column density contours with those of Rots shows that on average we resolve out $N_{H_I} = 2.3 \times 10^{20} \text{ cm}^{-2}$, or roughly 30% of the flux in the mapped region. Taking the missing flux into account, IC 342 has an average column density $\overline{N}_{H_I} \sim 7 \times 10^{20} \text{ cm}^{-2}$, similar to estimates of the Milky Way average H I column density, $N_{H_I} = 6.2 \times 10^{20} \text{ cm}^{-2}$ (Dickey & Lockman 1990). If we assume a Milky Way value for the H I gas scale height of 120 pc (Burton 1976), the mean H I density is 0.8 cm$^{-3}$. The addition of the under-sampled H I flux ($\theta > 15^\circ$), at a level of $\sim 0.3 \text{ Jy beam}^{-1} \text{ km s}^{-1}$ flux spread over the entire galaxy, is below the first contour in Figure 3 and would not affect the clumpy
appearance of the H I. Correcting for missing flux, inclination, and the He fraction, we obtain a mean gas surface density $\Sigma_{\text{gas}} = 6.5 M_\odot \text{pc}^{-2}$.

3.4. A Kinematic Analysis of the H I Disk: The "Inner" and "Outer" Disks

The intensity-weighted radial velocity and velocity dispersion maps of IC 342 are presented in Figure 4. Fluxes greater than 1.5 $\sigma$ were used to produce both moment maps. The velocity map with contours has the overall "spider" pattern characteristic of a differentially rotating inclined disk. The spiral arms can be recognized in the isovelocity map as distinct kinks in the velocity contours along the spiral arms. There is no indication of warping in the inner 9 kpc (16') radius of the H I disk, since the line of nodes is perpendicular to the isovelocity symmetry axis. Beyond 10 kpc (17') we begin to see a clockwise shift in the line of nodes, indicative of a warped disk. In general, the largest values in the velocity dispersion map coincide with large $N_{\text{H}_2}$. The velocity dispersion peaks near the nucleus at $\sim 35$ km s$^{-1}$, even though the H I column density drops, implying that some gas component other than H I($\text{H}_2$) is contrib-
A Brandt model rotation curve was fitted to the radial velocity map. Derived values for the systemic velocity, dynamical center, inclination, and position angle are listed in Table 1. The rotation curve is plotted in Figure 5, including Newton's (1980a) rotation curve. Considering that Newton's rotation curve was generated from velocities along the major axis only, it is still consistent with ours when one allows for differences in inclination and resolution. The maximum rotation velocity (corrected for 31° inclination), $170 \pm 35 \text{ km s}^{-1}$, is attained at a radius of 4.8 kpc (500'' ± 15''). The total dynamical mass derived from the Brandt model is $M_{\text{tot}} = 1.1 \pm 0.3 \times 10^{11} \, M_\odot$, same as found by Newton (1980a). We note that in our rotation curve the rotation velocity decreases from $\sim 4.8$ kpc (500'') to $\sim 12.6$ kpc (1300''). The rise in rotation velocities between $\sim 12.6$ and $\sim 14.5$ kpc may be because of interaction with a companion (Rots 1979) and may be related to the warp seen in the disk beyond 17'.

The morphology of the velocity residuals, differences between the rotation model and the observed velocities, can...
be used to locate SDW resonances (Canzian 1993). Because of streaming motions along the spiral arms, for a spiral pattern with $m$ arms, there will be $m + 1$ pairs of approaching-receding ($a$-$r$) residual arms outside the corotation radius (CR) and $m - 1$ pairs inside corotation. The corotation radius, $R_{CR} = 4.2 \pm 0.7$ kpc ($7.2 \pm 1.2$) was assigned by determining where the inner bipolar pattern changes into a multiple $a$-$r$ pattern (Fig. 6). This is not a sharply defined region and the assignment of the $a$-$r$ pairs outside of corotation is subject to interpretation (three have been tentatively assigned). Angular velocities, $\Omega$, and epicyclic frequencies, $\kappa$, derived numerically from the rotation curve, along with the assignment of $R_{CR}$, were used to assign the pattern speed, at $40$ km s$^{-1}$ kpc$^{-1}$ ($0.40 \pm 0.06$ km s$^{-1}$ arcsec$^{-1}$), and locate the Outer Lindblad Resonance (OLR) radius, $R_{OLR} = 6.9 \pm 0.9$ kpc ($11.8 \pm 1.6$) (see Fig. 5). No Inner Lindblad Resonance (ILR) is indicated from the angular velocity plot, but the 38" beam provides insufficient resolution for a detailed analysis of the nuclear region. The Turner & Hurt (1992) study of the inner kinematics suggests that, if an ILR exists at all, it lies within the inner 50 pc of IC 342.
Our location of the principal resonances agrees fairly well with the locations found by Elmegreen et al. (1992) determined from optical tracers, $R_{\text{CR}} = 6.0'$ and $R_{\text{OLR}} = 12.3'$. This differs considerably from the location of the corotation resonance $R_{\text{CR}} = 15'$ suggested by Newton (1980b) from an evaluation of the expected amplitude of velocity perturbations across spiral arms.

