Part 2. Origin
The Outskirts of Galaxies

https://doi.org/10.1017/S007418090019727X Published online by Cambridge University Press

Recycling Intergalactic and Interstellar Matter
IAU Symposium Series, Vol. 217, 2004
Pierre-Alain Duc, Jonathan Braine and Elias Brinks, eds.

Evidence for Gas Accretion in Galactic Disks

Thijs van der Hulst

Kapteyn Astronomical Institute, P.O. Box 800, NL-9700 AV Groningen, The Netherlands

Renzo Sancisi

Osservatorio Astronomico, Via Ranzani 1, I-40127 Bologna, Italy and Kapteyn Astronomical Institute, Groningen, The Netherlands

Abstract.
Studies of the HI in galaxies have clearly shown that subtle details of the HI distribution and kinematics often harbour key information for understanding the structure and evolution of galaxies. Evidence for the accretion of material has grown over the past many years and clear signatures can be found in HI observations of galaxies. We have obtained new detailed and sensitive HI synthesis observations of three nearby galaxies which are suspected of capturing small amounts of HI and show that indeed accretion of small amounts of gas is taking place in these galaxies. This could be 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

It has long been an important question how galaxies form and evolve into the great variety of morphologies we see in the nearby universe. The common view is that galaxies form hierarchically from small building blocks through a sequence of merger events. This view has been motivated by the cold dark matter (CDM) simulations which suggest that all galaxies form initially as discs (e.g. Baugh, Cole & Frenk 1996, Klypin et al. 1999, Moore et al. 1999, Steinmetz & Navarro 2002, Abadi et al. 2003). The signatures of the disks can subsequently be erased by multiple galaxy mergers (Barnes 1992).

In this paper we consider the formation of large disks through the accretion of small companions, the process often indicated as the nurture of galaxies. Evidence in support of the prediction of this scenario by cold dark matter simulations has come from several directions. Zaritsky (1995) and Zaritsky & Rix (1997) determined the star formation rate of several tens of galaxies from stellar population studies. They also determined the shapes of these galaxies from photometry and found that overall the galaxies with asymmetries in their shapes have the youngest stellar populations. They acsribed this to recent accretion events. Kinematic lopsidedness, observed in the 2-dimensional HI velocity fields of galaxies (Verheijen 1997, Swaters et al. 1999) has also been considered as a result of recent minor mergers. Finally there are at least some twenty examples

https://doi.org/10.1017/S007418090019727X Published online by Cambridge University Press

of galaxies which in H I show either signs of interactions and/or have small companions (Sancisi 1999). This suggests that galaxies often are in an environment where material for accretion is available.

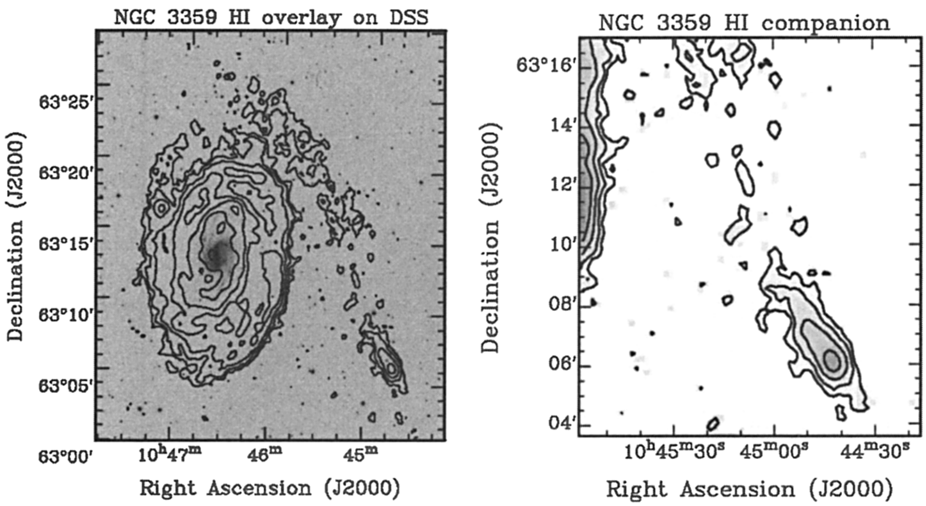

Figure 1. H I distribution of NGC 3359 at a resolution of 30″ superposed on the digital sky survey image (left panel). Contours are 0.1, 0.2, 0.4, 0.8, 1.6, 3.0, and 5.0 $\times 10^{21}$ cm^{-2}. The right panel shows a blow up of the H I companion.

