The role of dwarf galaxy interactions in shaping the Magellanic System and implications for Magellanic Irregulars

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Accepted 2011 December 23. Received 2011 December 16; in original form 2011 November 9

ABSTRACT

We present a novel pair of numerical models of the interaction history between the Large and Small Magellanic Clouds (LMC and SMC, respectively) and our Milky Way (MW) in light of recent high-precision proper motions from the Hubble Space Telescope. Given the updated velocities, cosmological simulations of hierarchical structure formation favour a scenario where the Magellanic Clouds (MCs) are currently on their first infall towards our Galaxy. We illustrate here that the observed irregular morphology and internal kinematics of the Magellanic System (in gas and stars) are naturally explained by interactions between the LMC and SMC, rather than gravitational interactions with the MW. These conclusions provide further support that the MCs are completing their first infall to our system. In particular, we demonstrate that the Magellanic Stream, a band of HI gas trailing behind the Clouds 150° across the sky, can be accounted for by the action of LMC tides on the SMC before the system was accreted by the MW. We further demonstrate that the off-centre, warped stellar bar of the LMC, and its one-armed spiral can be naturally explained by a recent direct collision with its lower mass companion, the SMC. Such structures are key morphological characteristics of a class of galaxies referred to as Magellanic Irregulars, the majority of which are not associated with massive spiral galaxies. We infer that dwarf–dwarf galaxy interactions are important drivers for the morphological evolution of Magellanic Irregulars and can dramatically affect the efficiency of baryon removal from dwarf galaxies via the formation of extended tidal bridges and tails. Such interactions are not only important for the evolution of dwarf galaxies but also have direct consequences for the build-up of baryons in our own MW, as LMC-mass systems are believed to be the dominant building blocks of MW-type haloes.

Key words: galaxies: evolution – galaxies: interactions – galaxies: irregular – galaxies: kinematics and dynamics – Magellanic Clouds.

1 INTRODUCTION

The Large Magellanic Cloud (LMC) is the prototype for a class of dwarf galaxies known as Magellanic Irregulars. Like the LMC, these galaxies are characterized by being gas-rich, one-armed spirals with off-centre bars (de Vaucouleurs & Freeman 1972). Although there are numerous examples of Magellanic Irregulars in our Local Volume, they are rarely found about massive spirals. This has been confirmed by recent studies of the frequency of LMC analogues about Milky Way (MW) type galaxies in the Sloan Digital Sky Survey (SDSS) Data Release 7 catalogue (Liu et al. 2011; Tollerud et al. 2011). Based on similar statistics, de Vaucouleurs & Freeman

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The idea that the LMC’s evolution has not been dictated by interactions with the MW is given further credence by the distance morphology relationship exhibited by MW and M31 satellites, whereby gas-rich satellites are located at larger galactocentric radii than gas-poor spheroidals. The Magellanic Clouds (MCs), at a mere 50–60 kpc away, are notable exceptions to this relationship, leading van den Bergh (2006) to describe them as interlopers in our system. Along the same lines, recent studies indicate that the LMC is much bluer in colour relative to analogues in its magnitude range (James & Ivory 2011; Tollendorf et al. 2011). This fact is difficult to reconcile with the expected gas loss and quenching of star formation the LMC should have incurred if it were indeed a long-term companion of the MW (Greveovich & Putman 2009). These conclusions are further supported by recent proper motion measurements (Kallivayalil et al. 2006a, hereafter K1; Kallivayalil, van der Marel & Alcock 2006b, hereafter K2) which indicate that the LMC is moving ~80 km s⁻¹ faster than previously believed (Gardiner & Noguchi 1996). Given the measured energetics of the LMC’s orbit today, backward orbital integration schemes (Besla et al. 2007) and statistics from large-scale cosmological simulations (Boylan-Kolchin, Besla & Hernquist 2011; Busha et al. 2011) indicate that the LMC is likely on its first infall towards the MW. Consequently, the MW cannot have been the driver of its morphological evolution.

In this study, we ask the following: if not interactions with the MW, then what is the origin of the asymmetric appearance of the LMC and what is its connection to Magellanic Irregulars in general?

Notably, the LMC has a nearby companion, the Small Magellanic Cloud (SMC). In fact, many Magellanic Irregulars also have companions (Odewahn 1994), although the frequency of such configurations is debated (Wilcots 2009). Particularly striking examples include the Magellanic Irregular galaxies NGC 4027 (Phookun et al. 1992) and NGC 3664 (Wilcots & Prescott 2004); both have a low-mass companion to which each is connected by a bridge of gas. The LMC and SMC are also connected by a bridge of H I gas, known as the Magellanic Bridge (Kerr 1957), suggesting that interactions between dwarf pairs may hold clues to understanding the current morphology of Magellanic Irregular galaxies.

In addition to the Magellanic Bridge, the MCs are associated with both leading and trailing streams of gas, referred to as the Leading Arm and Magellanic Stream (MS), respectively. The MS extends over 150° across the southern sky (Wannier & Wrixon 1972; Mathewson, Cleary & Murray 1974; Putman et al. 2003; Nidever, Majewski & Burton 2008; Nidever et al. 2010) and has been traditionally modelled as the product of MW tides (Murai & Fujimoto 1980; Gardiner, Sawa & Fujimoto 1994; Heller & Rohlfs 1994; Lin, Jones & Klemola 1995; Gardiner & Noguchi 1996; Connors, Kawata & Gibson 2004; Bekki & Chiba 2005; Mastropietro et al. 2005; Ružička, Theis & Palouš 2009, 2010) and ram pressure stripping (Moore & Davis 1994; Mastropietro et al. 2005). A purely hydrodynamic solution cannot pull material forward to explain the Leading Arm Feature (LAF), meaning that MW tides must be invoked in some form in all of these models. However, on a first infall, MW tides are negligible until very recently; it is thus difficult to reconcile the new proper motions and updated orbits with the formation of the MS, Bridge and Leading Arm in the context of the existing scenarios.

Alternatively, Besla et al. (2010, hereafter B10) introduced a model to explain the observed large-scale gas morphology of the Magellanic System through tidal interactions between the LMC and SMC (see also Diaz & Bekki 2011a). Because MW tides are not responsible for removing material from the system, this picture is consistent with a first infall scenario. In this model, the Magellanic Bridge, Arm and Stream are hypothesized to be analogues of the classical Toomre & Toomre (1972) tidal bridge and tail scenario and should be commonly found about interacting pairs/groups of dwarf galaxies.

