THE ASTROPHYSICAL JOURNAL, 330:667–671, 1988 July 15

SPIRAL STRUCTURE OF M51: THERMAL AND NONTHERMAL EMISSION

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Received 1987 November 30; accepted 1988 January 19

ABSTRACT

VLA continuum observations of M51 at 6 and 20 cm are combined into two images which are estimates of the thermal and nonthermal emission in the galaxy. These images, each with a resolution of 8″, are compared with two optical tracers of spiral structure: the giant H II complexes and the dust lanes.

The thermal component accounts for ~5% of the total radio emission from M51 at 20 cm, and its distribution correlates well with that of the giant H II complexes. The nonthermal emission can be further separated into an extended "base disk," which contributes 60%, and spiral arms which make up the remaining 35%. The radio "base disk" resembles the optical exponential disk. The nonthermal spiral features correlate well with the dust lanes, and are generally not coincident with the H II complexes.

The shape of the nonthermal spiral radio arms disagrees with that expected from a simple one-component fluid model of the interstellar gas flowing under the influence of a spiral density wave. One possible explanation for this discrepancy is that the interstellar medium in M51 consists of several components and that near the spiral shocks there is a kinematic separation of the cool-cloud component from the component in which the radio-synchrotron emission is embedded.

Subject headings: galaxies: individual (M51) — galaxies: interstellar matter — galaxies: structure — radio sources: galaxies

I. INTRODUCTION

The Whirlpool Nebula, M51 (NGC 5194), is both the first galaxy in which spiral structure has been distinguished optically (Parsons 1850) and the first galaxy outside the Local Group in which radio continuum emission has been detected from the spiral arms (Mathewson, van der Kruit, and Brouw 1972; hereafter MKB). This latter discovery was made by MKB using the Westerbork Synthesis Radio Telescope at 21 cm with a resolution of 24″ × 32″. A prominent two-armed spiral structure was observed; within their resolution limit, the radio ridges are located along the inside edges of the bright optical arms and are generally coincident with the dust lanes. MKB interpreted this striking coincidence as strong evidence both for the existence in M51 of density waves, of the sort first descirbed by Lin and Shu (1964), and also for the nonlinear response of the interstellar gas to these waves (e.g., Roberts 1969). In addition, MKB reported the detection of a "base disk" component accounting for roughly half of the total 21 cm continuum flux density of M51.

Following the discovery paper by MKB, Segalovitz (1976, 1977) observed M51 at 6, 21, and 49 cm. He noted that the "nonthermal" arms (actually the 20 cm arms) follow the dust lanes to within 1 kpc of the nucleus, and that the H I arms are roughly coincident with the continuum arms at 6 cm. Using the same data, van der Kruit (1977) argued that the distribution of 6 cm emission is predominantly thermal, and that the total amount is in agreement with the total Hα emission assuming an internal absorption of ~1.5 mag. Van der Kruit noted further that the 6 cm continuum arms are displaced away from the dust lanes and towards the H II regions and that the radio spectra are nonthermal at the positions of the dust lanes. Although van der Kruit did not further remark on the coincidence of the H I and the 6 cm continuum noted by Segalovitz, this coincidence suggests to us that the H I ridges in M51 are more closely associated with the strings of giant H II complexes than with the dust lanes. New H I observations of M51 made with the Westerbork telescope indeed confirm this correspondence of H I and H II in major segments of the spiral arms (Tilanus and Allen 1988) similar to the situation first found in parts of M83 by Allen, Atherton, and Tilanus (1986). Allen *et al.* have proposed that the H I in these arm regions is predominantly a product of dissociation of H_2 in the neighborhood of the giant H II complexes. Lo *et al.* (1987*a*) have recently resolved several bright CO(1–0) features in the central 1′ region of M51. These CO features are organized into a spiral shape which, within the 7″ resolution, is roughly coincident with the 20 cm radio arms, although the latter are smoother. However, it is not clear that the relation between CO(1–0) brightness and H_2 column density is a universal constant. Evidence is mounting that the CO excitation conditions at least in the nuclei of several galaxies so far observed may be very different from those in the disk of the Galaxy (e.g., Lo *et al.* 1987*b*; Ho, Turner, and Martin 1987).

