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H I STREAMERS AROUND M82: TIDALLY DISRUPTED OUTER GAS DISK

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ABSTRACT

Our new VLA observations of M82 reveals a triangular central concentration of neutral atomic gas (1.9×10^8 $M_\odot$) and several $\gtrsim 10$ kpc long tidal streamers originating from M82 itself. The coincidence of the beginning of the tidal streamer with the flaring of the optical disk as well as the smooth continuation of the disk velocity field into the H I streamer strongly suggest the *tidal disruption of the disk of M82*, contrary to the widely proposed scenario of tidal stripping and gas accretion from its neighbor M81. The velocity characteristics of H I within M82 are that of disk rotation as seen in CO. The gas kinematics appear complex because of large velocity dispersions that may be due to a tidally induced bar potential and the interaction between the disk gas and the nuclear wind. Closer to the nucleus, the H I features are associated with both optical filaments and dust lanes, and it is suggested that these H I clouds are the sites of reflection and scattering of the light originating from the nuclear region. The extinction characteristics of the dust associated with the H I gas are similar to the Galactic dust and argue against an intergalactic origin for this H I gas.

Subject headings: galaxies: individual (M81, M82) — galaxies: interactions — galaxies: irregular — galaxies: spiral — galaxies: starburst

1. INTRODUCTION

Recent studies of starburst galaxies with high far-infrared luminosity suggest that a large fraction of them have undergone a recent merger or a close interaction with a companion galaxy (e.g., Carico et al. 1990). Numerical studies of gas and stellar dynamics in interacting and merging galaxies show the channeling of the disk gas into the nuclear region of the galaxy—presumably fueling the subsequent burst of star formation—as well as tidal removal of the outer disk material to a larger radius (e.g., Olson & Kwan 1990a, b; Hernquist & Barnes 1991). M82 (NGC 3034, 3C 231) is one of the best-known examples of such a starburst galaxy with high infrared luminosity ($L_{\rm IR} = 3 \times 10^{10}$ $L_\odot$; Telesco & Harper 1980) and a cluster of young supernova remnants in the nuclear region (Kronberg, Biermann, & Schwab 1985). Its close proximity ($D = 3.3$ Mpc; Freedman & Madore 1988) makes it an ideal testing ground for the starburst phenomenon.

Here we chose to study the kinematics and morphology of the atomic hydrogen gas in M82. Previous H I studies of M82 were at low resolutions so that only a large-scale clumpy envelope of gas surrounding the entire M81–M82–NGC 3077 group was found (Cottrell 1977; Gottesman & Weliachew 1977; Appleton, Davies, & Stephenson 1981). With heretofore the best resolution (1′), Crutcher, Rogstad, & Chu (1978) reported a close association between H I and optical features, as well as a bar to the northeast which did not have an optical counterpart. With improved UV coverage and the use of self-calibration, our new VLA[1] study is a twentyfold improvement in sensitivity and a threefold improvement in angular resolution. We identify a system of prominent H I streamers emanating from M82 as well as a first clear view of the H I distribution within the M82 disk.

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

2. OBSERVATIONS AND ANALYSIS

The H I aperture synthesis observations reported here were made with the VLA in the C- (6.5 hr on 1988 March 22) and D- (3.5 hr on 1988 July 17) configurations. The phase-tracking center was $\alpha(1950) = 9^{\rm h}51^{\rm m}43\overset{\rm s}{.}85$ and $\delta(1950) = +69°54'59\overset{''}{.}0$. 3C 286 and 3C 48 were observed for the flux and bandpass calibration while 0831+557 and 0836+710 were observed for short-term gain and phase calibration. The 64 spectral channels span a 3.125 MHz bandpass centered at $V_{\rm LSR} = 270$ km s^{-1} ($V_{\rm HEL} = V_{\rm LSR} - 6$ km s^{-1}) with a spectral resolution of 48.8 kHz (10.3 km s^{-1}). Phase self-calibration (Cornwell 1982) improved the dynamic range of the images by an order of magnitude. The line-free channels ($V_{\rm LSR} = 520 \sim 550$ km s^{-1}) were combined to produce a model of the continuum, which was subtracted from the UV data. An rms noise of 2 and 3 mJy beam^{-1} was attained in each channel using natural weighting in the C- ($\theta_{\rm FWHM} = 18'' \times 17''$) and D-array ($\theta_{\rm FWHM} = 69'' \times 62''$) observations, respectively.

3. RESULTS

Figures 1 and 2 (Plates L1 and L2) show contour maps of the integrated H I flux from the C- and D-arrays overlaid on an R-band CCD image. A total of $(3.5 \pm 0.8) \times 10^8$ $M_\odot$ of H I is detected within the 30′ field centered on M82. Using the same flux to mass conversion of Dickey (1990), the detected D-array H I flux in our study corresponds to $\sim 50\%$ of the total H I flux in the 12′ resolution single-dish observaton by Appleton et al. (1981). The missing flux is largely due to the limited dynamic range (1900:1 for this study) and the short spacing information missing in the D-array data. Combined C- and D-array maps were made but are not included in the discussion here since

