The disk-halo connection in NGC 6946 and NGC 253

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Publication date:
2007

6 Summary and concluding remarks

6.1 Summary of observational results

We have obtained deep H I observations of NGC 6946. These observations provide a detailed picture of the kinematics and the density distribution of the H I in that galaxy. Here are the main results.

- We have discovered several high-velocity gas complexes (about $2.9 \times 10^8\ M_\odot$ total mass) deviating by more than 50 km s^{-1} and up to 100 km s^{-1} from local galactic rotation. This is 4 % of the total H I mass and seems to from a slowly rotating halo. Some of the high-velocity H I complexes show a large velocity spread and seem to be connected to H I holes or H II regions in the disk. They may be due to vertical flows of gas, either blown out of the disk or falling (back) onto the disk.
- We have found a large number of H I holes (more than 100) spread over the H I disk, with the highest concentration in the region of the bright optical inner part. Their sizes range from about 700 pc to a few kpc. There are several indications that the formation of the holes is related to star formation, i.e. supernovae and stellar winds.
- Both the holes and the high-velocity gas are mostly seen in the direction of the bright optical disk. Mass and energy estimates indicate that the high-velocity H I could have originated from the holes and could have been blown into the halo by the SNe explosions that also created the holes.
- The H I disk is more extended than the optical and in its outer parts it shows strong spiral arms. There are large-scale non-circular motions associated with these spiral arms. Furthermore, the disk is clearly lopsided with respect to the nucleus.
- A 24 kpc long plume of H I with a mass of $7.5 \times 10^7\ M_\odot$ is seen at the north-western edge of the disk. This gas is in the same velocity range as two companion galaxies (also detected in H I). However, there is no connection between the

plume and the companions. The plume may be an infalling extragalactic H I cloud or the remains of an accreted, small companion.

These results on NGC 6946 bear on the general issues of disk formation and evolution. In the following section we outline the picture emerging from the deep H I observations of NGC 6946 and of other nearby spiral galaxies and mention the main mechanisms playing a role in the formation of gaseous halos like galactic fountains and accretion.

6.2 Emerging picture

The overall picture of spiral galaxies coming from recent, deep H I observations, such as those of NGC 6946 reported here is that of a disk full of holes, surrounded by a cold, gaseous halo. The halo is made up of clouds and cloud complexes with anomalous velocities. Its global kinematics is characterized by a slower rotation with respect to the disk. Some of the holes are associated with outflows of H I.

The main supporting evidence for this picture comes from observations of edge-on galaxies such as NGC 891 (Fraternali et al. 2005; Oosterloo et al. 2006, in preparation) and UGC 7321 (Matthews & Wood 2003), of galaxies seen at intermediate inclination angles: NGC 2403 (Fraternali et al. 2001) and NGC 4559 (Barbieri et al. 2005), and of galaxies close to face-on: NGC 6946 (this thesis) and M 101 (Van der Hulst & Sancisi 1988; Kamphuis 1993).

In particular, the slow rotation (-15 km s^{-1}kpc^{-1} gradient) of the halo and its vertical extent (of a few kpc) have been inferred mainly from the deep H I observations of NGC 891 and NGC 2403. The H I distribution and kinematics derived for NGC 6946 agree with this picture. This galaxy has a lagging halo which is seen in the direction of the bright optical disk. Also the HVCs and IVCs of the Milky Way probably fit in a picture like this (see Section 6.3).

The origin of the H I halos is not known. It may be related to star formation in the disk (galactic fountain) or to accretion of gas from intergalactic space, or both.

6.2.1 Galactic Fountain

A galactic fountain is the mechanism responsible for blowing gas from the galaxy disk into the halo by the combined effect of stellar winds and supernova explosions. This gas, hot at first, cools and rains back onto the disk (Shapiro & Field 1976; Bregman 1980).

Supporting evidence that this process is taking place comes from observations of several nearby galaxies and also of the Milky Way. Of particular interest in this respect is the presence of H I holes and of warm and hot gas.

Many galaxies show holes in their H I disk (M 101, NGC 2403, NGC 4559, M 33, M 31, LMC, SMC). In M 101, a giant H I superbubble has been found by Kamphuis, Sancisi & Van der Hulst (1991). Chimneys and superbubbles are seen in the H I layer of the Milky Way and OB associations have been inside the superbubbles (Forbes 2000; Reynolds, Sterling, & Haffner 2001; McClure-Griffiths et al. 2006).

Warm gas is associated with H I halos. In NGC 891, extra-planar Diffuse Ionized Gas (DIG) has been observed (Dettmar 1990). NGC 2403 has a lagging H α halo (Fraternali et al. 2004). Such warm, ionized halos are probably similar to the Reynolds layer in the Milky Way. NGC 2403 furthermore shows small regions with very broad line profiles in H α, up to 300 km s^{-1}, which may indicate fast gas outflows (Fraternali et al. 2004).

NGC 6946 now provides a detailed picture of the connection between the H I halo and the disk. The high-velocity gas in this galaxy is seen in the direction of the bright optical disk and of the regions with the highest density of H I holes. Furthermore, there is evidence for vertical outflows of H I. This suggests a direct link between the star formation activity in the disk and the presence of high-velocity gas in the halo.

6.2.2 Accretion

There is increasing evidence from H I observations of nearby spiral galaxies (Van der Hulst & Sancisi 2005) for frequent minor mergers and for gas infall. The infalling gas may be due to the accretion of a small satellite galaxy, or to the fall-back of tidally stripped gas. Alternatively, it may be primordial gas falling into a galaxy for the first time.

