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Cold gas accretion in galaxies

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Abstract Evidence for the accretion of cold gas in galaxies has been rapidly accumulating in the past years. HI observations of galaxies and their environment have brought to light new facts and phenomena which are evidence of ongoing or recent accretion:

1) A large number of galaxies are accompanied by gas-rich dwarfs or are surrounded by HI cloud complexes, tails and filaments. This suggests ongoing minor mergers and recent arrival of external gas. It may be regarded, therefore, as direct evidence of cold gas accretion in the local universe. It is probably the same kind of phenomenon of material infall as the stellar streams observed in the halos of our galaxy and M31.

2) Considerable amounts of extra-planar HI have been found in nearby spiral galaxies. While a large fraction of this gas is undoubtedly produced by galactic fountains, it is likely that a part of it is of extragalactic origin.

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Also the Milky Way has extra-planar gas complexes: the Intermediate- and High-Velocity Clouds (IVCs and HVCs).

3) Spirals are known to have extended and warped outer layers of HI. It is not clear how these have formed, and how and for how long the warps can be sustained. Gas infall has been proposed as the origin.

4) The majority of galactic disks are lopsided in their morphology as well as in their kinematics. Also here recent accretion has been advocated as a possible cause.

In our view, accretion takes place both through the arrival and merging of gas-rich satellites and through gas infall from the intergalactic medium (IGM). The new gas could be added to the halo or be deposited in the outer parts of galaxies and form reservoirs for replenishing the inner parts and feeding star formation. The infall may have observable effects on the disk such as bursts of star formation and lopsidedness.

We infer a mean “visible” accretion rate of cold gas in galaxies of at least $0.2 M_{\odot} \text{yr}^{-1}$. In order to reach the accretion rates needed to sustain the observed star formation ($\approx 1 M_{\odot} \text{yr}^{-1}$), additional infall of large amounts of gas from the IGM seems to be required.

Keywords galaxies, neutral hydrogen, accretion, extra-planar gas, interactions, mergers

1 Introduction

Gas accretion plays a fundamental role in the evolution of galaxies. Fresh supplies of gas are needed for the ongoing process of star formation. Such a process of galaxy “nurture” is expected to continue to the present day. The importance and role of gas infall for the evolution of disk galaxies have been recognized for many years [71; 72; 129; 131].

The rate of star-formation in the solar neighborhood has been remarkably constant over the Milky Way’s life [132; 10], which suggests that the gas consumed by star formation has been replaced by accretion. Steady accretion of metal-poor gas would also explain the discrepancy between the observed stellar metallicity distribution in the solar neighbourhood and that predicted by closed-box models of chemical evolution [130; 76]. It is not clear how much new gas is needed to sustain star formation. The star formation rate (SFR) varies throughout the Galactic disk and from galaxy to galaxy. Its value is still very uncertain. Here, we assume a reference global value of $1 M_{\odot} \text{yr}^{-1}$ both for the average SFR and for the required gas accretion rate.

Several arguments suggest that most of the baryons in the local universe still reside in the intergalactic medium [143; 41; 121]. Out of this medium galaxies are expected to grow through a series of infall events ranging from a small number of major mergers down to an almost continuous infall of dwarf galaxies and gas clouds, the latter being more and more important at low redshifts [13; 70]. Recent, high-resolution cosmological simulations show that there are two modes of accretion: hot accretion, mainly around massive structures, and cold accretion (clouds, streams or filaments) for galaxies with

lower halo masses, which correspond to the population of star forming galaxies [32]. These arguments also point to a rate of gas accretion for galaxies which is very close to their star-formation rate [64].

Direct observational evidence of accretion actually taking place has, however, been difficult to obtain. The study of HI in the Milky Way and in external galaxies has played a central role. For several decades HI observations have given valuable information on gaseous content, structure and kinematics of galaxies and on their environment. In particular, the HI rotation curves have provided the crucial evidence for dark matter in spiral galaxies. New facts have been revealed, especially in recent deep observations, which now constitute the best evidence for cold gas accretion. We briefly review them here.

First (Section 2), we focus on those phenomena – interactions, minor mergers, peculiar HI structures around galaxies – which in our opinion point directly at ongoing or recent processes of accretion. We believe that the stellar merger remnants recently discovered in the halo of our galaxy (e.g. Sgr Dwarf) [54] and of M 31 [55; 34; 79], and other faint optical features found around some nearby galaxies [74; 117], are manifestations of the same phenomena as those revealed by HI observations and described here.

Subsequently we draw attention to other aspects of the structure and kinematics of HI in galaxies – the extra-planar gas, the extended and warped outer layers and the lopsidedness – which may be part of the accretion process. The connection between accretion and the above phenomena, however, is not entirely clear and most of the evidence is indirect. The extra-planar gas (Section 3), although in part undoubtedly a product of galactic fountains [39], must also have a component which originated from infall or minor mergers [85; 40]. In our discussion of extra-planar HI we include, together with the recent evidence from external galaxies, the long-known High-Velocity Clouds (HVCs), most of which are now conclusively regarded as a Milky Way halo population and direct evidence for infall of intergalactic gas [141; 142]. The warped outer HI layers (Section 4) of spirals may also be the result of infall and form a source of continuous supply of fresh gas for the inner disks. Finally (Section 5), also the lopsided HI morphology and kinematics and the asymmetric optical images of a large number of disks may have originated from recent minor mergers or large-scale cosmological gas accretion [20]. The question of the intergalactic origin of the infalling gas is addressed in Section 6.

2 Interactions and minor mergers

2.1 Dwarf companions and peculiar structures

There are several cases of multiple systems with similar mass (e.g. M 81-M 82-NGC 3077 [144], NGC 4631-4656-4627 [95], NGC 5194(M51)-5195 [101]) which show heavily disturbed HI images with associated cloud complexes, long tails, bridges and ring-like structures. For many of these systems, it is the peculiar HI picture that unmistakably points at the ongoing strong tidal interactions and major mergers.

Table 1 Galaxies with dwarf companions and/or peculiar HI structures

Object	Features	Masses ($10^8 M_{\odot}$)	Reference
IC10	-	-	[53]
NGC 210	tail	6	^a
NGC 262 (Mkn 348)	tail	> 20	[50; 120]
NGC 628	high-velocity complexes	2	[60]
NGC 925	tail	3	^b
NGC 1023 (Arp 135)	tail/ring	10	[109]
NGC 1961 (Arp 184)	wing	~54	[119]
NGC 2146	cloud	46	[35; 126]
NGC 2782 (Arp 215)	plume	~10	[122]
NGC 2985 (UGC 5253)	tail, interaction	> 3.6	^b
NGC 3067	plume	2	[26]
NGC 3310 (Arp 217)	tails	5	[83; 68]
NGC 3359	companion/bridge	9.6	[62; 135]
NGC 4027 (Arp 22)	companion/ring	6.6	[89]
NGC 4565	companions/bridge	~1	[102]
NGC 4826	counter-rotating disk	a few	[21]
NGC 5457 (M 101, Arp 26)	high-velocity complexes	2	[133; 61]
NGC 5635	cloud	2	[105]
NGC 6946	plume	~1	[15]
Milky Way	Magellanic Stream	1.2	[75; 25]
NGC 2865			[115]
NGC 3656 (Arp 155)			[2]
NGC 4472 (Arp 134)			[80]
NGC 5128 (Cen A)			[114]

^a G. Gentile, private communication; ^b T. Oosterloo, unpublished data.

Here, however, we draw attention to galaxies which are interacting with gas-rich dwarf companions and to galaxies with no apparent interaction but with peculiar HI structures and/or kinematics. All these systems can be considered as minor mergers at different stages. Those with companions show HI tails and bridges indicating that an interaction is indeed taking place. The others, with no visible companions, have peculiar features in their HI structure and kinematics, especially in their outer parts, which are reminiscent of interacting systems. They may, therefore, have had some recent encounter and may be in an advanced stage of merging [111; 112]. However, as far as we know, they may also be the result of the infall of intergalactic gas clouds.

A number of representative cases are listed in Table 1. This list is by no means complete. A compilation of a large number of HI maps of peculiar galaxies, which includes many cases of the kind discussed here, is provided by “An HI Rogues Gallery” [53].

Prototypes of galaxies with interacting dwarf companions are NGC 3359 (Fig. 1), NGC 4565-4565A (Fig. 4) and NGC 4027-4027A. The companions have systemic velocities close to those of the main galaxy and HI masses less than 10 % of the main galaxy. The HI picture suggests the capture of a gas-

rich dwarf by a massive system, probably to be followed by tidal disruption and accretion of the dwarf. This would bring in gas, stars and dark matter.

The Milky Way and the Magellanic Clouds are in this class of phenomena and the Magellanic Stream [75; 25] is the gas component (about $1.2 \times 10^8 M_\odot$) probably destined to be accreted by our galaxy. The HI masses of LMC and SMC (4.4 and $4.0 \times 10^8 M_\odot$, respectively) are of the same order as those of the companions discussed here.

The cases just mentioned probably represent early stages of the interaction-accretion process. At later, more advanced stages, the victim may be no longer visible or not easy to be identified unambiguously. Examples are M 101 (see 2.2.1, Fig. 2), NGC 210 (see 2.2.2, Fig. 1), NGC 1023, NGC 3310, NGC 628 and Mkn 348 (Fig. 1). NGC 1023 is an S0 galaxy surrounded by a clumpy and irregular HI structure of $1.0 \times 10^9 M_\odot$ [109], reminiscent of the tails and bridges found in interacting multiple systems. There are a few dwarf neighbours, one in particular on its eastern edge, which might be merger relics. NGC 3310 is a peculiar (Arp 217) Sbc starburst galaxy. Mulder et al. (1995) [83] and Kregel & Sancisi (2001) [68] have shown the presence of extended HI emission, which has a well developed two-tail structure. This must be an advanced merger that has either preserved the old disk of one of the progenitors or, perhaps more likely, has led to the formation of a new disk. Although the optical images of both NGC 1023 and NGC 3310, as of several other objects in Table 1 (e.g. M 101, NGC 925), already show some peculiarities, it is their HI structure and kinematics that fully reveal the ongoing mergers. Other galaxies, such as NGC 210, NGC 628 and Mkn 348, have a clean, regular optical image and only the HI betrays a possible recent accretion. For NGC 628 this is indicated by the presence in its outer parts of two giant high-velocity HI complexes, which are symmetrically placed with respect to the galaxy center. These complexes have HI masses of about $10^8 M_\odot$, and maximum velocity excesses of 100 km s^{-1} [60]. For Mkn 348 (NGC 262) a probable past interaction and gas accretion is suggested by the presence of an enormous HI envelope (176 kpc diameter [50]) and a large tail-like extension (Fig. 1) [120]. In all cases, like these latter, where there is no optical victim visible, we may be dealing with the accretion of a dwarf galaxy or of intergalactic clouds. In the case of a dwarf, the stellar component has either already fallen in and has been digested, or it has been totally disrupted and the stars are now scattered around. Deep optical imaging may be able to reveal them. Examples may be the unusual faint features around some galaxies reported by Malin and Hadley [74] (see also below).

