The Magellanic System: Stars, Gas, and Galaxies
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The many streams of the Magellanic Stream

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Abstract. As a part of the ongoing H I survey by the consortium for Galactic studies with the *Arecibo* L-band Feed Array (GALFA-HI), we have recently imaged the tip of the MS and found several long filamentary structures. This demonstrates that the northern portion of the MS, which has been interacting with the Galactic halo for a long time, is more extended than previously thought and in the form of highly organized H I structures. The observed filaments, and especially the kinematic dichotomy of H I clouds observed for the first time, agree with predictions by the Connors, Kawata & Gibson (2006) tidal model. However, specific time-stamps in the history of the Magellanic System are required to explain these phenomena. The 20-degree long filaments are accompanied by a large population of small H I clouds. We investigate the observed properties of these clouds and explore various instabilities that affect a warm tail of gas trailing through the Galactic halo. Interestingly, if the observed H I structure is mainly due to thermal instability, then the tip of the MS is at a distance of ~70 kpc.

Keywords. ISM: structure, Galaxy: halo, galaxies: interactions, intergalactic medium, galaxies: ISM, Magellanic Clouds

1. Introduction

The Magellanic Stream (MS) is a huge neutral hydrogen (H I) structure representing the most fascinating signature of the wild past interaction of our Galaxy with the Magellanic Clouds (MCs), and of the MCs with each other. Many past and recent H I studies have provided illuminating clues regarding the origin and evolution of the MS. One of the first H I images of the MS was obtained with the *Parkes* telescope (angular resolution of 15′) by Mathewson & Ford (1984), revealing complex diffuse structure and six discrete concentrations (labeled as MS I to VI). More recent and fully-sampled *Parkes* observations by Putman *et al.* (1998, 2003) and Brüns *et al.* (2005) showed interesting H I sub-structure in the form of two 100-degree long interwoven (helix-like) filaments. It was thought that the filaments are becoming overwhelmed by the Galactic halo around Dec $\sim 0^\circ$, ending up in a chaotic network of small filaments and clumps. A strong velocity gradient was observed from about +400 km s^{-1} at the location of the Large Magellanic Cloud (LMC), to −400 km s^{-1} at the tip of the MS, the farthest away from the MCs.

However, the latest observations of the MS tip, obtained with the *Arecibo* telescope, show a highly organized structure instead of a chaotic H I distribution (Stanimirović *et al.* 2008). Several filamentary structures extend to the north up to Dec $\sim 30^\circ$, and reach a heliocentric velocity of −420 km s^{-1}. The filaments have a great deal of small-scale structure, mainly in the form of discrete H I clouds. These observations are part of the ongoing Galactic H I survey (GALFA-HI; Stanimirović *et al.* 2006) and cover an area of 870 square degrees. When completed, the GALFA-HI survey will fully sample the declination range from $-1°$ to $38°$, with a (3-σ) sensitivity of a few $\times 10^{18}$ cm^{-2} (over ~ 20 km s^{-1}).

The northern extension of the MS has been a subject of sporadic attention in the past. Mirabel (1981) suggested that nearly all high-negative velocity gas in the MS direction may be originating from the MS. Lockman *et al.* (2002) noticed several lines of sight outside of the traditional MS borders, up to $b = -30°$, while Braun & Thilker (2004) suggested that the diffuse MS extends up to Dec 40°. Recently, Westmeier & Koribalski (2008) detected about 150 isolated H I clouds tens of degrees away (RA $0^{\rm h}$ to $2^{\rm h}$) from the traditional MS, but organized in several long filaments running almost parallel to the MS.

In this paper, we focus on the northern extension of the MS by summarizing the main results from Stanimirović *et al.* (2008). We provide a brief comparison of H I observations with recent numerical simulations, and investigate physical processes that may be responsible for the small-scale H I structure of the MS. We also use the small-scale H I structure of the MS to place constraints on the distance of the MS tip.

2. H I filaments at the MS tip

With *Arecibo*'s angular resolution of 3.5′, four separate filaments were revealed at the MS tip, each with distinct H I morphology and velocity gradient (Figure 1). In terms of morphology, the three streams starting from RA $23^{\rm h}$ appear similar and are clumpy, while the stream starting at RA $23^{\rm h}40^{\rm m}$ appears to consist of mainly diffuse H I. This could be interpreted as the more diffuse stream being younger and less fragmented than the other three. The velocity gradient of the three clumpy streams subsequently decreases in steepness.

