Neutral Hydrogen in the Magellanic System

Lister Staveley-Smith[1], Sungeun Kim[2], Mary Putman[2] and Snezana Stanimirović [3]

[1] Australia Telecope National Facility, CSIRO, PO Box 76, Epping, NSW 2121, Australia (email: lstavele@atnf.csiro.au)

[2] Mount Stromlo and Siding Spring Observatories, ANU, Weston Creek PO, Canberra, ACT 2611, Australia

[3] University of Western Sydney Nepean, P.O. Box 10, Kingswood, NSW 2747, Australia

Abstract

The structure and dynamics of the neutral hydrogen in the Magellanic System are reviewed. Instruments such as the Australia Telescope Compact Array and the Parkes multibeam receiver have recently provided a wealth of new observational data. We discuss this new data with respect to the nature of the interaction between the Galaxy and the Magellanic Clouds and the geometry and mass of the LMC and SMC. We also discuss other physical parameters related to the neutral ISM in the Clouds (e.g. temperature, pressure and topology) and note the important role that supernovae and stellar winds appear to play in the physics of the ISM.

1 Introduction

The Magellanic System consists of a pair of low-mass galaxies and their associated debris which orbit the Galaxy. The components of the system, as currently recognised and as shown in Figure 1, are:

- The Large Magellanic Cloud (LMC) – this has a diameter of about 8 kpc and a mass of 3.5×10^9 $M_\odot$ (Kim et al. 1998a). With an absolute blue magnitude of -17.9 mag (de Vaucouleurs et al. 1991), the LMC does not really count a dwarf galaxy as it is only 1.2 mag fainter than M33 (de Vaucouleurs et al. 1991; Huterer et al. 1995).

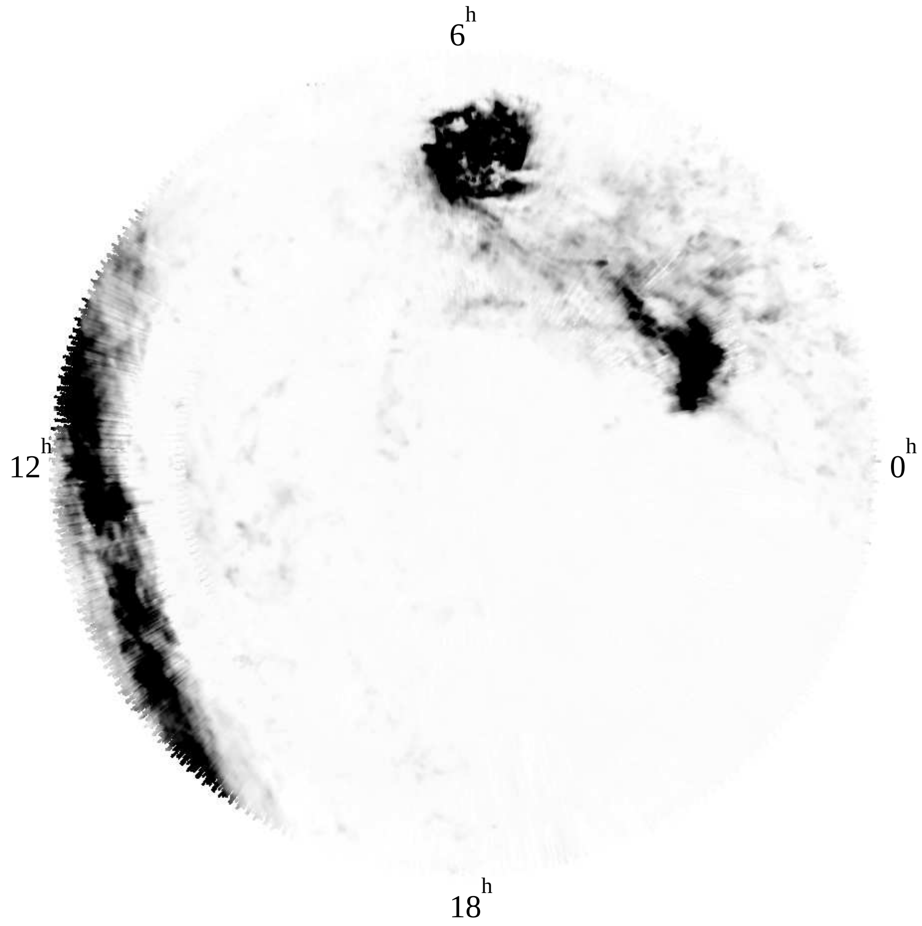

Figure 1: An HI peak-brightness-temperature image of the South Celestial Cap from the HIPASS survey (Putman et al. 1998). This 2400 deg^2 image shows a large-area view of the LMC (at the top), the SMC (to the right) and the Galaxy (to the left). The Magellanic Stream extends from the SMC outside of this image. The leading arm region lies between the Galactic Plane and the Clouds.