As we shall see in § 4, since the properties of the disk inside and outside of corotation are markedly different, we shall designate regions with $R < R_{\text{CR}}$ as “inner disk” and $R > R_{\text{CR}}$ as “outer disk.”

4. DISCUSSION

We divide our discussion of the H I disk into an “inner” disk and an “outer” disk based on morphological changes appearing near $R_{\text{CR}}$. Strictly speaking, both lie within the inner portion of the overall H I disk of IC 342 that has a diameter of 80' (Rogstad et al. 1973; M. A. Holdaway & M. P. Rupen 1999, private communication).

4.1. Morphology of the Inner Disk, $R < R_{\text{CR}}$

The appearance of H I in the inner disk is different from that in the outer disk. Much of the arm-interarm contrast disappears, and at lower resolution, it can appear featureless. It is here that we expect the interaction with the molecular gas component and concurrent star formation to be its greatest.

Neutral atomic hydrogen is depleted within the inner 2 kpc (3') of IC 342 but is not entirely absent. This is a common feature of many spiral galaxies (Bosma 1981; Giovanelli & Haynes 1988). For reasons not completely understood, the hydrogen gas changes from a predominantly atomic state in the outer regions to a mainly molecular one, strongly peaked at the nucleus (Morris & Lo 1978; Young...
& Scoville 1982; Sage & Solomon 1991; Crosthwaite et al. 2000). The two phases have equivalent azimuthally averaged surface densities in IC 342 at a radius of 3 kpc (5'). The distribution of CO and its relation to H i in IC 342 will be treated in a separate paper.

The dynamical center (Table 1) determined from the kinematics of our observed H i disk is offset by 15° north and 4° east from center of the H i hole at $\alpha = 3^h 46^m 49^s 3$, $\delta = 68^\circ 5^\prime 7\arcmin$, which is coincident with the nucleus. However, without a better determination of the distribution of the missing H i flux, this is not a secure result. Both the 100 $\mu$m and 21 cm continuum peak at the centroid of the H i hole ($\alpha = 3^h 46^m 49^s 1$, $\delta = 68^\circ 5^\prime 2\arcmin$ and $\alpha = 3^h 46^m 48^s 4$, $\delta = 68^\circ 5^\prime 48\arcmin$, respectively).

In Figure 7, we compare an optical image (contours), far-IR 100 $\mu$m (contours), the location of H ii regions from Hodge & Kennicutt (1983; points), and 21 cm continuum (contours) with our H i integrated intensity maps. All show some degree of spiral structure along with a bifold “bar” symmetry. The optical image of IC 342 contains a prominent lens, or “fat” or “boxy” bar, 30 $\times$ 18 kpc (5' $\times$ 3', P.A. $\sim$ $-15^\circ$). The 100 $\mu$m map contains a central bar aligned with the fat optical bar. The 21 cm continuum map also contains a bar that leads the far-IR bar by 10° (counterclockwise rotation). While the H i velocity residuals map (Fig. 6) inside of corotation has the single approaching-receding arm pair pattern expected for a $m = 2$ mode SDW, the pattern is distinctly bipolar with predominantly negative residuals to the northwest and positive to the southeast, an indication of a bar potential. This large-scale bar has no signature in H i surface density.