The only numerical study that addressed in detail the internal MS structure is that by Connors *et al.* (2006). While considering only gravitational interactions, Connors *et al.* were able to reproduce the observationally-inferred two long MS filaments by Putman *et al.* (1998, 2003). They also predicted the existence of the kinematic bifurcation along the MS. Within this numerical framework, several important events needed to happen in the MS history and leave strong marks on the current Magellanic System. In the close passage between the Small Magellanic Cloud (SMC) and the LMC 2.2 Gyrs ago, the H I gas was pulled out of the SMC outskirts. This resulted in the formation of a very distant stream which is now located at a distance of 170–220 kpc. The major perigalacticon about 1.5 Gyrs ago resulted in the formation of the main MS. This was followed by two close passages between the SMC and the LMC, which resulted in the spatial, and then kinematic bifurcation of the main MS filament. The two bifurcated filaments follow each other along most of the MS, however have different velocities; while one filament follows roughly the LMC's orbit, the other one is at a higher negative velocity reaching almost -500 km s^{-1}. Only < 200 Myr ago, two additional tidal tails were drawn from the Magellanic Bridge and follow spatially the main MS.

Within this framework, a plausible scenario could be that the three new clumpy streams represent a 3-way splitting of the main MS, which happened 0.5–1 Gyr ago, while the diffuse (fourth) stream represents one of the younger tidal tails, formed < 200 Myr ago. While it is highly encouraging that tidal effects alone can produce large-scale spatial and kinematic sub-structure of the MS, many details still need to be worked out. From an observational perspective, the number and full extent of the new filaments have to be

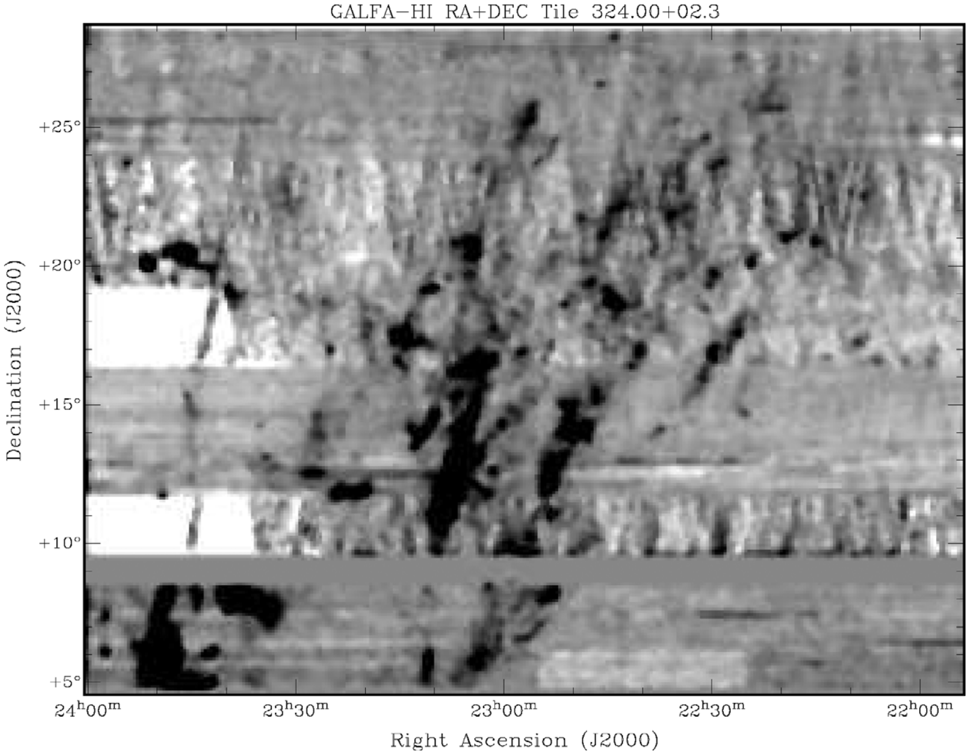

Figure 1. An H I image of the MS at a LSR velocity of -386 km s^{-1} obtained with the *Arecibo* telescope. To enhance our sensitivity to diffuse emission, the image was smoothed to $10'$, and then median filtered. Two white areas at RA $\sim 23^{\rm h}45^{\rm m}$, and a grey strip across the whole image centered at Dec $9°$, currently have no data. Note that the GALFA-HI survey is still under way and better sensitivity images, with a full coverage, will be available in the near future.