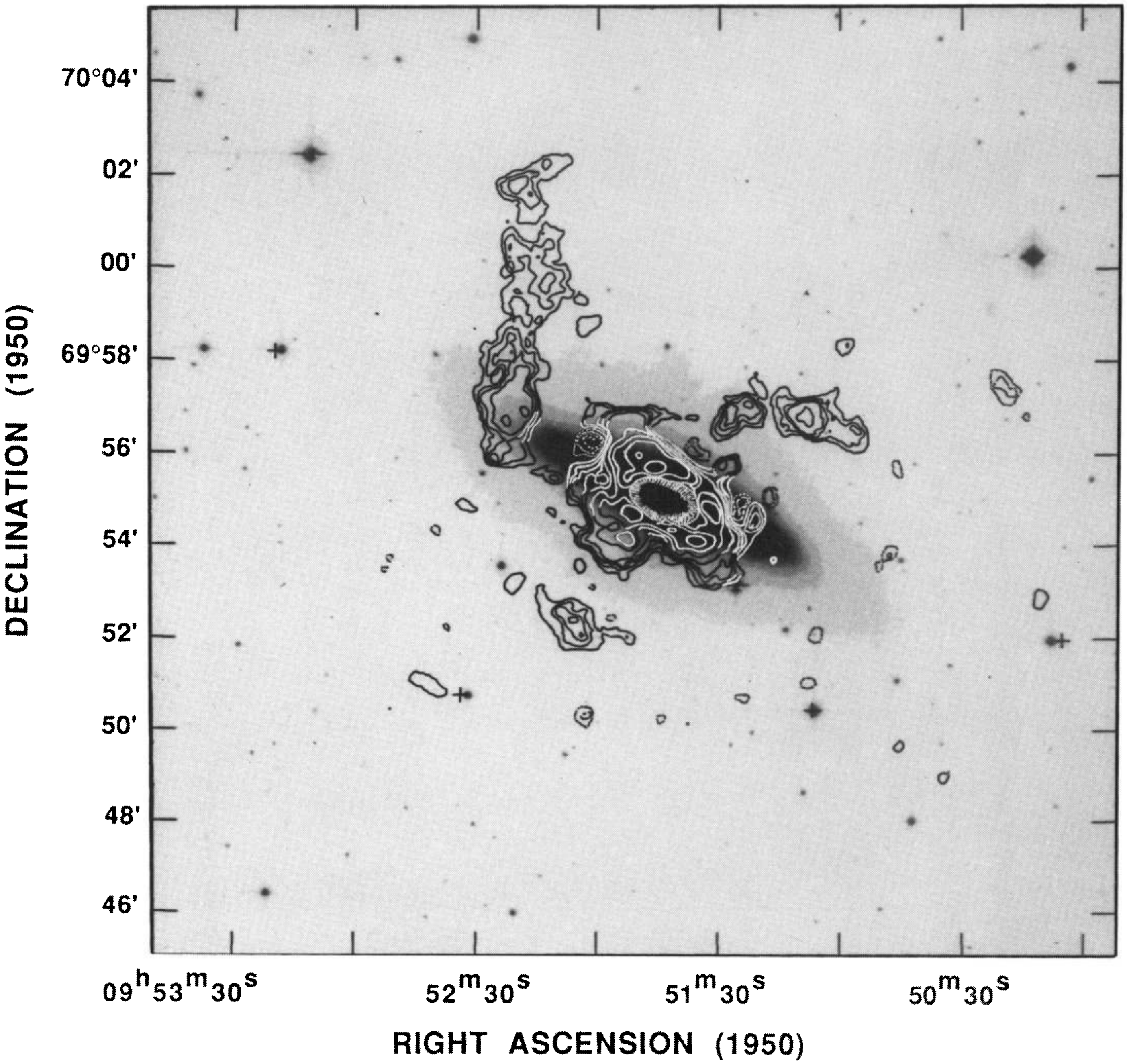

FIG. 1.—Integrated H I flux map from the C-configuration of the VLA in contours (θ_{FWHM} = 18" × 17") over the R-band CCD image of M82. The dotted contours represent absorption while solid contours represent H I column density in 1.8×10^{20} cm^{-2} (50 mJy km s^{-1} $beam^{-1}$) times 1, 2, 3, 4, 6, 10, 15, and 25. The H I gas inside M82 is centrally concentrated and is confined within the low-level isophotes of the optical light. The position angle of the nuclear "ring" seen in absorption is displaced from that of the optical disk by ~20° as is in CO (Lo et al. 1987; Carlstrom 1988) and 2μ (Dietz et al. 1986) and may be due to the nuclear stellar bar (Telesco et al. 1991).

YUN, HO, & LO (see 411, L17)