- The Small Magellanic Cloud (SMC) – a much less massive system which lies at a projected angular separation of 21° from the LMC. The true spatial separation is about 22 kpc from the LMC and about 60 kpc from the Galactic Centre. The SMC is a very gas-rich, low metallicity object with a disturbed morphology at most wavelengths.

- The Magellanic Bridge – a bridge, or Inter Cloud Region, which connects the LMC and SMC and consists mainly of gas (McGee & Newton 1981), and some stars (Irwin 1991). It appears to have been drawn out by a recent interaction between the two Clouds (e.g. Gardiner et al. 1994).

- The Magellanic Stream – a thin arc of neutral hydrogen which extends behind the LMC and SMC for about 100° (Mathewson et al. 1974). Apart from some faint Hα emission (Weiner & Williams 1996), no optical counterpart has been seen so far.

Why are the Magellanic Clouds and their debris important to us? Firstly, next to the recently discovered Sagittarius dwarf spheroidal galaxy (Ibata et al. 1994), the Clouds are the nearest satellites of the Galaxy. But, unlike the Sagittarius dwarf, the Clouds lie in a direction unobstructed by extinction and confusion from the Milky Way. The typical extinction towards the LMC is $E_{B-V} = 0.13$ mag (Massey et al. 1995). The aspect of the Clouds is also favourable for most purposes – they are not edge-on. Secondly, compared with other galaxies (and objects within our own Galaxy), the distance to the Clouds is relatively well known. A variety of methods, including geometric methods based on SN1987A, have been reviewed by Westerlund (1997) who adopts distance moduli of 18.45 ± 0.10 for the LMC, and 18.90 ± 0.10 for the SMC, corresponding to linear distances of 49 kpc and 60 kpc, respectively. Finally, both Clouds are 'young' objects in that they each have a rich interstellar medium (ISM) and have reasonably high star-formation rates (e.g. Filipović et al. 1998). As such, they allow a detailed study of the relationship between stars and the ISM from which they form.

2 Origin and Large-Scale Structure

The Magellanic Clouds are widely believed to have formed in close proximity to the Galaxy, and to have always been satellites. However, eccentric orbits (see Shuter 1992) are not ruled out by existing observations of proper motion (e.g. Kroupa & Bastian 1997). The discovery of the Magellanic Stream (Mathewson et al. 1974) lead to a number of models which attempted to explain the large-scale distribution of gas and the origin of the Clouds. The *tidal* model (Gardiner & Noguchi 1996) is the most natural explanation but has received criticism because of the lack of stars in the Stream, and the lack of a leading Stream. This criticism resulted in the development of *ram-pressure* models (e.g. Moore & Davis 1994) which attempt to explain the Stream by interaction of the Clouds with gas in the halo and the extended disk of the Galaxy. Some models (e.g. Heller & Rohlfs 1994) combine aspects of both tidal and ram-pressure models. Support for ram pressure comes from features in the Stream and the LMC which are morphologically reminiscent of bow shocks.

Recent observations have focussed attention back onto the region *leading* the Magellanic Clouds at Galactic coordinates $\ell \approx 300°$ and $b \approx -30°$ to $+25°$. This is the location of several high velocity clouds which have often been rejected as members of a leading arm (e.g. Moore & Davis 1994), despite their positions being in reasonable agreement with tidal models (Gardiner & Noguchi 1996). Firstly, an absorption study of HVC 287.5+22.5+240 by Lu et al. (1998) gives an abundance S/H $= 0.25 \pm 0.07$ times solar, suggestive of a Magellanic Cloud origin. Secondly, and more importantly, new observations from the HI Parkes All-Sky Survey (HIPASS) by Putman et al. (1998) show a much more detailed view of the HI in this region. A panoramic image from these observations is shown Figure 1 which is a peak-brightness-temperature image in the velocity range 82 to 400 km s^{-1}. This image shows emission from the Magellanic Clouds, the region encompassing the leading HVC arm, and the Galaxy. Putman et al. use the data to show that, at certain velocities, there is strong connectivity between the Magellanic Clouds and the leading features. This conclusively demonstrates their Magellanic Cloud origin, and strongly supports the tidal model for the creation of the Stream.