An example of accretion may be M 101, where an H I complex with a mass of a few $10^8\ M_\odot$ seems to have punched through the galaxy disk (Van der Hulst & Sancisi 1988). In the Milky Way, the Magellanic Stream (mass $2.8 \times 10^8\ M_\odot$), on the other hand, is considered to be gas stripped from the Magellanic Clouds, destined for accretion by the Milky Way.

More often the observed accretion candidates have smaller masses, of the order of $10^7\ M_\odot$, such as an 8 kpc long filament in NGC 2403 (Fraternali et al. 2001) and a similar structure in M 33 (seen in data by Deul & Van der Hulst 1987).

M 51 is an example of a galaxy with a large H I tail pulled out by a satellite galaxy that will eventually fall back on the disk. Such a process may take a few Gyrs (Hibbard & Mihos 1995). These long timescales for the fall-back of gas may explain why, in some cases, the companion galaxy can no longer be identified.

NGC 6946 may also be accreting gas as suggested by the plume at its north-western edge. Indeed, it is possible that NGC 6946 has been accreting for a long time and that this has produced some of the large *anomalous* complexes. Also the lopsidedness of the H I disk and the strong outer arms (see Chapter 2) may be related to accretion events.

The appearance of the plume in the deep H I observations of NGC 6946 is an example of accretion at a low density level in a non-interacting galaxy. This may well indicate the sensitivity level at which a search for accretion of low-mass objects in other nearby galaxies needs to be carried out.

6.3 HVCs and the high-velocity gas in NGC 6946

The origin of the High-Velocity Clouds (HVCs) of the Milky Way is still a puzzle. The distances to most of them are not yet known. Could the HVCs be similar to the extra-planar and high-velocity H I that we now observe in other spiral galaxies? How does this Galactic *anomalous* H I compare with that in NGC 6946? In Table 6.1 we compare a few HVCs to some distinct high-velocity complexes in NGC 6946.

The Magellanic Stream is often considered as a type of its own, different from the HVCs. It has a known distance and origin, while the history of the HVCs is still

Table 6.1– HVCs in the Milky Way and high-velocity complexes in NGC 6946

Milky Way				NGC 6946			
name	V_{dev} ($km\,s^{-1}$)	size (kpc)	mass ($10^6\ M_\odot$)	name	V_{dev} ($km\,s^{-1}$)	size (kpc)	mass ($10^6\ M_\odot$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
A	–141	8	1	NW plume	0	24	75
C	–122	10	5	W complex	60	12	4
H	–48	5	2.4	SW complex	50	17	60
MS	155	79	280	E arch	50	7	9.5
WA	126	3.5	0.1	S interarm cloud	40	1	2.5
WB	52	3.5	0.7	large cloud	80	4	2
				small cloud	125	2	0.4

Notes – Columns: (1) Name as defined by Wakker & van Woerden (1991); (2) Deviating velocity as in Wakker (1991); (3) Size, assuming a distance of 10 kpc, except for MS, which is at 50 kpc; (4) H I mass; (5) Names as used in Chapter 3, except the 'arch' at α $20^h35^m14^s$ δ $60°7'44''$ and the 'small cloud' at α $20^h34^m33^s$ δ $60°8'37''$; (6) Deviation from local rotation, absolute value; (7) Physical size; (8) H I mass;

unknown. A comparable structure is not seen in NGC 6946, but NGC 6946 has no such close companions as the Magellanic Clouds.

At an assumed distance of about 10 kpc, the sizes of the HVCs would be similar to those of the high-velocity H I complexes in NGC 6946. The latter seem, however, to be somewhat more massive than the HVCs (Table 6.1). The HVCs are comparable to the smallest complexes in NGC 6946 that are listed in this table. Nevertheless, NGC 6946 has a similar population of *anomalous* H I , albeit with some differences: there are more *anomalous* complexes than in the Milky Way and they are more massive. Perhaps, they reflect the difference in star-formation activity and/or accretion history between the two galaxies.

The deviating velocities of the HVCs seem higher than the velocities of the complexes in NGC 6946. These are, however, seen from a different perspective, which makes a good comparison difficult. In one of the models that Wakker (1990) explores to understand the HVC phenomenon, he shows that a maximum vertical velocity of $\pm 80\ km\,s^{-1}$ adequately produces the observed velocity range. This is comparable to the velocity spread found for NGC 6946 (Table 6.1).

In contrast to the HVCs, the IVCs are less easy to separate from the gas in the Milky Way disk, because of their smaller velocities. Surveys of these clouds are therefore far from complete. The known IVCs are generally located at about 1-2 kpc in the lower Galactic Halo. Their large-scale distribution is poorly known. In this thesis, we have focussed on H I clouds in NGC 6946 with velocities deviating by more than $\pm 50\ km\,s^{-1}$, of which a large fraction is comparable to the HVCs. NGC 6946, however, contains also H I with smaller deviating velocities. Figure 4.21 in Chapter 4, for example, shows H I that deviates about $42\ km\,s^{-1}$ and is seen in the direction of the H I holes, also in the outer disk. As in the case of the IVCs, this gas is hard to separate from the disk of NGC 6946 and a good comparison with the IVCs is, therefore, difficult.

6.4 Conclusion

It is very likely that H I halos as found in NGC 6946 are present in all spiral galaxies and the HVCs and IVCs may be the analogous population in our Galaxy.

There is evidence that both fountain and accretion play a role. In NGC 6946, probably a galactic fountain is mainly responsible for the high-velocity gas. It is not clear, however, that all H I halos found around spiral galaxies have this same origin.