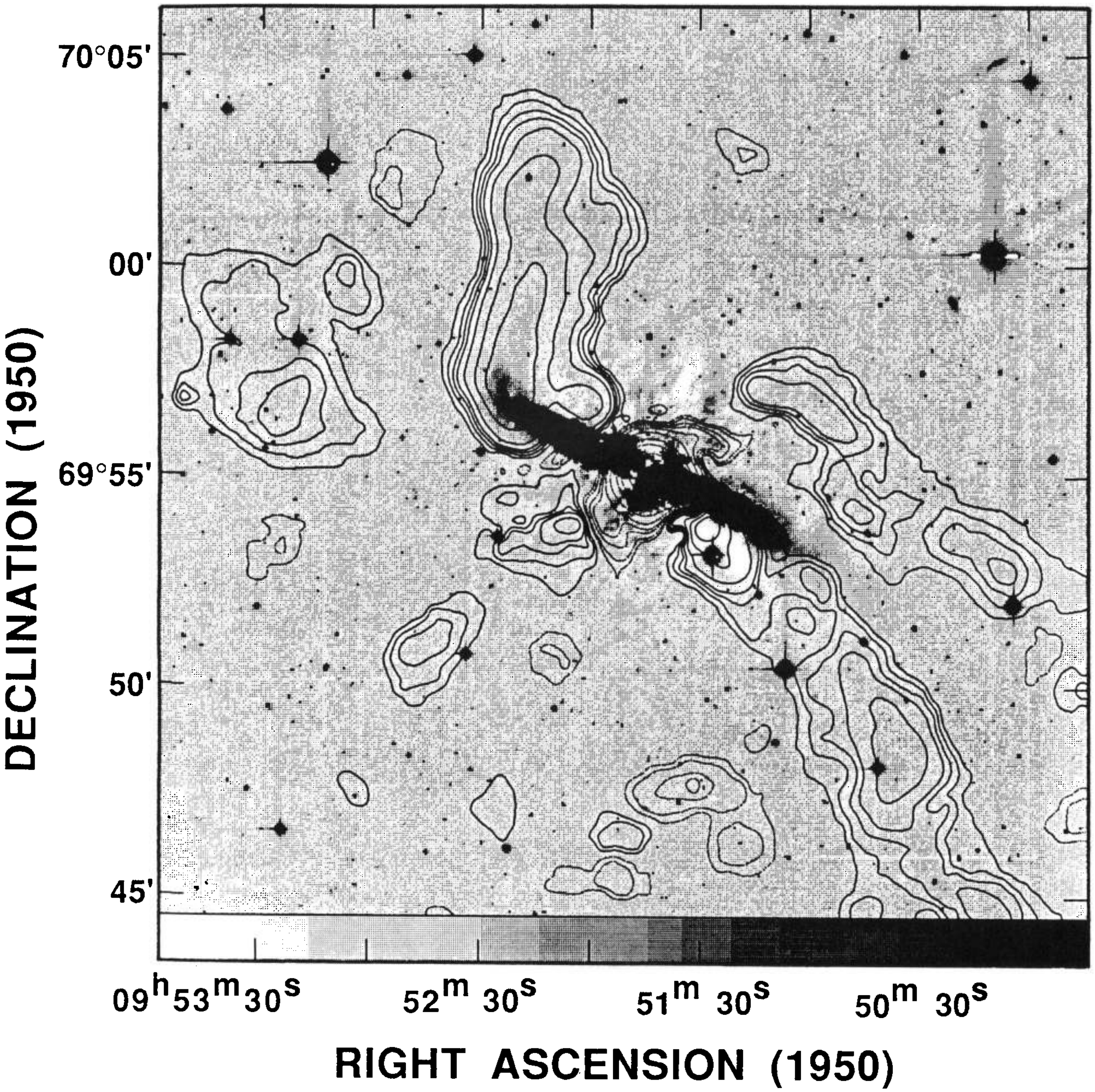

FIG. 2.—Integrated H I flux map from the D-configuration of the VLA in contours ($\theta_{FWHM} = 69'' \times 62''$) over the R-band CCD image of M82, whose extended optical halo is removed by subtracting a 1'.5 × 1'.5 median weight filtered image to enhance the optical filaments and dust lanes. The contour levels correspond to column densities in 2.7×10^{19} cm^{-2} (100 mJy km s^{-1} beam^{-1}) times 1, 2, 3, 4, 6, 10, 15, and 25. The coincidence between the flaring of the optical disk on the NE edge and the base of the northern H I streamer is strongly suggestive of a physical association and the tidal origin. Two-thirds of the flux for the northern streamer seen in the D-array is also detected in the C-array observation, suggesting that this gas is clumpy. The emission from the southern streamer is just below the sensitivity of our C-array observation.

YUN, HO, & LO (see 411, L17 and L18)

TABLE 1

SUMMARY OF H I STRUCTURES

Structure	Projected Angular Size	H I Mass ($M_\odot$)	N_{peak} C-array (cm^{-2})	N_{peak} D-array (cm^{-2})	Note
H I disk	1.′5 × 4.′0	$\gtrsim 1.9 \times 10^8$	9.6×10^{21}	5.0×10^{20}	
Streamer S	$\gtrsim 15$	6.1×10^7	...	2.6×10^{20}	M81-M82 tidal tail
Streamer N	10	6.4×10^7	1.1×10^{21}	5.6×10^{20}	Countertail
Streamer W	10	1.6×10^7	1.1×10^{21}	1.4×10^{20}	
Eastern clump	4 × 5	1.6×10^7	...	1.2×10^{20}	

they did not provide any significant new insight. Nearly all of the H I gas detected in our experiment is found in well-organized gas complexes rather than in a large diffuse cloud as suggested by earlier studies. Table 1 summarizes the physical characteristics of the main features which we further discuss below.

H I *Disk*.—Figure 1 shows that the H I distribution within the optical boundary of M82 is centrally concentrated in a triangular configuration. The atomic gas mass of 1.9×10^8 $M_\odot$ is 10 times smaller than the molecular gas mass found in the same region (Young & Scoville 1984). Unlike other normal disk galaxies, the H I disk is asymmetrical and poorly defined. The H I extent in the minor axis is nearly as great or perhaps greater than the extent in the major axis, while the optical disk appears nearly edge-on ($i = 82$; Lynds & Sandage 1963). Both the morphology and kinematics of atomic gas associated with M82 suggest a severe disruption of the gaseous disk in recent past. The highest measured H I column density is found in the nuclear region, seen in absorption against the extended nuclear continuum emission. The column density deduced from the H I absorption at 18″ resolution ($T_{ex} = 100$ K; see Weliachew, Fomalont, & Greisen 1984), 2.6×10^{22} cm^{-2}, is significantly larger than the peak emission column density found at ~500 pc from the center, 9.6×10^{21} cm^{-2}. The excess H I gas in the nuclear region is likely associated with the "200 pc ring" detected in molecular line observations (Lo et al. 1987; Nakai et al. 1987; Carlstrom 1988).

Streamers.—In the D-array observation, the H I distribution is dominated by several long linear structures (Figs. 2 and 3 [Pls. L2 and L3]). The highest H I column density outside of the optical boundary of M82 is found in the northern streamer ($N_{H\,I} = 5.6 \times 10^{20}$ cm^{-2}). Its associated H I mass of 6.4×10^7 $M_\odot$ is 33% of the total H I found within the disk. The spatial coincidence of the flaring of the optical disk at the northeast end (Fig. 2) and the beginning of the northern streamer is suggestive of a physical association of the H I streamer with the edge of the stellar disk. The northern streamer was in the earlier H I map of Cottrell (1977) and as the northeast "bar" of Crutcher et al. (1978). Our new maps define its structure much more clearly. In addition, we have detected two other streamers. The southern streamer extends out to a large clump of H I gas over 20′ away, well outside the field of view of this experiment. Its average column density is only about one-third of its northern counterpart, but a greater length results in a total mass of 6.1×10^7 $M_\odot$, nearly identical to the northern streamer. A ridge of H I gas is also seen along the minor axis of M82 which continues out to another streamer-like emission structure to the west (see Fig. 2). This streamer is more fragmented, and only the eastern tip near M82 is detected in emission in the C-array map (Fig. 1). Many of the H I peaks seem associated with optical filaments and dust patches as discussed in greater detail below.