In this paper we present new observations of the distribution of *thermal* and *nonthermal* radio-continuum emission in M51 and compare then with two optical tracers of spiral structure: the Hα emission from giant H II complexes and the dust lanes. A detailed study of the radio-continuum and optical properties of individual H II complexes will be published elsewhere (van der Hulst *et al.* 1988); we concern ourselves here with the relationship of these components to each other and to the spiral structure.

II. OBSERVATIONS AND DATA ANALYSIS

a) *Optical Data*

Two plates of M51 were taken (one in Hα and one in the red continuum at a wavelength of 6400 Å) in 1981 March with a

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two-stage Carnegie image-tube direct camera on the Kitt Peak National Observatory 0.92 m telescope (KPNO No. 1), scanned on a PDS microdensitometer at the observatory, and calibrated using sensitometer exposures. An emission-line image was produced by scaling and subtracting the red-continuum image from the Hα plate. The absolute flux scale in Hα was calibrated using photoelectric observations obtained with the Video Camera on the KPNO 2.1 m telescope and spectrophotometry obtained with the UM/UCSD 1.5 m telescope at Mount Lemmon (van der Hulst *et al.* 1988).

A major practical difficulty is to determine the coordinate system on the optical images with sufficient accuracy to permit precise positioning on the radio data. We have used a two-step process, starting with AGK3 standard star positions and a blue POSS print, in order to determine the positions of a set of secondary standard stars near the galaxy (Table 1). The statistical accuracy of these positions is 0".3.

These positions were then used to find plate constants for the Hα image-tube observations, and also on a print from a plate obtained with the KPNO 4 m telescope which we have used to identify the dust lanes. The statistical accuracy of the fit on the 4 m print was 0".4. However, the pixel size limited the accuracy to 1".5 on the image-tube plates.

b) Radio Data

The radio-continuum observations were obtained with the Very Large Array (VLA) using the 1 km (D), 3 km (C), and 10 km (B) configurations at wavelengths of 20 and 6 cm during 1981 and 1982. Zero-spacing visibilities of 1.5 and 0.53 Jy were included in the reconstructions at 20 and 6 cm, respectively. The images were further processed with the CLEAN procedure as implemented at the VLA (Clark 1980) in order to remove sidelobes from the point-spread function and to apply a first-order correction for the undersampling of large-scale structures in the images. The final images have 8" resolution with rms noise of 0.04 mJy per beam at 6 cm and 0.11 mJy per beam at 20 cm.

The next step toward a separation of the thermal and nonthermal contributions to the spiral-arm emission is to subtract the extended "base-disk" component. Following MKB, this disk can be identified in the interarm regions. At 20 cm it is well represented by an exponential with a scale length of 1'.9, a position angle of 345°, and an inclination of 39°. The base disk must in addition fall more rapidly to zero in the region of 4'.5–5'.5 radius. At 6 cm the gap in the aperture plane (measured in wavelengths) between the data point added at the origin and the shortest interferometer spacing available in the observations was unfortunately still too large, and the CLEAN reconstruction procedure was unable to produce a satisfactory estimate of the missing low spatial frequencies. The extended features in the 6 cm image were nevertheless removed by fitting a smooth, centrally symmetric distribution to cross cuts at various position angles through the center of the galaxy, similar to the procedure followed at 20 cm. However, the model adopted at 6 cm is an artifact and is not amenable to further interpretation.

After subtracting the base-disk contributions the resulting 6 cm and 20 cm images of the spiral arms were corrected for the primary-beam response of the VLA and combined into two other images which provide estimates of the thermal and nonthermal emission. In order to achieve this separation, one must assume uniform, global values for the thermal and nonthermal spectral indices. The thermal spectral index will be close to −0.1. The nonthermal value is more difficult; we have already subtracted a substantial amount of the emission in the extended disk. What we need is the expected spectrum of the arms themselves, which is unknown. The spectral index of the total nonthermal radio emission (disk plus arms minus thermal) from M51 in the frequency range from 0.1 to 10 GHz is about −0.98 (Klein, Wielebinski, and Beck 1984). Values varying from −0.2 to 0.0 for the thermal emission and −1.2 to −0.8 for the nonthermal component were tried. Fortunately, the shapes of the resulting images were not very sensitive to the exact choice; values of −1.0 and −0.1 were finally adopted. The resulting total radio emission from M51 at 20 cm wavelength is 5% thermal, 35% nonthermal spiral arms, and 60% nonthermal base disk. The distributions of nonthermal and thermal emission are shown in Figures 1*a* and 1*b* (Plate 17) as contour plots overlaying the red-continuum and the Hα image-tube observations, respectively.