Here we explore whether interactions between the MCs can also account for the internal morphology and kinematics of the LMC and therefore shed light on the dynamical state of Magellanic Irregulars more generally.

In particular, the nature of the LMC’s off-centred stellar bar has been a long-standing puzzle, as it is not present in any other tracer of the interstellar medium (ISM); it is neither apparent in the H I gas disc nor a site of active star formation as traced by H α emission. Strong bars in more massive galaxies serve to funnel gas towards the centre; streaming motions and characteristic ‘S-shaped’ isovelocity contours are thus evident in their gas velocity fields. While weak large-scale streaming motions along the bar may be evident in the LMC H I velocity field (Kim et al. 1998), the expected ‘S-shaped’ isovelocity contours are not present. Interestingly, this is also true for many other Magellanic Irregulars (Wilcots 2009); bars in these systems do not appear to strongly affect the underlying gas distribution. There is also evidence that the bar may be warped relative to the LMC disc plane (Subramaniam 2003; Lah, Kiss & Bedding 2005; Koerwer 2009). Using relative distance measurements to Cepheids, Nikolaev et al. (2004) concluded that the bar is in fact located ~0.5 kpc in front of the main disc. For this reason, it has been described as a ‘levitating’ bar. Zaritsky (2004) suggests that this may be a result of viewing a triaxial stellar bulge that is embedded in a highly obscuring thick disc. Along the same lines, Zhao & Evans (2000) postulate that the off-centred bar is an unviralized structure, inclined relative to the plane of the LMC disc by as much as 25° in order to explain the microlensing optical depth observed towards the LMC. Clearly, the nature of the LMC’s bar is an ongoing subject of debate.

We posit here that a recent direct collision between the LMC and SMC has left the LMC with a warped, off-centred stellar bar and pronounced one-armed spiral. We further claim that such asymmetric structures are characteristic of Magellanic-type galaxies undergoing minor mergers. In this study, we illustrate that such a scenario is consistent with a first infall towards our MW and can simultaneously explain both the morphology and kinematics of the LMC as well as the large-scale gas morphology of the Magellanic System. Thus, Magellanic Irregulars with nearby companions should also be associated with faint extended gaseous tails and bridges. As in the Magellanic System, such features could hold ~50% of the baryonic mass of the original system, indicating that dwarf-dwarf tidal interactions are an important mechanism for the loss of baryons in low-mass systems (see also D’Onghia et al. 2009), as a consequence of resonant interactions between spinning discs (D’Onghia et al. 2010).

We stress that the goal of our study here is not to reproduce every detail of the Magellanic System, as we have not conducted a complete parameter search of all the possible orbital configurations, mass ratios and gas fractions, which influence the final outcome.

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1 Kim et al. (1998) comment on the existence of a distorted S-shaped isovelocity contour across the LMC’s minor axis. However, Olsen & Massey (2007) find that this feature straightens out when the higher proper motions are accounted for.
The aim of this investigation is rather to determine which of the observed peculiarities of the Magellanic System can be directly linked to interactions between the MCs.

Moreover, our work has broader implications for understanding the properties of accreted satellites. Minor mergers are frequent events that shape galaxies and their haloes; however, little attention has been given to the accretion of binary pairs or groups of smaller galaxies (but see Sales et al. 2007; D’Onghia & Lake 2008). This study represents a first step towards understanding the morphological evolution and gas loss rates of such galaxies immediately after their capture by a massive host. LMC-mass objects are expected to be the primary building blocks of MW-type galaxies (Stewart et al. 2008), making this study of direct relevance to our understanding of the evolution of the MW.

In this paper, we begin by outlining our methodology and introducing two possible models for the interaction history of the MCs, one of which invokes a recent direct collision between the MCs. In the subsequent sections, we discuss the resulting large-scale gas structure and internal structure and kinematics of the LMC. The results for the SMC and the expected stellar counterpart to the MS will be presented in future work.

2 METHODOLOGY

We follow the general method outlined in B10 to set up the initial galaxy models and orbits in order to reproduce the observed large-scale gaseous structure of the Magellanic System. Details about our numerical methods, initial conditions and chosen orbital parameters are described below.

2.1 Numerical methods

All of the numerical simulations performed in this work use the N-body smoothed-particle hydrodynamics (SPH) code, GADGET3 (Springel 2005). The GADGET3 code incorporates a subresolution multiphase model of the ISM that includes radiative cooling (Springel & Hernquist 2003), and incorporates a fully conservative approach to integrating the equations of motion (Springel & Hernquist 2002). Star formation from the cold phase (i.e. all cold gas – no distinction is made between atomic and molecular components) follows a Schmidt volume density law \( \rho_{\text{SFR}} \propto \rho_{\text{gas}}^3 \) (with \( N = 1.5 \)) that is normalized to approximate the star formation rate (SFR) of the MW. A local threshold volume density cut-off of 0.004 \( M_\odot \) \( \text{pc}^{-3} \) is adopted, below which stars do not form. As pointed out by many authors (e.g. Robertson & Kravtsov 2008; Gnedin & Kravtsov 2010; Hopkins, Quataert & Murray 2011; Kuhlen et al. 2011), such a star formation prescription is likely inappropriate for dwarf galaxies. We discuss the implications of our adopted prescriptions to our results in Section 6.1.

Stellar feedback in the form of galactic winds is not employed in our simulations; however, we comment on the relative importance of outflows to the formation of the MS in Appendix B.

We note that the reliability of SPH for cosmological simulations has recently been called into question by Vogelsberger et al. (2011), Sijacki et al. (2011), Keres et al. (2011), Torrey et al. (2011) and Bauer & Springel (2011). However, comparisons between SPH and calculations done with the moving mesh code AREPO (Springel 2010) show good agreement for applications involving galaxy collisions, at least when the subresolution model mentioned above is used to represent star-forming gas (Hayward et al., in preparation). The tests done by, e.g., Sijacki et al. (2011) indicate that SPH can fail when applied to situations in which gases in very different phases are in motion relative to one another. The use of an effective equation of state to describe the ISM effectively circumvents this issue because the different phases of the gas are not modelled explicitly.

