

## Extra-planar H I in the starburst galaxy NGC 253

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**Abstract.** Observations of the nearby starburst galaxy NGC 253 in the 21-cm line reveal the presence of neutral hydrogen in the halo, up to 12 kpc from the galactic plane. This extra-planar H I is found in only one half of the galaxy and is concentrated in a half-ring structure and plumes which are lagging in rotation with respect to the disk. The H I plumes are seen bordering the bright H $\alpha$  and X-ray halo emission. It is likely that, as proposed earlier for the H $\alpha$  and the X-rays, the origin of the extra-planar H I is also related to the central starburst and to the active star formation in the disk. A minor merger and gas accretion are also discussed as possible explanations.

The H I disk is less extended than the stellar disk. This may be the result of ionization of its outer parts or, alternatively, of tidal or ram pressure stripping.

**Key words.** galaxies: individual: NGC 253 – galaxies: ISM – galaxies: halos – galaxies: structure

### 1. Introduction

NGC 253 is a barred Sc galaxy in the Sculptor group of galaxies, at a distance of 3.9 Mpc (Karachentsev et al. 2003). It is one of the best nearby examples of a nuclear starburst galaxy. Outside of its very active nuclear region, NGC 253 shows the global morphology in gas and stars expected for a normal spiral galaxy.

The nuclear starburst is thought to be forming stars at a fairly high rate and to produce a superwind (Heckman et al. 1990) which brings material into the halo. Starburst, disk and halo of NGC 253 have been studied at various wavelengths. The X-ray emission has been observed with ROSAT (Pietsch et al. 2000), with Chandra (Strickland et al. 2002), and with XMM-Newton (Pietsch et al. 2001, data on the halo unpublished). The ROSAT observations have revealed diffuse soft X-ray emission from the nucleus, the disk, and a halo extending up to a distance of 9 kpc from the disk. Narrow band H $\alpha$  imaging (Hoopes et al. 1996) has shown the presence of a diffuse ionized gas (DIG) component. The radio continuum study by Carilli et al. (1992) has revealed a bright disk and a radio halo extending to a height of at least 9 kpc above the plane of NGC 253. Infrared studies with IRAS (Rice 1993; Alton et al. 1998) and ISO (Radovich et al. 2001) show that there is also dust in the halo region.

Studies of a number of nearby spirals with active star formation show considerable amounts of H I in their halos (Fraternali et al. 2001, 2003). Also the well-known IVCs

and HVCs of our Galaxy (Wakker & Van Woerden 1997; Van Woerden et al. 2004) may represent a similar halo component. The origin of such cold halo gas is not known with certainty, but it is thought that galactic fountains set up by the active star forming regions of the disk may be at least partly responsible. One would therefore expect a significant amount of extra-planar gas also in NGC 253, because of the starburst and of the star formation which is very active over a large fraction of its disk. But up till now no extra-planar H I had been found in this galaxy (cf. Puche et al. 1991; Koribalski et al. 1995).

Here we present the results of a new and deeper H I study of NGC 253 which shows that there is indeed H I in the halo of this starburst galaxy. Although the central starburst and the active star formation in the disk are likely to cause gas to flow into the halo, there can be other explanations for the origin of this extra-planar H I. For example, in many galaxies, including the Milky Way, observations show ongoing accretion. We will discuss the different possibilities for the origin of this extra-planar H I.

### 2. Observations and reduction

We have obtained new 21-cm line observations with the Australia Telescope Compact Array (ATCA) and have combined these with archival H I data obtained by Koribalski et al. (1995). These new observations have been taken between February and September 2002 in four different configurations (1.5A, 1.5B, 750B, EW367). The total bandwidth is

8 MHz with 512 spectral line channels. The total integration time, including the data of Koribalski et al. (1995), is  $8 \times 12$  h.

The data have been reduced using the MIRIAD software package (Sault et al. 1995). The continuum has been derived from the line-free channels and subtracted in the *uv*-plane. Subsequently, the data have been Fourier-transformed using robust weighting 0 (Briggs 1995), Hanning-smoothed, and CLEANed (Högbom 1974; Clark 1980). The final dataset has been obtained by smoothing to a circular beam of  $70''$ . The resulting rms noise is 1.4 mJy/beam (0.17 K) and the velocity resolution is  $13.2 \text{ km s}^{-1}$ . We tried further smoothing, but that does not reveal any new H I features. For the subsequent analysis of the data we used the GIPSY package (Van der Hulst et al. 1992; Vogelaar & Terlouw 2001). The channel maps, after averaging in groups of three, are shown in Fig. 1.

### 3. Results

#### 3.1. The extra-planar H I

Figure 2 shows the H I distribution together with the DSS optical and the ROSAT soft (0.1–0.4 keV) X-ray images. The H I contour map shows two components: the H I disk and, in the northeast half of the galaxy, gas concentrations in the halo region with a plume extending  $11'$  from the major axis to the NW, or 12 kpc for the assumed distance of 3.9 Mpc. A smaller plume reaches a distance of  $8'$  from the major axis to the SE. These H I plumes border the X-ray halo emission (Pietsch et al. 2000) and the H $\alpha$  (see Fig. 3) (Hoopes et al. 1996) on their northern side. The spatial relationship between the different components suggests a common origin. This is further discussed in Sect. 4.1.

