The gaseous tidal arms of the Magellanic System

C. Brüns[1,2], J. Kerp[1], L. Staveley-Smith[2]

[1]Radioastronomisches Institut Univ. Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany
[2]Australia Telescope National Facility, CSIRO, PO Box 76, Epping NSW 1710, Australia

Abstract

The LMC, SMC, and the Milky Way are a spectacular set of interacting galaxies with tidal arms that protrude from the Magellanic Clouds covering a large part of the southern sky. The proximity of these arms make them a highly suitable object for a detailed investigation of an interacting galaxy system. We present early results of the Parkes narrow-band HI survey of the tidal arms of the Magellanic System. The data provide not only information on the column density distribution of the HI gas, but also on the variation of the shape of the line profiles over the extent of the tidal features with high velocity resolution ($\Delta v = 0.8$ km s^{-1}). We present a cloud catalogue of Magellanic gas clouds and discuss the distribution relative to the observational parameters position and radial velocity. The analysis of the data in the Leading Arm region shows that it is most likely interacting with the outer edge of the Galactic Disk.

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 now the "Magellanic Stream", but she did not identify these HI clouds as a coherent structure. Mathewson, Cleary & Murray (1974) discovered the connection between this "south pole complex" and the Magellanic Clouds and denoted it as the "Magellanic Stream".

We now know that the LMC, the SMC and the Milky Way form the nearest and certainly one of the most spectacular ensembles of interacting galaxies (next to the Milky Way/Sagittarius dwarf interaction). We can differentiate between individual tidal features that are traced by the HI 21-cm line: (1) the Magellanic Bridge (MB), a high column density gas stream 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 (see Fig. 1), 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 (see Fig. 2).

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

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 to derive tighter constraints which are needed to improve interaction models.

"Dwarf Galaxies and their Environment"; Bad Honnef, Germany, 23-27 January 2001; Eds. K.S. de Boer, R.-J.Dettmar, U. Klein; Shaker Verlag

2 Observations and Data Reduction

The HI observations were performed within 10 days in Feb. and Nov. 1999, using the narrow-band multi-feed facility of the 64-m Parkes radiotelescope. At 21-cm the telescope has a HPBW of 14.1 arcmin. The narrow-band system utilises the central 7 beams with two orthogonal polarizations and a bandwidth of 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 between both signals. In-band frequency-switching doubles the useful integration time but reduces the usable bandwidth. 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[1], as both the southern poles of Equatorial and Galactic coordinates fall into the region of interest. The Magellanic coordinate system is defined 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. The offset between two adjacent scans was set to 0.56°. The rms noise in the final data cubes is $\sigma_{\mathrm{rms}} \approx 0.12$ K at a velocity resolution of $\Delta v = 0.8$ km s^{-1}. We used the standard calibration sources S8 and S9 for the gain calibration. The data presented here are preliminary as there remain some baseline and interference problems to be removed. Nevertheless, the data are of high quality and considerably improvement on previously published observations. We used the HI Parkes All-Sky Survey (HIPASS, Staveley-Smith et al. 1996) to define the regions of interest with emission from the Magellanic Clouds and their tidal arms.

3 The Distribution of Magellanic Gas Clouds

In this section we discuss the distribution of the HI gas in the Magellanic System in the position-velocity space. The column density distribution of the Magellanic Clouds and the gas in the tidal features is presented in Figures 1 & 2. Figure 1 shows the column density distribution of the Magellanic Clouds, the Magellanic Bridge (MB) and the Magellanic Stream (MS). The velocity regime of the local gas (-25 km s^{-1} $\leq v_{\mathrm{LSR}} \leq$ 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} $\leq v_{\mathrm{LSR}} \leq -25$ 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 Stream. Figure 2 shows the column density distribution of the Leading Arm (LA). Velocities lower than 150 km s^{-1} were excluded to avoid confusion with gas belonging to the Milky Way. In addition, a catalogue of clouds in the tidal arms of the Magellanic System was compiled excluding emission from the LMC or SMC (see Fig. 3). We catalogued all clouds and condensations in the Magellanic System adopting the same restrictions for the velocities as in Figures 1 and 2. In the cases, where a coherent structure (for instance in the Magellanic Stream) contains a number of condensations, every condensation was catalogued separately. This preliminary catalogue counts more then 700 clouds spread over the extent of the Magellanic System.

