The Magellanic System's Interactive Formations

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Abstract

The results of the interaction between the Milky Way and the Magellanic Clouds are revealed through several high velocity complexes which are connected to the Clouds. The complexes are known as the Magellanic Bridge, an HI connection between the Large and Small Magellanic Clouds, the Magellanic Stream, a $10° \times 100°$ HI filament which trails the Clouds, and the Leading Arm, a diffuse HI filament which leads the Clouds. The mechanism responsible for these features formation remains under some debate, with the lack of detailed HI observations being one of the limiting factors in resolving the issue. Here, I present several large mosaics of HI Parkes All-Sky Survey (HIPASS) data which show the full extent of the three Magellanic complexes at almost twice the resolution of previous observations. These interactive features are connected, but unique in their spatial and velocity distribution. The differences may shed light on their origin and present environment. Dense clumps of HI along the sightline to the Sculptor Group, which may or may not be associated with the Magellanic complexes, are also discussed.

Keywords: intergalactic medium — Local Group — Magellanic Clouds — galaxies: HI

1 Introduction

Almost every galaxy in the Universe is either currently, or was at some time, part of an interacting system. This includes our Galaxy, but until the recent discovery of the Sagittarius dwarf, HI features about the Magellanic Clouds were the only clear sign of our interactive past. Giant neutral hydrogen structures, known as the Magellanic Stream, the Magellanic Bridge and the Leading Arm, depict the Clouds' interaction with each other and the Milky Way. These Magellanic HI complexes make up a large fraction of the high velocity HI concentrations in the southern sky which are known as high-velocity clouds (HVCs). High-velocity clouds are objects which do fit into the classical picture of Galactic HI rotation and fall in the velocity range of $|v_{lsr}| = 90 - 400$ km s^{-1} (see Wakker & van Woerden 1997 for a review). The overall HVC population has had a number of origin possibilities put forth: from superbubbles in the Galactic disk, to tidal debris, to building blocks of the Local Group. To distinguish between the range of possibilities and determine if more HVCs are related to the interaction of our Galaxy with the Magellanic Clouds, we must better understand the overall HI distribution of high-velocity clouds. Maps from the HI Parkes All Sky Survey (HIPASS) have enabled this by providing a marked improvement in spatial resolution compared to previous HVC surveys (see Putman & Gibson 1999), and revealing previously hidden structure and small high velocity clumps about the Magellanic System.

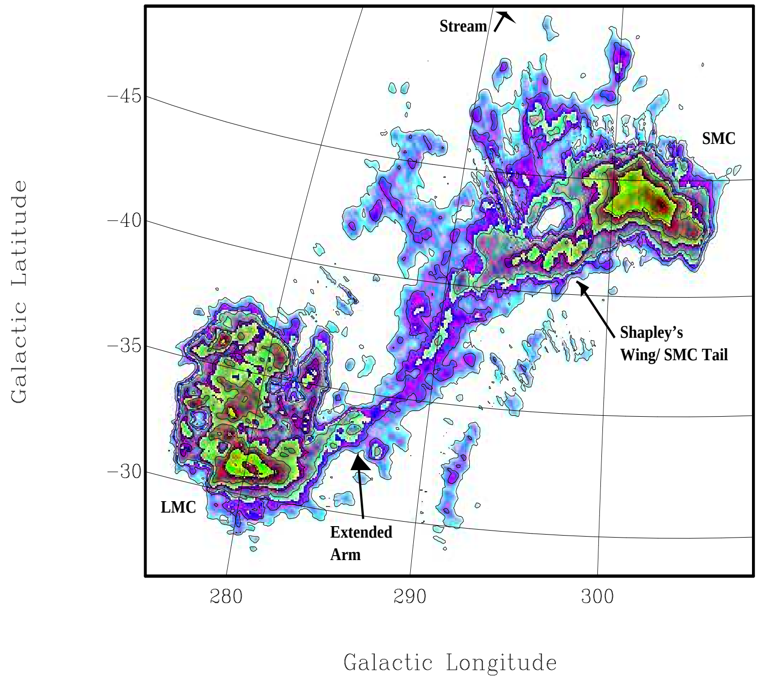

Figure 1: Neutral hydrogen column density map of the Magellanic Bridge which joins the Large and Small Magellanic Clouds. The projection was chosen based on previous maps of the system and the main features are labelled. The contours are 1, 2, 4, 8, 16 and 32 $\times 10^{20}$ cm^{-2}.

