Mapping the Hidden Universe: The Universe Behind the Milky Way – The Universe in HI
ASP Conference Series, Vol. 3×10^8*, 2000*
R. C. Kraan-Korteweg, P. A. Henning, and H. Andernach, eds.

The first complete & fully sampled HI survey of the tidal arms of the Magellanic System

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Abstract. The LMC, SMC, and the Milky Way are a spectacular set of interacting galaxies. The prominent tidal arms which protrude from the Magellanic Clouds extend for tens of kiloparsecs and cover a large part of the southern sky. These arms, and the Magellanic Clouds themselves, are therefore a highly suitable subject for the detailed investigation of an interacting galaxy system. We present the first results of the Parkes narrow-band HI survey of the tidal arms of the Magellanic System. It is the first fully sampled, spatially complete survey of this system. The data provide information on the column density distribution and the variation of the shape of the line-profiles over the extent of the tidal features. We present a cloud catalogue of the tidal features of the Magellanic System and discuss the distribution relative to the observational parameters longitude, latitude and radial velocity (v_{LSR} and v_{GSR}). We find a new stream-like feature that is most likely related to the Leading Arm. Detailed investigation reveals a number of clouds showing a cometary appearance in the position-velocity representation (so called head-tail structures). These head-tail structures are interpreted as clouds that are currently interacting with an ambient medium.

1. Introduction

Dieter (1965) surveyed the Galactic poles with the Harvard 60-ft antenna and noted several detections with high radial velocities near the southern Galactic pole which have no counterparts towards the northern pole. This was the first detection in HI 21-cm line emission of what we call today the "Magellanic Stream", but she did not identify it as a coherent structure. Further observations of the northern part of the Magellanic Stream, called the "south pole complex" at this time, were done by Kuilenburg (1972) and Wannier & Wrixon (1972). Mathewson, Cleary, & Murray (1974) observed the southern part of the Magellanic Stream using the 18-m Parkes telescope. They discovered the connection between the "south pole complex" and the Magellanic Clouds and called

it the "Magellanic Stream". Later on, several parts of the Magellanic Stream were observed with higher resolution and sensitivity.

We now know that, next to the Milky Way/Sagittarius dwarf interaction, the LMC, the SMC and the Milky Way form the nearest and certainly one of the most spectacular examples of a galaxy interaction. Individual tidal features that are traced by the HI 21cm line are: (1) the Magellanic Bridge (MB), a high column density gas stream ($N_{HI} \geq 1{\cdot}10^{21}\,cm^{-2}$ at 14' angular resolution) connecting the stellar bodies of the LMC and SMC (see Fig. 1); (2) the Magellanic Stream (MS), a coherent structure which starts from the Magellanic Clouds and trails over 100° passing the southern Galactic pole. The column density in the bright parts of the MS is up to $N_{HI} \approx 5{\cdot}10^{20}\,cm^{-2}$ at 14' angular resolution; and (3) the Leading Arm (LA, Putman et al. 1998) that was found to protrude from the Magellanic Bridge and the LMC along several clumpy filaments. The existence of the LA was anticipated in interaction models but not previously detected as a coherent tidal structure.

There are two major approaches to explain these features. The first is a pure gravitational model (e.g. Gardiner, Sawa, & Fujimoto 1994), and the second is a ram-pressure model (e.g. Moore & Davis 1994). The first model is able to explain the existence of a LA feature, while the ram-pressure model fits the morphology of the MS much better, but fails in explaining the LA. Recent models combine both approaches by introducing drag forces to the gravitational model (Gardiner 1999).

