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SPIRAL STRUCTURE OF M51: DISPLACEMENT OF THE H I FROM THE NONTHERMAL RADIO ARMS

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ABSTRACT

The neutral atomic hydrogen (H I) in the grand design spiral galaxy M51 has been observed with the Westerbork Synthesis Radio Telescope at a resolution of 12″ × 18″ and compared with other tracers of spiral structure: the dust lanes, the H II regions, and especially the nonthermal radio continuum emission. Over major sections of the inner spiral arms, the H I ridge is parallel to the ridge of nonthermal radio continuum but not coincident with it. The H I ridge is displaced to larger radii by about 200 pc in a segment of the northern arm and 450 pc over a large segment of the southern arm. We have earlier observed this phenomenon in portions of the spiral arms of M83. The present results confirm that the displacement of the H I arms from the region of maximum compression of the interstellar gas is not an isolated peculiarity of one particular galaxy.

We present a simple picture which describes the observations in the framework of density-wave streaming of the interstellar gas. This picture was proposed earlier to account for the same phenomenon which we observed in M83. Presuming that the nonthermal continuum ridge traces the locus of maximum density of the interstellar gas, the observations are consistent with the view that most of the H I in the inner spiral arms of M51 is a product of the dissociation of predominantly molecular gas by the star-formation process.

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

I. INTRODUCTION

The observational study of spiral structure has received new impetus during the past few years by further improvements in the resolution, sensitivity, and wavelength coverage of radio synthesis telescopes and by the advent of optical imaging Fabry-Perot spectrometers. The ability to measure the distribution and motions of various components of the interstellar medium with a resolution of 5″ to 15″ in the arms of the nearby spiral galaxies has already led to a number of unexpected results which have been reviewed recently in a historical context by Allen (1988). In particular, a resolution improvement from 25″ to 10″ in H I observations of M83 made at the VLA revealed a systematic displacement of the H I ridge from the dust lane over a 7 kpc section of the inner eastern spiral arm (Allen, Atherton, and Tilanus 1986). This displacement amounts to about 700 pc in the radial direction in the plane of M83 for an assumed distance of 8.9 Mpc and an inclination of 24°. The H I ridge in this part of M83 corresponds closely with the locus of the giant H II regions instead of with the position of maximum interstellar gas density (assumed to be outlined by the dust lane).

In this *Letter* we present new observations of the distribution of H I in the grand design spiral M51. Over a major section of spiral arm we find a situation in M51 analogous to that in M83: the ridge line of the H I is coincident with the string of H II regions, and both are displaced to larger radii with respect to the dust lanes and the nonthermal radio emission. A preliminary report of these results has been made by Tilanus and Allen (1987). The thermal and nonthermal radio continuum emission of M51 and its relation to spiral structure has been discussed in more detail by Tilanus *et al.* (1988, hereafter Paper I).

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II. OBSERVATIONS, DATA ANALYSIS, AND RESULTS

A radio spectral synthesis observation of the H I in M51 was carried out with the Westerbork Synthesis Radio Telescope (WSRT) during a 2 × 12 hour period in the summer of 1983. The final data set which was reconstructed from the observed visibilities is a cube of size 512 × 512 × 63 points (right ascension × declination × velocity), centered at $\alpha = 13^h28^m00^s$, $\delta = +47°27'00''$, $V = 440$ km s^{-1}, with sizes of 46.′1 × 62.′5 × 520 km s^{-1} and resolutions (FWHM) of 12.″3 × 18.″0 × 16.5 km s^{-1}. A two-dimensional continuum image was formed by averaging, at each position, the spectral channels which were determined to be free from line emission. This image was then subtracted from each spectral channel to yield a data cube which contains only H I line emission. A minor distortion in the data set was traced to visibility phase errors of unknown origin; the effects were reduced to a fraction of the rms noise in the line channels after the continuum emission was subtracted. At each spatial position, the spectral channels containing appreciable H I emission were then identified with a computer-aided interactive procedure and summed to produce the total H I distribution.

The inner part of the final total H I image is shown in contour representation in Figure 1*a*. For comparison, we show in Figure 1*b* the nonthermal radio continuum emission (after subtraction of the underlying exponential disk) and in Figure 1*c* the Hα contours, both described in more detail in Paper I. The thick spiral curves in Figure 1 serve as a positional reference, drawn in the same position on all three parts of the figure. These curves trace the loci of troughs in the red continuum optical image of M51, as we have determined by applying an unsharp-masking technique to a digital image of the galaxy. The spiral curves in Figure 1 provide an indication of the location of the main dust lanes; however, in this *Letter* we take the nonthermal radio continuum emission as the primary tracer of enhanced interstellar gas column density in the galaxy.