2 Magellanic Complexes

The three high velocity complexes which are classified as Magellanic debris are the Magellanic Bridge, the Magellanic Stream and the Leading Arm (see Putman (2000) for a review). The Magellanic Bridge (see Figure 1) is a $\sim 10^8$ M$_\odot$ filament of neutral hydrogen which joins the two Magellanic Clouds and has a velocity gradient which proceeds from 125 km s^{-1} at the tail of the SMC or Shapley's Wing, to $\sim$ 300 km s^{-1} at the extended arm of the LMC. Tidal models predict that the Bridge was pulled from the SMC during a close encounter between the two Clouds 0.2 Gyr ago (Gardiner & Noguchi 1996). The HIPASS data reveal new structure along the Bridge, as well as an extension from the LMC which suggests that the Bridge is made of both SMC and LMC material. The Bridge is the only high-velocity cloud which is known to contain stars, and the age of many of the stellar concentrations (10 - 25 Myr) indicates that the Bridge is a star forming region (Grondin, Demers and Kunkel 1992).

The HIPASS map of the Magellanic Stream is shown in Figure 2. The Stream trails the Magellanic Clouds for over 100° and is not a confined filament as previous maps depict (Mathewson, Cleary and Murray 1974), but a complex network of filaments and clumps. The beginning of the Stream consists of multiple filaments and bow-shock structures as it spews from the northern side of the SMC and Bridge at $v_{lsr} = 90 - 240$ km s^{-1}. Most of these filaments end at declination $\sim 60°$, but the main filament of the Stream continues to march northward, its bifurcated structure diminishing towards the northern tip[1]. Dense clumps follow the Stream in position and velocity, except for the region of the Sculptor Group which will be discussed in the next section. There are no stars in the Stream (e.g. Guhathakurta & Reitzel 1998), but H$_\alpha$ appears to be detectable at

[1]Figure 2 does not show the last $\approx 15°$ of the Stream. See Wayte (1989) for detailed maps of this region.

