GALAXY INTERACTIONS: THE HI SIGNATURE

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Abstract. HI observations are an excellent tool for investigating tidal interactions. Ongoing major and minor interactions which can lead to traumatic mergers or to accretion and the triggering of star formation, show distinct HI signatures. Interactions and mergers in the recent past can also be recognized in the HI structure and kinematics. Recent 21cm line surveys of large samples of galaxies indicate that at least one out of every four galaxies shows signs of a present interaction or merger/accretion events in the recent past.

1. Introduction

This review focuses on the role of neutral hydrogen in galaxy interactions. Neutral hydrogen serves, in the first place, as a very good tracer of tidal disruption. This is simply because it is generally more extended than the stars in the outer parts of galaxies and is, therefore, the component most affected by the interaction. Indeed HI tails and bridges or other peculiar features in the HI distribution and kinematics around images of optically undisturbed galaxies are sometimes the only evidence that the galaxies are really interacting.

The HI gas plays a fundamental role in the formation of disks and in their evolution. In the course of an interaction the HI complexes can be either directly accreted or displaced by the tidal forces and fall back onto the interacting systems later. In the latter case a reservoir of fresh material is created which, at a later stage, contributes to the process of disk building and star formation.

It is also interesting to note that the extended HI structures of tidal origin observed in the neighborhood of interacting systems provide large

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cross sections, of order 100 kpc diameter, as needed for systems capable of explaining the absorption lines in the spectra of QSOs.

In this study a distinction is made between two types of interactions: a major and a minor one. The "major" one involves systems of comparable masses and usually produces large tidal effects. It may lead to the destruction of disks and to mergers and elliptical galaxies as end products. The "minor" interaction takes place between a main galaxy and one or more satellites or companions of small mass (mass ratio usually less than 0.1). It leads to gas accretion and the building up of disks, and may cause localized star formation and starbursts. Attention is also drawn to a number of systems which despite their isolation show the peculiar HI properties typical of interacting systems. They may, therefore, have had some recent encounter and at present be in an advanced stage of accretion.

A brief review of the morphology and main properties of interacting systems is presented. A few examples are illustrated (Fig. 1) and briefly discussed. At the end, the question of the frequency of galaxy interactions and infall is addressed.

2. Major Interactions

There are several cases of multiple systems with two or more members which show heavily perturbed HI images: in addition to the gas which is seen associated with the individual galaxies, there are cloud complexes, usually long tails, bridges or ring-like structures, in the regions near and around them. A list of well-known, representative cases is given in Table 1. For many of these systems it is the peculiar gas picture (Fig. 1) that unmistakably points at the ongoing strong tidal interaction.

The galaxy pairs in the table (see also the sample of Chengalur et al. 1995b) present a characteristic HI picture with long tails and bridges. M51 and its companion are a classic example. The VLA observations of Rots et al. (1990) show a highly disturbed picture. The most striking feature is a 90 kpc long HI tail connected loosely to the outer disk of M51, which has no optical counterpart.

A number of optically disturbed systems, characterized by bridges and long tails, were proposed by Toomre (1977) as a possible sequence of ongoing galaxy mergers. Four of these and one system at a slightly earlier stage have been recently imaged in HI with the VLA (Hibbard 1995, Hibbard and van Gorkom 1996). These observations seem to indicate some trends along the merging sequence. In the early stages, large amounts of HI are still present within the galaxy disks. In the final stages there is little or no HI within the remnant bodies. Tidal material is seen falling back towards the remnant, as beautifully illustrated by the observations of NGC 7252