Beyond the central bar structures but within $R_{CR}$, all of the maps except the H i map show some degree of two-arm spiral structure, starting at the ends of the optical bar’s major axis and winding for $\sim 180^\circ$ with pitch angle $\sim 10^\circ$. The 100 $\mu$m and 21 cm maps trace the two inner spiral arm structure, predominantly the northern inner arm. The weakness of the southern inner arm leads to the illusion of a single arm spiral structure noted by earlier investigators. All of the star formation tracers (thermal, nonthermal, H ii regions) indicate substantial star formation occurring along the leading edge of the northern inner arm. Elmegreen et al. (1992) suggest that a weak $m = 3$ mode is simultaneously present in the disk of IC 342. An examination of their enhanced symmetry images of IC 342 provides an intriguing explanation for the preponderance of star formation tracers located along the northern inner arm. In their analysis of superposed modes, the $m = 2$ and $m = 3$ patterns, with the same pattern speeds, overlap at the location of northern inner arm. The simultaneous passage of two

### TABLE 1

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<th>Property</th>
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<tr>
<td>Hubble type*</td>
<td>Scd</td>
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</tr>
<tr>
<td>Decl. (J2000)*</td>
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<tr>
<td>$S_{HI}$ (with missing flux estimate)</td>
<td>7 $\times$ 10^{20} cm$^{-2}$</td>
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* Obtained from the NASA/IPAC Extragalactic Database.
* Dynamical center based on fit of Brandt rotation model.
* Kinematic parameters from fit of Brandt rotation model.
* Total dynamical mass based on Brandt model fit.
* Newton 1980b, adjusted to a 2 Mpc distance.
density wave patterns increases the concentration of gas in the arm beyond that possible by either mode alone, which then increases the rate of formation of massive stars, which in turn leads to the higher thermal dust emission, higher synchrotron emission, and an increase in the density of H II regions seen along the arm. However, this requires the existence of the $m = 3$ SDW, which we cannot confirm from our H I observations.

Just inside of $R_{CR}$, the two inner arms bifurcate into multiple arms and the strong two-arm pattern disintegrates. The termination of the inner two spiral arm pattern and bifurcation of the spiral arms are both optical signatures of the corotation radius (Elmegreen 1991; Elmegreen & Elmegreen 1995). Beyond the two-arm spiral structure, the 21 cm continuum emission traces the beginning of H I spiral structure. In general, the 21 cm continuum emission lies slightly inside (0.3 kpc or 30") corresponding strong H I arms. The H II regions tend to lie along arms seen in the optical as well as in neutral hydrogen. This displacement of nonthermal continuum and H I arms can be understood if the H I emission is the downstream by-product of star formation. A density wave causes compression and induces star formation as traced by the continuum. Further downstream, the predominantly molecular gas is dissociated by UV from star formation, forming H I arms, which will eventually recombine into molecular form (Tilanus et al. 1988; Tilanus & Allen 1989, 1993). In this case, one expects the inner spiral structure to be better defined by molecular gas tracers such as CO emission (Crosthwaite et al. 2000). Once the optical arms begin to bifurcate, the H I arm structure can be seen as a continuation of the optical arm pattern.

To summarize, within the inner disk, IC 342 undergoes a transition from a bar morphology to a two-arm spiral. These arms ultimately bifurcate in the outer disk, beyond corotation. All of the star formation tracers are primarily contained within $R_{CR}$. H I emission is patchy in the region of the optical lens and the two inner arms. H I features tend to strongly correlate with optical structure outside of the two inner arm region. However, the inner disk can only be completely understood when the molecular gas is included.

4.2 Morphology of the Outer Disk, $R > R_{CR}$

Outside $R_{CR}$, the appearance of the H I disk of IC 342 depends on the scales being considered. On the scale of a few kiloparsecs, a feathery pattern is seen, reminiscent of the flocculent pattern seen in optical images of other galaxies. There are numerous short, parallel, interconnected spiral arm segments, and the disk appears to be riddled with holes and clumps scaled on a variety of sizes. On a slightly larger scale, the two optical inner arms bifurcate into a many-armed pattern that extends beyond $R_{CR}$, and continue to wind intact through large azimuthal angles, but at a much larger pitch angle (≈25°) than the inner two arms. The leading edges of the bifurcating outer arms are outlined by H I emission. As these optical arms fade, they appear to continue in H I, as can be seen in the H I–Digital Sky Survey (DSS) overlay (Fig. 7). The outer stellar/H I spiral arms appear to be continuous, defined by their stellar content near $R_{CR}$ and H I outside of $R_{CR}$. The majority of H I regions lie on the H I arms. H I in these arms is no longer predominantly downstream but rather coincident with other spiral arm tracers, indicating that dissociation of H$_2$ plays a less dominant role in the appearance of the H I disk than it does inside of $R_{CR}$.