4. DISCUSSIONS

4.1. *Disk* H I *and Comparison with Optical Light*

In Figure 2 we see that a patch of heavy dust extinction on the SW side of the optical disk coincides with the base of the southern H I streamer. The heavy dust lane which bisects the optical disk also has a counterpart in the ridge of H I gas running along the minor axis. If this dust lane is interpreted as absorption seen against the smooth stellar background, the measured V-band optical extinction of 1.7 ± 0.2 mag (Yun & Ho 1993) in turn implies H I column density of $N_{H\,I} = (3.4 \pm 0.4) \times 10^{21}$ cm^{-2} using the Galactic conversion of Frerking, Langer, & Wilson (1982). This compares well with the measured value, $N_H = (3\text{–}7) \times 10^{21}$ cm^{-2}, and this agreement implies a galactic (M82) origin for this gas rather than an intergalactic (metal-poor) origin (see Solinger, Morrison, & Markert 1977).

A comparison between the C-array H I map and an optical image reveals a close association of the H I peaks with the prominent optical and dust filaments (Fig. 4 [Pl. L4]). In particular, the brightest optical filament patch on the NW side coincides exactly with the dense tip of the minor axis H I loop. The optical polarization study by Scarrott, Eaton, & Axon (1991) has suggested that nearly all optical light along the optical filaments is scattered light originating from a small but bright nuclear region, and we propose that the atomic gas clumps found along the minor axis may be the material which scatters and reflects the optical light. The optical extinction seen as dust patches is likely associated with the foreground H I gas on the near side of the disk.

The presence of wind-driven gas along the minor axis of M82 has been well formulated by both theoretical and observational works such as Tomisaka & Ikeuchi (1988), McCarthy, Heckman, & van Breugel (1987), Watson, Stanger, & Griffiths (1984), and Seaquist & Odegard (1991). The intensity-weighted mean velocity map (Fig. 5) displays a velocity gradient along the minor axis, which may indicate that a significant fraction of the detected H I interacts with the nuclear wind. The H I complex immediately SE of the nucleus also shows a broad blueshifted line wing up to 200 km s^{-1} (FWZP). Such large line widths may also be consistent with the impact of a wind on the gaseous medium. However, no redshifted gas is found to the NW, and this reflects the asymmetry in the wind geometry or in the H I distribution.

4.2. *Gas Kinematics in a Bar Potential*

As outlined in Figure 6, the S-shaped signature in the major axis velocity-position plot confirms that the disk H I gas partakes in rotation as does the stellar disk (Mayall 1960). The observed H I line width is quite broad, but the overall kinematic signature of H I along the major axis is similar to that of CO (see Figure 6 of Young & Scoville 1984). As noted by

