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THE COOL PHASE OF THE INTERSTELLAR MEDIUM: ATOMIC GAS

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Abstract. The purpose of this review is to discuss high resolution HI observations of a sample of nearby galaxies and to explain what they can teach us about the composition, structure and energy balance of the Interstellar Medium or ISM. The first part presents a summary of what is known about the ISM of the Galaxy and is followed by an overview of the current theoretical models. It continues by showing that it has become feasible to extend studies of the local ISM to nearby spirals, thus avoiding the well known problems associated with Galactic studies such as distance ambiguities and line of sight confusion. The second part is devoted to a discussion of the individual galaxies, addressing both the global properties of the ISM as well as its detailed structure, focussing on the properties of HI shells and supershells.

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1. INTRODUCTION

The study of the interstellar medium (ISM) in galaxies has reached a very exciting stage as it has become feasible with present day instruments to observe nearby galaxies at similar resolutions as has been hitherto reserved to studies of the Galaxy. By looking at nearby systems it is now possible to complement our very detailed but necessarily restricted view of the local ISM. The restrictions are mostly caused by our unfavorable position. As we are located within the disk we suffer from line of sight confusion and are hindered in determining accurate distances within the Galaxy. In addition, at optical and shorter wavelengths the line of sight in the disk becomes prohibitively small.

In this review I will mainly deal with the ISM as it is traced by its major constituent, neutral atomic hydrogen or HI. Recently two outstanding reviews have been written by Kulkarni and Heiles (1987, 1988) who describe in detail the diffuse ISM in our Galaxy and the rôle which is played by HI. Another fine review concentrating on the global HI properties of galaxies was written by Giovanelli and Haynes (1988). I will assume that the reader is familiar with these reviews. What I hope to achieve is

to describe the structure of the ISM in several of the nearby galaxies which were described by Giovanelli and Haynes, but in as much detail as possible and in the terms used by Kulkarni and Heiles.

In order to limit the scope of this paper I will refrain from describing the kinematics and large scale dynamics of galaxies nor will I discuss at any length spiral structure or spiral density waves. Obviously, as this review is concerned with the atomic gas it will be dealing with the extreme Population I or, in other words, the disk component of spiral galaxies. As a result I will ignore their bulges. For the same reason I will not cover E and S0 galaxies which are really in a class of their own. High sensitivity surveys have recently revealed the presence of detectable amounts of HI in several early type systems. There are many indications that a lot of this gas is due to infall, i.e., it is not necessarily remnant material from which the galaxy was formed (but see also the contribution by G. Knapp in this volume). For a statistical analysis the reader is referred to Knapp et al. (1985) and Wardle and Knapp (1986).

There are, of course, other ways to probe the atomic gas component such as via emission lines in the infrared which can be used to study the higher density neutral gas which occurs near photodissociation regions (see for example Wolfire et al. 1990). A more direct way to determine hydrogen column densities is by observing the Lyman-α absorption line in the UV. This technique has been successfully applied to look for neutral hydrogen in the Galaxy (Shull and Van Steenberg 1985), the LMC (Koornneef 1982) and the SMC (Bouchet et al. 1985). The advantage of this technique is that HI column densities can be determined which are independent of saturation effects or spin temperature. The disadvantage is that it only samples HI along lines of sight towards individual objects. Also, one will need powerful UV satellites in order to push this method to the nearest galaxies.

The structure of this review is as follows. It starts with a brief description of the basic radiation transfer equations which are needed to interpret HI observations. After that the main properties of some of the instruments which have opened up this new field of research are discussed. This is followed by a description of the structure of the ISM as we now know it, mainly from observations of the Galaxy. Finally a description is given of the new HI observations of about a dozen nearby galaxies, explaining what they have taught us thus far and indicating which questions one might hope to get answered in the foreseeable future.

2. BASIC RADIATIVE TRANSFER

There are numerous textbooks which derive the basic radiative transfer equations for the 21-cm line of neutral hydrogen, mostly following Wild (1952). For the sake of completeness and to avoid ambiguities due to a different choice of notation I will summarize the most significant formulae involved, following the notation used by Kulkarni and Heiles (1988).

The starting point is the equation of radiative transfer:

$$\frac{dI(\nu)}{ds} = j(\nu) - \kappa(\nu)I(\nu) \quad (1)$$

where $I(\nu)$ is the specific intensity at frequency ν, $j(\nu)$ the emissivity, $\kappa(\nu)$ the absorption coefficient and s the distance along the line of sight. Let us introduce the usual definitions for the optical depth $d\tau(\nu) = \kappa(\nu)ds$ and for the source function $S(\nu) = j(\nu) / \kappa(\nu)$. In thermodynamic equilibrium Kirchoff's law applies so that, using the Rayleigh-Jeans approximation for the Planck law, the source function at radio wavelengths can be written as:

$$S(\nu) = \frac{2\nu^2 k}{c^2} T_s \quad (2)$$

Here c is the speed of light in vacuum, k Boltzmann's constant and T_s the spin temperature. In an equivalent way one can define a brightness temperature T_B which corresponds to the temperature which a black body would have at frequency ν if it were to emit the specific intensity $I(\nu)$. Now we can rewrite the equation of transfer as:

$$\frac{dT_B}{d\tau(\nu)} = T_s - T_B(\nu) \quad (3)$$

This equation can be solved in the case of a homogeneous isolated HI cloud embedded in a background radiation field with a brightness temperature of T_{bg}. Employing e^{τ} as an integrating factor one finds the following important relation:

$$T_B(\nu) = T_{bg}(\nu)e^{-\tau(\nu)} + T_s(1 - e^{-\tau(\nu)}) \quad (4)$$

Let us assume that one can ignore the background radiation (T_{bg} << T_s). In the case of an optically thick cloud ($\tau(\nu)$ >> 1) the formula for the brightness temperature simply reduces to $T_B = T_s$, or the measured brightness temperature is equal to the spin temperature, or characteristic temperature, of the cloud. If the cloud is optically thin ($\tau(\nu)$ << 1) we find that $T_B = \tau(\nu)T_s$. It is important to realize that $\tau(\nu)$ is directly related to the absorption coefficient per H atom which is dependent on atomic constants only. Then

$$\tau(v) = \frac{N_H(v)}{1.823 \times 10^{18} T_s} \quad (5)$$

In this relation N_H is defined as the column density of HI along the line of sight in atoms cm^{-2} and the dependence on frequency has been changed for dependence on velocity, expressed in km s^{-1}. In general the profile of the HI line is determined by its Doppler width which in turn is dominated by the macroscopic motion of the gas. Combining all this, we find in the optically thin case the following useful relation:

$$N_H = 1.823 \times 10^{18} \int T_B dv \quad (6)$$

When reporting HI column densities and HI masses based on this formula, radio astronomers implicitly assume that the emission comes from an optically thin medium. However, HI absorption studies of the Galaxy have indicated that an appreciable fraction of the gas is optically thick so that column densities derived under the assumption of τ << 1 represent a lower limit to the true HI content.