3 Morphology and Dynamics

Table 1: HI-derived properties of the LMC and SMC. Distances of 50 and 60 kpc are assumed, respectively.

Property	Value	Reference
	Large Magellanic Cloud	
HI mass, M_{HI}	$3.1 \times 10^8 M_\odot$	1
HI mass-to-light ratio, M_{HI}/L_B	0.14 $M_\odot/L_\odot$	1,2
HI Size (5×10^{20} cm^{-2})	7.3×6.8 kpc	1,3
Rotation Velocity	67 km s^{-1} ($i = 33°$)	3
Total mass, M_T (< 4 kpc)	$3.5 \times 10^9 M_\odot$	3
	Small Magellanic Cloud	
HI mass, M_{HI}	$4.2 \times 10^8 M_\odot$	4
HI mass-to-light ratio, M_{HI}/L_B	0.61 $M_\odot/L_\odot$	2,4
HI Size (1.5×10^{21} cm^{-2})	5.2×3.4 kpc	5
Rotation Velocity	~ 36 km s^{-1}	6
Total mass, M_T (< 2.6 kpc)	$\sim 1.5 \times 10^9 M_\odot$	6

References: (1) Luks & Rohlfs (1992); (2) de Vaucouleurs et al. (1991); (3) Kim et al. (1998a); (4) Stanimirović et al. (1988); (5) this paper; (6) Hindman (1967).

Detailed HI observations of the LMC and SMC were made in the 1960's in two studies by McGee & Milton (1966) and Hindman (1967). These studies were extremely important in characterising the overall morphology and dynamics of the Clouds. McGee & Milton were able to delineate an HI spiral pattern and make estimates of the HI and total mass of the LMC. Hindman was able to derive estimates for the HI and total mass of the SMC, as well as recognise the important dynamical influence of expanding supershells. The overall HI properties of the

LMC and SMC are listed in Table 1.

