SMALL-SCALE PROPERTIES OF HI IN NEARBY GALAXIES

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ABSTRACT. The instrumental requirements and current observational results are outlined for the study of resolved neutral hydrogen structures in both emission and absorption in external galaxies. Neutral super-shell structures exterior to ionized shells around OB associations seem to be a common phenomenon. Further analysis of existing data should allow quantification of the degree and rate of energy deposition in the ISM by massive stars. HI absorption studies offer great promise in constraining the physical properties of the neutral ISM, including an estimate of the gas pressure. Together these data will provide hard constraints on the existence and prevalence of chimney formation, and hence disk – halo interactions in a variety of galactic environments.

1. INTRODUCTION

Within the last few years a new phase in the study of the neutral, interstellar medium (ISM) has begun. Instrumental capabilities have now advanced to the point where observations of the ISM in the closest external galaxies can probe physical scales and sensitivities comparable to those accessible to studies of the Galaxy. The opportunity to study external systems at known distances, at a variety of inclinations and over a range of galaxy types opens a wide range of possibilities for better understanding the physical conditions and processes in the neutral ISM which have remained elusive up to this point.

A basic requirement of an observation which is intended to address physical conditions of the ISM is that the source structure be resolved both spatially and, in the case of a spectral line like that of HI, in velocity. In this paper we will consider to what extent these requirements can be satisfied in the context of current instrumentation, which will lead to definitions of the terms “small” and “nearby” which appear in the title. Since observations of resolved HI emission and absorption have only been fully reduced for one external galaxy to date (M31) we will consider the emerging results for this system in some detail.

H. Bloemen (ed.), The Interstellar Disk-Halo Connection in Galaxies, 213–222.

2. OBSERVATIONAL REQUIREMENTS

HI emission structures observed in the Galaxy have a large range of physical sizes, from some 100's of pc down to only a few pc. Most of the power appears to be concentrated in the larger spatial scales, as evidenced both by power spectrum analyses (e.g. Crovisier and Dickey 1983) and the simple observational result that the highest brightness temperature seen in emission of about 125 K was observed with the 35 arcmin angular resolution of the early surveys done with 25 m telescopes, and this value has not increased significantly with the much higher angular resolution of more recent work. The corresponding spatial resolution is about 100 pc at a typical inner galaxy distance of about 10 kpc. Similarly, velocity resolutions in excess of about 5 km/s have not resulted in higher observed brightnesses. Observations of HI absorption, which are sensitive to the high opacity component of the neutral gas, reveal somewhat narrower linewidths than those seen in emission, although even here the velocity dispersions, σ, are usually greater than 2 km/s (e.g. Dickey, Salpeter and Terzian 1978) so that the linewidth, FWHM $= 2.36\ \sigma$, is typically greater than about 5 km/s.

The range of brightness of HI emission, just as the range of structural scales, spans about two orders of magnitude from a few to a few hunderd degrees K. At low brightnesses, there appears to be a threshold column density of a few times 10^{19} cm^{-2} below which neutral hydrogen is not detected independant of sensitivity (e.g. Sancisi et.al. 1990). At high brightnesses, as we will see below, the limit is primarily determined by the kinetic temperature of high opacity HI which is expected to reach between some ten's and a few hunderd K depending on the physical conditions (e.g. Draine 1978). A practical criterion for the study of resolved HI emission is then a sensitivity better than about 20 K, corresponding to a column density less than about 2×10^{20} cm^{-2}. Together with the 100 pc spatial resolution this implies a sensitivity to an HI mass less than about 2×10^{4} $M_{\odot}$.

These observational constraints are summarized in Table 1 for the study of resolved HI emission at a variety of distances. The column density noted above, together with a kinetic temperature of 200 K, lead to a limiting opacity in HI absorption, $\tau = 0.1$. Twelve hours of integration with an extended VLA configuration give sensitivity to this opacity against background sources brighter than about 5 mJy independant of the absorber's distance. Integrating background source counts at 20 cm wavelength (e.g. Windhorst, Van Heerde and Katgert 1984) down to 5 mJy leads to an expected source density of 26 deg^{-2} or about 1 per 10 by 10 arcmin, the angular size of a 15 kpc galactic disk seen at a distance of 5 Mpc. Together with the integration times listed in Table 1, it becomes clear that only galaxies within about this distance are currently accessible to studies of resolved HI emission, and have a reasonable *a priori* probability of detectable absorption against a background source. It is somewhat frustrating to note that the volume of space we can effectively probe will not extend to the Virgo cluster or various well known "nearby" galaxies until a new instrument of 40 km extent and about 10 times the collecting area of the VLA is built. Such an instrument is not yet being seriously discussed.