Outside of 6 kpc ($10'$), the ≈2–5 kpc–long H I arm segments appear to be loosely organized in a four-arm pattern. The southeastern arm is twice as broad (4 kpc) and twice as massive ($2.2 \times 10^8 M_\odot$) as the other three large-scale arms. Although we have some evidence for an $m = 2$ mode SDW with an OLR at ≈7 kpc ($12'$), it is difficult to explain the presence of this four-arm pattern between 6 and 15 kpc. A weak $m = 4$ SDW with a completely different pattern speed...
we take the inner termination of the four-arm pattern to be interpreted as a tight winding of the four outer arms. If absent (Rots et al. 1990). The four large-scale spiral arms in IC 342 are comprised of multiple, parallel, interconnected, shorter arm segments. For comparison, the two H I arms of M51, while lumpy, appear to be discrete structures.

It is instructive to consider how the appearance of the H I disk would change if IC 342 was viewed with the same resolution but at a greater distance, similar to M51 (10 Mpc) or NGC 4414 (18 Mpc). When convolved to a 3’ beam size (Fig. 7b), the IC 342 H I integrated intensity map takes on the appearance of a thick, lumpy ring with four spiral arms beyond the ring. The appearance of the ring is similar to that of H I in the flocculent galaxy NGC 4414 (Thornley & Mundy 1997). Alternatively, the H I ring in IC 342 might be interpreted as a tight winding of the four outer arms. If we take the inner termination of the four-arm pattern to be the location of the ILR for an $m = 4$ mode, a pattern speed of $\sim 25$ km s$^{-1}$ kpc$^{-1}$ and $R_{\text{cr}} \sim 7$ kpc are implied.

The overall impression is that a SDW, although clearly present, is not the primary driver for fine-scale structure in the H I disk, which is extremely filamentary and flocculent. This filamentary and flocculent H I appearance can only be seen because IC 342 is so nearby; it would not be apparent in a galaxy as distant as M51, unless imaged at correspondingly higher angular resolution.

4.3. Fine H I Structure in the Disk of IC 342: Shells or Flocculent Arms?

We are still left with the necessity to explain much of the smaller scale structure seen in the H I arms, the numerous H I spurs, “holes,” and spaces between the spiral arm segments. We consider three possibilities for this fine structure.

First, the “holes” are shells created by multiple supernovae. The 0.4 to 1 kpc range of size scales for the H I holes is similar to that found in the Milky Way (Heiles 1979). H I...
Fig. 7.—IC 342 emission morphology comparisons. (a) HI integrated intensity in gray scale range from 0 to 3.2 Jy beam$^{-1}$ km s$^{-1}$, with uncalibrated contours of the DSS image. The white ovals bound the probable location of corotation. (b) HI integrated intensity map convolved to a 3' beam size in order to display large-scale features. Gray scale ranges from 0 to 35 Jy beam$^{-1}$ km s$^{-1}$. (c) HI integrated intensity with IRAS 100 μm HIRES contours and the location of HI regions. Contours are at 30, 45, 60, 90, 225, and 650 MJy sr$^{-1}$. The IRAS 100 μm HIRES map was produced by 200 iterations of the maximum correlation method. The effective beam varies over the HIRES map with an average 88$''$ x 70$''$ FWHM and position angle of 62$. Squares mark the locations of HI regions as traced by Hz emission (Hodge & Kennicutt 1983). (d) HI integrated intensity with 21 cm continuum contours. Contours are at 0.001, 0.003, 0.005, 0.01, and 0.05 Jy beam$^{-1}$.

studies of Holmberg II (Puche et al. 1992), M31 (Brinks & Bajaja 1986), M33 (Deul & den Hartog 1990), and NGC 2403 (Thilker, Braun, & Walterbos 1998) find similar results. The most reliable way to identify such holes is through their kinematic signatures. Specifically we looked for evidence of midplane, kinematic, “hollow” shell structures (“type 3” structures defined and used by Brinks & Bajaja 1986 and Deul & den Hartog 1990). We examined spectra taken from the channel maps at “hole” locations for multiply peaked profiles. We examined the maps at hole locations for a pattern of emission at the location of a “hole” in a channel, followed by one or more channels with no or lower emission, followed again by a channel with emission. That is, we looked for “caps” of an expanding shell in velocity space. Another indicator for SN shell candidates is a ring of H II regions surrounding a hole. Such a pattern would be expected from a second generation of star formation occurring in the compressed gas of the shell.