The H I kinematics in NGC 253 is illustrated in Figs. 1, 4, 5 and 6. Figure 4 shows three position-velocity diagrams, one along the major axis, and two parallel to and on either side of the major axis (see Fig. 3 for the positions of the cuts on the sky). The H I disk shows the regular pattern of differential rotation with an approximately flat rotation curve. In the plot along the major axis, the hole in the direction of the galaxy centre is due to H I absorption against the bright radio continuum source. In addition to the bright, normal, rotating H I disk there is another component which shows up as weak emission close to systemic velocity. This is seen only on the approaching NE side of the galaxy. In the major axis map this weak H I emission is only present in the outer parts, between 8 and 12 arcmin, whereas in the two slices away from the major axis it is seen at all radii and also at “forbidden” velocities. In these two cuts, similar weak H I emission seems to be present also in the receding SW part of the galaxy at the high rotation velocity side. This may, however, be partly the result of beam-smearing from parts of the galaxy nearer to the major axis, where H I is present with such velocities.

Figure 5 shows the overall space-velocity distribution of H I in NGC 253 in the direction parallel to the major axis. It has been obtained by integrating in the direction of the minor axis. The presence and extent of the weak emission (to be called henceforth the “anomalous H I”) close to systemic velocity and on the NE half of the galaxy are particularly clear in this

map. Part of this gas has forbidden velocities. In the SW half of NGC 253 there is no indication at all of such a component. The presence of the anomalous H I can easily be seen in the channel maps (Fig. 1) in the velocity range from 166.7 to  $298.7 \text{ km s}^{-1}$ . The kinematics of this anomalous H I is similar to that of the H I halos of NGC 891 (Swaters et al. 1997; Fraternali et al. 2003) and of NGC 2403 (Schaap et al. 2000; Fraternali et al. 2001) which rotate more slowly than the gas in the disk and, in position-velocity diagrams, also show up as emission close to the systemic velocity. However, contrary to what has been found in NGC 891 and NGC 2403, the distribution of the anomalous gas in NGC 253 presents an intriguing asymmetry between the two halves of the galaxy.

Figure 6 shows position-velocity diagrams for two slice positions (cf. Fig. 3) parallel to the minor axis of NGC 253. The top panel is for the northeast half of the galaxy, the bottom one for the southwest half. In the top panel, the anomalous H I shows up as low-intensity emission at approximately systemic velocity. It appears to be smoothly connected to the thin disk rather than being a kinematically distinct component. In the bottom panel there is no trace at all of such anomalous H I near the systemic velocity, in agreement with Figs. 4 and 5.

We have separated the anomalous H I from the normal, rotating H I disk and constructed a map of its distribution on the sky (Fig. 7). The separation was obtained by masking out the emission from the regular, rotating disk. The masking was done by visual inspection of the position-velocity diagrams parallel to the major axis as those shown in Fig. 4.

