THE COLD INTERSTELLAR MEDIUM

An HI View of Spiral Galaxies

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Abstract. An HI view of spiral galaxies is presented. In the first part the standard picture of isolated, normal spiral galaxies is briefly reviewed. In the second part attention is drawn to all those phenomena, such as tidal interactions, accretion and mergers, that depend on the galaxy environment and seem to have played a significant role, in addition to the internal metabolism, in the galaxy evolution.

1. Introduction

In recent years there has been considerable progress in our knowledge of the neutral hydrogen properties of galaxies. High spatial and velocity resolution studies of nearby spirals have provided detailed information on scales of 0.1 to 1 kpc about the filamentary and diffuse structure and the temperature of the interstellar medium (Braun 1996), the HI holes and high velocity gas and, in general, on the star formation regions and the spiral arm structure (Deul and den Hartog 1990, Kamphuis 1993). The radial distribution and extent and the kinematics of the HI disks have been studied with synthesis observations of an increasing number of objects (e.g. Broeils and van Woerden 1994, Rhee and van Albada 1996). HI observations of interacting galaxies, groups and clusters have shown the presence of tails, bridges and other extended tidal structures around and between galaxies, and the dramatic effects of gas stripping like in some of the Virgo galaxies (Cayatte et al. 1990). Also, the global HI properties and their relationship with other physical properties along the Hubble sequence have been reviewed again recently (Roberts and Haynes 1994).

From this wealth of information it is important now to recognize those aspects that are significant for galaxy formation and evolution. We can

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distinguish between 'internal' phenomena, related to processes in the disk (e.g. star formation), and 'external' effects due to interaction with the environment. A tentative classification can be based on HI morphology and kinematics, in which the 'normal' characteristics of well-behaved, isolated systems are identified and the unusual, 'peculiar' aspects of the HI structure and kinematics can be recognized.

In the first part of this review we present the essential HI features of normal, isolated disk galaxies: the spiral arm structure and holes, the radial extent, the disk-halo connection and the general shape of the HI disk. In the second part we tentatively identify those peculiar aspects of the HI density distribution and kinematics which may reveal past or present events, such as interactions with the environment, presumably playing an important role in the galaxy evolution.

2. Isolated 'Normal' Galaxies

2.1. SPIRAL STRUCTURE, HI HOLES AND HIGH-VELOCITY GAS

The distribution of neutral hydrogen in disk galaxies follows closely the spiral structure outlined by the young stellar population and the HII regions. In the outer parts, beyond the optical image, the extended HI layer shows clearly the continuation of the spiral pattern seen in the inner parts. This is best shown by the nearby spiral galaxies M 101, NGC 628, NGC 3198 and NGC 6946.

The velocity dispersion of the HI layer, which had been reported in the past as being approximately constant and close to 10 km/s at all radii, appears in more recent work on nearby face-on galaxies to be decreasing monotonically from about 10–13 km/s in the optically bright inner regions to 6–8 km/s in the very outer parts (Kamphuis 1993).

When the HI distribution is mapped with sufficiently high angular resolution, as in M 31, M 33 (Deul and den Hartog 1990) and in other, large nearby spirals, like M 101 and NGC 6946 (Kamphuis 1993), it shows the presence of a large number of holes of various sizes, from about 100 pc to a few kpc. In general, the holes are seen in the region of the optical spiral arms and only a few are found in the far outer parts outside the bright optical image. The smaller, presumably younger ones correlate in position with the HII regions and OB associations. It is likely, therefore, that they are produced by collective stellar winds and supernovae. This is also supported by the detection of high velocity gas associated with some of them, as in the prototype, large hole with expanding shell found in M 101 (Kamphuis et al. 1991). The velocities are usually less than 100 km/s. In NGC 6946, a spiral galaxy rich in giant HII regions and HI holes, there is evidence of a widespread high velocity gas component (Kamphuis and Sancisi 1993). In conclusion, holes and high velocity gas seem to characterize the HI layers of spiral galaxies in the optical region, to be related to the star formation process and to be at the origin of the disk-halo gas circulation discussed below.

2.2. RADIAL DISTRIBUTION AND EXTENT

The HI radial distribution is known for about 100 field galaxies (see e.g. surveys by Broeils and van Woerden 1994 and by Rhee and van Albada 1996) and for a somewhat smaller number of systems in nearby clusters (Cayatte et al. 1994, Verheyen 1996). The radial surface density profile, in general, is roughly flat or slowly decreasing in the region of the optical disk, and shows a rapid, approximately exponential drop-off in the outer parts. The break occurs at a characteristic radius, which usually marks the edge of the bright optical disk and is often located close to the De Vaucouleurs or the Holmberg radius. In some objects, especially of early type, a hole or a depression is seen in the central region. The HI surface density in the dense, optical part averages about 10 $M_\odot/pc^2$. This value remains remarkably constant for galaxies of different mass and luminosity. Only low surface brightness galaxies, recently surveyed in HI by de Blok et al. (1996), have systematically lower (factor 3) HI surface densities. The HI radial extent is usually larger than the optical radius. For their sample of 50 isolated galaxies Broeils and van Woerden find an average ratio of HI to optical diameters, D_{HI} (defined at 1 $M_\odot/pc^2$) to D_{25}, of 1.8±0.4. There is a strong correlation between these HI and optical diameters. The HI disk seems to cut off sharply at a density level of about 10^{19} atoms cm^{-2} or $\sim$0.1 $M_\odot/pc^2$, as shown by the deep 21-cm line observations of the spiral galaxy NGC 3198 by van Gorkom et al (1993). This may mean either that the gas layer ends there or that it becomes ionized.

