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Abstract.
Evidence for the accretion of material in spiral galaxies has grown over the past years and clear signatures can be found in H I observations of galaxies. We describe here new detailed and sensitive H I synthesis observations of a few nearby galaxies (NGC 3359, NGC 4565 and NGC 6946) which show that indeed accretion of small amounts of gas is taking place. These should be regarded as examples illustrating a general phenomenon of gas infall in galaxies. Such accretion may also be at the origin of the gaseous halos which are being found around spirals. Probably it is the same kind of phenomenon of material infall as observed in the stellar streams in the halo and outer parts of our galaxy and M 31

1. Introduction

In this paper we present new evidence bearing on the formation of disks and halos of spiral galaxies through the accretion of small companions. This process is generally indicated as the nurture of galaxies. Evidence in support of it comes from various directions. The asymmetric shape of stellar disks (Zaritsky 1995 and Zaritsky & Rix 1997) and the morphological and kinematic lopsidedness observed in the H I density distributions and velocity fields of spirals (Verheijen 1997, Swaters et al. 1999) may have originated from recent minor mergers. Furthermore, there is an increasingly large number of galaxies which in H I show either peculiar features or clear signs of interactions with small companions (Sancisi 1999a and b). This indicates that galaxies often are in an environment where material for accretion is available.

Cold extra-planar gas has been found in several spiral galaxies. The best examples are those of NGC 891, NGC 2403 and UGC 7321 (cf. Oosterloo et al., Fraternali et al., Matthews, this volume). The origin of this gas is not known. It has been suggested that it may, at least partly, be the product of galactic fountains. But some of its structural properties suggest that it may have originated from minor mergers.

Recently, clear evidence that accretion events play an important role has come from studies of the distribution and kinematics of stars in the Milky Way halo. The discovery of the Sagittarius dwarf galaxy (Ibata et al. 1994) is regarded as proof that accretion is still taking place at the present time. Since such minor merger remnants retain information about their origin for a long time (Helmi & White 2000) studies of the distribution and kinematics of "stellar streams" can in principle be used to trace the merger history of the Milky Way (Helmi & de Zeeuw 2001). Such "stellar streams" are not only seen in the Milky Way, but have also been discovered in the Local Group galaxy M 31 (Ibata et al. 2001, Ferguson et al. 2002, McConnachie et al. 2003). The substructure in the halo of M 31 is another piece of clear evidence that minor mergers still take place.

Such events are difficult to trace in more distant galaxies, where we can not observe individual stars. Other means are needed for detecting the signature of accretion. In this respect, the use of HI is very powerful as it can image interactions very effectively by studying the HI distributions and kinematics. The latter is particularly useful for modelling. Examples can be found in Sancisi (1999a). The improved sensitivity of modern synthesis radio telescopes brings within reach the detection of faint HI signatures of accretion events and we expect that new observations of nearby and also more distant galaxies will reveal these in the coming decade. To further illustrate this point we here present a few examples of such signatures: NGC 3359, NGC 4565 and NGC 6946.