Table 1.
Instrumental Requirements for the Study of Resolved HI Emission

Source (1)	Distance (2)	Baseline (3)	Instrument (4)	Integration Time (5)
The Galaxy	10 kpc	25 m	many	$\sim 1^m$ / position
LMC/SMC	50 kpc	125 m	compact AT	$\sim 2^h$ / field
eg. M81, M101 groups	5 Mpc	12 km	VLA B config.	$\sim 12^h$
			GMRT	$\sim 2^h$??
eg. Virgo cluster	20 Mpc	40 km	VLA A config.	$\sim$ 1/2 year
			GMRT	$\sim$ 1 month ??

3. STRUCTURES IN EMISSION

High resolution observations of HI in nearby galaxies have revealed a wealth of structural information, even though almost none have had the requisite resolution (better than about 100 pc and 5 km/s) to resolve the emission structures. The most noted form of structure, up to this point, has been local minima in the distribution of HI. Hindman (1967) detected three such minima in the SMC, Shostak and Skillman (1989) report seven in IC10, while extensive catalogs have been published by Brinks and Bajaja (1986) for M31 (140 entries) and by Deul and Den Hartog (1990) for M33 (150 entries). It should be noted that less than 10 % of the HI "holes" in the M31 and M33 catalogs were considered by these authors to be of "high quality" in the sense of possessing a relatively elliptical boundary and reasonably high contrast.

While some fraction of the HI "holes" detected in nearby galaxies almost certainly represent physical entities, the question which naturally arises is how many of these local minima are really connected structures rather than simply a consequence of the projected topology. This distinction is aggravated by the obviously filamentery, frothy HI structure which is apparently left behind by multiple generations of massive star formation. In cases of moderate signal-to-noise, where a clear limb-brightening and possibly an expansion signature are not detectable it must be concluded that it remains impossible to identify physically connected structures on the basis of the distribution of HI emission alone.

The intrinsic ambiguity of moderate signal-to-noise local HI minima, suggests an alternate approach in the analysis of small-scale HI emission structures in which a search for HI counterparts is undertaken relative to positions of a less confused population such as molecular clouds, HII regions, OB associations or X-ray bubbles. Specifically, HII super- or super-giant shells offer an obvious parent population to search for associated, expanding HI shells.

3.1 The Magellanic Clouds

The type of directed search that was just outlined has as yet been appplied in only a limited way to the LMC/SMC, although the possibilities are very graphically

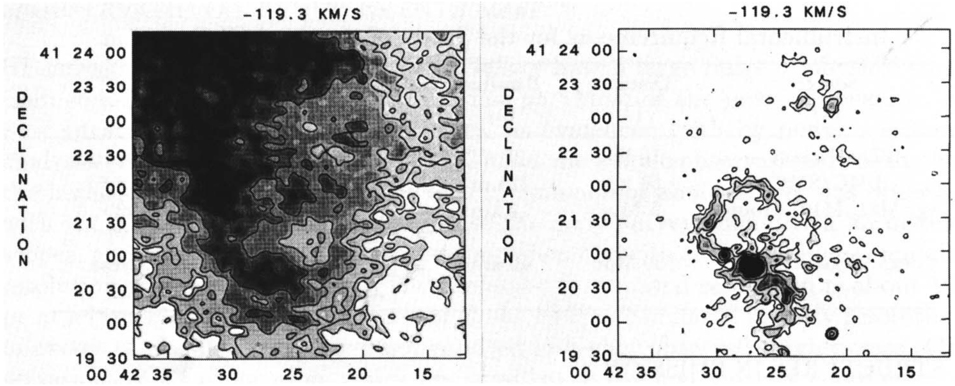

Figure 1. Narrow-band images in neutral hydrogen (left) and ionized hydrogen (right) at a heliocentric velocity of −119.3 km/s of a region of about 1 kpc on a side within Messier 31. Neutral counterparts are seen exterior to many of the ionized shells surrounding OB associations at their systemic velocities. Expansion signatures are sometimes apparent at outlying velocities.

illustrated by the narrow-band image in Hα + [NII] of the LMC made by Davies, Elliott and Meaburn (1976). The tabulated properties of the many observed nebulae (Figure 3 of Meaburn 1980) indicate a population of super-shells with diameters less than about 300 pc associated with individual OB associations. These in turn are sometimes organized into super-giant shells with diameters between 600 and 1200 pc. Existing HI data for the LMC and SMC are severely limited by the 220 pc spatial resolution obtainable with the Parkes 64 m telescope. Comparative studies, like that of Dopita, Mathewson and Ford (1985), have therefore only been able to access the super-giant shells, which are in fact found to be clearly associated with expanding neutral shells. Major advances in this study are bound to follow from the availability of the Australia Telescope (AT) during the coming years.