It is important to note that in all cases with no obvious interaction, a careful study of the structure and kinematics of the HI is necessary to distinguish between configurations that can be considered “normal” and configurations that are definitely “peculiar” and point to a recent interaction and infall. There are recognizable signatures in the HI that make this distinction possible, but it is not always easy to draw the line between effects due to the internal metabolism of the galaxy and those due to the environment. As an example of this difficulty, it is interesting to consider lopsidedness, which affects spiral galaxies and seems to occur quite frequently (Section 5). Should it be attributed to past interactions and accretion events? This is not at all ob-

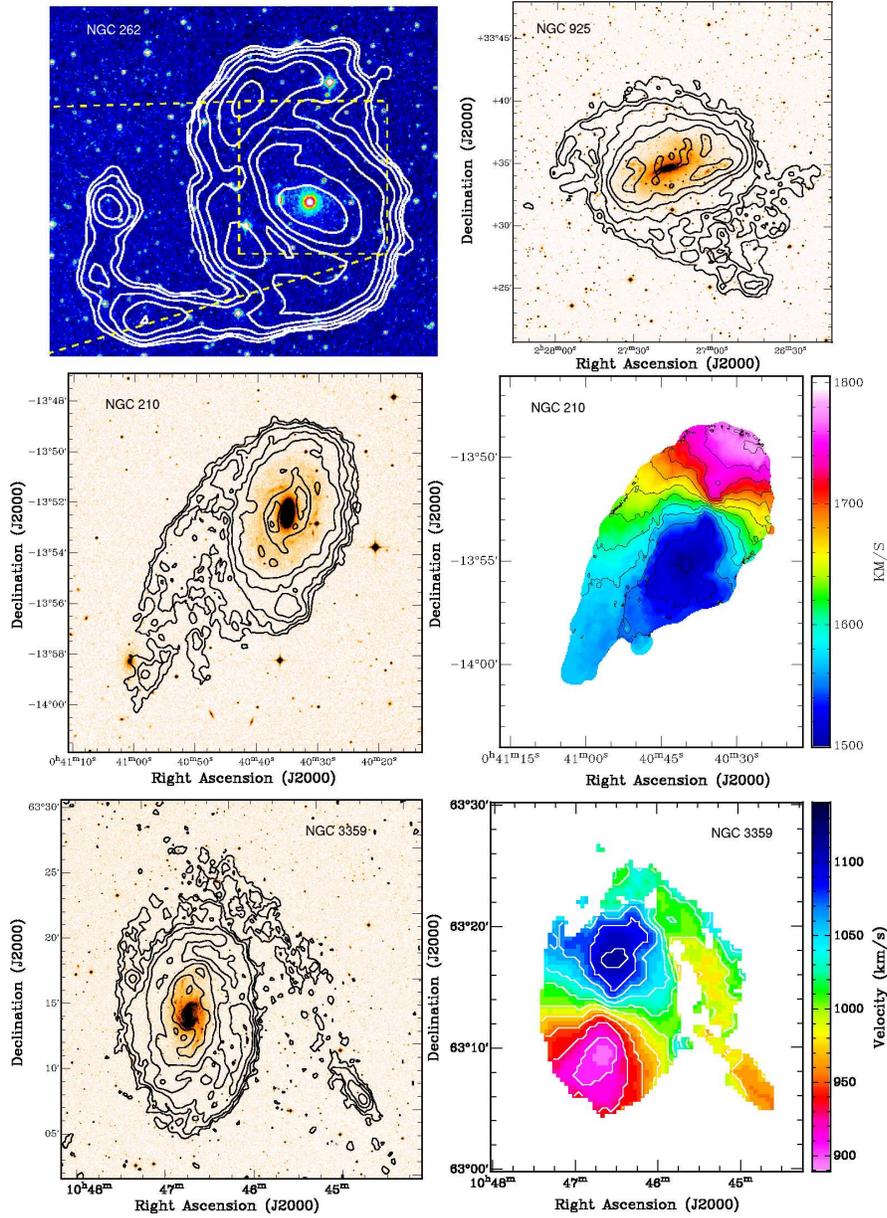


Fig. 1 Examples of galaxies showing signs of interactions/accretion. In each panel the contours show the HI density distribution superposed on the optical image. For NGC 925 the levels are 5, 10, 20, 50, 100 $\times 10^{19}$ atoms cm^{-2} ; for NGC 210: 5, 10, 20, 50, 100, 200 $\times 10^{19}$ atoms cm^{-2} ; for NGC 3359: 10, 20, 50, 100, 200, 400 $\times 10^{19}$ atoms cm^{-2} . The HI data for NGC 262 are from Simkin et al (1987) [120]. The middle and bottom right panels show the velocity fields of NGC 210 and NGC 3359.

vious and there may be other explanations related to the intrinsic dynamics of the system ($m = 1$ mode) [106].

Recently, accretion of satellites has also been revealed by studies of the distribution and kinematics of stars in the halos of the Milky Way and of M31. The discovery of the Sgr Dwarf galaxy [54] is regarded as proof that accretion is still taking place. Since such minor merger remnants retain information about their origin for a long time [51], studies of the distribution and kinematics of “stellar streams” can in principle be used to trace the merger history of the Milky Way [52]. Stellar streams have also been discovered in M31 [55; 34; 79]. Such events are more difficult to trace in more distant galaxies, where it is not possible to observe individual stars. However, deep optical images of a number of spiral galaxies, such as NGC 253, M 83, M 104, NGC 2855, [74] and NGC 5907 [117], do show unusual, faint features in their surroundings. These galaxies do not have obvious interactions or companions (except NGC 5907 which has a nearby dwarf). To our knowledge, a clear association of these features with HI has not been shown yet, except, perhaps, for the association between the Orphan stream and complex A discussed by Belokurov et al. (2007) [9]. It would be interesting to have deep optical images for HI systems like those illustrated in Fig. 1.

For the study of interactions and accretion, especially in the case of distant galaxies, the HI has clear advantages. As has been shown for our galaxy and for nearby galaxies, HI not only provides a direct measure of the accreting gas, but is also a powerful tracer of merger events. In particular, the HI distributions and kinematics can be used for modelling and for estimating timescales. The improved sensitivity of modern synthesis radio telescopes brings within reach the detection of fainter and fainter HI signatures of accretion events and we expect that new observations of nearby and also more distant galaxies will reveal many more examples in the coming decade.

Neutral hydrogen found in early-type galaxies (E and S0) reveals a similar picture as illustrated above for spirals, indicating that the accretion phenomenon is probably playing an important role in all types of galaxies (see bottom Table 1). Recent surveys of HI in early-type galaxies in the field [86; 103; 104; 82] show that about 60–70% of them have detectable amounts of HI (detection limits $10^7 M_{\odot}$). Similar detection rates were found in E and S0 galaxies with optical fine structure, such as optical shells [116; 136] (e.g. NGC 5128 (Cen A) [114] and NGC 2865 [115]), and also near ellipticals with dwarf companions, like NGC 4472 [80] and NGC 3656 [2]. About half of these galaxies do show apparently relaxed, gaseous disks in regular rotation. The other half have irregular HI distributions suggesting accretion and minor mergers in progress [116; 86]. It is also interesting to note that there are gas-rich ellipticals, such as NGC 4278, that contain a lot of HI but have a purely old stellar population, indicating that gas accretion and star formation are not tightly correlated.

2.2 Specific examples

To further illustrate the processes of interaction with dwarf companions and of merger/accretion we describe a few examples in detail.

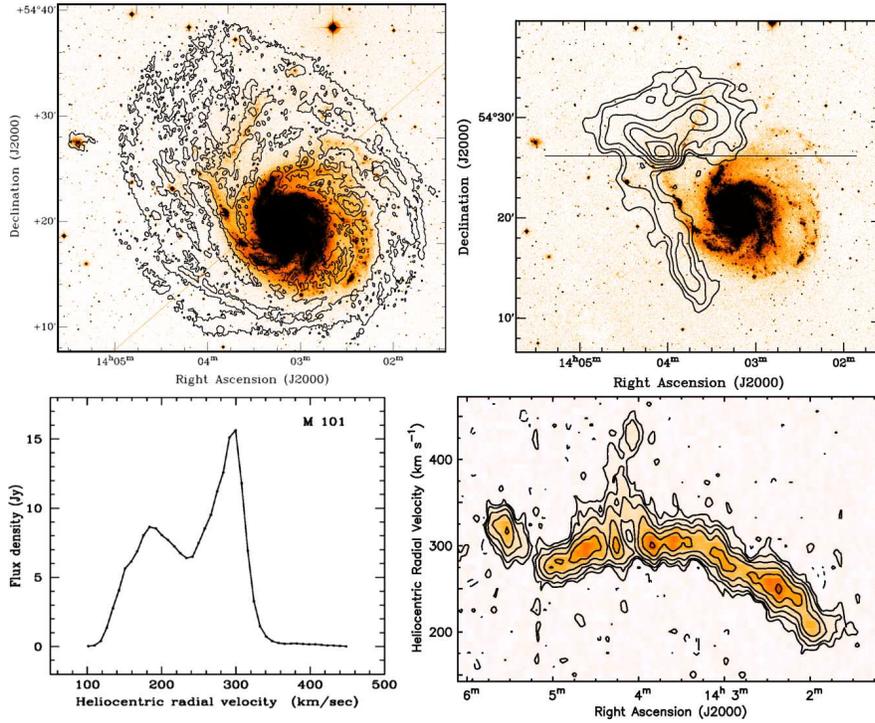


Fig. 2 Top left: WSRT total HI map for M101 (contours) overlaid on a DSS image. Top right: high-velocity gas complex (contours) overlaid on the optical image. Bottom left: global HI profile. Bottom right: Position-velocity diagram ($45''$ beam) at constant declination (see horizontal line in top right panel) showing the high-velocity HI complex. The HI data are from [61] (see also [133]).

2.2.1 M101

In M101 an HI complex of about $2 \times 10^8 M_{\odot}$ (Fig. 2, top right panel) has been found moving with velocities of up to 150 km s^{-1} with respect to the local disk and in correspondence with a large trough in the HI layer (Fig. 2, bottom right). It has been suggested that this is the result of a collision with a dwarf companion (not visible) or with a gas cloud complex which has gone through the HI layer of M101 and has created the observed trough [133; 61]. The high-velocity gas will eventually rain back down onto the M101 disk. It is interesting to note that M101 is a prototype lopsided galaxy [3] (Fig. 2, top left; see Section 5). The lopsidedness is also manifested by the global HI profile (Fig. 2, bottom left).