Now let us look at what happens when T_{bg} > T_s. In general an HI spectrum is measured with respect to the background emission,

$$\Delta T_B(v) = T_B(v) - T_{bg} = (T_s - T_{bg})[1 - e^{-\tau(v)}] \quad (7)$$

If there is a strong background source present a spectrum along the line of sight towards this source will show an absorption feature. By measuring a spectrum along a nearby line of sight which presumably has an identical *emission* spectrum, and assuming that the brightness temperature, T_{src} of the source has been determined separately, one can determine the optical depth profile

$$\tau(v) = -\ln\left(1 + \frac{\Delta T_{B,on} - \Delta T_{B,off}}{T_{src}}\right) \quad (8)$$

Once the optical depth profile is known the spin temperature can be derived directly via $T_s(v) = \delta T_{B,off} / (1 - e^{-\tau(v)})$. As explained in Kulkari and Heiles the spin temperature is in general a column-density weighted harmonic-mean temperature. Therefore, and to enable a meaningful comparison between different regions in the Galaxy, a better parameter is the integrated optical depth which was introduced by Crovisier (1981) and which is defined as:

$$\Delta V_{abs} = \int (1 - e^{-\tau(v)}) dv \quad (9)$$

Correspondingly one can define the mean spin temperature as:

$$\langle T_s \rangle = \int T_B(v) dv / \Delta V_{abs} \quad (10)$$

In the case that the spin temperature would drop as low as the 2.7 K cosmic background temperature, no HI emission could be observed above the background and clouds such as the giant HI ring in Leo detected by Schneider et al. (1983), but with even

lower densities, could go unobserved. However, it seems that this situation is unlikely as pointed out by Schneider et al. (1989) for the M96 group and by Corbelli and Salpeter (1990), who report on an extensive HI absorption line survey of High Velocity Clouds (HVCs) and a study of HI absorption towards bright extragalactic sources whose lines of sight pass close to galaxies. They find no evidence for HI column densities of about 5×10^{18} atoms cm^{-2} or larger which are hidden from detection in emission because their spin temperature approaches the microwave background temperature (the subthermal HI effect). Secondly, they infer from their data a lower limit for T_s of several hundred Kelvin for clouds with column densities of the order of 10^{20} atoms cm^{-2} with some evidence for cold HI being present in directions with larger column densities (cf. the review by J. Kenney in this volume for more information on this subject).

3. HIGH RESOLUTION IMAGING FACILITIES

The two telescopes which have been instrumental in obtaining high resolution radio maps of nearby galaxies are the Westerbork Synthesis Radio Telescope (WSRT) operated by the Netherlands Foundation for Research in Astronomy (NFRA) and the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO) [(1)]. No doubt, the compact array of the Australia Telescope (AT) will soon begin to supplement our knowledge by providing high resolution observations of galaxies which are located in the southern hemisphere.

In order to study the structure of the ISM it is necessary to work at linear resolutions of the order of 100-200 pc. Even for galaxies as nearby as M31, M33 or M81 this corresponds to angular resolutions of 10-20 arcsec, clearly only within the realm of synthesis telescopes. Table 1 lists some of the characteristic properties of the WSRT, VLA and AT and gives representative figures for the angular and velocity resolution and sensitivity which can be reached during a typical observing session. These figures are strictly for guidance only and are likely to change rapidly as more sensitive receivers and increasingly complicated correlators are brought on-line. General information about synthesis imaging can be found in the volume on *Synthesis Imaging in Radio Astronomy* (Perley et al. 1989).

Table 1: Characteristics of the WSRT, VLA and AT-Compact Array at 1420 MHz.

Instrument	WSRT	VLA				AT
Configuration		A	B	C	D	Compact Array
Number of elements	14		27			6
Antenna diameter (meter)	25		25			22
Primary beam (arcmin)	37.6		30			35
System temperature (K)	55		60			18
Sensitivity* (mJy beam^{-1})	2.0		0.7			1.1
(K)	7.2	220	28	2.7	0.22	16
Longest Baseline (km)	2.8	36.4	11.4	3.4	1.03	6.0
Shortest Baseline (km)	0.036	0.68	0.21	0.073	0.033	0.030
Synthesized beam (arcsec)	$13 \times 13 / \sin\delta$	1.4	3.9	12.5	44	$6.5 \times 6.5 / \sin\delta$
Largest structure (arcmin)	14	0.6	2	7	15	12

*The sensitivity in mJy beam^{-1} corresponds to the one sigma rms noise reached after a 12^h period. The frequency resolution of respectively 19.5, 12.2, and 15.6 kHz converts to a velocity resolution of 2.5-4.1 km s^{-1}. The sensitivity in terms of surface brightness, expressed in Kelvin, assumes that the emission is distributed uniformly and fills the beam.

All instruments are extremely sophisticated and there usually is a wide choice in baseline coverage, defining the lowest and highest spatial frequency for which one is sensitive, and velocity resolution and coverage. In general the VLA is the preferred instrument for sources which lie within the declination band $-30° < \delta < 30°$ as the East-West oriented WSRT and AT rapidly loose resolution in the declination direction when approaching the equator.

[1] The NRAO is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

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4. THE STRUCTURE OF THE INTERSTELLAR MEDIUM OF THE GALAXY

4.1 The Composition of the ISM

The composition of the ISM is dominated by hydrogen which contributes 90% of all interstellar matter in either its molecular, neutral or ionized form. Based on Spitzer (1978) one can produce the following breakdown for the composition of the ISM:

- H_2, HI, HII, e^-
- He
- other atoms and molecules
- dust
- cosmic ray particles and magnetic fields

Averaged over the Galaxy, about equal amounts of molecular and neutral hydrogen are found; each component comprises ~ 4×10^9 $M_\odot$. The ratio of molecular to atomic gas varies as a function of position, the molecular gas being concentrated in giant molecular cloud complexes which are most abundant in the molecular ring. There is a steep decrease of molecular material as a function of radius and atomic hydrogen dominates outside the solar circle. Hydrogen in its ionized form has until recently been solely associated with HII regions, contributing about 1% in mass. However, as argued by Kulkarni and Heiles (1987) there now is ample evidence that diffuse ionized hydrogen is ubiquitous in the solar neighborhood and that there might be about 10^9 $M_\odot$ of it present in the Galaxy.

Helium is usually considered to be uniformly mixed with hydrogen. It makes up ~ 8% of the ISM by number, but contributes ~ 40% by mass. This point is often overlooked, especially by radio astronomers when they quote the mass of neutral gas in a galaxy based on observations of the 21-cm line of HI. Other elements, such as C, N, O, Ne and Fe make up only minor fractions of at most 10^{-3} to 10^{-4} by number. All other atoms and molecules can be considered as trace elements. This, of course, does not in any sense reduce their tremendous value for probing the physical conditions of the ISM. Dust particles and grains are thought to contribute 1-2% of the mass of a typical interstellar environment. Lastly, the ISM is permeated by a magnetic field of a few μG which constrains the motion of cosmic ray particles, mainly protons.

4.2 The Structure and Phases of the ISM

The various components which make up the ISM in the Galaxy can find themselves in any of the following five phases (Mihalas and Binney 1981, Kulkarni and Heiles 1988):

- **Molecular Medium** (MM). Typical values for the temperature, volume density and volume filling factor are $T \backsimeq 20$ K, $n > 10^3$ cm^{-3}, $f < 1\%$. The MM is characterized by cold dense molecular clouds which are mostly gravitationally bound. Although, on average, this phase contains as much mass as the atomic hydrogen, it occupies only a very small fraction of the ISM.

- **Cold Neutral Medium** (CNM; $T \backsimeq 100$ K, $n \backsimeq 20$ cm^{-3}, $f \backsimeq 2$ - 4%). The CNM is distributed in rather dense filaments or sheets, occupying a minor fraction of the ISM. The CNM is most readily traced by HI measured in absorption.