2.2 Initial conditions

The initial conditions for the construction of the LMC and SMC galaxies used for all models are outlined in Table 1. As in B10, the total initial mass of the LMC is determined using current halo occupation models to relate the observed stellar mass of the LMC to its original halo mass before infall into the MW halo (Guo et al. 2010). Reflecting their stellar mass ratio, the SMC is then chosen to be 10 times less massive than the LMC. Consequently, the MCs are modelled here to have infall masses an order of magnitude larger than employed in previous models. The number of particles of each component (gas, stars, dark matter) is chosen such that the mass resolution per particle of a given type is roughly the same in both galaxies.

The SMC is modelled with an extended gaseous disc with a scale length three times that of the stellar component. Much larger ratios are common for isolated dwarfs found in voids (Kreckel et al. 2011), and neutral hydrogen observations of SMC-like dwarfs with the Westerbork Synthesis Radio Telescope by Swaters et al. (2002) find H\(_1\) disc scale lengths ranging from 1.4 to 4.5 kpc (Connors et al. 2008), making this study of direct relevance to our understanding of SMC-less groups of isolated dwarfs. Other changes in parameter values are minor and reflect attempts to match various observed mass constraints for the MCs (see Table 2).

Table 1. LMC/SMC initial conditions.

| Property       | LMC          | SMC          |
|----------------|--------------|--------------|
| \( M_\star \) (\( M_\odot \)) | \( 2.5 \times 10^9 \) | \( 2.6 \times 10^8 \)^a |
| \( M_{\text{gas}} \) (\( M_\odot \)) | \( 1.1 \times 10^9 \) | \( 7.9 \times 10^8 \) |
| \( \rho_{\text{gas}} \) | 0.3 | 0.75 |
| \( M_{\text{toal}} \) (\( M_\odot \))^b | \( 1.8 \times 10^{11} \) | \( 2.1 \times 10^{10} \) |
| \( R_{\text{S20}} \) (kpc)^b  | 117.1 | 57.1 |
| \( C \) | 9 | 15 |
| \( r_\text{S} \) (kpc)^b  | 13.0 | 3.8 |
| \( r_\text{H} \) (kpc)^b  | 21.4 | 7.3 |
| Stellar disc scale length (kpc) | 1.7 | 1.1^a |
| Gas disc scale length (kpc) | 1.7 | 3.3 |
| Gravitational softening gas/stars (kpc) | 0.1 | 0.1 |
| Gravitational softening halo (kpc) | 0.29 | 0.29 |
| \( N_{\text{stars}} \) | \( 10^6 \) | \( 10^5 \) |
| \( N_{\text{gas}} \) | \( 3 \times 10^5 \) | \( 3 \times 10^4 \) |
| \( N_{\text{halo}} \) | \( 10^6 \) | \( 10^4 \) |
| \( q \) | 0.3 | 0.3 |

^a Note that the initial stellar mass and stellar disc scale length chosen for the SMC deviate from the values adopted in B10. Here the disc is chosen to be more extended in order to increase the number of stars removed by LMC tides. Other changes in parameter values are minor and reflect attempts to match various observed mass constraints for the MCs (see Table 2).

^b The gas fraction relative to the total disc mass (stars + gas). The gas fractions of isolated dwarf galaxies are known to be large (e.g. Geha et al. 2006).

^c The total mass of the LMC/SMC at infall is determined using the observed stellar mass of the LMC (SMC) \( M_\ast = 3 \times 10^9 M_\odot (3 \times 10^8 M_\odot) \) (van der Marel et al. 2002; Stanimirović, Staveley-Smith & Jones 2004) and the relations from Guo et al. (2010). The total halo mass used to define the Hernquist dark matter profile is then \( M_{\text{halo}} = M_{\text{total}} - M_\ast - M_{\text{gas}} \).

^d The radius where the average enclosed density is 200 times the critical density of the universe.

^e The scale radius for the NFW profile (\( r_\text{S} \)), which is used to define the scale radius of the Hernquist profile (\( r_\text{H} \)), following Springel et al. (2005).

^f The effective equation of state parameter, \( q \), defines the pressurization of the ISM following Springel et al. (2005).

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et al. 2004). Our adopted scale length of 3.3 kpc is consistent with the upper end of the observed range.

The LMC is modelled with gas and stellar discs with the same scale length, rather than with an extended gaseous disc. In reality, the interaction with the ambient hot gaseous halo of the MW would serve to truncate the LMC’s extended gas disc. The scale height of the stellar disc is taken as 0.2 of the disc scale length. The modelled scale height of the LMC’s stellar disc is thus initially $z_0 = 0.34$ kpc (the observed value today is $R_{200} = 1.4$ kpc and $z_0 = 0.27$ kpc; van der Marel et al. 2002). The gaseous disc height is determined by self-gravity and the pressurization of the ISM, as prescribed by the chosen effective equation of state (Springel et al. 2005).

2.3 Orbit of the SMC about the LMC and definition of models

Following the method outlined in B10, the MCs are evolved as an isolated interacting binary pair over a period of $\sim 7$ Gyr since the SMC first crossed within $R_{200} = 117$ kpc of the LMC.

The SMC is placed on an eccentric orbit about the LMC ($e_{\text{cc}} = 0.7$). Higher orbital eccentrics for the SMC result in fly-by encounters between the MCs, while lower values cause the SMC’s orbit to decay too quickly.

The simulation is stopped at characteristic points in time, defining two models for the orbital history of the SMC about the LMC, referred to as Model 1 and Model 2. Model 1 is stopped after 5.1 Gyr and Model 2 after 5.9 Gyr. Thus, Models 1 and 2 differ based on the number of passages the SMC has completed about the LMC. In Model 1, the SMC has completed two passages about the LMC, whereas in Model 2 it has completed three. The stopping times are chosen such that 1 Gyr after this time, the LMC will have travelled from a distance of 220 kpc ($R_{200}$ for the MW) to its current location and the SMC will have completed the desired number of orbits about the LMC.

The choice of these two models is motivated by the overarching goal of this study to assess the role of interactions between the MCs to their evolution. Given the chosen LMC/SMC mass ratio of 1:10, it is unlikely that the SMC could have survived more than three passages about the LMC, making Model 2 a maximal interaction scenario. Model 1 is very similar to the solution presented in B10—the analysis of such a model is a direct extension of the B10 work. Tidal forces between the MCs have been acknowledged as playing an important role in the formation of the MS in many previous studies. In fact, in Connors, Kawata & Gibson (2006), the tidal force from the LMC on the SMC dominates over MW tides for most of the SMC’s orbit. However, to explain the LAF and extent of the MS, MW tides have been invoked in all of these studies. Instead, here and in B10 we illustrate how such extended structures can form without requiring the MCs to complete an orbit about the MW.