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The optical and radio images have been aligned using positions of secondary standard stars from Table 1 in Paper I. The positions of these stars have been determined to a statistical accuracy of $0''.3$. The routine calibration of both the VLA (used for the nonthermal radio continuum distribution) and the WSRT provide astronometric accuracy which is considerably better than $1''$. The overall relative positioning error of the radio and optical images in Figure 1 is therefore less than $1''$. The crosses shown in Figure 1 are not relevant to the present discussion.

Although there is a wealth of detail to be discussed in Figure 1, we wish to focus at present on the relative location of the H I with respect to the nonthermal radio continuum along the inner spiral arms. The ridges of nonthermal radio continuum in Figure 1*b* correlate reasonably well with the major dust lanes as indicated by the spiral curves; however, the detailed cross sectional shape of the radio arms is unexpected as we have described in Paper I. The H I in the inner parts of the galaxy is clearly also organized into two major spiral arms, which at first glance appear to be roughly coincident with the dust lanes in Figure 1*a*. However, on closer examination, we see that over long sections of the arms *the* H I *is actually located at slightly larger radii than the dust lanes and nonthermal emission and is more coincident with the ridge line of the giant* H II *complexes*. This is especially clear for the "southern" spiral arm which starts about $30''$ southwest of the nucleus and winds clockwise around to the east side of Figure 1. Here, the H I arm is displaced from the nonthermal ridge over an interval of position angle (measured east from north) from about $+180°$ back to $+30°$ in the region to the east of the galaxy nucleus. The H I ridge delineating this arm in Figure 1*a* is approximately coincident with the ridge of thermal Hα emission in Figure 1*c*. The separation between the H I ridge and the nonthermal radio continuum ridge is also present in the "northern" arm (which starts about $30''$ northeast of the nucleus), from p.a. around $+10°$ decreasing to about $-100°$. However, the displacement is less pronounced there.

In order to further quantify this separation, the H I image of Figure 1*a* was transformed to polar coordinates around a center at $\alpha = 13^h27^m46^s.5$, $\delta = 47°27'9''$, and the first moment of the distribution was computed in the radial direction. No correction for the uncertain inclination of the galaxy was made in this transformation, thereby preserving the angular scale. The data were smoothed over azimuthal segments of about $15°$ width; regions of faint surface brightness or which otherwise did not clearly belong to the main spiral features were excluded. Figure 2 shows the resulting locus of the H I ridge for segments of the southern and northern arms, compared to the centroid of the nonthermal radio continuum computed from the data in Paper I. The average separation between the H I and the nonthermal continuum centroids is about $10''$ over the range of position angle from $30°$ to $120°$ in the southern arm and about $4''$ over the range from $-100°$ to $-20°$ in the northern arm. These separations are roughly 450 pc and 200 pc in

