A new look at the large-scale H I structure of the Large Magellanic Cloud

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ABSTRACT

We present a Parkes multibeam H I survey of the Large Magellanic Cloud (LMC). This survey, which is sensitive to spatial structure in the range 200 pc to 10 kpc, complements the Australia Telescope Compact survey, which is sensitive to structure in the range 15–500 pc. With an rms column density sensitivity of $8 \times 10^{16}$ cm$^{-2}$ for narrow lines and $4 \times 10^{17}$ cm$^{-2}$ for typical linewidths of 40 km s$^{-1}$, emission is found to be extensive well beyond the main body of the LMC. Arm-like features extend from the LMC to join the Magellanic Bridge and the Leading Arm, a forward counterpart to the Magellanic Stream. These features, whilst not as dramatic as those in the Small Magellanic Cloud, appear to have a common origin in the Galactic tidal field, in agreement with recent 2MASS and DENIS results for the stellar population. The diffuse gas that surrounds the LMC, particularly at PAs of $90^\circ$–$330^\circ$, appears to be loosely associated with tidal features, but loosening by the ram pressure of tenuous Galactic halo gas against the outer parts of the LMC cannot be discounted. High-velocity clouds, which lie between the Galaxy and the LMC in velocity and that appear in the ultraviolet spectra of some LMC stars, are found to be associated with the LMC if their heliocentric velocity exceeds approximately $+100$ km s$^{-1}$. They are possibly the product of energetic outflows from the LMC disc. The HI mass of the LMC is found to be $(4.8 \pm 0.2) \times 10^8 M_\odot$ (for an assumed distance of 50 kpc), substantially more than previous recent measurements.

Key words: surveys – Magellanic Clouds – radio lines: galaxies.

1 INTRODUCTION

The Large Magellanic Cloud (LMC) plays a key role in our understanding of diverse areas in astronomy, including the extragalactic distance scale that uses the LMC as a zero-point (Feast 1999; Gibson 2000), the formation of star clusters (Johnson et al. 1999) and H II regions (Oey 1996), molecular cloud astrophysics (Johansson et al. 1994), and for providing background stars with which to study possible microlenses in the Galactic halo (Alcock et al. 2000). With this in mind, Kim et al. (1998a) surveyed the LMC in H I at high spatial resolution with the Australia Telescope Compact Array (ATCA). This data has since served to help study the interaction between star-forming regions and the interstellar medium at small scales (e.g. Kim et al. 1998b, 1999; Points et al. 2000, Olsen, Kim & Buss 2001.) However, its use for large-scale studies (with notable exceptions, e.g. the study of the LMC disc and halo dynamics by Alves & Nelson 2000) is largely confined to morphological studies and comparisons (e.g. Wada, Spaans & Kim 2000). The reason for this is that, being an interferometer, the ATCA is insensitive to structure on an angular size scale larger than $\lambda/B$, where the shortest baseline is $B = 30$ m ($\sim 20$ m when the finite antenna size is taken into consideration and when the sky is Nyquist-sampled by the antenna primary beams). This corresponds to $\sim 0.5^\circ$ or approximately 0.4 kpc at the distance of the LMC (assumed here to be 50 kpc).

The missing large-scale structure means that H I column densities are difficult to derive. For example, accurate optical depths for X-ray photoelectric absorption cannot be obtained. It also makes it difficult to compare the H I structure of large shells against competing formation models, e.g. stellar winds (Dopita, Mathewson & Ford 1985), high-velocity cloud (HVC) collisions (Braun 1996) and gamma-ray bursts (Efremov, Ehlerová & Palouš 1999). Similarly, the outer tidal structure of the LMC cannot be compared with the recent stellar results from 2MASS and DENIS (van der Marel 2001).

Observations sensitive to large spatial scales may be taken from the autocorrelations from the individual antennas of an interferometer. However, these data are often not calibrated in a suitable way. Moreover, for a homogeneous interferometer such as the ATCA, there exists a serious gap in the uv-plane between the autocorrelation and cross-correlation data. It is usually more useful to collect data from a large single-dish antenna such as the Parkes...

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telescope which, with a diameter of 64 m, is much larger than the smallest ATCA baseline. There are several excellent studies using Parkes of H I in the LMC, however, none is particularly suitable for the present purpose. Needless to say, the older studies (McGee & Milton 1966) are not available digitally. The observations of Luks & Rohlfis (1992) do not cover a sufficient spatial area (they cut-off the LMC disc north of Dec. ∼66°) and are not Nyquist-sampled. The HIPASS observations (Putman et al. 2003) have insufficient velocity resolution and, since HIPASS was designed to detect compact extragalactic objects (Barnes et al. 2001), also impose a high-pass filter on the sky.

The task of mapping a large area such as the LMC at the Nyquist rate (5.7 arcmin for Parkes at λ = 21 cm) is not straightforward as ∼10⁷ pointings are required. Fortunately, the advent of a 21-cm multibeam receiver at Parkes (Staveley-Smith et al. 1996) makes the task easier, so observations were undertaken following the installation of new narrow-band filters in late 1998. We describe the Parkes observations in Section 1 and discuss the general morphology, tidal features and spatially integrated properties in Section 2. We also compare our results with previous work. In Section 3, we discuss halo gas in the LMC, particularly in the sightline from our Galaxy. In Section 4, we look again at the largest H I holes and associated high-velocity gas. Finally, in Section 5, we use the Galactic part of the velocity range to rediscuss foreground absorption. The combination of the existing data with the ATCA data is separately described in Kim et al. (2003), and some early results from the combined data set are discussed by Elmegreen, Kim & Staveley-Smith (2001) and Padoan et al. (2001).

