The origin of large-scale H\textsc{i} structures in the Magellanic Bridge

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ABSTRACT

We investigate the formation of a number of key large-scale H\textsc{i} features in the interstellar medium of the Magellanic Bridge using dissipationless numerical simulation techniques. This study comprises the first direct comparison between detailed H\textsc{i} maps of the Bridge and numerical simulations. We confirm that the Small Magellanic Cloud (SMC) forms two tidal filaments: a near arm, which forms the connection between the SMC and the Large Magellanic Cloud, and a counter-arm. We show that the H\textsc{i} of the most dense part of the Bridge can become arranged into a bimodal configuration, and that the formation of a ‘loop’ of H\textsc{i}, located off the north-eastern edge of the SMC, can be reproduced simply as a projection of the counter-arm, and without invoking localized energy-deposition processes such as supernova events or stellar winds.

Key words: methods: numerical – ISM: evolution – ISM: structure – galaxies: interactions – galaxies: ISM – Magellanic Clouds.

1 INTRODUCTION

The formation and evolution of the interstellar medium (ISM) are affected by processes which cause the deposition of energy across a complete range of spatial scales: galactic collisions and interactions deposit energy into the ISM over scales which are comparable to the dimensions of the galaxies themselves (e.g. Gardiner, Sawa & Fujimoto 1994; Goldman 2000; Berentzen et al. 2001); while accumulated energy from stellar winds, supernovae (SNe) or gamma-ray bursts (GRBs) can deposit approximately $10^{51}$ erg per event into a relatively confined volume (e.g. Lozinskaya 1992; Bloom, Frail & Kulkarni 2003) and reorganize the ISM on kiloparsec scales (e.g. de Blok & Walter 2000). Energy injected into a system via these and other mechanisms can subsequently propagate down through smaller spatial scales according to a power law (e.g. Goldman 2000). In order to obtain a full understanding of the processes active in shaping the ISM, it is clear that studies of the large-scale structure are necessary in addition to smaller-scale analyses.

The Magellanic Bridge (MB) is the epitome of tidal features, and its origin as such is well established as the product of an interaction between the H\textsc{i}-rich Small and Large Magellanic Clouds (SMC, LMC), some 200 Myr ago (e.g. Gardiner et al. 1994; Yoshizawa & Noguchi 2004). At 50–60 kpc (e.g. Abrahamyan 2004), the Magellanic system represents the closest interacting system to our Galaxy.

The ISM in the MB and SMC is turbulent, and conforms to a featureless, Kolmogorov power spectrum (Muller et al. 2004; Stanimirović, Staveley-Smith & Jones 2004) from kpc scales, down to the limit of current radio observations of $\sim$30 pc. Even so, the arrangement of structure of the ISM in the MB is not completely homogeneous at the larger scales: Muller et al. (2003) (see also Wayte 1990) identified three statistically interesting features which dominate the overall structure of the densest parts of the MB. These manifest as: (1) a distinct and separable high-velocity H\textsc{i} component, which exists only at the more northerly declinations, and appears shifted in velocity from the brightest H\textsc{i} component by $\sim$35 km s\(^{-1}\) (see ‘counter-arm’ feature in Fig. 2, E2); (2) a large ($R \sim 1.3$ kpc) loop, located off the north-eastern edge of the body of the SMC (see Fig. 1, panels labelled A and B); and (3) a bimodal arrangement of the brightest (i.e. most dense) parts of the MB (see Fig. 2, E1).

Muller et al. (2004) were able to show that the higher velocity component [feature (1), from above] is morphologically distinct from the southern, denser component; the range of velocity modifications (i.e. spurious modifications to the three-dimensional power distribution by a turbulent component) to the ISM within the northern part is significantly smaller than for the southern part. These authors argue that the distinction in turbulence and power structure between the northern and southern regions is consistent with numerical simulations by Gardiner et al. (1994), which predict that the two components represent two arms emanating from the SMC. In this case, the northern part is the projection of an almost radially extending arm which does not form a contiguous link between the SMC and LMC. The more southern component comprises matter drawn out from the SMC body following the SMC–LMC interaction. It remains to understand the evolution of features (2) and (3).

