The vertical structure and kinematics of HI in spiral galaxies

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Abstract. We discuss the distribution and kinematics of neutral hydrogen in the halos of spiral galaxies. We focus in particular on new results obtained for the nearby Sc galaxy NGC 2403 which have revealed the presence of extended HI emission (here referred to as the ‘beard’) at anomalous velocities with respect to the ‘cold’ HI disk. Modeling shows that this component has a mass of about 1/10 of the total HI mass and is probably located in the halo region. Its kinematics differs from that of the thin HI disk: it rotates more slowly and shows radial inflow. The origin of this anomalous gas component is unknown. It could be the result of a galactic fountain or of accretion of extragalactic ‘primordial’ gas.

1. Introduction

The study of the vertical structure and kinematics of the HI disks of spiral galaxies has in recent years been pursued in two main directions. One has been the investigation of the large-scale dynamics, with special attention to the phenomena of warping and flaring in the outer parts of the HI disks. Attempts have been made (e.g. Van der Kruit 1981, Olling 1995) to determine the mass of the stellar disks and to investigate the properties of dark matter halos. The other has been the search, in the inner parts of the disks, for evidence of vertical extensions and motions of the HI gas, possibly related to star formation activity, the expansion of superbubbles and the circulation of gas between disk and halo. The results are helpful for understanding the observations of the Milky Way and indeed, as we will see below, some of the HI features discussed here do have properties similar to those of the galactic High Velocity Clouds.
In addition to these ‘internal’ phenomena, there are other events of external origin. These are the gravitational interactions with other systems and the accretion of gas, which may affect the density distribution and kinematics of the gas in the halo region and may also play an important role in the formation and evolution of disks (see for a recent review Sancisi 1999).

2. Edge-on and face-on galaxies

Traditionally, the study of the disk-halo connection and gas circulation has been carried out on edge-on and face-on systems, the former to obtain the projected distribution of the HI density, and the latter to observe possible vertical motions. Probably the best studied edge-on galaxy is NGC 891. The HI maps obtained by Rupen (1991) and by Swaters, Sancisi, & van der Hulst (1997) show the presence of emission extending up to about 5 kpc on both sides of the plane of the galaxy. This emission had been interpreted in the early study of Sancisi & Allen (1979) as a huge outer flare of the gas layer seen in projection. Later on Becquaert & Combes (1997) proposed a line-of-sight warp. More recently, Swaters et al. (1997) have carried out a detailed 3D analysis of the data investigating the possible projection effects. They have concluded that the extended emission comes from gas in the inner halo region of NGC 891 (and not in the outer flare) and have proposed that this gas has a rotation velocity about 25 to 100 km s$^{-1}$ lower than the gas in the plane. They have tentatively attributed this velocity difference to a gradient in the gravitational potential and have pointed out that this may serve to discriminate between disk and spheroidal mass distributions.

The HI in the halo of NGC 891 has a mass of about $6 \times 10^8$ M$_\odot$, corresponding to 15% of the total HI mass and to ~0.3% of the total dynamical mass. The origin of this halo gas is probably related to star formation activity in the disk of NGC 891 and to disk-halo circulation. This is supported by the presence of a thick disk component which is observed in the radio continuum (Dahlem, Dettmar, & Hummel 1994) and in H$\alpha$ (Rand, Kulkarni, & Hester 1990), and is also indicated by the extended dust structures visible in the high-resolution optical WIYN images (Howk & Savage 1997). The lack of information on the vertical motions is obviously the main limitation in the study of edge-on galaxies like NGC 891.

The motion of the gas in the vertical direction has been studied in several nearly face-on spiral galaxies. Emission with non-zero vertical velocity has been found, often associated with large ‘holes’ in the cold gas distribution. Detailed studies have been done, for example, in M33 (Deul & den Hartog 1990), M101 (Kampuis 1993) and some dwarf galaxies like HoII (Puche et al. 1992). The general interpretation of these features is that they are the results of the formation and expansion of supershells around stellar associations due to stellar winds from massive O and B stars and/or supernova explosions. A link between the vertical motions of HI and star formation activity is also supported by the high values of the velocity dispersion of HI found in the central, bright optical regions of these galaxies (Kampuis 1993). Such HI observations of face-on galaxies do not provide, however, any direct information on the z-distribution of the gas.
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Figure 1. NGC 2403. Upper panels: optical image and HI density map (VLA). Bottom panels: velocity field of all HI gas (left) and of the "anomalous" gas only (right). All plots are on the same scale, 1 arcmin ≃ 1 kpc.

3. Galaxies with ‘beards’

The limitations and difficulties in studies of the vertical structure of HI that are encountered with galaxies viewed either edge-on or face-on can be partly overcome by taking objects of intermediate inclinations. The nearby spiral galaxy NGC 2403 (see Fig. 1) offers a good illustration and is an excellent candidate for such a study because of its ideal inclination of ∼60°, its extended HI layer (about twice the optical), its regular kinematics and symmetric, flat rotation curve.