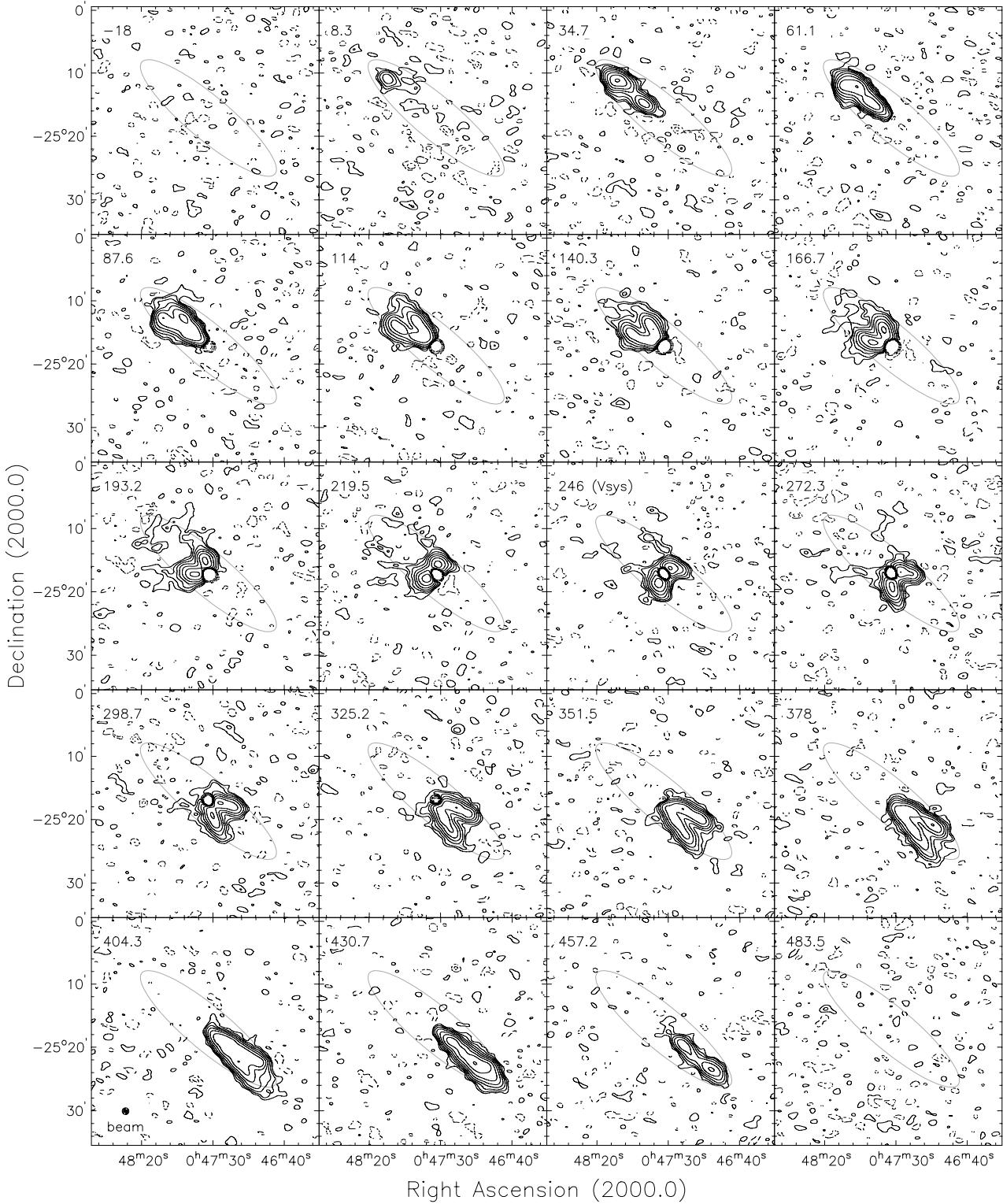
The total mass of the anomalous H I is  $8 \times 10^7 M_\odot$ . This is about 3% of the total amount of H I in NGC 253 ( $=2.5 \times 10^9 M_\odot$ ). The column densities in the plumes reach peak values of about  $5 \times 10^{19} \text{ cm}^{-2}$ . However, beam smearing is likely to be important and locally the densities may be considerably higher.

This anomalous H I is found only in the northeast half of NGC 253 and is all concentrated on the border of the bright optical disk. This particular aspect of the distribution of the anomalous gas with respect to the optical and H I disk – i.e. its absence in the inner parts of the galaxy – can be directly verified in Fig. 4, where the middle panel shows that the anomalous H I is lacking inside the inner 8 arcmin. Over the whole southwest half of the galaxy anomalous H I is not detected at all. The 3-D distribution of the anomalous gas is discussed further in Sect. 4.1.

However, this intriguing northeast/southwest asymmetry and the absence of signal in the direction of the bright optical disk should be taken with caution as the derived signal is close to the detection limit. It needs to be confirmed with new, more sensitive measurements.