Even clearer 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) has been major 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.

The question now is how to trace such events in more distant galaxies, where we cannot observe individual stars, but require other means of detecting the signature of accretion. The use of H I is very powerful as it can image interactions very effectively by studying the H I distributions and kinematics of nearby galaxies. Examples can be found in Sancisi (1999). The improved sensitivity of modern synthesis radio telescopes brings within reach the detection of faint H I signatures of accretion events and we expect that new observations of nearby galaxies will reveal these in the coming decade. To further illustrate this

https://doi.org/10.1017/S007418090019727X Published online by Cambridge University Press

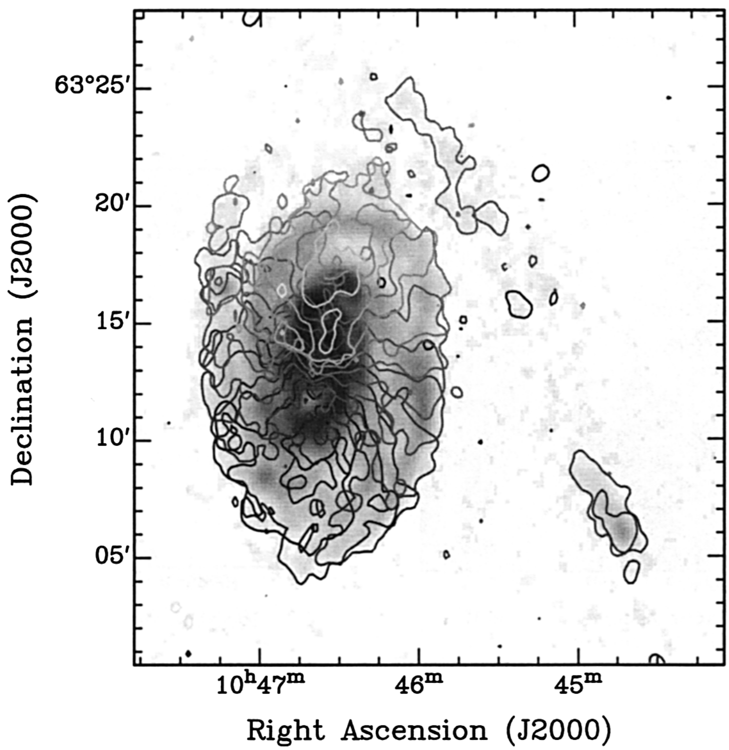

Figure 2. Outer contours of the H I emission in individual channels superposed on the total H I emission in NGC 3359. The low velocities are dark grey, the high velocities light grey.

point we here present a few examples of such signatures: NGC 3359, NGC 4565 and NGC 6946.

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. NGC 3359 and NGC 4565 were each observed for 12 hours providing a sensitivity of 0.85 mJy beam^{-1} for spatial and velocity resolutions of 30″ and 10 km s^{-1}. NGC 6946 was observed for 15 × 12 hours and reaches a sensitivity of 0.5 mJy beam^{-1} for spatial and velocity resolutions of 60″ and 5 km s^{-1}. We will discuss each case individually below.

2.1. NGC 3359

NGC 3359 is a nearby barred spiral galaxy (Hubble type SB(rs)c) which has been observed in H I 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

https://doi.org/10.1017/S007418090019727X Published online by Cambridge University Press

an H I mass of 7.5×10^9 $M_\odot$ (Broeils & Rhee, 1997, adjusted for a Hubble constant of 72 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$). It has well developed spiral structure both in the optical and in H I. Kamphuis & Sancisi (1994, see also Sancisi 1999) pointed out the presence of an H I companion which appears distorted and may connect to the main H I disk of NGC 3359. This observation already suggested the possibility of witnessing accretion of gas by a large galaxy. Our new, more sensitive observations are shown in Figure 1 and convincingly display an H I connection between the distorted H I companion and the main galaxy. The mass of the H I companion is 1.8×10^8 $M_\odot$ or 2.4% of the H I mass of NGC 3359. Also shown in Figure 1 is a blow-up of the H I distribution of the companion which is clearly distorted and shows a tail pointing towards and connecting with the outer spiral structure of NGC 3359. No optical counterpart has yet been identified.

