

Galaxy evolution begins at home: GALFA, EVLA, and GASKAP

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While studies of galaxy evolution generally focus on extensive HI surveys at large redshifts, we argue in this paper that the understanding of *detailed* physical processes that drive HI evolution in galaxies is equally important. Specifically, we focus on three open questions regarding the very first step in the star-formation cycle in galaxies: How much galaxy halos flavor and tax the accretion flows that are postulated to bring fresh star-formation fuel to galaxy disks? What are the basic properties of the warm neutral gas, the progenitor of cold star-forming clouds? What are the origin and level of interstellar inhomogeneities as seeding agents for molecule and star formation? The very local Universe (The Milky Way and nearby galaxies) offers an unparalleled high-resolution view for answering these questions and the upcoming radio telescopes (e.g. EVLA, ASKAP, MeerKAT, ATA-256) promise great advances.

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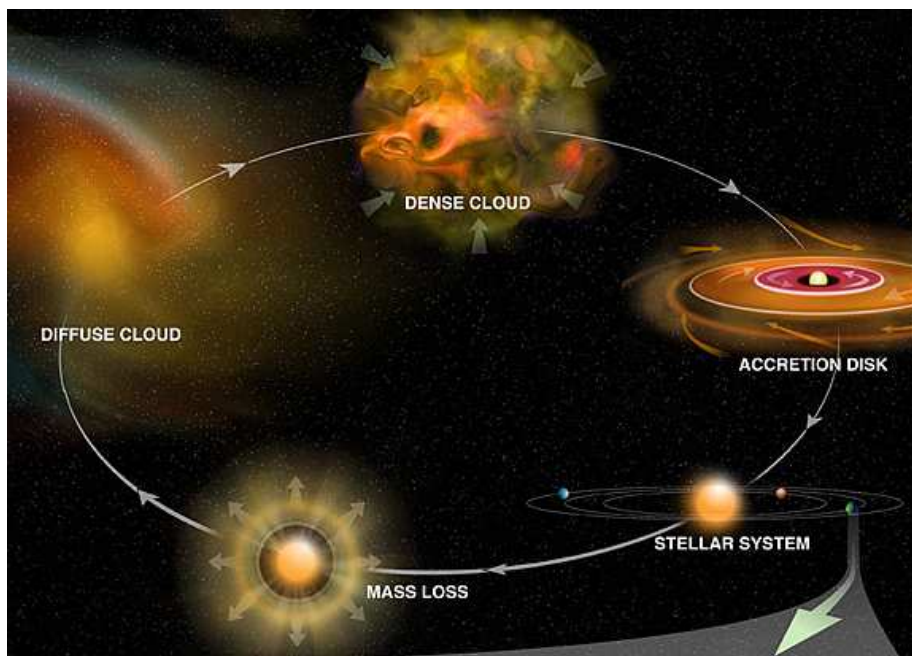


Figure 1: Schematic summary of our current understanding of the star-formation cycle in galaxies. Credit: Bill Saxton (NRAO)

1. Introduction

In our current understanding of the star formation cycle in galaxies (illustrated in Figure 1), diffuse interstellar gas transforms first into dense cold clouds, which further fragment and produce stellar and planetary systems. Throughout their lifetime and particularly at the end, stars greatly affect the surrounding medium through stellar winds and supernovae stirring and structuring the diffuse gas and affecting the next generation of star formation. While other components of this cycle have received significant attention, the first step, or the conversion of diffuse interstellar gas into dense cold (molecular) clouds, is largely unexplored despite the fact that it has long-reaching manifestations. For example, the outstanding “missing satellite problem” whereby galaxy formation models over-predict the number of low-mass dark matter halos, stems from our limited understanding of the physical processes (and their efficiencies) involved in the molecular cloud and star formation (Putman et al. 2009).