The orbit of the SMC about the LMC in Model 1 and Model 2 is plotted in the top panel of Fig. 2. The black line indicates the evolution of the system in isolation (no MW potential) and is continued 1 Gyr past the respective stopping point for each.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The initial rotation curve is plotted for the LMC (left) and SMC (right). The different lines indicate the contribution from the dark matter halo (green, dashed) and the disc (red, dotted). The solid black line indicates the total rotation curve.

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model. The red line shows how the orbit of the SMC is modified if instead the binary pair is captured by the MW after the stopping point.

In Model 1, MW tides work to keep the LMC and SMC further apart than they would have been in isolation. In Model 2, the opposite occurs; the MW’s gravitational pull forces the SMC to collide directly with the LMC. The distinct outcomes occur because of differences in the SMC’s separation from the MW relative to its separation from the LMC at the pericentre of its orbit about the MW. At pericentre, the SMC is closer to the LMC in Model 2 than in Model 1 (see Fig. 4).

The bottom panels of Fig. 2 show the gas distribution of the LMC/SMC at the stopping points for each model as contours plotted over the stellar distribution. After 5.1 Gyr (stopping point for Model 1), the SMC is at the apocentre of its second orbit about the LMC. After 5.9 Gyr (stopping point for Model 2), the SMC is just completing its second orbit. As outlined in B10, a tidal bridge and extended tail form as a result of the action of LMC tides on the SMC; these features form before the system is captured by the MW.

2.4 Orbit of the MCs about the MW

At the stopping time (5.1 Gyr for Model 1 and 5.9 Gyr for Model 2), the isolated MC pair is placed at $R_{200} = 220$ kpc of the MW. This occurs after 5.1 Gyr for Model 1 and after 5.9 Gyr for Model 2; these times are referred to as the stopping times for each model. Bottom panel: the gas column density of the isolated LMC–SMC system is projected in the binary orbital plane as contours over the stellar distribution at the stopping time for Model 1 (left) and Model 2 (right). Gas contours span a range of $10^{18} – 10^{20}$ cm$^{-2}$, where each contour represents an increase in column density by a factor of 1.5. These images thus depict the gas distribution of the simulated system before it is influenced by the MW’s gravitational potential. An extended tail of gas is stripped from the SMC and a bridge of gas connects it to the LMC in both models (see also fig. 1 of B10).
In Model 2, the SMC completes an additional passage about the LMC since entering the virial radius, versus in Model 1. This additional passage results in a direct collision between the MCs and the formation of a new bridge. Tidal bridges and tails are formed at each pericentric passage of the SMC about the LMC (Toomre & Toomre 1972). Thus, in Model 2, the bridge connecting the MCs will have formed $\sim 100$ Myr ago, during this direct collision (separation approaching zero).

2.5 Comparison of modelled orbits with data

For each model, the initial velocities and positions of the LMC and SMC at $R_{\text{200}} = 220$ kpc from the MW and their final values today are summarized and compared to data from K1 and K2 in Table 2. The proper motion error space for the K1 HST proper motion measurements of the LMC is indicated in Fig. 5. Overplotted are various other measurements for the LMC’s proper motion and the simulated Model 1 and 2 results. The final LMC velocities and positions are designed to be within $1\sigma$ of the observations in both models. The differences between the two models are the orbital parameters for the SMC.

In Model 1, the SMC velocity is significantly larger than that indicated by the HST proper motions of K2. In Model 2, the SMC velocities are in better agreement; however, the separation between the LMC and SMC is smaller than observed (by about 10 kpc). As such, the line-of-sight velocity and proper motions for the SMC are also different than observed.

While the SMC velocities and positions are not perfect matches to the observations, it is unlikely that significantly new insight would be gained as to the physical processes at work if an exact solution were found. Slightly different choices of orbital parameters and timing in the orbit can change the SMC’s final position and velocity, but not the physical picture. This is practically illustrated by comparing the resulting large-scale gas distribution in Model 1 and 2 (see Section 3); despite differences in the SMC orbital properties, the same overall scenario has produced similar global features (i.e. a Leading Arm, Bridge and Stream). To match the exact properties of the Magellanic System, a more detailed study, varying orbital parameters, LMC/SMC mass ratios, MW mass, etc., is required; this is beyond the scope of the present study.

We have obtained another epoch of data with Wide Field Camera 3 (WFC3), resulting in an average time baseline of 7 years (Kallivayalil et al., in preparation). These new data are expected to reduce the errors on the proper motions by a factor of 3, potentially narrowing the SMC’s parameter space. We note that, within this error space, the exact choice of LMC and SMC velocity today will
The Magellanic System

3 LARGE-SCALE GAS MORPHOLOGY

The resulting large-scale gas distributions in Models 1 and 2 are shown in a Hammer–Aitoff projection in Fig. 6. In both models, the final gas distribution can be described as an extended tail, a leading component and a bridge of gas connecting the two galaxies. As such, the main components of the Magellanic System are reproduced by both models. Moreover, in both cases the simulated stream stretches $\sim 150^\circ$ across the sky, as observed (Nidever et al. 2008).

In Fig. 7, the simulated stream is plotted in Magellanic Coordinates, a variation of the galactic coordinate system where the Stream is straight (Nidever et al. 2008). In both models, the simulated stream deviates away from the projected location of the past orbits on the plane of the sky, as expected according to the recent proper motions (see e.g. fig. 8 in Besla et al. 2007). The deviation is a natural result of the proposed stream formation mechanism. It occurs largely not alter the physical picture presented in this work, which is that tidal interactions between the two Clouds are the main driver for their morphological and kinematic evolution.