The Magellanic Bridge is a complex structure having high column densities (up to $N(\mathrm{HI}) \approx 10^{21}\,\mathrm{cm}^{-2}$ at 14′ angular resolution). The highest column densities are found in a wing emerging from the SMC pointing towards the LMC. The velocity field is quite complex with multiple components in most spectra. The total HI mass of the MB assuming a distance of 50 kpc for all clouds in the Bridge is $M(\mathrm{HI}) \approx 1.1\times10^{8}\ \mathrm{M}_{\odot}$. The interface region between the Bridge and the Stream is

---

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

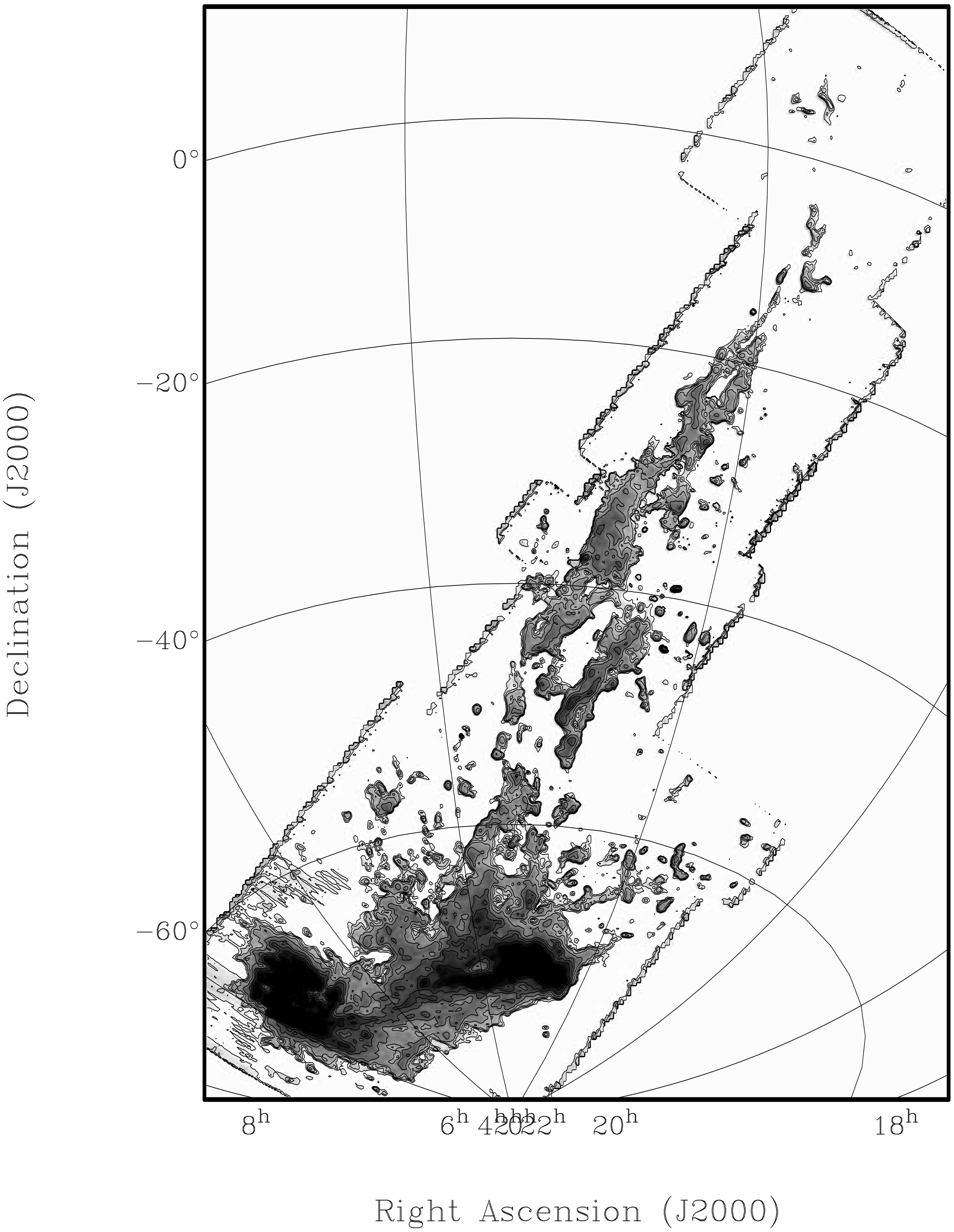

Figure 1: HI column density distribution of a part of the Parkes narrow-band HI Survey of the Magellanic System. The gray-scale has a logarithmic intensity scale. The LMC and the SMC are on the lower left part of the figure. The Magellanic Bridge is the high column density connection between both galaxies. The Magellanic Stream starts near the Bridge and continues to the upper right corner of the figure. The contour lines corresponds to column densities of 1, 2, 3, 5, 10, 20, 30, 50, 100, and $200\times10^{19}\mathrm{cm}^{-2}$. The region near to the LMC is affected by strong interferences.