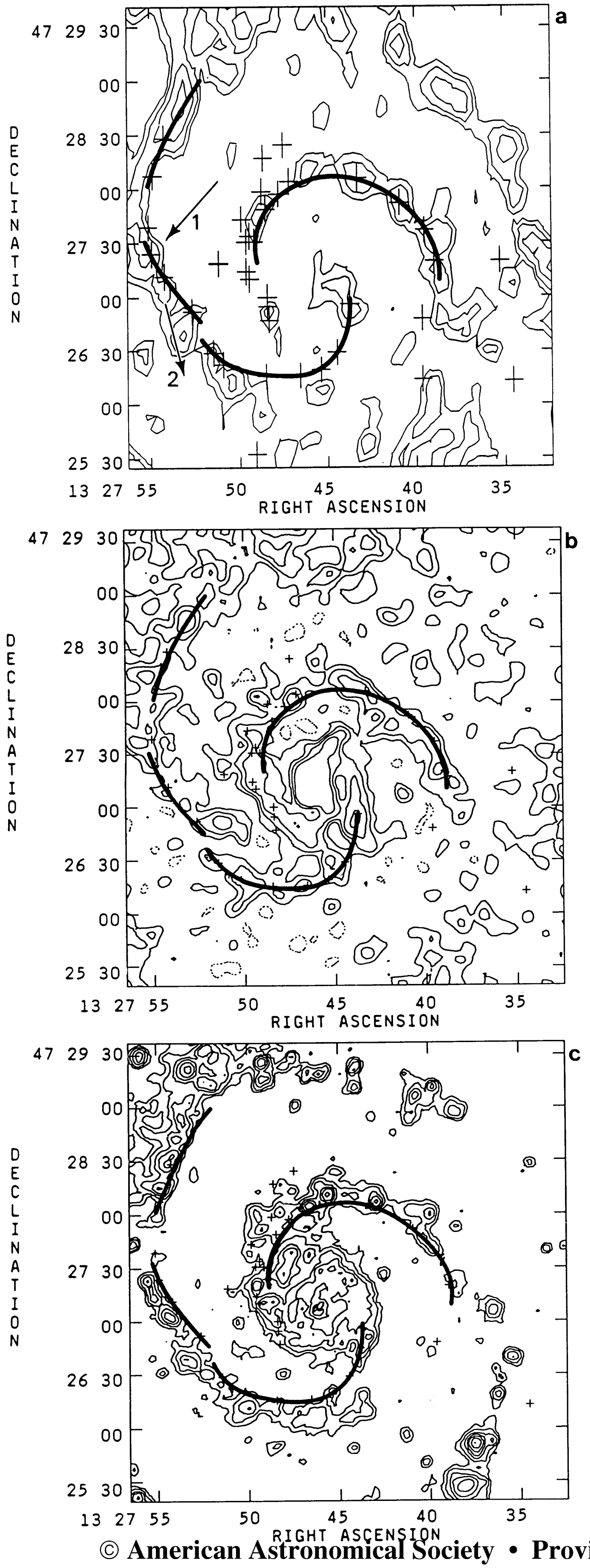

FIG. 1.—(*a*) Contours of the surface density of neutral atomic hydrogen (H I) in the inner regions of M51 as observed with the Westerbork Synthesis Radio Telescope at a resolution of $12''.3 \times 18''.0$ FWHM. Only the bright peaks of the emission are shown. Contour levels are 5, 7, 10.5, and 14.5×10^{20} H I atoms cm^{-2}. The rms noise is about 1.5×10^{20} cm^{-2}. (*b*) Contours of the nonthermal radio continuum emission in M51, after subtraction of the base disk, from Paper I. Contour levels are -4 (*dashed*), 4, 8, 13, and 20 K beam-smoothed brightness temperature. The conversion is 9.6 K = 1 mJy per beam, and the rms noise is 1.3 K. The resolution is $8''$ FWHM. (*c*) Contours of the Hα emission in M51, from Paper I. Contour values are 50, 75, 125, 200, 350, 700, and 1400 in arbitrary linear units. The resolution is $5''$ FWHM.

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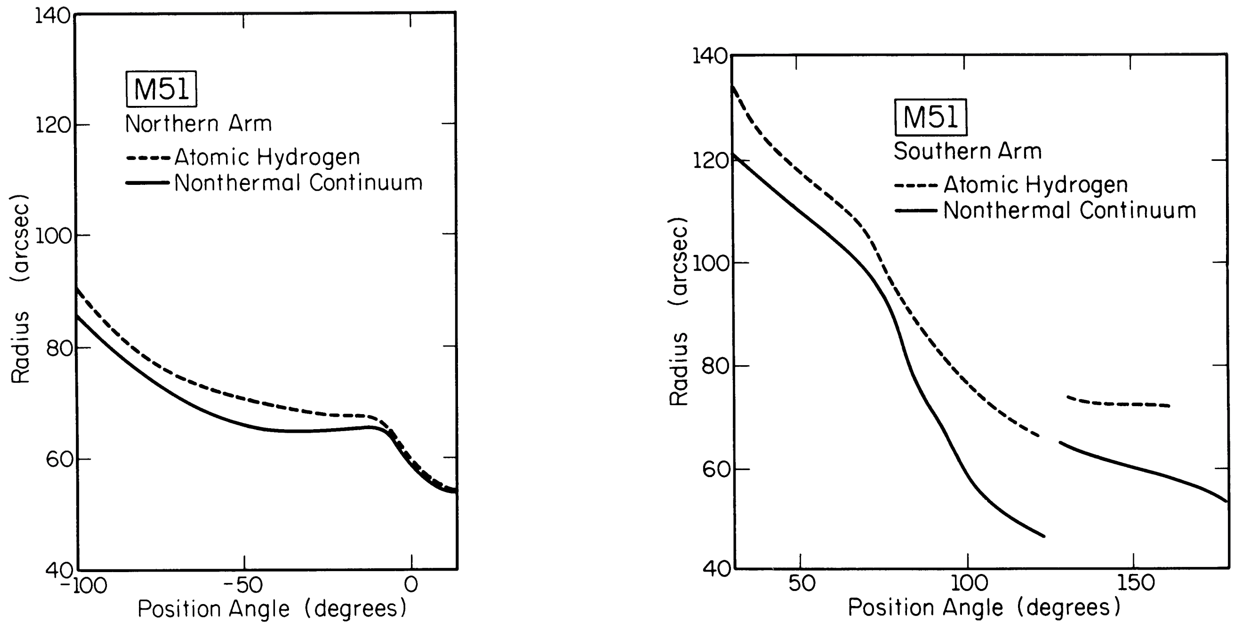