2 OBSERVATIONS

Observations were taken with the inner seven beams of the Parkes 21-cm multibeam receiver (Staveley-Smith et al. 1996) on 1998 December 13–17. The telescope was scanned across the LMC in orthogonal great circles aligned approximately east–west and north–south. The receiver was continuously rotated such that the rotation angle was always at 19.1° to the scan trajectory, the appropriate angle in a hexagonal geometry for ensuring uniform spatial sampling of the sky. The area covered was 13 × 14 deg² in RA and Dec., respectively, and centred on RA 05 h 20m, Dec. −68°44′ (J2000). This corresponds to 8–9 disc scalelengths in the optical or infrared (Bothun & Thompson 1988; van der Marel 2001). In a single scan, the spacing between adjacent tracks is 9.5 arcmin, which is smaller than the mean FWHP beamwidth of 14.1 arcmin, but greater than the final track spacing of 1.6 arcmin. In total, 12 RA scans and 11 × 6 Dec. scans were made. Seven scans were dropped or edited out owing to drive problems, leaving a total of 131 scans consisting of a total of 29 h of on-source integration on each of seven beams. The average integration time per beam area is 360 s (both polarizations).

The scan rate of the telescope was 1.0 deg min⁻¹ and the correlator was read every 5 s. Therefore, the beam was slightly broadened in the scan direction to 14.5 arcmin (Barnes et al. 2001). After averaging orthogonal scans, the effective beamwidth reduces to 14.3 arcmin. The central observing frequency was switched between 1417.5 and 1421.5 MHz, again every 5 s. This allowed the bandpass shape to be calibrated without spending any time off-source. A bandwidth of 8 MHz was used with 2048 spectral channels in each of two orthogonal linear polarizations. H I emission from the LMC (and the Galaxy) appeared within the band at both frequency settings. After bandpass calibration, the data from both settings were shifted to a common heliocentric reference frame. The velocity spacing of the multibeam data is 0.82 km s⁻¹, but the final cube was Hanning-smoothed to a resolution of 1.6 km s⁻¹. The useful velocity range in the final cube (i.e. after excluding frequency sidelobes of the LMC and the Galaxy, and band-edge effects) is −66 to 430 km s⁻¹.

Bandpass calibration, velocity shifting and preliminary spectral baseline fitting were all performed using the AIPS++ LIVEDATA task. Baselines were adaptively fitted using polynomials of degree eight. Subsequently, the data were convolved on to a grid of 4 arcmin pixels using a Gaussian kernel with a FWHP of 8.0 arcmin. This broadens the effective, scan-broadened, beamwidth of the inner seven beams from 14.3 to approximately 16.4 arcmin. Residual spectral baselines were removed by fitting polynomials in the image domain (MIRIAD task CONTSUB). The multibeam data were calibrated relative to a flux density for PKS B1934-638 of 14.9 Jy at the observing frequency. The brightness temperature conversion factor of 0.80 K Jy⁻¹ was established by an observation of S9 (T B = 85 K, Williams 1973). On the same scale, we measured a brightness temperature for pointing 416 (Stanimirović et al. 1999) in the Small Magellanic Cloud (SMC) (RA 00°47′ 52.6″, Dec. −73°02′19.8″, J2000) of T B = 133 K, compared with the 137 K measured by Stanimirović et al. The 3 per cent difference is probably caused by the different characteristics of the feeds used in the two observations, and residual uncertainties in absolute bandpass calibration. The rms noise in the line-free region of the cube is 27 mK, which is close to the theoretical value. This corresponds to a column density sensitivity of 8 × 10¹⁶ cm⁻² across 1.6 km s⁻¹, and 4 × 10¹⁵ cm⁻² for linewidths of 40 km s⁻¹, typical of those in the LMC.

3 RESULTS

3.1 Channel maps

The area covered by the present observations is shown in Fig. 1 together with some prominent features, referred to later in the text. Relevant directions and proper motion vectors to the Galaxy and other parts of the Magellanic system are also plotted. Channel maps, formed by averaging groups of six channels are shown in Fig. 2. Maps between heliocentric velocities of 185.9 and 359.0 km s⁻¹ are shown, spaced by 6 × 0.82 ≈ 4.92 km s⁻¹. Although this velocity range covers the main body of H I emission in the LMC, the emission does extend in a continuous manner down to ∼100 km s⁻¹ and up to ∼425 km s⁻¹, but at faint levels (see Section 4). There appears to be a small, but clean separation between H I in the LMC and H I in the Galaxy that extends from ∼90 km s⁻¹ through to ∼50 km s⁻¹. The Galactic component, important for extinction and photoelectric absorption estimates, is discussed in Section 6.

The main feature in the channel maps between 186 and 211 km s⁻¹ is the arm (hereafter arm ‘B’) of the LMC noted before in the Parkes observations by McGee & Newton (1986), the ATCA observations of Kim et al. (1998a), and in the HIPASS map presented by Gardiner, Turft & Putman (1998). Arm B appears to be a tidal feature that directly connects the LMC with the Magellanic Bridge joining the LMC and SMC. We discuss this further in Section 3.4.

Between 220 and 240 km s⁻¹, the southern part of the main body of the LMC becomes visible. The main body appears bounded by
3.2 Integrated H I maps and the morphology of the LMC

The peak brightness–temperature image and the column density image of the LMC are shown in Fig. 3. The peak brightness temperature is 83.1 K at RA 05h 39m 22s, Dec. −69° 51′13″ (J2000), a position slightly south of N159 and the 30 Doradus H I complex. The peak column density of $5.6 \times 10^{21}$ cm$^{-2}$ lies at the same position. Both values are $\sim 50$ per cent higher than the values in the Luks & Rohlfs (1992, hereafter LR92) data (53 K and $3.6 \times 10^{21}$ cm$^{-2}$, respectively). Part of this difference is resolution. The present data were obtained with the multibeam receiver that has a mean beamwidth of 14.1 arcmin, broadened to 16.4 arcmin after scanning and gridding effects are taken into account (Section 2). The LR92 data were taken with a feed with a beamwidth of $\sim 15$ arcmin on an undersampled grid of spacing 12 arcmin and interpolated on to a grid with similar spacing, presumably resulting in an effective resolution of $\geq 20$ arcmin. However, there must also be a calibration difference as the H I mass measured here is $\sim 30$ per cent higher than that of LR92 (Section 3.3). A pixel-by-pixel comparison of the LR92 column densities and the column densities in this paper shows that this is the case (Fig. 4). The column density ratio is $N_{\text{lr}}/N_{\text{hb}}$ (LR92) = 1.43. This sizeable calibration anomaly has been noted before (Blondiau et al. 1997, rescaled the temperatures of LR92 by a factor of 1.5), and seriously affects the use of LR92 column densities. As confirmed in Luks (1991), LR92 base their calibration on an earlier paper (Rohlfs et al. 1984). This paper quotes column densities and temperatures based on the antenna temperature, $T_A$, rather than the brightness temperature, $T_B$ (their equation 5 and the legend to Table 1). They further state that their H I column density ‘can be converted approximately into a true column density by multiplication by $1/\eta_{\text{mb}} = 1.25$. Assuming this factor has been neglected in LR92, the residual calibration difference then appears to be 1.43/1.25 = 1.14. This may be explained by the high main beam efficiency (or low antenna efficiency) measured by Rohlfs et al. They measure a ratio $T_B/S_B = 0.775$ K Jy$^{-1}$ for the Parkes telescope. In contrast, other measurements with the same single-beam, hybrid-mode feed suggest $T_B/S_B = 0.85–0.93$ K Jy$^{-1}$ (Davies, Staveley-Smith & Murray 1989; Stanimirović et al. 1999), a similar factor of 1.12 ± 0.05 higher.