#### 3.2. The small H I disk

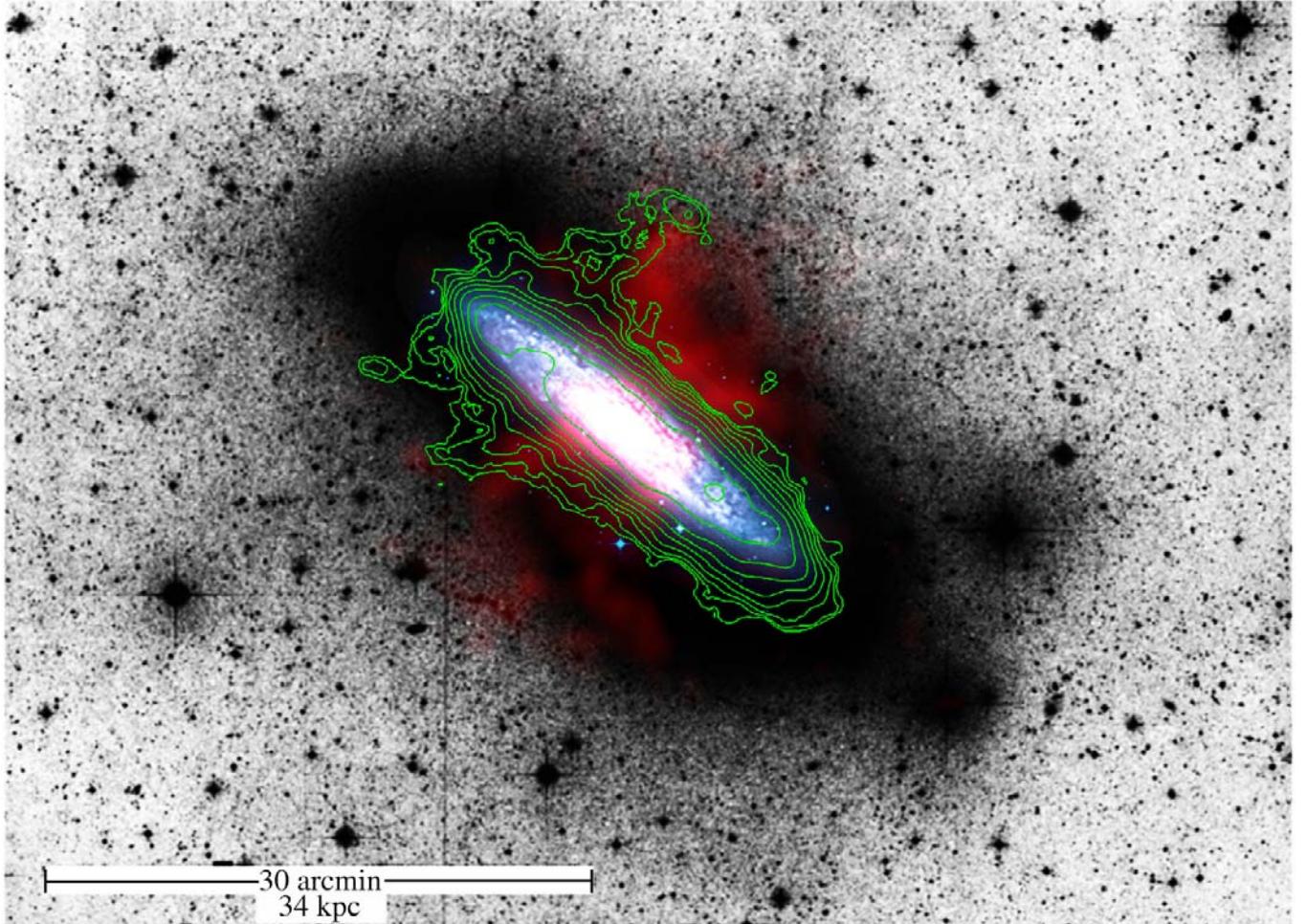
A striking characteristic of the H I disk is its small size compared to the optical. Normally, the H I disks of spiral galaxies are larger than the stellar disks (see e.g. Bosma 1981; Broeils 1992; Verheijen 1997). For NGC 253 the H I diameter at the  $1 M_\odot \text{ pc}^{-2}$  contour level ( $1.25 \times 10^{20} \text{ cm}^{-2}$ ) is  $26'$ , whereas the optical diameter  $D_{25}$  is  $27.7'$  (Pence 1980). The deep optical



**Fig. 1.** NGC 253: H I channel maps. The ellipse outlines the bright optical disk ( $R_{25}$ ). Contours are at  $-4.6, -2.3, 2.3 (1.75\sigma), 4.6, 9.2, 18.4, 36.8, 73.6, 147.2$ , and  $294.4 \text{ mJy/beam}$ , with negative contours dashed. The heliocentric radial velocities ( $\text{km s}^{-1}$ ) are given in the upper left corners. The  $70''$  beam is shown by the filled circle in the bottom left panel.

exposure by Malin & Hadley (1997) in Fig. 2 shows that the stellar disk reaches even further out. The H I disk on the contrary shows a cutoff. Although our map goes deeper than that of Koribalski et al. (1995), we find only a slightly larger radial extent.

Figure 5 shows that the H I disk of NGC 253 is asymmetric, in extent as well as in the kinematics. On the northeast side, where also the anomalous H I is seen, the disk appears to be less extended. The channel maps in Fig. 1 show a structure and a change of position angle with radius suggesting an outer



**Fig. 2.** Multi-wavelength image of the nearby spiral galaxy NGC 253. The deep optical image is from Malin & Hadley (1997), the blue shows the DSS optical disk, the red the X-ray emission (0.1–0.4 keV) from ROSAT (Pietsch et al. 2000), and the green contours our Compact Array H I observations. Contours are at 0.18, 0.36, 0.72, 1.4, 2.9, 5.8, 12 and  $23 \times 10^{20} \text{ cm}^{-2}$ . The circular beam has a full half-width of 70''.

warping of the H I disk (see also tilted ring analysis by Puche et al. 1991).

A lopsidedness and a minor warp as found in this starburst galaxy are, however, common features of spiral galaxies. Apart from its relatively small H I radius compared to the optical, NGC 253 looks normal. The overall structure and kinematics of its H I disk are regular and unperturbed. They do not show large disruptions (even in the central parts and near the starburst) or other anomalies that might point to recent, major merger events.

#### 4. Discussion

The present H I observations of NGC 253 have revealed the presence of extra-planar gas in the northeast half of the galaxy. Furthermore, they have shown that the H I disk is unperturbed and apparently truncated well inside the stellar disk.