The position-velocity diagram along the major axis of NGC 2403 shows systematic asymmetries in the form of wings on the side of the lower velocities, towards the systemic velocity. This was already visible in the early WSRT data (Wevers, Van der Kruit, & Allen 1986, p. 551, Fig. 6a, Begeman 1987, p. 46, Fig. 3) but it is more clearly shown in our new VLA data (see Fig. 2, right panels). Such a pattern (we refer to it as the ‘beard’) is similar to that found in edge-on galaxies and also in objects observed at relatively low angular resolution. Both VLA and WSRT observations of NGC 2403 have, however, a sufficiently high angular resolution and the galaxy is not too highly inclined. It
is, therefore, quite surprising to see such systematic asymmetries in the position-velocity maps.

What can be the explanation for the beard? Clearly, it cannot be simply the result of a high velocity dispersion or of gas moving away from or toward the disk in the perpendicular direction, because that would produce extensions symmetric with respect to the rotation velocity.

Recently Schaap, Sancisi, & Swaters (2000) have analyzed the WSRT observations obtained by Sicking (1997) and have investigated the effect of the layer thickness on the shape of the HI velocity profiles along the major axis of NGC 2403. In order to do this they have constructed 3D models of the galaxy, examining the possibilities of i) a thick HI disk, as opposed to the usually assumed thin layer, and ii) a two-component structure, with a thin layer and a thicker but less dense one. They have concluded that, in order to reproduce the observations, the HI disk of the one-component model considered in i) would have to be unrealistically thick, with a FWHM of at least 5 kpc. The best solution has been obtained by considering a model as ii) with a slower rotation velocity for the gas located above the plane of the disk. They found for this ‘halo’ component a mass of about 15% of the total HI mass and a difference in rotation velocity of about 25-50 km s\(^{-1}\). Clearly, this is a result very similar to that found by Swaters et al. (1997) for NGC 891.

3.1. The VLA Observations

We present here the results of a new investigation of the HI structure and kinematics of NGC 2403 with observations obtained with the VLA in C configuration and 48 hours integration. Fig. 1 shows the optical picture, the total HI map (top right) and the HI velocity field (bottom left). These data have significantly better sensitivity and higher velocity resolution than those used by Schaap et al. (2000) and have led to a considerable improvement of the observational picture. The existence of the ‘beard’ is confirmed and also new surprising features have been discovered.

Fig. 2 shows three representative channel maps and three position-velocity diagrams for NGC 2403. The position-velocity diagrams are taken along the major axis at position angle 124° (the central panel) and parallel to it at + 2′ and − 2′ from the centre of the galaxy. The slice along the major axis shows pronounced tails towards the systemic velocity (the ‘beard’) and also unexpected emission in the quadrants of ‘counterrotating’ or ‘forbidden’ velocities. These features are recognizable also in the other slices. Their spatial location can be seen in the channel maps. The upper map clearly shows the location of the ‘forbidden’ gas in the inner (∼4 kpc) region of the HI disk, to the North-West of the centre. The bottom plot shows the faint ‘forbidden’ emission on the South-East side of the galaxy and the central panel shows a remarkable 8 kpc long HI filament.

Also on the high velocity side of the line profiles there are some weak extensions of HI emission up to about 25-30 km s\(^{-1}\) with respect to the rotational velocity which may represent de-projected vertical motions of about 50-60 km s\(^{-1}\). These are, however, much smaller deviations than those of the extended ‘beard’ and of the ‘forbidden’ gas which has projected differences from the rotation velocity of up to 150 km s\(^{-1}\).
The overall picture that emerges from the new data is that of an extended zone of gas which seems to ‘know’ about the general pattern of disk rotation but deviates from it strongly. This gas is detected out to about 15 kpc from the centre of the galaxy (the radius of the total HI disk is more than 20 kpc). The velocity deviations are largest in the inner regions. We will refer to all this gas detected at velocities significantly different from rotation as the ‘anomalous’ gas. Its total mass is $3.5 \times 10^8 \, M_\odot$, which corresponds to $\sim 10\%$ of the total HI mass of NGC 2403, and to $\sim 0.3\%$ of its total dynamical mass. Similar values were found for NGC 891 (Swaters et al. 1997). The spatial structure of this gas shows a certain clumpyness with filaments, up to $\sim 10$ kpc in length, and spurs with masses of up to $10^7 \, M_\odot$ as seen in the channel maps of Fig. 2.
3.2. Models

The first step in the analysis of the HI observations reported above has been the construction of 3D models for the gas layer of NGC 2403 in order to test simple possibilities such as that of a single thick gas layer, of an outer flare and of a line-of-sight warp. We have been able to exclude them and to conclude, in agreement with Schaap et al. (2000), that such anomalous emission must come from a component with peculiar kinematics. In order to determine the properties of such a component we have proceeded to separate the anomalous gas from the cold, thin HI disk. This has been done by assuming that the line emission from the thin disk can be represented by a Gaussian profile symmetrical with respect to the rotation velocity. We have fitted such profiles at each position and subtracted them from the data.