Our peak column density of $5.6 \times 10^{21}$ cm$^{-2}$ is also higher than that of McGee & Milton (1966) who quote $4.0 \times 10^{21}$ cm$^{-2}$. This is probably a resolution difference because, as noted in Section 3.3, their total H I mass is virtually identical to ours. The ATCA data of Kim et al. (1998a) at 1-arcmin resolution show a higher peak brightness temperature of 106 K, increasing to a true value of 138 K when combined with the present multibeam data (Kim et al. 2003).

The main features of the H I distribution in Fig. 3 are as follows.

(i) A well-defined, nearly circular disc forms the main body of the LMC, indicating a nearly face-on inclination if it is assumed that the LMC has an intrinsically circular disc. This agrees with other recent values based on this assumption (e.g. 22°–26°, Weinberg & Nikolaev 2001; 22° ± 6°, Kim et al. 1998a), though not with values based on a direct distance determination (42° ± 7°, Weinberg & Nikolaev 2001; 35° ± 6°, van der Marel 2001). The influence of tidal forces and non-circular motions in the outer parts of the disc doubtless contribute to this disagreement. van der Marel (2001) deduces an intrinsic ellipticity of 0.31 for the outer disc at near-infrared wavelengths. The bulk of the LMC H I regions (Kennicutt et al. 1995; Kim et al. 1999) are contained within the gaseous disc.
Figure 2. Channel maps of H I in the LMC formed by averaging six adjacent planes of the cube (for display purposes). The resultant velocity spacing is 4.92 km s\(^{-1}\). The full intensity range 0–83.1 K is shown, with a square root transfer function. The heliocentric velocity of each velocity plane is shown on the top left-hand side in km s\(^{-1}\).

(ii) The body of the LMC is punctuated by large holes, and has a general mottled appearance. The main H I gaps are at RA 05h 32m, Dec. –66° 45’ (J2000), corresponding to LMC 4 (Meaburn 1980) and, in the column density image, the large east–west gap centred at RA 05h 00m, Dec. –70° 12’ (J2000) and bounded by LMC 2 and arm S. This void includes LMC 8, LMC SGS 4 (Meaburn 1980; Kim et al. 1999) but is substantially larger. This void is discussed in Section 4 and the population of H I holes is further discussed in Section 5.

(iii) The body of the LMC exhibits limb-brightening in H I as shown in the surface density profile of Fig. 5. The azimuthally averaged surface density peaks at 2 × 10\(^{20}\) cm\(^{-2}\) near the dynamical
centre, but also again at a radius of 2.2 kpc where it reaches $1.7 \times 10^{20} \text{ cm}^{-2}$. The limb-brightening is accentuated by arm E and the body of gas near LMC 2 and 30 Doradus in the south-east, especially in the column density image, and by arms S and W in the south and west, respectively. The column density increase in the south-east is sometimes identified as compression arising from the proper motion of the LMC through the tenuous halo of the Milky Way (e.g. de Boer et al. 1998).

(iv) Diffuse gas is present around much of the LMC, especially at PAs from 90° to 330°. At 5-kpc radius, Fig. 5 shows that the mean column density remains $1 \times 10^{20} \text{ cm}^{-2}$. A logarithmic version of the surface density profile is shown in Fig. 6. This shows that, although

Figure 2 – continued
there a rapid decrease in column density beyond 2.5 kpc, there is no cut-off. The surface density decrease is approximated by $\Sigma(H_\text{I}) \propto r^{-3.3}$. This is shallower than the exponential profile that seems to characterize the late-type dwarf galaxies studied by Swaters (1999).

(v) The main arms B and E both emanate, at different velocities, from the south-east of the LMC. These arms appear to be associated with much of the diffuse gas in the southern half of Fig. 5. These arms are unlikely to be coplanar (see Section 3.4). Arm S is also clearly visible, and appears to be associated with some of the diffuse gas in the west. Arm W is less visible and more curved in Fig. 3 than in the channel maps and may therefore be a superposition of several components. As has been noted by several authors recently (Kim et al. 1998a; Gardiner et al. 1998) that, although disturbed, the LMC has distinct spiral features. This is in contrast with the
near-infrared map of the stellar distribution (van der Marel 2001) which, aside from the bar and bar-related arm-like features, is remarkably uniform.

The main features in the outer body of the LMC are summarized in Fig. 1.

3.3 Spatially integrated properties of the LMC

Assuming a distance of 50 kpc and optically thin emission, the column density image in Fig. 3 can be integrated to give a total H\textsc{i} mass for the LMC, \( M_{\text{HI}} = (4.8 \pm 0.2) \times 10^8 \, M_\odot \) (Table 1). McGee & Milton (1966) quote a similar value, \( 5.0 \times 10^8 \, M_\odot \) (adjusted to
the distance scale used here), though they applied an optical depth correction based on a spin temperature of 200 K. As already noted, LR92 quote a smaller value, $3.1 \times 10^8$ $M_\odot$. Their survey was limited in spatial extent. When our image is integrated over the same area, the mass remains 30 per cent higher than quoted by LR92. Possible reasons for this have already been given. It is worth mentioning that our new mass estimate makes the LMC H\textsc{i} mass higher than that of the SMC, which is $4.2 \times 10^8$ $M_\odot$ (Stanimirović et al. 1999). The isodensity ($>10^{20}$ cm$^{-2}$) mass and disc mass (radius $<3.5$ kpc) of the LMC are also listed in Table 1.