Although the formation of the Magellanic Stream and the evolution of the LMC and the SMC have already been investigated by previous numerical simulations of tidal interaction between the Clouds and the Galaxy (e.g. Gardiner et al. 1994; Bekki & Chiba 2005; Connors, Kawata & Gibson 2006), the formation of the MB...
has not been extensively investigated on a detailed level. Here, we compare our observational results on H I structure and kinematics with the corresponding simulations and discuss the tidal interaction model in the context of the observations. We will also discuss alternative formation mechanisms and processes and we will see that, although the processes that shape the ISM of the MB are not yet fully understood to a fine, detailed level, we can at least begin to understand the mechanisms that are responsible for the development of the larger scale structures in this unique filament.

2 THE H I DATA SET

Being the primary constituent of the ISM, H I is the most useful probe of its bulk and turbulent motions. We make extensive use of a lower resolution data set of the entire Magellanic system, obtained by Brüns et al. (2005) using the Parkes telescope. These data have a sensitivity of 0.05 K and a spatial and velocity resolution of 16 arcmin and 1 km s$^{-1}$. Other details of the measurements and analysis of the lower resolution data set are covered by Brüns et al. (2005). We also make frequent reference to high-resolution observations of the western MB only ($1.5 < RA < 3^h$), using the Australia Telescope Compact Array and Parkes telescopes, which have a sensitivity of 0.8 K per $1.6$ km s$^{-1}$ channel, and a spatial resolution of $\sim$98 arcsec. A description of the observations and reduction process of the high-resolution data set can be found in Muller et al. (2003). The features that form the focus of this simulation study were identified in work by Muller et al. (2003), using the high-resolution data set.

2.1 Loop feature and bimodal structure

The H I loop manifests as an enormous, localized deficiency of material in the line of sight; subtending an ellipse with axes $\sim$1.6 and 1.0 kpc. The loop is marked in Fig. 1 (panel labelled A), and appears to be located in H I that is shifted by $\sim$40 km s$^{-1}$ relative to the bulk of the Bridge: approximately 190.7–231.9 km s$^{-1}$ (Local Standard of Rest, LSR). Based on the mean column density around the loop ($\sim$5 $\times$ 10$^{20}$ cm$^{-2}$; Muller et al. 2003), the loop appears to represent an H I deficiency (i.e. the mass of material that appears to be missing) of $\sim$2 $\times$ 10$^7$ M$_\odot$.

Previous proposals regarding the origins of the loop include speculation that its position corresponds to that of the second SMC–LMC Lagrange point (Wayte 1990); however, the concept is not subjected to a quantitative test.

The brightest part of the H I in the Bridge (roughly bounded by Dec. $\sim$72° 30′ to $\sim$73° 30′ and RA $1^h$30′ to $2^h$30′, J2000) has been shown to be organized into two ‘sheets’ (Muller et al. 2003), approximately parallel in velocity and separated by $\sim$30 km s$^{-1}$. The feature can be seen in Fig. 2 (panel labelled E1), where the bimodal arrangement appears to originate in the eastern edge of the SMC and extends eastward. It is clearly a dominant feature in the MB, and involves $\sim$8 $\times$ 10$^7$ M$_\odot$ of H I, approximately 80 per cent of the total H I mass of the western MB. We may gauge the significance of this structure by temporarily assuming that it is a kinematic process: $\sim$8 $\times$ 10$^7$ M$_\odot$ of H I expanding at $\sim$30 km s$^{-1}$ requires approximately 1/2 $\sum$ MV$^2$ = $9 \times$ 10$^{52}$ erg. This feature is clearly indicative of a large-scale and energetic process and is worthy of attention when attempting to understand the formation of the Bridge.

3 NUMERICAL SIMULATIONS

We investigate dynamical evolution of the Clouds from 0.8 Gyr ago ($T = 0.8$ Gyr) to the present ($T = 0$) by using numerical simulations in which the SMC gas particles are modelled in a self-gravitating discy system, and the LMC is a test particle. The key epoch for the MB formation is 0.2 Gyr when the SMC passed its pericentre distance with respect to the LMC (e.g. Gardiner & Noguchi 1996).