Recently, three large scale surveys in the southern sky have been made. The first is the Argentinian survey (HI Southern Sky Survey, HISSS), presented in these proceedings (Bajaja et al.). It is the counterpart to the Leiden/Dwingeloo survey and offers an angular resolution of 30' with grid-spacings of 30'. At a velocity resolution of $\Delta v = 1$ km s^{-1} the rms noise is $\sigma_{rms} \approx 0.07$ K. The second is the HIPASS survey, also presented in these proceedings. It offers a velocity resolution of $\Delta v = 18$ km s^{-1} and an rms noise of $\sigma_{rms} \approx 0.01$ K. The observing mode of the HIPASS is in-scan beam-switching. This mode filters out all large-scale structure of the Milky Way or the Magellanic System. The northern part of the Magellanic Stream is not (yet) complete (it is complete for $\delta_{2000} < +2°$). The third survey is presented in this paper. Our survey was performed using the narrow-band facility of the 64-m Parkes telescope. It is fully sampled and covers the complete Magellanic System offering a velocity resolution of $\Delta v = 0.8$ km s^{-1} and an rms noise of $\sigma_{rms} \approx 0.12$ K.

Our narrow-band HI survey of the Magellanic System comprises full sampling and high velocity resolution. Both are necessary for a detailed investigation of the physical condition of the gas in the Magellanic System and for improving the constraints which are needed to improve the tidal and ram-pressure interaction models.

2. Observations and Data Reduction

The observations were made within 10 days in Feb. and Nov. 1999, using the narrow-band multi-feed facility of the 64 m Parkes radio-telescope. At 21-cm the telescope has a FWHP beamwidth of 14.1 arcmin. The narrow-band system utilises the central 7 beams with two orthogonal polarizations and a bandwidth of