- **Warm Neutral Medium** (WNM; $T \geq 6000$ K, $n \backsimeq 0.3$ cm^{-3}, $f \geq 30\%$). This phase provides the bulk of the HI seen in emission line surveys.

- **Warm Ionized Medium** (WIM; $T \backsimeq 8000$ K, $n \backsimeq 0.3$ cm^{-3}, $f \geq 15\%$). Until recently this phase was mainly associated with HII regions, but observations by Reynolds (1984) have convincingly shown that a considerable fraction of the ISM is filled with ionized gas.

- **Hot Ionized Medium** (HIM; $T \backsimeq 10^6$ K, $n \backsimeq 10^{-3}$ cm^{-3}, $f \leq 50\%$). The hot gas which is produced by supernova explosions has a long cooling time and consequently a large fraction of the ISM is filled with this "coronal" gas.

As mentioned above, the molecular material is mostly confined to molecular clouds which are held together by gravitation. The cold, warm and hot phases are in global pressure equilibrium. The filling factor for each of the phases is highly uncertain, as is the topology of the ISM (see also section 4.3). The values listed above represent what are currently thought to be the most realistic estimates. It is in trying to determine these values that observations of nearby galaxies will be most useful.

In general, the ISM has structures on all scale lengths, from smaller than 1 pc to larger than 1000 pc. HI observations of the Galaxy have painted a picture of a violent ISM. Heiles (1979, 1984) has shown that there exist dozens of HI shells and supershells, some of them showing clear signs of expansion. The energetics involved suggest that the HI shells are the result of the cumulative effect of supernovae going off within their parent OB association. The shells are the swept up matter whereas the inner portions of these shells are probably filled with HIM. This picture of the ISM is confirmed by HI observations of M31 (Brinks and Bajaja 1986) and other nearby galaxies which will be described in more detail below. The features which Heiles calls supershells are too energetic to be explained in this way (see for a thorough discussion the review article by Tenorio-Tagle and Bodenheimer 1988) and it might be necessary to invoke a different mechanism, such as the infall of material from outside the galaxy.

4.3 Models Describing the ISM

Several models have been proposed over the years to explain the ever more detailed observations of the ISM. The first attempt to explain the different absorption and emission characteristics of the ISM was due to Clark (1965) whose description was formalized by Field, Goldsmith and Habing (1969) in their famous two-phase model for the ISM. In modern terms, they describe the ISM as consisting of a cold and a warm neutral phase in static equilibrium. Cox and Smith (1974) soon realized that the ISM is far from static and that supernovae dominate the energy input. They noticed that the cooling time of the HIM created by SN explosions is comparatively long and that the supernova blown bubbles can link up to form a tunneling network.

In order to better understand Cox and Smith's model and subsequent descriptions of the ISM it is perhaps useful to review briefly the evolution of a region of massive star formation or OB association. The most massive stars, i.e., $M > 25\ M_{\odot}$, firstly ionize their immediate surroundings and blow an initial cavity though the action of their stellar winds. Each star quickly evolves and explodes as a supernova after some 5×10^6 year, depositing about 10^{51} erg in the ISM, partly in the form of kinetic energy, enlarging the wind blown cavity. Less massive stars with $M > 8\ M_{\odot}$ evolve more slowly and will go off as supernovae after about 5×10^7 year. Although the most massive stars have a large influence on their surroundings via photoionization and stellar winds, averaged over a typical galaxy, the larger number of less massive stars makes that the effects of supernova explosions dominate (assuming a normal Initial Mass Function or IMF, of course). An instructive calculation of the energy balance of the local ISM has been given by Abbott (1982). A more complete account is given by Tenorio-Tagle and Bodenheimer (1988) who review the multitude of models which describe the evolution of an ensemble of O and B stars and the effects which they have on the surrounding ISM.

McKee and Ostriker (MO, 1977) incorporated the idea put forward by Cox and Smith into their famous thee phase model, in which the cool, warm, and hot phases of the ISM are in global pressure equilibrium. The MO model proved a major step forward and has been very successful in explaining several key features of the ISM, e.g., the occurrence of highly ionized lines such as the OVI line which was observed in absorption by the *Copernicus* satellite, the interstellar pressure, and the observed cloud dispersion. However, partly as a result of increased observational efforts over the last decade, it has come under serious criticism (cf. Shull 1987). Some of the main shortcomings of the MO model are:

- the assumption of a uniform distribution of supernova explosions. This is a gross simplification as in reality supernovae, especially those of Type II, tend to cluster. Also, the adopted supernova rate by MO is quite high.

- the topology for the WIM and WNM is radically different from the predicted onion skin model in which a cool cloud is surrounded by a warm neutral envelope which in turn is surrounded by a warm ionized layer, the whole being immersed in the HIM. HI observations rather suggest the HI to be in sheets or filaments. Moreover, the inferred filling factor of the WNM is much higher than that predicted.

- the predicted filling factor for the HIM is too high in comparison with HI observations of the Galaxy and other nearby spirals (see e.g., Heiles (1987) for a discussion on the Galaxy and Brinks and Bajaja (1986) who reach a similar conclusion for M31).

These findings have prompted considerable efforts to try to improve upon the MO model and to gain a better understanding of the ISM. Ikeuchi et al. (1984) propose a set of models based on MO which incorporate time evolutionary effects. They show that depending on the supernova rate and ambient density the ISM can either be in a three phase or a two phase state, or even cycle between two states. Heiles (1987) explicitly takes into account the difference in distribution between Type I and Type II supernovae and uses a more reasonable value for the supernova rate. In a more recent effort Heiles (1989) reviews the observational evidence related to the number of supernovae per OB association and takes into account the effect which the thickness of the HI layer has on the confinement of expanding HI shells. He includes in his calculations the full thickness of the disk, including the low density part which decreases exponentially with increasing distance from the plane, known as the Lockman disk (Lockman 1984).

A possible way to avoid creating models which have too high a filling factor for the HIM is to vent hot material into the halo via a galactic fountain (Bregman 1980, Cox 1981, Corbelli and Salpeter 1988). A particularly interesting model for the ISM in this respect is the one proposed by Norman and Ikeuchi (1989) in which they combine the virtues of the MO model with those of the galactic fountain models. Norman and Ikeuchi show that in their chimney model they can allow for a two phase and a thee phase regime *à la* MO by simply changing the SN rate. In their model most of the hot phase resides in the halo of the Galaxy.

It will be clear that the main problem, in fact, does not lie with a lack of models and ideas, but with the fundamental limitations posed by our unfavorable position within the disk of the Galaxy. In order to test the validity of the improved descriptions for the ISM it will be necessary to look at nearby galaxies in as much detail as possible.

5. THE ISM IN NEARBY GALAXIES

Before continuing it is perhaps best to first define what is meant with the term nearby. Present day instrumentation allows angular resolutions of typically 10 arcsec or slightly better. To study the ISM in the line of HI one would like to have at least 200-300 pc linear resolution. This translates to a distance limit of about 4-6 Mpc. A quick survey of for example the nearby galaxy catalogue published by Kraan-Korteweg and Tammann (1979, see also Huchtmeier and Richter 1988), excluding from their list all dwarf irregulars and gas poor systems, and selecting only those systems which are suitably oriented shows that there are some two dozen nearby galaxy candidates. Below I will discuss the currently available results for several of these. In this discussion I will concentrate on the morphology of the HI distribution and I will make some excursions to other areas of interest such as the spin temperature, volume density and velocity dispersion of the gas.