TABLE 1

POSITIONS OF SECONDARY STANDARD STARS AROUND M51

R. A. (1950)	Decl. (1950)
13h27m 3s.093	47°36′ 2".69
27 23.319	27 31.55
27 21.414	24 51.56
27 42.063	23 9.50
28 1.481	20 45.33
28 8.622	25 53.88
28 2.739	17 36.95
28 20.629	17 49.14
28 15.648	24 32.73
28 19.741	32 5.29
28 26.325	33 11.50
27 35.742	32 59.27
27 49.061	25 32.08

III. DISCUSSION

a) Base Disk

The exponential shape and 1'.9 scale length of the radio disk is in excellent agreement with that obtained for the optical disk, which is also exponential out to ~3'.5 radius (see references in van der Kruit 1977). At larger radii both the radio and the optical disks fall more rapidly to zero, but the similarities may be less striking. The 39° inclination of the radio disk also agrees well with the optically derived values of 35° used by van der Kruit (1977) and 33° by Boroson (1981). These coincidences further support the suggestion (Allen 1975; van der Kruit, Allen, and Rots 1977) that the radio and optical disks are generally spatially coincident in *R* and *Z*. Further consideration of the possible relation between these apparently unconnected components is beyond the scope of this paper.

b) Spiral Structure

i) *Thermal Emission and the Giant H II Complexes*

From Figure 1*b* it is apparent that the distribution of thermal radio-continuum emission is closely coincident with the giant H II complexes. These regions are generally located along loci parallel to but *just outside* the dust lanes. However, as has been observed previously in other galaxies (e.g., in M101 by Israel, Goss, and Allen [1975] and in NGC 6946 by van der Kruit, Allen, and Rots [1977]), individual peaks of the Hα emission are not always precisely coincident with the peaks in

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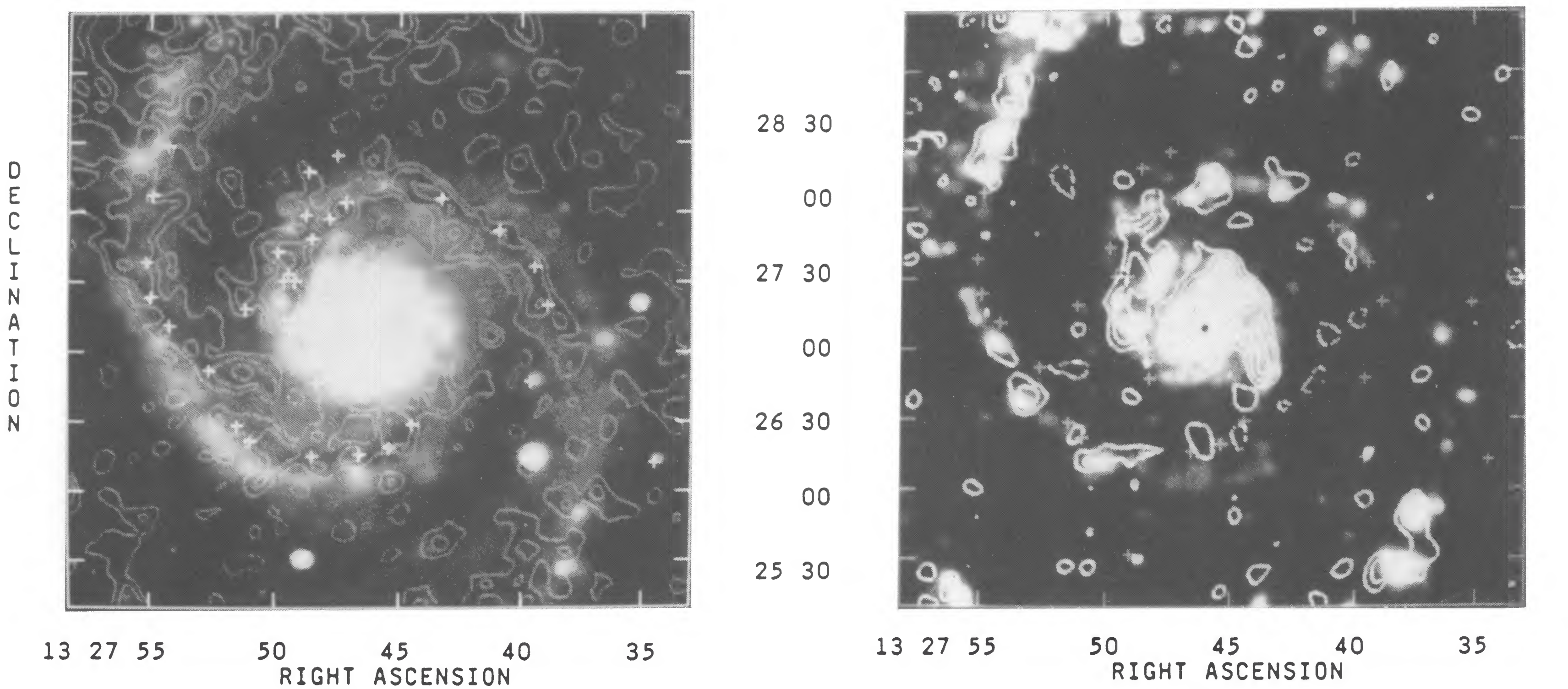

