

THE SMALL-SCALE STRUCTURE OF THE MAGELLANIC STREAM AS A FOUNDATION FOR GALAXY EVOLUTION

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(Received: May 13, 2010; Accepted: May 13, 2010)

SUMMARY: The Magellanic Stream (MS) is the nearest example of a gaseous trail formed by interacting galaxies. While the substantial gas masses in these kinds of circumgalactic structures are postulated to represent important sources of fuel for future star formation, the mechanisms whereby this material might be accreted back into galaxies remain unclear. Recent neutral hydrogen (HI) observations have demonstrated that the northern portion of the MS, which probably has been interacting with the Milky Way's hot gaseous halo for close to 1000 Myr, has a larger spatial extent than previously recognized, while also containing significant amounts of small-scale structure. After a brief consideration of the large-scale kinematics of the MS as traced by the recently-discovered extension of the MS, we explore the aging process of the MS gas through the operation of various hydrodynamic instabilities and interstellar turbulence. This in turn leads to consideration of processes whereby MS material survives as cool gas, and yet also evidently fails to form stars. Parallels between the MS and extragalactic tidal features are briefly discussed with an emphasis on steps toward establishing what the MS reveals about the critical role of local processes in determining the evolution of these kinds of systems.

Key words. Galaxy: halo – Galaxies: evolution – Magellanic Clouds – Hydrodynamics – Instabilities

1. INTRODUCTION

Numerical simulations of galaxy formation show that galaxies can grow by accreting gas from cosmic filaments and satellite galaxies (e.g. Kereš et al. 2005, Dekel et al. 2009). Even at the present time, $z=0$, accretion processes are likely to be ongoing and help galaxies to sustain star formation (Sancisi et al. 2008, Kereš and Hernquist 2009). In any case, the response of the gas and any associated material on approaching a giant galaxy is an important factor in determining the fate of the accreted matter; e.g. does infalling gas act as clouds on approxi-

mately ballistic orbits or does it become part of a diffuse medium? Recent studies suggest a multi-phase nature of the accreted material: while some inflowing gas is shock-heated to near virial temperatures, a significant amount is accreted at lower temperatures of $T < \text{few} \times 10^5$ K where cooling times are short. Brooks et al. (2009) show that for a Milky Way (MW) type galaxy, about 60-70% of accreted gas is shocked to $T \sim 10^6$ K temperature, while both cold accretion (from cosmic filaments) and accretion for previous mergers and satellites ('clumpy' component) contribute each about 30-40%. While containing a smaller amount of gas in general, the unshocked and 'clumpy' components play a very important role

for building up the disk: 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.

Gas stripped from satellites and by interacting galaxies are both important sources of galactic gas infall and provide the most direct possibilities for observing accretion processes. As emphasized by Kereš and Hernquist (2009), the multiphase nature of galactic halos also enters into this issue by modifying gas stripping processes (see also Silk et al. 1987, Gallagher and Smith 2005, and Türlmann et al. 2006 for additional perspectives on these issues). Understanding the astrophysics of satellite gas accretion events thus requires knowledge of the operation of gas stripping processes to determine the rate and nature of gas that is injected into the surroundings as well as models to assess the fate of the stripped gas.

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

In this paper, we summarize the latest observational results and outstanding puzzles concerning the evolution of the MS gas. We start with recent observations in Section 2. In Section 3 we investigate

the large-scale kinematics of the MS, while in Section 4 we extensively focus on physical properties of the small-scale structure of the MS. We contrast the MS to other tidal tails in Section 5, and conclude with a future outlook in Section 6.

2. RECENT STUDIES OF THE MAGELLANIC STREAM

The MS is a huge (> 100 degree long) starless neutral hydrogen (HI) structure trailing behind the MCs. It is a remnant of the wild past interaction of the MW with the MCs (the Large Magellanic Cloud, LMC, and the Small Magellanic Cloud, SMC), and of the MCs with each other. Theories have swung back and forth about the origin of the MS, with the relative importance of tidal (Gardiner and Noguchi 1996, Connors et al. 2006) versus ram pressure stripping (Moore and Davis 1994, Mastropietro et al. 2005) being still under debate. Especially challenging in recent years have been the latest proper motion measurements (Kallivayalil et al. 2006, Piatek et al. 2008) which increased the 3-d velocity for both Clouds, from 220 to 370 km s^{-1} for the SMC, and from 293 to 350 km s^{-1} for the LMC.