3.2 Messier 33

Comparable opportunities exist in M33, where the photographic imagery of Courtes et al. (1987) delineates the extensive population of Hα super-shells. The recent HI survey of Deul and Van der Hulst (1987), with 65 pc by 8 km/s resolution and 3000 $M_\odot$ sensitivity may partially resolve emission structures, although another factor of two in velocity resolution would clearly be desirable. A systematic analysis of the HI database from the perspective of super-shell associations is now being planned (Van der Hulst, private communication).

3.3 Messier 31

The only external galaxy for which reduced observations now exist that satisfy the criterion derived in §2 for resolved detection of HI emission structures is M31. The data covering the north-east half of M31 at 35 pc by 5 km/s resolution and 500

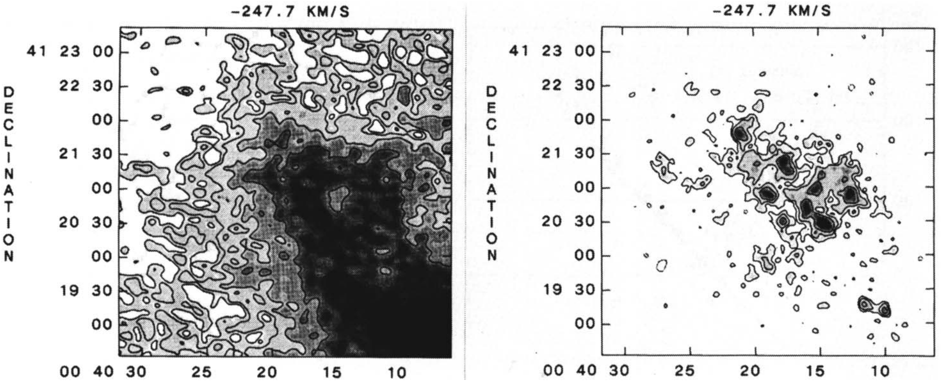

Figure 2. As for Figure 1, but for another region in Messier 31 and at a velocity of −247.7 km/s. The major shell structure in this example shows a clear expansion at outlying velocities in both HI and Hα at about 20 and 30 km/s respectively.

$M_\odot$ sensitivity were recently published (Braun 1990). Analysis of limited portions of this database has already taken place in conjunction with Hα kinematic data (Brinks, Braun and Unger 1989, 1990), while a systematic analysis in conjunction with narrow-band imagery in Hα and [SII] (Walterbos and Braun 1990) is still underway. Some of the correspondences between Hα and HI super-shells are illustrated in Figures 1 and 2, where corresponding images are shown at the indicated velocities for two regions of about 1 kpc on a side.

Virtually all of the Hα shells seen in these figures have at least low contrast ($>$ 50 % of the background) HI counterparts at the systemic velocities. The best developed examples show neutral shells which are clearly exterior to the ionized shells. A detectable expansion signature in HI is less common, and when present is always slower than in Hα. In particular, the major shell structure in Figure 2 (at $\alpha_{50} = 0^H 40^M 15^S$, $\delta_{50} = 41°20'50''$) has a clear expansion signature in both Hα and HI with expansion velocities of about 30 and 20 km/s respectively. The kinetic energy associated with the expanding HI shell in this case is a few times 10^{51} erg. In is interesting to note that none of the HI structures in these figures has been previously identified as an HI “hole”.

No obvious cases of disk–halo communication have yet come to light in the analysis of HI and Hα counterparts. More detailed study of individual regions as well as statistical analysis of counterparts to stellar associations and a sample of more than 900 emission nebulae cataloged by Walterbos and Braun (1990) will be carried out in the coming year. This analysis should allow assessment of the degree and rate of kinetic energy deposition in the ISM and hence hard observational data pertaining to the issue of chimney formation.