FIG. 1a

FIG. 1b

FIG. 1.—(a) *Left panel:* contours of the nonthermal radio emission at 8″ resolution after subtraction of the exponential base disk, superposed on the red continuum image of M51. Contours are at −2 (*dashed line*), 2, 4, 7, 10, 25, 50, and 100 units, with one unit equal to 0.21 mJy per beam (1.5 σ). Crosses mark standard stars from Table 1, and prominent dust lanes in the spiral arms from the KPNO 4 m plate. (b) *Right panel*: contours of the thermal radio emission at 8″ resolution, superposed on the Hα image of M51. Contours are at −2 (*dashed line*), 2, 4, 7, 10, 25, 50, and 100 units, with one unit equal to 0.11 mJy per beam (1.5 σ). Crosses as in (a). The declination scale omits the degrees (47°).

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the thermal radio emission. These differences of detail are also well known on smaller length scales in Galactic H II regions; they occur because of patchy obscuration of the optical emission by dust. Figure 1*b* also shows that there are no giant H II complexes hidden in the dust lanes in M51, although some fainter H II regions (comparable to Galactic objects) could have escaped radio detection.

ii) *Nonthermal Emission and the Dust Lanes*

Figure 1*a* shows that the peaks of nonthermal radio-continuum emission fall generally very near to the dust lanes, which are in turn thought to outline the spiral shock. This confirms the original, lower resolution results of MKB. However, our improved resolution, the separation of the thermal continuum, and the subtraction of the nonthermal base disk reveal several new details: although they both outline the spiral structure, the thermal, and nonthermal radio emission are not spatially coincident. The nonthermal emission is much smoother than the thermal and organized in longer, more coherent structures which are resolved by our 8″ beam. Also, the ridges of nonthermal continuum generally reach maximum intensity *just inside* the dust lanes. The shape of the nonthermal emission across the arms is asymmetrical, generally falling off more steeply toward the outside of the arm and less steeply towards the inside. This asymmetry causes the centroid of the nonthermal emission to move even further toward the inside of the spiral arm.

The results can be further quantified by transforming the images of the galaxy to polar coordinates and computing the first moments of the various distributions in the radial direction. In order to preserve the angular scale, no correction for the (uncertain) inclination of the galaxy was made. The data were smoothed over 15° azimuthal segments, and regions of surface brightness fainter than $\sim 2.5\ \sigma$ (or which otherwise did not clearly belong to the main spiral features) were excluded. The loci of the centroids of the thermal radio, nonthermal radio, optical Hα, and dust lanes (from the red continuum) obtained by this analysis are shown in Figure 2. The spiral arms in Figure 2 are nearly straight lines inclined at the spiral pitch angle. The centroids are well defined for both arms over more than 90° of azimuth; at radii smaller than $\sim 40''$ the angular resolution becomes insufficient to separate the arms from the nuclear regions, and at larger radii bifurcation of the southern arm and the (unsubtracted) emission from the companion NGC 5195 disturb the results.

Figure 2 confirms first the correspondence between the thermal radio and the Hα emission. For the southern arm, the loci of the dust lanes and the nonthermal continuum emission are separated from the thermal/Hα by a gap with an average width of $\sim 10''$ (450 pc for a distance of 9.3 Mpc) from P.A. $-180°$ to $-270°$. The northern arm shows the effect as well and, although the dust lane cannot be followed reliably for radii larger than $\sim 80''$, the gap between the thermal/Hα and the nonthermal emission persists from $\sim$ P.A. 0° out to at least $-150°$.