5.1 The Magellanic Clouds

The Magellanic Clouds are the odd ones out, and for two reasons. Firstly they are dwarf companion systems to the Galaxy with which they are in obvious interaction and as such their ISM might not be representative of a typical galaxy. Secondly, they are close enough, at a distance of about 50 kpc, that they can be meaningfully studied by a single dish telescope such as the Parkes 64-m dish. I include them in this discussion because they form a valuable step between the very detailed view which is obtained in Galactic studies and the necessarily more crude pictures which can be obtained of the nearest galaxies. Their importance will only increase once AT maps of parts of the LMC and SMC become available.

The first maps which had enough sensitivity and resolution to reveal structure in the ISM were obtained by McGee and Milton (1966), who mapped the LMC, and by Hindman (1967) who studied the SMC. Both studies were carried out with the Parkes telescope which has a resolution of 14.6 arcmin at 21-cm. They used a velocity resolution of 7.8 km s^{-1}. The angular resolution corresponds to linear sizes of about 230 pc at the distance of the LMC. The characteristics of the HI gas in the clouds are generally similar to those of the Galaxy. The measured one-dimensional velocity dispersion is about 11 km s^{-1} and the average volume density of HI lies around 1 atoms cm^{-3}. A plausible value for the spin temperature is about 200 K with some areas in the SMC, despite the large beam and consequently large area over which the ISM is averaged, showing brightness temperatures as high as 150 K.

Not only were the Magellanic Clouds the first extragalactic systems in which neutral hydrogen was detected (Kerr et al. 1954), they were the first galaxies to show HI shells. Hindman, in his 1967 paper, points out thee distinct HI shells in the SMC for which he measures the position, central velocity, expansion velocity, diameter and amount of HI mass associated with the shell. Figure 1 shows an example of one of his shells. He tentatively explains their origin as due to a super-supernova explosion. To my knowledge Hindman was the first to recognize the HI shells which were found only much later in surveys of the Galaxy by Heiles (1979) as such and the first to provide their most likely interpretation. However, regarding the SMC there has arisen some controversy and it should be mentioned that several groups prefer to interpret the multiple peaked velocities in the SMC as evidence that it is being tidally disrupted (see e.g., Martin et al. (1989) and references therein).

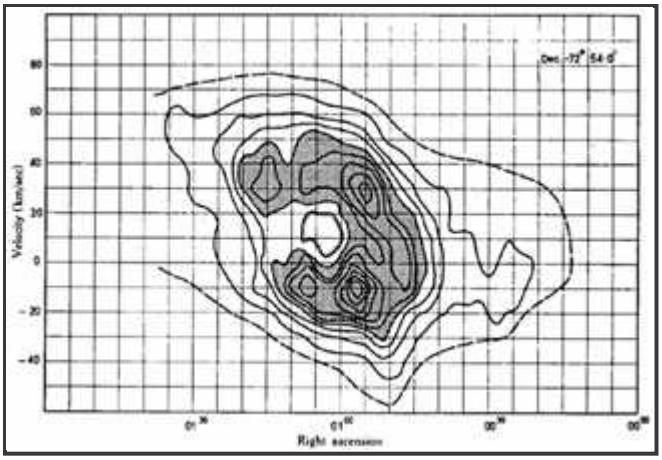

Figure 1. Position velocity diagram though one of the thee SMC HI shells which were discovered by Hindman (1967). Contour levels are at 5, 10, 15... x 1.75 K brightness temperature. The shell has a diameter of 1.8 degree, corresponding to 1600 pc, and an expansion velocity of 23 km s^{-1}.

In the LMC, mainly due to the efforts of Meaburn (1980) who imaged giant and supergiant shells in the light of Hα, the existence of the HI shells and their relation with other constituents of the ISM has been well established. Meaburn lists nine supergiant shells which together cover 12-15% of the surface of the LMC. Their diameters range from 600 to 1400 pc. The largest complex, LMC4, coincides with the Shapley Constellation III. He estimates that energies of order 10-200 × 10^{51} erg are required to produce these structures. There is no doubt that the HI holes are regions in which gas has really been removed. The neutral gas cannot have been entirely ionized as the predicted Hα flux would exceed the observed emission by a large factor. Also, the HI cannot have turned into H_2. In that case one would expect a detectable ^{12}CO signal, even taking into account that the metallicity of the LMC is only about one fifth of the Solar neighborhood (see Cohen et al. (1988) for the first complete ^{12}CO survey of the LMC). In addition one would expect that the presence of molecular material would be associated with a high value for the optical extinction which is in contradiction with what is actually found (Dopita et al. 1985).

The parameters describing the HI shells in the Magellanic Clouds are very similar to those of the Galaxy. The advantage of looking at the LMC is that one can study the relation between these shells and for example optical data and that a direct picture of their spatial distribution can be obtained. Such a comparison shows that the Hα supergiant shells lie along the inside of the HI shells. In turn numerous giant Hα shells, powered by young OB associations, can be found lining the inside of the supergiant shells. The OB associations have to be younger than about 5 × 10^6 year. The stars at the very center of a supergiant shell tend to be older, about 2 × 10^7 year. Meaburn (1980) suggests that this is all evidence of star formation propagating from the center of the shell outwards, giant Hα shells chiseling out a supergiant shell. This process continues until the HI shell breaks out of the disk and the excess pressure is lost.

Some interesting follow-up work has been done by Dopita et al. (1985) and Meaburn et al. (1987), both groups reporting on new HI data covering either a small region of the LMC or crosscuts though a series of shells. Dopita et al. studied in detail Shapley Constellation III which coincides with LMC4. They support the idea that self propagating star formation has determined its structure. They estimate that between 32 and 100 × 10^{51} erg are involved. The reason why LMC4 is such a near perfect shell is attributed to the fact that Magellanic Irregulars tend to show hardly any differential rotation. Furthermore, they claim, on the basis that 15% of the surface area of the LMC is covered by HI shells and using some assumptions for the time needed to cycle the gas though the various phases of the ISM, that the LMC is in a steady state of star formation. Both Clouds have recently been reobserved using once more the Parkes telescope but with vastly improved sensitivity and velocity resolution. Rohlfs et al. (1984) remeasured the inner 6° × 6° of the LMC and Mathewson et al. (1988) reobserved three 40 arcmin diameter areas in the SMC. But because the angular resolution is the same as in the previous surveys not much more can be learned regarding the structure of the ISM. It will be up to the AT to provide the necessary increase in angular resolution.

5.2 Messier 31

The WSRT survey of M31 (Brinks and Shane 1984) has thrown new light on the nearest normal spiral which closely resembles the Galaxy in shape and size. The HI observations were done at a resolution of 24 × 36 arcsec which corresponds to a linear resolution of 80 × 120 pc. The effective velocity resolution was 8.2 km s^{-1}. Although at about ten times the distance of the

Magellanic Clouds, the availability of synthesis telescopes made it possible to study M31 in at least as much detail. In order to determine beam averaged values for the parameters describing the physical state of the gas, such as the spin temperature, velocity dispersion, gas volume density, etc., Brinks and Burton (1984) developed a model for the HI distribution of M31 in which they took the basic radiative transfer into account. The model calculations implied beam averaged values for M31 which are broadly consistent with values derived for the Galaxy from early single dish surveys. They found the following values for the:

- spin temperature, $< T_s > = 125$ K
- one dimensional velocity dispersion, $\sigma = 8$ km s^{-1}
- one sigma scale height, h = 120 pc
- gas volume density, $n_H = 0.6$ atoms cm^{-3}

It should be emphasized that these values are beam averages, representing the mean value over an elliptical area of 80 × 120 pc. Moreover, due to the high inclination of M31 of 77° the quoted values are averages along the line of sight as well which traverses an effective one sigma scale height of ~ 500 pc.