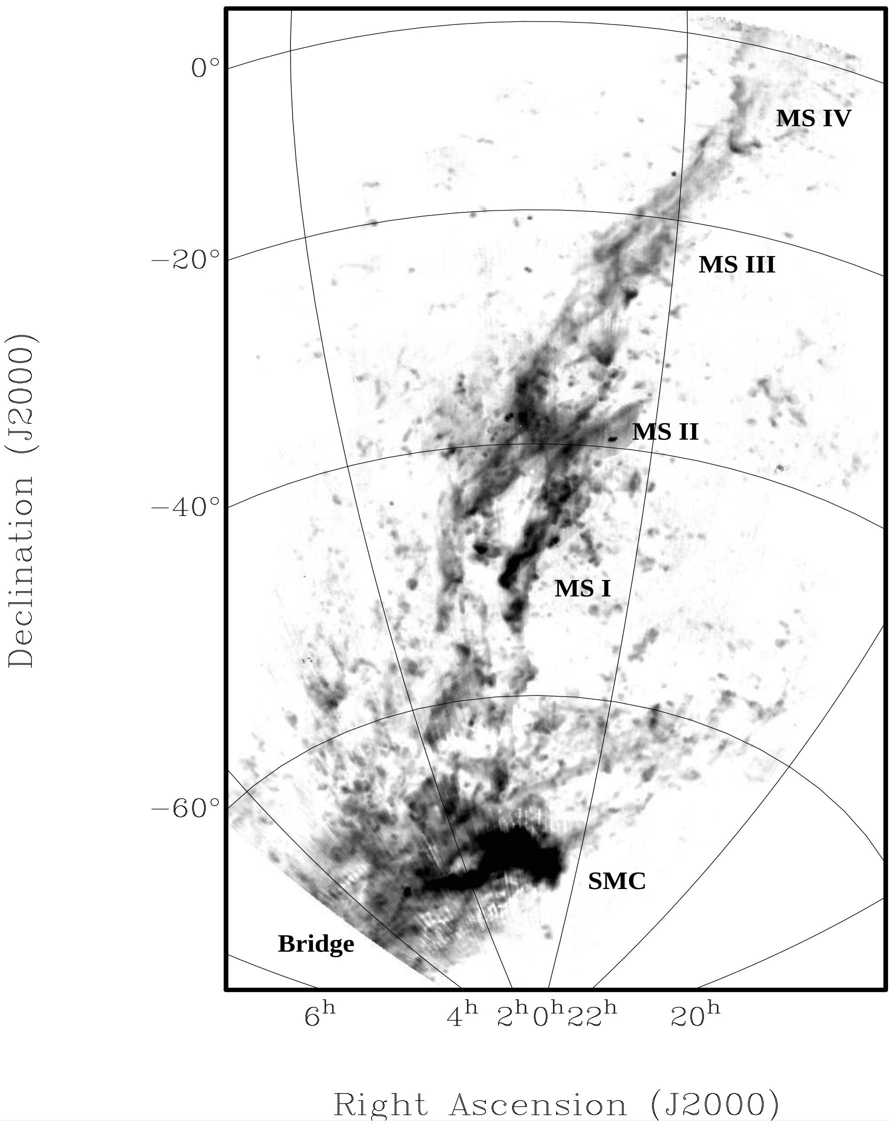

Figure 2: Integrated intensity map of the Magellanic Stream ($v_{LSR} = -400$ to $+400$ km s^{-1}), which starts at the SMC and Bridge and extends to declination $+02°$. The location of the clumps MS I to MS IV, which were originally classified by Mathewson et al. (1979), are labelled for reference. The Stream passes through the velocity of Galactic emission at approximately declination $-35°$, making it somewhat difficult to trace. At these velocities, Galactic emission has been blanked as much as possible.

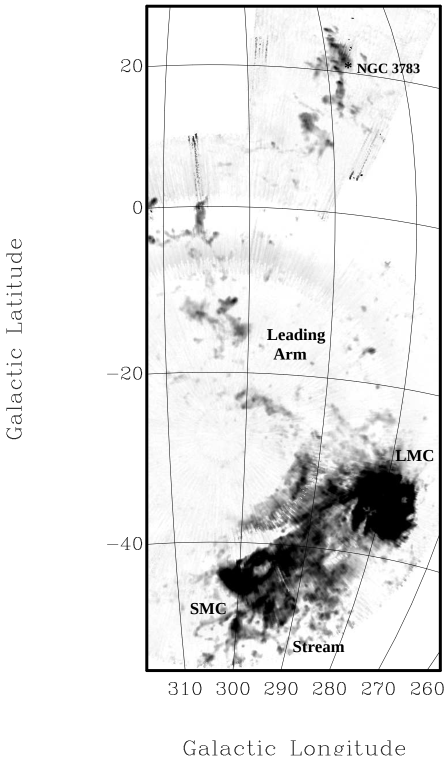

Figure 3: A HIPASS peak intensity map which shows the full extent of the Leading Arm, as well as the Magellanic Clouds, the Bridge and the beginning of the Stream (as labelled). The position of the background galaxy, NGC 3783, is also noted (see text). To avoid the emission from the Galactic Plane (which extends out to 120 km s^{-1} in this direction), only velocities between 130 and 400 km s^{-1} were used. (Thus the truncated appearance of the SMC which begins at $\approx$ 80 km s^{-1}.)

every location along the Stream with a column density greater than 10^{19} M$_\odot$ (Weiner & Williams 1996; Bland-Hawthorn & Maloney 1999a). These detections, together with the fact that no [OIII] has been detected from the Stream, indicates that the Stream is being ionized by photons escaping from the Galaxy (Bland-Hawthorn & Maloney 1999b).

The third Magellanic complex is a natural tidal counterpart to the Stream, and is called the Leading Arm (see Figure 3). This feature is more diffuse than the Stream and its leading position indicates that tidal forces are the dominant mechanism responsible for forming the Magellanic Stream. This complex was only recently confidently defined as Magellanic debris (Putman et al. 1998), as the course resolution and observing grid used in the previous surveys missed the filaments between the clumps and the connection to the Magellanic Clouds. Further evidence that this feature is of Magellanic origin is the metallicity determination of Lu et al. (1998), using the background galaxy NGC 3783.