The velocity structure of the H I companion and the connecting H I fits in very well with the regular velocity field of NGC 3359. This is shown in Figure 2 where we display the emission in the individual channels superposed on the total H I image of NGC 3359. Contours of different shades of grey (low velocities are dark, high velocities are light) denote the outer edge of the H I emission in each of the velocity channels and thus display the basic kinematics of the H I 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 SAb which was first observed in H I by Sancisi (1976) in an early search for galaxies with warped H I 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 of NGC 4565, F378-0021557, which has 7.4×10^7 $M_\odot$ of H I compared to an H I mass of 2.0×10^{10} $M_\odot$ for NGC 4565. Another companion, NGC 4562, somewhat larger in H I (2.5×10^8 $M_\odot$) and brighter optically can be found found $15'$ to the south-west of the center of NGC 4565. The H I distribution, superposed on the DSS is shown in Figure 3. The asymmetric warp is clearly visible. The warp sets in at the edge of the optical disk and does exhibit a bit of apparent thickening of the H I disk visible to the north-west and south-east of the disk, a result from projection effects along the line of sight.

Inspection of individual channel maps brings to light that in addition to the warp the H I distribution shows additional, low surface brightness emission to the north of the center, in the direction of the faint companion F378-0021557. This is best shown in Figure 4 where we show the outer contours of the H I emission in individual velocity channels superposed on the total H I distribution of NGC 4565. In this Figure one clearly sees that there is an additional extra-planar H I component pointing into the direction of F378-0021557, suggestive of a connection between the presence of F378-0021557 and disturbances in the H I disk of NGC 4565. Whether this is recently accreted material cannot easily be verified, but it definitely shows that there is a component in the H I disk of

https://doi.org/10.1017/S007418090019727X Published online by Cambridge University Press

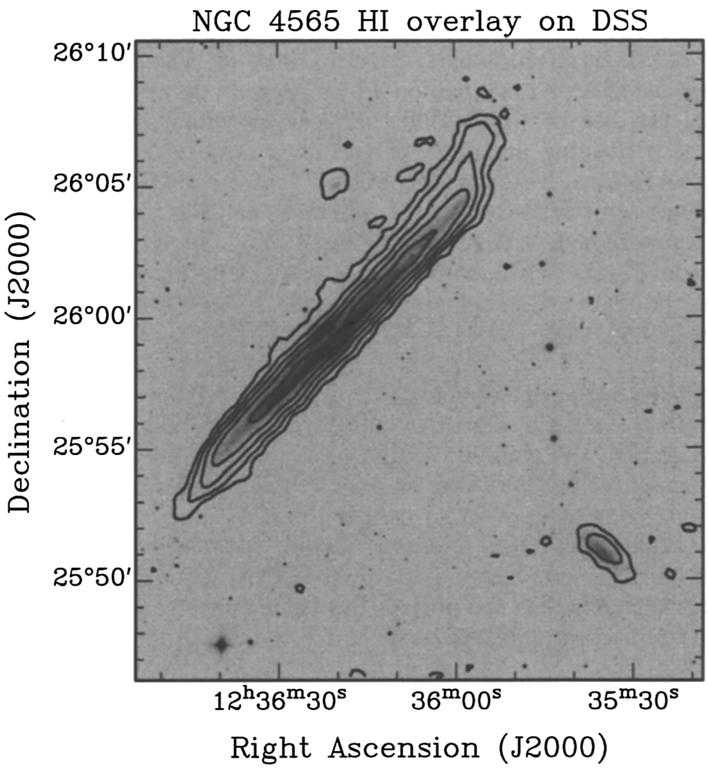

Figure 3. H I distribution of NGC 4565 at a resolution of 30″ superposed on the digital sky survey image (left panel). Contours are 0.4, 0.8, 1.6, 3.2, and 6.4 $\times 10^{21}$ cm^{-2}.