For comparison with other late-type galaxies, the spatially integrated H\textsc{i} spectrum of the LMC is shown in Fig. 7. The
area integrated in this figure is centred on the dynamical centre of Kim et al. (1998a). The heliocentric velocity (mean and $V_{\text{hel}}$) is 273 km s$^{-1}$, similar to Kim et al.’s (1998a) kinematic value of 279 km s$^{-1}$ and the LR92 kinematic value of 274 km s$^{-1}$. We summarize velocity and velocity width parameters in Table 1.

Table 1 shows that the ratio of the H\textsc{i} to total mass in the LMC disc is 8 per cent, the H\textsc{i} mass to blue luminosity ratio is 0.21 M$_\odot$/L$_\odot$, and the star formation time-scale ($M_{\text{gas}}$/SFR) is 2.4 Gyr, where we have assumed a 30 per cent He contribution. The H\textsc{i} mass is a factor of 10 higher than the condensed molecular mass estimated by Fukui et al. (1999), and a factor of 60 higher than the diffuse molecular
mass measured by Tumlinson et al. (2002). The H I diameter of the LMC at 1 M⊙ pc−2 is 9.3 kpc and the ratio of the H I diameter to the optical diameter is \(D_{\text{H I}}/D_{25} = 1.1\), in line with the mean value for spirals of 1.7 ± 0.5 (Broeils & Rhee 1997), though less than the mean value for late-type dwarf galaxies of 3.3 ± 1.5 (Swaters 1999). As its absolute magnitude of \(M_B = -17.9\) mag and its morphology indicate, the LMC has properties somewhat closer to those of spiral galaxies than to those of late-type dwarf galaxies.

3.4 Tidal and other interaction features

In Section 3.1, we referred to arms B, E and W, which are marked in Fig. 1. Arm B leads directly into the Magellanic Bridge where it appears to merge with SMC gas, possibly explaining the multiple-peaked emission profiles in this region (McGee & Newton 1986). The Bridge appears to be tidal in origin and, in the model of Gardiner & Noguchi (1996), was formed 0.2 Gyr ago. The existence of arm B demonstrates the presence of some LMC gas in the Bridge, although the major component is undoubtedly stripped from the lower-mass SMC. Arm B consists of at least two separate filaments with a separation of up to \(\sim 0.5\)° (see Figs 1 and 3). The velocity differential between the filaments was sufficient to warrant listing the position RA 04 h 58m 36s, Dec. −73°33′57″ (J2000) as the centre of the candidate supergiant shell LMC SGS 1 by Kim et al. (1999).

Arms E and W lead directly south and north, respectively, of their starting point in the LMC. As already noted, arm E points to the beginning of the Leading Arm clouds mapped by Putman et al. (1998). Although these clouds lie 4° beyond the edge of the present map, deep reprocessed HIPASS data (Putman et al. 2003) show a continuous connection between this point and the Leading Arm at heliocentric velocities between 260 and 300 km s\(^{-1}\). Arm W leads directly north, extending into the diffuse gas to the north-west at \(\sim 270\) km s\(^{-1}\). As noted by Putman et al. (2003) and seen in their fig. 5, this gas then seems to bypass the Bridge and makes what appears to be a direct connection with the Magellanic Stream.

What causes the arm-like features arms E and W? As with spectacular systems such as NGC 4038/4039 (the ‘Antennae’;
Table 1. Global properties for the LMC based on distance of 50 kpc.

| Parameter                         | Units | Value     | Reference                        |
|-----------------------------------|-------|-----------|----------------------------------|
| Total HI mass, $M_{\text{HI}}$    | $M_\odot$ | $4.8 \times 10^9$ | This paper                      |
| Isodensity mass ($>10^{20} \text{ cm}^{-2}$) | $M_\odot$ | $4.6 \times 10^8$ | This paper                      |
| Disc HI mass ($<3.5 \text{ kpc}$) | $M_\odot$ | $3.8 \times 10^8$ | This paper                      |
| HI diameter, $D_{\text{HI}}$      | kpc   | 10.2      | This paper                      |
| Heliocentric velocity, $V_{\odot}$| km s$^{-1}$ | 273       | This paper                      |
| Velocity width, $W_{40}$          | km s$^{-1}$ | 80        | This paper                      |
| Velocity width, $W_{20}$          | km s$^{-1}$ | 102       | This paper                      |
| Foreground extinction, $E(B-V)$   | mag   | 0.06      | This paper                      |
| Total dynamical mass ($<4 \text{ kpc}$), $M_T$ | $M_\odot$ | $5 \times 10^9$ | Kim et al. (1998a), Alves & Nelson (2000) |
| Molecular mass                    | $M_\odot$ | $(4-7) \times 10^7$ | Fukui et al. (1999)             |
| Blue luminosity, $L_B$            | $L_\odot$ | $2.3 \times 10^9$ | de Vaucouleurs et al. (1991)    |
| Blue diameter, $D_{25}$           | kpc   | 8.7       | Bothun & Thompson (1988), de Vaucouleurs et al. (1991) |
| Blue scalelength, $\alpha_B^{-1}$| kpc   | 1.5       | Bothun & Thompson (1988)        |
| Hz luminosity                     | erg s$^{-1}$ | $2.7 \times 10^{40}$ | Kennicutt et al. (1995)         |
| Hz diameter                       | kpc   | 5.5       | Kim et al. (1999)               |
| Star formation rate, SFR          | $M_\odot$ yr$^{-1}$ | 0.26     | Kennicutt et al. (1995)         |
| $M_{\text{HI}}/M_T$ ($<4 \text{ kpc}$) |          | 0.08     |                                  |
| $M_{\text{HI}}/L_B$               | $M_\odot/L_\odot$ | 0.21     |                                  |
| $(M_{\text{HI}}+M_{\text{He}})/\text{SFR}$ | yr | $2.4 \times 10^9$ |                                  |
| $D_{\text{HI}}/D_{25}$            |       | 1.1       |                                  |
| $D_{\text{HI}}/\alpha_B^{-1}$    |       | 6.2       |                                  |

$^2$Based on $B_\pi = 0.57$ (de Vaucouleurs et al. 1991) and $M_B(\odot) = 5.50$ mag (Lang 1991).