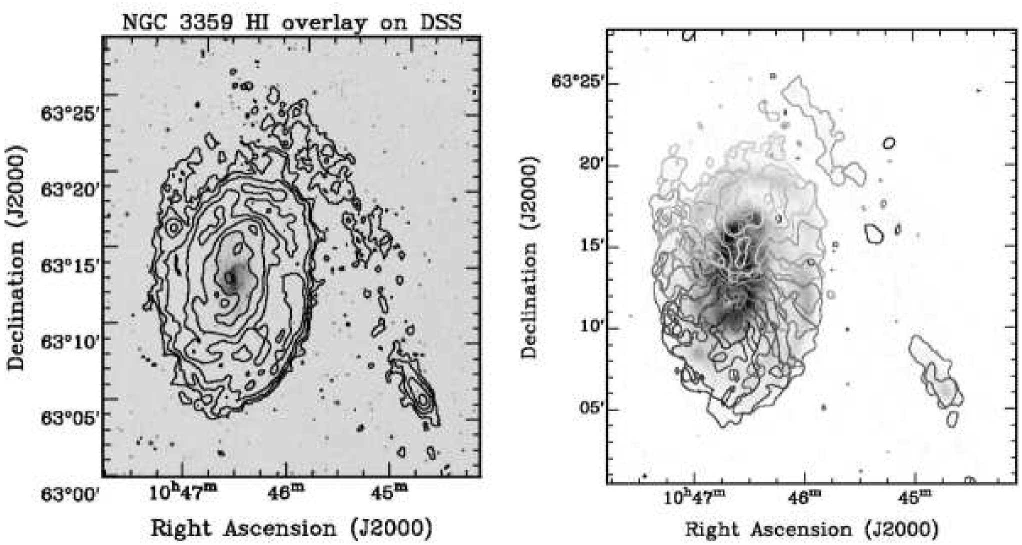

Figure 1. The left panel shows the distribution of NGC 3359 at a resolution of 30″ superposed on the digital sky survey image. Contours are 0.1, 0.2, 0.4, 0.8, 1.6, 3.0, and 5.0 $\times 10^{21}$ cm^{-2}. The right panel shows outer contours of the HI emission in individual channels superposed on the total HI emission in NGC 3359. The low velocities are dark grey, the high velocities light grey.

2. The observations

All three galaxies have been observed recently with the Westerbork Synthesis Radio Telescope (WSRT) using the new front-end and correlator providing a much improved sensitivity. We will discuss each case individually below. Details of the observations and some of these results have already been reported by van der Hulst & Sancisi (2004).

2.1. NGC 3359

NGC 3359 is a nearby barred spiral galaxy (Hubble type SBc) which has been observed in HI by Broeils (1992) as part of a study of the mass distribution of a sample of nearby spiral galaxies. It has a total mass of 1.2×10^{11} $M_{\odot}$ and an HI mass of 7.5×10^{9} $M_{\odot}$ (Broeils & Rhee, 1997, adjusted for a Hubble constant of 72 km/s/Mpc). It has well developed spiral structure both in the optical and in HI. Kamphuis & Sancisi (1994, see also Sancisi 1999a) pointed out the presence of an HI companion which appears distorted and has a long tail which may connect to the HI disk of NGC 3359. This observation already indicated the possible accretion of gas by a large galaxy. Our new, more sensitive observations (rms noise of 0.85 mJy/beam for velocity and spatial resolutions of 10 km s^{-1} and $30''$ respectively) are shown in Figure 1 (left panel) and convincingly display an HI connection between the distorted HI companion and the main galaxy. The mass of the HI companion is 1.8×10^{8} $M_{\odot}$ or 2.4% of the HI mass of NGC 3359. The HI distribution of the companion is clearly distorted and shows a tail pointing towards and connecting with the outer spiral structure of NGC 3359. No clear optical counterpart of the HI companion has yet been found.

The velocity structure of the HI companion and the connecting HI fits in very well with the regular velocity field of NGC 3359. This is shown in the right panel of Figure 1 where we display the emission in the individual channels superposed on the total HI image of NGC 3359. Contours of different shades of grey (low velocities are dark, high velocities are light) denote the outer edge of the HI emission in each of the velocity channels and thus display the basic kinematics of the HI without any further analysis of individual velocity profiles. The regularity of the velocities suggests that the process has been going on slowly for at least one rotational period which is of the order of 1.7 Gy.