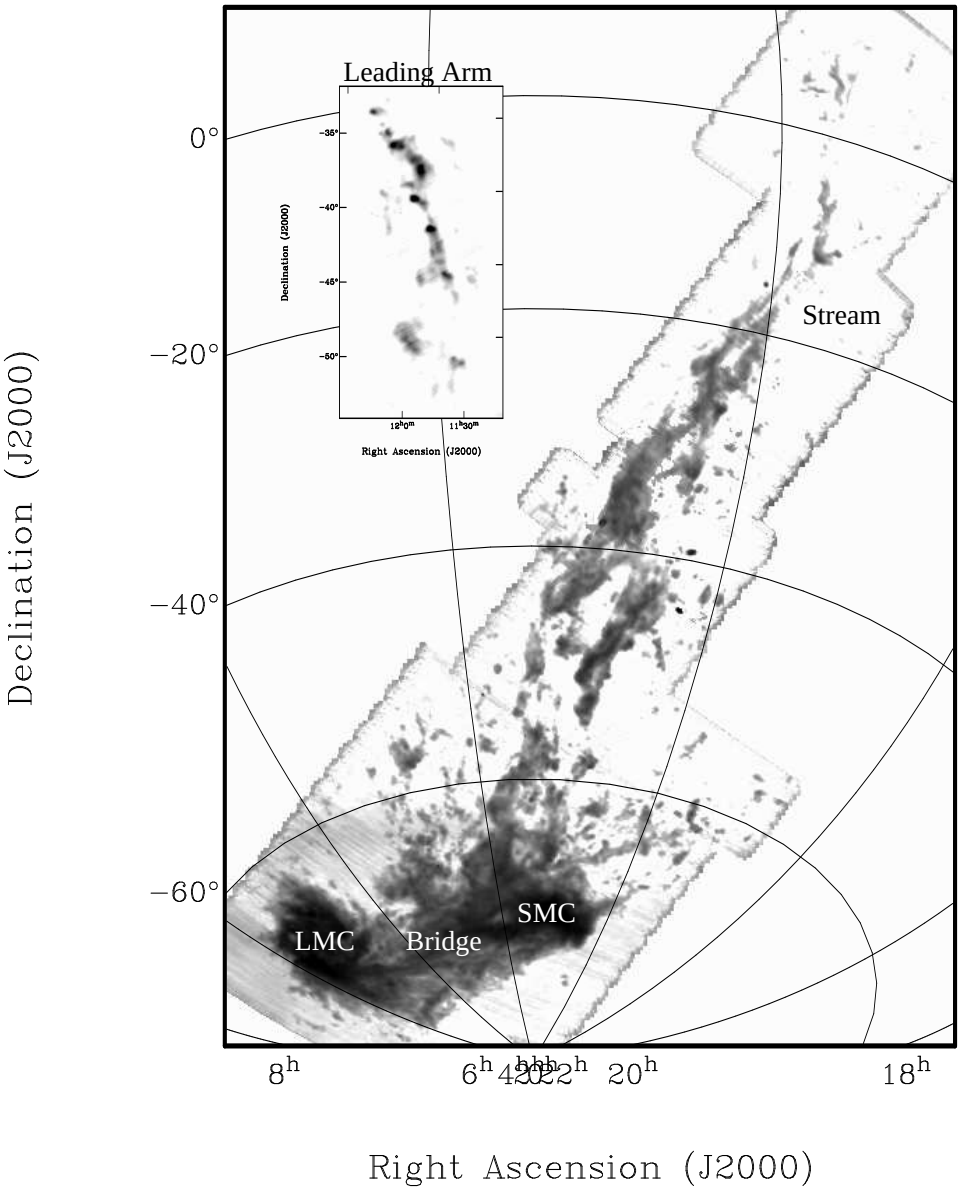

Figure 1. HI column density distribution of a part of the Parkes narrow-band HI Survey of the Magellanic System. The gray-scale has a logarithmic intensity scale. The LMC and the SMC are on the lower left part of the figure. The Magellanic Bridge is the high column density connection between both galaxies. The Magellanic Stream starts near to the Bridge and continues to the upper right corner of the figure. The inset shows the northern part of the Leading Arm feature. The gray-scale for the inset is linear.

8 MHz with a 2048 channel autocorrelator for each beam and polarization. This configuration allows in-band frequency-switching, i.e. the "reference-spectrum" also contains the spectral line. We used a frequency offset of 3.5 MHz. In-band frequency-switching doubles the integration time but reduces the usable bandwidth to 4.5 MHz (950 km s^{-1}). The HI data were observed in on-the-fly mode with a telescope scanning speed of 1° per minute. The integration time per spectrum was set to 5 seconds for both the "ON" and the "OFF"-spectra. The feed-angle was set to 19.1°. The scans were aligned to Magellanic coordinates. The offset between two adjacent scans was set to 0.56°. The rms noise in the final data-cubes is $\sigma_{\rm rms} \approx 0.12$ K at a velocity resolution of $\Delta v = 0.8$ km s^{-1}.

Because this survey is not a whole sky survey, we used the available parts of the HIPASS survey to define the regions of interest with emission from the Magellanic Clouds and their tidal arms.

The data presented here are preliminary as there remain calibration, baseline and interference problems to be removed. Nevertheless, the data are of high quality and considerably improve on previously published observations.

3. The Distribution of Magellanic Gas Clouds

In this section we discuss the distribution of the HI gas in the Magellanic System with respect to the observational parameters Magellanic longitude, latitude and radial velocity.

3.1. General distribution

Fig. 1 shows the column density distribution of the Magellanic Clouds, the Magellanic Bridge (MB), the Magellanic Stream (MS), and a part of the Leading Arm (LA). The velocity regime of the local gas (–25 km $s^{-1} \leq v_{\rm LSR} \leq 25$ km s^{-1}) was excluded to avoid confusion with the Galactic gas. In addition, in the northern regions of the Magellanic Stream ($\delta_{2000} > -15°$) the velocity interval –80 km $s^{-1} \leq v_{\rm LSR} \leq -25$ km s^{-1} was excluded to avoid confusion with the intermediate velocity clouds (IVCs) in this area. The IVCs are most likely associated with the Milky Way and not with the Magellanic System.

The Magellanic Bridge is a complex structure having high column densities (up to N(HI) $\approx 10^{21}\,{\rm cm}^{-2}$ at 14' angular resolution). The interface region between the Bridge and the Stream is very complex. There is a lot of gas moving at different velocities in different directions. The Stream itself appears to be much more confined. With the current resolution and sensitivity the premise of the Stream consisting of six main clumps does not hold any longer. Moreover, the main clumps contain several dense condensations that appear partly as unresolved point sources. The Stream is divided into two streams appearing like a twisted structure. This is possibly due to the motion of the LMC and the SMC relative to each other, producing a helix-like structure. The column density decreases from N(HI) $\approx 5{\cdot}10^{20}\,{\rm cm}^{-2}$ at the southern part of the stream to N(HI) $\approx 1{\cdot}10^{19}\,{\rm cm}^{-2}$ at the northern tip.