The properties of the HI density distribution depend to some extent on galaxy morphology and on the environment. In the sample discussed by Broeils (1992) the HI surface density is very weakly correlated with morphological type, but there is no evidence of a correlation of the HI-to-optical diameter ratio with type or luminosity. The effects of dense, group and cluster, environments are described below. An investigation of galaxies in voids, recently carried out by Szomoru (1994), has shown that galaxies in very low density environments, like voids, do not differ significantly in their HI properties from field galaxies. The existence of objects made up of only neutral hydrogen, without optical counterparts, has not been proven yet. The only cases known to date of large intergalactic HI clouds are those found near interacting galaxies.

2.3. WARPS

The outskirts of galaxy disks are usually not flat, but show a large-scale, integral-sign shape distortion in the vertical direction. This phenomenon is known as warping. Warps are clearly visible in galaxies seen edge-on, or are inferred from the velocity fields of systems viewed at lower inclination angles. They seem to be quite common: according to Bosma (1991) the fraction of warped HI disks is of order 50% at least. One of the most prominent cases is that of NGC 4013 (Bottema 1995). Some edge-on galaxies, like NGC 4565, show also an optical warp; it is not at all clear, however, how frequently this occurs and whether the bend is in the old stellar disk. The systematic properties of warps have recently been investigated by Briggs (1990). He finds that the warps develop at the edge of the optical disk, and that their lines of nodes are not straight but curve so as to form a leading spiral. On the observational side there is now a clear need for better statistics on the frequency of occurrence of warps, for a more rigorous study of the possible influence of the environment, and for a more detailed analysis of the warp properties and the relationship with the optical counterpart when this is present.

2.4. DISK-HALO CONNECTION

The best information on the vertical structure of the HI layer in spiral galaxies, on the disk-halo connection and on the gas circulation between disk and halo comes from recent observations of nearby edge-on and face-on systems. Such observations are complementary and both necessary. The edge-on view allows direct determination of the vertical density distribution of the HI, but not of its vertical motion, whereas the face-on view offers the velocity information needed to understand the gas circulation upward and downward between disk and halo. The observations of giant face-on spirals like M 101 and NGC 6946, already mentioned above, and of the edge-on NGC 891 (Rupen 1991, Swaters et al. 1996) provide this kind of information.

NGC 891 shows HI wings extending up to about 5 kpc on both sides of the disk (Swaters et al. 1996). This HI gas at large distances from the plane, already detected (but with much lower S/N ratio) in earlier Westerbork observations, had been interpreted as being part of a flaring outer layer of NGC 891 (Sancisi and Allen 1979) and not as halo gas above the bright inner stellar disk. New, better sensitivity, HI observations and more sophisticated analysis with three-dimensional modelling have led to the conclusion that at least part of this gas must be located in the halo regions of the galaxy directly above and below the bright stellar disk. At the same time it has become clear that the standard assumption of cylindrical rotation is not valid and that the halo HI must have a somewhat lower (about 25 km/s) rotation velocity than the gas in the plane.

2.5. LOPSIDEDNESS

Large-scale asymmetries in the density distribution and in the kinematics of the neutral hydrogen disk are observed often in spiral galaxies. Since the first studies (Baldwin et al. 1980) based on a small number of galaxies much new evidence has accumulated. The frequency of asymmetries among spiral galaxies has been recently estimated (Richter and Sancisi 1994) from a large sample of global HI profiles of field galaxies. More than 50 percent of the systems examined show strong or mild asymmetries. Large deviations from axial symmetry seem, therefore, to be the rule rather than the exception. Examination of the HI maps and velocity fields has shown that the lopsidedness is present in general in both the density distribution and kinematics. In several such cases the rotation curves are clearly asymmetric: on one side of the galaxy they rise more slowly and reach the flat part at larger radii than on the other side. It should be noted that these are isolated, not tidally interacting systems. Although the asymmetric pattern is most clearly seen in the HI data, there is often evidence of asymmetry also in the distribution of blue light and in some cases studied recently also in the near infrared. All these facts suggest that the phenomenon of lopsidedness in spiral galaxies is quite common, structural for the disk, and long-lived.