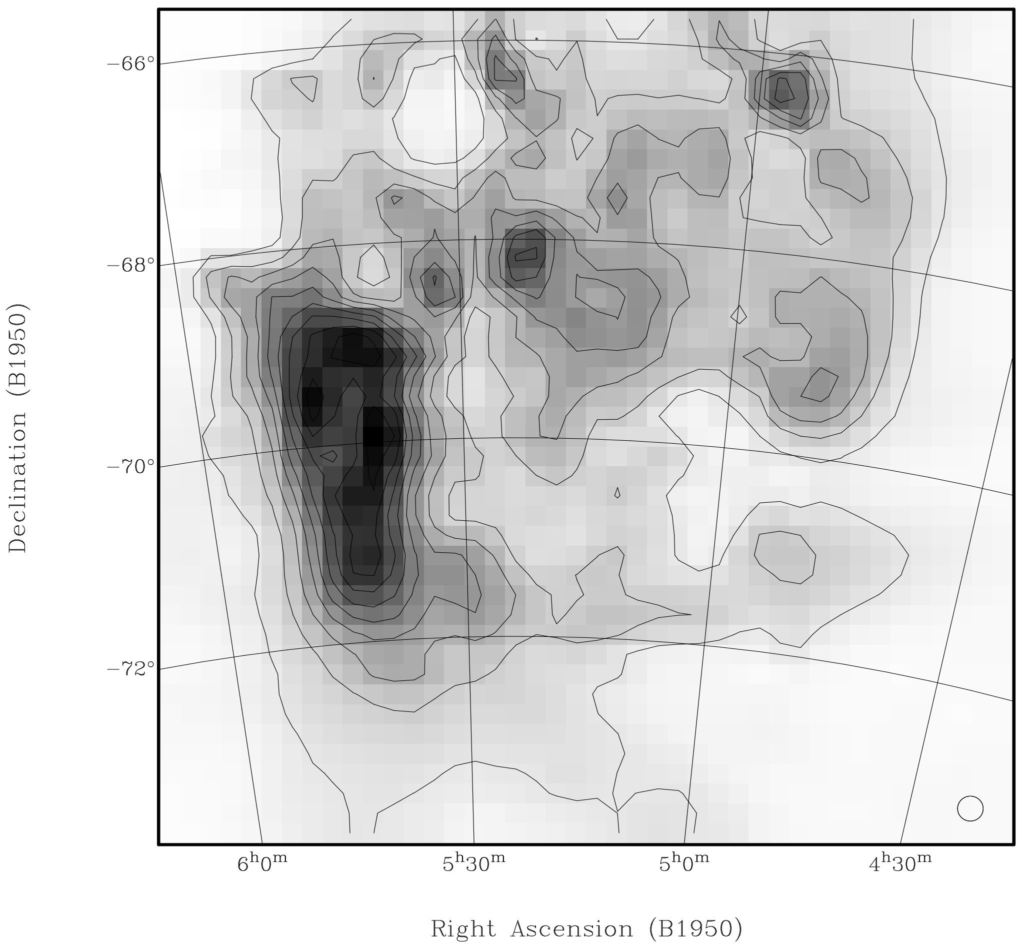

Figure 2: An HI column density image, with contours overlayed, of the LMC from Luks & Rohlfs (1992). The contour interval is 3.6×10^{20} atoms cm^{-2}. The northern part of the LMC was not fully surveyed in these observations.

More recent single-dish HI observations of the Clouds have been conducted by McGee & Newton (1981), Bajaja & Loiseau (1982), Rohlfs et al. (1984), Mathewson et al. (1988) and Luks & Rohlfs (1992). An HI column density image of the Luks & Rohlfs survey of the LMC is shown in Figure 2. This survey shows the high column densities near the Giant Molecular Cloud (GMC) region (south of 30 Doradus) at RA 05^h40^s Dec $-70°00'$ (B1950) and the puncturing of the HI disk by 'holes' such as LMC 4 (Dopita et al. 1985) at RA 05^h31^s Dec $-66°43'$ (B1950). The steep gradient to the west of the GMC/30 Dor region has been cited as evidence for a shock due to interaction with material in the Galactic halo (Mathewson & Ford 1984, de Boer et al. 1998).

With the advent of the Australia Telescope Compact Array (ATCA), much

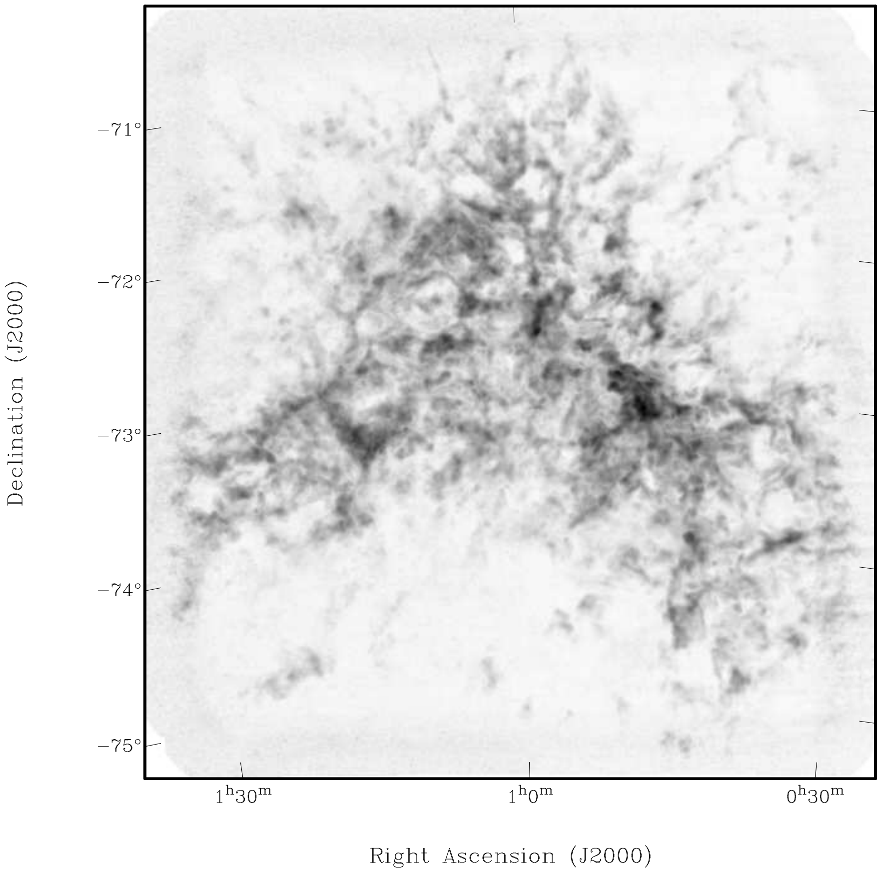

Figure 3: An HI peak-brightness-temperature image of the SMC from the ATCA (Staveley-Smith et al. 1997). The maximum observed brightness temperature is 126 K.

