Spiral structure of M51:

Streaming motions across the spiral arms

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Streaming motions

The atomic hydrogen (H I) and the Hα emission line in the grand-design spiral galaxy M51 have been observed with the Westerbork Synthesis Radio Telescope and the TAURUS Fabry–Perôt imaging spectrometer, respectively. Across the inner spiral arms significant tangential and radial velocity gradients are detected in the Hα emission after subtraction of the axi-symmetric component of the velocity field (Figure 1).
The shift is positive on the inside and negative on the outside of the northern arm. Across the southern arm this situation is reversed. The direction of the shifts is such that the material is moving inward and faster compared to circular rotation in both arms, consistent with the velocity pertubations predicted by spiral density wave models[2,3] for gas downstream of a spiral shock. The observed shifts amount to 20–30 km s^{-1}, corresponding to streaming motions of 60–90 km s^{-1} in the plane of the disk (inclination angle 20°). Comparable velocity gradients have also been observed by Vogel *et al.*[9] in the CO emisson from the inner northern arm of M51. The streaming motions in M51 are about 2–3 times as large as the ones found in H I by Rots[4] in M81, and successfully modelled by Visser[7,8] with a self-consistent density wave model. We have not been able to detect conclusively streaming motions in the H I emission from the arms, perhaps due to the relatively poor angular resolution (~15″) of the H I observations.

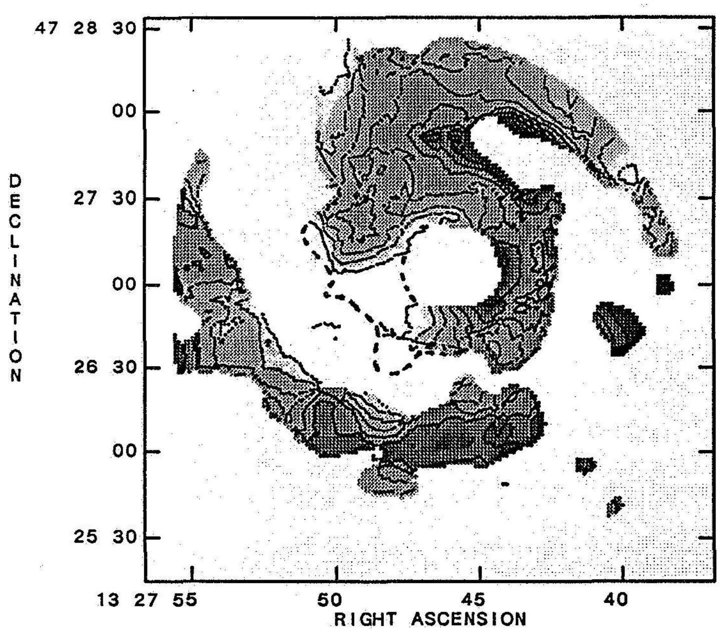

Figure 1.
M51 (Hα) streaming motions: the residual velocities across the ionized spiral arms, after subtraction of the axi-symmetric component of the velocity field. The axi-symmetric model used has been derived from a flat rotation curve. The gray levels correspond to observed residual velocities of −45, ±20, ±12.5, ±7.5, and ±2.5 km s^{-1}. The direction of the streaming motions is consistent with that the gas is flowing under the influence of a density wave perturbation.

The structure of the spiral arms

The location of various components of the ISM in the inner part of M51 is shown in Figure 2*a-d*. Figure 2 illustrates the main conclusions reached in Paper I[5] and Paper II[6]:

i) The thermal radio continuum in M51 (Figure 2*d*) correlates closely with the optical Hα emission from the giant H II complexes along the outside of the arms, and is in general well separated *spatially* from the nonthermal emission on the inside of the arms (Paper I).

ii) The ridges of maximum brightness of the nonthermal radio continuum emission in Figure 2*b* correlate closely with the dust lanes (Paper I). This observation is consistent with the nonthermal radio emission originating from shocked gas on the inside of the spiral arm, however...