FIG. 2*a* FIG. 2*b*

FIG. 2.—Loci of the centroids of the 21 cm H I and of the nonthermal radio continuum emission in the southern and northern spiral arms of M51. The centroids are computed in the radial direction in a polar coordinate system in the plane of the sky, centered on the galaxy. No corrections for inclination have been made. The total positional uncertainty in the determination of the radial centroids due to noise (mainly in the H I) and astrometric errors is about 1″, too small to be plotted on the figure.

the plane of the galaxy for an assumed distance of 9.3 Mpc, inclination of 35°, and position angle of −15° for the line of nodes. The locus of the centroids for the southern arm in Figure 2 also shows an interesting "break" at position angle 125°. This break is also visible in the dust lanes drawn on Figure 1 at the same position angle.

The observed separation between the H I and the radio continuum ridges is less than the FWHM of the synthesized beams. For the northern arm especially, 4″ corresponds to only about one-fourth of the H I beamwidth and one-half of the continuum beamwidth. The observed separation would therefore hardly be significant if it were confined to one beam area, in spite of the fact that the relative positional accuracy of the radio-optical superposition is better than 1″. However, the azimuthal smoothing which has been applied to the data in Figure 2 improves the signal-to-noise ratio; the centroids of both the radio continuum and the H I can be determined on Figure 2 with an accuracy of about 1″, comparable to the astrometry of the images.

III. DISCUSSION

A general spatial coincidence of the various tracers of spiral structure in a galaxy may scarcely be surprising, and indeed both in M83 and here in M51 there are many regions where such a rough coincidence is found. On the other hand, *the systematic and large-scale separations which we have discovered also require an explanation.* If we presume that the dust lanes and nonthermal radio continuum ridge mark the locus of highest total interstellar gas density, then we have to explain why the highest density of atomic hydrogen is not in the same place. Furthermore, why are the loci of the inner H I arms more closely coincident with the H II arms? One possible explanation is provided by the model which we first proposed to account for a similar displacement of the H I arms in M83 (Allen, Atherton, and Tilanus 1986). This model was developed in the framework of the density wave theory of spiral structure (Lin and Shu 1964), and in particular with the description of the gas flow in a spiral potential first presented by Roberts (1969). In this picture, the matter is rotating faster than the density-wave pattern in the inner parts of the galaxy of interest here. The interstellar gas in this region of the galaxy is presumed to be mostly in molecular form as it overtakes the spiral arm from the inside (along arrow 1 in Fig. 1*a*) and collides with gas already present there. The total gas density reaches its highest value as indicated by the dust lanes and especially the nonthermal radio continuum ridges in Figure 1*b*. Star formation is enhanced/triggered in this region, but the surrounding gas remains mostly molecular until the increasing star formation activity (along arrow 2 in Fig. 1*a*) eventually results in giant H II complexes, and in a fraction of the H_2 becoming dissociated into H I. Clouds of H I then appear downstream from the shock in the immediate neighborhood of the H II regions. This process will lead naturally to a separation of the nonthermal radio continuum emission from the H I if the flow velocities perpendicular to the arm are ordered on the large scale and are greater than the local turbulence. Further downstream, the H I must eventually mostly recombine back to the molecular form before it encounters another spiral arm.

Elsewhere in the galaxy the same dissociation process may still operate, but if the flow velocities are too low the temporal sequence will not be spread out into a spatial one, and it will appear as if everything is piled up in the same place. The differences between the northern and southern arms of M51, the changes in the separation of the H I and radio continuum with position along an arm, and the discontinuity in the southern arm at position angle 125°, are also among the features for which a more detailed model will be required.

While the present manuscript was under revision, we received a preprint of a paper by Vogel, Kulkarni, and Scoville (1988) reporting high-resolution CO observations over the

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northern arm of M51. These authors have discovered that the CO emission is indeed closely coincident with the dust lane in this arm, confirming a result first reported for regions of M51 closer to the nucleus by Lo *et al.* (1987) and in the southern arm by Lo *et al.* (1988). Furthermore, Vogel *et al.* have measured peculiar motions in the northern CO arm which are consistent with density-wave streaming, in agreement with the basic assumption of our model. Their results considerably strengthen our conclusion that the H I ridges found downstream from the dust lanes in M83 and M51 are the result of dissociation of molecular gas by the star formation process.