3 Is it all Magellanic debris?

The ability of HIPASS to uncover the Leading Arm leads to speculation about the origin of the other HI clouds about the Magellanic System. An important class of HVC that HIPASS is successful in revealing is the compact HVCs (CHVCs) which surround the Magellanic Stream and Leading Arm (see Figures 2 & 3). Are these objects additional interactive debris or possibly distant remnants of the Local Group (Blitz et al. 1999; Braun & Burton 1999)? The majority of the compact HVCs follow the Magellanic complexes in position and velocity, suggesting they are related to the Stream or Leading Arm; however, between declinations $-30°$ to $-40°$ the CHVCs have a much larger velocity dispersion (~ 500 km s^{-1}; from $v_{lsr} \approx -250$ to 250 km s^{-1}) than the narrow dispersion of the Stream material (~ 80 km s^{-1}). This declination range also encompasses the southern and near side (at ~ 2 Mpc) of the Sculptor Group of galaxies. Figure 4 shows the complexity of this region, with the positive velocity CHVCs mixed in amongst the galaxies while the Magellanic Stream continues southwards. These results are particularly interesting when one considers the recent distance determination work of Jerjen, Freeman and Binggeli (1998) which indicates that the Sculptor Group is not actually a separate group, but an extension of the Local Group, forming a 6×2 Mpc filament of galaxies with M31 and the Milky Way at one end[2]. The compact HVCs along this sightline do not fit into the normal distribution of Magellanic Stream material, and could lie anywhere along this filament of galaxies. At a distance of 2 Mpc most of the clouds would have HI masses of $\sim 10^7$ $M_\odot$ and diameters of ~ 20 kpc. The clouds may represent leftover galactic building blocks and the local equivalent of the Ly-limit absorber systems (e.g. Stocke et al. 1995). They also fit nicely into hierarchical structure formation simulations which predict that there should be more satellites associated with the Local Group galaxies than is currently observed (e.g. Moore et al. 1999).

The Sculptor Group sightline may be a nearby tracer of the cosmic web and should be investigated more closely. H_α observations are in progress and will provide significant insight into the origin of the compact HVCs. If the CHVCs are within a 100 kpc radius from the Galactic Plane they should be detectable, as ionizing photons from the Milky Way can easily reach this radius (Bland-Hawthorn & Maloney 1999a). This is shown through the H_α detections of the Magellanic Stream and other HVCs which have been detected at the 0.2 - 0.4 Rayleigh level (Weiner & Williams 1996; Tufte, Reynolds and Haffner 1998). If the population of compact HVCs shown here are truly extragalactic objects at Mpc distances they should not be detectable in H_α.

4 Conclusions

HIPASS provides a monumental amount of information on the distribution of neutral hydrogen in the southern sky. The interaction of the Magellanic Clouds with the Milky Way has created striking features, and the structure revealed here will offer important clues as to the exact mechanism responsible for their formation. The resolution and spatial sampling of HIPASS also allow the first thorough investigation of the population of compact HVCs and their possible extragalactic nature. The sightline to the Sculptor Group is an ideal place to begin this investigation. Further studies in progress of both the Magellanic and compact HVCs include sensitive H_α observations, higher velocity resolution HI observations, and optical and UV measurements to determine metallicities.

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[2]This prolate cloud of galaxies is actually part of an even larger structure known as the Coma-Sculptor cloud which stretches out to the Coma I cluster at 15 Mpc, in the direction of the Virgo cluster.