The inset in Fig.1 shows the northern part of the Leading Arm. The LA is a very narrow stream containing a number of dense condensations that are not resolved with the Parkes telescope. In contrast to the MS, the highest column

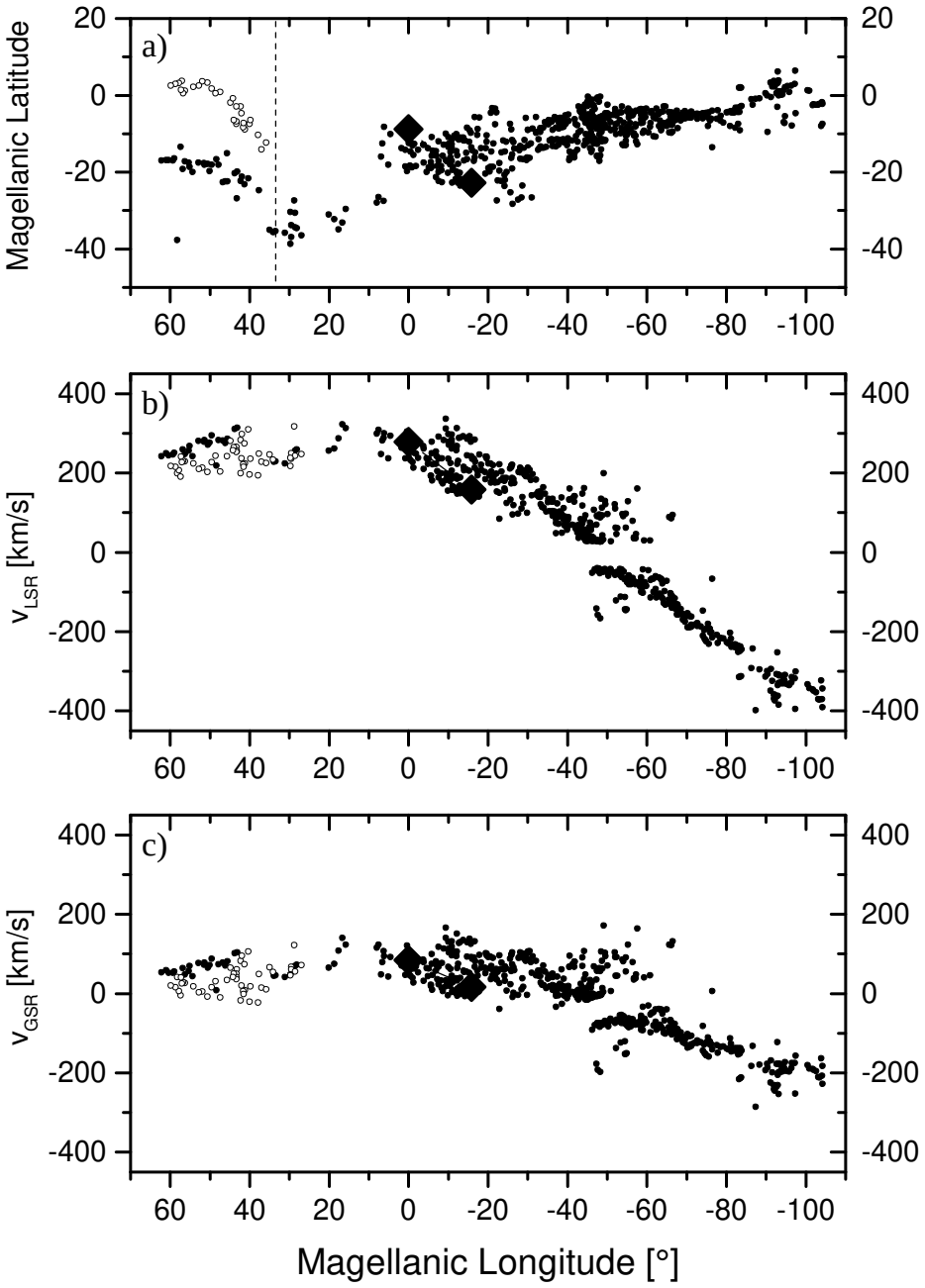

Figure 2. Each marker represents an entry in our cloud catalogue of the tidal arms of the Magellanic System. **a**: Magellanic latitude vs. Magellanic longitude. **b**: v_{LSR} vs. Mag. longitude. **c**: v_{GSR} vs. Mag. longitude. The Magellanic Clouds themself are marked by diamonds. The dashed line in the upper panel represents the location of the Galactic Plane. Filled circles are clouds that belong to the Magellanic Stream or the Leading Arm as defined by Putman et al. (1998). Open circles represent a newly discovered feature that is most likely related to the Leading Arm feature.

densities in the LA are not found near to the Magellanic Clouds but in the most distant condensations. They show up with the narrowest line-width. In the MS, the most distant clouds show up with the narrowest line-width, too.

3.2. The Catalogue

We have compiled a catalogue of clouds in the tidal arms of the Magellanic System. We exclude emission that is directly associated with the LMC or the SMC. In addition, we exclude emission features in the Magellanic Stream that have radial velocities similar to the local gas of our own Galaxy (–25 km $s^{-1} \leq v_{LSR} \leq 25$ km s^{-1}). In the region of the Leading Arm emission was catalogued if it shows up with radial velocities $v_{LSR} > 150$ km s^{-1}, because there are a number of HVCs at lower velocities in this area that are most likely not associated with the Magellanic System.

A proper representation of the Magellanic System in common coordinates is difficult, as both the southern poles of Equatorial and Galactic coordinates fall into the region of interest. Therefore, we use a "Magellanic" coordinate system[1] as follows: the line of zero latitude is defined as the line from Galactic longitude $l = 90°$ across the southern Galactic pole to $l = 270°$. Zero longitude is defined by the position of the LMC.