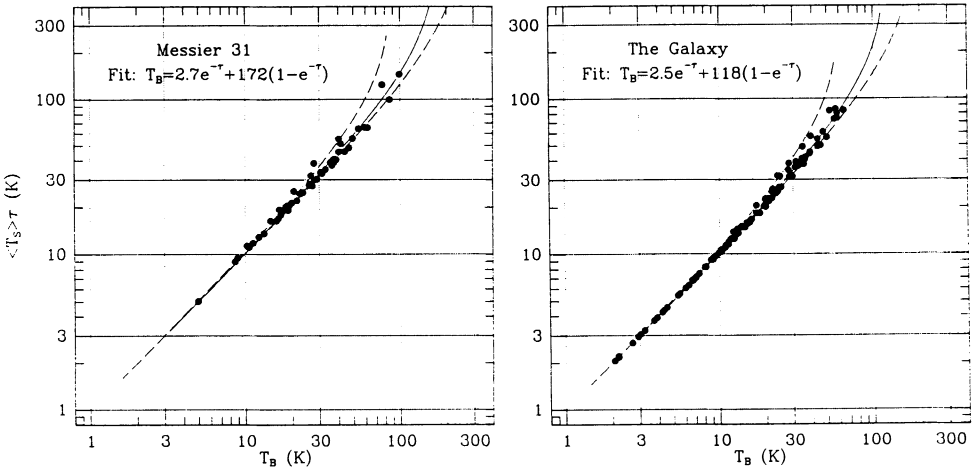

Figure 3. Implied column density as a function of brightness temperature of emission for M31 and the Galaxy. This product isolates the asymptotic behaviour at large T_B. Asymptotic temperatures derived here are consistent with those obtained directly from HI emission studies, and are almost 50 % higher in M31 than in the Galaxy.

4. ABSORPTION STUDIES

There have, as yet, been few detections of HI absorption outside of the Galaxy. Besides a handful of detections against bright nuclear sources (Van Gorkom et al. 1989) single lines-of-sight have been detected against a few systems including NGC891 (Rupen et al. 1987) and M31 (Dickey and Brinks 1988). The recent high sensitivity survey of M31 (Braun 1990 (B90)) has made possible the detection of seven lines-of-sight through that galaxy's disk, with a total equivalent width of absorption and sampled path length comparable to that obtained in the Arecibo surveys of HI absorption in the Galaxy (Dickey, Salpeter and Terzian 1978, (DST78) Payne, Salpeter and Terzian 1982 (PST82)). The analysis of these data (Braun and Walterbos 1990) has been very instructive in delineating the physical properties of the neutral gas in M31.

In analyzing the absorption properties of HI, the implied spin temperature, $<T_S>$ defined by,

$$<T_S>= \frac{T_B}{(1-e^{-\tau})} \tag{1}$$

has often been plotted as a function of the measured opacity, τ, since Lazereff (1975) sugggested there might be some correlation between these quantities. In fact, these quantities are clearly not independant of eachother and their relation offers little insight into the gas properties. A more revealing relationship turns out to be that between implied column density, $< T_S > \tau$ and emission brightness, T_B. These quantities are plotted in Figure 3 using the data of DST78 and PST82

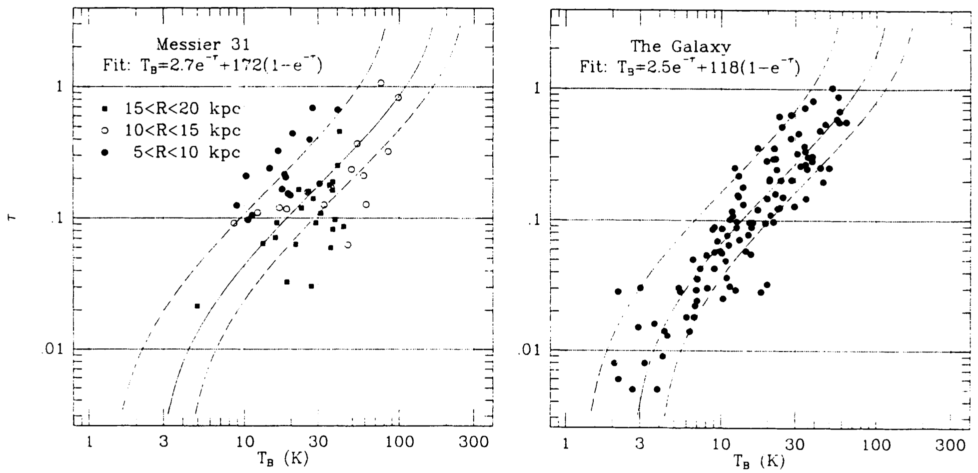

Figure 4. HI opacity against emission brightness for M31 and the Galaxy. This form is sensitive to the asymtotic behaviour at small T_B. The values for M31 are binned by radius in that system, while the galactic data are for gas within about 1 kpc of the sun. The plotted fit and envelope at ± 50 % of the variable values corresponds to a simple two component model. The inner disk of M31 has a systematically lower temperature than the outer disk.