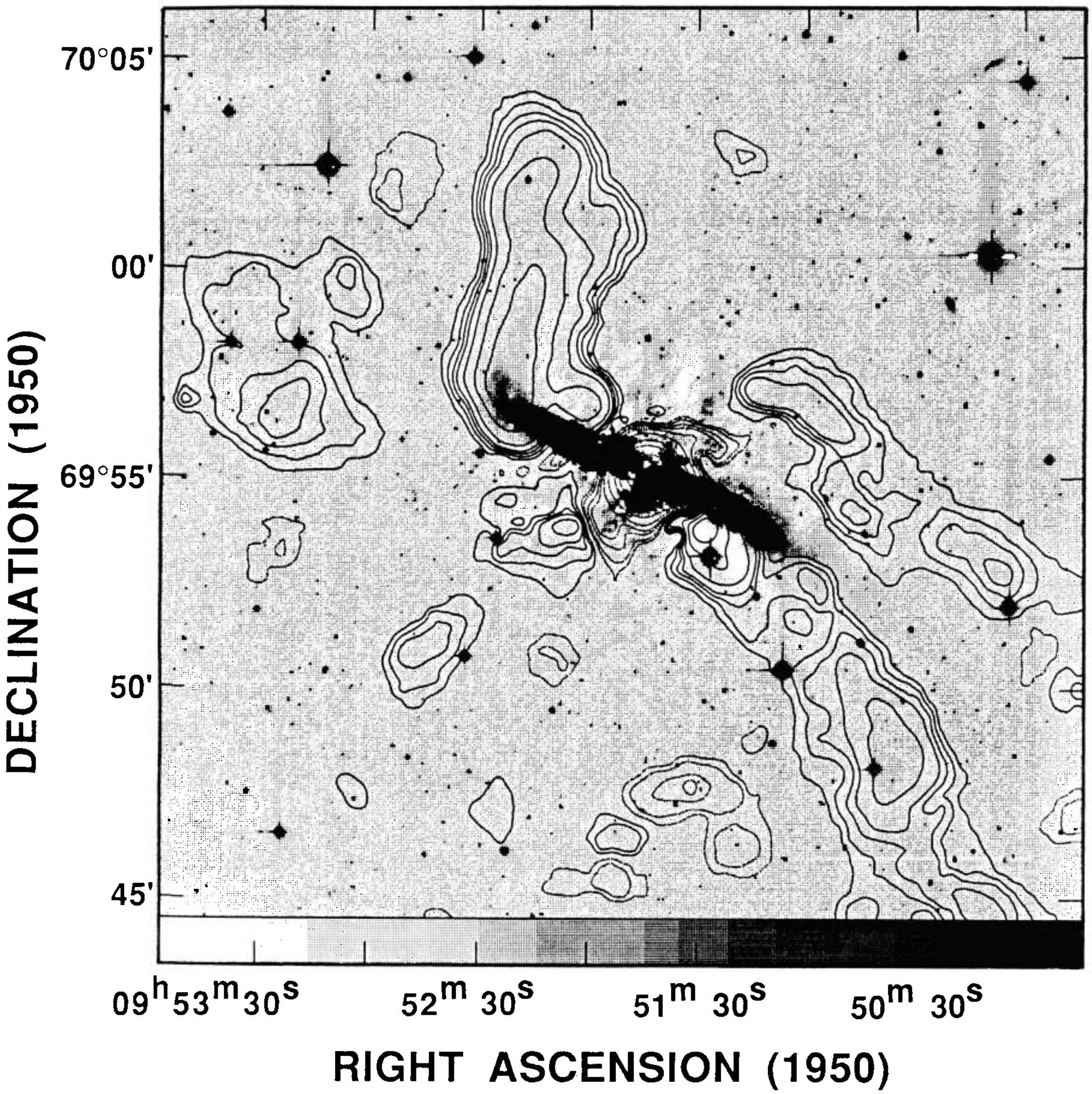

FIG. 2.—Integrated H I flux map from the D-configuration of the VLA in contours ($\theta_{\rm FWHM}$ = 69″ × 62″) over the R-band CCD image of M82, whose extended optical halo is removed by subtracting a 1.′5 × 1.′5 median weight filtered image to enhance the optical filaments and dust lanes. The contour levels correspond to column densities in 2.7×10^{19} cm^{-2} (100 mJy km s^{-1} beam^{-1}) times 1, 2, 3, 4, 6, 10, 15, and 25. The coincidence between the flaring of the optical disk on the NE edge and the base of the northern H I streamer is strongly suggestive of a physical association and the tidal origin. Two-thirds of the flux for the northern streamer seen in the D-array is also detected in the C-array observation, suggesting that this gas is clumpy. The emission from the southern streamer is just below the sensitivity of our C-array observation.

YUN, HO, & LO (see 411, L17 and L18)

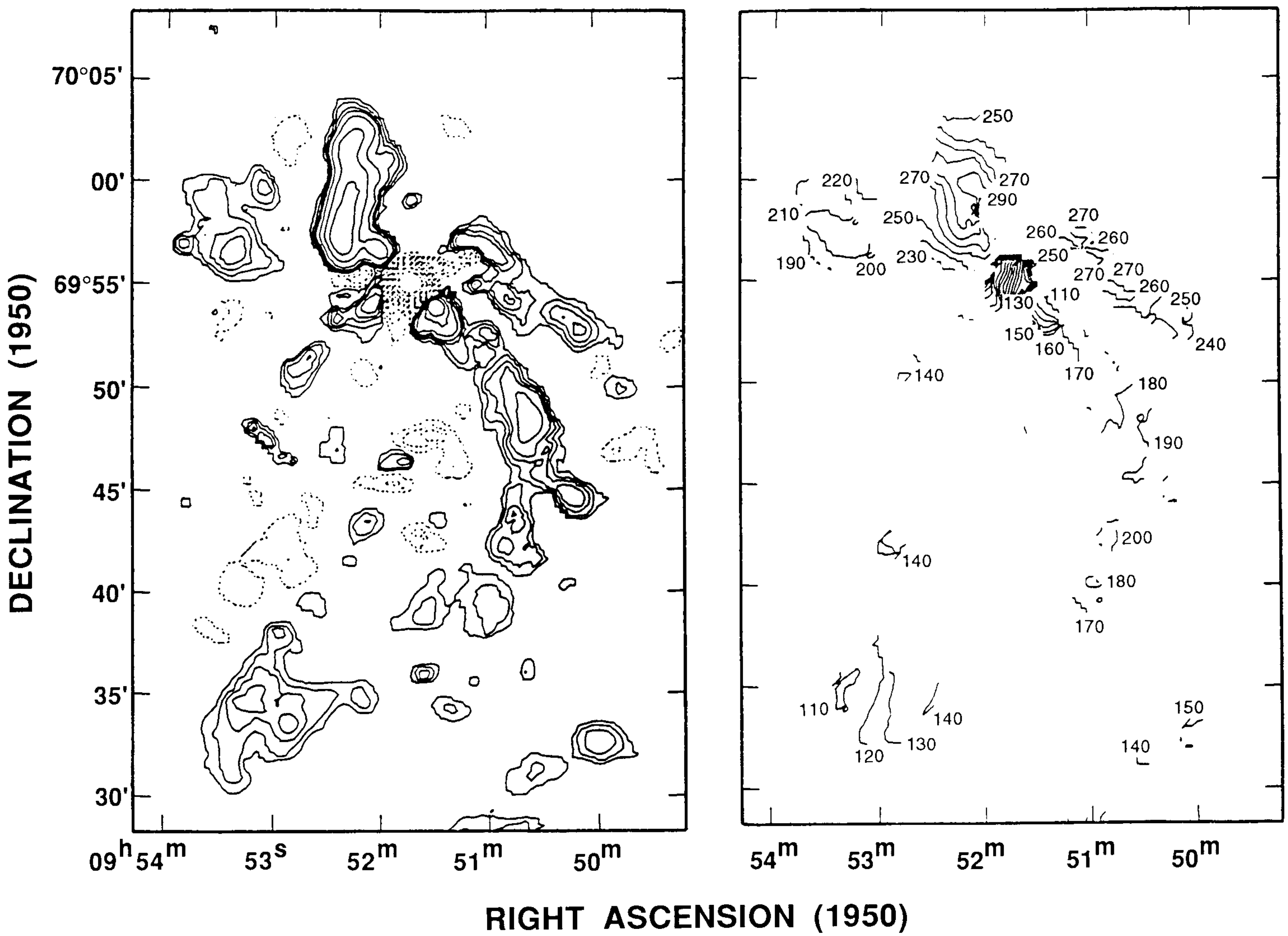

FIG. 3.—Contour map of integrated H I flux and intensity-weighted mean velocity map from the D-array observation. The integrated H I contour levels are identical to Fig. 2. The LSR velocity labels are in km s^{-1}. The disk rotation is dominant only in the inner disk. The overall velocity gradient is along SE to NW, and it is likely a tidally induced radial motion rather than captured gas in a polar orbit as suggested in earlier studies.