3. Interacting and Peculiar Systems

There is clear evidence from HI observations that a number of galaxies are undergoing tidal interactions. It is useful to distinguish between two types of interaction: major and minor ones. The “major” one involves systems of comparable masses, usually produces large tidal effects and may lead to destruction of disks and to mergers with, as possible end-product, elliptical galaxies. The “minor” one takes place between a galaxy and one or more satellites or companions of smaller mass (mass ratio usually less than 0.1). This leads to gas accretion, build-up of disks and may cause local star formation and starbursts. There are also systems which, despite their being isolated, show peculiar HI properties typical of interacting systems. These may have had some recent encounter and now be in an advanced stage of accretion (Sancisi 1992).

3.1. MAJOR INTERACTIONS. TIDAL TRAUMAS

Several cases are known of multiple systems with three or more members showing heavily perturbed HI images: in addition to the gas seen associated with the individual members, there are cloud complexes, tails, bridges or ring-like structures in the regions around them. Examples for this type of interaction are the M81-M82-NGC3077 (Yun et al. 1994), and NGC4631-4656-4627 (Rand 1994) groups. In all these systems it is the peculiar gas picture that unmistakably points at the ongoing strong tidal interaction.

The galaxy pairs present a simpler but similar picture of long tails and bridges. M51 and its companion form a well-known example. The VLA observations of Rots et al. (1990) have shown a highly disturbed picture. The most striking feature is a 90 kpc long HI tail without optical counterpart, connected loosely to the outer disk of M 51.

A number of such systems, characterized by optical bridges and long tails, were presented by Toomre (1977) as a possible sequence of ongoing galaxy mergers. Five of these have been recently imaged in HI with the VLA by Hibbard and van Gorkom (1995). 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, and tidal material is seen falling back towards the remnant; the HI is almost completely concentrated in tidal tails often more extended than the optical parts. One of the key questions in such interactions of two disk systems is whether the end product is an elliptical galaxy or whether there are, depending on the kind of impact, possibilities for a disk to survive. An interesting case in this connection is that of NGC 3310 (Arp 217), a disk galaxy which has been recently found to have two extended, well developed HI tails (Mulder and Sancisi 1996) and may, therefore, be an advanced stage in this category of systems. And yet this system has been able to preserve its disk structure.

3.2. MINOR INTERACTIONS. GAS ACCRETION

Several galaxies have dwarf companions and when mapped in HI show clear indications of present tidal interactions. The prototype is NGC 3359. 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 (Sancisi et al. 1990). The companion is a hydrogen-rich object with a very faint optical counterpart. Its HI mass is 10^8 $M_\odot$, only 2% of the HI mass, and 0.1% of the total mass of NGC 3359. Its head-tail structure indicates that it is probably being tidally disrupted. Very similar situations are found in the edge-on galaxy NGC 4565 and other spiral galaxies. The HI masses of these companions are much smaller, less than 10%, than those of the main galaxy. The picture emerging from these observations is that of the capture of gas-rich dwarfs by a massive system followed by tidal disruption and accretion, while the damage suffered by the main galaxy is small.

Cases of a probably more advanced stage in the interaction-accretion process have also been observed. The giant nearby spiral galaxy M 101 may be in such a stage. The HI complex of about 2×10^8 $M_\odot$ moving with velocities of up to 150 km/s with respect to the disk and the corresponding large cavity in the HI layer (Van der Hulst and Sancisi 1988) are interpreted as being due to the collision with a dwarf companion which has gone through the HI layer of M 101. The high velocity gas will eventually rain down back onto the M 101 disk. There are more systems, like M 101, 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 strongly interacting systems. They may represent cases of past interactions and be at present in an advanced stage of accretion in which the victim is not visible any longer. Interesting examples are those of NGC 1023, Mkn 348 and NGC 628.

Similar interactions with dwarf companion galaxies and accretion phenomena are also found in a number of elliptical and S0 systems. We mention here only some of the most recently studied systems: NGC 4472 and UGC 7636 (McNamara et al. 1994), NGC 3656 (Balcells and Sancisi 1996), NGC 5128 (Cen A) (Schiminovich et al. 1994) and NGC 2865 (Schiminovich et al. 1995).

All these cases form circumstantial evidence that even in the present epoch there is episodic infall of gas onto galaxies. How often do interactions take place? and how important are they for the formation of elliptical galaxies or for the build-up of disks, star bursts and galaxy evolution in general? A rough estimate is that probably 25 to perhaps 50 percent of the galaxies show some signs of present or recent interaction.

3.3. CLUSTERS

In a cluster environment tidal interactions between galaxies and ram pressure due to the hot intergalactic gas affect the distribution of neutral hydrogen in the individual galaxies. In the central part of the Virgo cluster, in the region of the hot X-ray gas, spiral galaxies appear to have been stripped of part of their HI, especially in their outer parts (Cayatte et al. 1990, Cayatte et al. 1994). Some HI disks are even truncated inside the optical disks. The spirals in the Hydra cluster do not show any HI deficiency or stripping in spite of the X-ray emitting hot gas (Mc Mahon 1992). Similarly in Ursa Major, but perhaps less surprisingly since there is no X-ray source, no

HI deficiency or stripping are observed (Verheijen 1996). These effects depend on the location of the galaxies in the cluster and the different results probably reflect the different stages of cluster formation and evolution.

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