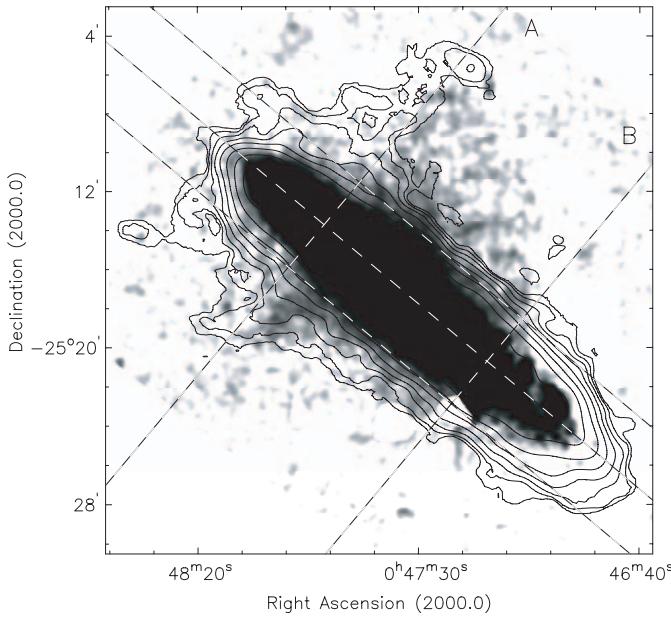
These results will be discussed here in connection with the nuclear starburst and galactic fountains in the central regions of the disk. Also the possibility of a minor merger and gas infall will be given some consideration.

#### 4.1. Structure and kinematics of the extra-planar H I

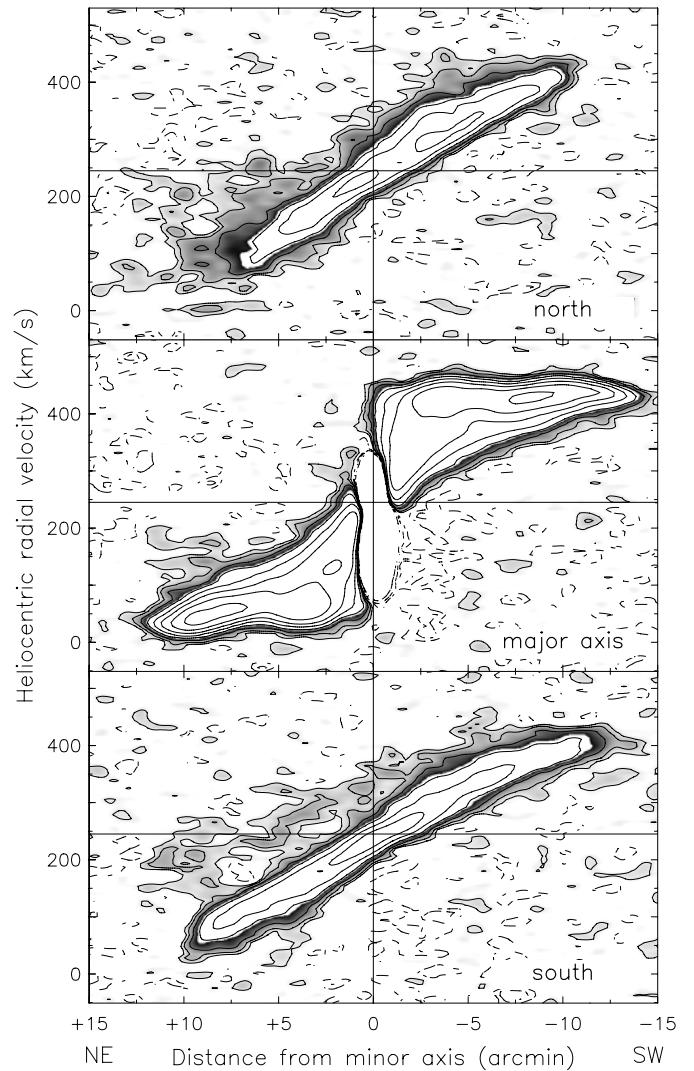
We have constructed models of the 3-D structure and kinematics of NGC 253 consisting of a thin H I disk and a thick disk with different kinematics. The picture we derive for the latter is that of a thick disk with a large, central cavity. As seen in Figs. 4 and 5, this structure, resembling that of a half-ring, seems only present on the northeast side of the galaxy. The neutral gas forming it is located above and below the outer border of the northeast half of the disk. The ring rotates more slowly than the thin disk. Radial motions, both inward and outward, may also be present. The H I plumes seen above and below the disk may be filaments or wall-like extensions of the ring to high  $z$ -distances. The cavity in the halo outlined by ring and plumes has a radius of about 6 kpc.

Two questions arise in connection with the puzzling northeast/southwest halo asymmetry. One is whether there is no extra-planar gas at all on the southwest part of NGC 253, either in neutral or ionized form. The other is what might have caused such asymmetry.