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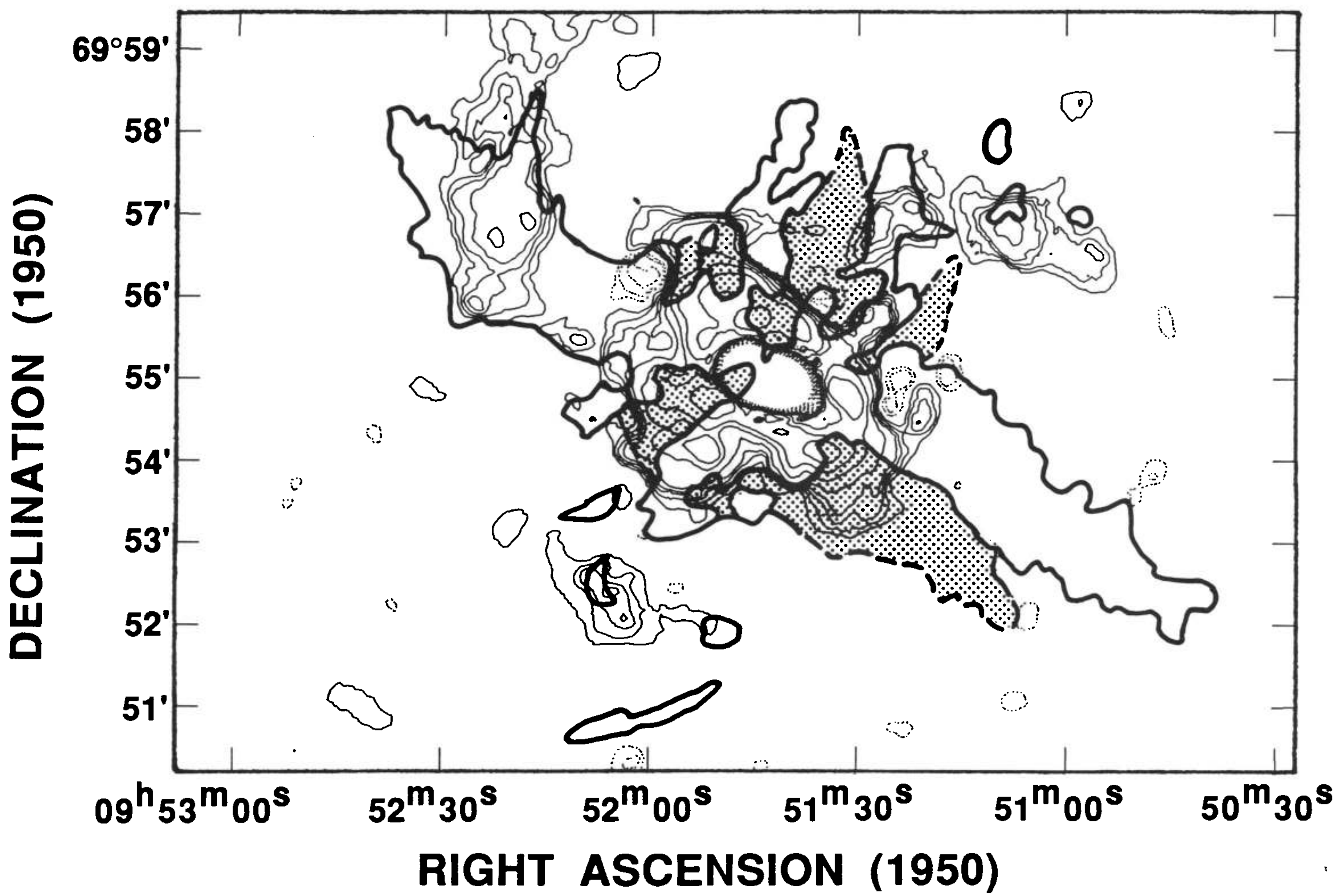

FIG. 4.—Comparison between the C-array integrated H I map and the optical features. The H I distribution is shown in thin contours, identical to Fig. 1, and the 3 σ contour of the optical image described in Fig. 2 is sketched in for the comparison. The shaded area corresponds to the optical dust lanes. The H I peaks are closely associated with both the optical filaments and dust patches. Coupled with the optical polarization study of Scarrott et al. (1991), this observation suggests that the H I clouds are the sites of reflection and scattering of light from the bright nuclear source(s) which is otherwise hidden.

YUN, HO, & LO (see 411, L18)

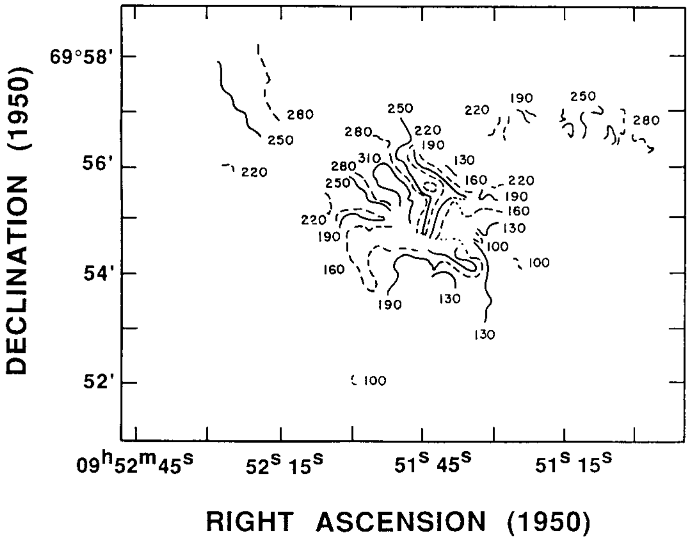

FIG. 5.—Intensity-weighted mean H I velocity map from the C-array observation. The LSR velocity labels are in km s^{-1}. Rotation dominates the kinematics of the central 1 kpc, but the outer regions display a significant nonrotational component, which is probably tidally induced. The minor axis velocity gradient in the immediate surroundings of the nuclear region may be due to the interaction between the nuclear wind and the disk H I gas.

Young & Scoville, however, the observed rotation signature has peculiarities such as a sudden drop in rotation velocity at $R \sim 1$ kpc, which may be interpreted as a falling rotation curve. Sofue et al. (1992) offer an interpretation of Keplerian rotation, implying no massive halo for M82. We note here that gas orbital motions about a bar potential may be yet another explanation for the observed velocity peculiarities. The motivations for this last consideration is that bar formation is an immediate and natural consequence of a tidal interaction (e.g., Noguchi 1988), and Telesco et al. (1991) have already presented observational evidence for a stellar bar in M82.