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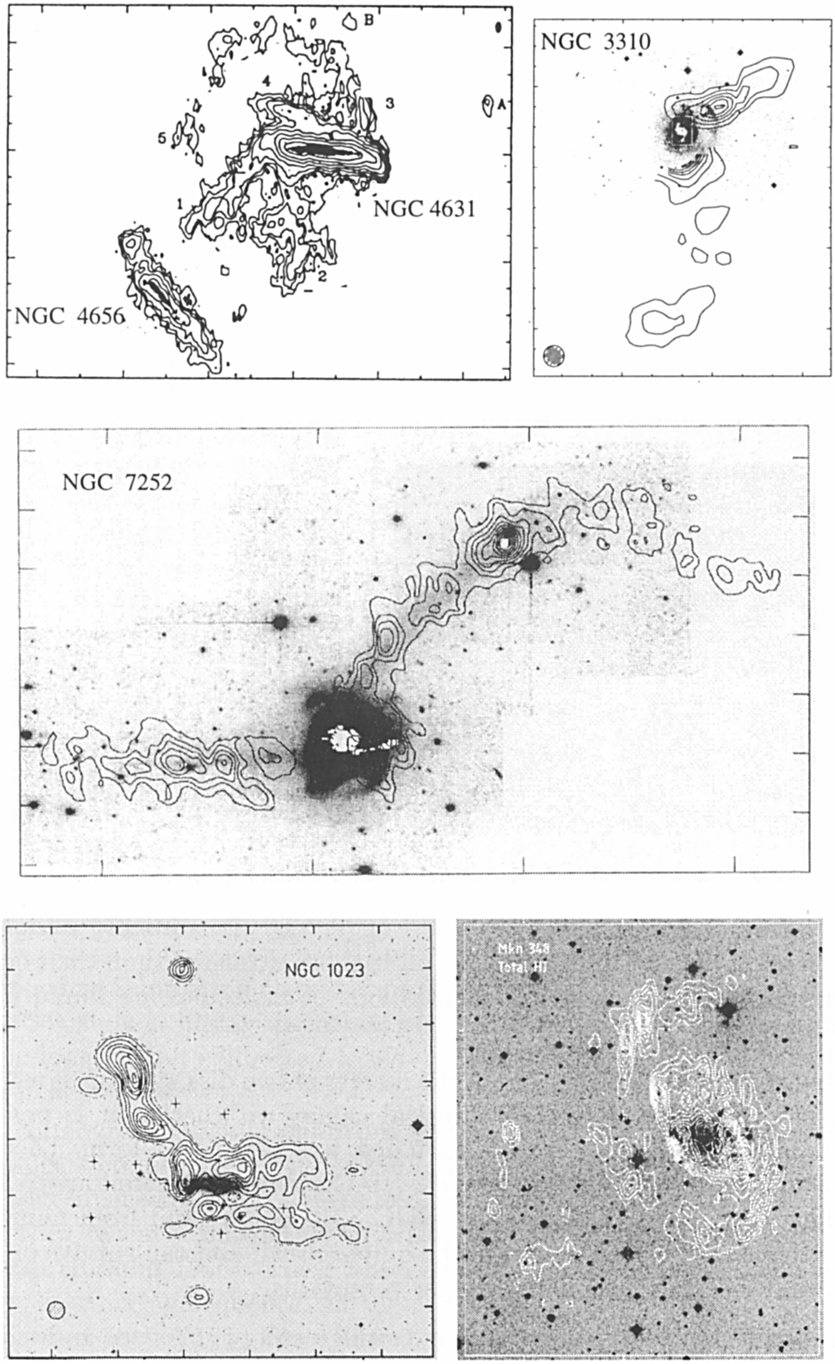
TABLE 1. Multiple Systems

M81/M82/NGC3077	Yun et al. 1994
NGC3165/3166/3169	Haynes 1981
NGC3623/3627/3628 (Arp 317, Leo Triplet)	Haynes et al. 1979
NGC4631(=Arp 281)/4656/4627	Rand 1994
NGC7448/7463/7464/7465	Haynes 1981
Stephan's Quintet	Shostak et al. 1984
Galaxy-Magellanic Clouds	Mathewson et al. 1974 (and refs.)
M96 Group (Leo ring)	Schneider et al. 1989
NGC5194(M51)/5195 (Arp 85)	Rots et al. 1990
NGC520 (Arp 157)	Hibbard and van Gorkom 1996
NGC678/680	Haynes 1981
NGC1510/1512	Hawarden et al. 1979
NGC3226/3227 (Arp 94)	Mundell et al. 1995
NGC3690/IC694 (Arp 299)	Stanford and Wood 1989
NGC3921 (Arp 224, MKN 430)	Hibbard and van Gorkom 1996
NGC4038/4039 (Arp 244, The "Antennae")	van der Hulst 1979
Arp 295	Hibbard and van Gorkom 1996
NGC4485/4490 (Arp 269)	Viallefond et al. 1980
NGC4676 (Arp 242, "The Mice")	Hibbard and van Gorkom 1996
NGC4725/4747(=Arp 159)	Wevers et al. 1984
NGC7252 (Arp 226)	Hibbard et al. 1994
IIZw70-71	Balkowski et al. 1978
UGC6922/6956	Appelton 1983
HI 1225+01	Chengalur et al. 1995a

(Hibbard et al. 1994) shown here in Fig. 1. The HI is almost completely concentrated in tidal tails which are often more extended than their optical counterparts, while massive concentrations of molecules are found in the central region.