Figure 5. Azimuthally averaged H I column density profile of the LMC in units of $10^{20} \text{ cm}^{-2}$. The dynamical centre at RA 05$^h$17$^m$.6, Dec. $-69^\circ$02$'$ (J2000) (Kim et al. 1998a) has been used, and a distance to the LMC of 50 kpc has been assumed. The mean column density is highest near the centre of the LMC, and the disc of the LMC appears to be limb-brightened. Various optical disc radii are marked: the $B$ scalelength, $\alpha_B^{-1}$; the Hα radius; and the radius at $\mu_B = 25$ mag arcsec$^{-2}$, $R_{25}$. See Table 1 for details.

(Hibbard et al. 2001), a plausible explanation is again tidal interaction. However, in this case, the tidal force arises from the Galaxy and not the SMC. As Fig. 1 shows, the great circle to the Galactic Centre lies directly south$^2$ of the LMC, therefore the tidal force projects along this line, at more or less the same position angle as the two arms. The two arms E and W may be wound up owing to the clockwise rotation of the LMC (Kroupa & Bastian 1997).

It is unusual that arms B and E appear to emanate from similar points at the south-east of the LMC, with the former flowing into the Bridge and the latter flowing into the Leading Arm. The chronology of events is likely to be that the gaseous tide in the LMC was disturbed by the close passage of the SMC 0.2 Gyr ago, funnelling a portion of the gas near the LMC–Galaxy Lagrangian L1 point into the Bridge. At the present time, the tidal force ($\propto M/R^3$) from the Galaxy is likely to be many times stronger than that from the SMC. For an LMC total mass of $5 \times 10^9 M_\odot$ (Kim et al. 1998a; Alves & Nelson 2000) a distance of 50 kpc, an SMC total mass of 1.5 $\times$
Thus the Magellanic system, and similar multiple systems may be useful in determining the tidal force in the MOND regime (Milgrom 1983) theory of modified Newtonian dynamics (MOND) is more or less the same as the Newtonian prediction. However, because there is little requirement for dark matter in the SMC even in the Newtonian model, the tidal force in the MOND regime ($\propto M/R^2$) will be relatively stronger. Thus the Magellanic system, and similar multiple systems may be useful laboratories for studying inertia and gravity at low accelerations).

$10^{9}$ $M_\odot$ and an SMC/LMC separation of 22 kpc (Staveley-Smith et al. 1998), the tidal force ratio is $\sim 30$. However, for an encounter at 7 kpc the force ratio would be unity.

Current numerical models predict that most of the gas in the Leading Arm (and the Stream) comes from the SMC, (Gardiner & Noguchi 1996; Li 1999), with the LMC merely serving to disrupt the Leading Arm that passes in front of it. However, it seems to be the case that, as with the Bridge, significant LMC gas is ‘leaking’ into the Leading Arm. Metallicity measurements of Leading Arm clouds such as HVC 287.5+22.5+240 (Lu et al. 1998) may give clues as to the ratio of LMC gas to the slightly less enriched SMC gas.

Cepheid distances (Welch et al. 1987) suggest that the closest part of the LMC is at PA 77° ± 42°. Recent AGB and RGB stellar distances give a more accurate near-side PA of 32° ± 8° (van der Marel & Cioni 2001). Therefore, the north-eastern part of the disc is the closest to the Galaxy, closest to the L1 point and the most easily perturbed by the SMC. This is not inconsistent with the point of origin of arms B and E.

A suggested geometry for the LMC tidal features is that arms B and E both arise from the outer parts of the LMC in the east. The arms extend southwards where they bifurcate at a position close to the LMC tidal radius. The low-velocity arm B swings around, probably upwards out of the plane of the LMC, curves around to the south-west where it eventually joins the Magellanic Bridge at somewhat larger distances than the LMC. This feature is evident in the simulations of Li (1999). The high-velocity arm E extends directly south, probably remaining at the same Galactocentric distance as the LMC. It then joins the general Leading Arm gas, which mainly arises from the SMC. The large amount of star formation in the 30 Doradus region may well be a manifestation of the tidal shear occurring in the region near the origin of arms B and E.

However, the question remains as to why the near-infrared stellar distribution is so smooth in the outer parts of the LMC. van der Marel (2001) reports no clearly discernible spiral structure at radii out to 9°, which is beyond the radius surveyed in this paper. Tidal distortion must apply to stars and gas, and the usual argument that the H\textsc{i} is well outside the stellar distribution does not apply. Could it be that the evolved stars in the 2MASS and DENIS images are not tracing the same thin disc as the H\textsc{i}? Or has orbit-crossing and dissipation made the H\textsc{i} density evolve in a non-linear manner? The significant gas self gravity ($\sim 10$ per cent of the total mass is in the form of H\textsc{i} and He; see Table 1) makes the latter a distinct possibility. Nevertheless, the stellar distribution shows strong evidence of tides. van der Marel (2001) argues that the distribution of stars is significantly elongated in the direction of the Galactic Centre, as predicted by tidal theory.

The diffuse gas in Fig. 3, and labelled in Fig. 1 appears to be strongly related to the tidal arms. The gas in the south-east occurs at similar velocities to arm E. In the channel maps (Fig. 2), some of this gas at 290 km s$^{-1}$ itself falls into diffuse linear features. The more extensive HIPASS data again shows a connection to the Leading Arm. This would tend to argue for a tidal origin for this gas also. Weinberg (2000) also points out the dramatic effect of the Galaxy on the stellar structure of the LMC through torquing of disc orbits and tidal stripping, and suggests a mass-loss rate of $3 \times 10^9$ $M_\odot$ per orbit, even without the SMC. He also predicts tidally stripped stars some tens of kiloparsecs away from the LMC, which have possibly already been seen in the 2MASS data (Weinberg & Nikolaev 2001). With an LMC inclination of $\sim 30$, and a line of nodes at PA~$\sim 0°$, the spin vectors of the Galaxy and the LMC are perpendicular, a geometry not suitable for strong tidal interaction. However, if the higher values for the inclination and PA suggested by van der Marel (2001) are correct, then the spin vectors of the Galaxy and the LMC will be better aligned, and the current interaction will be stronger.