for the Galaxy and B90 for M31. A very tight correlation of the implied column density is seen with the emission brightness. This relation follows the one-to-one correspondence expected for low optical depth at low T_B and then becomes increasingly non-linear for high T_B. It allows a sensitive determination to be made of the asymptotic brightness, T_∞ from,

$$T_B = T_\infty(1 - e^{-<T_s>\tau/T_\infty}) \tag{2}$$

yielding $T_\infty = 118 \pm 2$ K for the Galaxy and $T_\infty = 172 \pm 3$ K for M31. These values of asymptotic brightness are in good agreement with the highest values of T_B observed directly in emission, indicating that the "single component" opacity corrections that have sometimes been employed in determining HI masses and dust-to-gas ratios are a good approximation to the actual dependance of opacity on brightness.

The different linewidths and detailed line shapes of HI absorption and emission spectra have made it clear from early on that HI emission is due to at least two distinct physical components; a cool component of significant opacity and a warm component with negligible opacity. This need is also obviated by the relationship between the primary observables shown in Figure 4; the opacity and the emission brightness. Not only is there an asymptotic brightness at high opacity, but also at low opacity; a relationship incompatible with a single temperature gas. The simplest physical model which can accomodate these trends is one composed of two temperatures, T_c and T_w for which $\tau_w << 1$ and $T_w\tau_w$ = constant. Placing one half of the warm gas in front and one half behind the cooler gas yields an emission brightness,

$$T_B = \frac{T_w \tau_w}{2} + T_c(1 - e^{-\tau_c}) + \frac{T_w \tau_w}{2} e^{-\tau_c} \tag{3}$$

which yields the asymptotic brightness, $T_\infty = T_c + T_w \tau_w / 2$. Rewriting eqn. 3 in terms of T_∞ yields,

$$T_B = T_w \tau_w e^{-\tau_c} + T_\infty(1 - e^{-\tau_c}) \tag{4}$$

Having already fixed the value of asymptotic brightness from the $< T_S > \tau$ – T_B relation above, permits a single parameter fit for the column of warm gas, $T_w \tau_w$. This yields $T_w \tau_w = 2.5 \pm 0.1$ K for the Galaxy and $T_w \tau_w = 2.7 \pm 0.2$ K for M31, which implies that the cool HI component temperatures are, $T_c = 117 \pm 2$ K for the Galaxy and $T_c = 171 \pm 3$ for M31. The fits to eqn. 4 are overlaid on the data in Figures 3 and 4 together with an envelope at plus and minus 50 % of the variable values to illustrate the functional dependance and quantify the degree of scatter.

While the contribution of warm HI is not significantly different in M31 and the (solar neighbourhood of the) Galaxy, and corresponds to about 2×10^{19} cm^{-2} per 5 km/s interval, the cool component temperatures are significantly different. Furthermore, there is evidence for a gradient in the temperature of cool HI in M31, as illustrated by the binning by radius in Figure 4. Cool component temperatures vary from about 80 K in the inner galaxy to about 200 K beyond about 10 kpc radius. The kinetic temperature of neutral hydrogen is regulated by photoelectric heating from dust and radiative cooling by gas-phase heavy elements (e.g. Draine 1978). The relevant physical parameters for these processes are the ionization rate due to cosmic rays and soft X-rays, the gas-to-dust ratio, the gas-phase metal abundance and the gas pressure. The only plausible mechanism for producing the higher cool HI temperatures (at R > 10 kpc) in M31 than in the Galaxy appears to be a lower gas phase pressure by about a factor of 2 (Braun and Walterbos 1990).