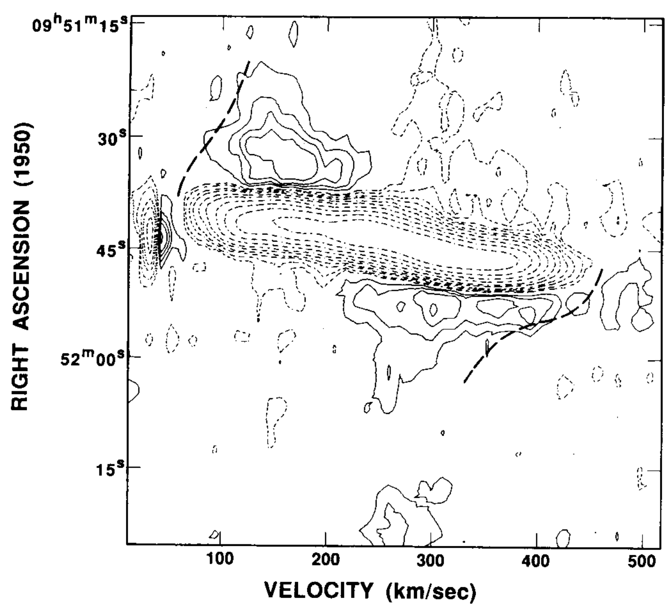

FIG. 6.—Position vs. velocity plot of C-array H I data along the major axis of M82 (averaged over 1' strip). The contours are 1.5 mJy beam^{-1} times -40, -25, -15, -10, -6, -4, -2, -1, 1, 2, 3, and 4. Along the major axis, one second of time in right ascension corresponds to ~ 90 pc. Presence of a large-scale bar potential offers a natural explanation for the sudden drop in the rotation curve (traced in thick dashed lines) at $R \sim 1$ kpc, and counterrotating gas seen in absorption in the zones of avoidance (Quadrants I and III). The best estimate for the systemic velocity based on the emission away from the nuclear region is 210 ± 20 km s^{-1} (LSR).

Binney et al. (1991) infer the presence of a bar in our Galaxy using a gas flow model of Athanassoula (1988) and the observed molecular gas kinematics in the Galactic Center. As noted by Binney et al., when the bar is oriented nearly parallel to the plane of the sky, the observed gas flow velocity along the bar results in a sudden drop in the rotation curve, just as seen in Figure 6 near $R \sim 1$ kpc. This occurs because the outer elliptical orbits ("x_1") are near the apocenter, resulting in observed velocities less than those in circular orbits, while the inner orbits ("x_2") are near the pericenter with observed velocities in excess of the circular orbits. This also nicely explains the apparently counterrotating gas seen in absorption in the zones of avoidance in Figure 6 since parts of the highly elliptical outer gas orbits, when observed at the same viewing angle as above, introduce redshifted line-of-sight velocity components on the approaching side and blueshifted velocity components on the receding side.

While the bar model is qualitative in nature, some important general inferences can still be made. There is a strong dependence on the viewing angle in this model, and the observed characteristics are met only for a narrow range of the bar orientations (see Binney et al. 1991). The stellar bar suggested by Telesco et al. (1991), which has its approaching side toward us and 22° off the plane of the sky, has the correct orientation to mimic the observed sudden drop in the rotation curve. On the other hand, the extent of the proposed stellar bar, 1 kpc long, is insufficient to explain the spatial extent of the counterrotating gas. Therefore, if a bar distortion of the gravitational potential is responsible for the observed kinematic signatures, then it must be at a scale $\gtrsim 2$ kpc, larger than what is apparent in the infrared, and is likely tidally induced.

4.3. *Tidal Streamers*

What is the nature of these streamer-like H I gas structures found around M82? If not bound gravitationally, they should have dispersed in $\lesssim 10^8$ yr if the observed line width is interpreted as the random velocity dispersion. If they are bound, the fragmentation and collapse time scale is also $\lesssim 10^8$ yr unless some other means of support exists. Therefore, they are likely to be transient in nature. The explanation of *tidally captured gas cloud from M81* was first offered by Cottrell (1977) based on his observation of H I gas around M81 and M82 and the numerical results of galaxy interaction by Toomre & Toomre (1972). However, the anchoring of the two main streamers to the stellar disk of M82 is problematical for an accretion model. Even though historically less frequently considered because M82 is an apparently gas-poor dwarf galaxy, *tidal disruption of the outer* H I *disk of M82 itself* appears to be the scenario most consistent with the observations.

The two main H I streamers may be best explained as the *tidal tail* (southern streamer) and the *counter tail* (northern streamer) found in numerical studies such as Toomre & Toomre (1972) and Eneev, Kozlov, & Sunyaev (1973). These streamers have no optical counterpart, but the beginning of the northern streamer coincides with the flaring of the optical disk while the base of the southern streamer coincides with a prominent optical dust patch that traces back toward the inner stellar disk (see Figs. 2 and 4). The velocity field of both streamers also connect smoothly with those of the adjacent disk rotation (Fig. 3), and this is suggestive of a dynamic link between the H I streamers and the M82 disk. The velocity gradient along the southern streamer, 3–6 km s^{-1} kpc^{-1}, is typical of tidal H I structures found in other interacting systems (see Table 3 of van der Hulst 1979) while the northern streamer displays a significantly larger velocity gradient along its length (12 km s^{-1} kpc^{-1}). Interpreting the southern streamer as a tidal tail of strung-out material pointing toward the perturber (M81) and the northern streamer as the countertail made up of a sheet of warped disk (e.g., Fig. 6b2 of Eneev et al. 1973) may explain both the larger velocity gradient and the velocity dispersion ($\Delta V = 60$–80 km s^{-1} for the northern streamer and 30–40 km s^{-1} for the southern streamer) in terms of the crowding of the various kinematic components seen along the line of sight for the countertail. Nearly identical masses further suggest the intrinsic similarity between the two H I streamers.