higher spatial resolution HI observations have been possible. The mosaicing capability of the ATCA has, in particular, made possible large-area surveys of the Clouds. For the SMC, Staveley-Smith et al. (1997) describe the results from a 320-field mosaic using the 375-m array with a spatial resolution of 98″. These results show the SMC to have a very chaotic nature, dominated by filaments, shells, and arc-like features. The morphology, shown in Figure 3, is reminiscent of the wind-blown features seen in interferometric studies of other dwarf galaxies such as Holmberg II (Puche et al. 1992). Detailed studies of the velocity field of the SMC lead to the identification of 501 expanding shells in the SMC, ranging in radius from 12 to 482 pc.

The presence of such an extensive population of expanding shells appears to imply that much of the well-known line-splitting in the SMC is due to this phenomenon. The mean dynamical shell age of 5.4 Myr, an order of magnitude lower than for Holmberg II, and the low intrinsic age dispersion of 2 Myr are puzzling. However, Oey & Clarke (1997) were able to show that the shell size distribution

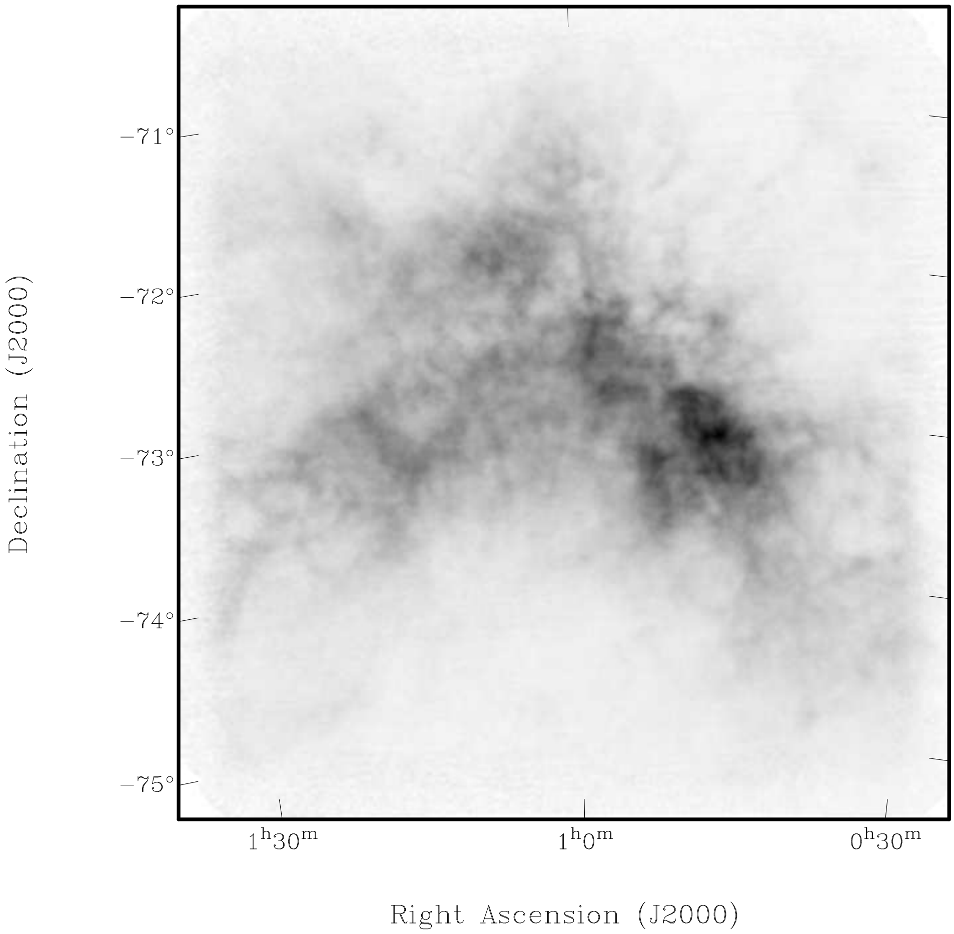

Figure 4: The HI column density image of the SMC (Stanimirović et al. 1998). The peak column density is 1.43×10^{22} atoms cm^{-2}.

was in fact consistent with a conventional wind-blown and supernova-driven origin using a reasonable HII region luminosity function, and assuming a constant star-formation rate.