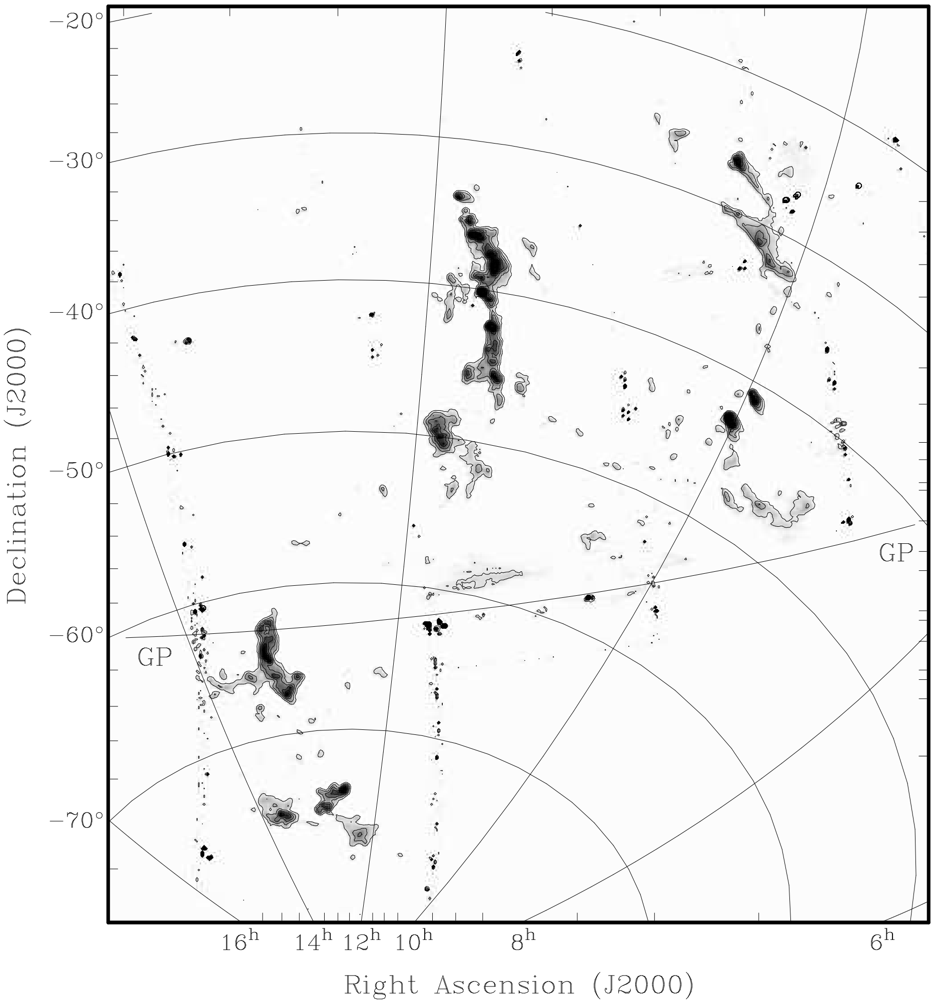

Figure 2: HI column density distribution of the Leading Arm integrated over the velocity interval 150 km s^{-1}≤ $v_{\rm LSR}$ ≤ 400 km s^{-1}. The gray-scale has a linear intensity scale. Contour lines represent column densities starting with $1{\times}10^{19}$cm^{-2} increasing in steps of $1{\times}10^{19}$cm^{-2}. The location of the Galactic Plane is indicated by a line marked with “GP”.

very complex – a number of filaments are pointing in different directions at different velocities.