A new survey of the northern half of M31 by Braun (1989) with the VLA at a resolution of $\delta\alpha \times \delta\delta \times \delta V$ = 10" × 10" × 5.1 km s^{-1} will eventually allow more specific values to be determined. An interesting new result which has already been extracted from this impressive data set and presented at this meeting (Braun and Walterbos 1989) is the finding that there exist clumps of HI with brightness temperatures up to 180 K. Braun and Walterbos argue that the peak brightness temperatures in M31 represent the upper envelope of optically thick kinetic temperatures. This is based on the experience in the Galaxy where peak brightness temperatures of 135 K, which are found in the direction of spiral arm tangents, are interpreted as representative for the harmonic mean of the spin temperature, $< T_s >$. The value for M31 is significantly higher than that for the Galaxy. On the other hand, M33 shows peak brightness temperatures of only 95 K (Deul and van der Hulst 1987). It should be kept in mind, however, that this value is most likely a lower limit to the intrinsic peak brightness temperature due to the relatively large size of the beam which was used to map M33. The value for the HI spin temperature depends on many processes, such as the heating due to photoelectric emission from dust and cooling by heavy elements. Important parameters in that respect are the metallicity, grain depletion, ionization rate, and gas pressure. Braun and Walterbos argue that the complex interplay between these factors can be parameterized in terms of the current and past star formation rates. If this is correct, the differences in peak brightness temperatures in the Galaxy, M31, and M33 reflect the relative star formation rate in these galaxies. Braun (1989) also points out that many HI spectra show deviations from a Gaussian profile such as steeper wings and a flatter top which indicates that HI has an appreciable optical depth and that at places an amount of HI equivalent to 50% of the detected amount may be hidden. In fact, it is only with the present high spatial and velocity resolution that this shows up.

A different approach to probe the physical parameters of the ISM is by HI absorption measurements. The snag here is that, compared to similar such studies in the Galaxy, there are very few extragalactic background sources of a sufficient strength which happen to shine through the HI disk of nearby galaxies. Nevertheless, Dickey and Brinks (1988), using the VLA, made a successful attempt to detect HI absorption towards M31. Because of the very high resolution it was possible to eliminate from the absorption measurements all traces of 21-cm emission. The results are summarized in Figure 2 which compares the number density of absorption lines per unit path length as a function of optical depth in M31 with similar data for the Galaxy. The observations indicate that within the errors the absorbing clouds in M31 are as abundant as in the Galaxy. The mean spin temperature of the gas, $< T_s > \simeq$ 300 K, is similar or higher than the local value. The fraction of HI which is in the cool (CNM) phase is about 25% or less, much higher than predicted by the MO model, and implies that in M31 the mixture of cool and warm phases is similar to that in the solar neighborhood. Moreover, as the star formation rate in M31 is much lower than in the Galaxy, these observations prove that the mixture of phases is not strongly dependent on the precise values for the interstellar pressure or supernova rate and that the WNM is a robust phase (Cowie 1987).

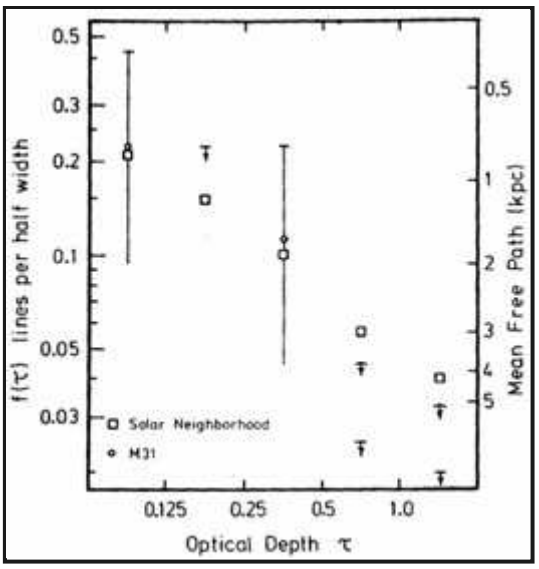

Figure 2. The differential number density of absorption lines in M31 compared to that measured in the Galaxy. The left hand scale indicates the probability of detecting a line per half width of the disk as a function of the optical depth of that line. The general agreement between M31 and the Galaxy suggests an identical abundance of absorbing clouds (Dickey and Brinks 1988).

The M31 HI integrated surface brightness map which is shown in Figure 3, as well as the individual channel maps show a stunning amount of detail in the form of loops, arcs and filaments. Brinks and Bajaja (1986) have compiled a list of 141 roughly elliptical features which show a relative absence of neutral gas and which they call HI holes. Figure 4 shows a blowup of one such hole. The properties of the holes in M31 can be summarized as follows. Their sizes range from 100 pc, the lower limit imposed by the resolution limit of the survey to 1000 pc. Some holes show a clear shell structure although for most holes the shell, if present, is washed out due to the limited resolution. The majority show deviations in the local velocity field which can be ascribed to expansion velocities of the order of 10-30 km s^{-1}. The amount of HI which appears to be absent as compared to neighboring areas is 10^4 to 10^7 $M_\odot$. Kinematic ages for the M31 holes range from 2.5 to 30 x 10^6 year. The estimated energy requirements are 10^{49} to 10^{53} erg. Based on the observed number of holes and some assumptions, Brinks and Bajaja estimate a Type II supernova rate for M31 of 10^{-14} pc^{-3} yr^{-1}, an order of magnitude lower than the corresponding local value for the Galaxy. Also, if the holes trace the distribution of the HIM, the hot gas in M31 does not form a tunneling network.

Figure 3. Integrated surface brightness map of M31 at a resolution of 24 × 36 arcsec from Brinks and Shane (1984). Dark shading corresponds to HI emission. Column densities in the pronounced ring at 10 kpc correspond to about 5×10^{21} atoms cm^{-2}. The rectangular X,Y-coordinate system is aligned along the principal axes and the linear scale and size of the beam are indicated. The white spot near 7.5N and 12.1W is caused by absorption against a bright far-extragalactic radio continuum source. Due to the limits of the survey the noise increases rapidly towards the northern and southern ends of the major axis.