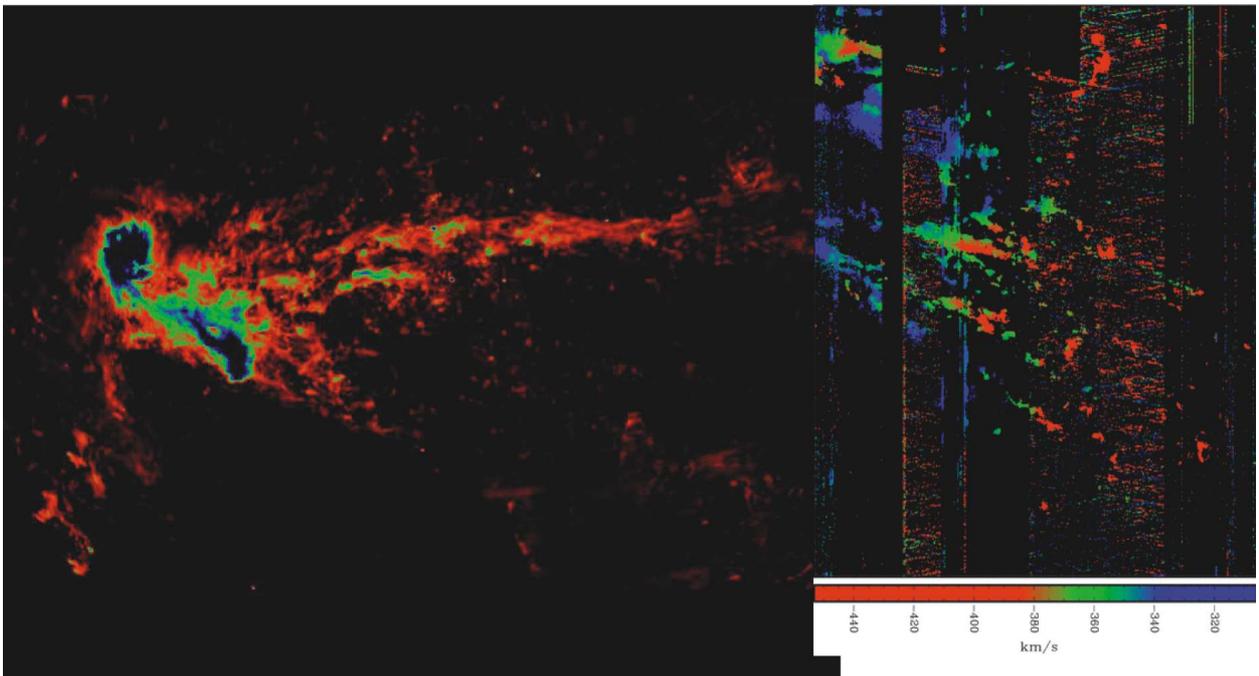


Fig. 1. A collage of HI observations of the MS. The left-hand side image shows the HI column density distribution from Putman et al. (2003) and was produced from observations obtained with the Parkes radio telescope (angular resolution of $15'$). The right-hand side image shows the HI velocity field at the tip of the MS; this image is from Stanimirovic et al. (2008) and was obtained using Arecibo observations (angular resolution of $3.5'$). The color bar corresponds to the Arecibo image and shows a velocity range from -320 km s^{-1} (blue) to -440 km s^{-1} (red).

After incorporating these new measurements into the orbit calculation, Besla et al. (2007) suggested, contrary to all previous studies, that the MCs are not likely to be bound to the MW and may be approaching the MW for the very first time. This leaves essentially very little time for the SMC-LMC-MW interactions and the formation of the MS either through tidal or ram pressure forces. In the mean time, several observational studies have suggested that the MW's rotational velocity is significantly higher (254 km s^{-1}) than the IAU standard of 220 km s^{-1} (Reid et al. 2009). This implies that the MW itself is more massive, with a virial mass of $1.5 \times 10^{12} M_{\odot}$. Shattow and Loeb (2009) showed that with a more massive MW binary orbits of the MCs are again possible and the MCs may be gravitationally bound by the MW.

While apparently starless, the MS is the host of frequently detected $H\alpha$ emission. The origin of this $H\alpha$ emission has been mysterious as the expected $H\alpha$ signal excited by the cosmic and Galactic UV background is significantly lower than what is observed (Bland-Hawthorn and Maloney 1999). Additional sources of ionization have been invoked, including shocks, magnetic fields, and/or interactions between the MS clouds and the hot halo gas.

Many past and recent low-resolution HI studies have provided illuminating insights into the structure of the MS. A strong velocity gradient was observed from about $+400 \text{ km s}^{-1}$ at the location of the LMC (Dec ~ -68 deg), to -400 km s^{-1} at the tip of the MS (Dec $\sim 20^{\circ}$), the farthest away from the MCs. Observations with the Parkes radio telescope at angular resolution of $15'$ (Staveley-Smith et al. 1998, Putman et al. 2003, Brüns et al. 2005), showed interesting large-scale HI structure in the form of two 100-degree long interwoven filaments (see Fig. 1, left). It was thought that the filaments become overwhelmed by the MW halo around Dec $\sim 0^{\circ}$, ending up in a chaotic network of small filaments and clumps. The total HI mass of the MS is $2 \times 10^8 M_{\odot}$ (Putman et al. 2003). For comparison, the HI mass of the SMC is $4.2 \times 10^8 M_{\odot}$ (Stanimirovic et al. 1999).