In hindsight, the disruption of the outer H I disk of M82 is a natural consequence of a tidal interaction. Given that H I in disk galaxies typically extends out to 1–3 times the optical radius (e.g., Bosma 1980; Corbelli, Schneider, & Salpeter 1989), these streamers may have originally been the outer H I disk of M82. Also, assuming the line-of-sight extent is comparable to the projected width, the derived volume density of 0.01–0.1 cm^{-3} for the gas streamers is more characteristic of the outer gas disks of galaxies or tidal plumes than that of intergalactic H I clouds such as the Leo Cloud ($n_H \sim 10^{-3}$ cm^{-3}; Skrutskie, Shure, & Beckwith 1984). It is unlikely, however, that these are the outer spiral arms of M82 since they clearly do not lie in the plane of the disk. Using the numerical results of Toomre & Toomre (1972) and Eneev et al. (1973), Gottesman & Weliachew (1977) speculated that much of the H I gas found around M82 is tidally stripped material from M81. Considering the gas content of the two galaxies, O'Connell & Mangano (1978) first suggested that the gas around M82 may be intrinsic to M82. The anchoring of the streamers to the edges of the M82 disk appears to support this latter model. The improved sensitivity and spatial resolution of our new study should allow a more detailed comparison between the data and the numerical model, and this is the next natural step in our study.

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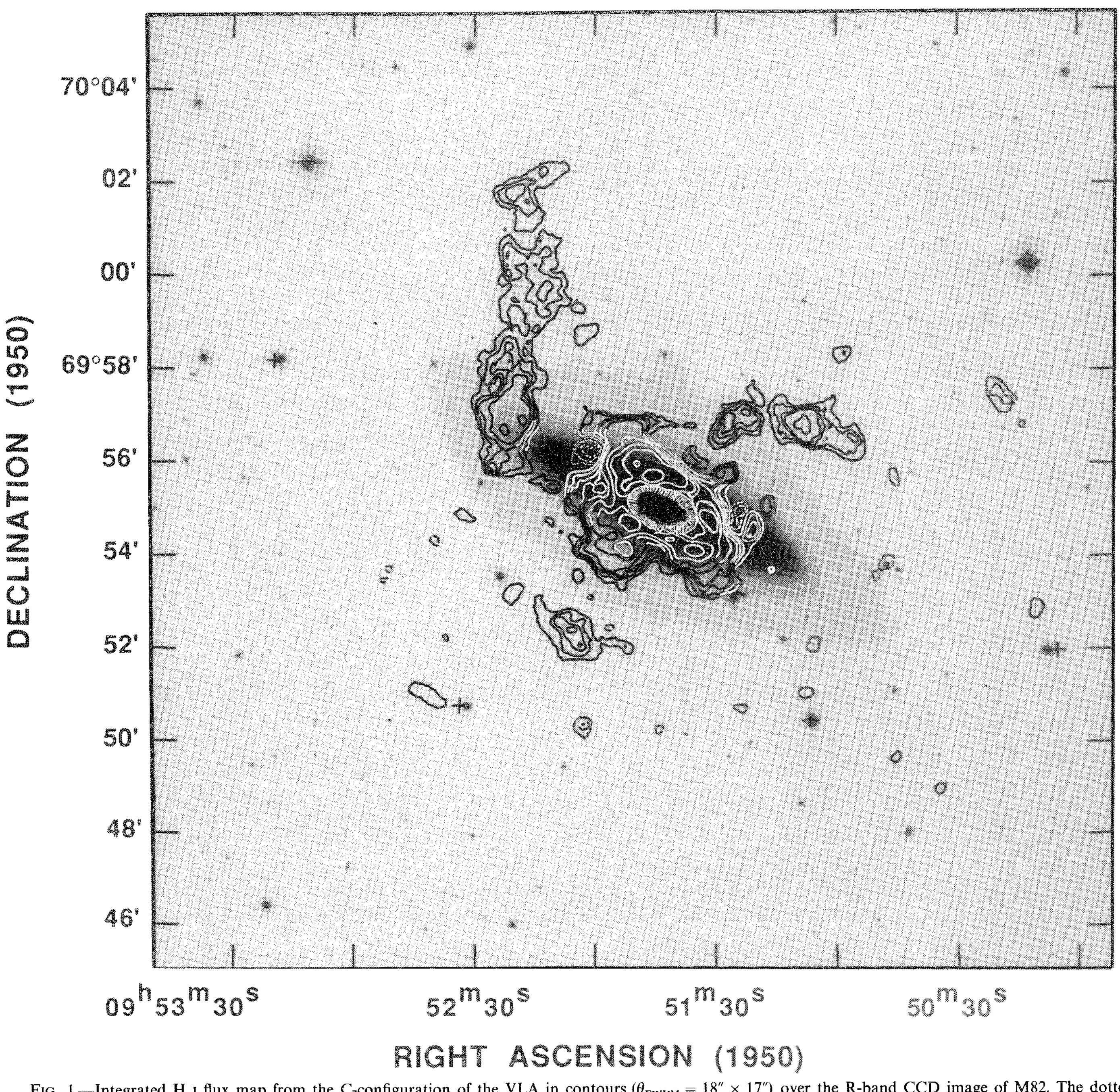

FIG. 1.—Integrated H I flux map from the C-configuration of the VLA in contours (θ_{FWHM} = 18″ × 17″) over the R-band CCD image of M82. The dotted contours represent absorption while solid contours represent H I column density in 1.8×10^{20} cm^{-2} (50 mJy km s^{-1} $beam^{-1}$) times 1, 2, 3, 4, 6, 10, 15, and 25. The H I gas inside M82 is centrally concentrated and is confined within the low-level isophotes of the optical light. The position angle of the nuclear "ring" seen in absorption is displaced from that of the optical disk by ~20° as is in CO (Lo et al. 1987; Carlstrom 1988) and 2μ (Dietz et al. 1986) and may be due to the nuclear stellar bar (Telesco et al. 1991).

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