Table 2. Initial and final orbital parameters: model 1 and 2.

| Galaxy | Parameter | Model 1 | Model 2 | Observed today |
|--------|-----------|---------|---------|---------------|
|        | (x, y, z) (kpc) | At $R_{200}$ | Today | At $R_{200}$ | Today | K1 and K2 |
| LMC    | (35, 203, -63) | (-1, -40, -25) | (48, 198, -85) | (-1, -42, -26) | (-0.8, -41.5, -26.9) |
|        | (-14, -157, -29) | (-72, -267, 250) | (-17, -160, -29) | (-82, -263, 249) | (-87 ± 12, -268 ± 11, 252 ± 16) |
| SMC    | (5, 243, -62) | (18, -46, -46) | (56, 193, -90) | (6, -39, -35) | (15.3, -36.9, -43.3) |
|        | (6, -146, -70) | (-88, -384, 246) | (-51, -289, 88) | (-66, -258, 198) | (-87 ± 48, -247 ± 42, 149 ± 37) |
|        | 215 | 201 | 146 ± 0.6 |

The SMC proper motions are not included in this table: since the line-of-sight velocities are not well matched to the observations, the proper motions cannot be meaningfully compared to the data.
Figure 5. Concentric circles indicate the 4σ error space for the K1 proper motion error space for the LMC (where the mean value is indicated by the X). The asterisk indicates the mean of all proper motion estimates for the LMC prior to 2002 (van der Marel et al. 2002). The circled dot indicates the recent proper motion estimate by Vieira et al. (2010) and the open square shows the reanalysis of the K1 proper motion data by Piatek, Pryor & Olszewski (2008). The red triangle and blue square indicate the proper motion of the LMC today in Model 1 and 2, respectively. These values were chosen to closely match the K1 data.

because the Stream is removed in the binary LMC–SMC orbital plane by LMC tides. This binary plane is not parallel to the LMC–SMC–MW orbital plane; thus, the Stream is not coincident with the orbit of the MCs about the MW. A second factor is the orientation of the SMC’s disc; the location of the simulated stream can be modified by changing this angle. In both of these models, the SMC disc is initially oriented 90° with respect to the SMC–LMC orbital plane. The deviation between the simulated stream and the orbits is more pronounced in Model 1 than in Model 2. However, this could be altered if the SMC disc were oriented differently initially and is not a physical distinction between the models; the magnitude of the offset is a tunable parameter. Note that this offset is not expected in a ram pressure solution for the Stream, as the material should be removed along the direction of motion (see Appendix A).

The structure of the LAF is distinct in each model. In Model 1, the LAF represents material that was stripped from the SMC on earlier passages and captured by the LMC. Since this material is bound to the LMC, it does not extend further than 50° (see Fig. 7). In Model 2, the LAF is better described as a tidal tail or loop, resulting from tidal stripping of the SMC on its most recent orbit about the LMC. The tidal tail gains energy and deviates to larger distances away from the SMC’s orbit (e.g. Choi, Weinberg & Katz 2007). The resulting simulated LAF in Model 2 spans 80°–90° across the sky, which is larger than observed. Unlike the Stream, this material is leading to the MCs and so will experience a significant ram pressure headwind. Consequently, its final appearance, position and angular extent on the plane of the sky cannot be well captured without including hydrodynamic effects (see Appendix A; Binney & Fraternali 2011).

Model 2 does illustrate, however, that the observed 70° span of the LAF (Nidever et al. 2010) can be reproduced without invoking a previous orbit about the MW.

The MS is observed to have a pronounced H1 column density gradient along its extent (Putman et al. 2003; Brüns et al. 2005; Nidever et al. 2010). The maximum gas column density along the simulated Magellanic System is determined from Fig. 7 and plotted as a function of Magellanic Longitude in Fig. 8. Both models underestimate the observed values, which are indicated by the solid red line (Brüns et al. 2005). There are a number of possible explanations for this discrepancy. This problem could be alleviated if the gas reservoir in the SMC were depleted less efficiently at earlier times, for example if the SMC’s gas disc were initially less extended or if star formation was not quite so efficient. Ram pressure stripping has also not been modelled and could also increase the amount of gas removed as the MCs get closer to the MW. Furthermore, hydrodynamic instabilities are not well modelled with SPH (Agertz et al. 2007; Sijacki et al. 2011), and so clumping of the gas is not captured in these simulations. This is a process that will clearly influence the resulting gas column density in the Stream (Bland-Hawthorn et al. 2007; Nigra et al. 2010).

At the same time, there are notable consistencies between the models and the data. Nidever et al. (2010) find that the column density along the LAF is fairly constant along its ~70° span (~4 × 10^{21} cm^{-2}); this is true for Model 2. The column density in the bridge in Model 2 also matches the observations: the maximum column density in the Bridge is 1.64 × 10^{21} cm^{-2} (Brüns et al. 2005); the simulated bridge column density for Model 1 is too low. Also in Model 2, the simulated column density of the SMC is higher than that of the LMC, as observed (Brüns et al. 2005, the maximum column density is 5.45 × 10^{21} and 9.98 × 10^{21} cm^{-2} for the LMC and SMC, respectively).

There is a well-defined velocity gradient along the length of the Stream (Putman et al. 2003; Nidever et al. 2008), ranging from 200 km s^{-1} near the Clouds to ~400 km s^{-1}. The simulated results are plotted in Fig. 9 for both models. The observed line-of-sight velocities along the MS (yellow line) and the rest of the system are well traced by Model 1. Model 2 also reproduces the observed range of velocities, but the slope of the velocity gradient along the MS is not well matched to the data.

Given that the only difference between Model 1 and Model 2 is the SMC’s orbital parameters, it is doubtful that this discrepancy in predicted velocities owes to missing physics. Rather, a detailed search of the SMC’s orbital parameter space will likely yield better matches for Model 2. It is possible that gas drag effects (not modelled here) may also modify the velocity profile – particularly in the LAF, where the velocities are currently too high in Model 2.

No direct distance measures exist for the MS, as no stellar counterpart has yet been identified (Guhathakurta & Reitzel 1998). Jin & Lynden-Bell (2008) present a geometrical method to determine distances along streams with well-defined velocity gradients. Using this method, they find the tip of the 100° long Stream defined in Putman et al. (2003, i.e. not including the extension recently described by Nidever et al. 2010) to be located at 75 kpc from the Galactic Centre. The line-of-sight distances of the gas in the simulated Magellanic System are plotted in Fig. 10. The stream produced by Model 1 is generally closer (80–150 kpc) than that of Model 2 (80–230 kpc). Both simulated streams are further away than predicted by the Jin & Lynden-Bell (2008) method; however, gas drag and changes in the model parameters (such as increasing the MW mass) can alter the distance to the simulated stream.
4 LMC MORPHOLOGY

In this section, we study in detail the resulting structure of the simulated LMC stellar and gaseous discs in our two models of the large-scale gas distribution of the Magellanic System.