Most recent observations highlight two important observational phenomena: the MS is significantly more extended than previously thought, and has a significant abundance of small-scale structure. Braun and Thilker (2004) suggested that the *diffuse* northern portion of the MS extends up to Dec 40° , while the latest high-resolution observations by the GALFA-HI survey (Stanimirovic et al. 2006) showed a highly organized structure. Instead of a chaotic HI distribution, Stanimirović et al. (2008) found several filamentary structures extending up to Dec $\sim 30^{\circ}$ to the north, and reaching a heliocentric velocity of -420 km s^{-1} . These filaments have a great deal of small-scale structure, mainly in the form of discrete HI clouds, and have distinct HI morphologies and velocity gradients (Fig. 1, right). Very recently, Nidever et al. (2010) combined all available HI data sets with some new Green Bank Telescope observations and showed that there is indeed a *continuous* extension of the northern MS from the areas cov-

ered by Parkes and GALFA-HI surveys all the way to Dec 40° as suggested by Braun and Thilker (2004).

In summary, the present-day MS is at least 40% longer, and about 10% more massive, relative to the MS we knew about a few years ago.

3. WHAT PROCESSES SHAPE THE LARGE-SCALE HI STRUCTURE OF THE MS?

Attempts to reproduce the observed HI morphology and velocity gradient along the MS have had a varying level of success. For pros and cons of various models please see Connors et al. (2006) and Besla et al. (2008). The model-predicted HI velocity gradients especially differ at the northern tip of the MS, making a comparison with observations the easiest. For example, the Connors et al. (2006) tidal model predicts a heliocentric velocity of $\sim -400 \text{ km s}^{-1}$ at the extreme north tip of the MS, while the latest gravity + ram-pressure model by Mastropietro et al. (2005) predicts $V_{\text{LSR}} \sim -250 \text{ km s}^{-1}$. In Fig. 2 we show these two predictions with a solid and a dashed line, respectively. The data points represent MS clouds cataloged by Putman et al. (2003) (crosses) and Stanimirovic et al. (2008) (triangles). The observed velocity of $\sim -430 \text{ km s}^{-1}$ by Stanimirovic et al. (2008) is clearly in a reasonable agreement with the purely tidal predictions. However, this is lower than the prediction by Besla et al. (2008) of $< -500 \text{ km s}^{-1}$ at the extreme MS tip (dot-dashed line in Fig. 2) obtained when the latest proper motions of the MCs are taken into consideration in a cosmologically-motivated gravitational model.

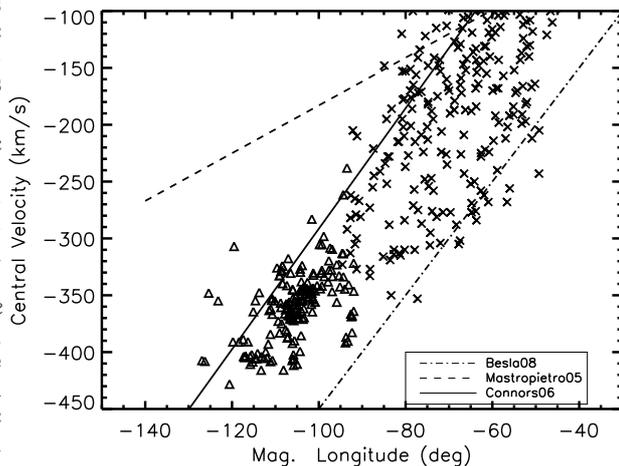


Fig. 2. The local standard of rest (LSR) cloud velocity as a function of Magellanic longitude. Crosses are from Putman et al. (2003) and triangles are from Stanimirovic et al. (2008). Three lines represent the predicted relationship from different models: Mastropietro et al. (2005, dashed line), Connors et al. (2006, dot-dashed line), and Besla et al. (2008, solid line).

This comparison clearly shows that gravity plays a major role in the large-scale structuring of the MS kinematics. While the updated mass of the MW (Shattow and Loeb 2009) is higher than what has been considered in Besla et al. (2008) and may affect the MS velocity, secondary effects like the gas drag due to the interaction of the MS with the halo may also be required to slow down the MS and address details of its spatial orientation and morphology.

4. WHAT PROCESSES SHAPE THE SMALL-SCALE HI STRUCTURE OF THE MS?

Recent Arecibo high-resolution HI observations reveal a wealth of substructure in the MS gas, down to an angular size of ~ 3 arcmin. Many HI clouds have multi-phase medium, while signatures for interaction of gas structures with each other and with the background medium are also common (Putman et al. 2003, Bland-Hawthorn et al. 2007). The complex morphology of the HI gas, and its observed physical properties, indicate that processes are clearly at work on these small scales that could affect star formation, the transfer of gas to the halo, and also may provide additional drag affecting MS global dynamics. Although these processes play a crucial role for gas evolution of the MS (Murray et al. 1993, Bland-Hawthorn et al. 2007, Heitsch and Putman 2009), it is still not clear exactly how they operate, and on what timescales.

For example, theoretical arguments as well as simulations (Mori and Burkert 2001, Quilis and Moore 2001, Heitsch and Putman 2009) suggest that instabilities act on rather short timescales (~ 100 Myrs). This implies that the MS is being continuously replenished, and that the stripped gas may eventually constitute a substantial source for the MW's star formation in the form of infalling warm ionized gas (so called "warm drizzle", Bland-Hawthorn et al. 2007). It is puzzling, however, that high-resolution observations of MS HI clouds show characteristics that indicate stability and longevity rather than rapid destruction; they are often compact, some have a multi-phase medium, and there are regions dense enough for the onset of molecule formation (which we describe and discuss below).