Furthermore, recent cosmological simulations suggest an even higher complexity of the star-formation cycle by introducing one additional step: the accretion of the initial star formation fuel (Kereš et al. 2005). Even at the present time, a large fraction of the multi-phase diffuse gas in galaxies is expected to be accreted from cosmic filaments and satellite galaxies enabling a healthy star formation rate. However, this process is not passive and the interplay between the inflowing material and the host galaxy leaves a strong, multi-phase mark on the accreted gas. In the case of a Milky Way (MW) type galaxy, Brooks et al. (2009) show that about 60-70% of the inflowing gas is shock-heated to near virial temperatures of $T \sim 10^6$ K, while about 30-40% is accreted at lower temperatures of $T < \text{few} \times 10^5$ K through both cold accretion (from cosmic filaments)

and accretion from previous mergers and satellites ('clumpy' component). The unshocked and 'clumpy' components in particular play an important role for building up the disk as the cold gas is delivered close to the disk and goes on to form stars faster than the shocked gas, which must cool before supporting star formation.

The star formation cycle provides chemical and energy enrichment and directly affects how galaxies age and evolve with time. Therefore, to make advances in our understanding of galaxy evolution, we need to start with the necessary first step: the diffuse interstellar gas. We focus here on three scientific questions concerning the diffuse interstellar gas where the upcoming radio telescopes promise great advances: (i) what are the nature and fate of the accreted star formation fuel; (ii) what are the physical conditions required for cycling of interstellar phases; and (iii) what is the origin and nature of interstellar inhomogeneities as seeds for molecule (and later star) formation?

2. The Magellanic Stream as a template for *detailed physics of accretion flows*

We are fortunate that the Magellanic Stream (MS) offers a nearby example of a gaseous remnant from interactions between the Magellanic Clouds (MCs; the Large Magellanic Cloud, LMC, and the Small Magellanic Cloud, SMC) and the Milky Way (MW). This feature, which extends in an arc nearly half way across the sky, offers a unique, close-by laboratory to study physical processes of accretion flows in the MW halo.

The MS is a huge (> 100 degree long) starless neutral hydrogen (HI) structure trailing behind the MCs. After decades of studies, numerous puzzles remain regarding the formation and evolution of the MS gas (a recent summary is provided in Stanimirovic et al. 2010). Two most recent observational surprises are: (i) the present-day MS is at least 40% longer, and $\sim 10\%$ more massive, relative to the MS we knew about a few years ago (Braun & Thilker 2004, Stanimirović et al. 2008, Nidever et al. 2010); and, (ii) the MS has a significant abundance of small-scale structure.

A compilation of various HI observations of the MS is shown in Figure 2 (Nidever et al. 2010, in preparation) and includes recent Arecibo HI observations from the GALFA-HI survey (Stanimirovic et al. 2006, Peek & Heiles 2008) focusing on the MS tip. The GALFA-HI survey has been mapping the entire Arecibo sky at a velocity resolution of 0.18 km s^{-1} and an angular resolution of 3.5 arcmin, operating mainly commensally with other surveys undertaken with the Arecibo L-Band Feed Array. The complex small-scale morphology of the HI gas, revealed for the first time down to an angular size of ~ 3.5 arcmin, indicates that processes are clearly at work in the MW halo on scales of tens of parsecs and at a distance of > 60 kpc. These processes affect the MS's potential for star formation, the transfer of gas from the MS to the halo, and also may provide additional drag affecting the global MS dynamics. Although these processes play a crucial role for gas evolution of the MS (Murray et al. 1993; Bland-Hawthorn et al. 2007; Heitsch & Putman 2009), it is still not clear exactly how they operate, and on what timescales. As global numerical simulations rarely have resolution necessary to resolve such small scales, observational constraints of the effectiveness of various hydrodynamical instabilities are needed.

Analytical considerations of timescales (Mori & Burkert 2001, Quilis & Moore 2001, Stanimirovic et al. 2008) as well as recent numerical advances (Bland-Hawthorn et al. 2007, Heitsch & Putman 2009), suggest that thermal and Kelvin-Helmholtz instabilities operate on timescales much shorter than the MS formation time and hence must be important. This, together with large-scale