One of the key questions about the merger of two disk systems is whether the end product is always an elliptical galaxy or whether it is possible, depending on the kind of impact, for a disk to survive or re-form. There are indications from the observations (cf. van Gorkom and Schiminovich 1997, Stanford and Wood 1989, see also NGC 3310 below) and from numerical work (Barnes 1996) that disks can be quite robust, and can survive or form again under certain encounter-merger conditions.

Another class of objects that may be the result of collisions and interactions as described here are the ring galaxies and the associated remarkable HI structures such as Arp 143 (Appleton et al. 1987).



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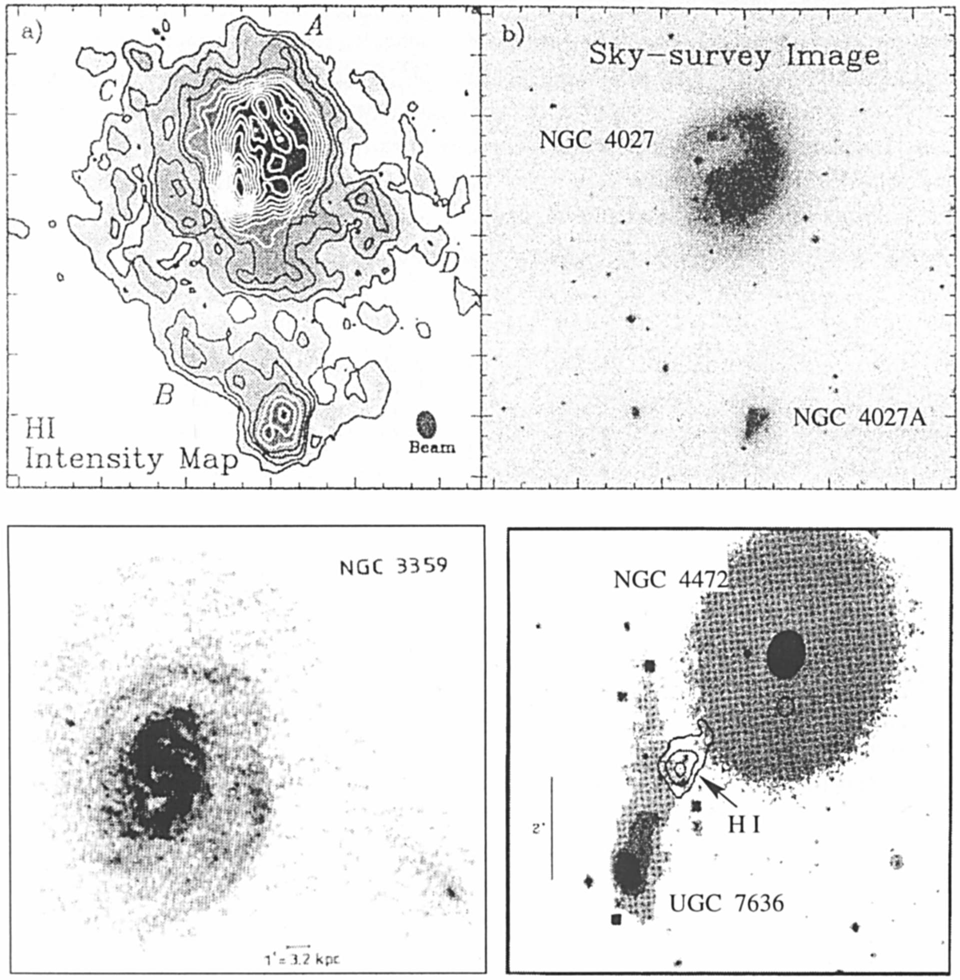