2.2.2 NGC 210

NGC 210 is a good example of a galaxy that shows no indications of accretion or interaction in the optical, but where the HI data give clear evidence for a recent merging event. Fig. 1 (middle left panel) shows that NGC 210 is a

regular barred galaxy with well developed, symmetrical spiral arms. In the region of the optical disk, the HI contours indicate a regular structure. In the outer parts, however, the HI shows a long tail extending to the SE and containing about $6 \times 10^8 M_\odot$. This is 10% of the total HI mass of NGC 210. The kinematics of the tail is similar to that of the gas disk, i.e. the tail is co-rotating with the disk, at similar projected velocities (Fig. 1, middle right panel). Its orbital period is $1 - 2 \times 10^9$ years. This is about the time it will take for the asymmetric structure to wind up and disappear. Near the end of the tail, a small galaxy is visible in the optical. However, its redshift is known [29] and shows that it is a background object at about ten times the distance of NGC 210, excluding an interaction. It is possible that the HI tail is caused by a merger, although no signs of a victim are seen in optical data.

2.2.3 NGC 925

Another example of a galaxy with an HI tail suggesting an accretion event is NGC 925. Fig. 1 (top right) shows the HI distribution in relation to the optical image (see also [90]). The HI properties are similar to those of NGC 210, and it appears that also NGC 925 has suffered an accretion event fairly recently. NGC 925 has a tail of HI extending to the South. The tail contains about $3 \times 10^8 M_\odot$ of HI, or 5% of the total HI mass of NGC 925. Also in NGC 925 the kinematics of the gas in the tail is not too different from that of the gas in the galaxy, i.e. it appears to co-rotate at similar projected velocities. The winding up and disappearance of this structure may take about $0.5 - 1.0 \times 10^9$ yr. NGC 925 is different from e.g. NGC 210 in that in the optical [91] the galaxy is fraught with asymmetries, both morphological and kinematical, suggesting that the accreted object may have been relatively more massive than in NGC 210.

2.2.4 NGC 3359

NGC 3359 is a nearby SBc galaxy with a dynamical mass of $1.6 \times 10^{11} M_\odot$ [24] and an HI mass of $1.9 \times 10^{10} M_\odot$. It has well developed spiral structure both in the optical and in HI. The observations [62; 135] have revealed the presence of an HI companion and a long tail/bridge connecting to the outer spiral structure of NGC 3359 (bottom Fig. 1). The companion has an HI mass of $4.4 \times 10^8 M_\odot$. There is also evidence for an optical counterpart. Together with the connecting structure the total HI mass is about $9.6 \times 10^8 M_\odot$ or 5% of the total HI mass of NGC 3359. The HI image of the companion is distorted. The velocity structure of the HI companion and the connecting HI (bottom right Fig. 1) fits in very well with the regular velocity field of NGC 3359. The regularity of the velocities suggests that the process has been going on slowly for at least about one rotational period (about 1.5×10^9 yr).

2.2.5 NGC 2985 (UGC 5253)

Fig. 3 shows the total HI map (contours) for NGC 2985 (the galaxy on the right) and its surroundings overlaid on a DSS image. NGC 2985 is a spiral galaxy at a distance of 18 Mpc. A number of features can be noted

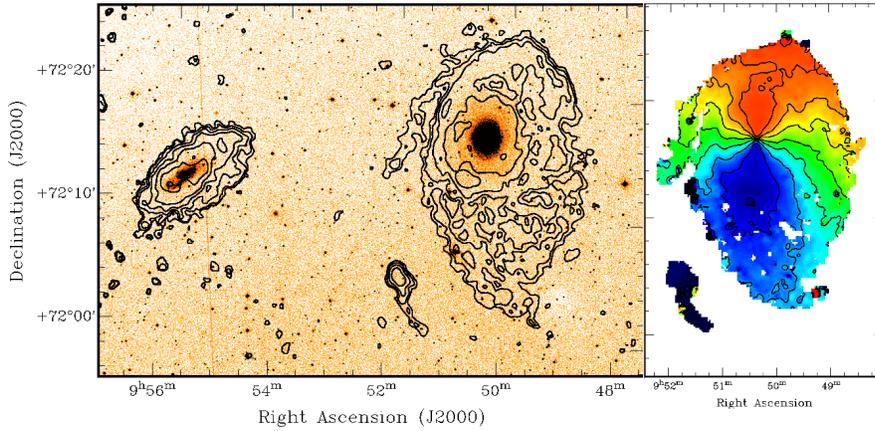


Fig. 3 Total HI map of NGC 2985 (UGC 5253) and its companions and velocity field. On the left plot, the shade is the DSS and contours are HI. Contour levels are: 5, 10, 20, 50, 100, 200 $\times 10^{19}$ atoms cm^{-2} .

that are relevant here. First, the HI distribution is very asymmetric. This may be due to an interaction with NGC 3027, the galaxy 20' (120 kpc) east of NGC 2985 and of similar redshift as NGC 2985 (velocity difference $\sim 250 \text{ km s}^{-1}$). NGC 3027 also has an asymmetric HI distribution. Interestingly, the velocity field of NGC 2985 is, overall, fairly regular and dominated by differential rotation (Fig. 3, right panel). It looks as if the passage of NGC 3027 has caused a tidal displacement of the outer disk of NGC 2985 with respect to the inner disk without destroying it and making NGC 2985 very lopsided in appearance. The timescales for the disappearance of the asymmetry are about $1.5 - 3 \times 10^9$ yr.

Another interesting feature is the small galaxy SE of NGC 2985. In the optical, there is a faint, low surface brightness object, coincident with the peak of the HI. The HI map shows a comet-like structure suggesting that this small galaxy is interacting with NGC 2985, losing part of the HI in the process. It is likely that this is an accretion of a small galaxy that we observe at an early stage of the process. NGC 2985 is very HI rich, its HI mass is $1.1 \times 10^{10} M_{\odot}$. The HI mass of the small companion is about 3% of that of NGC 2985, or $3.6 \times 10^8 M_{\odot}$, its systemic velocity is 185 km s^{-1} blue-shifted with respect to that of NGC 2985.

2.2.6 NGC 4565

NGC 4565 is a large edge-on galaxy of Hubble type Sb with a dwarf companion 6' (~ 30 kpc) to the north of the center, F378-0021557, which has $7.4 \times 10^7 M_{\odot}$ of HI compared to an HI mass of $2.0 \times 10^{10} M_{\odot}$ for NGC 4565 (using a distance of 17 Mpc) [135]. An HI detection of this same companion has also been reported (with the name NGC 4565A) by Rupen (1991) [102]. Another companion, NGC 4562, somewhat more massive in HI ($2.5 \times 10^8 M_{\odot}$) and brighter optically is located 15' (~ 75 kpc) to the south-west of the center

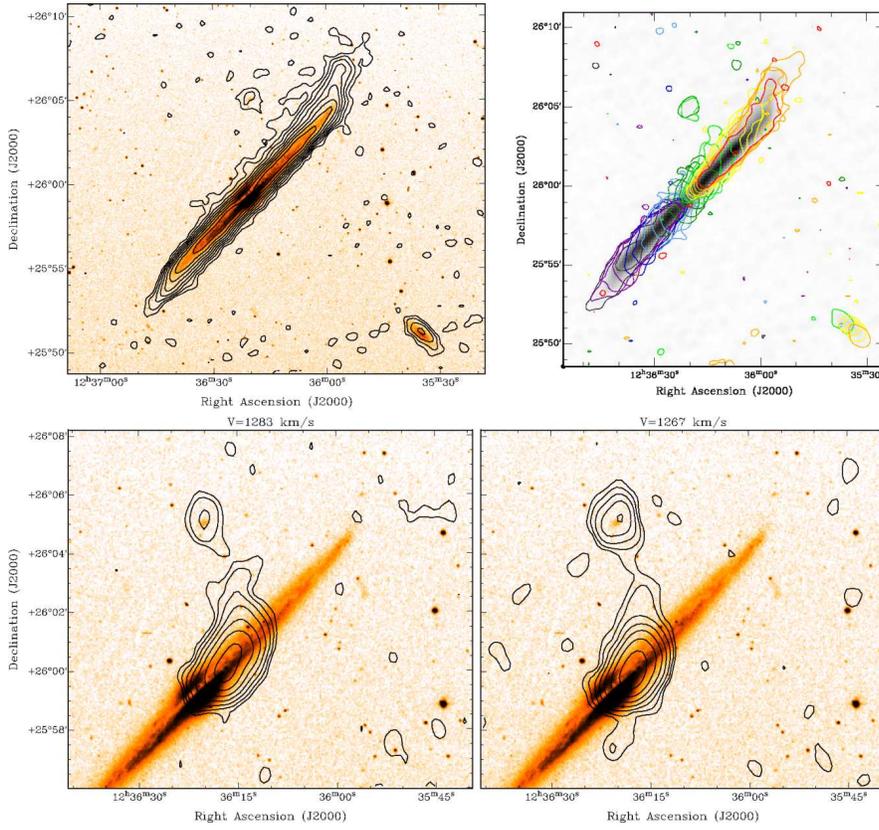


Fig. 4 Top left: HI map of NGC 4565 at a resolution of $30''$ superposed on the DSS image. Contours are 2, 4, 8, 16, 32 and $64 \times 10^{20} \text{ cm}^{-2}$. Top right: outer contours of the HI emission in individual channels (from blue to red) superposed on the total HI density map. Bottom panels: HI channel maps at two representative velocities superposed on the DSS image of NGC 4565. They clearly show the interaction between NGC 4565 and its small companion. Contours are 1, 2, 4, 8, 16, 32 and 64 mJy/beam .

of NGC 4565. The HI distribution, derived (by us) from a new sensitive observation with the Westerbork Synthesis Radio Telescope (WSRT) by Dahlem et al. (2005) [30], is shown in Figure 4 (top left panel) superposed on the DSS. The asymmetric warp is clearly visible.