First results Fig. 2 shows the catalogued distribution of the Magellanic gas clouds with respect to the parameters Magellanic latitude (Fig. 2a), v_{LSR} (Fig. 2b), and v_{GSR} (Fig. 2c) as a function of Magellanic longitude. Each detected cloud (i.e. resolved clump) is represented by a marker. The Magellanic Clouds themself are marked by diamonds. The dashed line represents the Galactic Plane. The dots represent clouds that belong to the Magellanic Stream, the Magellanic Bridge or the Leading Arm as defined by Putman et al. (1998). The Magellanic Stream is connected to the Magellanic Bridge (see Fig. 1 and 2a). In the interface region between Bridge and Stream, the gas clouds have higher radial velocities than the gas located in the Bridge and the SMC. The radial velocity changes dramatically from $v_{LSR} \approx +250$ km s^{-1} near the Magellanic Bridge to $v_{LSR} \approx -400$ km s^{-1} at the northern tip. Fig. 2c shows that this velocity gradient is much lower in the Galactic-standard-of-rest frame, but still significant ($\Delta v \approx 3.5$ km s^{-1} deg^{-1}). While the Magellanic Stream shows up with a large velocity gradient, the velocity in the Leading Arm remains pretty constant in both v_{LSR} and v_{GSR}.

The highest dispersion of the observed radial velocities is observed near to the southern Galactic pole. There are a number of gas clouds having high velocities relative to the velocities of the Magellanic Stream in the region where the Magellanic Stream passes the line of sight to the Sculptor group (near Magellanic longitude –50°). There has been some debate as to whether the HI clouds with radial velocities comparable to the Sculptor galaxies are located within the Sculptor group, or whether they are part of the Magellanic Stream or "normal" Galactic high-velocity clouds (Mathewson et al. 1975).

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[1] The Magellanic coordinates used in this paper are *not* the coordinates defined by Wannier & Wrixon (1972).