It is important to emphasize that the global numerical simulations rarely have resolution necessary to resolve physical processes on small scales. For example, simulations using smoothed particle hydrodynamics (SPH) can suppress development of hydrodynamic instabilities due to smoothing (Agertz et al. 2007), while N-body simulations ignore gas processes altogether. Grid-based modeling can capture these small-scale instabilities better, exemplified by simulations exploring mechanisms for excess H α emission in the MS (Bland-Hawthorn et al. 2007), galaxy replenishment (Bland-Hawthorn 2009, Heitsch and Putman 2009), and high velocity clouds (HVCs) in

the halo (Quilis and Moore 2001). It is therefore essential to observationally constrain the effectiveness of various hydrodynamical instabilities for the formation and evolution of small-scale structure.

4.1. Cloud angular size distribution

Stanimirovic et al. (2008) produced a catalog of HI clouds and their basic observed properties. The cloud angular size distribution, shown in Fig. 3, peaks at about $10'$, while the HI column density peaks at about 10^{19} cm $^{-2}$. If at a distance of 60 kpc (this is the distance of the SMC), then typical clouds have a radius of ~ 100 pc and a HI mass of $\sim 10^3$ M $_{\odot}$.

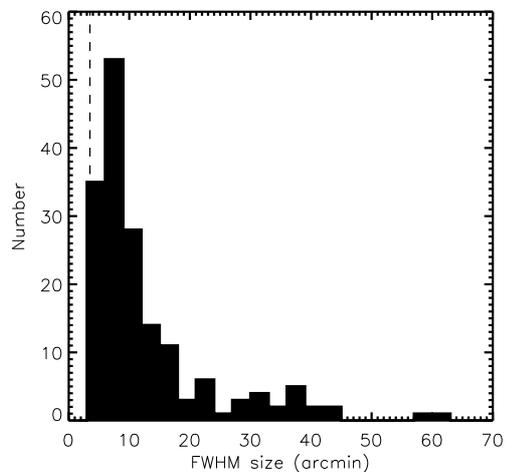


Fig. 3. Histogram of cloud angular size (in arcmins) for the MS cloud population from Stanimirovic et al. (2008). The dashed line shows the angular resolution limit of the Arecibo radio telescope.

To investigate the importance of various hydrodynamical effects on evolution of the MS gas we estimate their approximate timescales.

(i) Thermal instability (TI) develops due to gas cooling and would fragment a warm stream of gas left behind the MCs. Assuming that the original MS had properties similar to those found in the outskirts of the SMC, the TI fragmentation will occur on timescales < 100 Myrs (for details please see Stanimirovic et al. 2008).

(ii) Kelvin-Helmholtz instability (KHI) occurs at the interface between the moving warm stream and the hot ambient medium and provides a continuous stripping mechanism for the MS. The KHI timescale depends on the properties of the halo gas as well (temperature, density), which are not well constrained observationally. However, its typical timescale is in the range of a few hundreds to a few thousands of Myrs.

(iii) The small fragments made by TI and/or KHI are subject to the heat transfer from the much warmer ambient medium. If undergoing classical evaporation by heat conduction (McKee and Cowie

1977), the HI clouds evaporate on a long timescale, > 1 Gyr. In the case of turbulent mixing layers the evaporation timescale would decrease, while a magnetic field would tend to make clouds longer lived.

To conclude, TI and KHI must have had important effects on the shaping of the small-scale HI structure over the MS lifetime (in most theoretical frameworks at least 1 Gyr). While undergoing evaporation, the HI clouds can survive for long times, and therefore it may not be surprising to observe such clumpy morphology at the MS tip.

If we assume that TI is the dominant shaping agent, then we can predict a typical size of thermal fragments λ_{cool} :

$$\lambda_{\text{cool}} = \frac{kT_w}{\Lambda n_w} c_s, \quad (1)$$

where, Λ is the cooling function, k is the Boltzmann constant, c_s is the sound speed, and T_w and n_w are the temperature and volume density of the warm neutral medium (WNM). For the density and temperature conditions characteristic of the SMC outskirts ($T_w = 8000$ K and $n_w = 5 \times 10^{-2} \text{ cm}^{-3}$), "typical" thermal fragments should be about $\lambda_{\text{cool}} \sim 200$ pc. A comparison with the peak of the cloud angular size distribution, which corresponds to $10'$, suggests that the MS tip is at a distance of ~ 70 kpc. While this simple, back-of-the-envelope calculation is only demonstrative, it is interesting that our distance estimate agrees well with the predictions from tidal models (e.g. Connors et al. 2006). Even more impressively, our distance estimate is in agreement with the recent estimate of 75 kpc based on a model by Jin and Lynden-Bell (2008). This model assumed that energy and angular momentum are conserved along the MS, and that the MS is trailing on a planar orbit around the Galactic center.