A possible variant of the picture presented above is to start with a primarily *atomic* interarm medium, which is compressed as it overtakes the spiral arm and becomes molecular in the region of the shock. Further downstream, the molecular gas may still dissociate into H I and H II as a consequence of the star-formation process, as we have already suggested. The new CO results by Vogel *et al.* place constraints on this "atomic interarm gas" variant, as follows: these authors give the peak CO brightness in the clumps of the northern arm to be about 45 Jy beam^{-1} km s^{-1}, and state that the average ridge brightness is about one-third of the peak. The average spiral arm CO ridge brightness is therefore about 15 Jy beam^{-1} km s^{-1}, which converts to approximately 25 K km s^{-1} over their $7'' \times 10''$ beam. In order to determine if this amount of CO could be associated with H_2 molecules produced from interarm H I, we need values for the interarm H I column density, the conversion factor between H_2 and CO brightness, and the compression ratio in the spiral shock. Since our own WSRT H I synthesis does not include interferometer spacings shorter than 36 m, the base level outside the spiral ridges in Figure 1*b* is not reliably determined. However, the average H I column density in the disk of M51 at a distance of about 1′ from the center can be obtained from the single-dish observations with the 300 foot (91 m) telescope by Rots (1980) as about 6×10^{20} cm^{-2}; the interarm column density of atomic gas will certainly be less than this. If this amount of atomic gas were to be *entirely* converted into molecular form, then the average molecular surface density in the spiral shock region would not exceed $R \times 3 \times 10^{20}$ H_2 molecules cm^{-2}, where R is the compression ratio. According to Vogel *et al.* the average arm-to-interarm CO contrast in the northern arm is 2.4 over a scale size of 10″; this is a good measure of the compression ratio for the present purposes. Finally, we assume that the conversion factor for $N(H_2)/I(CO) = 2.6 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$, determined for the general disk regions of the Galaxy from gamma-ray data (as reviewed by van Dishoeck and Black 1987). This value is probably also appropriate to the present case of the northern arm of M51, where the CO is in cool, dusty regions far from the sources of heat in the giant H II complexes further downstream. We would therefore not expect the average CO surface brightness in the spiral arms of M51 to exceed about 3 K km s^{-1}. However, *the observed average CO brightness is greater than this expected upper limit by a factor of about 10*. We therefore conclude that the interarm gas in the inner parts of M51 is indeed predominantly molecular, and that the contribution of interarm H I to the molecular component in the region of the spiral shock is small.

Lo *et al.* (1987) have pointed out that, if our "dissociation" picture for the H I spiral features is correct, the fraction of molecular gas which is converted into H I downstream from the shock as a consequence of star-formation activity cannot be large. We can now further quantify that conclusion, as follows: In the region of the northern arm H I ridge, downstream from the CO ridge, the observations by Vogel *et al.* show that the average molecular surface densities have decreased to roughly the interarm values of about 10 K km s^{-1}. Again assuming the Galactic conversion factor, the interarm column density is therefore about 2.6×10^{21} H_2 molecules cm^{-2}. The average H I column density along the ridge of the northern arm in Figure 1*b* is about 5×10^{20} cm^{-2} above any smooth background (which would not have been measured by the present observations). From this we conclude that *on the average about 10% of the molecular gas is dissociated into its atomic form by the star-formation process*, although locally the conversion factor may be much larger.

IV. CONCLUSIONS

The improved angular resolution of the H I observations we have described here has revealed large-scale displacements of the atomic gas from the region of maximum interstellar gas density in major parts of the inner spiral arms of M51. The separation in parsecs is about half of the value we first discovered in M83. We have proposed an explanation for this phenomenon in which the H I in the inner spiral arms is predominantly dissociated molecular gas; i.e., the atomic gas is a product of the star formation process instead of being a direct precursor to it.

We have used recent results on the distribution of CO in M51 along with the present H I observations in order to provide quantitative support for this picture. It is unlikely that the atomic component of the upstream interarm gas in the inner parts of M51 contributes significantly to the formation of molecular clouds in the region of the shock; the upstream gas must already be mostly molecular. Downstream from the shock, about 10% of the molecular gas is turned into atomic form by the star-formation process. Most of this atomic gas must eventually recombine into its molecular form after it leaves the region of active star formation.

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