iii) ...the detailed cross-sectional shape of the nonthermal radio arms (Figure 2*b*) disagrees with that expected from a simple one-component fluid model of the interstellar gas flowing under the influence of a density wave model. Opposite to the model arms[7,8] the observed radio arms have their larger extent on the inner than on the outer side and terminate sharply just outside the dust lanes.

iv) The H I arms are displaced to a larger radius with respect to the nonthermal emisson and the dust lanes (Figure 2*a*), and are found along the same ridges as the H II regions and the thermal radio continuum emission (Figures 2*c,d*) (Paper II). This is especially clear for the southern spiral arm which starts out just south of the nucleus and winds around to the left in Figure 2. Here, the H I arm is displaced from the dust lane and the nonthermal radio continuum by 450 pc. A more pronounced displacement has been found previously in M83 over a 7 kpc section of the inner eastern arm, where the H I arm is displaced downstream from the dust lane by 700 pc[1].

The model we have proposed[1,6] to account for the separation of the H I arms with respect to the nonthermal continuum and/or dust lanes, as well as its coincidence with the ionized arm in both M51 and M83, explains the H I to arise from a partial photo-dissociation of a predominantly molecular ISM. This scenario was developed within the framework of the density wave theory of spiral structure[2], in particular with the description of the gas flow in a spiral potential first presented by Roberts[3]. The molecular material reaches its highest density at the position of the spiral shock on the inside of the arms as indicated by the nonthermal radio continuum ridges and the dust lanes in Figure 2*b*. Star formation is enhanced/triggered in this region, but the surrounding gas remains mostly molecular until the increasing star formation activity eventually results in giant H II complexes, and in a fraction of the H_2 becoming dissociated into H I. The process naturally leads to the H I clouds to appear downstream from the shock in the immediate neighborhood of the H II regions.

This picture of the constitution and distribution of the ISM in the spiral arms of galaxies is considerably strengthened by a recent high-resolution observation of the distribution of the CO emission in the inner northern spiral arm of M51 by Vogel *et al.*[9]. These authors find the 300 pc wide CO arm to be closely coincident with the dust lane well inside of the luminous H II regions. Using their observation we find that the H_2 column density in the arms is 10 times larger than can be expected from a compression of the interarm H I in the shock, confirming our initial assumption that the ISM is predominantly molecular in the inner region of M51. It also follows that on average about 10% of the molecular gas is dissociated into its atomic form by the star-formation process. Assuming that the number of dissociating photons is roughly equal to the number of ionizing photons, the dissociation process yields the observed column density of H I on a timescale of roughly a million years.