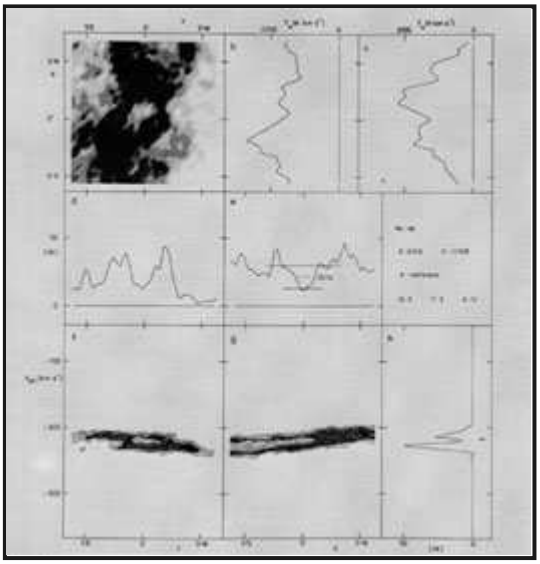

Figure 4. Collection of pictures taken from Brinks and Bajaja (1986) showing the detailed characteristics of one of the holes in M31. The panels show the following: a) expanded view of the channel map at which the hole is best seen. The contour level is drawn at 12.0 K which corresponds to the level at which the hole reaches 50% of its minimum depth; b) and c) are cross-cuts plotted on the same linear scale, made parallel to the X- and Y-axes respectively, through the total HI surface brightness map of M31; d) and e) are cuts made along the same lines and on the same scale through the channel map shown in panel a); to the right of panel e) some information is listed regarding the position of the hole within M31 and the velocity of the channel map; f) and g) are position-velocity maps made along the same cuts and on the same linear scale. The contour levels are at 10, 20, 40, and 60 K; h)

shows a spectrum through the center of the hole. The arrow indicates the velocity at which the hole is best seen.

None of the M31 holes would be classified as an HI supershell. This could either reflect the much lower star forming activity or be related to the fact that no high velocity clouds have been detected thus far near M31. As is the case in the LMC it is clear that the HI holes are regions in which the gas has been removed. Although Hα emission is associated with many of the holes, the observed emission measure falls far short of what would be expected if all the gas were ionized. Following the same argument, the HI cannot have been all transformed into H_2. The most likely explanation is that evolving OB associations through the combined effects of photoionization, stellar winds and supernova explosions shape the ISM. A comparison between the location of the HI holes and OB associations shows indeed that there is a correlation. Contrary to the LMC, the disk of M31 is in differential rotation. Palous et al. (1990) studied the effects which shear has on the evolution of the shells and presented a parameterization for the evolution of their shape under the influence of shear. They predict that matter will pile up at the tips of the hole which can lead to molecular cloud formation and eventually star formation by the time an HI hole closes onto itself, thus allowing for propagating star formation. Their calculations show that the efficiency with which this occurs depends, among other things, on the radial distance from the center of the galaxy.

5.3 Messier 33

The next nearest galaxy to be discussed is M33. This system was studied with the WSRT by Deul and van der Hulst (1987) and Deul (1988). They used a resolution of $\delta\alpha \times \delta\delta \times \delta V$ = 12" × 24" × 8.2 km s^{-1}, corresponding to spatial details of 40 × 80 pc Figure 5 shows the integrated surface brightness map. Although M33 is smaller than M31 it is presently much more active in forming stars. Deul and den Hartog (1989) made an analysis similar to the one discussed above for M31 and came up with the following results. M33 contains some 148 HI holes larger than 40 pc, the resolution limit. Their diameters range from 40 pc to 1000 pc, the larger holes lying preferentially at larger galactocentric distances. The swept up mass ranges from 10^3 to 10^5 $M_\odot$ and their kinematic ages peak around 5×10^6 year. The estimated energies cover the same range as the holes in M31, none of them clearly belonging to the class of supershells. The distribution of the HI holes in M33 is shown in Figure 6 which can be directly compared with Figure 5, the HI map. Deul and den Hartog confirm the correlation of HI holes with OB associations and suggest that smaller HI holes tend to coincide with single HII regions and OB associations whereas the larger, and presumably older holes tend to show star formation along their periphery. This would be in agreement with the description given by Meaburn (1980) and Dopita et al. (1985) for the holes and supergiant Hα shells in the LMC, although in the case of M33 one should also take into account the effects which differential rotation has on the shape of the holes as explained by Palous et al. (1990). The three giant HII regions, NGC595, NGC604 and IC133 all coincide with well-contrasted holes of similar morphology.

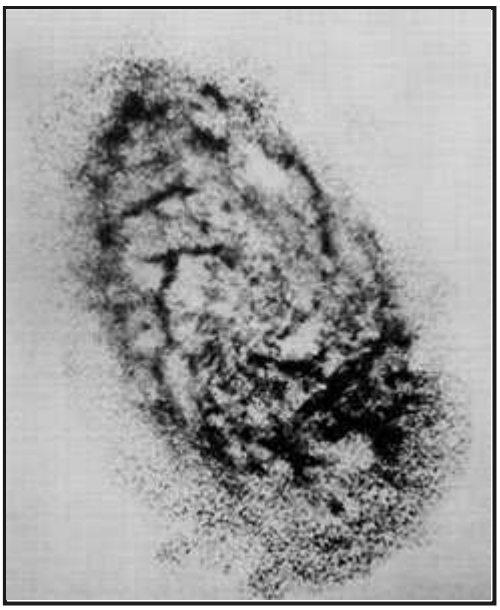

Figure 5. Radio photograph of the HI column density distribution in M33 at full resolution. The column densities range from 1.5×10^{20} to 5.5×10^{21} atoms cm^{-2}. Note the enormous amount of detail and the many loops, arcs and filaments. (Photo courtesy of E. Deul).

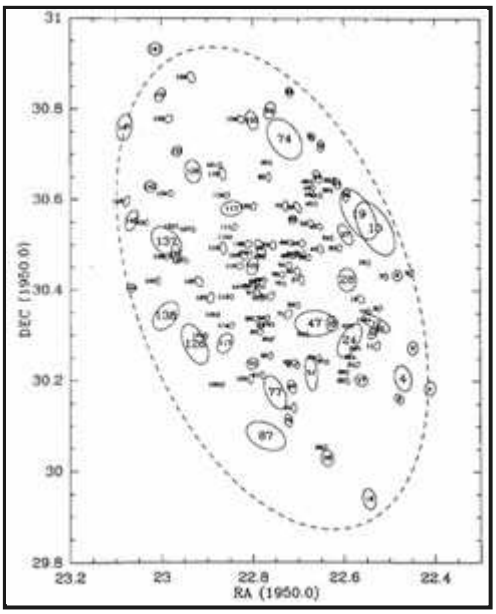

Figure 6. Spatial distribution of the HI holes in M33 as outlined by Deul and den Hartog (1989). The scale for this picture is the same as for the integrated surface brightness map shown in Figure 5. Note the concentration of small holes in the inner galaxy. The larger holes are generally interarm cavities.

Deul and den Hartog searched for ^{12}CO emission at the location of four holes to test the hypothesis that neutral gas is transformed into molecules. Their upper limits confirm that there is less material at the locations they sampled, unless the conversion factor between the measured ^{12}CO surface brightness and H_2 column density is smaller than 0.3 times the Galactic

conversion factor. More sensitive ^{12}CO observations and at a higher spatial resolution would settle this question once and for all. In brief, the results on M33 generally agree very well with what has been found in M31, the LMC and the Galaxy.

5.4 IC10 and IC1613

IC10 is a Local Group galaxy at a distance of 1.3 Mpc which has been mapped in HI by Shostak and Skillman (1989, and references therein). Its HI distribution is quite unusual and the authors propose that the outer HI envelope is still in a collapse phase. In the inner disk seven prominent holes are visible (see Figure 7). Due to the patchy nature the holes are somewhat less easily defined than, for example, those in M31 or M33. The derived linear sizes range from 200 to 800 pc. The estimated energies which are required to produce them are 2-300 × 10^{51} erg, agreeing quite well with what we know about similar features in other galaxies. Interestingly, in addition to the HI holes, Skillman finds an area measuring about 230 pc in diameter which stands out in non-thermal radiation and which coincides with the most massive HI concentration. He interprets this region as a superbubble in an early stage of its evolution and predicts that eventually this bubble might evolve to a supergiant shell with a diameter of the order of 1000 pc.