As to the first question, it should be noted, as already pointed out earlier, that in the northeast part of the galaxy the H I emission is barely detected and a factor 2 weaker emission



**Fig. 3.** H I contours overlaid on an H $\alpha$  image (smoothed with a Gaussian beam of 20'') of NGC 253 (Hoopes et al. 1996). Contours are the same as in Fig. 2. The dashed lines parallel to the major axis indicate the locations of the slices shown in Fig. 4. These are separated by 3'. The lines labeled “A” and “B” correspond to the slices in Fig. 6, and are at 5.5' distance from the minor axis



**Fig. 4.** Position-velocity diagrams along the major axis of NGC 253 (middle panel) and parallel to the major axis to the NW (top) and to SE (bottom). The positions of the slices with respect to the galaxy are shown in Fig. 3. The horizontal lines indicate the systemic velocity. Contours are at -21.6, -10.8, -5.4, 5.4 (1.5 $\sigma$ ), 10.8, 21.6, 43.2, 86.4, 192.8, 385.6 and 770.2 mJy/beam. Negative contours are dashed.

in the southwest would be below detection. Therefore deeper H I observations are necessary to confirm the asymmetry and place better upper limits on the H I emission in the southwest halo region. At any rate, the present limits already imply an unexpectedly low column density of H I. For comparison, H I densities as found in the halo of NGC 891 and of NGC 2403 would have been detected with the present observations of NGC 253.

There is the possibility that the asymmetry in H I is simply caused by complete ionization over most of the halo including all of the southern part. This will be briefly considered below.

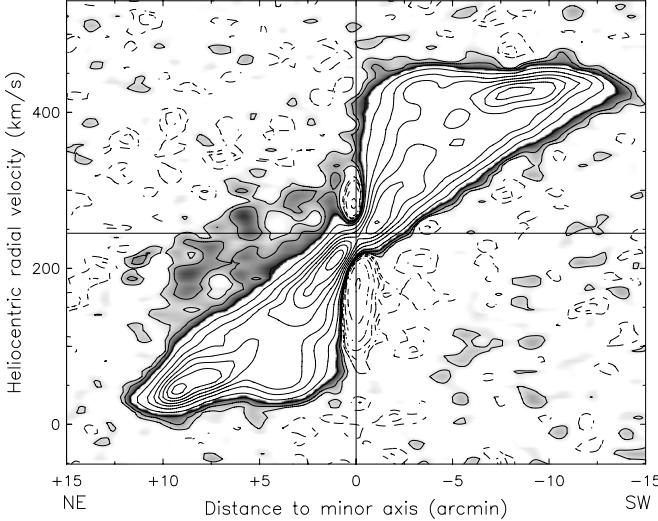
An asymmetry is also seen in the X-rays plumes and in the H $\alpha$ , although not as pronounced as in H I, whereas no striking asymmetry is present in the inner galaxy disk either in the optical, in the infrared (see the Two Micron All Sky Survey, Jarrett et al. 2003, and the 60  $\mu$ m dust, Rice 1993), or in the H I. In H $\alpha$  and the radio continuum (Carilli et al. 1992) the northern spiral arm is brighter than the southern arm. It is plausible that these asymmetries are related to the asymmetry found for the extra-planar H I emission, as will be discussed in Sect. 4.2.

#### 4.2. Galactic fountains and starburst

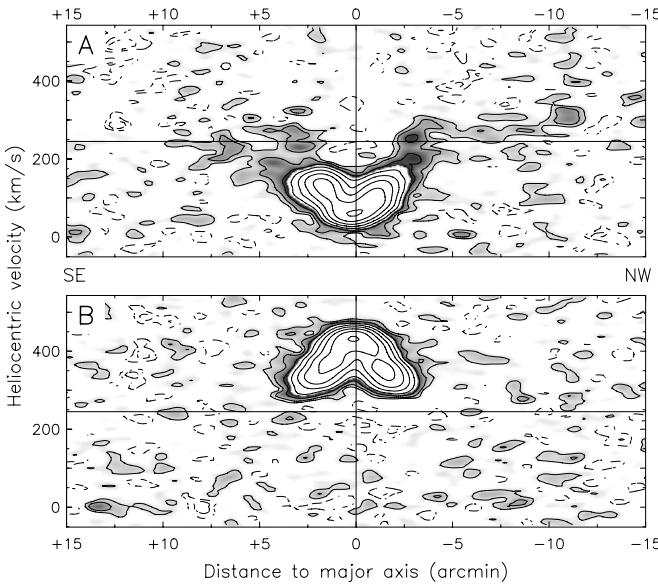
The main source of energy input into the halo is probably the central starburst. A significant amount of the flux, however, comes from the region of active star formation within a 4 kpc radius of the center of the disk (Ulvestad 2000), which is particularly bright in the radio continuum (cf. Carilli et al. 1992), the H $\alpha$  and the soft X-rays. The superbubble expanding into the

halo is therefore the combined effect of the nuclear starburst and of the star formation in the inner disk or ring.