Figure 1. HI maps (see facing page) superposed on the optical pictures of the interacting system NGC 4631/4656/4627 (Rand 1994) and of the "merger" galaxies NGC 3310 (Kregel and Sancisi 1998), NGC 7252 (Hibbard 1995), NGC 1023 (Sancisi et al. 1984) and Mkn 348. The HI map of NGC 3310 shown here is incomplete. It shows only the two extended tails and not the main body HI. The HI map of Mkn 348 was obtained with the WSRT (Sancisi, unpublished). The lowest contour and the contour step are 6 10^{19} cm^{-2}, the beam FWHM is $25'' \times 48''$.
This page shows, as representative examples of galaxies interacting with dwarf companions, the spirals NGC 4027 (Phookun et al. 1992) and NGC 3359 (Kamphuis and Sancisi 1993) and the elliptical NGC 4472 (McNamara et al. 1994).

3. Minor Interactions. Accretions

A large number of galaxies have dwarf companions and when mapped in HI show clear indications of present tidal interactions. The best examples

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known are listed in Table 2, and a few are illustrated in Fig. 1. The prototype is NGC3359. The HI map of this galaxy clearly shows a small companion with a long tail pointing back to NGC 3359 and almost connecting with its extended HI layer (Kamphuis and Sancisi, 1993). The companion is a hydrogen-rich object with a very faint optical counterpart. Its total HI mass is 10^8 $M_{\odot}$, only 2 percent of the HI mass and 0.1 percent of the total mass of NGC 3359. Its head-tail structure indicates that it is probably being tidally disrupted.

TABLE 2. Galaxies with dwarf companions and/or peculiar structures

NGC262 (Mkn348)	Heckman et al. 1982, Simkin et al. 1987
NGC628	Kamphuis and Briggs 1992
NGC1023 (Arp 135)	Sancisi et al. 1984
NGC1961 (Arp 184)	Shostak et al. 1982
NGC2146	Fisher and Tully 1976, Briggs 1988
NGC2782 (Arp 215)	Smith 1994
NGC2865	Schiminovich et al. 1995
NGC3067	Carilli and van Gorkom 1992
NGC3310 (Arp 217)	Mulder et al. 1995, Kregel and Sancisi 1998
NGC3359	Kamphuis and Sancisi 1993
NGC3656 (Arp 155)	Balcells and Sancisi 1996
NGC4027 (Arp 22)	Phookun et al. 1992
NGC4254	Phookun et al. 1993
NGC4472 (Arp 134)	McNamara et al. 1994
NGC4565	Rupen 1991
NGC4694	Cayatte et al. 1990, van Driel and van Woerden 1989
NGC4826	Braun et al. 1994
NGC5128 (Cen A)	Schiminovich et al. 1994
NGC5635	Saglia and Sancisi 1988
NGC5457 (M101, Arp 26)	van der Hulst and Sancisi 1988, Kamphuis 1993

Very similar situations are found in NGC 4565-4565A (Rupen, 1991) and in NGC 4027-4027A (Phookun et al 1992). The HI masses of the companions are usually less than 10 percent of the HI masses of the main galaxies and their systemic velocities are generally close to those of the larger systems. The picture which emerges from the observations is that of the capture of a gas-rich dwarf by a massive system followed by tidal disruption and accretion of the dwarf, but only minor damage to the main galaxy.

The specific cases just mentioned probably represent early stages of the interaction-accretion process. More advanced cases have also been observed. The giant nearby spiral galaxy M101 may be in such a stage. An HI complex of about $2 \times 10^8\ M_\odot$ moving with velocities of up to 150 km/s with respect to the disk and the corresponding large hole in the HI layer are interpreted as being due to a collision with a dwarf companion which has gone through the HI layer of M101 creating a large cavity (van der Hulst and Sancisi 1988, Kamphuis 1993). The high velocity gas will eventually rain back down onto the M101 disk.

