

HI as a Probe of Structure in the Interstellar Medium of External Galaxies

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Abstract. This review presents a perspective on recent advances in understanding neutral ISM structure in external galaxies. HI is a fundamental probe of galactic baryonic material, and its structure and distribution offer vital signatures of dynamical and evolutionary processes that drive star formation and galaxy evolution. New, high-resolution HI data cubes for external galaxies now reveal the features and topology of the entire neutral ISM, which here are considered on scales of 10 – 1000 pc. I focus on the two principal candidates for HI structuring, mechanical feedback from massive stars and turbulence; other mechanisms are also considered, especially with respect to supergiant shells. While confirmation for both mechanical feedback and turbulent processes exists, it remains unclear how these mechanisms yield the global, steady-state, scale-free HI properties that are observed. Understanding the formation of filamentary structure may be key in resolving these puzzles. New HI surveys of nearby galaxies, combined with further theoretical studies, promise continuing important advances.

1. Introduction

The distribution of neutral hydrogen in galaxies is an essential tracer of structure in the interstellar medium (ISM), and hence, of dynamical and evolutionary processes that drive structure formation. The HI distribution itself, which often dominates the gas mass in galaxies, is one of our principal probes of galactic baryonic material. In particular, HI mapping of late-type galaxies is well-known to reveal a gas distribution that can extend many times the characteristic optical or stellar radius of the galaxy; vivid examples are NGC 4449 (Hunter et al. 1998) and NGC 6822 (de Blok & Walter 2000), among many others. These galaxies show massive extended disk structure and tidal features that are unseen in other galactic components.

I will present here an extragalactic, “user’s” perspective on the role of HI structure as a probe of interstellar processes relevant to galaxy evolution. The HI structure bears directly on phenomena that are fundamental to galaxy evolution and star formation: mechanical feedback from massive stars and their supernovae (SNe); cloud formation and star formation; porosity of the cool ISM, especially to ionizing radiation; ISM phase balance and physics of phase interface regions; interstellar mixing and chemical enrichment. These processes are manifested in the neutral ISM in varying ways: superbubbles and shells

presumably result from massive star mechanical feedback; fractal structure has been associated with turbulence; filaments result from various processes including feedback and magnetic activity; clouds result from gravitational effects and influence from other processes; tidal features and spiral structure are dominated by gravitation.

Structure on scales of 10 – 1000 pc is thought to be dominated by two principal processes: mechanical feedback from massive stars and turbulence, which are discussed in turn below. At larger spatial scales, gravitational processes will dominate, and these will not be considered here. The smallest spatial scales are best studied in the Galaxy and are discussed in these proceedings by Faison.

2. Mechanical feedback

At present, more is known about the effects of mechanical feedback on the ISM than about turbulent effects. Supersonic winds from massive stars, single SNe, and multiple SNe from OB associations are well-documented to generate wind-blown bubbles, supernova remnants (SNRs), and superbubbles in both ionized and neutral gas. Whether the shell is mainly ionized or neutral depends primarily on whether the parent massive stars are still present and hot enough to ionize it, although in some circumstances, shock ionization can also be an important effect (e.g., Oey et al. 2000). The standard model for wind-blown and SN-driven shells assumes that the maximum available mechanical energy heats the interior of the shells to $\sim 10^6 - 10^7$ K at an inner, reverse shock, while the outer forward shock piles up the cool shell. The pressure of the hot, adiabatic interior drives the growth of the outer shell. For continuous wind or SN input power, this model can be described by simple analytic relations (e.g., Ostriker & McKee 1988). For example, a constant input mechanical luminosity L and uniform ambient density n imply an evolution for the radius R , expansion velocity v , and interior pressure P (e.g., Weaver et al. 1977):

$$R \propto (L/n)^{1/5} t^{3/5} \quad , \quad (1)$$

$$v \propto (L/n)^{1/5} t^{-2/5} \quad , \quad (2)$$

and

$$P \propto L^{2/5} n^{3/5} t^{-4/5} \quad , \quad (3)$$

where t is elapsed time.