For the diffuse gas in the south-east, it is also worth noting that ram pressure is a viable alternative. Any gas outside the influence of the LMC that is slowed by ram pressure will tend to drop in its orbit around the Galaxy. By doing this, its angular velocity increases and it will tend to lead the LMC, unless dynamical friction on the LMC is more important (Moore & Davis 1994). Although Murali (2000) suggests that ram pressure is not a viable possibility for a remnant as old as the Magellanic Stream (otherwise there is too much evaporation), this argument does not apply to the clouds near the LMC. On the other side of the LMC, the diffuse gas to the south-west is clearly associated with the Bridge.

As well as having a strong tidal influence on the LMC and SMC, the Galaxy has left a clear tidal signature on the Sagittarius dwarf galaxy that is responsible for a trail of stars forming a great circle on the sky (Ibata et al. 2001). Martínez-Delgado et al. (2001) confirm the existence of tidal tails in Ursa Minor, a dwarf spheroidal galaxy lying at a distance of 70 kpc. Other objects such as the Carina dwarf spheroidal galaxy also appear to have stellar distributions that are radially truncated (Majewski et al. 2000). However, a lack of a clear understanding of the internal dynamical state of these systems has contributed to an uncertainty concerning whether the truncation can strictly be interpreted as being tidal in origin.

The importance of tidal signatures in satellite galaxies lies in their usefulness in measuring the total mass of the Milky Way, the extent of its dark halo, and for detecting any substructure within the halo. Present results for the LMC and the Magellanic Stream appear to confirm the existence of a massive halo around the Galaxy, with the total mass out to a radius of 50 kpc of $\sim 5 \times 10^{11}$ $M_\odot$. However, the existence of tidal debris around the LMC complicates interpretation of results from the MACHO experiment (Alcock et al. 2000), which attempted to measure the fraction of the dark halo of the Galaxy in

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$^{3}$ As an aside, the predicted tidal force of the Galaxy on the LMC in Milgrom’s (1983) theory of modified Newtonian dynamics (MOND) is more or less the same as the Newtonian prediction. However, because there is little requirement for dark matter in the SMC even in the Newtonian model, the tidal force in the MOND regime ($\propto M/R^2$) will be relatively stronger. Thus the Magellanic system, and similar multiple systems may be useful laboratories for studying inertia and gravity at low accelerations.)
the form of compact objects. Stars that are tidally stripped and lie slightly behind the LMC, rather than in a thin disc, contribute substantially to the frequency of microlensing events (Weinberg 2000). This implies that the measurement of the Galactic halo mass in the form of compact objects (currently $\sim 10^{11} M_{\odot}$) should probably be regarded as an upper limit until the geometry of the halo of the LMC is better understood.

4 THE HALO OF THE LMC

Because the present study has velocity information, we can attempt to probe the halo of the LMC by searching for H I at anomalous velocities. Such gas is expected to occur owing to outflows from star-forming regions and stripping of the outer disc owing to tidal and ram pressure forces. Non-planar occurrence of gas and stars has previously been reported or suggested by Luks & Rohlfs (1992), Zaritsky & Lin (1997), Wakker et al. (1998) and Graff et al. (2000) and, as reported by the latter, is an important factor in determining the self-lensing optical depth of the LMC. Of particular interest are the HVC complexes below $+180$ km s$^{-1}$, whether they belong to the Galaxy or the LMC. de Boer, Morras & Bajaja (1990) use an H I strip scan to conclude that the gas at local standard of rest (LSR) velocities $+70$ and $+140$ km s$^{-1}$ is Galactic in origin. Richter et al. (1999) concur, suggesting that the $+120$ km s$^{-1}$ H$_2$ absorption feature seen against HD269546 is an HVC originating in the disc of our Galaxy.

Fig. 8 shows the prominent HVCs (column densities over $2 \times 10^{18}$ cm$^{-2}$) with velocities in the range 115–176 km s$^{-1}$ (heliocentric).

They are extensive over much of the south-west LMC, but extend elsewhere in the field at lower column densities. Some or most of the emission in the south-west lies projected between arms B and S, and is probably related to the Bridge and the tidal interaction with the SMC. However, the peak column of $2.4 \times 10^{19}$ cm$^{-2}$ projects on to the position of the giant H I void containing LMC 8 (Meaburn 1980) and LMC SGS 4 (Kim et al. 1999) (see also Sections 3.2 and 5). Oey et al. (2002) show a high-resolution H I mosaic of this region that also contains the superbubbles DEM L25 and L50. Moreover, the HD269546 absorbing cloud seen by Richter et al. (1999), which has a peak column density $1.0 \times 10^{19}$ cm$^{-2}$, is at RA 05$^h$ 27$^m$, Dec. $-68^\circ$ 50$'$ (J2000), which corresponds to the H I void at LMC 3 (Meaburn 1980) and LMC SGS 12 (Kim et al. 1999). This suggests that this gas has been removed from the LMC disc. A position-velocity cut across both the HD 269546/LMC 3 and the LMC 8 clouds is shown in Fig. 9. The latter shows clear connections with LMC gas. The former shows a probable connection at low column density. At other PAs, both complexes also appear to have gas at velocities higher than the LMC disc. This suggests an explosive origin for the gas, rather than a tidal or ram-pressure-stripped origin. However, the kinematics of the high-velocity gas are not simple, and certainly cannot be modelled as a simple expanding bubble or double-sided mushroom cloud.

The association of some high-velocity clouds with the LMC implies that the outflow velocities, however they are attained, are substantial. In the case of the HD269546 cloud, the mean velocity differs by 126 km s$^{-1}$ from the systemic value. In the case of the LMC 8 cloud, the mean velocity differs by 97 km s$^{-1}$ from the systemic value. Outflows at these velocities ought to be accompanied by X-ray and the H$\alpha$ emission already known to be present. However, the strength depends on the density of the medium being shocked.