Stanimirović et al. (1998) have been able to make a more complete HI study of the SMC by combining new Parkes observations with the ATCA mosaic. They were able to identify new and larger shells missed by the ATCA-only study and were, importantly, able to begin a quantitative study of the overall HI structure of the SMC. Their column-density image is shown in Figure 4, from which they derive an HI mass, after correction for self-absorption, of 4.2×10^{8} $M_{\odot}$ (Table 1).

Following the studies of Galactic structure by Crovisier & Dickey (1983), Stanimirović et al. (1998) were able to calculate the power spectrum of emission fluctuations for the SMC. Despite extending over a much larger size range than possible

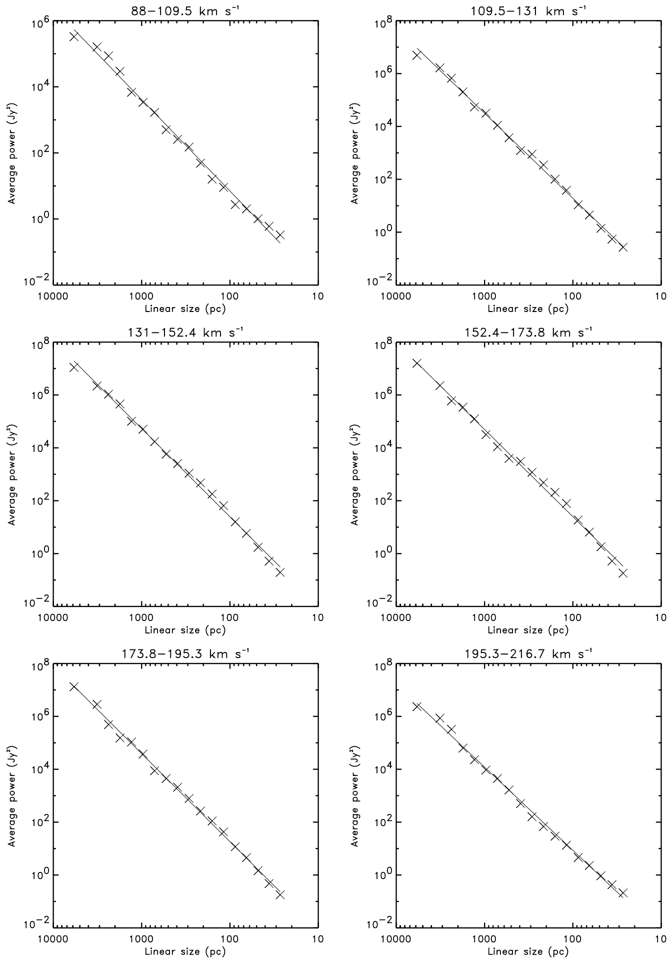

Figure 5: The power spectrum of HI emission fluctuations in the SMC in six consecutive heliocentric velocity ranges. The average slope ($P(k) \propto k^{\gamma}$) is $\gamma = -3.0$ (Stanimirović et al. 1998).

in the Galaxy, Figure 5 shows that the spectrum remains very close to a power law with a slope $\gamma = -3.0$, in agreement with Galactic values (Green 1993). This leads to the immediate conclusion that there is no preferred HI cloud size in the SMC, a result which has some importance for the nature of the ISM (see below).