While clear examples of shells and superbubbles around massive stars do exist (e.g., Cappa et al. 1999; Oey 1996), quantitative confirmation of this standard, adiabatic model for shell formation is essential to understand the actual role of mechanical feedback in interstellar processes and galaxy evolution. Mechanical feedback is effective over about three decades in spatial scale, and the investigations thus use several approaches: 1. Detailed, kinematic tests of the adiabatic model on individual wind-blown bubbles and superbubbles; 2. Comparison of statistical properties of superbubble populations with model predictions; 3. Spatial correlation of shells with recent massive star formation; 4. Evaluation of starburst superwind properties with respect to the model.

2.1. Individual shell systems

On an individual basis, the numerous observations of ring nebulae and superbubbles leave no doubt that these structures are generated by mechanical feedback from massive stars. The youngest objects are stellar wind-dominated and ionized by the parent stars, and are easily visible as optical shell nebulae surrounding these stars (e.g., Meaburn 1980; Braunsfurth & Feitzinger 1983). Soft X-ray emission is found in many optical superbubbles (Chu & Mac Low 1990; Wang & Helfand 1991), as is qualitatively predicted by the adiabatic model. Intermediate ions of C IV and Si IV are usually seen in absorption through lines of sight within these young superbubbles, presumably originating in the interface region between hot and cool gas (Chu et al. 1994).

2.2. Populations of superbubbles

As these structures age, the hot stars cool and expire, allowing the ionized gas in the shells to recombine. Thus, the majority of such shell structures should be found in HI, and most nearby late-type galaxies that have been mapped in HI do indeed show HI distributions that are riddled with holes and shells. The earliest examples were M31 (Brinks & Bajaja 1986), M33 (Deul & den Hartog 1990), and Holmberg II (Ho II; Puche et al. 1992). More recently, many late-type dwarfs have been surveyed, for example, IC 2574 and DDO 47 (Walter & Brinks 1999, 2000). The most revealing datasets to date are the Australia Telescope Compact Array surveys of the Small Magellanic Cloud (SMC; Staveley-Smith et al. 1997) and Large Magellanic Cloud (LMC; Kim et al. 1998).

SNe continue to power the now-neutral shells for up to ~ 40 Myr, the life expectancy of the lowest-mass core-collapse SN progenitors. Thus, the typical stellar populations within the HI shells are much fainter and more difficult to observe than in the young, nebular objects. However, the statistical properties of entire HI shell populations in galaxies offer an important probe of mechanical feedback and ISM structuring. For example, Oey & Clarke (1997) derived predictions for the size distribution of superbubbles from equations 1 – 3. We assumed a mechanical luminosity function for the OB associations,

$$\phi(L) dL \propto L^{-\beta} dL \quad , \quad (4)$$

where $\beta \simeq 2$ from observed HII region luminosity functions (e.g., Kennicutt et al. 1989). We also assumed that the shell growth stalls when the interior pressure (equation 3) reaches that of the ambient ISM. A few other simple assumptions yield a steady-state differential size distribution,

$$N(R) dR \propto R^{1-2\beta} dR \quad (5)$$

for continuous creation of the OB associations. A value of $\beta = 2$ thus implies $N(R) \propto R^{-3}$. This power-law distribution extends down to the smallest shells, which correspond to individual SNRs in this analysis. Oey & Clarke (1997) also derived predictions for a constant (single-valued) mechanical luminosity function, for a single-burst creation scenario, and for the interstellar porosities. The porosity analysis is extended by Oey et al. (2001).

The SMC HI shell catalog, compiled by Staveley-Smith et al. (1997) from combined morphological and kinematic criteria, is perhaps the most complete

shell catalog for any galaxy to date, thanks to both the high spatial resolution and survey sensitivity. Number counts of HI shells and HII regions (Kennicutt et al. 1989) are consistent with the relative life expectancies of these respective objects (Oey & Clarke 1997), thus indicating that the HI shell catalog is essentially complete. Significantly, the predicted and observed slopes of the shell size distribution, respectively -2.8 ± 0.4 and -2.7 ± 0.6 are in excellent agreement, suggesting that mechanical feedback may fully explain the bubbly HI structure in the SMC.