Figure 8. H I column density contours of high-velocity clouds. The heliocentric velocity range 115–176 km s$^{-1}$ is included. Contours are in steps of $2 \times 10^{18}$ cm$^{-2}$ starting at $2 \times 10^{18}$ cm$^{-2}$. Noisy regions at the edge of the image have been excluded. The map has been smoothed by a Gaussian FWHM of 20 arcmin. The narrow feature is better understood.

Figure 9. An H I position–velocity slice centred on 05$^h$ 17$^m$ 02$^s$, Dec. $-68^\circ$ 49$'$ 19$''$ (J2000) at PA 250$^\circ$. The emission from the LMC (at $\sim 260$ km s$^{-1}$) and the Galaxy (at $\sim 10$ km s$^{-1}$) has been saturated to reveal the faint emission from the HD269546 absorbing cloud (Richter et al. 1999) at 05$^h$ 27$^m$, Dec. $-68^\circ$ 50$'$ (J2000), 131 km s$^{-1}$ (heliocentric) and the LMC 8 cloud at 04$^h$ 59$^m$, Dec. $-69^\circ$ 35$'$ (J2000), 155 km s$^{-1}$ (heliocentric). The data has been smoothed with a Gaussian FWHM of 20 arcmin. The narrow feature at $\sim 85$ km s$^{-1}$ is an artefact.
Because a substantial H I column is present in the HD269546 cloud, its temperature is lower than \(10^4\) K, but higher than the lower limit to the \(H_2\) excitation temperature of \(10^3\) K measured by Bluhm et al. (2001). These clouds probably exist in a cocoon of hotter material. Bluhm et al. (2001) suggest a neutral hydrogen fraction of 5–20 per cent, from observations of O and O \(^{18}\).

The height of the neutral clouds above the LMC disc can only be speculated. The projected radii of LMC SGS 4 and 12 (Kim et al. 1999) provides a weak lower limit of \(\sim 0.5\) kpc. The \(\sim 30^\circ\) inclination of the LMC possibly provides an upper limit of a few kpc, otherwise the non-planar gas would project elsewhere on the LMC disc (though this may indeed be the case for much of the gas in Fig. 8).

5 H I HOLES

Several holes, or gaps in the H I column density image in Fig. 7 are apparent. As originally noted by Westerlund & Mathewson (1966), the positions of some holes show a very strong correlation with stellar associations, H II regions and supernova remnants (SNRs). Six of the nine candidate supergiant H\(\alpha\) shells listed by Meaburn (1980) are clearly associated with holes. These shells are marked in Fig. 10. LMC 1, 4 and 5 are well aligned with an H I hole; LMC 2 and 3 are more complex than simple circular holes; and LMC 8 is associated with an H I hole that is at least twice as large as the H\(\alpha\) shell. In addition to the six Meaburn shells shown in Fig. 10, Kim et al. (1999) list a further 17 supergiant shells. Some of the largest of these (LMC SGS 6, 17 and 23) are also clearly visible as H I holes in Fig. 10.

As discussed by Kim et al. (1999), there is a good association between H I and H II regions, and some evidence for regions of star formation providing direct mechanical input into the expansion of the shells and therefore the evacuation of the H I. However, Wada et al. (2000) point out that thermal and gravitational instabilities can also lead to the formation of cavities and filaments. In cases such as LMC 4, numerous studies (Dopita et al. 1985; Domgörgen et al. 1995; Efremov & Elmegreen 1998; Olsen et al. 2001) paint a picture of progressive star formation propagating outwards from the centre of the shell. Ionization, dynamical pressure and conversion to molecules and stars depletes the H I, with the remainder forming a rim where the newest star formation occurs. In other cases such as LMC 2, the geometry is more complex and, although energy input by stellar winds and supernovae (Weaver et al. 1977) may dominate, the simple model of outward-propagating star formation requires modification (Points et al. 1999, 2000). Finally, in cases such as LMC SGS 6 (Kim et al. 1999), no correlation between H I and anything else is evident. In these cases, it is possible that an older population of stars with an initial mass function skewed towards higher-mass stars is responsible. However, it is also possible that other dynamical events are responsible.

For each of the holes marked in Fig. 10, we have plotted a position–velocity slice in Fig. 11. These slices commonly show a dip in the column density at the position of the hole (except where the image is saturated), evidence for a velocity gradient that reflects the rotation of the LMC, and, in some cases, evidence for a high-velocity gas. LMC 2, 4 and LMC SGS 17 and 23 show evidence for multiple velocity components close to the systemic velocity (\(\Delta V \sim 20\) km s\(^{-1}\)) and may be construed as continued slow momentum or pressure-driven expansion of gas away from the interior of the evacuated shell. In addition, most of the holes (except LMC 4 and LMC SGS 6) show evidence for higher-velocity gas (\(\Delta V \sim 100\) km s\(^{-1}\)) at low column densities (as discussed in Section 4 for LMC 3 and 8). The origin of this gas and its definite association with the H I holes remains unclear. However, expulsion by stellar and supernova shocks, or other explosive events, remains a good possibility. Further studies of the coronal gas towards such regions (e.g. Bomans et al. 1996; Wakker et al. 1998) are desirable.

6 THE GALACTIC FOREGROUND

Its closeness, favourable inclination and low internal extinction make the LMC an ideal object to study in the optical range for many purposes. However, its mean Galactic latitude of \(-34^\circ\) means that foreground extinction is of some importance. IRAS is unable to separate LMC dust from Galactic dust (although Schwering & Israel 1991 attempted to incorporate low-resolution H I data to isolate the foreground component). For example, the LMC, SMC and M31 are not removed from the IRAS/DIRBE extinction maps of Schlegel, Finkbeiner & Davis (1998). Around the outskirts of the LMC, the maps of Schlegel et al. (1998) show a variation from \(E(B-V) = 0.04\) to the north-west of the LMC to around 0.12 in the south-west, implying that extinction is significant and variable. The SMC, lying slightly further from the Galactic Plane appears to lie in a region with foreground extinction at the lower end of this range. A strong linear feature, now known to be associated with Galactic gas and dust also complicates the picture (de Vaucouleurs 1955; McGee et al. 1986).