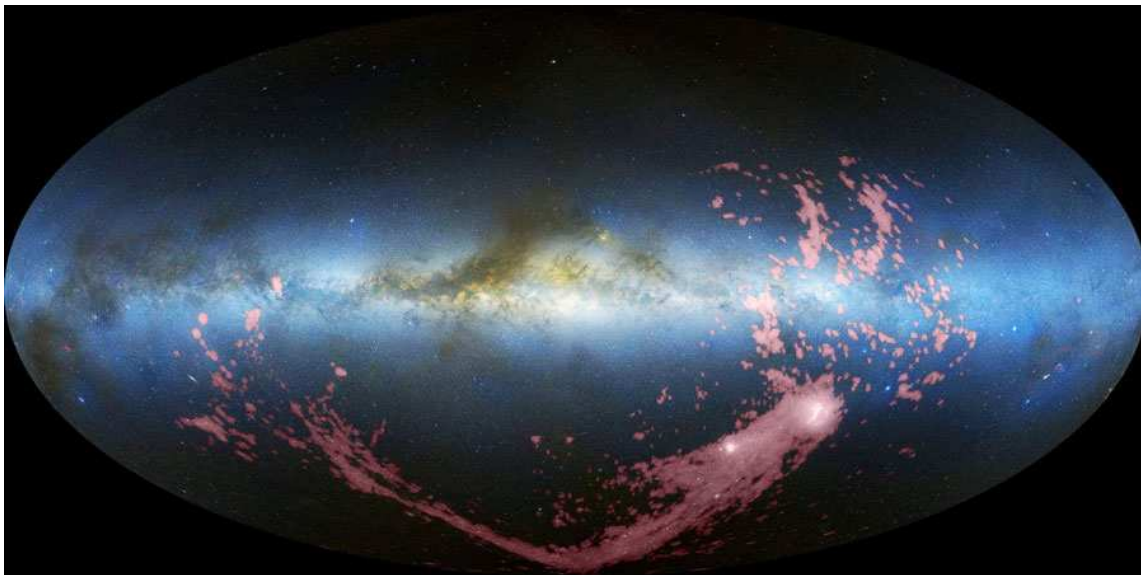


Figure 2: The compilation of HI observations of the Magellanic Stream by David Nidever superimposed on an all-sky image of the MW in visible light by Axel Mellinger. Credit: Astronomy picture of the day.

shearing due to tidal interactions in the MW-MCs system, results in an expectation of a highly turbulent environment. Yet, the physical properties of the MS gas revealed by the high-resolution observations indicate stability and longevity of HI clouds. For example, cool HI cores subsonically moving within warmer HI envelopes have been found along the MS (Karberla & Haud 2006, Stanimirovic et al. 2008). The coldest ($T \sim 70$ K) pockets of HI have been recently revealed through absorption observations by Matthews et al. (2009). Diffuse ionized gas with $T \sim 10^{4-4.5}$ K, further enveloping the HI component, has been studied with SiIII observations by Shull et al. (2009). An even hotter component with $T \sim 10^5$ K, observed through OVI absorption lines, has been interpreted as tracing the interface between the cool MS gas and the hot MW halo ($T \sim 10^6$ K). From this work, a picture emerges of cold MS cores shielded from the $T \sim 10^6$ K MW halo by many layers of a multi-phase warm gas.

Further, the direct comparison between the observed HI column density probability density function (PDF) and the latest simulated distributions reveals significant differences. As a demonstration, we use here data from the Bland-Hawthorn et al. (2007) shock-cascade model of the MS, which starts with an initially clumpy HI distribution of the MS gas and allows for strong interactions between the MS clouds and the MW halo. As the MS clouds upstream experience gas ablation by the oncoming hot MW halo, the ablated gas is slowed down and further collides with the clouds downstream, resulting in shock ionization of HI clouds. This shock-cascade model can explain measured $H\alpha$ intensities along the MS (Bland-Hawthorn et al. 2007). It also predicts large changes in the HI distribution on timescales of 100-200 Myrs caused by the ablation process.

In Figure 3 we compare the observed HI column density PDF for the MS tip (from Stanimirovic et al. 2008) with the same quantity at two snap-shots in the Bland-Hawthorn et al.'s simulation: 70 and 270 Myrs after the initial exposure of the MS to the halo wind (shown as dashed and dot-dashed lines in Figure 3). The large difference in the simulated data after 200 Myrs is clearly