Our best candidates are the three “shells” shown in Figure 8, located just to the west of the nuclear region. The holes have radii ~0.9 kpc (1.5'). They are surrounded by H II regions, as seen in Hz, occurring at the shell boundary, and the holes occur at only one velocity channel. In order to estimate the energy required to produce these holes via SNR expansion, we use the expression derived from SN expansion models (Chevalier 1974; Heiles 1979):

$$E = 5.3 \times 10^{43} n_0^{1.12} R^{3.12} V_{sh}^{1.4},$$
Fig. 8.—H I “shell” candidates in IC 342 channel maps. Four channels of emission in the vicinity of a H I “hole” are shown. Small squares are locations of H II regions as traced by Hα emission (Hodge & Kennicutt 1983). The “shell caps” are seen in the extreme velocity channels.

where \( E \) is the energy (ergs), \( n_0 \) is the average density (cm\(^{-3}\)), \( R \) is the shell radius (pc), and \( V_{sh} \) is the shell expansion velocity (km s\(^{-1}\)). The mean energy required to produce expanding shells of this size is \( 3.2 \times 10^{53} \) ergs, which we regard as a lower limit since we have not adjusted the density for contributions from the molecular gas content, which increases the average density by a factor of \( \sim 2 \) at the locations of these holes. For Type II SNe ener-
gies, on the order of \( 10^{51} \) ergs, we need several hundred SNe to produce the holes examined here.

We have four arguments against an SN origin for the H I holes:

1. Most of the holes do not show the kinematic signatures we would expect for SN-generated holes. While there is some evidence for an expanding shell at the previously men-
tioned locations, we lack similar convincing evidence at the locations of most of the holes. What we find is decreased emission at the location of a hole with the peak emission in the hole at the center channel of the velocity spread. The majority of the holes have singly peaked spectra centered at the mean radial velocity for that portion of the disk. The peaks of the hole spectra are not displaced in velocity from surrounding regions. This indicates that we are not simply looking at a shell that has “blown” out of one or more surfaces in the gas plane.

2. Most of the H II regions are not located where they are expected for wind-driven holes. Puche et al. (1992), examining holes in Holmberg II, and Thilker et al. (1998), studying expanding shells in NGC 2403, found that in general the smaller H I holes were filled with H$_\alpha$ emission, while H$_\alpha$ was found at the edges of the larger ones. We do not see this correlation between H$_\alpha$ and H I holes (Fig. 7c). H II regions seem to simply line up along the optical and H I spiral arm and increased column density features, suggesting that star formation is occurring at the locations of large H I clouds as might be expected.

3. Too many (greater than 300) massive stars (assuming the high end of the Type II SNe energy range, 10$^{51}$ ergs) are required to produce holes in regions of the disk where there is no evidence for the required level of star formation. The thermal (100 $\mu$m), nonthermal (21 cm continuum), and ionized gas (H$_\alpha$) tracers of massive star formation fail to the limits of detection at radii where holes in the H I disk are still prominent (Fig. 7). The holes in the outer disk are of sizes comparable to those located in regions where massive star formation tracers exist. Specific examples include the holes located at (J2000): $\alpha = 3^h 45^m 04^s$, $\delta = 67^\circ 58' 56"$; $\alpha = 3^h 45^m 42^s$, $\delta = 68^\circ 12' 51"$; $\alpha = 3^h 47^m 48^s$, $\delta = 68^\circ 18' 32"$; $\alpha = 3^h 48^m 28^s$, $\delta = 68^\circ 01' 44"$; $\alpha = 3^h 48^m 48^s$, $\delta = 68^\circ 05' 34"$