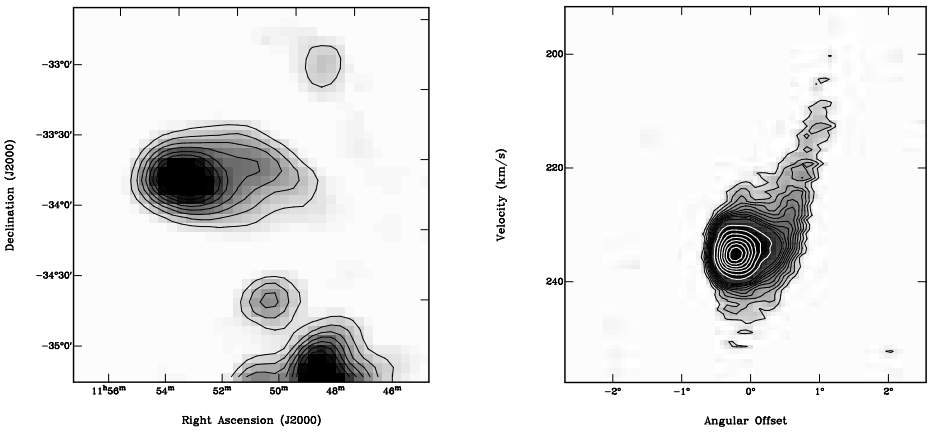

Figure 3. An example for an head-tail cloud. **right**: HI column density distribution. There is a clear peak at the left side of the cloud and a tail of lower column density to the right. **left**: a slice through the data-cube in direction of the column density gradient (v_{LSR} vs. position). Associated with the column density gradient is a significant velocity gradient.

The LA starts in the opposite direction of the MS. Near to the Galactic Plane it performs a 90° bend, possibly consistent with deflection by a rotating, extended disk of the Galaxy. We plan to examine this in more detail. Open circles in Fig.2 represent a newly discovered feature that is most likely related to the LA. It is also a stream-like structure but it is not as contiguous as the "old" Leading Arm feature. The radial velocities of this new feature fit very well to the LA defined by Putman et al. (1998)

4. Head-tail structures

The high velocity resolution ($\Delta v = 0.8$ km s^{-1}) of this HI survey allows a detailed analysis of the shape of individual line-profiles. Despite the fact that there are a lot of baseline-problems near to the Galactic Plane, a detailed analysis of individual clouds in the tidal features at high Galactic latitudes is possible. A number of clouds have simultaneously a velocity and a column density gradient. These clouds have a cometary appearance in the position-velocity representation and are called henceforward head-tail clouds (Brüns et al. 2000). Fig. 3 shows an example of a head-tail cloud. The left figure shows the column density distribution. There is a clear column density peak at the left side of the cloud and a tail of lower column density to the right. The right figure shows a slice through the data-cube along of the column density gradient. Associated with the column density gradient is a significant velocity gradient.

A simple interpretation of the head-tail clouds is that they are currently interacting with an ambient medium. In the context of this model, the head (i.e. the high column density core of the cloud) is the interacting cloud while the tails represent material that was stripped off from the clouds core. Recent

halo-models (e.g. Kalberla & Kerp 1998) predict very low densities in the outer halo ($n \approx 10^{-5}$ cm^{-3} at a distance of 50 kpc). The existence of head-tail clouds may be an indicator for an (at least locally) increased halo density. Nevertheless, more detailed analysis of the complete HI survey and theoretical calculations are necessary to reveal the nature of the head-tail clouds.

5. Summary and next steps

We have presented early results of the first spatially complete and fully sampled HI survey of the Magellanic System. We have also compiled a catalogue of tidal gas clouds in the Magellanic System. This catalogue may help to improve tidal models which attempt to reproduce the morphology of the Magellanic System in detail. We have discovered a new stream-like structure that is most likely a part of the Leading Arm. A future, detailed investigation of the small-scale structure within the tidal arms may address whether there is any interaction with the ambient medium.

Acknowledgments. The authors thank P.M.W. Kalberla, U. Mebold, R. Haynes, M. Putman, M. Filipovic and E. Muller for their help during the observations. C. Brüns thanks the *Deutsche Forschungsgemeinschaft, DFG* (project number ME 745/19) as well as the CSIRO for support.

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