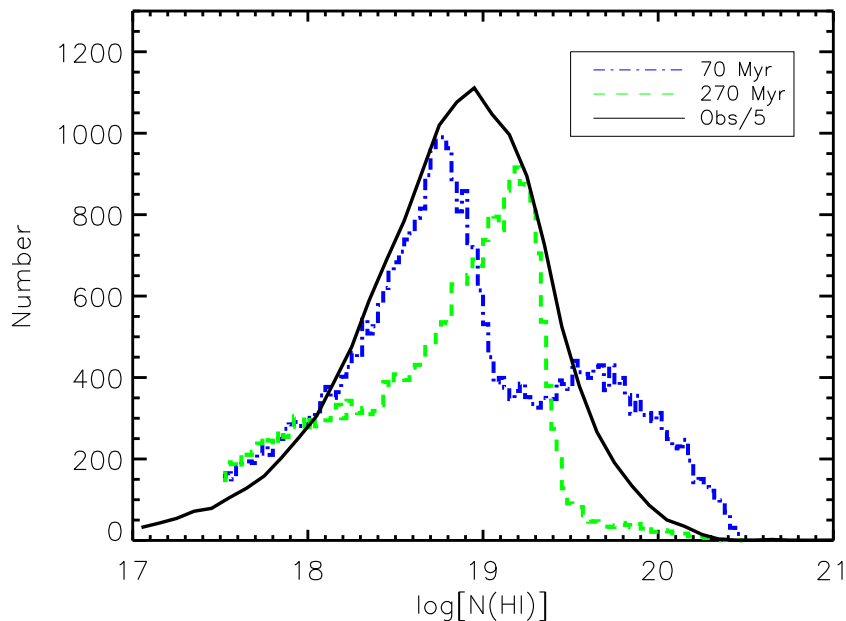


Figure 3: Evolution of the HI column density probability density function in the shock-cascade simulation by Bland-Hawthorn et al. (2007). The blue dot-dashed and green dashed lines shows time stamps in the simulation at 70 and 270 Myrs, respectively. The solid line shows the HI column density PDF derived by using observations from Stanimirovic et al. (2008). The observed PDF was divided by 5 to account because observations sample five times larger projected area than the simulation.

visible, and the later distribution is missing both low- and high-density gas. However, the observed PDF is not similar to any of the simulated PDFs. Contrary to a highly asymmetric simulated $N(\text{HI})$ PDF, the observed PDF is highly symmetric and almost Gaussian. It clearly contains more low- and high-density gas than the end point of the simulation. As shown in Burkhardt et al. (2010), subsonic turbulence produces Gaussian column density distributions, while supersonic turbulence produces highly skewed PDFs. This highlights the difference between observations and the simulation: simulated distributions appear highly turbulent due to fast ablation processes. As a result, the neutral gas is relatively quickly shredded and turned into an ionized warm drizzle, which eventually infalls onto the MW disk.

The structure of the boundary between clouds and the hot atmosphere of the MW is one factor that could slow down the rate of mass ablation in the MS through heat conduction (e.g. Vieser & Hensler 2007). To study these boundary regions along the MS, and also other tidal tails, we need large-area observations with both high angular resolution and excellent sensitivity. Several upcoming radio telescopes will provide exactly that (e.g. ASKAP, MeerKAT, ATA-256). In particular, the Galactic spectral line survey with the Australian Square Kilometre Array Pathfinder (GASKAP, Dickey et al. 2010), one of several survey science projects accepted for ASKAP, will image the MS at an angular resolution of ~ 1 arcmin. We will be able to study the “aging” processes of the HI gas injected into the vicinities of galaxies by interactions or other cosmologically related processes.

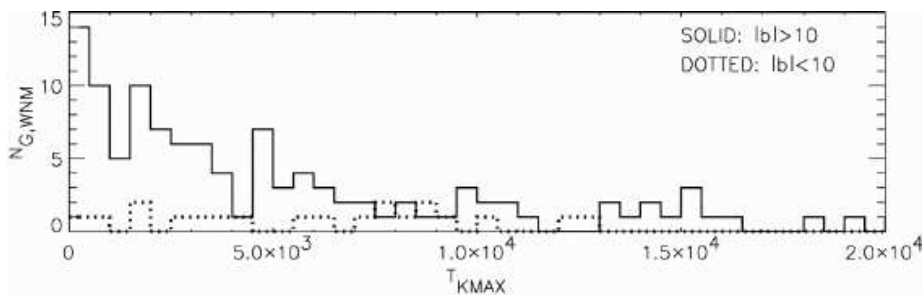


Figure 4: Histogram of the WNM kinetic temperature in the case of no non-thermal motions. From Figure 2 in Heiles & Troland (2003).