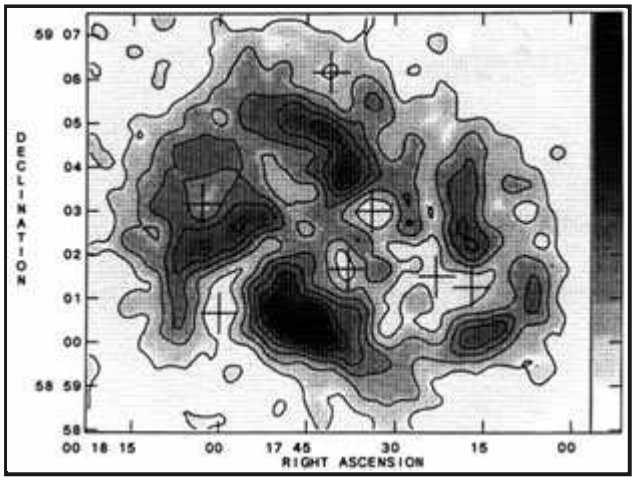

Figure 7. A close-up of the inner HI disk of the local irregular galaxy IC10, identifying the positions of the HI holes (taken from Shostak and Skillman 1989). The peak column density is 4.1 × 10^{21} atoms cm^{-2} and the contour levels are placed at 10% intervals of the peak value.

Another galaxy worth mentioning is IC1613 which was imaged in Hα by Meaburn et al. (1988) and in HI by Lake and Skillman (1989). As in, for example, the LMC a multitude of Hα filaments is visible which link up to form giant and supergiant Hα shells. The HI maps, although made at a moderate resolution, show several HI holes. It would be interesting to reobserve this galaxy at a higher resolution and to compare the HI morphology with the Hα structures.

5.5 M101 and NGC 6946

Until now I have mainly dealt with those features in the ISM of nearby galaxies which can be understood in terms of the evolution of a group of massive stars and their influence on their environment. But, at several instances it was pointed out that some of the structures might in fact be too large or require too much energy to be explained this way. Van der Hulst and Sancisi (1988) recently reobserved M101 with the WSRT (see Figure 8). They noticed in their HI maps two regions in which the HI is displaced to very high velocities with respect to the normal disk rotation. An example is shown in Figure 9. Simple energy considerations would imply kinetic energies of over 10^{54} erg. There are no obvious signs of young stars which could be held responsible for creating these giant structures. Similar features, though with lower energies, have been found by Kamphuis et al. (1990) in another system, NGC6946, but in this case it is not yet quite clear if a supernova origin is ruled out by the data.

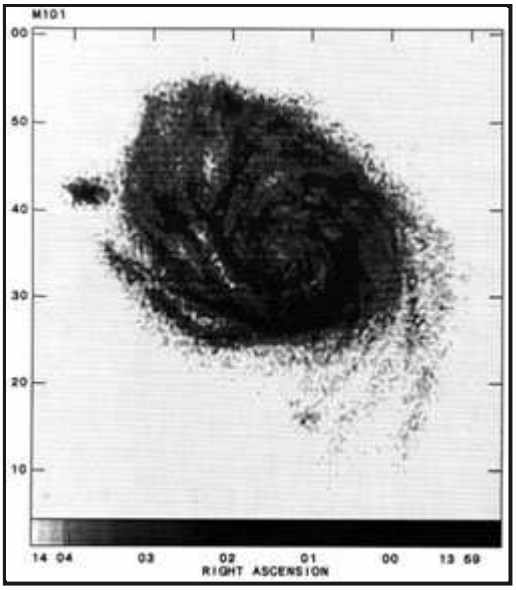

Figure 8. Total HI surface brightness map of M101 . At the assumed distance of 7.2 Mpc, 1 arcmin corresponds to 2 kpc. The most prominent area where deviating HI gas is found is located at 14 ^{h} 02 ^{m} and 54°44'. (Image courtesy of J. Kamphuis).

The explanation which van der Hulst and Sancisi propose for their observations of M101 is the infall of high velocity clouds. Support for this interpretation can be found in the Galaxy. As argued by Tenorio-Tagle and Bodenheimer (1988) it is very difficult to account for the supershells found by Heiles (1979) by multiple supernova explosions. The reason is that once a shell grows large enough to break through the disk, all the energy from subsequent supernova events will be channeled to the halo. On the other hand, infall of a cloud with a velocity of 100 km s^{-1} and a mass of 10^5 $M_{\odot}$ corresponds to the deposition of some 10^{52} erg in the disk of a galaxy. As shown by Tenorio-Tagle et al. (1987) the conversion efficiency is in the region of 15-25%, much higher than the few percent of the total energy output of an OB association which is converted to kinetic energy. In other words, HVC infall can be an efficient mechanism to create large scale remnants. Another point of interest is that the infall model explains why many of the shells show one hemisphere only, as was noticed by Heiles (1979). Tenorio-Tagle et al. show that extrapolation of such a partial shell to a complete bubble overestimates their energy tremendously.

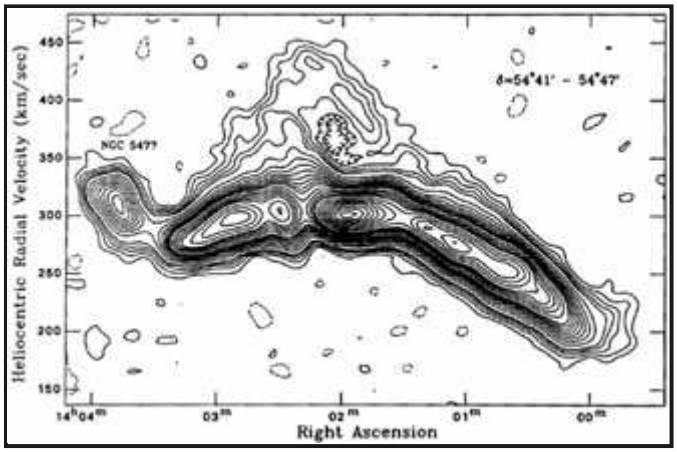

Figure 9. Position-velocity diagram averaging the emission in a declination strip some 7 arcmin wide and centered on the hole mentioned in Fig. 8. Local minima are indicated by tick marks. Contours levels are -2, 2, 4..., 10, 15, ..., 50, 60, ..., 100, 120, ..., 280 K. Figure taken from van der Hulst and Sancisi (1988).

From the large scale surveys of Hulsbosch and Wakker (1988) and Bajaja et al. (1985) it is clear that the sky is filled with HVCs. Looking at those clouds which have the highest velocities (VHVCs), Mirabel and Morras (1984) and Mirabel (1989) claim that they represent high velocity *inflow* of material toward the Galaxy. This does not settle the question if the VHVCs are infalling intergalactic matter or tidal debris from the Magellanic Stream, or if the material is indirectly connected to star formation. It could be hot matter which was expelled from the disk after an HI shell has broken through and which is condensing out and raining down on the disk, as described in galactic fountain and chimney models (Bregman 1980, Corbelli and Salpeter 1988, Norman and Ikeuchi 1989). Additional observations might eventually provide an answer.