One of the first ATCA HI studies of the LMC was a small mosaic (3 fields) of the region surrounding 30 Doradus and incorporating SN1987A and the GMC region (Mebold et al. 1997). This study revealed surprisingly low temperatures for the diffuse gas in this region, and is currently being used (Düsterberg 1998) to study the interaction between HII regions and the ISM. A survey of the complete LMC, requiring a mosaic of 1344 pointings of the ATCA, was conducted between 1994 and 1996. Results from this survey are described by Kim et al. (1998a) who, as with the SMC, find a structure dominated by filaments, shells

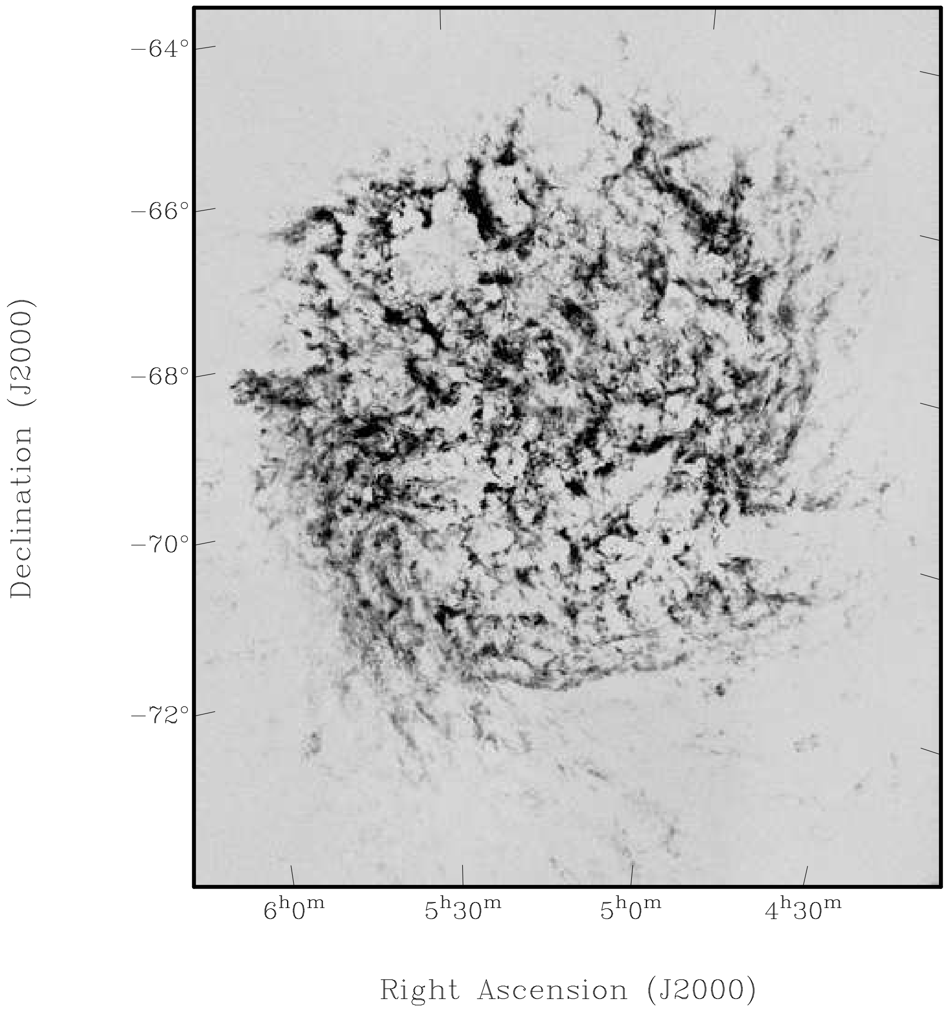

Figure 6: . An HI peak-brightness-temperature image of the LMC from the ATCA (Kim et al. 1998a). The maximum brightness temperature is 109 K.

and holes. However, on the largest scales Kim et al. find the HI disk of the LMC to be remarkably symmetric and to have a well-organised rotational velocity field. The peak-brightness-temperature image from Kim et al. is shown in Figure 6, and provides a stark contrast to the low-resolution image of Figure 2.

The morphology of the LMC shown in Figure 6 was used by Kim et al. (1998a) to derive an inclination of $22° \pm 6°$. Unfortunately, this surprisingly face-on value was not supported by a kinematic study. In Table 1, we therefore choose the somewhat more conventional value of 33°. Westerlund (1997) gives a summary of the various techniques that have been applied to the determination of the LMC's inclination.