3. What are the physical conditions required for cycling of interstellar phases?

The accretion flows bring fresh star formation fuel to galaxies in various flavors of diffuse gas which is likely to get integrated with the diffuse interstellar medium (ISM) in the disk. Again, our home neighborhood (the MW disk) offers a high-resolution view of the crucial physical processes responsible for cycling of interstellar gas across various temperature regimes on the way to cold dense clouds, which are considered to be precursors of molecular, star-forming entities.

Traditionally, the diffuse neutral ISM is known to exist in two thermal equilibrium states: the cold neutral medium (CNM) and the warm neutral medium (WNM; McKee & Ostriker 1977; Wolfire et al. 2003). While the CNM properties have been measured extensively, surprisingly only *three* direct measurements of the WNM temperature exist thus far. The main reason for this observational paucity is the low optical depth of the WNM, $\tau \lesssim 10^{-3}$, which creates a need for very sensitive radio instruments. Properties of the WNM are traditionally indirectly inferred only through HI emission line profiles. Out of all ISM phases, the WNM is the least understood, yet it seems to hold the key to constraining ISM models and the formation of cold interstellar clouds.

One of the key observables that theoretical and numerical models of the ISM attempt to predict is the gas fraction as a function of temperature. McKee & Ostriker (1977) and Wolfire et al. (2003) predict that cold gas should dominate, while its enveloping counterpart—the WNM—should be mainly in thermal equilibrium and comprise only a few percent of the total diffuse interstellar gas. More recent ISM models emphasize the highly dynamic and turbulent character of the ISM and the consequences this can have on cold cloud formation. For example, in Audit & Hennebelle (2005)’s simulation of a collision of incoming turbulent flows a fast condensation of WNM into cold neutral clouds is initiated. The fraction of cold gas is controlled by turbulence, and ranges from 10% in a strong turbulent case to about 30% in a weak turbulent case. Mac Low et al. (2005) simulate how shocks driven into warm, magnetized, and turbulent gas by supernova explosions create dense, cold clouds. They find a continuum of gas temperatures, with a fraction of the thermally-unstable WNM ($T < 5000$ K) being constrained by the star formation rate.

One of the observational studies that has had a large impact on recent ISM simulations is the ‘‘Arecibo Millennium’’ survey of the 21-cm line absorption by Heiles & Troland (2003, HT03). They found that a substantial fraction (48%) of the WNM is in the thermally unstable phase, with kinetic temperatures in the range of 500–5000 K. Yet, we must emphasize that HT03 did not mea-