constrained with future high resolution observations. It is not clear at the moment how are all these filaments related, whether they are localized in certain areas of the MS or are present along the whole length of the MS. From a theoretical perspective, a potential problem is the need of separate special events (encounters) between the SMC and the LMC to produce the small-scale filamentary structure of the MS. Considering that the new proper motion measurements (Kallivayalil, van der Marel & Alcock 2006) imply a different history of the SMC-LMC-MW interactions (Besla *et al.* 2007), it is not clear how many actual encounters were available in the past for shaping of the MS. Therefore, other and/or additional structuring mechanisms may be required.

3. Clumpy H I structure

Besides several long H I filaments, GALFA-HI observations also show a wealth of small H I clumps. As the clumpiness of the MS is visually striking we produced a catalog of H I clouds and measured their basic observed properties. The cloud angular size distribution peaks at about $10'$, while the H I column density peaks at about 10^{19} cm^{-2}. If at a distance of 60 kpc, then typical H I clouds have a mass of $\sim 10^3$ M$_{\odot}$. The cloud central velocity decreases with Galactic latitude, from -300 km s^{-1} at $b = -50°$, to -420 km s^{-1} at $b = -20°$. This is shown in Figure 2 (left), where we plot H I clouds from Stanimirović

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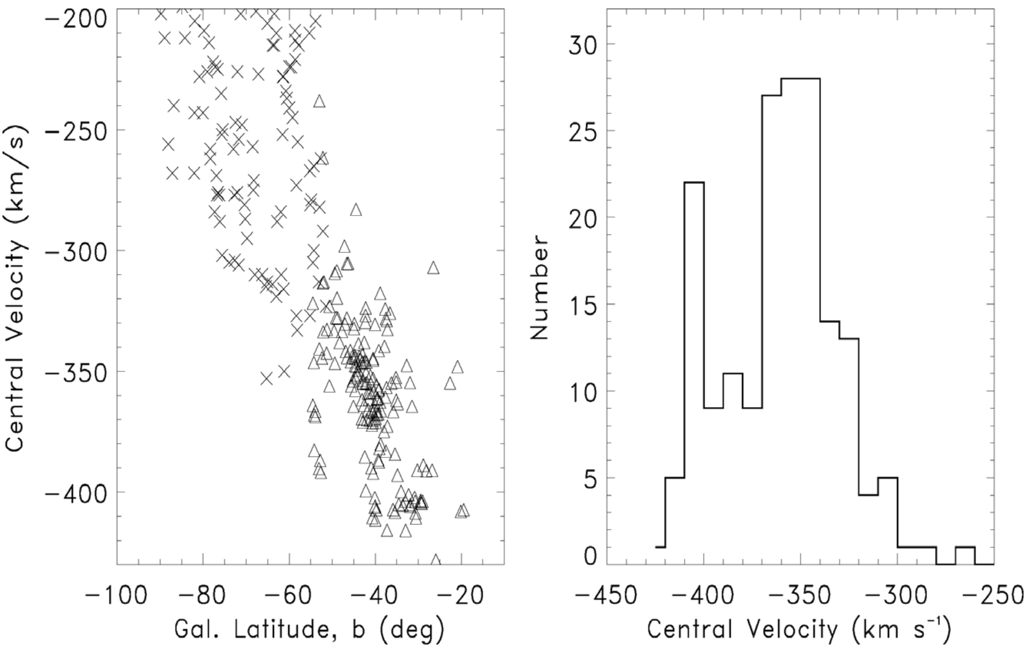

Figure 2. (left) Central velocity of MS clouds as a function of Galactic latitude. Crosses are from the Putman *et al.* (2002) catalog, based on observations with the *Parkes* telescope, while triangles are from Stanimirović *et al.* (2008), based on the observations with the *Arecibo* telescope. (right) Histogram of the cloud central velocity, from Stanimirović *et al.* (2008).

et al. (2008) and Putman *et al.* (2002). The two catalogs merge smoothly, confirming that the new cloud catalog represents an northern extension of the MS population. The same figure (right) also shows the histogram of H I central velocities. Interestingly, there are two strong peaks at -350 and -405 km s^{-1}. This velocity dichotomy may correspond to the kinematic bifurcation of the MS predicted by Connors *et al.* (2006) and never previously confirmed observationally.