4. The strongest argument that these large holes are not wind driven is the response to differential rotation. Shearing timescales are too short for wind-driven holes to retain their shapes. We consider initially spherical, 10 pc–radius shells placed at galactic radii $R = 2, 5$, and 8 kpc. In lieu of any measurement of an expansion rate for the holes in IC 342, we assume a 12 km s$^{-1}$ expansion rate, based on the mean calculated for type 3 holes in M33 (Deul & den Hartog 1990). The effect of differential rotation on the appearance of the shells as they expand in a face-on disk, with IC 342’s rotation curve, can be seen in Figure 9. The time required for shells to uniformly expand to the 0.5 and 0.9 kpc radii of our two previously mentioned holes is $\sim 35$ Myr and greater than 70 Myr, respectively. Shells in the $R = 2–5$ kpc range will be severely sheared in these time frames. Typically, 30 Myr is a sufficient timescale to severely distort an expanding shell.

Undoubtedly the wind and especially the SN-driven shells would expand at much higher rates early in their evolution, which reduces the shearing time frame and subsequent distortion of the hole (Chevalier 1974; Chevalier & Gardner 1974; Brinks & Bajaja 1986; Deul & den Hartog 1990; and references therein). The initial expansion rate is expected to slow substantially after a mass of the ambient medium equivalent to the ejected SN mass is swept up. A simple calculation, assuming 20 $M_\odot$ ejected and a 800 km s$^{-1}$ expansion rate, shows this occurs within a 10 pc radius on the order of 10$^4$ yr, an insignificant fraction of size and timescales for our holes. If these are wind-driven shells, the current expansion velocities must be lower than the 10 km s$^{-1}$ channel width of our H I data, and the shell would have had to have been expanding over timescales comparable to those calculated here.

We considered other forces that might lead to less elongated shapes for the holes. The azimuthal expansion velocities may be less than the radial expansion velocities as the distance to discrete driving sources increases faster in the shearing direction. While this would lead to a more spherical shape for a hole, at least over the lifetime of the energy sources, the age of the holes is several times larger than the age of the OB associations needed to drive the shells (assuming that the self-regulatory nature of massive star formation prohibits a subsequent generation of OB stars at the same location). Tidal acceleration, $V^2/R$, might lead to

![Fig. 9.—Expanding H I holes in a differentially rotating disk. This sequence of frames illustrates the appearance of shells expanding at a uniform rate of 12 km s$^{-1}$ in a rotating disk whose rotation curve defined by the Brandt model solution derived for IC 342. The disk is viewed at a face-on inclination ($i = 0^\circ$). The holes are initially spherical shells of radius 10 pc. Each point on the surface of the shell is allowed to expand in its initial direction while being sheared by differential rotation. Contours of constant galaxy radius are supplied, and rotation is counterclockwise. Each frame is labeled with the number of years elapsed from the initial 10 pc–radius hole.](image-url)
increase the affected area along the gas arms and cannot in itself account for the majority of the short radially directed structure seen in the disk.

Third, the flocculent H I structure is the result of instability in the gas disk. In this case the holes are artifacts, not unlike the voids seen in simulations of an initially homogeneous gas that is allowed to gravitationally collapse. We look for evidence that this is actually the case. Toomre (1964) specified a critical wavelength, \( \lambda_{\text{crit}} \), which defines the size scale for the onset of unstable structure in a differentially rotating disk,

\[
\lambda_{\text{crit}} = \frac{4\pi^2 G \Sigma_{\text{gas}}}{\kappa^2}.
\]

Over the range of 4–8 kpc, the surface density of H I does not vary substantially, \( \Sigma_{\text{HI}} \approx 8 M_\odot \text{pc}^{-2} \), while the epicyclic frequency, \( \kappa \), steadily declines (see Fig. 5). As a result, if instabilities in the gas disk are the primary cause of structure, then we expect to see size scales for gravitationally bound gas on the order of \( \lambda_{\text{crit}} \) and an increase in the maximum size of the gas clumping at larger galactic radii.

To arrive at an estimate of the clumping scale, unbiased by the confusing shapes, we measure the lengths of clump structures by their azimuthal extent (arclength) above a specified threshold \( \Sigma_{\text{avg}} \), at a given radius. This ignores the pitch angle of arm segments and subclumping within an already dense structure. Because the overall pitch angle is low, 25°, the azimuthal measurement yields scales close to the major-axis lengths of subclumps within an arm segment formed by a bead of clumps. When measured over the entire outer disk, \( R > 5 \) kpc, any trends in the clumping scales with radius should become apparent. We corrected the integrated intensity image for inclination and missing flux and made polar plots of the deprojected gas disk, and then we computed the average intensity at a given radius. We then counted the number and size of gas clumps along that radius that exceeded \( 1.4 \Sigma_{\text{avg}} \). While the 1.4 \( \Sigma_{\text{avg}} \) selection factor was somewhat arbitrary, it was the largest value that did not severely flatten the spectrum of sizes into beam-sized clumps but was still well above the mean surface density.