Fig. 1 (bottom right) shows the resulting velocity field for the anomalous gas, which can now be compared with that derived for the total HI (bottom left). The kinematics of the anomalous gas is clearly dominated by differential rotation, but the mean rotation velocities are lower than in the regular disk, about 50 km s$^{-1}$ in the inner and 20 km s$^{-1}$ in the outer parts. Moreover, its kinematical minor and major axes appear to be somewhat rotated as compared to those of the regular disk and are non-orthogonal. A likely explanation for this may be radial in-flow of gas towards the centre of the galaxy.

In order to test this hypothesis, we have constructed 3D models of the HI layer of NGC 2403 adopting a two-component structure: a thin cold disk and a thicker layer rotating more slowly—. Fig. 3 shows a position-velocity diagram parallel to the minor axis at 2$'$ S-E from the centre of the galaxy, a position suitable to illustrate the effects of radial motions. The diagram shows asymmetries (in the “V” shape) especially visible at the low density levels which are produced by the anomalous gas component. For the thicker layer (or halo) component we have adopted a smaller rotation velocity, a lower density and a higher velocity dispersion as compared to the thin disk component. All these quantities (except the velocity dispersion assumed 20 km s$^{-1}$) are derived from the data after the separation between the two components. The two models labeled with “in-flow” and “out-flow” are obtained by adding, for the anomalous
component, a constant radial motion of \(-20 \text{ km s}^{-1}\) and \(+20 \text{ km s}^{-1}\) respectively. The anomalous HI in NGC 2403 clearly indicates a preference for in-flow.

Configurations involving a mis-alignment of the rotation axes of the halo and of the disk, as proposed in connection with the origin of warps (Debattista & Sellwood 1999), have also been considered here for NGC 2403. A mis-alignment of the axes with no distortions in the halo potential is likely to produce a change of the position angle of major and minor axis but not the observed non-orthogonality of the two. This seems to argue in favour of radial motions. Another way to explain the non-orthogonality of the kinematical axes would be to assume a pattern of elliptical orbits as expected for a triaxial halo potential. Such a possibility is, however, unlikely and not supported by the harmonic analysis of the velocity field of NGC 2403 made by Schoenmakers, Franx, & de Zeeuw (1997).

Finally, the decrease in rotation velocity and the high velocity dispersion could be the result of a large asymmetric drift of an HI halo. This possibility has not been investigated yet.

4. Discussion and Conclusions

What are the origin and nature of the anomalous gas in NGC 2403? The overall pattern and the large-scale regularity indicated by the position-velocity maps (Fig. 2) suggest that this gas (both the ‘beard’ and the forbidden emission) forms one coherent structure. Its anomalous velocities, despite a big spread of more than \(150 \text{ km s}^{-1}\), are confined inside the range of the rotational velocities of the disk.

The overall pattern of this anomalous gas and its coherent spatial and velocity structure seem to point to one phenomenon and one common origin. Possibilities are:

1. A galactic fountain (Shapiro & Field 1976; Bregman 1980) powered by supernova explosions and stellar winds which blow up the ionized gas from the disk into the halo. The gas may reach large distances from the plane and then cool and fall back onto the plane. This explanation finds some support in the active star formation and the presence of bright HII complexes in the disk of NGC 2403. Also the presence of a large number of holes in the HI layer (see Fig. 1) and of expanding supershells (Mashchenko, Thilker, & Braun 1999) supports the picture of an effervescent disk and of a significant disk-halo-disk circulation. We are pursuing the study of these phenomena further with deep spectroscopy of the Hα emission from the bright inner parts of NGC 2403 and Chandra observations of the bright optical disk. The main difficulty with a standard fountain interpretation lies in the presence of the apparently counter-rotating, ‘forbidden’ emission in NGC 2403. In order to explain that, a new approach and different assumptions for the fountain dynamics, for instance no conservation of angular momentum, may be necessary.

2. Infall of primordial intergalactic gas. The hypothesis of cosmological gas infall has been proposed in the past and discussed (cf. Oort 1970) in connection with the problem of the origin of the HVCs in our galaxy and with the need to re-supply the disks of spiral galaxies with fresh gas. Such a possibility has to be considered here. In that connection it would be essential to understand the
overall kinematical pattern of the anomalous HI and to understand its large-scale coherent structure which follows the rotation of the disk of NGC 2403. Also, it would be important to determine its metal abundance and to find out whether it is as low as found for the intergalactic gas or closer to solar.

The results of the present HI observations of NGC 2403 have also interesting implications regarding the High Velocity Clouds observed in the Milky Way (Wakker & van Woerden 1997) which are still a mystery and whose distances, nature and origin are still a matter of debate. Is it possible that the anomalous HI complexes discovered around NGC 2403 are analogous to the HVCs seen in the Galaxy? With what we know of the HVCs it seems fair to suggest that we probably have detected in NGC 2403 a population of HI clouds of the same type as those intermediate and high velocity clouds which are thought to be closely associated with the Galaxy and to be probably a galactic fountain type of phenomenon. Clearly, they would be different from the Magellanic Stream.

How common are the ‘beards’ of galaxies? As far as we know there are some cases, like M 33 and UGC 7766, which indicate the presence of similar structures. HI observations of higher sensitivity would tell whether there is any correlation with luminosity or mass or high surface brightness or environment, and which of these may play the crucial role.

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