The Magellanic Stream appears to be much more confined than the interface region. The data clearly shows that a simple subdivision in six clouds MSI to MSVI is not appropriate with the current resolution and sensitivity. Moreover, the main filaments contain several dense condensations that appear partly as unresolved sources. The column density decreases from N(HI) ≈ $5{\times}10^{20}$ cm^{-2} at the southern part of the MS to N(HI) ≈ 1×10^{19} cm^{-2} at the northern tip. The total HI mass of the MS is M(HI) ≈ $1.0{\times}10^{8}$ M$_\odot$ if all clouds of the MS are located at a distance of 50 kpc. The radial velocity changes dramatically from $v_{\rm LSR}$ ≈ +250 km s^{-1} near the MB to $v_{\rm LSR}$ ≈ –400 km s^{-1} at the northern tip. 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}). The Stream is divided into two filaments appearing like a twisted helix-like structure. These two filaments show also slightly different kinematics – this is well observable near Magellanic longitude –70°(Fig. 3). If the MS is produced by a single eruptive event, the matter would be stretched afterwards forming a long stream. On the other hand, if the MS is produced in a process of constant mass loss, the morphology should pattern the footprint of the motion of the LMC and the SMC relative to each other – a helix-like structure. The

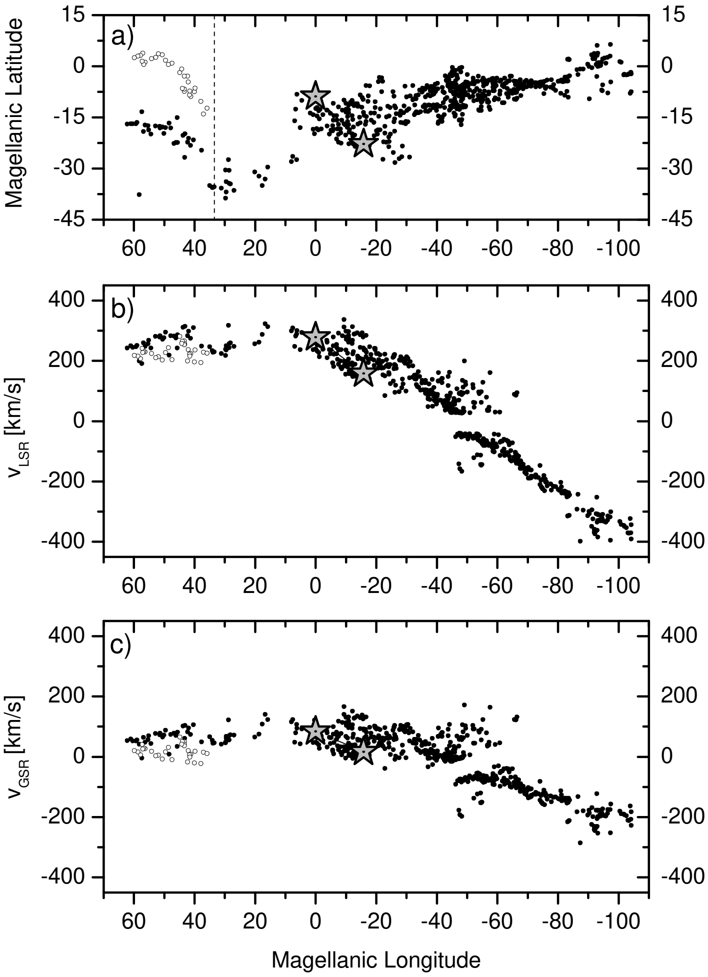

Figure 3: Each marker represents one entry in our catalogue of clouds in the tidal arms of the Magellanic System. **a**: Magellanic latitude vs. Magellanic longitude. **b**: $v_{\rm LSR}$ vs. Mag. longitude. **c**: $v_{\rm GSR}$ vs. Mag. longitude. The Magellanic Clouds themself are marked by stars. The gas in the Magellanic Stream near $v_{\rm LSR} = 0\ {\rm km\,s^{-1}}$ was excluded to avoid confusion with gas in the Galactic Plane (see text for more details). 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 second stream-like feature that is most likely related to the Leading Arm. Note that the Leading Arm changes its orientation where it crosses the line of sight of the Galactic Plane.

currently available data seem to indicate the latter process, but improved models are necessary to confirm this statement. The highest dispersion of the observed radial velocities is observed near the southern Galactic pole (near Magellanic Longitude $-50°$, Fig. 3). There are a number of gas clouds having high velocities relative to the velocities of the MS in the region where it passes the line of sight to the Sculptor group. 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 (e.g. Mathewson et al. 1975).