Individual channel maps show low surface brightness HI emission to the north of the centre, in the direction of the faint companion F378-0021557. The HI emission from NGC 4565 in the velocity range from 1250 to 1290 km s^{-1} (close to the velocity of F378-0021557 and to the systemic velocity, 1230 km s^{-1} , of NGC 4565) clearly shows distortions above the plane pointing towards the companion. This is seen in the map (Fig. 4, top right) showing the HI velocity structure and in the bottom panels of Figure 4 which show two channel maps chosen at velocities in this range. In these maps one can clearly see the HI layer bending towards F378-0021557, suggesting a connection

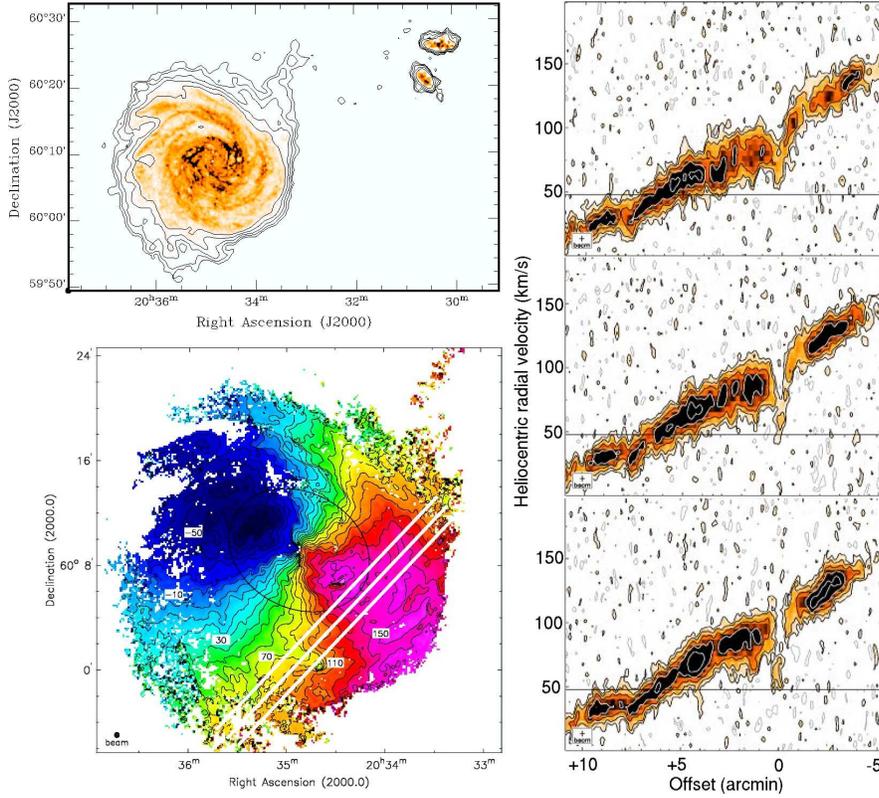


Fig. 5 Top left: total HI map of NGC 6946 and two companions. The map has been corrected for primary beam attenuation. The shading shows the high resolution (13'') HI map, the contours (1.25, 2.5, 5, 10, and 20×10^{19} atoms cm^{-2}) show the low resolution (60'') HI distribution in the outer parts. Bottom left: velocity field at 22'' resolution. The iso-velocity contours are separated by 10 km s^{-1} running from 70 (blue) to 150 km s^{-1} . The small ellipse indicates the size and orientation of the optical disk (R_{25}). Right panels: position-velocity plots along the three white lines overlaid in the velocity field in the bottom left panel [16].

with the dwarf and a strong disturbance in the HI disk of NGC 4565. While there seems to be little doubt that this bending of the HI layer is due to the interaction with the companion, it is not clear whether there is any relationship with the warp. It is likely that, eventually, the companion will merge with NGC 4565.

2.2.7 NGC 6946

Fig. 5 (top left) shows a total HI image of NGC 6946 down to column density levels of $1.3 \times 10^{19} \text{ cm}^{-2}$ [16]. At about $36'$ ($\sim 70 \text{ kpc}$) to the north-west there are two small companions. An intriguing feature in the HI image of NGC 6946 is the plume to the north-west. This is 20 kpc long and blends smoothly (also kinematically) with the HI disk of NGC 6946. A lower limit

to its HI mass is $7.5 \times 10^7 M_\odot$. This is similar to the HI masses of the companions ($1.2 \times 10^8 M_\odot$ and $8.8 \times 10^7 M_\odot$). Although the plume is in the same range of radial velocities as the two companion galaxies there is no detected connection with them. As in many other cases of peculiar features found around galaxies, it is not clear what its origin is and whether this is new material arriving from outside or whether it is the result of a tidal perturbation of the outer gaseous layer of NGC 6946. It might even be the accretion, seen at an advanced stage, of a third companion galaxy similar in mass to the other two.

In NGC 6946 there is further evidence pointing to a possible infall of material from outside. In the first place there are the striking spiral arms in the outer HI disk (see section 3.1.5), well outside the bright stellar disk and the regions of star formation. Secondly, in the arm-interarm regions and following the spiral arms, there are strong velocity wiggles. These wiggles, clearly visible in the velocity field (Fig. 5, bottom left), are abrupt velocity deviations from circular motion reaching amplitudes of about 50 km s^{-1} (see p-v plots in the right panels of Fig. 5). The corresponding troughs in the HI density distribution seem to indicate that the HI layer has been punched by infalling clumps of material. The picture is similar to that seen in M 101 and attributed to collision with intervening gas clouds.

The high resolution HI image of NGC 6946 is shown in Fig. 10, where it is compared with optical images, and the extra-planar HI is discussed below in subsection 3.1.5.

2.3 Frequency of accretion events

How frequent are the interactions of galaxies with small companions and what is the fraction of galaxies with peculiar morphology and kinematics? What is the rate of accretion expected from all these presumed minor mergers? In the past years, a large number of galaxies have been mapped in HI with the WSRT, the Very Large Array (VLA), the Australia Telescope Compact Array (ATCA) and the Arecibo radio telescope. A first estimate made on the basis of about one hundred galaxies led to the conclusion [110] that at least 25% of field galaxies show signs of either present or recent tidal interactions. The incompleteness and inhomogeneity of the sample examined made such an estimate rather uncertain. An HI survey carried out for a magnitude and volume limited sample of galaxies from the Ursa Major cluster [139] provides more solid statistical evidence on the frequency of tidal interactions and of accretion phenomena. This cluster differs from Virgo or Coma type clusters. It has a low velocity dispersion and long crossing time, comparable to the Hubble time. It has no central concentration and no detected X-ray emission and the sample is dominated by late-type systems. It can be considered, therefore, representative for a galaxy population in the field. Out of the 40 galaxies mapped in HI, about 10 show clear signs of interactions with small companions or have peculiar structures. About half of the sample galaxies show asymmetries in their kinematics or in the HI density distribution. A larger sample of galaxies is the one provided by WHISP [134]. About 25% of 300 spirals and irregulars show evidence of minor interactions.

In conclusion, the available evidence from HI observations indicates that at least 25% of field galaxies are undergoing now or have undergone in the recent past some kind of tidal interaction. The lifetimes of the observed features are typically ~ 1 Gyr. If lumps of gas with HI masses of order $10^{8-9} M_{\odot}$ (as indicated by the 21 cm observations) are accreted at a rate of 1 per 10^9 yr, the mean accretion rate for the gas would be around $0.1 - 0.2 M_{\odot} \text{ yr}^{-1}$. This is certainly a lower limit for gas accretion as a fraction of the HI involved in the interaction may be undetected and neither ionized hydrogen nor helium have been considered. Furthermore, the number of past interactions and mergers may be higher. Indeed, if one is willing to accept also the lopsided structure and kinematics as evidence (see below), as also proposed in optical studies [145], then the conclusion would be that more than 50% of present day galaxies have been through one or more merger events in a recent past. In such a case the accretion rate would be difficult to estimate, but it could be considerably higher than the values given above.

3 Extra-planar HI

3.1 Galaxies with HI halos

The presence of cold gas in the halo region of disk galaxies (extra-planar gas) is well established. For a small number of systems (Table 2) seen at various inclination angles and, in particular, for the edge-on galaxy NGC 891 (see Fig. 6) there is now detailed information on the HI structure and kinematics. This has been obtained from very deep observations with the WSRT and the VLA. Also the HVCs of our galaxy (at least the largest) are now regarded, as a result of the recent distance determinations [141; 142], as a Galactic halo population. The analogy between the Galactic HVCs and the high-velocity HI in external galaxies has been discussed by Oosterloo (2004) [84].

What is the origin of the extra-planar gas? Undoubtedly, a large fraction has originated from the disk as an effect of star formation. The mechanism is that of a “galactic fountain” in which hot gas rises into the halo, condenses into cold clouds and returns to the disk (first suggested by Shapiro & Field 1976 [118]; see also [22]). There are various indications from the HI observations that extra-planar gas is indeed driven by star formation. One is the distribution of the extra-planar HI in NGC 891, which is concentrated very close to the star-forming disk (see 3.1.3). Another is the remarkable concentration of the majority of the high-velocity clouds in NGC 6946 (see 3.1.5) in the direction of the bright inner disk.

However, there is also evidence that a fraction of the extra-planar gas must be infall from intergalactic space. This is indicated primarily by the low metallicity of the HVCs, which points directly to an external origin: infall of pristine gas clouds or gas-rich dwarf companions. Similarly, in other galaxies, such infall is supported by the presence of huge HI filaments and clouds with peculiar motions. An argument in favour of accretion may also come from the large-scale kinematics of the halo gas, which is characterized by rotational velocity gradients along the z direction and a global inflow motion. It has been suggested that such kinematics can be explained by the interaction between

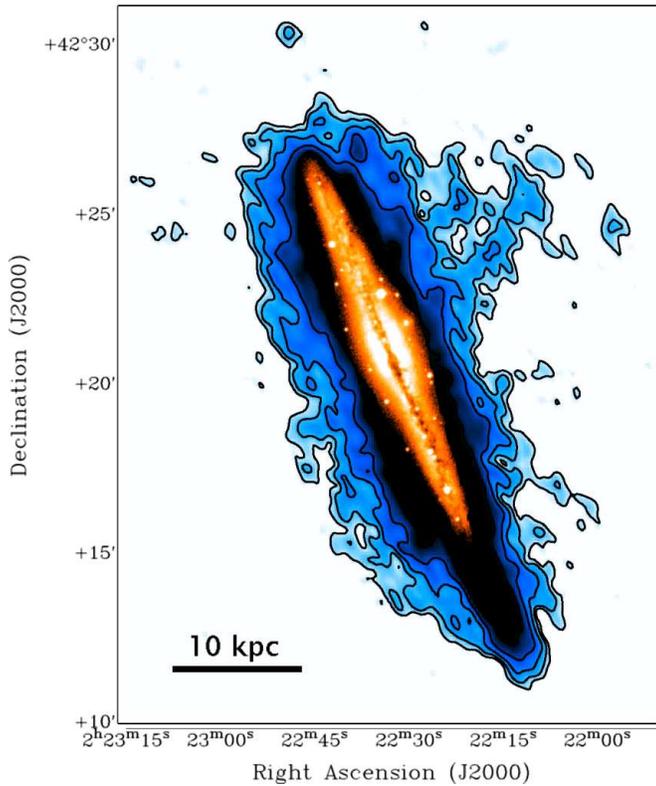


Fig. 6 Optical DSS image (red) and total HI map (contours + blue shade) of the edge-on galaxy NGC 891. HI contours are at $1, 2, 4, 8, 16 \times 10^{19}$ atoms cm^{-2} [85]. The beam size is $25'' = 1.1$ kpc.

the fountain gas and infalling gas, which carries low angular momentum [40]. However, the gradients by themselves may not necessarily require infall (e.g. [5]).

Here, we give a short review of the main, relevant observational results and we end with estimates of accretion rates. We describe the observations for the best cases known. For the edge-on galaxies (e.g. NGC 891) the extent and structure of the halo are observed directly and the rotational velocities are measured at various distances from the plane. In galaxies at lower inclination angles, such as NGC 2403 and NGC 6946, the presence of extra-planar gas is inferred from the observed anomalous kinematics (high velocities, slow rotation). Indeed, it is this anomalous kinematics that is used to separate the extra-planar gas from the thin disk. In particular, in NGC 6946, which is closer to face-on, one sees a large number of clouds with high velocities, i.e. with large velocity deviations from circular motion, which can be unambiguously separated from the differentially rotating disk. It should be emphasized that all these galaxies are not undergoing strong gravitational interactions and, therefore, the observed high-velocity structures are not tidal features.