In developing the simulations, we search for the models that most closely reproduce (1) the current locations of the Clouds and the MB, (2) an apparently contiguous H I filament clearly seen in the sky, and (3) the total mass of $\sim$10$^7$ M$_\odot$ in the MB. It is necessary to explore a very wide parameter space for orbits, masses and disc inclinations of the LMC and the SMC, and we therefore investigate the formation processes of the MB based on dissipationless simulations in the present study. Our future studies, based on full-blown chemodynamical simulations such as those of Bekki & Chiba (2005), will discuss the importance of hydrodynamics and star formation in the MB formation. A discussion of fundamental...
methods and techniques for numerical simulations of the evolution of the Clouds is given in previous papers (Bekki & Chiba 2005), and these will not be re-addressed here.

### 3.1 Initial conditions

The model SMC is composed of a stellar disc, and a collisionless ‘gas’ disc, embedded in a massive dark halo having an ‘NFW’ profile (Navarro, Frenk & White 1996). Typically for gas-rich systems, the $H\text{I}$ diameters are much larger than the optical disc (e.g. Broeils & van Woerden 1994), and we configure the simulations such that the radius of the SMC gas disc ($R_g$) is twice as large as that of its stellar disc ($R_s$). We use masses of the LMC and the SMC ($M_L$, $M_S$) that are consistent with observations by van der Marel (2002) and Staveley-Smith et al. (1997).

The Galactic gravitational potential $\Phi_g$ is represented by $\Phi_g = -V_0^2 \ln r$, where $V_0$ and $r$ are the constant rotational velocity (220 km s$^{-1}$ in this study) and the distance from the Galactic Centre. The orbits of the SMC and LMC are bound.

We use the same coordinate system $(X, Y, Z)$ (in units of kpc) as those used by Gardiner & Noguchi (1996) and Bekki & Chiba (2005). The adopted current positions are $(−1.0, −40.8, −26.8)$ for the LMC and $(13.6, −34.3, −39.8)$ for the SMC, and the adopted current Galactocentric radial velocity of the LMC (SMC) is 80 (7) km s$^{-1}$. Current velocities of the LMC and the SMC in the Galactic $(U, V, W)$ coordinates are assumed to be $(-5, -225, 194)$ and $(40, -185, 171)$ in units of km s$^{-1}$, respectively.

The initial spin of an SMC disc in a model is specified by two angles, $\theta$ and $\phi$, where $\theta$ is the angle between the $Z$-axis and the vector of the angular momentum of a disc and $\phi$ is the azimuthal angle measured from the $X$-axis to the projection of the angular momentum vector of a disc on to the $X$–$Y$ plane.

Although we investigate a large number of models with different $R_s/R_g$, $\theta$, and $\phi$, we show only the results of the two best-performing models: Model 1 and Model 2. The fundamental parameters of these models are summarized in Table 1.

### 3.2 Simulation results

From a qualitative study of Fig. 1, we see that the large-scale and general filamentary arrangement of the numerical simulations is consistent with observations: the dense ‘Bridge’ filament is well reproduced, as well as the central body of the SMC.

The velocity projections in Fig. 2 show that the bimodal properties of the densest part of the Bridge can easily be duplicated by Model 1. The two distinct velocity ranges represent similar orbital ‘families’ which are present in the Bridge itself. The simulations are able to duplicate the observed velocity separation of $\sim$40 km s$^{-1}$ as well as the approximate spatial extent of the bimodal arrangement for $2^h 0^m \leq \alpha \leq 3^h 0^m$ and $150 \leq V_b \leq 200$ km s$^{-1}$. A significant quantity of material is drawn into the more northerly declinations and out into a velocity range which is different from that of the ‘Bridge’ itself.

Both Models 1 and 2 reproduce the SMC as having two filaments: a lower-declination, low-velocity and nearer arm (forming the Bridge proper), and a higher-declination, high-velocity counter-arm component that has more radial extension (see also Fig. 4, later). These results are completely consistent with earlier numerical simulations by Gardiner et al. (1994), and with a quantitative analysis of the turbulent structure of the $H\text{I}$ by Muller et al. (2004). Finally, we see in Fig. 3 that Model 2 can convincingly reproduce the observed ‘loop’ off the north-eastern corner of the SMC. Muller

![Figure 2](https://academic.oup.com/mnrasl/article-abstract/381/1/L11/106854iners
et al. (2003) report that the loop is found within a contiguous velocity range. A study of their figs 3 and 4 reveals that the bulk of the loop is consistent with the velocity-shifted northern component, and that the bottom of the loop is delimited by the lower-velocity and brighter southern component.