Fig. 11 shows the LMC’s stellar disc in Model 1 (left) and Model 2 (right) in our line-of-sight view. The RA and Dec. coordinate grid is overplotted in green across the face of the disc. In both models, the LMC disc is inclined $\sim 35^\circ$ with respect to the plane of the sky, as observed (i.e. despite the recent collision of the SMC in Model 2, the inclination of the LMC’s disc remains unchanged).

The Model 1 disc is fairly uniform and symmetric. In Model 2, however, there are perturbations induced in the LMC’s stellar disc by the recent encounter with the SMC. In particular, there are significant distortions in the north-east. Only LMC stellar particles are plotted in these images, and so these structures are in the plane of the LMC disc and do not represent tidal debris from the SMC. Such structures are observed in deep observations of the periphery of the LMC’s disc (de Vaucouleurs & Freeman 1972; Martinez-Delgado et al., in preparation).

The initial LMC disc was bar unstable, and so the bar feature in both models was present since the beginning of the simulation – it was not induced by external tidal perturbations from the SMC or MW. Interestingly, in Model 2, the bar of the LMC is now off-centred relative to the disc, as observed. No such perturbations are observed in Model 1: without a close encounter, the LMC looks like a symmetric spiral disc galaxy and it is doubtful that such a galaxy would be classified as a Magellanic Irregular galaxy.

In Figs 12 and 13, we take a closer look at the LMC’s gas and stellar disc by deprojecting the disc from the line-of-sight frame into a Cartesian coordinate system centred on the LMC disc plane for both Model 1 and Model 2. Only particles associated with the LMC are plotted. The images are centred on the peak of the stellar density distribution (i.e. the photometric centre).
Figure 7. The total gas distribution of the simulated Magellanic System for Model 1 (top) and Model 2 (bottom) is plotted in Magellanic Coordinates. The orbital trajectory of the LMC (SMC) is indicated by the solid (dashed) yellow line. The actual location of the MS is roughly traced by the solid white line. The white circle represents the observed radius of the LMC.

Figure 8. The maximum total gas column density of the simulated Magellanic System is plotted as a function of Magellanic Longitude for Model 1 (black line) and Model 2 (green thick line). The red lines indicate the observed maximum H I column density from the Brüns et al. (2005) data set for each marked region: MS stands for Magellanic Stream and LAF for Leading Arm Feature. The various roman numerals refer to specific sections of the MS/LAF as defined in Putman et al. (2003) and Brüns et al. (2005). Neither model reproduces the observed H I column density gradient in the MS.

In Model 1, the bar of the LMC is clearly visible in both the stellar and gaseous discs. This is in disagreement with the observed H I maps of Kim et al. (1998): there is no distinguishable bar structure in the observed global H I emission that is comparable to the optical bar. The results for Model 2 illustrate the consequences of a recent (100–300 Myr ago) direct collision between the LMC and SMC. In this scenario, Model 1 represents the state of the LMC disc before the collision occurred, where the LMC is a symmetric barred spiral (SB). After the collision, the bar has become off-centred with respect to the underlying disc and it has almost disappeared from the gas disc of the LMC. The reason becomes clear when the disc is viewed edge-on along the x-axis. The bar has become warped by $\sim 10^\circ$–$15^\circ$ relative to the LMC disc plane and is therefore inefficient at funnelling gas in the way it could in Model 1. This warp of the bar is less extreme than that required by models such as Zhao & Evans (2000) for the microlensing optical depth and may be consistent with the observations of Subramaniam & Subramanian (2009). The simulated offset bar is also consistent with the structure of the observed bar, which is described as a cigar-shaped structure with dimensions of $1 \times 3$ kpc.

From the edge-on view of the Model 2 gas disc, it is clear that LMC gas particles have been pulled out of the disc by the passage...
Figure 9. The line-of-sight velocities for the total gas distribution of the simulated Magellanic System are plotted as a function of Magellanic Longitude for Model 1 (top) and Model 2 (bottom). The yellow line is a fit to the data of Nidever et al. (2010). The modelled line-of-sight velocities along the past orbit of the LMC (SMC) are plotted as the solid (dotted) white line.

Figure 10. The line-of-sight distances for the gas distribution of the simulated system are plotted as a function of Magellanic Longitude for Model 1 (left) and Model 2 (right). The modelled line-of-sight distance along the orbit of the LMC (SMC) is plotted as the solid (dashed) yellow line. The solid red line indicates the distance estimate from Jin & Lynden-Bell (2008).
of the SMC through the LMC. This causes the appearance of a gaseous ‘arm’ in the face-on view of the disc. Such ‘arms’ are seen in the LMC gaseous disc (Kim et al. 1998) and are believed to be related to the Magellanic Bridge and LAF (Nidever et al. 2008). In our interpretation, at least one of these ‘arms’ is extraplanar and located behind the LMC disc. The fact that LMC gas is removed from the disc towards the Bridge indicates that the formation of the Magellanic Bridge has been aided by hydrodynamic gas drag. It is not purely a tidal feature. The Bridge is known to be quite metal poor along two sightlines towards early-type stars (see Table B1 and Lehner et al. 2008). However, a full census of the metallicity across the Bridge does not yet exist. Regardless, it is clear that LMC gas cannot have contaminated the entirety of the Bridge. The Model 2 scenario predicts that the majority of the Bridge material originated from the SMC, but there should be some contribution from LMC gas that increases in importance with proximity to the LMC. Model 2 thus predicts that Bridge material towards the LMC should be increasingly metal enriched. This should not be true in Model 1.

In the edge-on view of the Model 1 disc, the gas disc appears to be tilted relative to the stellar distribution. This is likely because of the infall of gas from the SMC that forms the Magellanic Bridge. The outer stellar and gas discs in Model 2 are significantly warped and distorted in the edge-on view. The true disc is also observed to be both flared (Alves & Nelson 2000) and warped (van der Marel & Cioni 2001; Olsen & Salyk 2002; Nikolaev et al. 2004). Such results are in keeping with a study of Magellanic-type spirals by Wilcots, Lehman & Miller (1996), who also suggest that the observed lopsidedness in their H$_i$ discs may be a result of minor mergers.