We want to emphasize that, although the data have been extensively processed in order to effect the thermal-nonthermal separation, all the new features mentioned in the discussion

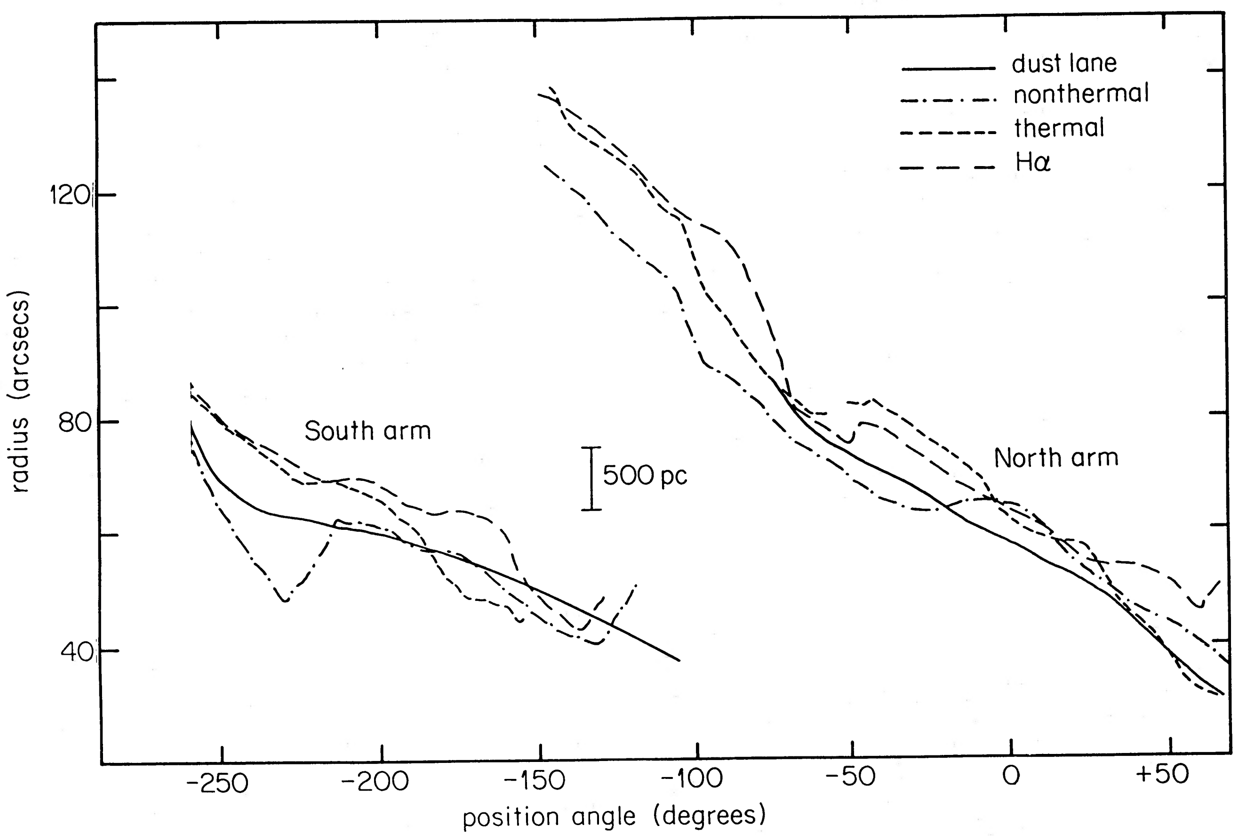

FIG. 2.—Loci of the centroids of various components of the northern and southern spiral arms of M51. The centroids are computed in the radio direction in a polar coordinate system in the plane of the sky and centered on the galaxy. The length scale of 500 pc is for an assumed distance to M51 of 9.3 Mpc; it strictly applies only on the major axis (P.A. about $-15°$ and $-195°$) although it can be used elsewhere as an approximate indication (the galaxy inclination is $\sim 35°$).

above can (with the benefit of hindsight) be found in the original 20 cm image. The reasons for this are first that the thermal emission contributes only 5%, and second that the base disk is essentially constant over the scale of a spiral arm.