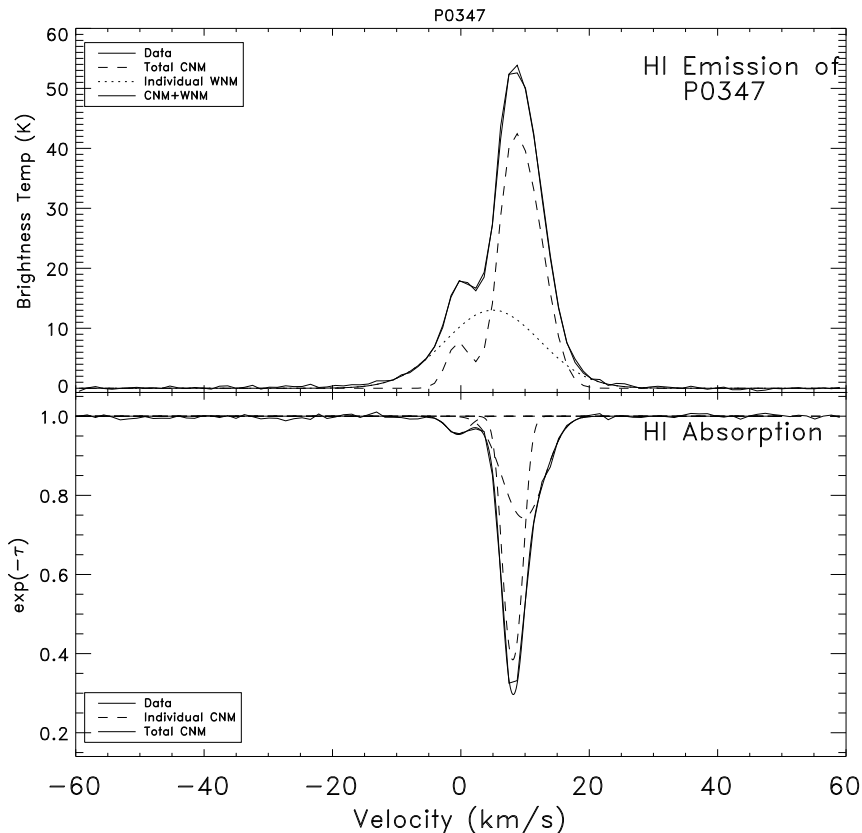


Figure 5: The HI absorption spectrum (bottom) from our EVLA pilot observations (Begum et al., submitted). The corresponding HI emission was obtained with the Arecibo radio telescope (top panel). The absorption spectrum was fit with three CNM Gaussian functions, shown with the dashed line. The emission spectrum was fit with a combination of the CNM (dashed) and the WNM (dotted line) components.

sure the WNM directly, but inferred its temperature mainly through observed narrow HI emission lines (Figure 4). Two out of three direct measurements of the WNM spin temperature (Carilli et al. 1998, Dwarakanath et al. 2002, Kanekar et al. 2003) also find $T \sim 3000 - 4000$ K and support the HT03 results.

To explore possibilities for sensitive HI absorption measurements with the Expanded Very Large Array (EVLA), we have recently obtained deep HI absorption spectra against several continuum sources along the lines of sight which have indicated the existence of the thermally-unstable WNM with $T < 5000$ K (Begum et al. 2010). As an example, in the direction of source P0347 HT03 found a narrow emission feature at a velocity of 0 km s^{-1} without corresponding absorption which indicated a thermally unstable WNM. Figure 5 shows our recent EVLA absorption spectrum (bottom panel), together with the Arecibo HI emission spectrum (top panel), for this source: our detection of an additional weak absorption feature at a velocity of -0.5 km s^{-1} results in the best-fit solution without any need for the thermally-unstable WNM. This shows that the detection of weak

absorption lines, which have been largely missed in shallow absorption surveys, can significantly affect the estimated fraction of the thermally-unstable WNM.

Clearly, large samples of very sensitive HI absorption/emission spectra are needed to characterize the basic properties of the WNM: temperature, column density, and abundance relative to the CNM. Current (Westerbork radio telescope and EVLA) and upcoming (ASKAP, MeerKAT, ATA-256) radio telescopes are becoming for the first time, technically ready for such experiments. A dedicated highly sensitive ($\Delta\tau \sim 10^{-4}$) survey of the WNM in absorption is necessary to measure the basic properties of the WNM and constrain possible scenarios for formation of cold clouds.

In addition, surprisingly little is known about the census and properties of cold gas even in very nearby galaxies. As the “demography” of cold gas is driven largely by the heating and cooling processes – which rates vary with metallicity, dust-to-gas ratio, and the strength of the interstellar radiation field – significant variations of the CNM/WNM properties and abundances are expected from a theoretical point of view (Wolfire et al. 2003). The reality is such that, even in our home neighborhood only a handful of measurements exists for the cold gas in the SMC and the LMC (Dickey et al. 1994, 2000, Marx et al. 1997), typically considered as prototypes of a relatively primitive ISM common in the early Universe. The only recent attempt to study properties of cold gas in a lower-metallicity environment offered by the outskirts of the MW resulted in highly puzzling results. Dickey et al. (2009) suggest that, contrary to all theoretical predictions, the spin temperature of the CNM is constant with Galactocentric radius all the way to 25 kpc.

To be able to study the conversion of cold gas into stars over cosmic time, we need to start by providing the census of cold gas in nearby galaxies and its environmental dependence. GASKAP will provide HI absorption spectra for several hundred of radio continuum sources both behind the Magellanic Clouds and the MW disk to study spatial variations of the CNM/WNM abundance and their correlations with the underlying physical conditions. Deeper observations over smaller areas with MeerKAT and ATA-256 should continue this work to other nearby galaxies.