Like M101, there are more systems which do not have any obvious bright companions and yet when mapped in HI display peculiar features which are reminiscent of those seen associated with interacting systems. They may represent cases of past interactions and be at present in an advanced merger stage in which the victim is no longer visible. Interesting examples are those of NGC 1023, NGC 3310, NGC 628 and Mkn 348. NGC 1023 is an SO galaxy surrounded by a clumpy and irregular HI structure of total mass $1.5 \times 10^9\ M_\odot$ (Sancisi et al. 1984) reminiscent of the tails and bridges found in the interacting multiple systems (see Fig. 1). NGC 3310 is a peculiar (Arp 217) Sbc-type starburst galaxy. Mulder et al. (1995) have shown the presence of extended HI, which has a well developed two-tail structure (Fig. 1, Kregel and Sancisi 1998). This must be an advanced merger of two galaxies, probably of similar masses, which 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 the several other Arp objects in the table, already show some peculiarities, it is their HI structure and kinematics that fully reveal the ongoing, possibly "major" mergers. In contrast to these, NGC 628 and Mkn 348 are different and very interesting because they have a very clean, regular optical image. Only the HI betrays a possible recent accretion. For NGC 628 this is indicated by the presence in its outer parts of two high-velocity HI complexes, which are symmetrically placed with respect to the galaxy center. These complexes have sizes of tens of kiloparsecs, HI masses of $10^8\ M_\odot$, and maximum velocity excesses of 100 km/s (Kamphuis and Briggs, 1992). For Mkn 348 a probable past interaction and gas accretion is suggested by the presence of an enormous HI envelope and a large tail-like extension to the east (see Fig. 1, cf. also Simkin et al. 1987).

It is important to note that in all these cases of spiral galaxies, 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 at a recent interaction and infall. There are distinct and recognizable signatures in the HI that make the difference possible to determine, 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. For example it is interesting to consider the asymmetries affecting spiral galaxies, which seem to occur quite frequently (Richter and Sancisi, 1994). The asymmetry is seen in the HI structure and, even more often and more strikingly, in the HI kinematics (Swaters et al., 1998). Should the origin of such asymmetries be attributed to past interactions and accretion events? This is not at all obvious and there may be other explanations. It should be noted that asymmetries are also found in the optical and that for them a past interaction is the favored interpretation (see paper by Zaritsky in this volume).

Neutral hydrogen found in elliptical galaxies with shells, like NGC 5128 (Cen A) (Schiminovich et al. 1994) and NGC 2865 (Schiminovich et al. 1995) (see also Schiminovich, this Symposium), and also near ellipticals with dwarf companions, like NGC 4472 (McNamara et al. 1994) shown here in Fig. 1 and NGC 3656 (Balcells and Sancisi, 1996), clearly indicates that the accretion phenomenon illustrated above for spirals is probably playing an important role in all types of galaxies, including ellipticals.

4. Conclusions

There is clear evidence from HI observations that a number of galaxies are undergoing strong tidal interactions. There is a wide range of interactions, from those occurring in groups or between galaxies of comparable masses, which may lead to mergers, to the less disruptive ones between a galaxy and one or more small companions which contribute new material to the disk and may produce starburst phenomena.

There are also systems which are not seen presently interacting with other galaxies, but possess peculiar HI morphologies and kinematics similar to those found in the tidal cases. These may represent more advanced stages of accretion-merger processes with the victims no longer visible. The interactions with small companions and these probable cases of recent mergers form circumstantial evidence that even in the present epoch there is episodic infall of gas onto galaxies.

How often do interactions, strong or mild, within multiple systems or with small companions take place? and how important are they for the formation of elliptical galaxies or for the building up of disks, the triggering of star bursts and for galaxy evolution in general? In the past years, a large number of galaxies have been mapped in HI with the Westerbork Synthesis Radio Telescope and with the VLA. A first estimate made on the basis of about hundred galaxies led to the conclusion (Sancisi 1993) that almost half of the systems observed showed signs of either present or recent interactions. The incompleteness and the various biases of such a spurious sample, however, make such an estimate highly uncertain.

A very recent HI survey carried out by Verheijen (1997) for a magnitude and volume limited sample of galaxies from the Ursa Major cluster 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 very low velocity dispersion and a long crossing time, comparable to the Hubble time. It has no central concentration and no X-ray emitting gas 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 and at least 30% are warped.

The available evidence from HI observations indicates, therefore, that at least 25% of field galaxies are undergoing now or have undergone in the recent past some kind of tidal interaction. If one is willing to accept the lopsided kinematics and structure as evidence of past interactions and mergers, as proposed in optical studies (see Zaritsky, this Symposium), 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. 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^{8-9} yr, the mean accretion rate for the gas would be at least 0.25 or, perhaps, even more than 0.5 $M_{\odot}$/yr. If dark matter were also included the total mass accretion rate could easily be a factor 10 higher.

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