With knowledge of the gas temperature, it becomes possible to derive line-of-sight filling factors for the various components, by assuming values of the gas pressure. Since the HI opacity is given by,

$$\tau = \frac{1.7ns}{T\Delta V} \qquad \left[\frac{cm^{-3}pc}{Kkm/s}\right] \tag{5}$$

in terms of a path length, s, the line-of-sight filling factor can be written as,

$$f = \frac{s}{S} = \frac{T^2 \tau \Delta V}{1.7pS} \tag{6}$$

in terms of the component scale height, S and the gas pressure, p. Various lines of evidence suggest that the warm HI component has a temperature of 8000 K, while the exponential scale heights of the dense and tenuous components appear to be

Table 2.
Global Properties of Neutral Gas in M31 and The Galaxy

Quantity			Messier 31			The Galaxy[a]		
Comment (1)	Symbol (2)	Unit (3)	Cool (4)	Warm (5)	Ref.[b] (6)	Cool (7)	Warm (8)	Ref.[b] (9)
Equivalent width to midplane	$< \tau\Delta V >_\perp$	km s^{-1}	0.936	...	1	0.706	...	2,3
Velocity width to midplane (at T_B >5 K)	$< \Delta V >_\perp$	km s^{-1}	...	6.62	1	...	7.03	2,3
Brightness temperature	$< T\tau >$	K	...	2.70 ± 0.16	1	...	2.54 ± 0.12	1
Temperature	$< T >$	K	171 ± 3	8000	1,4	117 ± 2	8000	1,4
Column to midplane	$< T\tau\Delta V >_\perp$	K–km s^{-1}	160.	17.9	1	82.6	17.9	1
Scale height	S	pc	150	400	1,5	150	400	4
Thermal pressure	$< p >$	cm^{-3}K	1500	1000	1	2960	2070	4
Density	$< n >$	cm^{-3}	9	0.13	1	25	0.26	1
Line-of-sight filling factor	$< f >$	%	7	20	1	1.3	9.5	1
Opacity-corrected HI mass	M_{HI}	10^9 $M_\odot$	4.6		1,6	3.5		1,7
Gas-to-dust ratio	N_H/E_{B-V}	$10^{21}cm^{-2}mag^{-1}$	4.4–5.6		1	4.8–5.3		8
Gas-phase "metallicity"	$< A >$	[O/H] 10^{-4}	5.0 ± 1.0		9,10	2.5 ± 0.5		10,11

[a] Galactic values refer to the extended (1 kpc) solar neighbourhood.

[b] References.—(1) Braun and Walterbos (1990), (2) Dickey, Salpeter and Terzian (1978), (3) Payne, Salpeter and Terzian (1982), (4) Kulkarni and Heiles (1988), (5) Braun (1990), (6) Cram et al. (1980), (7) Henderson, Jackson and Kerr (1982), (8) Savage and Mathis (1979), (9) Blair, Kirshner and Chevalier (1982), (10) Dopita et al. (1984), (11) Talent and Dufour (1979).

about 150 and 400 pc respectively (e.g. Lockman, Hobbs and Shull 1986). Midplane gas pressures in the Galaxy are approximately 4000 cm^{-3}K (Kulkarni and Heiles 1988). Using these values together with the mean column to the midplane $< T\tau\Delta V >_\perp$ and eqn. 6 yields the values of Table 2.

One of the noteworthy results of this analysis of HI absorption and emission is the small line-of-sight filling factors derived for the neutral gas. Taken together with the very large surface covering factor of neutral gas in both the Galaxy and M31, it becomes possible to constrain the three-dimensional topology of this component of the ISM. The most obvious topology which reproduces such filling factors is the one suggested by the projected distribution itself; an extensive, frothy network of bubbles like that detected in §3.

5. FURTHER PLANS AND DEVELOPMENTS

As indicated at the outset, a fascinating phase in our study of the neutral ISM has begun. Our first relatively unconfused glimpses of resolved HI structures in external galaxies are in hand. Neutral shells such as discussed in §3.3 appear to be a common phenomenon external to the ionized shells surrounding evolved OB associations. More extensive analysis of the M31 and M33 databases will be vital in refining our understanding of the physical properties, phase and energy balance of the ISM in normal galaxies. At the same time, our curiousity has been arroused by the fact that the neutral ISM of M31 appears to be so different than that of the Galaxy in terms of average pressure, temperature and density. What is the actual range of physical conditions which can occur and how do they depend on the galaxy type and position within the galaxy?

In an effort to address these questions, a sample of eleven major galaxies within about 5 Mpc (NGC 55, 247, 2366, 2403, 3031, 4236, 4736, 4826, 5457 and 7793) is being observed by an extended group (Braun, Van Gorkom, Walterbos, Kennicutt, Norman, Tacconi-Garman) utilizing not only resolved neutral hydrogen but all accessible ISM tracers. The coming years will likely yield important insights in our understanding of the ISM in general and the degree and prevalence of communication between the disk and halo in particular.

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