In Model 2, the gas disc has also formed a pronounced arc in the upper right. Since our star formation prescriptions depend sensitively on the gas density, this arc of gas will also be actively forming stars (see Section 6.1), giving the LMC the appearance of a one-armed spiral. A number of numerical studies have been conducted on the resulting structure of a large galaxy after a direct collision with a smaller companion in the context of explaining the origin of ring galaxies (Lynds & Toomre 1976; Weil & Hernquist 1993; Struck 1997). In particular, Struck (1997) finds that, in some cases, a one-armed spiral structure can be excited in the larger galaxy. Also, Bekki (2009) explored a scenario where the LMC bar becomes off-centre as a result of a recent encounter with a dark $10^6$ M$_\odot$ companion. The specific asymmetries induced depend sensitively on the mass ratio, inclination and the location of the smaller companion’s passage through the larger galaxy. A future study will explore these parameters in depth in the context of the LMC–SMC encounter and assess the longevity of the resulting asymmetric structures. For example, Levine & Sparke (1998) have illustrated that disc lopsidedness can be long-lived if the disc is displaced from the centre of the dark matter potential and spinning in a sense that is retrograde to its orbit about that centre.

Finally, we note that while we have not discussed the results for the SMC in detail, the simulated SMC morphology in Model 2 is consistent with the observations of a ‘bar’-like main body with a stellar wing leading towards the LMC and a significant line-of-sight depth. We will discuss these results in depth in a future paper (Besla et al., in preparation).

5 LMC KINEMATICS

The internal kinematics of the LMC has been quantified by many tracers. The LMC’s rotation curve rises roughly linearly to a radius of $\sim$4 kpc, after which it stays flat at a value of $V_{rot}$. The observed rotation curve has been noted to peak at different values depending on the kinematic tracer being studied. The H$_i$ kinematics yield $V_{rot} = 80 \text{ km s}^{-1}$ (Staveley-Smith et al. 2003a), data from red supergiants give $V_{rot} = 107 \text{ km s}^{-1}$ (Olsen & Massey 2007) and carbon stars yield $V_{rot} = 61 \text{ km s}^{-1}$ (van der Marel et al. 2002). However, recently Olsen et al. (2011) examined the kinematics of a combined population of massive red supergiants, oxygen-rich and carbon-rich asymptotic giant branch (AGB) stars in the LMC. After correcting for the LMC’s space motion and the asymmetric drift in the AGB population, they find a consistent rotation curve between all kinematic tracers with $V_{rot} = 87 \pm 5 \text{ km s}^{-1}$. This is in accord with the H$_i$ rotation curve and the initial value adopted in this study ($\sim 95 \text{ km s}^{-1}$).

The LMC disc initial conditions (gas fraction, equation of state) are chosen such that the LMC kinematics are representative of a symmetric, bar-unstable disc galaxy. It remains to be seen whether
MW tides will introduce kinematic anomalies in the disc in a first infall scenario, or, perhaps more significantly, whether the LMC can retain a kinematically stable disc after a direct collision with the SMC (i.e. in Model 2).

In Figs 14 and 15, the kinematics of the LMC disc in Models 1 and 2, respectively, are broken down for various kinematic tracers: gas (top panel), young stars (middle) and old stars (bottom), in the line-of-sight frame. In each panel, the disc is centred on the stellar centre of mass. The centre panels show the surface density of the tracer population. A slit is placed along the largest velocity gradient of the LMC’s older stellar distribution and is defined as the major kinematic axis (red). A second slit is placed 90° with respect to the major axis and referred to as the ‘minor’ kinematic axis (blue). The position angle of the kinematic major axis of the simulated disc for Model 1 is 55° anticlockwise from the x-axis in all panels and 50° for Model 2. The line-of-sight velocities along the slits are plotted in the left-hand panel. The right-hand panel shows the full line-of-sight velocity field. The middle and right boxes are 18 kpc a side.

**Figure 12.** The gas (left) and stellar (right) density of the LMC disc for Model 1. Top: face-on view (x, y plane). Middle: edge-on view along the x-axis. Bottom: along the y-axis. Both the gas and stellar projections have a centred, in-plane bar.
Figure 13. Same as Fig. 12 but for Model 2. The stellar bar is clearly off-centred and warped relative to the stellar disc; it is also absent in the gas. The SMC’s orbit in an LMC-centric frame is overplotted (dashed line) in the middle and bottom panels of the LMC’s gas distribution. Various times are also marked along the SMC’s past orbit. The SMC collides with the LMC 100 Myr ago and the SMC’s current position is marked. An extraplanar stream of gas is pulled out from the LMC by the passage of the SMC.

whereas the left box is scaled to the length of the slit (16 kpc along the x-axis).

In both models, the LMC disc retains a pronounced velocity gradient along the same major axis; perhaps surprisingly, the LMC disc retains a well-defined rotation curve despite a direct collision with the SMC. Indeed, Hopkins et al. (2008, 2009) showed that discs can survive even a 1:1 mass ratio major merger. However, the disc kinematics in Model 2 are more distorted than in Model 1, particularly the zero velocity field.

There are observed asymmetries in the LMC’s gas and stellar kinematics. It has long been noted that the H I kinematic centre is offset by ∼1 kpc from both the stellar kinematic and photometric centre, which is roughly centred on the stellar bar (as illustrated in Cole et al. 2005). However, upcoming work by Kallivayalil et al.
Figure 14. The kinematics of the simulated LMC’s gaseous disc (top), young stellar disc (<1 Gyr; middle) and old stellar disc (>1 Gyr; bottom) in Model 1 are illustrated in the line-of-sight frame (north to the top, east to the left; the SMC is located to the south-west). The right-hand panels show the line-of-sight velocity field, where the centre-of-mass velocity of the respective kinematic tracer has been subtracted. Density contours and major axis slit location are also indicated. The colour gradient denotes material moving towards (blue) and away (red) from the observer. The central panels show the surface density of the tracer, with density contours overplotted. The central and right-hand panel boxes span 18 kpc a side. Each box is centred on the stellar density peak. Slits are placed along the major (red) and minor (blue) stellar kinematic axes as indicated. The major kinematic axis slit is inclined 55° anticlockwise from the x-axis in all panels. The minor kinematic axis is placed 90° with respect to the major axis, although in practice this does not exactly trace the zero velocity regions. Note that even if the gas kinematics are being examined, the red slits still denote the locations of the stellar kinematic axes. In the left-hand panel, the line-of-sight velocities are plotted along the slit. The dashed vertical line indicates the location of the peak stellar density (photometric centre); in Model 1 it is coincident with the kinematic centres of all tracers.