Table 2 Extra-planar gas in spiral galaxies

Galaxy	Type	incl (deg)	v_{flat} (km s^{-1})	M_{HIhalo} ($10^8 M_{\odot}$)	$\frac{M_{\text{HIhalo}}}{M_{\text{HItot}}}$ (%)	Ref.
Milky Way	Sb	-	220	> 0.2	$> 1^a$	[141]
M31	Sb	77	226	> 0.3	> 1	[127]
NGC 891	Sb	90	230	12	30	[85]
NGC 6946	Scd	38	175	> 2.9	> 4	[15]
NGC 4559	Scd	67	120	5.9	11	[4]
NGC 2403	Scd	63	130	3	10	[37]
UGC 7321	Sd	88	110	$\gtrsim 0.1$	$\gtrsim 1$	[77]
NGC 2613	Sb	~ 80	~ 300	4.4^b	5	[27]
NGC 253	Sc	~ 75	~ 185	0.8	3	[14]

^a Only HVCs (IVCs not included); ^b from sum of the various extra-planar clouds.

3.1.1 Milky Way

The High-Velocity Clouds (HVCs) of neutral hydrogen in our galaxy [140] (see also recent review by Van Woerden et al. (2004) [137]) (Fig.7, top panel) have been considered since their discovery as possible direct evidence for infalling gas. The lack of information on their distances and therefore on their masses has been, however, a major obstacle. It has even been proposed that they are a population of clouds in the Local Group of Galaxies [11]. Recently it has been possible, through the study of absorption lines in the spectra of stars, to set distance brackets on some of the largest and more massive clouds like complex A (8–10 kpc, [138]) and complex C (3.7–11.2 kpc, [141]). For this latter, the conclusion is that it must be located high above the Galactic plane ($z=3-9$ kpc) and at a Galactocentric radius $R < 14$ kpc. Its mass estimate is $3 - 14 \times 10^6 M_{\odot}$, its metallicity is 0.15 times solar. Such low metallicities, also found for other HVCs [138], establish that most of this gas must be fairly pristine and hence of external origin (from gas-rich dwarfs or intergalactic clouds) and not ejected from the disk. The mass inflow is estimated at $0.1-0.25 M_{\odot} \text{ yr}^{-1}$, including ionized hydrogen and a 40% contribution from helium. The masses and sizes of these HVC complexes are similar to those of the filaments found in NGC 891 and in NGC 2403 and reported below. The Intermediate-Velocity Clouds (IVCs) form a component closer to the Galactic layer. It is now clear that IVCs and HVCs are a halo population of the Milky Way, analogous to the gaseous halos found in external galaxies. Indeed, seen from outside, the halo of our galaxy (IVCs included) might well look like the halos of NGC 891 and NGC 2403.

3.1.2 M31

HI observations with the Green Bank Telescope (GBT) by Thilker et al. (2004) [127] have revealed a population of faint HI clouds (at least 20) surrounding M31 within 50 kpc of its disk (Fig. 7, middle left) and with radial velocities comparable to those of the outer disk rotation. The masses of these

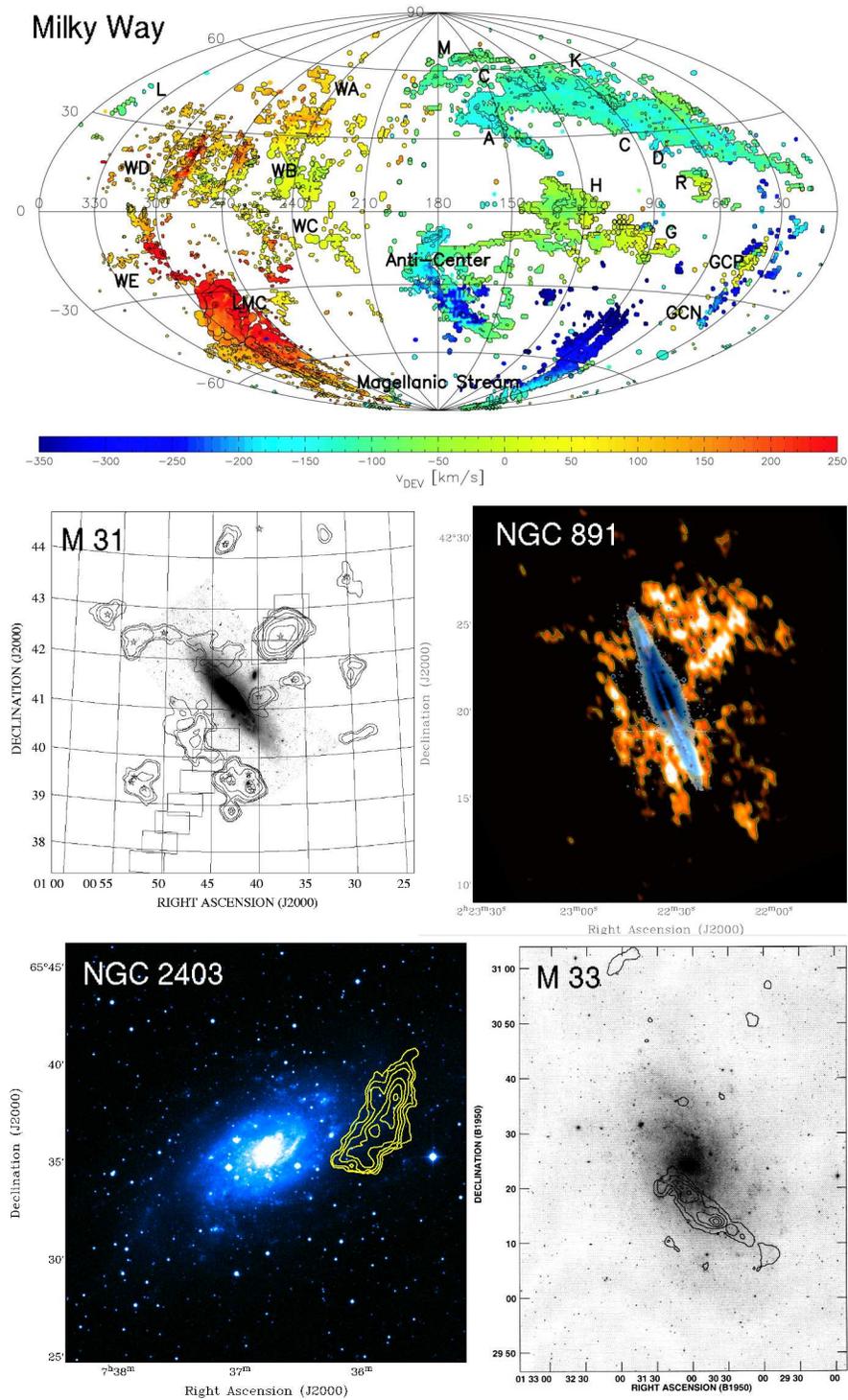


Fig. 7 Examples of extra-planar gas complexes around nearby galaxies. From top: High-Velocity Clouds in the Milky Way, extra-planar gas features in M 31 and NGC 891. The bottom panels show two massive HI filaments in NGC 2403 and M 33.

clouds are in the range $10^5 - 10^7 M_\odot$. In addition, a filamentary component of at least 30 kpc extent is concentrated at the M31 systemic velocity. Thilker et al. argue that all this gas is associated with M31. The total amount of HI for the halo cloud population within the GBT field is estimated to be $\sim 3 - 4 \times 10^7 M_\odot$, which is only 1% of the mass of the HI disk of M31. This is probably a lower limit. For the origin of this M31 halo Thilker et al. suggest various possibilities: a Local Group cooling flow, tidal debris from recent mergers or the gaseous counterpart of low-mass dark matter halos.

3.1.3 NGC 891

The nearby edge-on galaxy NGC 891 has been observed in HI a number of times over the past three decades with increasing sensitivity [108; 102; 123; 85]. With the sensitivity improvement by about a factor of 50 from the first to the latest observations (Fig. 6, see also [85]) it has been possible to trace the HI emission in the vertical direction to 22 kpc from the plane, whereas the size of the HI disk (as measured along the major axis) has remained unchanged [85]. Radially, the halo extends to the end of the disk on the N-E side but stops earlier on the S-W side where the disk is more extended. This is an indication that the main bulk of the halo is closely connected to the inner disk of NGC 891 where star formation is higher. The mass of the HI halo is about $1.2 \times 10^9 M_\odot$, $\sim 30\%$ of the total HI mass. Its kinematics is characterized by a slower rotation with respect to the disk, with a vertical gradient of $-15 \text{ km s}^{-1} \text{ kpc}^{-1}$ [38]. The same gradient has been found also in the ionized gas [48]. In addition there is, at velocities close to systemic, a remarkable filament extending up to 22 kpc from the plane and containing $1.6 \times 10^7 M_\odot$. There are also other structures and in particular some clouds with anomalous (counter-rotating) velocities and masses of $1 - 3 \times 10^6 M_\odot$.

In Fig. 7 we show the optical picture of NGC 891 surrounded by the HI left after subtraction of a “normal” (symmetrical, smooth, regular) disk and halo component (models from Oosterloo et al. 2007, Fig. 14 [85]). The features seen here, some of them (e.g. the filament) recognizable in Fig. 6, represent the HI around NGC 891 which is the most peculiar for its location and kinematics. Their total mass is about $1 \times 10^8 M_\odot$. We believe that these features may be regarded as the analogue of the HVCs in the Milky Way.

NGC 891 has also a small, gas-rich companion (UGC 1807) at about 80 kpc (projected distance) and 100 km s^{-1} higher radial velocity and with about one tenth of the total mass of NGC 891.