Using the epicyclic frequency \( \kappa(R) \) and a smoothed curve for the mean gas surface density, \( \Sigma_{\text{avg}}(R) \), we compute \( \lambda_{\text{crit}}(R) \). This \( \lambda_{\text{crit}} \) does not take into account the stellar content of a galaxy’s disk. From a two-fluid stability analysis, Jog & Solomon (1984) have shown that there is an increase in the effective \( \Sigma_{\text{gas}} \) when the gas is embedded in a higher surface density stellar disk. They argue that much of the “messy distribution” of spiral arm features can be attributed to randomly occurring two-fluid gravitational instabilities. In this case, the numerous arm segments are material arms rather than the coherent large-scale arms expected from a SDW. They found that the effective \( \Sigma_{\text{gas}} \) was increased by a factor of \( \sim 3.5 \) for regions of the disk where \( \Sigma_{\text{gas}}/\Sigma_{\text{stars}} \approx 0.1 \). We expect this effect to be more pronounced at the inner (4 kpc) end of our radius range, where the stellar content of disk is still apparent in the DSS image (Fig. 7). By 8 kpc, the stellar contribution to the disk is less obvious and the H I surface density becomes the dominant contributor to the total disk surface density. The measured spectrum of clump sizes can be expected to be a little closer to a two-fluid wavelength, 3.5\( \lambda_{\text{crit}}(R) \) at 5 kpc, and closer to \( \lambda_{\text{crit}}(R) \) at the disk extremities. A more accu-

![Graph](image-url)

**Fig. 10.**—IC 342 azimuthal clump sizes and \( \lambda_{\text{crit}} \). Plotted here are the azimuthal sizes of H I gas condensations vs. radius. A clump is defined as a region in which the contiguous surface density, \( \Sigma_{\text{clump}} \), remains greater than 140% of the azimuthally averaged surface density, \( \Sigma_{\text{avg}} \), at that radius. Individual clumps sizes are indicated by diamonds. The long-dashed line is \( \lambda_{\text{crit}} \) at that radius; the short-dashed line is the same but includes a gas amplification factor derived from a two-fluid analysis of galactic disks.

an elongation of hole shapes in radial dimension. But this would only be effective for holes in the inner 1.2 kpc (2′) galactic radius, the region of the rising rotation curve. Outside 1.2 kpc, the rotation curve flattens, and the difference in tidal acceleration across the hole will be negligible. In short, although there are many uncertainties in this model, the effects of shear cannot be avoided.

Second, the H I “holes” are the result of low or negative shear that creates “feathery” features projecting perpendicularly from existing gas arms. Balbus (1988) showed that there are preferred directions for the growth of perturbations in spiral arms (along the arms and perpendicular to the arms). The relative growth rates for perturbations are modified in regions of strong compression, favoring growth perpendicular to the arms. Tightly wound, growing wave crests can be distorted by a changing shear direction. Either case promotes the formation of “spurs” and “branches” and an overall “feathery” appearance. In the case of IC 342, “holes” are then the low-density regions between arms and spurs, beam-smeared into rounded elliptical and circular shapes. Shear along a spiral arm, \( A_{\text{arm}} \), differs from the average shear, \( A_0 \) (Oort’s constant A) by

\[
A_{\text{arm}} = A_0 \left( 2 - \frac{\Sigma_{\text{arm}}}{\Sigma_0} \right),
\]

where \( \Sigma_{\text{arm}} \) is the surface density along the arm and \( \Sigma_0 \) is the average. Assuming that an “epoch of negative shear” when the H I arm density distribution was substantially different did not exist, only a small fraction of gas arms are candidates for spurring because of negative shear. Nearly all of these lie at large radii, \( R > 6 \) kpc, and are located in patches along densest parts of arm structure. Including areas of low shear, those less than 0.05\( A_0 \), does not substantially
rate assessment of \( \lambda_{\text{crit}}(R) \) requires measurements of the stellar component of the disk that are not currently available.