Because there appears to be no Galactic gas >\(100\) km s\(^{-1}\) or LMC gas <\(100\) km s\(^{-1}\), there is a clean separation of the Galactic and LMC components in the H I data. Fig. 12 shows the peak brightness–temperature and column density images for the Galactic component using the same intensity range as the LMC images in Fig. 3. The Galactic component is smoother with a maximum column density around a quarter of that in the LMC, and a maximum temperature of around two-thirds of the LMC value. There
Figure 11. Position–velocity slices across the H\textsc{i} holes marked in Fig. 10. The slices are generally at PA 0° except for LMC 4 (10°), LMC SGS 6 (90°) and LMC SGS 17 (85°). To bring out fainter features, the grey-scale is saturated at 9 K. High-velocity gas appears to be associated with some of the holes (e.g. LMC 4), but in only two cases (LMC SGS 17 and 23) is there some evidence for a complete shell. The data have been smoothed with a Gaussian FWHM of 20 arcmin.

is a significant column-density gradient from the north-west to the south-east and a significant filament extending from the north at RA 05\textdegree\ 38\textquotesingle, Dec. −62° 26′ (J2000) to RA 04\textdegree\ 39\textquotesingle, Dec. −70° 50′ (J2000) in the south-east. Contours of H\textsc{i} column density are shown in Fig. 13 along with $E(B - V)$ contours based, for reference, on equation (7) of Burstein & Heiles (1978).

Over the disc of the LMC, the mean Galactic extinction is $(E(B - V)) = 0.06$ mag with a range between 0.01 and 0.14,
Figure 12. Left, peak brightness–temperature image of the Galactic gas in the foreground of the LMC showing, for each position, the maximum value of $T_B$ in the heliocentric velocity range $-64$ to $100$ km s$^{-1}$. The intensity range and transfer function is the same as for Fig. 3, although the peak temperature for the Galactic gas is lower, 56.3 K. Right, column density image over the same velocity range, formed by summing all emission brighter than 0.08 K ($3\sigma$). The column density range is the same as for Fig. 3, with the maximum column density for the Galactic gas being $1.3 \times 10^{21}$ cm$^{-2}$.

Figure 13. Left, Contours of H$\textsc{i}$ column density of Galactic foreground gas at heliocentric velocities $<100$ km s$^{-1}$. Contours are labelled in units of $10^{20}$ cm$^{-2}$; Right, contours of estimated extinction $E(B - V)$ owing to Galactic foreground dust. Contours are labelled in units of mag. and an rms of 0.02 mag. The extinction gradient is from northwest to south-east, with a systematic variation of $\Delta E(B - V) \approx 0.1$ mag over the full field. Although significant in $B(\Delta A_B \approx 0.4$ mag), the variation in $H$ is small ($\Delta A_H \approx 0.06$ mag) and should only affect the details of infrared structural results (Weinberg & Nikolaev 2001; van der Marel & Cioni 2001) rather than modify their overall conclusions. As pointed out by Schwering & Israel (1991), 30 Doradus has a low foreground extinction [$E(B - V) =$...
0.05]. The LMC values agree with the mean of 0.06 ± 0.02 mag and range of 0.00–0.15 mag from the cool star data of Oestreich, Gochermann & Schmidt-Kaler (1995) (see also Zaritsky 1999), a mean of 0.06 mag from a combination of polarization and H I data by Bessell (1991), and the range 0.07–0.17 mag suggested by Schwering & Israel (1991) from a combination of H I and IRAS data.

Finally, it should be emphasized that the H I data alone have zero-point problems caused by a combination of spilled radiation and intrinsic variations in gas-to-dust ratio. However, the range of IRAS/DIRBE extinctions around the LMC (0.04–0.12) is similar to the range, derived from the H I data (0.01–0.14), implying no large systematic problem (the random errors are negligible). Both results are consistent with the combined Galactic and LMC extinctions, measured by Dutra et al. (2001) using background galaxies, of $E(B - V) = 0.12 \pm 0.10$.

7 SUMMARY

Parkes multibeam observations have been made of neutral hydrogen in and around the Large Magellanic Cloud. The major results are as follows.

(i) The LMC has a total H I mass of $(4.8 \pm 0.2) \times 10^8 M_\odot$ (for an assumed distance of 50 kpc), of which $3.8 \times 10^8 M_\odot$ lies within a well-defined disc. This is 8 per cent of the total mass and is a factor of 10 more than the molecular mass so far identified.

(ii) We measure H I column densities that are 43 per cent higher than the previous survey by Luks & Rohlfs (1992).

(iii) Outer tidal arms are identified. These arms appear to channel gas into: (a) the Magellanic Bridge; (b) the Magellanic Stream; and (c) the Leading Arm, and appear to be a result of the two-way interaction of the LMC with both the Galaxy and the Small Magellanic Cloud. The gas at $r > 4'$ does not follow the outer stellar contours, suggesting that shocks, self-gravity or, possibly, external ram pressure contribute to their appearance. The existence of tidal shearing in the LMC argues for the presence of a massive Galactic halo, and as emphasized by Weinberg (2000), suggests that care needs to be taken to eliminate self-lensing when LMC gravitational microlensing events are used to measure the density of compact objects in the halo of the Galaxy.

(iv) High-velocity clouds, previously seen in absorption against LMC stars appear mainly to belong to the LMC in cases where their heliocentric velocity exceeds approximately 100 km s$^{-1}$, and not to the Galactic disc or halo.

(v) Some of the high-velocity clouds appear to be coincident with H I voids (e.g. LMC 3 and 8), which suggests that these voids were created by explosive events. However, most of the H I voids are just that – they show no clearly defined shells of expanding gas. Presumably, if created by supernova and stellar winds, the giant voids accessible for study at the resolution of the Parkes telescope (i.e. >0.7 kpc) have already expanded well outside the thickness of the LMC disc.

(vi) The Galactic foreground H I emission has been used to provide an image, at 16.4-arcmin resolution, of the likely foreground dust extinction over the field of the LMC. The mean Galactic extinction is $(E(B - V)) = 0.06$ mag within the disc of the LMC. Over the full field imaged, there is an extinction gradient from north-west to south-east of $\Delta E(B - V) \approx 0.1$ mag, corresponding to $\Delta A_B \approx 0.4$ mag and $\Delta A_V \approx 0.06$ mag.

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