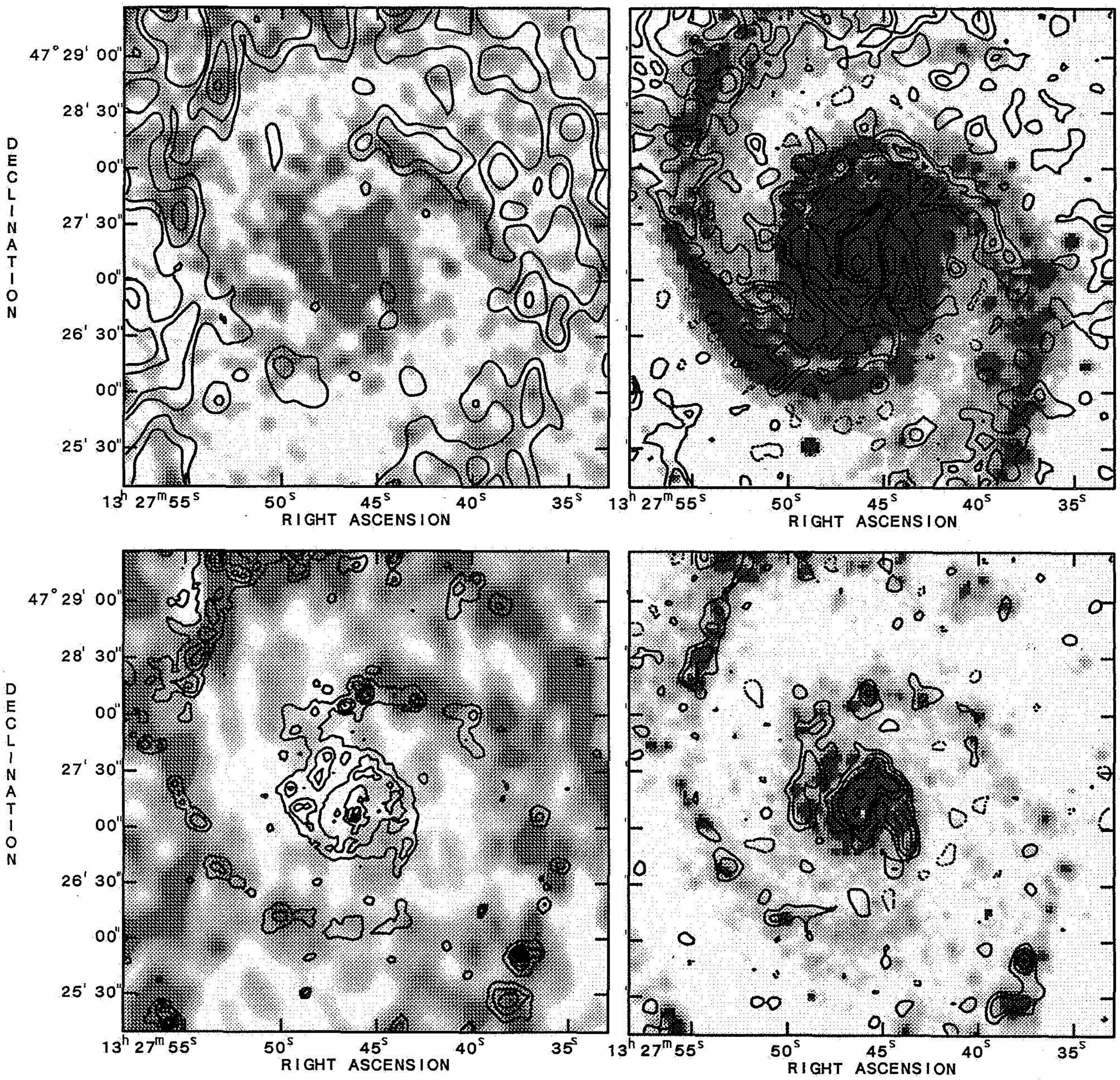

Figure 2. M51 central part: *(a) Top left panel:* the H I surface density distribution at a resolution of 12."3 × 17."5 (contours) and the nonthermal radio-continuum emission at 8″ (gray scales). *(b) Top right panel:* the distribution of the nonthermal radio-continuum emission at 8″ (contours) and the red optical continuum (gray scales) showing the dust lanes as white bands on the inside of the luminous arms. *(c) Bottom left panel:* the Hα emission from the major H II regions (contours) and the H I distribution at full resolution (gray scales). *(d) Bottom right panel:* the thermal radio-continuum emission at 8″ (contours) and the distribution of Hα emission (gray scales).

References: [1]Allen, R.J., Atherton, P.D., and Tilanus, R.P.J. 1986, *Nature* **319**, 296. [2]Lin, C.C., and Shu, F.H. 1964, *Astrophys. J.* **140**, 646. [3]Roberts, W.W. 1969, *Astrophys. J.* **158**, 123. [4]Rots, A.H. 1975, *Astron. Astrophys.* **45**, 43. [5]Tilanus, R.P.J., Allen, R.J., van der Hulst, J.M., Crane, P.C., and Kennicutt, R.C. 1988, *Astrophys. J.* **330**, 667 (*Paper I*). [6]Tilanus, R.P.J., and Allen, R.J. 1989, *Astrophys. J. Lett.* **339**, L70 (*Paper II*). [7]Visser, H.C.D. 1980a, *Astron. Astrophys.* **88**, 149. [8]Visser, H.C.D. 1980b, *Astron. Astrophys.* **88**, 159. [9]Vogel, S.N., Kulkarni, S.R., and Scoville, N.Z. 1988, *Nature* **334**, 402 (see also 382).