Figure 10 displays the results. The size of the individual clumps, the average size, and the calculated value of \( \lambda_{\text{crit}} \) as well as of 3.5\( \lambda_{\text{crit}} \) are shown. We see a trend to azimuthally clump on larger scales at larger galactic radii. The largest clump sizes are bounded by \( \lambda_{\text{crit}} \) and 3.5\( \lambda_{\text{crit}} \). The increase of H I arm segment or clump width with galactic radius is consistent with the interpretation of the holes in the outer disk of IC 342 being the voids in between self-gravitating arm segments. If the voids form on the same timescales as the largest clumps, they form in less than a rotation period, typically 10 Myr for IC 342 (Toomre 1964). On these timescales, the voids would be less likely to show shearing effects compared to SN/wind-driven holes, which require larger timescales to reach the same size.

5. CONCLUSIONS

We have presented H I maps of the nearby spiral galaxy IC 342 with better resolution (38') than previously available. We find a mean column density \( \overline{N}_H_I = 4.7 \times 10^{20} \) cm\(^{-2} \). The mean column density becomes \( 7.0 \times 10^{20} \) cm\(^{-2} \) when an adjustment for missing flux is taken into account. Analysis of the column density and spatial scale for the missing flux indicates that the structures seen in the H I disk of IC 342 are real. Considerable structure is seen in the disk in the form of spiral arms and "holes" with typical column densities \( 1.6 \times 10^{21} \) and \( 1.6 \times 10^{20} \) cm\(^{-2} \), respectively.

A kinematic analysis of the H I disk allows us to locate the corotation radius at 4 kpc for the inner two-arm SDW. The properties of the H I disk inside and outside of corotation are sufficiently different to warrant distinguishing between the "inner" (\( R < R_{\text{CR}} \)) and "outer" disk (\( R > R_{\text{CR}} \)).

Within the inner disk, H I is depleated relative to the mean disk H I column density, known to result from a change in the gas state from an atomic one to a molecular one. While no large-scale bar is seen in the H I surface density, the kinematic signatures of a bar are seen in the velocity residuals. The large-scale bar can be seen in the 21 cm continuum and 100 \( \mu \)m far-IR and at optical wavelengths as a lens or "fat" bar. An \( m = 2 \) mode SDW is detected in the velocity residuals, and an inner two-arm spiral is seen in the previously mentioned tracers. H I downstream of the non-thermal continuum in the inner disk indicates this H I is dissociated molecular gas resulting from star formation in the inner arms. The \( m = 2 \) mode pattern does not propagate to the outer disk. Instead, it bifurcates into a multiple-arm pattern in the vicinity of \( R_{\text{CR}} \). All of the strong star formation tracers are contained within \( R_{\text{CR}} \).

In the outer disk, the H I gas disk has a flocculent appearance, with short spiral arm segments, interconnected by "spurs" and filled with "holes." When the pattern is compared with the bifurcating optical arms, the H I segments can be seen as continuations of stellar arms out to larger radii. Well beyond \( R_{\text{CR}} \), the flocculent H I arm pattern begins to organize itself into an overall four-arm spiral pattern that extends beyond the OLR for the interior \( m = 2 \) mode SDW.

On a smaller scale, we considered three possible explanations for the rich structure seen primarily in the outer disk: (1) the holes are created by numerous localized supernovae; (2) spurring of gas arms due to negative shear creates "feathery" arms; and (3) the flocculent arms are gas instabilities and holes are what remains after the formation of flocculent structures. Rotational shearing would tend to distort the spherical shapes in the timescales shorter than that required for the holes, produced by an instantaneous burst of SNe or winds, to reach the observed sizes. There is not enough surface density enhancement in the H I spiral arms to promote negative shear and the subsequent formation of perpendicular spurs. The conclusion most consistent with the available observational data is that the majority of the H I spiral structure represents material arms formed from instabilities in the gas disk. The timescale for the formation of instabilities is a fraction of the rotation period, so the shearing of voids produced in the process will be minimized. The clump size and the change in clump size with radius are close to the size scales predicted from a simple analysis of the gas stability. The formation of material arms from instabilities results in a flocculent appearance. The holes seen in the H I disk are voids left from the formation of material arms.

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