4. What is the origin and nature of interstellar inhomogeneities?

Interstellar turbulence is an important ingredient in ISM models and governs many astrophysical processes, including the cycling across various gas phases, formation and evolution of ISM inhomogeneities (McKee & Ostriker 2007), and the onset of molecule formation (Glover et al. 2010). While pinning down sources of ISM turbulence observationally has been hardly explored, detailed numerical simulations of galaxies require inclusion of realistic ISM inhomogeneities. For example, Governato et al. (2010) show how only after tying star formation and its feedback to realistic highest-density regions can a sufficient removal of the angular momentum be achieved, resulting in reasonable rotation curves.

Statistical studies have proven to be essential in characterizing the inhomogeneous and turbulent ISM (Elmegreen & Scalo 2004, Lazarian 2009). However, while many statistical methods (spatial power spectrum, wavelets, probability density functions, principal component analysis etc) have been used, the interpretation of results is not always straightforward. The most challenging issue is the complex relationship between observables (brightness temperature in intensity as a function of velocity, in the case of radio observations) and the underlying physical quantities (3D density and velocity fields; Lazarian 2009). In addition, most of these statistical methods re-

quire large datasets with a large spatial or velocity dynamic range and produce a single, mostly one-dimensional, measure. This results in a lack of spatial information about turbulent properties across a given interstellar cloud or a galaxy, making a connection with the underlying physical processes (e.g., presence or absence of star formation, strength of magnetic field, presence of shearing motions) very difficult.

Recently, Burkhart et al. (2010) showed that the above problems can be alleviated by using modern simulations hand-in-hand with observations. They developed a new method to provide spatial information about the nature and level of interstellar turbulence. This method is based on applying high-order statistical moments to the HI column density distribution and bootstrapping the sonic Mach number (\mathcal{M}_s) from an extensive library of isothermal MHD simulations. Kowal et al. (2007) used 3D isothermal simulations of MHD turbulence; their work shows that variance, skewness, and kurtosis (the 2nd, 3rd and 4th order statistical moments, respectively) have a strong dependence on \mathcal{M}_s . As the sonic Mach number increases, so does the Gaussian asymmetry of the column density PDFs due to gas compression via shocks. This implies that the sonic Mach number of turbulence in an interstellar cloud can be characterized by applying high-order statistical moments to the observed column density distribution functions.

We demonstrated this idea on the HI column density image of the SMC (see Figure 6, left). By using the trends provided by simulations, we converted high-order statistical images of the HI distribution in the SMC into the sonic Mach number image shown in Figure 6. This image allowed us, for the first time, to quantify the fraction of subsonic versus supersonic HI. We found that $\sim 80\%$ of the HI in the SMC is subsonic or transonic with $\mathcal{M}_s < 2$, while $\sim 10\%$ appears quiescent with $\mathcal{M}_s \sim 0$. Another 10% or so has $\mathcal{M}_s > 2$. The highest supersonic regions, with $\mathcal{M}_s \sim 5$, point out large-scale tidal or shearing flows caused most likely by the interactions between the SMC, the LMC, and the MW. A confluence of observations and numerical simulations is clearly a powerful way of connecting physical sources and processes with the ISM structure formation, which seeds molecule and later star formation.

However, to have enough data points to reliably calculate statistical moments we essentially had to smooth the original HI image to a resolution of 30 arcmin and were therefore not able to reach scales of typical HII regions and/or supernovae which are generally considered as the main turbulence drivers (McCray & Snow 1979). The upcoming radio telescopes will ameliorate this problem. With an angular resolution of $10''$ - $20''$ provided by ASKAP we will reach linear scales of 50-100 pc (at a distance of 60 kpc) for the high-order moment maps. This will probe the supernova origin of interstellar turbulence at the distance of Magellanic Clouds. A huge number of high-resolution HI data cubes of the Magellanic Clouds, the MW plane (GASKAP) and other nearby galaxies (MeerKAT), in combination with the high-order moments method, will sample variations in the nature/level of interstellar turbulence with varying interstellar environments. In general, with data volumes increasing by a large factor, an exploration of new statistical methods for the analysis of HI data will be even more important in the future.