With this intriguing result for the SMC, it is thus essential to examine other galaxies. Kim et al. (1999) found that the size distribution for the LMC HI shells is also in good agreement with prediction. However, puzzlingly, the relative numbers of catalogued HI shells compared to HII regions in the LMC is much smaller than expected, thus casting doubt on the completeness and evolution of the shells. It appears that some process is prematurely destroying the HI shells, perhaps the merging of objects due to the much higher porosity and relative star formation in that galaxy (Oey et al. 2001). Unfortunately, the significance of results for M31, M33, and Ho II is severely limited by the incompleteness of the available survey data for those galaxies, although the existing HI hole size distributions are again consistent with predictions (Oey & Clarke 1997). Meanwhile, Thilker et al. (1998) and Mashchenko et al. (1999) have developed a shell-finding code that automatically identifies expanding shells in HI data cubes. Their preliminary results for statistical properties of shell populations in NGC 2403 are quite encouraging. Application of this code to new data cubes, e.g., M33 (Thilker & Braun, these proceedings) should offer important insights that are unhampered by selection effects of subjectively compiled catalogs.

Additional statistical properties of HI shell populations remain to be exploited. Oey & Clarke (1999) derived the differential distribution of the expansion velocities:

$$N(v) \propto v^{-7/2} \quad , \quad \beta > 1.5 \quad . \quad (6)$$

Comparison with the SMC catalog again yields encouraging agreement, with predicted and observed power-law slopes of -3.5 and -2.9 ± 1.4 , respectively. Additional datasets remain to be examined, and statistical properties of other parameters such as inferred t and L could also be similarly studied.

2.3. Spatial correspondence with star formation

One of the most obvious tests of the global effect of mechanical feedback and shell formation is to identify the parent stellar populations, or their remains, with the superbubbles. M31 (Brinks & Bajaja 1986) and M33 (Deul & den Hartog 1990) both show correlations of OB associations with HI holes. However, Ho II shows contradictory results, based on the HI hole catalog compiled by Puche et al. (1992). Tongue & Westpfahl (1995) found that the SN rate implied by radio continuum emission is consistent with the hole energetics in that galaxy. However, Rhode et al. (1999) carried out a direct, BVR search for remnant stellar populations within the HI holes, and found little evidence for the existence of the expected stars. This result was then contradicted by Stewart et al. (2000), who used far-UV images from the *Ultraviolet Imaging Telescope* and $H\alpha$ images to conclude that a significant correlation between the HI holes and recent star formation does indeed support a feedback origin for the holes.

It is perhaps unsurprising that studies of Ho II yield these confusing results in view of that galaxy's distance of 3 Mpc. The LMC, which is 60 times closer, presents much better spatial resolution and should therefore yield correspondingly less ambiguous results. Kim et al. (1999) examined the correspondence between their HI shell catalog, catalogued HII regions (Davies et al. 1976), and H α imaging. Not only do they find a correspondence, but they are also able to identify an evolutionary sequence with respect to the relative sizes and expansion velocities. For shells with associated H α , they find that the HI radius is larger than that for the HII, as would be expected for objects whose parent stars are producing both mechanical and radiative feedback. They also find that HI shells with associated H α show higher expansion velocities than those with only an associated OB association, and that these in turn show higher velocities than those with neither. This again is consistent with an expected evolutionary sequence, as the shell expansion velocities decrease (equation 2) along with the ionizing radiation and hot star population. Further investigation of the Magellanic Clouds should reveal more quantitative details of the mechanical feedback process (Oey, Gerken, & Walterbos, in preparation).

2.4. Outstanding problems

Although the above suggest that mechanical feedback is indeed a dominant process in creating the populations of HI holes and shells, a number of outstanding problems with this model remain. For example, quantitatively, it has been difficult to reconcile the adiabatic model (e.g., equation 1) with observed parameters for individual objects. Most shells appear to be too small for the inferred L/n implied by the observed parent stars, and this problem is seen in both Wolf-Rayet bubbles (e.g., Treffers & Chu 1982; García-Segura & Mac Low 1995) and young superbubbles around OB associations (e.g., Brown et al. 1992; Oey 1996).