4.2. Multi-phase medium

Another interesting phenomenon is the multi-phase HI structure of the MS. About 15% of clouds in the sample of Stanimirovic et al. (2008) have velocity profiles whose fits require two temperature components. This suggests the existence of a multi-phase medium at a significant distance from the MW plane. We find evidence for warm gas, with a velocity FWHM of about 25 km s^{-1} , and a cooler component, with a FWHM generally in the range $3\text{-}15 \text{ km s}^{-1}$. Similarly, Karberla and Haud (2006) investigated velocity profiles along the MS based on the Leiden/Argentine/Bonn data (Kalberla et al. 2005). They found that 27% of MS profiles at positive LSR velocities (close to MCs), and 12% of profiles at negative LSR velocities, require two temperature components.

In addition, Matthews et al. (2009) detected the first HI absorption lines against radio background sources in the direction of the MS close to the MCs. The two detected absorption features have a velocity FWHM of 4.2 and 5.0 km s^{-1} , respectively. The spin temperature of the absorbing clouds of 80 and 70 K was derived, resulting in the HI column density of $\sim 2 \times 10^{20} \text{ cm}^{-2}$. The only direct detection

of H_2 in absorption is by Richter et al. (2001), who used Far Ultraviolet Spectroscopic Explorer (FUSE), and found an excitation temperature of ~ 140 K and $N(\text{H}_2) = 3 \times 10^{16} \text{ cm}^{-2}$.

Clearly, the MS contains a multi-phase medium. This is exciting as some cold cores are reaching temperature and HI column densities usually required for molecule (CO) formation, providing potential for future star formation. One question that remains is whether these cold cores were formed in the MS, or have been stripped from the MCs.

In Fig. 4 we show the HI column density of single-phase and multi-phase clouds at the tip of the MS. While single-phase clouds peak at $N(\text{HI}) \sim 10^{19} \text{ cm}^{-2}$, the multi-phase clouds have higher column densities $N(\text{HI}) \sim 1.5 - 4 \times 10^{19} \text{ cm}^{-2}$. The two distinctly different histograms suggest intrinsic difference between single- and multi-phase clouds, with the latter one being found in better shielded, more condensed regions.

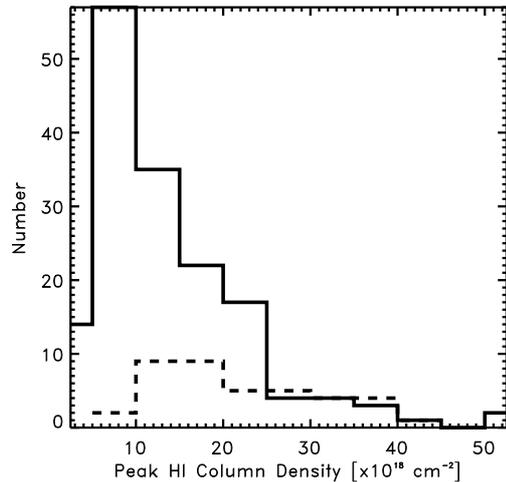


Fig. 4. Histograms of the peak HI column density (in 10^{18} cm^{-2}) for HI clouds with a single velocity component (solid line) and HI clouds with the multi-phase structure (dashed line). The $3\text{-}\sigma$ sensitivity limit of the GALFA-HI survey used for this study is $\sim 3 \times 10^{18} \text{ cm}^{-2}$.

The level of turbulent motions of colder cores with respect to the warmer envelopes can be gauged by calculating the sonic Mach number of cold cores: $M = |V_c - V_w|/\text{FWHM}_w$, with V_c and V_w being velocity centroids of the cold and warm cloud components, and FWHM_w being the velocity FWHM of the warm component. The histogram of M values is shown in Fig. 5; $\sim 90\%$ of data points are within $|M| < 1.5$ suggesting subsonic or mildly supersonic motions. For comparison, Heiles and Troland (2003) found supersonic internal motions for the MW cold neutral medium (CNM) clouds with $M \sim 3$, while Kalberla and Haud (2006) found that most HVCs have $M \sim 1.5$ for cold cores relative to their warm envelopes.

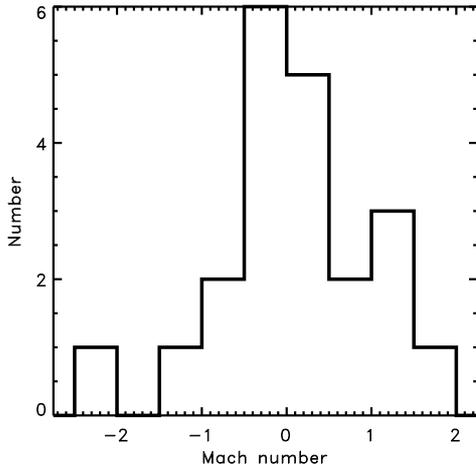


Fig. 5. Histogram of the sonic Mach number of MS cold HI cloud cores relative to warm cloud envelopes.