2.2. NGC 4565

NGC 4565 is a large edge-on galaxy of Hubble type Sb which was first observed in HI by Sancisi (1976) in an early search for galaxies with warped HI disks. Rupen (1991) observed NGC 4565 with much higher resolution and presented a detailed study of the kinematics and the warp. NGC 4565 has a small optical companion $6'$ to the north of the center, F378-0021557, which has 7.4×10^{7} $M_{\odot}$ of HI compared to an HI mass of 2.0×10^{10} $M_{\odot}$ for NGC 4565 (using a distance of 17 Mpc). An HI detection of this companion called NGC 4565A has also been reported by Rupen (1991). Another HI companion, NGC 4562, somewhat larger in HI (2.5×10^{8} $M_{\odot}$) and brighter optically can be found $15'$ to the south-west of the center of NGC 4565. The HI distribution, derived from a new sensitive WSRT observation by Dahlem (priv. comm.), is shown in Figure 2 superposed on the DSS. The asymmetric warp is clearly visible.

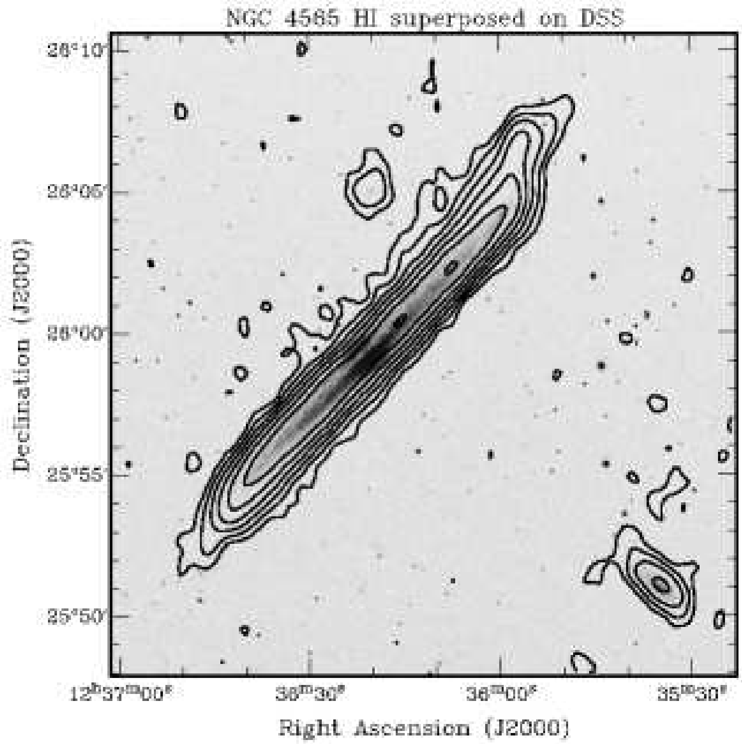

Figure 2. HI distribution of NGC 4565 at a resolution of 30″ superposed on the digital sky survey image. Contours are 0.2, 0.4, 0,8, 1.6, 3.2, and 6.4 $\times 10^{21}$ cm^{-2}.

Inspection of individual channel maps brings to light that in addition to the warp the HI distribution shows additional, low surface brightness emission to the north of the center, in the direction of the faint companion F378-0021557. The HI emission 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 best seen in Figure 3 which shows four channel maps chosen at velocities in this range. In these maps one can clearly see the HI layer bending towards F378-0021557, indicating a connection between F378-0021557 and a strong disturbance in the HI disk of NGC 4565. This disturbance is not associated with the warp. However, this bending of the HI layer, undoubtedly caused by the companion, is remarkably similar tot the outer HI warping. One wonders whether the type of interaction we are witnessing here is the mechanism also responsible for the creation of a warp. This interaction between NGC 4565 and its companion will eventually lead to a merger of the latter with NGC 4565.