3.1.4 NGC 2403

For other galaxies seen at intermediate inclinations (NGC 2403 [113; 37] and NGC 4559 [4]) or more “face-on” (M 101 and NGC 6946) the presence of gaseous halos has been inferred from the anomalous velocities. In NGC 2403 and NGC 4559 the signature is the asymmetric velocity shape of the HI line profiles (Fig. 8, bottom left). The deep HI observations of NGC 2403 with the VLA and a careful 3-D modelling [36] have led to conclusions very similar to those obtained for the edge-on NGC 891. Also in NGC 2403 there is a

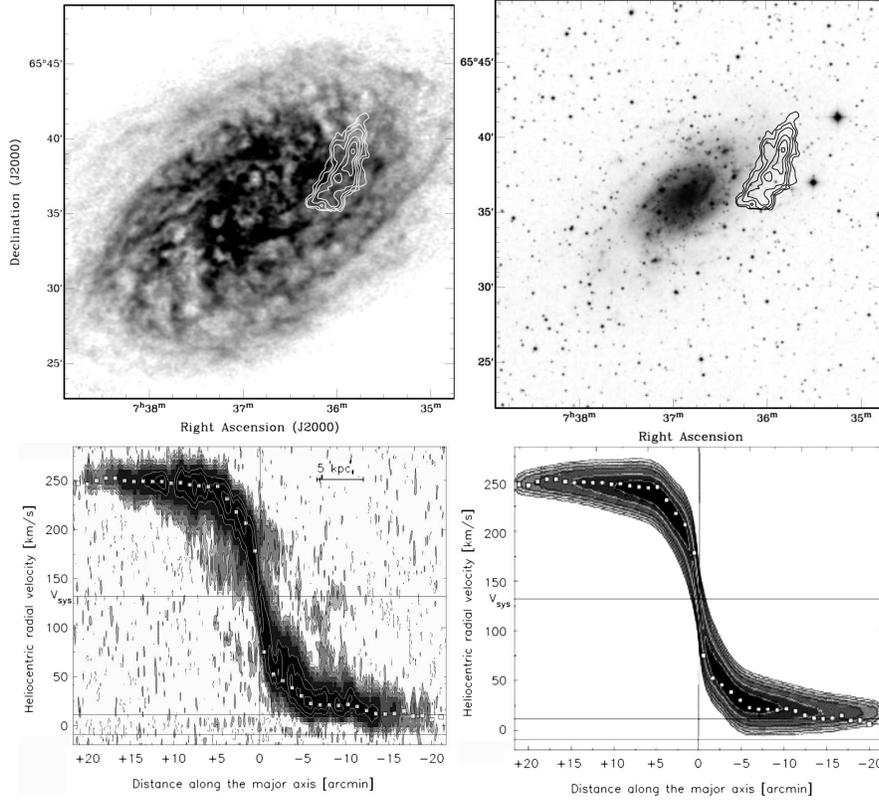


Fig. 8 Top panels: total HI (VLA) map (left) and optical DSS image (right), on the same scale, for the spiral galaxy NGC 2403. The contours show a 8-kpc long HI filament kinematically decoupled from the bulk of the disk gas. Bottom panels: comparison between the HI position-velocity plot along the major axis of NGC 2403 and the prediction for a thin disk model (right panel). The gas at anomalous velocities, not visible in the model, is extra-planar gas [37].

vertically extended (a few kpc) gas component with lagging rotation. It has a total mass of about $3 \times 10^8 M_{\odot}$ ($\sim 10\%$ of the total HI mass) and contains long filamentary structures. In addition to its lagging rotation, the halo gas has a large-scale inflow motion of about 15 km s^{-1} toward the center of the galaxy.

The most striking filament (Fig. 8 upper right, and Fig. 7 bottom left) has coherent (narrow) velocity structure (with radial velocities close to systemic), it is 8 kpc long and contains about $1 \times 10^7 M_{\odot}$. It is seen projected on the outer parts of NGC 2403, beyond the bright optical disk. This is similar to the filament found in the halo of NGC 891 and to the one found in M 33 (Fig. 7, bottom right) (J.M. van der Hulst, unpublished data). It is also close in size and mass to the largest Milky Way’s HVCs like complex C. Such filaments are the most remarkable and extreme structures found in the halo regions

of these galaxies (Fig. 7). They may be quite common among spirals and be direct evidence of cold gas accretion from intergalactic space (see 3.2).

3.1.5 NGC 6946

NGC 6946 is a bright, nearby spiral galaxy of Hubble type Scd (inclination angle 38°) which has been studied in HI several times [100; 125; 19; 61]. It was in this galaxy that Kamphuis and Sancisi (1993) [61] found evidence for an anomalous-velocity HI component which they interpreted as an outflow of gas from the disk into the halo as a result of stellar winds and supernova explosions. A more recent, very sensitive and detailed study of the anomalous HI and of the HI disk has been carried out by Boomsma (2007) [16] with the WSRT. The density distribution in the HI disk is characterized by the presence of a large number of holes of diameters up to 2 kpc. The average amount of HI missing from each hole is about $1 \times 10^7 M_\odot$, the total amount is $1.1 \times 10^9 M_\odot$. Widespread high-velocity gas has been detected amounting to a total of $2.9 \times 10^8 M_\odot$ (4% of the total HI mass) and deviating by $> 50 \text{ km s}^{-1}$ from local disk rotation. This gas is made of clumps and filaments of various sizes and most of it is seen projected against the $H\alpha$ bright inner disk of NGC 6946, which suggests a close relationship with the regions of star formation. A large part of it must be in the halo of NGC 6946, although its distance from the plane is not known. It follows the galaxy's differential rotation but there are clear indications that it is rotating more slowly than the gas in the disk. Overall, the picture is very similar to that of NGC 2403, and the conclusion reached by Boomsma (2007) [16] is that the disk of NGC 6946 is surrounded by a lagging HI halo similar to the halos found for NGC 891 and NGC 2403. The outer parts of the disk of NGC 6946 are discussed in subsection 2.2.7.

3.1.6 Other galaxies

There is, in addition to the galaxies described above, a number of other objects in which extra-planar gas (or traces of it) has been found. Some of these are Low Surface Brightness (LSB) galaxies, others have high surface brightness as those just described above or are even starbursts.

Matthews and Wood (2003) [77] find evidence for vertically extended HI emission up to 2.4 kpc in the edge-on, superthin LSB galaxy UGC 7321. They find tentative evidence that the vertically extended gas has declining rotational velocity as a function of z . They estimate the HI mass of the halo (above ~ 1.4 kpc) to be $\sim 1 \times 10^7 M_\odot$. This value is approximately 15 times lower than the fractional HI content (ratio between gas above 1.4 kpc and gas in the disk) at comparable z -heights in NGC 891. In a similar, superthin LSB galaxy, IC 2233, Matthews and Uson (2007) [78] report a component of "anomalous" extra-planar gas. Also in the LSB galaxy NGC 4395 (see Section 5), Heald & Oosterloo (2008) [49] find HI cloud complexes with anomalous velocities, and presumably located in the halo, with masses of a few $\times 10^6 M_\odot$ each and, in total, about 5% of the HI content of that galaxy.

In the starburst galaxy NGC 253, Boomsma et al. (2005) [14] find extra-planar HI concentrations reaching as high as 12 kpc above the disk. The gas seems to be lagging in rotation and has a total HI mass of $8 \times 10^7 M_\odot$. In the spiral galaxy NGC 4559, Barbieri et al. (2005) [4] find extra-planar HI with properties similar to those found for NGC 2403. Several high-latitude HI features are observed in NGC 5775 [73] and NGC 2613 [27; 57]; however, in the first case there is evidence for a strong interaction with the companion galaxy NGC 5774 [56].

3.2 Accretion rate

The fraction of HI present in the halo of spiral galaxies seems to vary considerably from galaxy to galaxy (see Table 2). However, only for a few cases there are good estimates of the amounts of HI gas in the halo. These range from about $3 \times 10^8 M_\odot$ for NGC 2403 ($\sim 10\%$ of the total HI) [37] to $1.2 \times 10^9 M_\odot$ (about 30% of total) found for NGC 891 [85]. In our galaxy, the HVCs probably are only a small fraction of the extra-planar HI and should be regarded as an “extreme” population. Clearly, for a better estimate and a proper comparison with external galaxies such as NGC 891, one should include the IVCs together with the HVCs.

To date, the number of objects studied with sufficient sensitivity and angular resolution is very limited and it is not possible yet to investigate possible dependencies on morphology, luminosity, surface brightness or star formation activity. However, concerning the origin of extra-planar gas, there seems to be little doubt that, in high surface brightness galaxies, galactic fountains are responsible for a large part of it; but accretion from IGM is also taking place. Low surface brightness galaxies are more intriguing: galactic fountains, if present at all, are expected to play a less important role and yet the observations of the LSB galaxies UGC 7321, IC 2233 and NGC 4395 do reveal the presence of some extra-planar gas. Unfortunately most of these observations are not deep enough to trace the halo emission to large heights and to obtain a good estimate of the extra-planar HI mass.

Accretion rates for extra-planar gas have been estimated using different techniques. Values for the gas accretion rate around 0.1 to $0.25 M_\odot \text{ yr}^{-1}$ have been reported for the HVCs of our galaxy [141]. These include ionized gas and helium. The observations of some of the galaxies discussed here (NGC 891, NGC 2403 and M 33) have revealed the presence of filamentary structures in their halos which are, like the HVCs, most likely of external origin. The main argument in favour of this interpretation is their high kinetic energy requirement (of order $10^4 - 10^5$ supernovae). Moreover, some gas complexes are observed at forbidden (“counter-rotating”) velocities (see e.g. [85]), which suggests material not dynamically linked to the galaxy disk. One expects that the metallicities (not known) of all these filaments and gas complexes are as low as those found for the HVCs. If we assume that all these features are accreted gas, we get values for the “visible” accretion rate of $0.1 - 0.2 M_\odot \text{ yr}^{-1}$ (HI only), similar to the values obtained for the HVCs of the Milky Way. This is of the order of 10% the SFR in spirals like NGC 891 and NGC 2403, and also in the Milky Way.



Fig. 9 Composite optical (yellow) and HI (blue) image of the dwarf galaxy NGC 2915 from Meurer et al. (1996) [81].

The actual accretion rate may, however, be significantly higher and reach values approximately equal to the SFR, as a large fraction of the accreting gas may already be mixed with the fountain gas coming from the disk. Such mixing could solve the problem of the peculiar kinematics of the extra-planar gas (negative rotational gradients and inflow) which cannot be reproduced in purely galactic fountain models [28; 48; 39]. Fraternali & Binney (2008) [40] have explored this possibility by including accretion of low angular momentum gas from the IGM in their models, and have calculated the amount of accreting material necessary to reproduce the observations of NGC 891 and NGC 2403. They have found that the accretion rates needed are very close to the respective SFRs.

In conclusion, the extra-planar gas seems to consist of two parts: a large one from galactic fountains and a smaller part accreted from intergalactic space. There is direct (HVCs in our galaxy and filaments in external galaxies) and indirect (rotational velocity gradients) evidence for the accretion from outside. Accretion rates range from a minimum of about $0.1 - 0.2 M_{\odot} \text{yr}^{-1}$ to values possibly ten times higher, as needed to meet SFR requirements. It is clear that the observed extra-planar gas cannot be purely and totally made up from accretion: on the one hand, accretion rates would be unrealistically high ($\sim 30 M_{\odot} \text{yr}^{-1}$ for NGC 891), and, on the other, there is strong observational evidence that galactic fountains do take place and have a major part in building up the halo (see 3.1).