NGC 4565 which cannot be associated with the warp and is the kind of small (in terms of H I mass) asymmetry that could be the result of accretion.

2.3. NGC 6946

NGC 6946 is a bright, nearby spiral galaxy of Hubble type SAB(rs)cd 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 events. Evidence for such a component is now evident in more galaxies as discussed by Fraternali et al. (2002, 2003, and also this volume). A much more 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, see also Fraternali et al. this volume) on the basis of very sensitive observations with the WSRT.

Here we concentrate on a low resolution (60″) version of these data. Figure 5 shows a total H I image of NGC 6946 down to column density levels of

https://doi.org/10.1017/S007418090019727X Published online by Cambridge University Press

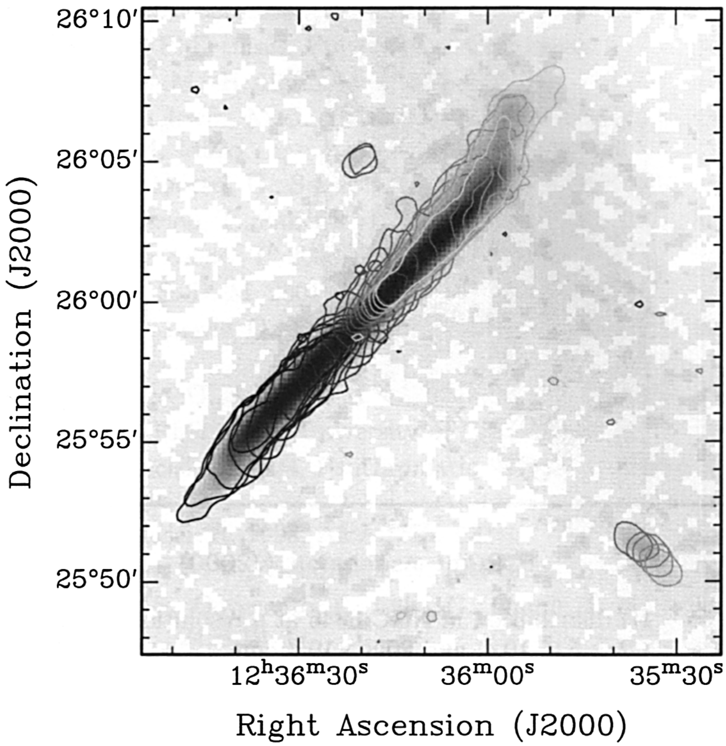

Figure 4. Outer contours of the H I emission in individual channels superposed on the total H I emission in NGC 4565. The low velocities are dark grey, the high velocities light grey.

1.3×10^{19} cm^{-2}. To the west two small companion galaxies can be seen. The most intriguing feature is the faint whisp to the north-west of the main 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 detectable connection with the two companion galaxies farther to the west. The spatial and velocity structure of the object are so regular, yet only 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 yet another example of accretion of a small amount of gas onto a large H I disk.

Similar examples, though much more massive in H I, are perhaps the filament discovered in NGC 2403 (Fraternali et al. 2002, 2003 and also this volume), a long H I filament in M 33 (van der Hulst, unpublished) and the extraplanar filaments in the northern part of the H I halo of NGC 891 (Fraternali et al., this volume).

https://doi.org/10.1017/S007418090019727X Published online by Cambridge University Press