Interestingly, Figure 6 reveals less of a spiral pattern in HI than the single dish study of McGee & Milton (1966). This shows that density waves (Dixon & Ford 1972) or the asymmetric bar of the LMC (Dottori et al. 1996) may not play a significant role in organizing the large-scale structure of the ISM. A fuller analysis of the large-scale structure of the LMC using a proper combination of ATCA and single-dish data is clearly required. Nevertheless, a number of more delicate spiral features are definitely seen on the periphery of the HI disk in Figure 6. Kim et al. (1998a) show that these features are trailing and have an average age of $\sim$ 90 Myr. They are probably due to differential rotation within coherent structures such as the large HI shells.

4 The Interstellar Medium

High resolution HI observations allow us to probe the temperature, pressure and topology of the ISM, and thus provide crucial information on physical conditions. The Magellanic Clouds have a number of features, such as low metallicity, gas-richness and high UV radiation field which may make the physical conditions different from the Galaxy.

Outside the optical confines of the LMC and SMC, HI appears to be in the warm phase. Mebold et al. (1991) detected no 21 cm absorption towards continuum sources behind the Magellanic Stream. Within the optical confines of the LMC, Dickey et al. (1994) find absorption against 19 out of a sample of 30 compact continuum sources. From this, they establish a mean temperature for the cool atomic clouds of 40 K, compared to 60 K in the Galaxy. However, they point out that cool gas phase is most abundant near the 30 Dor/GMC complex where densities are high. This result was confirmed by Mebold et al. (1997) who, for the first time, were able to use high resolution emission and absorption data to measure spin temperature.

The low temperatures measured in the LMC appear to be due to strong cooling and shielding near star-forming regions. Dickey et al. (1994) found that the fraction of cool gas in the LMC ($\sim$ 35%) is higher than for M33 and the Galaxy ($\sim$ 20%), and about the same as that for M31, a much earlier-type galaxy than the LMC. However, the high abundance of cool gas does not apply to CO, normally a good tracer of cool molecular clouds. In both Clouds, CO appears to be much less abundant than in our own Galaxy (Israel et al. 1993). Poglitsch et al. (1995) explain the low CO abundance and the coexistence of CO (1-0) and [CII] emission around 30 Dor as due to an open, fragmented structure to the ISM which allows UV radiation to penetrate deep into molecular clouds in places.

An open, fractal structure has also been proposed for molecular clouds in the Galaxy (Elmegreen & Falgarone 1996). Does such a structure extend to the warm phase of the neutral ISM as traced by maps of HI emission in the Clouds? The power-law nature of the HI power spectrum (Figure 5) gives some support to this, leading Stanimirović et al. (1998) to investigate some of the consequences of a fractal ISM. One of the most interesting results is that the volume-filling factor of neutral hydrogen could be quite low.

If the so-called Intercloud Medium (ICM) has a correspondingly high filling factor, what are its physical properties? Conventionally, this tenuous component of the ISM is assumed to be hot ($\sim 10^6$ K) so that it remains in pressure balance with the warm and cool components. However, given that interstellar turbulence may play a role in creating fractal-like structures, it is possible that the ICM may be relatively cool also.

Evidence for turbulent motions in the disk of the LMC has recently been examined by Kim et al. (1998a). They find that the distribution of cloud peculiar velocities closely follows an exponential function, implying that they may derive their velocity dispersion from a stochastic process (e.g. Miesch & Scalo 1995). Energy input from stellar winds and supernovae appears to be an important component in 'stirring' the ISM in both Clouds. Kim et al. (1998b) describe a multi-wavelength investigation of the N44 superbubble in the LMC which illustrates this phenomenon. However, the origin of some of the larger-scale features is less clear and it may be that gravitational shear and instability play a role. These phenomena are enhanced in galaxies with cold, gas-rich disks especially where, as appears to be the case for both Clouds, there is no stabilising dark halo present.

5 Future Studies

The Magellanic System has been under investigation for many years, yet interesting discoveries relating to questions as fundamental as their origin are still being made. Many questions remain to be answered. Further proper motion studies and an extended coverage of the HIPASS survey will answer some questions related to the history of the orbit of the Clouds. The detection of stars associated with the stream (if they exist) and the measurement of their velocities and ages will answer others. One of the most fruitful areas is likely to be the study of star-formation and the ISM in the Clouds. Large-area surveys at many new wavebands have being conducted recently, and these may help us understand the chemistry, ionization and energy balance in the ISM. Hopefully, this area will also receive theoretical study. Although they are complex systems, the Clouds are almost unique in allowing us to simultaneously interpret large-scale and small-scale phenomena, both of which are necessary for the complete study of galaxy evolution.

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