Furthermore, HI imaging of the environment around three nebular LMC superbubbles reveals highly diverse conditions, with little evidence of any HI components associated with the ionized shells (Oey et al. 2002). Although the shells will presumably eventually recombine, it is difficult to interpret the lack of obvious HI holes in the immediate environment in terms of understanding the global HI structure of the ISM. Another worry for aggregate populations of HI shells are a frequently-reported positive correlation of v with R , contrary to that implied by equation 2 (e.g., Kim et al. 1999; Puche et al. 1992). These problems suggest that, at a minimum, our evolutionary model for these objects is more complicated than represented by the simple adiabatic model.

3. Supergiant shells and starbursts

The very largest documented HI shells, having sizes of order 1 kpc, emphasize some of the problems with the mechanical feedback model, and also highlight possible alternative shell-creating mechanisms.

The existence of infalling high-velocity clouds (HVCs) suggests that the impact of these objects could be an important contributor to supergiant shell populations. This suggestion is further supported by galactic fountain models for disk galaxies (e.g., Shapiro & Field 1976), which are ultimately also powered by mechanical feedback in the disk. A number of hydrodynamical simulations

of infalling HVCs confirm that these impacts result in shell-like structures (e.g., Tenorio-Tagle et al. 1986; Rand & Stone 1996; Santillán et al. 1999).

In addition, tidal effects, which dominate energetics and structure formation at the largest length scales, could also create HI hole features that resemble shells. Note that many SN-driven shells will not exhibit expansion velocities if they have become pressure-confined by the ambient medium, thus a lack of observed expansion velocities cannot distinguish between the feedback model and other models. It has been suggested that some of the largest holes in, e.g., M33 are simply morphologically-suggestive inter-arm regions (Deul & den Hartog 1990). The same may be true of the giant hole identified by de Blok & Walter (2000) in NGC 6822. Simple self-gravity effects have also produced shell- and hole-like structures in numerical simulations (Wada et al. 2000), although morphologically these structures appear more filamentary than the observations.

While such alternative mechanisms for creating shell-like structures undoubtedly contribute to the supergiant shell population, the conventional mechanical feedback model nevertheless also appears to apply in many situations. For this largest category of shells, the required amount of star formation often may be implausible for certain individual objects, but plausible examples do exist. Meaburn's (1980) LMC-4 is a well-known example that is unambiguously linked to Shapley's Constellation III, a large, extended complex of young stars. Kim et al. (1999) are able to identify an evolutionary sequence for supergiant shells in the LMC, based on the location of H α emission, which is found on the interior of the HI shells in the youngest objects, and can highlight triggered star formation at the shell edges in older objects. In addition, Lee & Irwin (1997) considered formation mechanisms for supergiant shells in the edge-on SBc galaxy NGC 3044. They found no evidence of HVCs, and since the galaxy is isolated, tidal interactions are also unable to explain the supergiant shells. They therefore conclude that the active star formation seen in NGC 3044 is most likely to explain its supergiant shell structures.

Starburst galaxies are well-known to exhibit clear signatures of mechanical feedback, including soft X-ray emission (e.g., Watson et al. 1984; Martin & Kennicutt 1995; Strickland et al. 2000), and high-velocity outflows (Conti et al. 1996; Gonzalez Delgado et al. 1998; Johnson et al. 2000). The HI distribution of late-type dwarf galaxies also suggests that mechanical feedback from energetic star formation displaces the gas in these galaxies. Simpson & Gottesman (2000) show that, whereas blue compact dwarf (BCD) galaxies have centrally concentrated HI distributions (van Zee et al. 1998), low surface brightness (LSB) dwarfs show much more diffuse, ring-like distributions of HI. This suggests that these dwarf galaxies may undergo burst (BCD) stages when the gas accumulates in the center, which then disperse the gas, leading to quiescent (LSB) phases.