The existence of a multi-phase medium in the MW halo at a distance of ~ 60 kpc is however not expected from a theoretical point of view. Based on the consideration of cooling/heating processes, Wolfire et al. (1995) suggested that pressure-confined multi-phase clouds should not be found in the MW halo at distances larger than 25 kpc. The thermal pressure required for the co-existence of the CNM and WNM at a distance of 45 kpc from the MW plane is $> 100 \text{ K cm}^{-3}$, while a plane-stratified isothermal MW halo with $T = 10^6 \text{ K}$ provides a thermal pressure of $< 100 \text{ K cm}^{-3}$. While Sternberg et al. (2002) showed that dark matter can provide an additional confinement mechanism, thereby allowing the existence of multi-phase structure at distances < 150 kpc, the amount of dark matter associated with the MS is unknown. Re-consideration of halo properties and/or requirements for the existence of the multi-phase medium are clearly needed. For example, it is becoming well-accepted that dynamical events such as collisions between turbulent flows can initiate fast cycling of interstellar gas between multiple phases.

While our discussion above focused only on the HI multi-phase structure, further insights into the rich multi-phase structure in the MW halo have been provided by UV and optical absorption studies probing various ionization states. Detections of OVI absorption from gas associated with the MS by Sembach et al. (2003) give strong support for the existence of an ionized component around the MS with $T < 10^6 \text{ K}$. It is generally interpreted that this component represents an interface between the hot halo gas ($T \sim 10^6 \text{ K}$) and the cooler MS gas.

Studies of lower ionization states suggest the existence of diffuse envelopes of somewhat cooler, partially ionized gas that is not visible in current HI surveys. Specifically, SiIII provides a more sensitive probe of ionized components of the infalling gas, likely probing different phases than OVI with $T = 10^{4-4.5} \text{ K}$ and the corresponding $N_{\text{HI}} \sim 10^{17} \text{ cm}^{-2}$,

well below current HI survey sensitivity (Shull et al. 2009). Such gas has been detected along a sightline in the northern MS with velocities associated with the MS (Collins et al. 2009). Fox et al. (2010, in prep) have performed an analysis of many low- and high-ion species in UV and optical absorption, including SiIII, against background sources in the northern MS. From this work, a picture emerges of a diffuse, multi-phase transition structure between the warm, mostly neutral envelope gas detected in HI and the hot, mostly ionized envelope gas detected in OVI.

4.3. Turbulence as a generator of small-scale structure?

Instead of being predominantly formed out of the smooth diffuse WNM, the clumpy and multi-phase small-scale structure in the MS could be a result of turbulent inhomogeneities that originated in the MCs and were simply stripped during the MW-MCs interactions. Also, an alternative to hydrodynamical instabilities being the main driving source (as considered in previous sections), are large-scale shearing and tidal flows that can induce turbulence on large scales and provide an energy cascade and formation of structure on smaller scales. We briefly explore these possibilities in this section.

It has been shown that the HI distribution in the SMC and the LMC is turbulent and can be described with a spatial power spectrum $P(k) \propto k^{-\gamma}$ (Stanimirovic et al. 1999, Elmegreen et al. 2001). The power-law slope of the density field is $\gamma = 3.4$ in the case of the SMC (Stanimirovic and Lazarian 2001), and $\gamma = 3.7$ for the LMC (Elmegreen et al. 2001). One puzzling issue, however, is that these power spectra do not show significant changes at the largest sampled scales. This could be interpreted as evidence for interstellar turbulence being driven on scales larger than the size of the SMC/LMC, $> 4-5$ kpc.

Recently, Burkhart et al. (2010) developed a new method to gauge the spatial variations of turbulence by applying the 3rd and 4th statistical moments (or skewness and kurtosis) on the observed HI column density distribution. Based on MHD simulations, these high-order statistical moments are well correlated with the sonic Mach number. Therefore, by measuring skewness and kurtosis for the observed data, we can use the correlations derived from simulated data sets to retrieve the spatial distribution of the sonic Mach number, which provides an estimate for the local level of turbulence. Burkhart et al. (2010) applied this method to the HI column density image of the SMC and found that regions with the highest level of turbulence are located at the boundaries of the SMC bar. This suggests that large-scale motions between the bar and the surrounding diffuse HI, possibly induced by tidal interactions between the SMC, the LMC and the MW, or some kind of shearing flows, may be imprinting a strong energy signature on the HI gas.

Similarly, Goldman (2000) suggested that the HI turbulence in the SMC was induced by large-scale

flows from tidal interactions with the MW and the LMC about 2×10^8 yrs ago. Such large-scale bulk flows could have generated turbulence through shear instabilities. If shearing flows were able to leave such strong imprint on the SMC, they must be also affecting the MS gas as well and may be responsible for the formation of the small-scale structure we observe in HI.

The need for an initially clumpy MS gas has also been highlighted recently by Bland-Hawthorn et al. (2007) who proposed a shock-cascade process to explain the observed H α emission along the MS. Two most important aspects of this study are: an initially clumpy distribution of the MS gas, and a strong interaction between the MS clouds and the MW halo which drives the collisionally excited H α emission. As the MS clouds upstream experience gas ablation by the oncoming hot Galactic wind, the ablated gas is slowed down and transported behind the clouds. The ablated gas further collides with the clouds downstream, resulting in shock ionization of HI clouds. This shock-cascade model can explain measured H α intensities along the MS.