5.6 Edge-on Galaxies

In order to study the HI distribution of galaxies one usually chooses systems which are relatively face-on. However, to obtain information on the z-distribution one has to turn to edge-on galaxies. Rupen (1991) has successfully resolved the HI layer in two edge-on systems, NGC 4565 and NGC 891. His VLA data extend the work on the thee-dimensional structure of disks in spiral galaxies which was recently reviewed by van der Kruit (1988). Figure 10 shows a set of channel maps of NGC 891. Both galaxies show a flaring of the HI layer when moving to larger distances from the center. Rupen finds for NGC 4565 values for the one sigma scale height, *h(r)*, ranging from 120 pc for the inner disk to about 300 pc at around 16 kpc at which radius the warp sets in. Corresponding values for NGC 891 are 105 pc for the center and 235 pc at the last measured point near 11 kpc. The values at small radii agree comfortably with those quoted for the inner disks of the Galaxy and M31. These observations also confirm that the HI layers at large galactocentric distances flare. For the Galaxy this was discussed by Kulkarni et al. (1982). In the case of M31 this could only be inferred on the basis of the model fits (Brinks and Burton 1984).

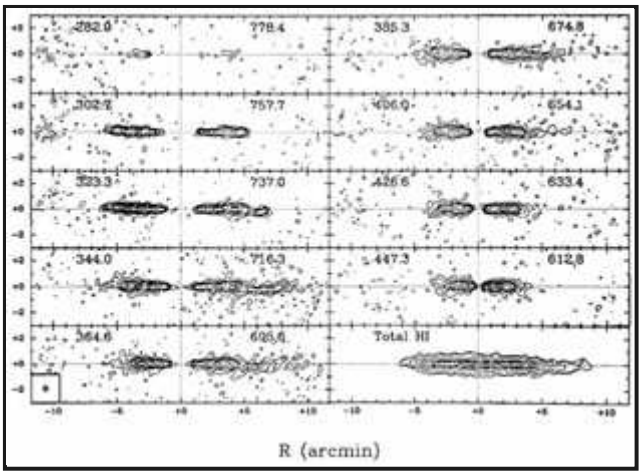

Figure 10. Series of HI channel maps at 20 arcsec resolution of NGC 891. The maps have been rotated to put the major axis horizontal, north pointing to the left. Each panel shows the two channel maps which are symmetrically placed with respect to the systemic velocity (530 km s^{-1}). The heliocentric velocities are indicated on top. Contour levels are plotted at -10, -8, ..., -2, 2, 4, ..., 10, 15, ..., 45 mJy $beam^{-1}$. The bottom right hand panel shows a map of the integrated HI distribution with contour levels at 0.1, 0.2, 0.5, 1.0, ..., 4.0 Jy $beam^{-1}$ km s^{-1}. (Map courtesy of M. Rupen).

The scale height of the gas layer is inversely proportional to the mass volume density, $\rho(r, z)$, in the disk at z = 0, and can be written as $h(r) = \sigma_g / [4\pi G \rho(r, 0)]^{1/2}$ where G is the gravitational constant (see e.g., Kulkarni et al. 1982). From studies of face-on galaxies it has been shown that σ_g is constant and ranges from 7-10 km s^{-1} (van der Kruit and Shostak 1984). Hanson et al. (1990) observed with improved sensitivity and velocity resolution the nearby face-on galaxy NGC 1058. They confirm that σ_g is constant over most of the disk at a value of 5.7 km s^{-1}, slightly lower than the value previously quoted by van der Krit and Shostak. Assuming a constant velocity dispersion, Rupen's observations of the edge-on systems yield a direct measurement of the mass volume density and, if the mass distribution follows the old star light, the *M/L* value as a function of radius. The data on both galaxies are consistent with a constant $M/L \approx 3\ M_\odot / L_\odot$. Although it is tempting to assume that all galaxies feature a flaring HI disk and that the velocity dispersion of the gas perpendicular to the disk is constant, one has to be cautious. Bottema et al. (1986) found at least one (dwarf) galaxy, NGC 5023, in which the scale height of the HI gas appears constant.

Interestingly the maps of NGC 891 show numerous wiggles which Rupen ascribes to non-thermal processes. It would be interesting to see to what extent these wiggles are associated with the features which are seen in Hα and which were presented at this meeting by Dettmar et al. (1990) and Kulkarni et al. (1990). Both groups indicate that there are filaments in their Hα maps which originate in star forming regions in the disk and which stick out of the plane. Are we seeing here evidence for the disk-halo interaction as proposed by the galactic fountain and chimney models?

The last galaxy which I would like to mention is the edge-on spiral NGC 3079 which was observed with the VLA in HI by Irwin and Seaquist (1990). This galaxy not only displays remarkable activity in the center but it also contains half a dozen HI shells in its disk. Their dimensions and energy requirements as derived by Irwin and Seaquist place them in the category of Heiles supershells. Again, if these features are caused by the collective effects of several star forming regions, it is tempting to interpret these observations in terms of chimney models in which hot material from a bubbling disk flows into the halo.

6. FORWARD LOOK

I hope that the above has indeed illustrated that studying the ISM in nearby galaxies via the 21-cm line of HI is not only feasible but very exciting and rewarding. Moreover, in order to put to the test the multitude of models which exist for the overall structure of the ISM and for the detailed evolution of an OB association, this kind of observations is indispensable. At present beam averaged values for several parameters describing the state of the neutral gas can be determined, typically sampling volumes with a diameter of a few hundred parsec. Values for the measured velocity dispersion, volume density and spin temperature are generally in line with values derived for the local Galaxy. There are indications that by employing yet higher resolutions these values might change. As mentioned above, Braun and Walterbos (1989) show that peak brightness temperatures might vary as a function of galaxy type and position in a galaxy. They argue that the peak brightness is a measure for the star formation rate. If this is correct then this should show up in their VLA high resolution HI survey of a dozen or so nearby galaxies. Another way to throw light on the intrinsic temperature of the gas is by HI absorption observations. A new survey, extending the observations reported by Dickey and Brinks (1988) is on its way.

It is evident from the high resolution HI imaging that all galaxies show a multitude of filaments, arcs, loops and shells. It seems as if most of these features can be explained by the effects which OB stars have on their environment. Some features, equivalent to Heiles' supershells and perhaps best exemplified by the observations of M101 (van der Hulst and Sancisi 1988) require much more energy and their most likely explanation is infall of material. One of the questions which can now be addressed is how this infall is related to the presence of high velocity clouds. A further step will be to try to decide where these clouds come from; are they tidal debris or is it material which has its origin in the disk and which has been ejected by supernovae upon breakthrough of a bubble blown by an evolving OB association. Alternatively, the HVCs could be disk material which has been shot into the halo by the impact of a small companion and which is falling back.

In this review I have restricted myself to HI observations which trace the cool and warm neutral medium. It is clear that for a complete picture one would like to include Hα and radio continuum data which trace the WIM. One such project, which looks at the smaller scale interaction of an OB association with the ISM and which combines radio and optical data is underway (Brinks et al. 1989). The aim of this project is to study in detail a number of OB associations in M31 and to provide constraints for the various models which have been proposed and to derive the energy balance for these regions. Other obvious components which should be added in order to gain a more complete understanding are the cool dust and the molecular phase whereas the last piece of the puzzle will have to come from the new generation of X-ray satellites such as ROSAT which will eventually supply information on the HIM, thus completing the picture of the ISM.

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