c) Density-Wave Theory and the Structure of Spiral Arms

In the context of a model where the interstellar gas flows into the shock region of a spiral arm under the influence of a spiral density wave, the particular shape which we have found for the continuum arms is unexpected. First, the nonthermal volume emissivity is expected to be proportional to the density of relativistic particles times a power of the magnetic field strength. If the synchrotron-emitting gas flows along with the rest of the interstellar medium as a one-component fluid into the spiral arm, then the surface brightness of the nonthermal radio-continuum emission will rise in regions of high gas compression (MKB), although the possible onset of the Parker instability (Mouschovias, Shu, and Woodward 1974) may reduce the amplitude of the effect. The nonthermal continuum should in any case be *monotonic* with the total gas density and, therefore, a good indicator of the locations of the shocks. We then expect the radio emission first to drop slightly as the arm is approached from the inside, reflecting a slight decrease in the total gas density. At the position of the shock, the radio brightness should increase sharply, followed by a slower decrease to fainter levels again downstream from the shock roughly according to the profiles computed by Visser (1980). Instead, we seem to be finding *just the opposite shape to the arm cross section.* The conclusion seems unavoidable that *the synchrotron-emitting gas does not behave as a cold fluid*; the gradual increase in intensity as one approaches the dust lane from the inside indicates rather that this gas has a high effective sound speed and is not shocking. This would be the case if the appropriate speed was the Alfvén velocity, i.e., if the magnetic field was having an important influence on the gas dynamics. On the other hand, the mere presence of a well-defined dust lane indicates that *some component of the interstellar medium is indeed suffering a shock.* This must be the cool molecular cloud component, which apparently separates from the synchrotron-emitting gas as the latter begins to slow down on its trajectory into the inside of the spiral arm. In this picture, the cool clouds then run away to collide with other cool gas already present in the dust lane.

Recent observations of M81 by Bash and Kaufman (1986) reveal yet another radio-continuum spiral arm morphology. The 20 cm continuum arms of M81 are broad, located downstream from the velocity shock front in the H I gas (Kaufman 1987) and generally coincide with the H II regions. Although the thermal-nonthermal separation was not done, the 20 cm emission is assumed to be substantially nonthermal. However, the radio-continuum surface brightness of M81 is considerably fainter than that of M51 and M83; this implies that M81 has a lower density of relativistic electrons or a weaker magnetic field, or both. Bash and Kaufman have compared their results to the "cloud fluid" models of Roberts and Hausman (1984) in which magnetic fields play no role in the dynamics.

IV. CONCLUSIONS

1. The presence of an underlying smooth nonthermal "base-disk" component of the radio-continuum emission in M51 is confirmed; this component has a morphology similar to the old disk stars in the galaxy.
2. As has been found in several other nearby galaxies, the thermal radio emission in M51 correlates well with the optical Hα emission from the giant H II complexes. There is no evidence that similar complexes are present but hidden in the dust.
3. We confirm the discovery by MKB that the ridges in the nonthermal radio emission correspond closely with the dust lanes along major portions of the spiral arms in M51. However, in several parts of the galaxy, the present observations show a number of features not previously recognized. First, the nonthermal spiral arm emission is in general well separated spatially from the thermal sources. Second, the transverse profile of the nonthermal spiral arms is asymmetric, with the shallow gradient on the inside of the arm. Finally, just beyond the dust lane, the nonthermal spiral-arm emission drops rapidly to faint levels again, followed by peaks in the thermal radio emission which mark the giant H II complexes.
4. Near the dust lane there is evidence that the cool-cloud component appears to separate kinematically from the component in which the nonthermal radio emission is embedded. This latter component apparently does not shock as it falls into the spiral potential well. It is likely that the magnetic field is significantly affecting the gas dynamics there.

We thank the staffs at the VLA and at KPNO; these facilities are operated by AUI and AURA, respectively, under contracts with the NSF. We have had helpful discussions on the interpretation of the results with T. Mouschovias and F. H. Shu. R. C. K. acknowledges support from NSF grant AST 86-13257. R. J. A. acknowledges the hospitality of the Kapteyn Laboratory in Groningen during the summer of 1987, when much of this paper was written. R. P. J. T. thanks the College of Liberal Arts and Sciences of the University of Illinois for financial support. Research on the structure of galaxies at the University of Illinois is supported in part by the National Science Foundation under grant AST 8715905.

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