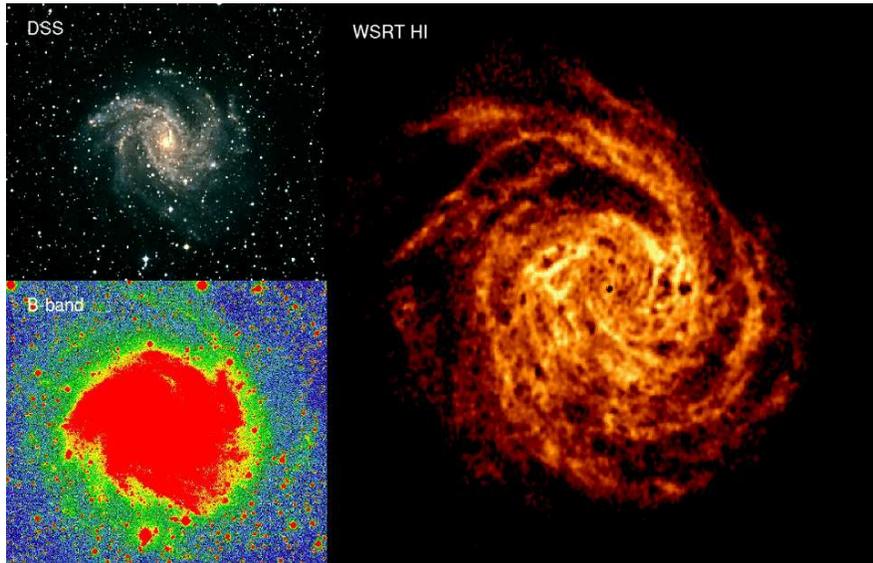


Fig. 10 Comparison between optical images and total HI map for NGC 6946. All images are on the same scale. Top left: colour composite of the Digitized Sky Survey plates. Bottom left: deep B-band image from Ferguson et al. (1998) [33]. Right: deep WSRT total HI map from Boomsma (2007) [16]. Column densities range from 6×10^{19} atoms cm^{-2} to 3×10^{21} atoms cm^{-2} .

4 Extended, warped HI outer disks

The HI disks of the large majority of spiral galaxies are known to extend considerably beyond the bright optical disk. Broeils and Rhee (1997) [24] find for the ratio of the HI radius (defined at a surface density level of $1M_{\odot} \text{pc}^{-2}$, $N_{\text{H}} = 1.3 \times 10^{20}$ atoms cm^{-2}) to the optical radius (R_{25}) an average value $R_{\text{HI}}/R_{25} = 1.7 \pm 0.5$. In some cases the HI extends much further out, to several optical radii. Striking examples are DDO 154 [69], NGC 4449 [1], NGC 2915 [81], and NGC 3741 [8; 43]. This large extent of the HI disks has made it possible to trace the rotation curves far beyond the bright stellar disk and thus provide the crucial evidence for the existence of dark matter in spiral galaxies. We consider the possibility that these outer layers have accumulated from tidal debris or infall of gas clouds, as described in section 2, and that they now form a reservoir of fresh gas for fuelling star formation in the inner regions.

Here, we show the HI images of the blue compact dwarf galaxy NGC 2915 (Fig. 9, [81]) and of the two spiral galaxies NGC 6946 (Fig. 10, [16]) and NGC 5055 (Fig. 11, [7]). Generally, in the galaxies studied with sufficient resolution, the outer HI layers show spiral features (see e.g. NGC 5055). Strong spiral arms are seen in the outer parts of NGC 6946; well-developed arms are also observed in the low luminosity galaxies NGC 2915 and NGC 3741 [43]. It is remarkable that there is such pronounced spiral structure in the outer regions of spirals where dark matter dominates and even in the dwarfs

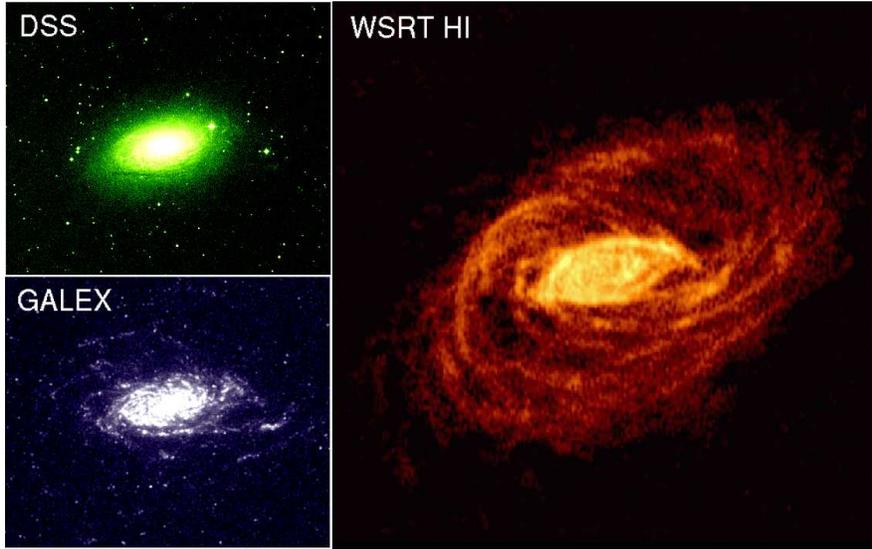


Fig. 11 Optical (DSS), GALEX and WSRT HI images of the warped galaxy NGC 5055 (all on the same scale). Column densities range from about 3×10^{19} atoms cm^{-2} to 1×10^{21} atoms cm^{-2} [7].

where the dark halo is believed to be predominant everywhere. The question is, therefore, whether these systems have light disks surrounded by massive dark halos or, rather, have heavy and dark disks.

These gaseous outer parts of disks are usually warped. This is especially clear in edge-on galaxies. In systems viewed at lower inclination angles, the warping is inferred from the velocity field. Prominent examples of warps are those of the edge-on galaxies NGC 5907 [107; 117] and NGC 4013 [18], shown in Fig. 12, and of the less inclined galaxy NGC 5055 [7] shown in Fig. 11. These are also among the most symmetrical. In general, warps are quite asymmetric, like the warp of our galaxy. Warps seem to be quite common: according to Bosma (1991) [17] the fraction of warped HI disks is at least 50%. A recent HI study of 26 edge-on galaxies [42] has shown that 20 galaxies are warped and that all galaxies with HI extending beyond the stellar disk are warped to some degree. There are also edge-on galaxies, such as NGC 4565, which clearly show the presence of an optical warp. As a result of a statistical study of 540 edge-on galaxies, Reshetnikov & Combes (1999) [96] present a sample of 60 of the clearest and strongest among the 174 S-shape optical warps found. The existence of stellar warps is not surprising. In a galaxy seen less inclined, such as NGC 5055, it is possible to see from its GALEX image (Fig. 11, see also [128]) that stars have formed in the warped gaseous layer, in correspondence with the HI spiral features. The systematic properties of warps have been investigated by Briggs (1990) [23] and more recently by Jozsa (2007) [59].

Although various possibilities for the origin and persistence of warps have been discussed, there still is no satisfactory explanation. The possibility that

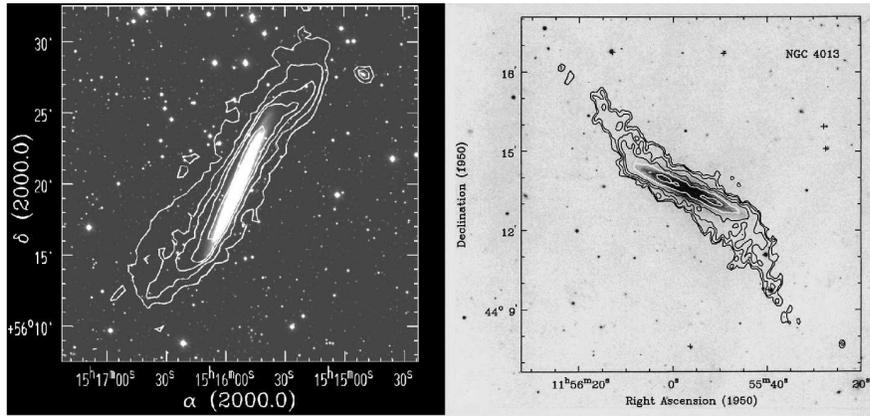


Fig. 12 Total HI maps (contours) of two warped edge-on galaxies overlaid on optical images. Left: NGC 5907 from Shang et al. [117]. Right: NGC 4013 from Bottema et al. [18].

warps are the consequence of accretion of gas with a slewed angular momentum due to cosmic infall has been suggested by Ostriker & Binney (1989) [87] and by Jiang & Binney (1999) [58].

The amount of HI located in the outer parts of spiral galaxies, beyond R_{25} , is on average approximately equal to the amount of HI in the bright inner stellar disk [24]. It ranges, therefore, from 10^8 to $10^{10} M_{\odot}$ from the small to the large galaxies. Potentially, this gas represents a huge reservoir available for the replenishment of the inner disk where the star-formation rate is higher. As far as we know, however, there is no direct evidence for a radial inflow of this cold gas toward the centre. In the case of NGC 2403 such a radial inflow, of about 15 km s^{-1} [37], has been found for the halo gas, but not for the disk. The HI velocity fields would reveal the presence of large-scale inflows larger than 5 km s^{-1} . The signature is the non-orthogonality of major and minor axis. To our knowledge, no such inflow motions have been reported. In order to flow inward, the outer gas has to lose part of its angular momentum. It is not clear how this can happen and, therefore, whether such a process of inflow would work. An overall radial motion is probably unrealistic. However, often the outer HI is not in circular orbits: bars, oval distortions and lopsided structures (see Section 5) are very common and may play a role. As an example, to reach an infall rate of $1 M_{\odot} \text{ yr}^{-1}$ one would need to move about $2 \times 10^9 M_{\odot}$ of gas from the outer to the inner parts with a radial inward speed of 5 km s^{-1} . This would take about 2×10^9 yr.

In conclusion, the possibility envisaged here is that gas accreted from satellites or directly from the IGM is deposited in the outermost parts of galactic disks. These outer layers of gas and, to some extent, also stars are characterized by spiral features and large-scale warping. They form a reservoir of gas which in turn could, from there, slowly migrate to replenish the inner parts of galaxies.

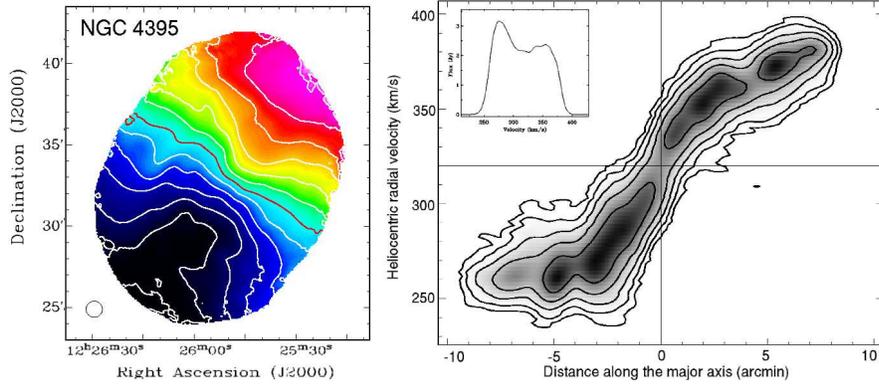


Fig. 13 Left: velocity field of NGC 4395 at $1'$ resolution (blue is approaching). The contours are at 10 km s^{-1} intervals and range from 260 km s^{-1} (SE) to 380 km s^{-1} (NW). Right: position-velocity plot along the major axis of NGC 4395 and global HI profile (Heald & Oosterloo 2008, in preparation).