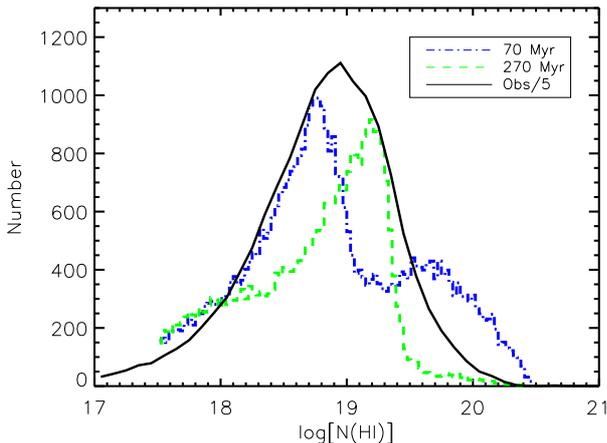


Fig. 6. Evolution of the HI column density PDF in the shock-cascade simulation by Bland-Hawthorn et al. (2007). The blue dot-dashed and green dashed lines shows times stamps in the simulation at 70 and 270 Myrs, respectively. The solid line shows the HI column density PDF derived by using observations from Stanimirovic et al. (2008). The observed PDF was divided by 5 because observations sample five times larger projected area than the simulation.

The shock-cascade model predicts that large changes should take place in the HI distribution on timescales of 100-200 Myrs. The ablation process erodes the low density HI gas, slowly eating into the high-density regions. As a result, after about 200 Myrs, the HI column density distribution is highly asymmetric (see Fig. 6): it peaks at $N(\text{HI}) \sim 10^{19}$ cm^{-2} and is missing both low- and high-density gas relative to the initial HI distribution. As the tip of the MS has been exposed to the halo the longest, the shock-cascade process should be clearly noticeable here.

In Fig. 6 we compare the observed HI column density probability density function (PDF) 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 Fig. 6). The observed PDF was derived by taking the data from Stanimirovic et al. (2008), deriving the HI column density distribution, and simply dividing this by 5 to account for the difference in the areas probed by observations and the simulation (the simulated area is about 5 times smaller than that probed by observations). The large difference in the simulated data after 200 Myrs is clearly 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 Burkhart et al. (2010), subsonic turbulence produces Gaussian column density PDFs, while in the case of supersonic turbulence PDFs are highly skewed. This again highlights the difference between observations and the simulation: simulated distributions appear significantly more turbulent than what observations show. This suggests that the proposed ablation process is too fast and something must be slowing it down and helping the MS clouds survive longer.

The structure of the boundary between clouds and the hot atmosphere of the MW is one factor which could account for the apparently slow rate of mass ablation in the MS. Numerical models by Vieser and Hensler (2007) indicate that while conductive heating promotes the evaporation of a cooler, dense cloud moving with respect to a rarified hot medium, it also can significantly reduce the action of the KTI. Since under these circumstances KTI is likely to be the dominant mode of cool cloud disruption, the net effect of conductive heating then is to substantially extend cloud lifetimes. This type of mechanism also is consistent with the presence of gas with a range of ionization potentials in the MS, and merits further exploration.

5. THE MS AS A VEHICLE FOR UNDERSTANDING CONDITIONS FOR STAR FORMATION IN TIDAL TAILS IN GENERAL

The evolution of gas-rich tidal debris involves processes operating on a variety of density, temperature and mass scales. Among these star formation is one interesting end point for small scale structures. While massive tidal tails, such as those in some of the Arp interacting galaxies, show clear evidence for active star formation (e.g. Schombert et al. 1990, Gallagher et al. 2001), other gas-rich tidal features, such as the eastern HI arm of M51 (Rots et al. 1990), remain as purely gaseous structures. However, the increased sensitivity of recent observations are re-

vealing star formation under a wider range of conditions than previously recognized.

On larger scales, these include the production of relatively large concentrations of gas that can become tidal dwarf galaxies and are capable of supporting extensive star formation (e.g. Mirabel et al. 1992, Bournaud and Duc 2006, Weilbacher et al. 2000, Smith et al. 2010 and references therein). A key point beyond this was the recognition that even relatively diffuse extragalactic tidal gas systems can contain significant amounts of molecular gas (Walter and Heithausen 1999, Braine et al. 2001, Taylor et al. 2001). Perhaps it then is to be expected that star formation on small scales in tidal debris also is showing up, especially in deep images obtained in the optical or in the ultraviolet with Galaxy Evolution Explorer (GALEX) (e.g. de Mello et al. 2008, Werk et al. 2008, Thilker et al. 2009).