The Leading Arm is a clumpy structure containing a number of dense condensations that are not resolved with the Parkes telescope (Fig. 2). The LA starts in the opposite direction of the MS. In contrast to the MS, the column densities in the LA are not decreasing with distance from the Magellanic Clouds. The highest column density in the LA is $N({\rm HI}) \approx 3 \times 10^{20}\,{\rm cm^{-2}}$. The total HI mass of the LA (at a distance of 50 kpc) is $M({\rm HI}) \approx 1.9{\times}10^7\ {\rm M_\odot}$ – about five times lower than the HI mass of the MS or the MB. While the MS shows up with a large velocity gradient, the velocity in the LA remains almost constant. The radial velocity decreases from $v_{\rm LSR} \approx 300\ {\rm km\,s^{-1}}$ near the Magellanic Clouds to $v_{\rm LSR} \approx 220\ {\rm km\,s^{-1}}$ towards the Galactic Plane (GP). The LA stops abruptly where it crosses the GP and continues on the opposite side of the GP shifted in direction of lower Galactic longitude. The radial velocity starts at $v_{\rm LSR} \approx 300\ {\rm km\,s^{-1}}$ and decreases to $v_{\rm LSR} \approx 230\ {\rm km\,s^{-1}}$ towards the northern tip. There is a second clumpy filament (represented by open circles in Fig. 3) shifted approximately 20° in the direction of lower Galactic longitudes that is most likely also part of the LA. The radial velocity decreases from $v_{\mathrm{LSR}} \approx 280\ \mathrm{km\,s^{-1}}$ near the GP to $v_{\mathrm{LSR}} \approx 180\ \mathrm{km\,s^{-1}}$ towards the northern tip.

4 Is the Leading Arm interacting with the Galactic Plane?

In the previous section we have seen that the LA changes the orientation and the kinematics where it crosses the line of sight of the GP (see Figures 2 and 3). A number of HI clouds near the GP show an asymmetry in the column density distribution and asymmetric shapes of the line profiles – this kind of morphology is called a "head-tail structure" (Brüns et al. 2000). In addition, the clouds near the GP have a higher velocity dispersion than clouds far away from the GP. A possible explanation would be an interaction of the LA with the outer edge of the Galactic Disk. The radial velocity of the fastest (and therefore most distant) component of the Galactic Disk at this position is $v_{\mathrm{LSR}} = 122\ \mathrm{km\,s^{-1}}$ – this corresponds roughly to a distance of ≈ 30 kpc. Recent simulations predict a similar distance for the LA at this position (see Fig. 2 of Gardiner 1999). In this picture, the Galactic Disk transfers momentum to the clouds in the LA while passing the Disk leading to an acceleration towards lower Galactic longitudes. This very simple model is consistent with the data that are currently available. Follow-up observations at various wavelengths are planed to further investigate the question of an interaction between the LA and the outer Galactic Disk.

5 Summary and Conclusion

We presented early results of the Parkes narrow-band HI survey of the Magellanic System. Our survey has a much higher velocity resolution than HIPASS allowing a detailed analysis of the distribution of the gas with respect to velocity gradients, velocity dispersion and asymmetries in the line profiles. We catalogued about 700 clouds in the tidal features. In this early stage, only the parameters position and radial velocity are included. We will add the data for the column densities, the angular diameters, and the velocity dispersions to the final catalogue.

We discussed the distribution of the gas clouds in the Magellanic System. The Magellanic Stream shows a helix-like structure in the position-velocity space. This may indicate a continuous loss of HI gas along the orbit of the Magellanic Clouds. The morphology of the Leading Arm suggests that it is most likely interacting with the outer edge of the Galactic Disk. The Parkes narrow-band HI survey of the Magellanic System will further constrain the physical parameters of the tidal features. New simulations including gravitational interaction as well as drag forces are needed to nail down the details of the LMC/SMC/Milky Way interaction.

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.

References

Brüns, C., Kerp, J., Kalberla, P.M.W., & Mebold, U. 2000, A&A, 357, 120
Dieter, N.H. 1965, AJ, 70, 552
Gardiner, L.T. 1999, in ASP Conf. Ser. Vol. 166, Stromlo Workshop on High-Velocity Clouds, ed. B.K. Gibson & M.E. Putman, (San Francisco: ASP), p. 292
Gardiner, L.T., Sawa, T., & Fujimoto, M. 1994, MNRAS, 266, 567
Mathewson, D.S., Cleary, M.N., & Murray, J.D. 1974, ApJ, 190, 291
Mathewson, D.S., Cleary, M.N., & Murray, J.D. 1975, ApJ, 195, 97
Moore, B., & Davis, M. 1994, MNRAS, 270, 209
Putman, M.E., Gibson, B.K., Staveley-Smith, L., et al. 1998, Nature, 394, 752
Staveley-Smith, L., Wilson, W.E., Bird, T.S., et al. 1996, PASA, 13, 243