The relative locations of H I, radio continuum, X-rays and H $\alpha$  provide important clues for understanding the 3-dimensional picture. There is a correspondence between H I and radio continuum features. The shapes of the halo extensions in the 0.33 GHz image (Carilli et al. 1992) look similar to the shape of the H I halo distribution. The H I plume (to the SE) appears at the same position as the radio continuum spur observed by Carilli et al. (1992). This spur might mark the eastern edge of the outflow cone of matter. As already noted, the H $\alpha$  and the X-ray emission are displaced with respect to the H I plumes. Similarly, there also seems to be a displacement between the X-rays and the H $\alpha$  emission (see Fig. 10b of Strickland et al. 2002). Strickland et al. (2002) made several models to explain the X-ray and the H $\alpha$  observations. The shape of the H I distribution as derived here

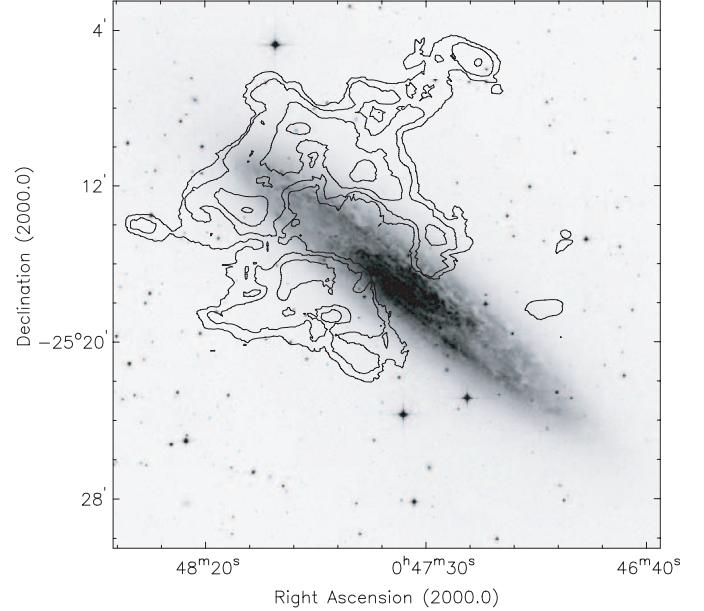


**Fig. 5.** Overall H I position-velocity map of NGC 253. All the emission has been integrated in the direction parallel to the minor axis. The halo emission is visible on the northeast side of the galaxy, near the systemic velocity. The hole in the middle is due to H I absorption against the bright radio continuum source in the nucleus. Contours are at  $-4, -2, -1, -.5, -.25, -.125, .125, .25, .5, 1, 2, 3, 4, 5, 6$  and  $7 \text{ Jy/beam}$ . Clearly, the anomalous gas is only present on the northeast side of the galaxy.

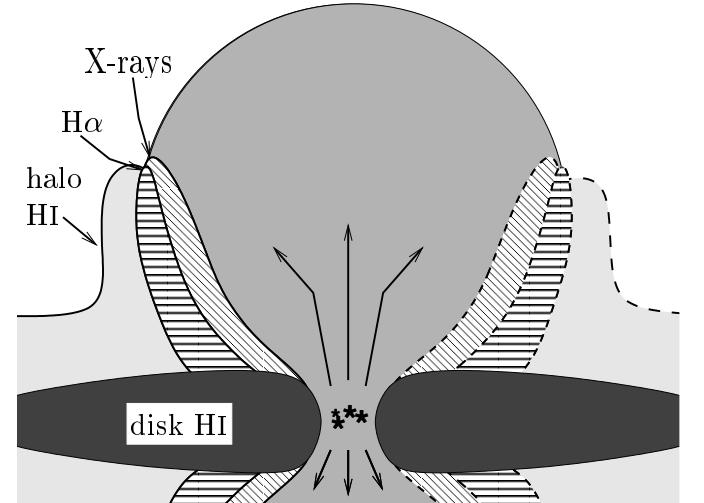


**Fig. 6.** Slices parallel to the minor axis from southeast (left) to northwest. Top panel is northeast of the centre; bottom panel southwest (see for positions on the sky Fig. 3). The emission has been integrated over  $2'$  wide strips. The horizontal line indicates the systemic velocity of NGC 253 ( $245 \text{ km s}^{-1}$ ). Contours are at  $-.06, -.03, .03, .06, .12, .24, .48, .96, 1.92$  and  $2.84 \text{ Jy/beam}$ . Note the extended emission near systemic velocity that is visible in the upper panel but absent in the lower one.

supports their model 5 (see their Figs. 11d and 8 in this paper). In this model, the X-ray emission originates from a shock-heated shell around a tenuous hot superbubble, which is surrounded by a cooler shell of H II and H I that was dragged up from a thick disk. The cartoon in Fig. 8, partly adapted from



**Fig. 7.** Contour map of the anomalous H I superimposed on the optical image of NGC 253 from the Digitized Sky Survey. Contours are at  $1.8, 3.6, 7.2$  and  $14 \times 10^{19} \text{ cm}^{-2}$ .



**Fig. 8.** Same as Fig. 11d of Strickland et al. (2002), but with an H I shell added. The various components are described in the text. The dashed lines on the right outline parts that have not been detected.