It is thus apparent that mechanical feedback and also other mechanisms form supergiant shell structures. Presumably the respective mechanisms will dominate under different circumstances, and these remain to be understood.

4. Turbulent structure

Besides mechanical feedback, turbulence is the other major process that is thought to structure the ISM on 10 – 1000 pc scales (see reviews by, e.g., Scalo

1987; Lazarian 1999). Unambiguously associating HI structure with turbulence is difficult, however, since the signatures of turbulence presently are not well-defined. The current approach for confirming the widespread effect of turbulent processes is to identify a correspondence between the observed and predicted statistical properties of ISM structure, especially in the power-law, essentially scale-free, characterizations of the neutral ISM. This approach is somewhat limited since a wide variety of astrophysical phenomena yield power law parameterizations, thus it is essential to model all available parameters. The interpretations are also hindered by projection effects that convolve three-dimensional distributions of spatial, density, and velocity information into two-dimensional HI intensity and velocity distributions. Self-absorption effects in the HI line emission also need to be considered. Nevertheless, important recent advances alleviate these problems, and new extragalactic datasets that can minimize projection effects offer vital leverage on the study of turbulence in the neutral ISM.

4.1. Power spectra

Empirically, the two-dimensional spatial power spectrum of HI structure has been determined in the SMC (Stanimirović et al. 1999) and LMC (Elmegreen et al. 2001) from the HI surveys of the Magellanic Clouds mentioned above. These probe spatial scales of 30 – 4000 pc, thus ranging over three orders of magnitude. For a power spectrum of wavenumber k given by

$$P(k) \propto k^{-\gamma} \quad , \quad (7)$$

the SMC is well-fitted with a power-law index $\gamma = 3.04 \pm 0.02$; and for the LMC $\gamma \sim 2.7$, having a spectrum that steepens at the smallest spatial scales (see below). These values are perhaps surprisingly similar, and also compare well with $\gamma \sim 3$, measured for the Milky Way angular power spectrum (e.g., Green 1993; Crovisier & Dickey 1983) over scales of 10 – 200 pc. These three galaxies presumably differ significantly in their dynamical processes: the SMC is a small, three-dimensional galaxy, whereas the LMC and Milky Way are spirals that vary dramatically in size and mass. Thus, the similarity in the spatial power spectra is notable, and may be indicative of similar structuring processes in these galaxies (Stanimirović et al. 1999).

The standard reference for turbulent power spectra is the Kolmogorov model, which predicts that for homogeneous, isotropic, incompressible, and adiabatic turbulence, the turbulent kinetic energy cascades to ever-smaller scales, generating a power-law in the energy spectrum:

$$E(k) \propto k^{-5/3} \quad . \quad (8)$$

This relation derives simply from the assumption of a constant energy transfer rate at all scales. The comparison of the observed 2D spatial power spectra with the Kolmogorov theory depends on how the projection and density effects are modeled. For example, Goldman (2000) assumes that density fluctuations are directly coupled to velocity fluctuations, thereby implying an observed 1D power spectrum exponent $m = \gamma - 1 \simeq 2$, which can be directly compared to the Kolmogorov value of 5/3. The steeper empirical value therefore suggests progressive energy losses that can be attributed to compressible, perhaps shock-dominated turbulence as is plausible for the ISM.

However, more compelling confirmation of turbulence lies in isolating the kinematic properties. Lazarian & Pogosyan (2000) present a powerful new formalism for disentangling the effects of density and velocity, by examining statistical changes induced by the binning width of the velocity slices. They show that density fluctuations dominate the spectral index for thick slices, while velocity fluctuations dominate for thin slices, and thus it is possible to recover the relevant spectral indices in these respective regimes. For Kolmogorov turbulence, they predict 2D indices of $11/3$ and $8/3$ for thick and thin slice regimes, respectively. This technique has been applied to the SMC (Stanimirović & Lazarian 2001), the LMC (Elmegreen et al. 2001), and the Milky Way (Dickey et al. 2001). In the LMC and Milky Way, a transition in spectral index between thick and thin velocity binning indeed has been identified, thereby revealing the velocity power spectrum. The observed spectral indices in all three datasets are broadly consistent with Kolmogorov turbulence, within an additive factor of ~ 0.2 . This ability to distinguish the spectrum of velocity fluctuations is one of our most powerful probes and confirmation of turbulence in the neutral ISM.