We show in Fig. 4 the position–radius projection of the simulations. We see that, in both cases, two filaments emanate from the forming SMC. The actual MB may be regarded as the more nearby component, whereas the tidal counterpart to the Bridge extends more radially. Importantly, both models predict an extremely large line-of-sight depth for the SMC (including the Bridge, SMC and counter-arm) consistent with some previous numerical simulation results (e.g. Gardiner et al. 1994); and also a line-of-sight depth through the Bridge which is consistent with the ∼5 kpc line of sight measured between adjacent stellar clusters by Demers & Batinelli (1998) in the MB.

Although neither of the two models can reproduce the observations fully self-consistently, we find that the three key large-scale features in the MB are produced by these two models. This suggests that the scenario where the Bridge is the result of a tidal interaction between the Clouds and the Galaxy for the last 0.2 Gyr is essentially important in explaining fundamental properties of large-scale organization of the ISM in the MB.

The lack of exact reproduction at this stage may be due to insufficiently complex simulations, which exclude ISM feedback processes. We note that other large-scale numerical simulations, such as those by Gardiner et al. (1994), are also unable to reproduce the loop feature clearly. Future and more sophisticated models with gas dynamics and star formation will confirm whether the tidal interaction model can explain both the two kinematical properties (i.e. the bimodal kinematics and the velocity offset) and the presence of the giant H1 loop in a self-consistent manner.

4 ALTERNATIVE LOOP FORMATION SCENARIOS

Given the preliminary nature of these results in predicting the formation of the Bridge ‘loop’, it is appropriate to explore alternative processes that also may develop similar structures such as H1 ‘shells’. Processes such as stellar winds, SNe and high-velocity cloud (HVC) impacts are commonly cited in the literature as shell formation mechanisms.

Using the canonical formulations by Weaver et al. (1977) to estimate the total input energy (shell evolution powered by stellar winds) along with data on the basic characteristics of the observed loop ($R = 1.3$ kpc), and based on its observed velocity position in the ‘high-velocity’ component which has a limiting velocity dispersion of ∼30 km s$^{-1}$, we estimate an energy requirement for the shell expansion: $E_{\text{Weaver}} = 10^{53.3}$ erg. Energies of this magnitude are equivalent to that provided by stellar winds, or SNe produced from ∼100 O-type stars (Chevalier 1974). In any other larger system, an association of a few hundred stars would be unremarkable. However, OB associations numbering more than ∼10 are uncommon in the MB (Bica & Schmitt 1995; Bica, private communication), and it is not clear how such a relatively well-populated association may come to be at the observed location. For this reason, formation of the loop by stellar winds (or SNe) is considered implausible.

Works by Tenorio-Tagle & Bodenheimer (1988) and Tenorio-Tagle et al. (1986) have shown, through a variety of two-dimensional numerical simulations, how an H1 cloud infalling into a stratified gas layer can generate an expanding shell-like structure. From Tenorio-Tagle et al. (1986), we can relate the expansion energy of the hole to the kinetic energy of a hypothetical infalling cloud, via the density and radius of the cloud:

\[ n(\text{cm}^{-3}) = 9.78 \times 10^{-43} \frac{E_{\text{kin}}}{R^2 V^2}, \]

Using the kinetic energy estimated previously under the weaver formalism, $E_{\text{kin}}$(erg), we can probe the ranges of HVC properties.
that are capable of generating a hole having the same observed parameters as the Bridge loop. We find that after limiting the density of the candidate infalling HVC to $0.2 < \rho < 5 \, \text{cm}^{-3}$, according to the range of HVC densities estimated by Brüns (2003), a $0.6 \times 10^9 \, \text{M}_\odot$ cloud need only move at a velocity of $\sim -350 \, \text{km s}^{-1}$ in the LSR frame to attain the estimated kinetic energy to create the observed loop. Such a velocity is not unusual for many of the known HVC population (e.g. Wakker, Oosterloo & Putman 2002; Putman et al. 2002). Recently, Bekki & Chiba (2006) have found that massive subhaloes can create kpc-scale giant HI holes such as those seen in the western MB. These results imply that if the MB interacted with low-mass subhaloes, which are predicted by a hierarchical clustering scenario to be ubiquitous in the Galactic halo region, giant HI holes can be formed. We plan to investigate this possibility in our forthcoming papers.

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