The MS, unlike the Magellanic bridge (Mizuno et al. 2006, Nishiyama et al. 2007), is not known to contain classical molecular clouds or candidate star forming regions. Thus the MS appears to be a large scale example of an HI stream that is sterile against star formation. How then does the MS differ from extragalactic HI features, including many tidal tails, that support star formation? Can studies of the MS provide insights into why the observed gas clumps evidently do not grow and become gravitationally unstable and yet also survive for long times? The low mean column density is likely to be one factor and dust content may be another. As discussed by Maybhate et al. (2007) and Boquien et al. (2009), star formation usually is observed when $N(H) > 3 \times 10^{20} \text{ cm}^{-2}$, which is larger than the $N(HI)$ seen in most of the stream.

However, since the gas in the MS can be studied in considerable detail, it should be possible to go beyond this type of important but empirical bulk diagnosis, and carry out detailed analysis of the evolution of typical MS clumps. For example, as we discussed earlier, the Bland-Hawthorn et al. (2007) provides useful initial predictions for the evolution of the column density distribution within the MS. Comparisons between even more sophisticated models and the new MS observations can be expected to yield insights not only into the astrophysics controlling the MS, but more generally into the fate of HI injected into the vicinities of galaxies by interactions or other cosmologically related processes (e.g. Keres and Hernquist 2009).

6. CONCLUSIONS, ON-GOING AND FUTURE STUDIES

With the improved resolution and sensitivity of radio telescopes, abundant and rich small-scale HI structure in the MS is being revealed even in regions located the farthest away from the parent MCs and deeply embedded in the hot MW halo. The

HI clouds often show multi-phase signatures and appear shielded from high turbulence caused by various types of gas stripping by the MW halo. Occasionally, even cold cores with column densities that could support molecule formation are found.

What physical processes produce such rich structure in a tidal tail like the MS, how will this structure evolve as it interacts with the surrounding hot medium, and will it eventually infall to the MW disk? These questions have led us to explore the importance of various hydrodynamical instabilities and their effectiveness. Our analytical consideration of timescales, as well as recent numerical advances, suggest that thermal and Kelvin-Helmholtz instabilities operate on timescale much shorter than the MS formation time and hence must be important. Indirect studies of turbulence in the MCs suggest that large-scale shearing/tidal flows may be able to drive turbulence and cascade to smaller scales. Yet, the observed HI column density distribution and highly rich temperature structure observed in the MS over a range from ~ 100 to $\sim 10^5$ K, paint a picture of stable, long-lived environments. One promising solution could be the nature of boundary regions between the MS clouds and the MW halo.

To investigate the role of the MW halo in shaping of the small-scale MS structure, we are in the process of placing constraints, in the radio and optical regimes, on characteristics of the gas in the transition region from the MS gas to the ambient MW halo medium. Using the National Radio Astronomy Observatory Green Bank Telescope we have obtained the most sensitive HI emission images of portions of the MS to date and have begun to analyze the structure and kinematics of the gas. Preliminary results from this study can be found in Nigra et al. (2009).

In the near future, a large step forward in understanding the MS properties will come from the Galactic Australian Square Kilometer Array Pathfinder GASKAP project. GASKAP is a study of the 21-cm line of HI and the 18-cm lines of OH in the Galactic Plane and the Magellanic Clouds and Stream using a new radio interferometer (ASKAP, Johnston et al. 2007) under development in Australia. ASKAP will consist of 36 12-m antennas, each with a focal plane phased array, and operating over a frequency range 700 MHz to 1.8 GHz. This new instrument is expected to become operational in late 2012. GASKAP images will have an order of magnitude higher angular resolution ($\sim 20''$) and sensitivity (~ 0.04 K) relative to any previous large-scale survey of the MS and will constrain various eroding processes shaping the MS.

Acknowledgements – It is a pleasure to thank Joss Bland-Hawthorn for stimulating discussions and sharing of simulations. We acknowledge support by the NSF grant AST-0908134 to SS and AST-0708967 to JSG. SS also thanks the Research Corporation for Science Advancement for their support.

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СТРУКТУРА НА МАЛИМ СКАЛАМА МАГЕЛАНОВОГ ПОТОКА КАО ОСНОВА ЗА ГАЛАКТИЧКУ ЕВОЛУЦИЈУ

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УДК 524.722 – 423.4

Прегледни рад по позиву

Магеланов поток (МП) је најближи пример гасног трага формираног међудејством галаксија. Како је значајна маса гаса у овим врстама окогалактичких структура претпостављена да представља важан извор горива за будуће формирање звезда, механизам који овај материјал може вратити назад у галаксију остаје нејасан. Недавна посматрања неутралног водоника (HI) су показала да северни део МП, који вероватно интерагује са врелим гасом из халоа Млечног Пута близу 1000 Муг, захвата већи простор него што је претходно било утврђено, мада такође садржи значајну количину структура на малој скали. После кратког разматрања кинематике на ве-

ликим скалама у МП условљеном недавно откривеном проширености МП, ми изучавамо старост процеса у гасу МП кроз дејство различитих хидродинамичких нестабилности и међузвезданих турбуленција. Ово нас води до разматрања процеса у којима материјал МП преживљава као хладна гасна фаза, и још увек евидентно не успева да формира звезде. Паралеле између МП и вангалактичких плимских формација су кратко дискутоване са наглашавањем корака који успостављају шта МП открива о правилима везаним за локалне процесе у одређивању еволуције система овакве врсте.