Another interesting phenomenon is the multi-phase H I structure. About 15% of clouds in our sample have velocity profiles whose fitting requires two temperature components. This suggests the existence of the multi-phase medium at a significant distance from the Galactic plane. We find evidence for a warm gas, with a FWHM of about 25 km s^{-1}, and a cooler component, with a FWHM of 10–13 km s^{-1}. The cooler component is most likely in the regime of the thermally unstable WNM. Kalberla & 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, and 12% of profiles at negative LSR velocities, require two temperature components.

4. Physical processes responsible for small-scale structure

One of the crucial issues regarding the structure of the MS is to what extent interactions with the halo determine or influence the MS gas. This is especially important for the MS tip as this part of the MS has been immersed in the hot halo for a long time. In trying to understand the origin and evolution of the small-scale H I structure in the MS, we ask the question of what happens to a warm stream of gas, resulted from tidal or hydrodynamical interactions, as it moves through a hot ambient medium?

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There are at least three hydrodynamical effects that play important roles. (i) Thermal instability (TI) develops due to gas cooling and results in the fragmentation of the warm stream. Assuming that the stream has properties similar to those found in the outskirts of the SMC, the TI fragmentation will occur on timescales of a few tens to a few hundreds of Myrs (for details please see Stanimirović *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. 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 will be subjected to the heat transfer from the much warmer ambient medium. In the classical evaporation by heat conduction (McKee & Cowie 1977), the H I clouds are undergoing evaporation but the evaporation timescale is long, > 1 Gyr. In the case of turbulent mixing layers the evaporation timescale would decrease, while an inclusion of a magnetic field would make clouds even longer lived.

To conclude, TI and KHI must have had important effects on the shaping of the small-scale H I structure over the MS lifetime (in most theoretical frameworks). As TI typically operates on shorter timescales than KHI, future high resolution observations along the MS should be able to explore the evolution of the MS gas and place constraints on the effectiveness of these instabilities. Also, while undergoing evaporation, the H I clouds can survive for a long time, 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. For the density and temperature conditions characteristic of the SMC outskirts, "typical" thermal fragments should be about 200 pc in size. A comparison with the peak of the cloud angular size distribution, 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. Even more impressively, our distance estimate is in agreement with the recent estimate of 75 kpc based on a model by Jin & 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.

Additionally, an upper limit on the MS distance can be placed by considering how far away from the Galactic plane the conditions are reasonable for the existence of a multi-phase medium. Based on the cooling/heating processes in the Galactic halo, Wolfire *et al.* (1995) suggested that pressure-confined multi-phase clouds should not be found at distances larger than 25 kpc. Sternberg, McKee & Wolfire (2002) considered both pressure and dark matter confinement of halo clouds, and concluded that the multi-phase medium can survive at distances < 150 kpc. Therefore, the MS tip is likely to be closer than 150 kpc. This causes difficulties for the existence of a very distant MS filament as suggested by Connors *et al.* Also, the latest orbit calculations by Besla *et al.* (2007) imply a significant distance to the MS, ~ 150 kpc, and may require refinements.

5. Conclusions

Several recent observational studies have shown that the northern portion of the MS is significantly more extended and consists of long filamentary structures. The velocity dichotomy of H I clumps at the MS tip, observed for the first time, agrees with predictions by the Connors *et al.* (2006) tidal model. However, special encounters in the Magellanic history are necessary to explain detail kinematic and spatial structure of the MS in this

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framework. While tides may be the dominant structuring agent on large-scales, we have demonstrated that hydrodynamical instabilities are the key for explaining the small-scale structure of the MS, and in turn could provide important constraints on the formation and evolution of the MS.

A few important questions remain for the future: how much more of the low column density MS debris remain to be discovered with future observations? what is the fate of this material? why are the head-tail and cometary H I clouds absent in high-resolution observations? do these morphological features really trace the cloud-halo interactions, or could they be possibly caused by cloud-cloud interactions? how turbulent is the MS gas, and how does this turbulence evolve along the MS?

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