5 Lopsidedness

Infall of substantial amounts of gas and stars may have observable effects on the disks of spiral galaxies. One of these is the lopsidedness in the HI density distribution and in the disk kinematics, which has been known for many years and seems to be a common phenomenon among spirals. Since the first study [3], based on a small number of objects, much new evidence has become available. The frequency of asymmetries among spiral galaxies has been estimated from the global HI profiles of a large sample of field galaxies [97]. Examples of asymmetric global HI profiles are shown in Fig. 2 for M 101 and in Fig. 13 for NGC 4395. About 20% of the systems examined showed strong asymmetries and up to more than 50% of the whole sample showed some mild asymmetries. This result has been confirmed by a 21-cm HI survey of 104 isolated galaxies with the Green Bank 43-m telescope [46] and also by more recent observations which image the HI distribution and the kinematics of a large sample of galaxies (WHISP). At least one half of about 300 objects from WHISP shows some lopsidedness either in the HI distribution or in the kinematics or in both. Deviations from axial symmetry seem, therefore, to be the rule rather than the exception. It should be noted that, in general, these lopsided galaxies are not interacting systems and that, therefore, the lopsidedness cannot be explained as a present tidal effect.

The lopsidedness is generally present in the HI density distribution as in M 101 (see Fig. 2) and also in the kinematics. In some cases, such as NGC 4395 (see Fig. 13), the asymmetry is only seen in the kinematics: on one side of the galaxy the rotation curve rises more slowly (almost solid body) and reaches the flat part at larger radii than on the other side. This is the signature of the kinematic lopsidedness as discussed by Swaters et al. (1999) [124]. In such cases there seems to be a well-defined pattern that pervades the whole velocity field and may be related to a lopsided potential.

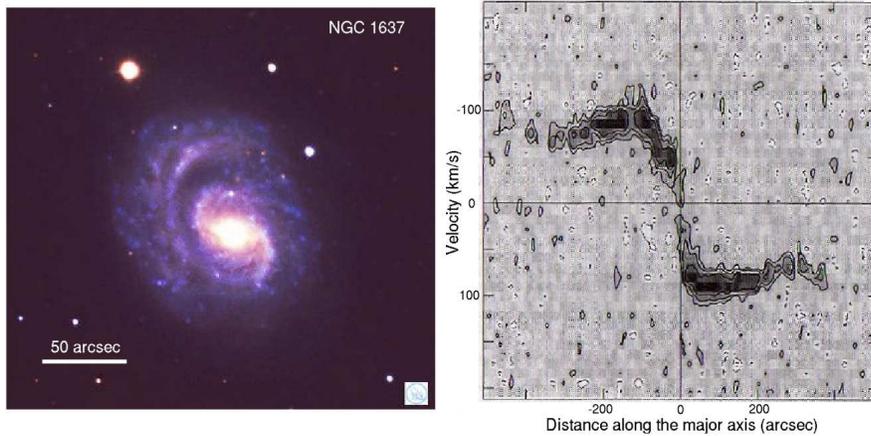


Fig. 14 Left: optical image of NGC 1637. Right: position-velocity plot along the major axis of NGC 1637 [99], North is on the left.

Although the morphological lopsidedness is most clearly seen in the HI data, there is often evidence of asymmetries also in the distribution of light, in the B-band as well as in the I and K bands [98; 145; 65]. One of the most striking cases is that of the spiral galaxy NGC 1637 (Fig. 14), which is exceptionally lopsided in blue light as well as in the near infrared [12], indicating that the lopsidedness is present not only in the young stellar population but also in the old stellar disk. In this galaxy there is clear evidence for a kinematical anomaly associated with the morphological asymmetry. Indeed, HI observations with the VLA [99] reveal a peculiarity in the velocity structure in correspondence with the northern anomalous arm. This shows up as a step in the position-velocity diagram along the major axis (at about $-60''$ in the p-v diagram in Fig. 14) implying a local deviation of at least 50 km s^{-1} from circular motion. This peculiar feature closely resembles the strong kinematic anomaly and the strong HI arm in the southern part of M 101 [61]. This suggests that the lopsidedness of NGC 1637 is not only manifest in the optical appearance, but it is also present in the disk dynamics. As Block et al. [12] point out, this is either an extreme $m=1$ asymmetry, and in such case its persistence should be explained, or it is the effect of a recent tidal interaction. We note that no companion for NGC 1637 is found on the Palomar Observatory Sky Survey within one degree.

All these facts suggest that the phenomenon of lopsidedness in spiral galaxies is quite common and structural for the disk. It is not clear what its origin is and how persistent it is. Minor mergers [145] and tidal interactions [66] have been suggested as possible causes. Bournaud et al. (2005) [20], however, have found from numerical simulations that galaxy interactions and mergers are not sufficient to explain all the properties of the observed lopsided galaxies and have concluded that cosmological accretion of gas on galactic disks must be responsible. At any rate, it seems likely that many of the asymmetries, especially some of those revealed by the HI distribution and

kinematics, as for instance in M101, are transient phenomena and are due to recent accretion events such as those described above in Section 2.

6 Intergalactic HI clouds

In the previous sections we have discussed direct and indirect evidence on the accretion of cold gas in galaxies. We have argued that part of this accretion may come from the merging with gas-rich dwarf companions and part may come *directly* from the IGM in the form of gas clouds or filaments without stellar counterpart. It is natural, therefore, to ask what is the role of dwarfs in bringing in the gas and whether HI clouds exist in intergalactic space, away from galaxies.

Several observations of the fields around galaxies and of groups similar to the Local Group have been undertaken [146; 31; 92; 93] as well as large blind surveys, such as HIPASS [6] and the ongoing large survey ALFALFA (e.g. [44]). Most of these observations have a sensitivity to detect clouds of HI with a mass of about $10^7 M_\odot$ (assuming a profile width of 30 km s^{-1}). One survey [67] has the sensitivity (over large volumes of space) to detect smaller objects, down to masses of $10^6 M_\odot$.

The results can be summarized as follows:

i) There is no evidence for a significant population of isolated HI clouds (so-called dark galaxies) in the IGM. Kovač (2007) finds no clouds without optical counterpart down to $10^6 M_\odot$. The first results from ALFALFA show that only 3% of their HI sources are not detected in the optical [47; 45]. There is a hint in Kovač's survey, that galaxies with low HI masses are missing in the Local Volume. This could indicate that there is a lower limit to the gas mass of field galaxies of around a few times $10^6 M_\odot$.

ii) In galaxy groups no clouds are detected, with detection limits of $10^7 M_\odot$. By analogy, this is an argument against the hypothesis that the HVCs are members of the Local Group with masses above $10^7 M_\odot$ [11], in line with the recent distance determinations [141; 142] and with the conclusion that HVCs are located in the Galactic halo (see Section 3.1.1) and have masses lower than $10^7 M_\odot$.

These results also agree with what is known from the very deep HI observations of some nearby galaxies, like those of NGC 891 and NGC 6946 reported above. Although the areas surveyed around these galaxies are not very extended, as they usually correspond to only a few times the galactic HI images, they do seem to be empty and, remarkably, all the clouds detected (with masses of $10^6 - 10^7 M_\odot$) are located very close to or within the halo regions of the galaxies. Yet, some of these clouds are likely to have an intergalactic origin and not to be the result of galactic fountains.

To sum up, there is no evidence for the presence of a population of gas clouds in intergalactic space capable of accounting for the gas now observed near galaxies (halos and surroundings) and, above all, capable of fuelling the whole process of star formation.

Could all the gas needed for star formation have been brought in by dwarf companions? The HI mass function shows that most of the HI in the local

universe is in large galaxies, with masses above about $10^9 M_\odot$ [147]. If we assume that large galaxies accrete gas only via minor mergers with smaller galaxies and we require that the rate of gas accretion is about $1 M_\odot \text{yr}^{-1}$ (\sim SFR), then all small galaxies would have been accreted by the large galaxies in a timescale of the order of 1×10^9 yr. Clearly, an accretion rate of $1 M_\odot \text{yr}^{-1}$ purely in the form of small galaxies cannot be sustained for much longer than one Gyr. This is inconsistent with the constancy of star formation in the Milky Way and also with the results of absorption studies of Damped Lyman Alpha (DLA) systems [94], which show that the cosmic integral HI mass density and the column density distribution of galaxies have evolved very little in the last 10 Gyr [148].

It is clear from the above considerations that constant gas accretion rates as high as required for star formation cannot be reached via mergers with satellite galaxies and that, therefore, a substantial amount of gas accretion must come *directly* from the IGM. Most of this accretion must take the form of gas clouds (or filaments). The reason why such clouds are not observed in intergalactic space remains an open question. Possibilities are that: i) the clouds are confined near the galaxies by the hot galactic halos, whereas they disperse in the IGM; ii) the clouds are intrinsically very small (smaller than $\approx 10^6 M_\odot$) and the accretion takes the form of a continuous drizzle of gas. Note that only the HI masses have to be small and a certain amount of dark matter cannot be excluded. iii) HI clouds are produced by large-scale cooling flows of the IGM in the regions surrounding the galaxies [63; 88].

7 Conclusion

We have drawn attention to a number of results from HI observations of nearby spiral galaxies which bear directly or indirectly on cold gas accretion. There are large HI complexes, with and without stellar counterparts, in the neighborhood of galaxies and in close interaction with them. There is little doubt about their extragalactic origin. Moreover, many galaxies have extra-planar gas components. Although most of this extra-planar gas must come from galactic fountains, a fraction of it, being in filaments and massive clouds like the Galactic HVCs, is likely to have an external origin. From the study of the gas seen in the neighborhood of galaxies and in their halos (the fountain gas excepted) we estimate a “visible” accretion rate of at least $0.2 M_\odot \text{yr}^{-1}$.

Furthermore, there are large amounts of HI, in the mass range $10^8\text{--}10^{10} M_\odot$, in the warped outer galactic disks which could be a gas reservoir for replenishing the inner parts and fuelling star formation. In some cases (e.g. NGC 5055) it is obvious that this gas, because of its symmetrical and regular structure and long timescales, must have been there for a long time (several Gyr). It is conceivable, however, that in other cases the outer gas layers have been accumulated from outside more recently and that warping and spiral arms are related to such a process. Finally, there is the phenomenon of disk lopsidedness, which is poorly understood, but may be pointing to recent infall. Although both the warped outer layers and the lopsidedness may well be the effect of accretion from intergalactic space, estimates of infall rates are difficult to obtain.

The visible gas accretion rate, estimated above, does not seem to be sufficient to account for the star formation in galaxies ($\approx 1 M_{\odot} \text{ yr}^{-1}$). Direct, indisputable evidence for the required levels of cold gas accretion does not exist. There is, however, the puzzle of the peculiar kinematics of the extraplanar gas (overall negative vertical gradients in the rotational velocities and inflow motion) that could be solved by invoking infall of gas from outside carrying low angular momentum. It seems that this would give accretion rates of the order of the SFRs.

Finally, the question arises of where the infalling gas, we hypothesized above, could originate from. Gas-rich dwarfs seem only to be able to account for a small fraction of the required gas and thus most of the accretion should come directly from the IGM. There is, however, no evidence for a population of large HI clouds in intergalactic space, in regions away from galaxies. Therefore, how and in what form gas infall onto galaxies takes place remains an open question and a challenge for future investigations.

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