4.2. Energy input and dissipation

The conventional energy source for turbulence is mechanical feedback, which is also thought to be a major source of structure in the ISM, as discussed above. The scale-free nature of the turbulent power spectra is consistent with the dominance of energy input on the very largest scales, that simply cascades to smaller scales. For example, Goldman (2000) suggests that the most recent tidal encounter between the LMC and the Galaxy could be an important source for the LMC, as could differential rotation. On the other hand, Norman & Ferrara (1996) compute the energy source function from only mechanical feedback, and find that feedback alone is apparently sufficient to maintain the turbulent velocity dispersion and multi-phase pressure support in the ISM. For their source function, contributions at all scales are relevant, which is consistent with the results of Oey & Clarke (1997) that the usual superbubble size distribution implies equal contributions to the interstellar porosity from objects of all sizes. The localized nature of turbulent dissipation (see below) also implies that multi-scale energy injection should be relevant. In addition, Sellwood & Balbus (1999) suggest that MHD instabilities, in particular Balbus-Hawley instabilities (Balbus & Hawley 1991) may be a dominant source for driving the lowest-velocity turbulence. This may set the uniform minimum HI velocity dispersions, particularly those seen beyond the star-forming disk in spiral galaxies, where mechanical feedback cannot explain the observed turbulent velocities.

Turbulent dissipation appears to take place rapidly, the kinetic energy decaying as $t^{-\eta}$, with roughly $\eta \sim 1$. This has been found for both incompressible and compressible isothermal, MHD turbulence for conditions relevant to molecular clouds (Mac Low et al. 1998 and references therein). Avila-Reese & Vázquez-Semadeni (2001) investigate turbulent dissipation in the large-scale, non-isothermal ISM and find similar results, with the caveat that their simulations are 2D. For both forced and decaying turbulence, the dissipation length scale is therefore of order the forcing length scale or less, and thus the dissipation time scale is of order the corresponding crossing time scale. This is consistent with the results of Kim et al. (1998), who find a correspondence between high-

velocity features in the LMC HI data cube and superbubble structures. This suggests that the kinetic energy injection indeed remains localized near the SN sources. A final issue raised by Avila-Reese & Vázquez-Semadeni (2001) and Norman & Ferrara (1996) is the fate of the dissipated energy: presumably this heats significant quantities of gas and could be important for the dynamics of the warm ionized medium and warm neutral medium (WNM).

5. Fractals and Filaments

The SMC and LMC HI surveys present the first characterizations of the entire neutral ISM of individual galaxies as fractal (Stanimirović et al. 1999; Elmegreen et al. 2001). Fractal structure has been invoked to explain scale-free properties of star formation, and can describe properties of Galactic molecular clouds (e.g., Elmegreen & Falgarone 1996). The scale-free nature of fractal structure also suggests that it results naturally from turbulence, which is correspondingly scale-free. Turbulent ISM models indeed are generally able to generate global fractal structure (e.g., Norman & Ferrara 1996).

If definitive physical links can be established between turbulent processes and global observed fractal structure, the resulting simple parameterizations would offer powerful probes and leverage for galactic evolutionary processes and modeling. However, while the correspondence between turbulence and fractal structure is plausible, the actual physical links remain to be established. Elmegreen’s et al. (2001) study of the LMC is the most thorough investigation with respect to the global HI fractal structure. As discussed above, they measured spatial power spectra that are consistent with a scale-free, fractal character. However, they also emphasize that the power spectra are insensitive to the specific morphology of the structure, which in the LMC is highly filamentary. Thus, the cloud and intercloud media are not homologous in topology, although the morphology is apparently self-similar. Elmegreen et al. (2001) also construct turbulence-based fractal simulations of the LMC HI, but are not able to reproduce this filamentary structure. They also find that the large observed variations in column density cannot be reproduced by the model, suggesting that phase transitions and shocks significantly modify the HI structure. Since shells and bubbles created by mechanical feedback are known to exist in large numbers, it is also likely that they play an important role. Thus it appears that turbulence is unlikely to exclusively explain the HI topology in the LMC. If fractals alone are invoked to characterize the structure, it will have to be in a more complex way, e.g., “multifractal” characterizations (Chappell & Scalo 2001).