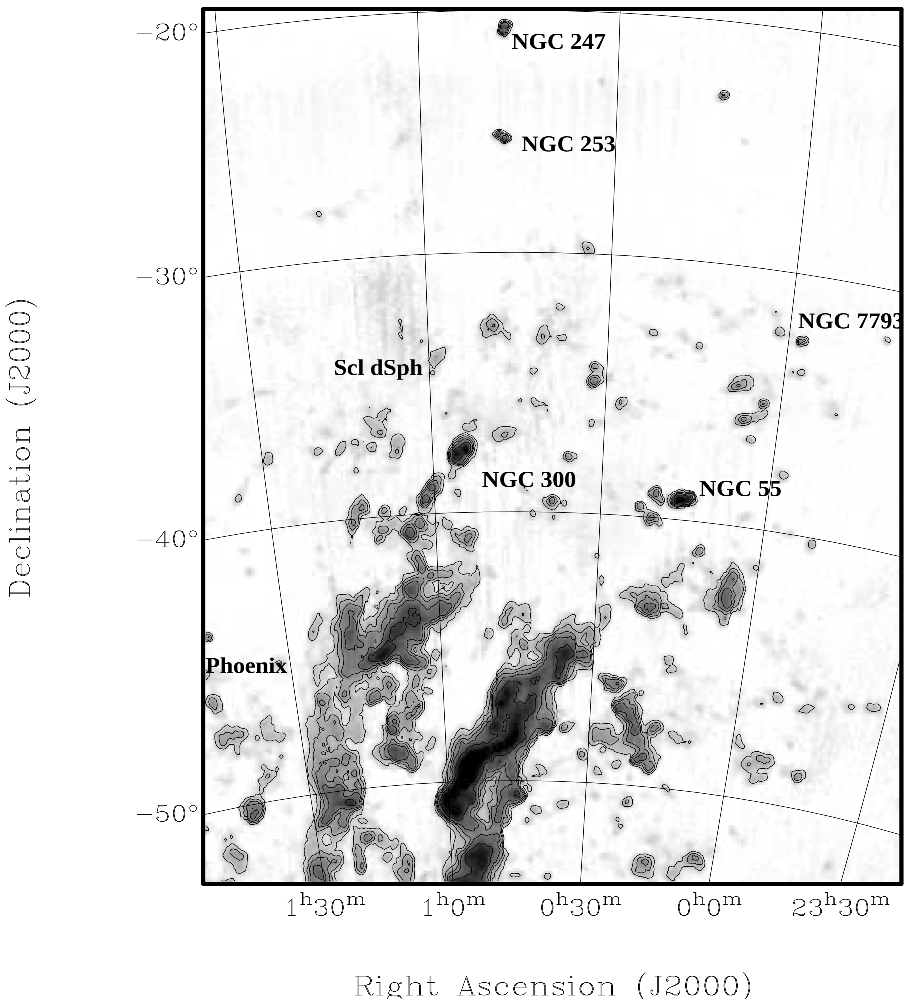

Figure 4: The Magellanic Stream meets the Sculptor Group. A peak HI intensity map including velocities from 73 - 450 km s^{-1}. Several galaxies of the Sculptor Group are labeled, as well as the positions of two nearby dwarf galaxies. The bifurcation of the Magellanic Stream and the clumps which follow the Stream are also depicted. The contours are 0.4, 0.8, 1.6, 3.2 and 6.4 K.

References

Bland-Hawthorn, J. & Maloney, P. 1999a, ApJ, 510, L33

Bland-Hawthorn, J. & Maloney, P. 1999b, in Stromlo Workshop on High-Velocity Clouds, ASP Conf. Series, Vol. 166, 212

Blitz, L. et al. 1999, 514, 818

Braun, R. & Burton, W.B. 1999, A&A, 341, 437

Gardiner L. & Noguchi, M. 1996, MNRAS, 278, 191

Grondin, L., Demers, S. & Kunkel, W.E. 1992, AJ, 103, 1234

Guhathakurta, P. & Reitzel, D.B. 1998, in Galactic Halos: A UC Santa Cruz Workshop, ed. Zaritsky, D., ASP Conf Series, Vol. 136

Jerjen, H. Freeman, K. & Binggeli, B. 1998, AJ, 116, 2873

Lu, L. et al 1998, AJ, 115, 162.

Mathewson, D.S. et al. , 1979, in The Large-scale Structure of the Galaxy, 556, Kluwer, Dordrecht

Mathewson, D.S., Cleary, M.N. & Murray, J.D. 1974, ApJ, 190, 291.

Moore, B. et al. 1999, ApJ, 524, L19

Putman, M.E. 2000, in *High-Velocity Clouds*, eds. van Woerden, H., Schwarz, U ., de Boer, K. & Wakker, B., Dordrecht: Kluwer (also astro-ph/9909080)

Putman, M.E. & Gibson, B.K. 1999, PASA, 16, 70

Putman, M.E., Gibson, B.K., Staveley-Smith, L. et al. 1998, Nature, 394, 752

Stocke, J.T., Shull, J.M., Penton, S., Donahue, M. & Carilli, C. 1995, 451, 24

Tufte, S.L., Reynolds, R.J. & Haffner, L.M. 1998, ApJ, 504, 773

Wakker, B.P. & van Woerden, H. 1997, ARA&A, 35, 21

Wayte, S.R. 1989, PASA, 8, 195

Weiner, B.J. & Williams, T.B. 1996, AJ, 111, 1156