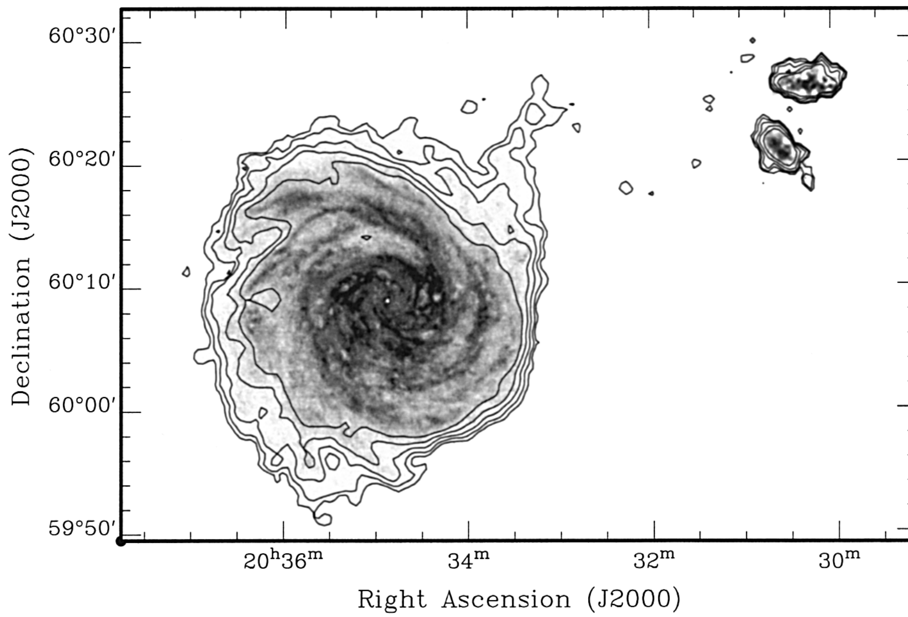

Figure 5. H I distribution in NGC 6946 at a resolution of 60″. Contours are 1.3, 2.6, 5.2, 10.4, and 20.8 $\times 10^{19}$ cm^{-2}.

3. Concluding remarks

We have shown three cases with strong evidence for the accretion of small amounts of H I. These will not be unique. Such faint features 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.

The next question to ask is what the effect of accretion will be on the disk of the main galaxy. There may very well be a connection with the star formation activity in galaxies such as NGC 6946 and NGC 2403 and the evidence for gas infall. This then in turn can cause the observed phenomenon of gas outflows from the active disks as seen in these galaxies (Boomsma et al. and Fraternali et al. this volume). 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.

References

Abadi M.G., Navarro J.F., Steinmetz M., Eke V.R. 2003, ApJ, 591, 499

https://doi.org/10.1017/S007418090019727X Published online by Cambridge University Press

Baugh C.M., Cole S., Frenk C.S., 1996, MNRAS, 283, 1361

Barnes J.E. 1992, ApJ, 393, 484

Broeils, A. H. 1992, PhD thesis, University of Groningen

Broeils, A. H., Rhee, M. -H. 1997, A&A, 324, 877

Ferguson, A. M. N., Irwin, M. J., Ibata, R. A., Lewis, G. F., & Tanvir, N. R. 2002, AJ, 124, 1452

Fraternali, F., van Moorsel, G., Sancisi, R., & Oosterloo, T. 2002, AJ, 123, 3124

Fraternali, F., Oosterloo, T., Sancisi, R., & van Moorsel, G. 2001, ApJ, 562, L47

Helmi, A. & Tim de Zeeuw, P. 2000, MNRAS, 319, 657

Helmi, A. & White, S. D. M. 2001, MNRAS, 323, 529

Ibata, R., Irwin, M., Lewis, G., Ferguson, A. M. N., & Tanvir, N. 2001, Nature, 412, 49

Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Nature, 370, 194

Kamphuis, J. 1993, PhD thesis, University of Groningen

Kamphuis, J. & Sancisi, R. 1994, Panchromatic View of Galaxies. Their Evolutionary Puzzle, 317

Kamphuis, J. & Sancisi, R. 1993, A&A, 273, L31

Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82

Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19

McConnachie, A. W., Irwin, M. J., Ibata, R. A., Ferguson, A. M. N., Lewis, G. F., & Tanvir, N. 2003, MNRAS, 343, 1335

Rogstad, D. H., Shostak, G. S., & Rots, A. H. 1973, A&A, 22, 111

Rupen, M. P. 1991, AJ, 102, 48

Sancisi, R. 1976, A&A, 53, 159

Sancisi, R. 1999, IAU Symp. 186: Galaxy Interactions at Low and High Redshift, 186, 71

Sancisi, R. 1999, Ap&SS, 269, 59

Steinmetz, M. & Navarro, J. F. 2003, New Astronomy, 8, 557

Tacconi, L. J. & Young, J. S. 1986, ApJ, 308, 600

Zaritsky, D. 1995, ApJ, 448, L17

Zaritsky, D. & Rix, H. 1997, ApJ, 477, 118

https://doi.org/10.1017/S007418090019727X Published online by Cambridge University Press