Understanding the properties of filamentary structure and the formation of filaments could be key in understanding the dominant structuring processes in the ISM. As illustrated by the Elmegreen et al. (2001) study, the existence and degree of filamentary structure constrains the role and nature of turbulent processes. Since filamentary structure pervades the global HI topology, understanding the various processes that generate filaments, and identifying those that dominate, will therefore constrain the dominant physical processes in the multi-phase ISM.

Braun (1995, 1997) studied the HI distribution at ~ 100 pc resolution in 11 nearby disk galaxies spanning the entire Hubble sequence. This comprehensive

study reveals the remarkable, ubiquitous existence of a “high brightness network” of filaments (HBN), which comprises 20 – 85% of the total HI line flux. Remarkably, this HBN is strongly associated with the star-forming disks, where it accounts for 60 – 90% of the total HI flux, while occupying only 15% of the face-on covering area. Radial gradients are seen in the brightness temperature, as well as a correlation with later Hubble type. The velocity dispersion of the HBN is $\sim 6 \text{ km s}^{-1}$ in the line core, with wings extending up to 30 km s^{-1} . From the narrow line core, Braun (1997) identifies the HBN with the cool neutral medium (CNM). These results are broadly consistent with earlier attempts by Dickey & Brinks (1993) to estimate the relative fractions of CNM and WNM in M31 and M33 by measuring the CNM absorption through lines of sight to background continuum sources. They obtained 40% and 15% CNM fractions in M31 and M33, respectively, and these values can now be viewed in terms of the filamentary CNM morphology. The Galactic CNM filament recently reported by Knee & Brunt (2001) can also be seen in this context, as can the self-absorption studies of Galactic HI structure (e.g., papers by Gibson and Dickey in these proceedings). The coincidence of the HBN with the star-forming disk found by Braun (1997) highlights the relation to star formation and the consequences of structuring processes for galaxy evolution.

A number of mechanisms for filament formation have been explored, although undoubtedly many others also need to be investigated. As mentioned above, simulations by Wada et al. (2000) generate filamentary structure from self-gravity, which is appealing in light of the HBN observations. Mechanical feedback, resulting in shells and superbubbles, clearly generate filamentary structures, although it is unclear whether these are more ordered than is observed. The interaction of these shells and their fragmentation is a promising source of filamentary structure (Scalo & Chappell 1999). However, filaments can also be created without direct dynamical structuring: Lazarian & Pogosyan (1997) find that simple Gaussian density fields also result in filamentary structure. Additional work to characterize observed filaments and model their properties will offer vital constraints on dominant structuring processes.

6. Conclusion

The two primary candidate mechanisms for structuring the neutral ISM in galaxies, mechanical feedback from massive stars and turbulence, are both clearly significant effects. Signatures of both processes are confirmed in the HI properties of external galaxies, and global characterizations of the ISM in terms of these processes are available. However, the specifics of the physical processes by which these mechanisms lead to the steady-state, observed global ISM properties are lacking. Neither mechanical feedback nor turbulence can exclusively explain the HI topology. Given the rapid, localized turbulent dissipation process, a global role for turbulent structuring remains to be confirmed. Further studies making use of HI and other datasets are therefore essential to clarify the circumstances under which these respective mechanisms dominate, as well as to identify additional relevant mechanisms, e.g., HVC impacts, gravitational and magnetic effects, and gas instabilities. This work must ultimately lead to an integrated

view of structuring and dynamics in the multi-phase ISM and the corresponding consequences for star formation and galaxy evolution.

Acknowledgments. It is a pleasure to thank Alex Lazarian for comments on parts of this manuscript. I also gratefully acknowledge support from the conference organizers and Lowell Observatory.

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