Strickland et al. (2002), illustrates schematically the gas structure of NGC 253. The thick layer in this picture is formed by the H I clouds in the lower halo. The cavity in the halo cloud layer is filled by a hot (about  $10^6 \text{ K}$ ) halo medium that is observed in the soft X-rays (see sketch (Fig. 10) in Pietsch et al. 2000).

In the picture suggested here, the absence of extra-planar H I over the largest part of the halo region of NGC 253 (the H I cavity described above), especially when compared with other galaxies with H I halos, raises interesting questions. Why is there less halo gas in NGC 253 than in NGC 891 and 2403? and even more striking, if the halos of NGC 891 and 2403 are the result of galactic fountains, why should there be less gas

in the halo of NGC 253, where there is a starburst and a high degree of star formation activity? Is it possible that there was a neutral gas halo in NGC 253 and that it has been swept away by the expanding superbubble? Or, alternatively, could there be extra-planar gas everywhere, filling the halo of NGC 253 also in the southwest part, and completely ionized? This should be addressed with deeper  $H\alpha$  studies, although it seems to be contradicted by the presence of fainter  $H\alpha$  emission in the SW part where the H I is missing. The extraplanar H I on the northeast side might be part of the gas swept away, or, in the case of a fully ionized halo, it could be cold (or cooling) gas not ionized because of its higher density.

#### 4.3. Minor merger, gas infall

The observed extraplanar H I could be accreted gas from a merger with a satellite. Perhaps such a minor merger could also explain the triggering of the starburst in an otherwise normal, non-interacting galaxy like NGC 253. The age of the starburst and the superbubbles is a few times  $10^7$  yr. It would take approximately  $10^9$  yr to spread accreted gas symmetrically over the whole disk. These timescales for the infall and for the starburst would all be consistent with the observed asymmetric H I halo distribution. There are also indications from the optical (see Sect. 4.4) that a minor merger may have occurred.

A minor merger would naturally account for the anomalous H I and the asymmetric picture. The question is, however, whether it could produce the remarkable velocity-space continuity and also the symmetry of the extra-planar H I with respect to the major axis of NGC 253 pointed out above and shown in Fig. 6. The X-rays and  $H\alpha$  would still have to be explained by the superwind from the starburst, while their apparent connection with the H I plumes could be due to the superwind hitting the tidal wreckage. Everything considered, a merger event seems unlikely in this case.

#### 4.4. The truncated H I disk

What causes the cutoff at the edge of the H I disk? According to Bland-Hawthorn et al. (1997) there is  $H\alpha$  emission along the major axis of NGC 253 beyond the SW edge of the H I disk and its velocity is in agreement with that of the H I. They conclude that most likely the hot stars in the disk of NGC 253 itself are responsible for the ionization. For the disk to be ionized in its outer parts by the stars and the starburst, its outer layer has to be warped. As noted in the previous section, there is evidence in the present data for the presence of such a warp, as also found by Puche et al. (1991) and Koribalski et al. (1995). The position and inclination angles of the disk change somewhat outside a  $9'$  radius. Ionization of the outer hydrogen disk by the central starburst seems, therefore, to be possible. Perhaps one should also consider the possibility of strong UV radiation from the halo region. In this connection, the reason why the extra-planar H I on the northeast side is not ionized may lie in its relatively high density.

A different mechanism for reducing the size of the H I disk in NGC 253 is ram pressure stripping. However, the Sculptor

group, of which NGC 253 is a member, is not a compact group but a loose filament of galaxies extended along the line of sight (Jerjen et al. 1998; Karachentsev et al. 2003). It is therefore unlikely to contain a significant amount of intra-group medium capable of causing the stripping.

A third possibility is that the gaseous disk of NGC 253 has been truncated as the result of a minor merger. A number of observational elements suggest that NGC 253 might have undergone an encounter. The galaxy shows an unusual stellar halo (Malin & Hadley 1997) with an optical loop extending to the south at the southwest edge of the galaxy (Beck et al. 1982) (see also Fig. 2). A minor merger has already been mentioned above as a possible, but unlikely cause for the anomalous gas.

#### 5. Summary

Extra-planar H I concentrations have been observed in the northeast half of the starburst galaxy NGC 253. Plumes of H I are seen reaching as high as 12 kpc above the disk. They seem to border the  $H\alpha$  and X-ray superbubble on its northern side. Apparently, this extra-planar H I has a half-ring structure and, similar to the H I halos found in NGC 891 and 2403, is rotating more slowly than the gas in the disk. The cavity in the H I halo and in particular the apparent absence of extraplanar H I in the southwest half of NGC 253 are puzzling results. More sensitive H I observations are necessary to confirm them. It is likely that, if real, they are due to the combined effects of the central starburst and star formation in the disk.

The H I disk is truncated. Some explanations have been mentioned. A possibility is that the warped outer parts have been ionized by the photons from the starburst and the active star formation in the disk. However, ram pressure or tidal stripping cannot be ruled out.

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