To further elucidate the connection between F378-0021557 and NGC 4565 we show a position-velocity diagram along the HI connection in figure 4. This position-velocity cut has been taken parallel to the minor axis of NGC 4565

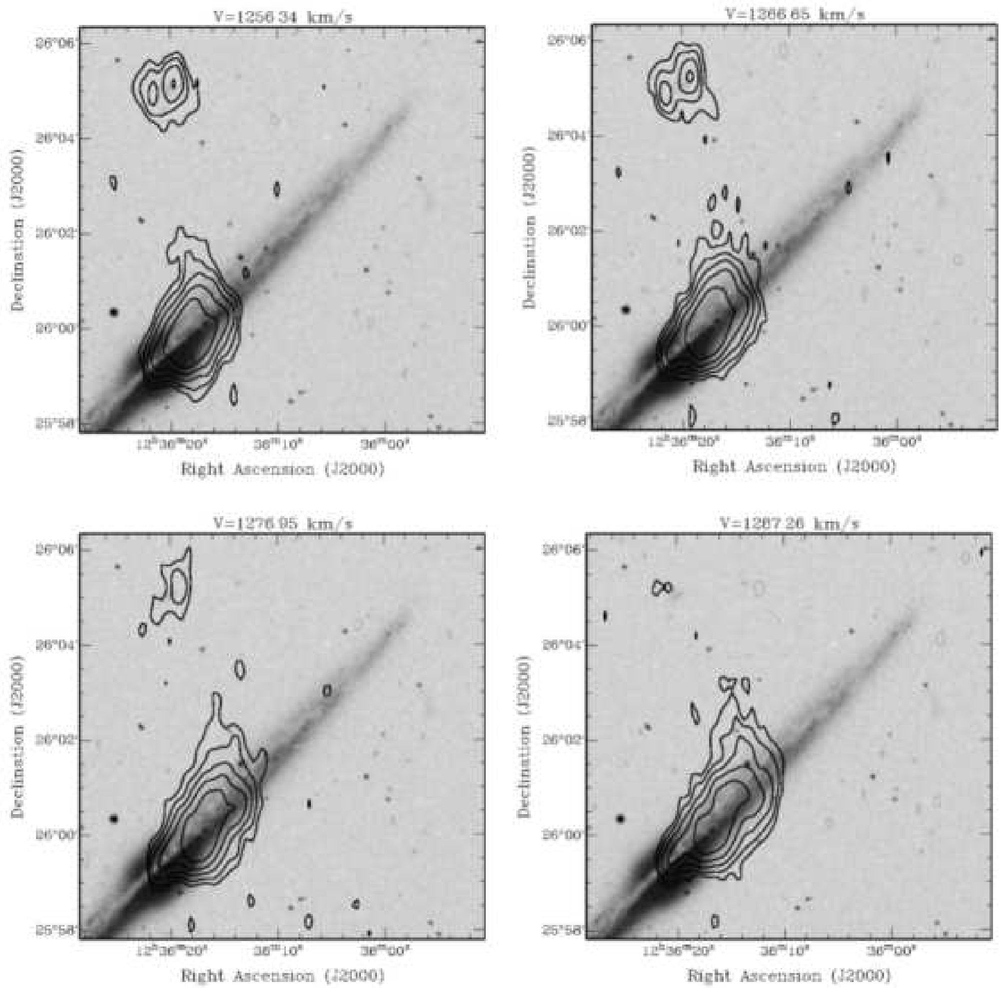

Figure 3. H I emission at four velocities between 1256 and 1287 km s^{-1} superposed on the DSS image of NGC 4565 at a resolution of $13'' \times 33''$. These channels clearly show the interaction between the companion and NGC 4565. Contours are -2.0 -1.0 1.0 2.0 4.0 8.0 160. 32 0. 64.0 120.0 mJy/beam

through F378-0021557 and clearly shows the velocity continuity of the H I disturbance in the disk of NGC 4565 and F378-0021557.