5. Conclusions

While significant effort in the near future will be focused on galaxy evolution by observing HI in galaxies at large redshifts, we argue in this paper that the understanding of *detailed* physical

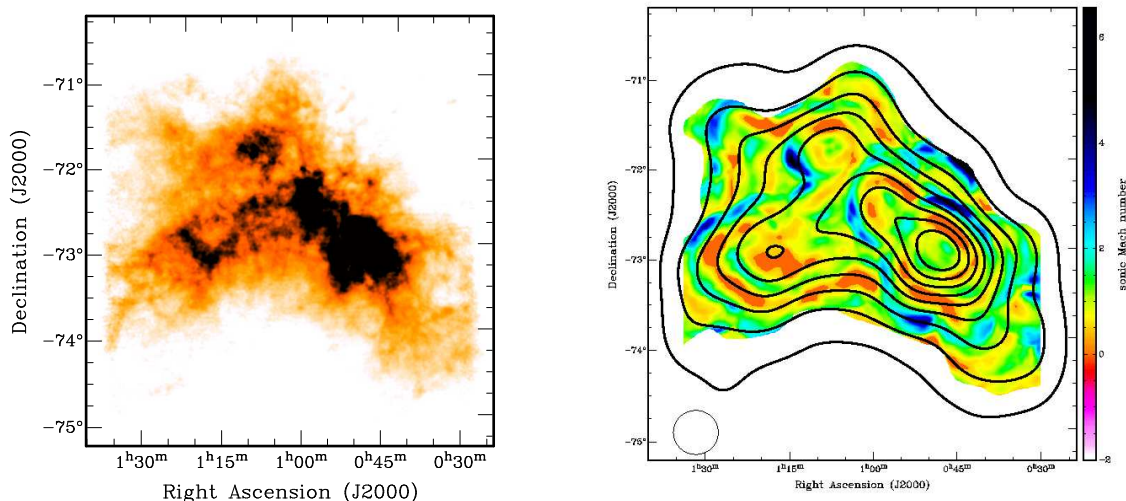


Figure 6: (left) The HI column density image of the SMC from Stanimirovic et al. (1999) at an angular resolution of $98''$. (right) The sonic Mach number image derived from the HI column density image of the SMC and overlaid with the HI column density contours (from Burkhardt et al. 2010). The circle in the bottom-left shows the angular resolution of the image, $\sim 30'$.

processes that drive evolution of the HI gas in galaxies is equally important. To expose processes in question at high resolution, the nearby Universe offers an unparalleled advantage. We have focused here on just three outstanding questions regarding the very first step in the star-formation cycle in galaxies where upcoming radio telescopes (e.g. EVLA, ASKAP, MeerKAT, ATA-256) promise great advances.

First, nearby examples of the infalling gaseous tidal tails like the Magellanic Stream offer a unique window into how much galaxy halos flavor and tax the accretion flows that are postulated to bring fresh star-formation fuel to galaxy disks. While current analytic and numerical studies suggest highly turbulent environments, created by fast shredding of incoming flows by hydrodynamic instabilities, the HI clouds in the Stream appear more quiescent with large reservoirs of low column density material that is potentially shielding them against destruction. Second, in our current understanding of the star-formation cycle in galaxies, the WNM transforms first into the CNM, which further reaches high enough density to form molecules and shield them from radiation. Yet, only three direct measurements of the WNM temperature exist to date in the MW disk. The WNM temperature is a crucial parameter for pinning down how exactly the warm-to-cold phase transformation occurs in galaxies. Similarly, very little is known observationally about the abundance of the CNM and the CNM/WNM fraction in even nearby galaxies. Third, interstellar turbulence is a key parameter when modeling the ISM and molecule/star formation, yet mapping out turbulent properties across various interstellar environments and connecting these variations with the underlying

energy drivers has been hardly explored. Statistical methods based on a confluence of observations and numerical simulations show promising results in this direction and call for higher-resolution data cubes.

The above questions call for extensive, highly-sensitive HI emission and absorption surveys. While deep HI emission surveys of tidal tails around galaxies (including the MW) will teach us about physical properties of accretion flows, deep HI absorption surveys will measure the temperature, abundance and interchange of the warm/cold star-formation fuel in galaxies. Recent results from Arecibo's GALFA-HI survey, as well as pilot EVLA observations, demonstrate a high potential of future surveys. At the same time, to analyze upcoming huge volumes of data, and to take the data analysis to a higher level, a strong confluence of observations and numerical simulations is becoming a necessary, not just desirable, approach.

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