2.3. NGC 6946

NGC 6946 is a bright, nearby spiral galaxy of Hubble type Scd which has been studied in H I numerous times (Rogstad et al. 1973, Tacconi & Young 1986, Kamphuis 1993). It was in this galaxy that Kamphuis and Sancisi (1993) found the first evidence for an anomalous velocity H I component which they associated with outflow of gas from the disk into the halo as a result of stellar winds and supernova explosions. Evidence for such a component is now being found in more galaxies as discussed by Fraternali et al. (2001, 2002, and also this volume). A

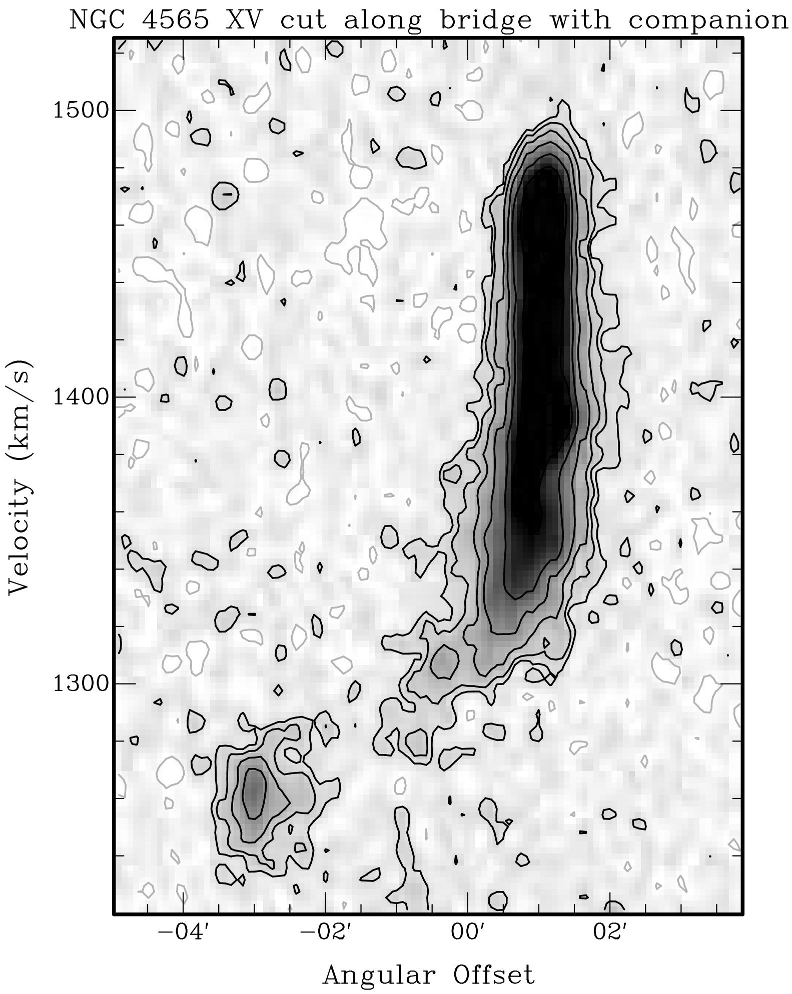

Figure 4. Position velocity diagram parallel to the minor axis of NGC 4565 across F378-0021557 and the disk of NGC 4565.

detailed study of the anomalous H I and the structure in the H I disk is being carried out by Boomsma et al. (this volume) on the basis of very sensitive observations with the WSRT (rms of 0.5 mJy/beam for spatial and velocity resolutions of 60″ and 5 km s^{-1} respectively).

Here we use a low resolution (60″) version of these data. Figure 6 shows a total H I image of NGC 6946 down to column density levels of 1.3×10^{19} cm^{-2}. To the west two small companion galaxies can be seen. The most intruiging feature is the faint whisp to the north-west of the H I disk of NGC 6946. This faint H I extension can only be brought out at this resolution and appears to form a faint H I filament which blends smoothly (also kinematically) with the H I disk of NGC 6946 at a position some 11′ (or 19 kpc) south of the tip of the filament. There is no detected connection with the two companion galaxies farther to the west. The spatial and velocity structure of the object are so regular, yet only

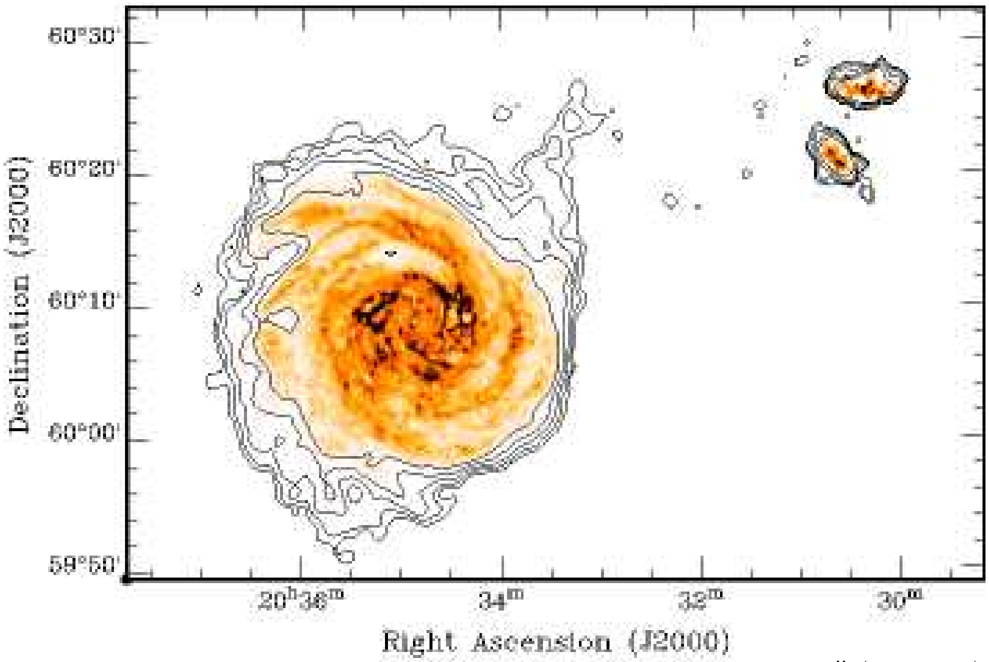

Figure 5. H I distribution in NGC 6946 at a resolution of 30″ (greyscale) and 60″ (contours, see also Boomsma et al. this volume). Contours are 1.3, 2.6, 5.2, 10.4, and 20.8 $\times 10^{19}$ cm^{-2}.

connected to the main H I disk at one side that we prefer an explanation in terms of a tidally stretched, infalling H I object. So this looks like yet another example of accretion of small amounts of gas onto a large H I disk.

Similar examples are perhaps the filament discovered in NGC 2403 (Fraternali et al. 2001, 2002 and also this volume), a long H I filament in M 33 (van der Hulst, unpublished) and the extra-planar filaments in the northern part of the H I halo of NGC 891 (Fraternali et al., this volume).

3. Concluding remarks

We have shown three cases with strong evidence for the accretion of small amounts of H I. These are certainly not unique. There are several more cases known (Sancisi 1999a and b). Furthermore, there are cases with such faint features that can only be seen in sensitive H I observations as the H I masses involved are rather modest. We therefore expect that with the increased sensitivity of modern synthesis radio telescopes, more examples will be discovered in the coming decade. There probably is a range of H I masses for these accretion events as is already apparent from the six cases mentioned here: NGC 891, NGC 2403, NGC 3359, NGC 4565, NGC 6946 and M 33.

What is the effect of accretion on the main galaxy? This can influence local star formation in the disks and starbursts. For instance, there may very well be a connection with the star formation activity in the disks of galaxies such as NGC 6946 and NGC 2403. The infall of gas may be at the origin of the extra-planar gas and gaseous halos recently discovered in spiral galaxies. Also, it may affect the structure of galactic disks in the outer parts and possibly also contribute to the formation of the outer layers and of warps in particular.

It is quite clear that future sensitive and detailed studies of the H I in nearby galaxies will provide a more complete census of the phenomena discussed in this paper and enable us to address these issues further and obtain more definitive answers. In particular, it should be possible to obtain estimates of the mean gas accretion rate in galaxies.

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