(in preparation) using a third epoch of HST data provides proper motions of high enough accuracy to independently constrain all parameters of the LMC rotation field and geometry, including the dynamical centre. The best-fitting stellar dynamical centre from the proper motions agrees with the H I dynamical centre determined by Kim et al. (1998), but remains offset from the photometric centre (van der Marel & Kallivayalil, in preparation).

Each panel in Figs 14 and 15 is centred on the peak of the stellar density of the simulated LMC disc, i.e. the photometric centre. In Model 1, the stellar density peak is coincident with the kinematic centres of all tracers (vertical dashed line in the left-hand panel crosses zero where the major slit velocities do). Thus, contrary to observations, the stellar and gas kinematic centres are coincident with the photometric centre and the centre of the stellar bar.

In Model 2, the zero velocity field of the stars and gas is twisted such that the velocity gradient does not cross zero at the location of the stellar density peak.

The kinematic centres of all tracers are offset by about 1 kpc from the photometric centres, as observed. However, the gas and stellar kinematics are somewhat discrepant from each other. This

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Figure 15. The same as in Fig. 14, except for Model 2. The kinematic major axis (red) is inclined 50° anticlockwise from the x-axis in all panels. In the left-hand panel, it is clear that the kinematic centres of all tracer populations are coincident, but not with the photometric centre (dashed vertical line). Furthermore, the shape of the velocity field as traced by gas versus stars is different across the face of the disc. This is illustrated by the inclusion of a new slit (in green), placed 1 kpc above the major axis. The line-of-sight velocities of the gas along the ‘New’ slit deviate from their stellar counterpart. This offset is likely a result of the warped stellar bar.

is illustrated by placing a third slit 1 kpc above the major axis (illustrated in the right-hand panel of Fig. 15, in green). The old and young stellar line-of-sight velocities along this slit are similar to those along the original major axis. The gas line-of-sight velocities, on the other hand, have changed, crossing the zero axis roughly 1 kpc further away than that seen for the stars. This implies that the shape of the zero velocity field across the face of the gaseous and stellar discs is different and is likely a result of the warped stellar bar. Note that neither model predicts strong differences in the rotation curves traced by the young (<1 Gyr) and older stellar populations, as expected from Olsen et al. (2011).

Again, the simulated SMC kinematics will be presented in a forthcoming paper. However, we mention here that the resulting kinematics are much more consistent with Model 2 than Model 1. It appears that a direct collision with the LMC is required to erase the initial velocity gradient in the older stellar population. Zaritsky et al. (2000) were unable to find a pronounced velocity gradient in the red giant branch (RGB) population within a radius of 2 kpc of the centre of mass, despite the existence of a 60 km s$^{-1}$ velocity gradient in the gas (Stanimirović et al. 2004). In our simulations, the gas is able to cool, since it is dissipative, and the original gas disc survives the tidal shocks resulting from the direct impact with the LMC, whereas the older stellar population does not. In Model 1 (no direct impact with the LMC), there is always a pronounced gradient in both the stellar and gaseous components of the SMC.

6 DISCUSSION

In this study, we have shown that it is possible to explain the nature of the LMC’s off-centre stellar bar (Section 4) and gas and stellar kinematics (Section 5) in a model that self-consistently reproduces the general large-scale gas morphology of the Magellanic System.
(Section 3) in a first infall scenario. To do this, we invoked a recent direct collision between the LMC and SMC (Model 2). Here we discuss some of the testable consequences of such a scenario.

Note that the resulting simulated SMC kinematics and structure and an expected stellar counterpart to the MS will be discussed in upcoming papers.

6.1 The recent star formation history of MCs

A direct recent collision between the LMC and SMC would likely leave notable marks in the star formation histories (SFHs) of both of these galaxies. A correlated burst of star formation during such a recent encounter has been theorized in many previous numerical studies (e.g. Gardiner & Noguchi 1996; Bekki & Chiba 2005, 2007). Observationally, there is significant debate over the existence of correlated bursts of star formation within both galaxies. Harris & Zaritsky (2009) claim that the total SFR in the LMC was higher than average \( \sim 100 \) and 500 Myr ago and in the SMC at \( \sim 60 \) and 400 Myr ago. Other authors claim that the LMC shows global enhancements \( \sim 125 \) and 800 Myr ago (Pietrzynski & Udalski 2000a) and in the SMC at \( \sim 100 \) Myr only (Pietrzynski & Udalski 2000b).

The general consensus does appear to be that both galaxies show a steadily increasing SFR over the past Gyr (McCumber, Garnett & Dufour 2005; Harris & Zaritsky 2009; Noël et al. 2009). Testing this scenario reliably depends on the accuracy of the timing of the collision/interactions between the LMC/SMC and the adopted star formation prescriptions.

We can bracket the time range for this impact to be within 100–300 Myr. The upper limit on the collision time-scale comes from the oldest detected stellar populations in the Magellanic Bridge, which are believed to form in situ (Harris 2007) and thus mark the formation of time of the Bridge. As such, given the model parameter uncertainties, we cannot use the models here to definitively predict the timing of the collision and consequent star formation.

The exact timing of the collision is strongly dependent on model parameters. In the presented Model 2, the most recent collision occurred \( \sim 100 \) Myr ago. However, the MCs are too close together today in this model, indicating that the true collision likely occurred earlier.

Given our adopted prescriptions, the modelled SFHs of both MCs are plotted as a function of time since they first crossed within \( R_{200} \) of the MW in Fig. 16. Note that the SFR is derived from the gas density above a set of threshold value. Contrary to Model 1, the SFH of the SMC over the past Gyr in Model 2 increases steadily, as observed (McCumber et al. 2005; Noël et al. 2009). The Model 2 result occurs because the separation between the MCs is smaller than in Model 1, hence the relative importance of tidal distortions from the LMC and consequent triggered star formation is also stronger.

The LMC is observed to be unusually blue relative to analogues with similar \( R \)-band magnitudes identified in SDSS (Tollerud et al. 2011). This is likely a result of the following two factors.

1. If the MCs are on their first infall and just past their first pericentric approach to our MW, they may be experiencing triggered star formation induced by MW tides.
2. Interactions between the MCs have likely kept the SFR in the LMC higher than it would be if it did not have a companion. The SFRs of galaxies are known to increase as a function of separation to a close companion (Larson & Tinsley 1978; Freedman Woods et al. 2010; Patton et al. 2011, and references therein). Since LMC–SMC pairs are rarely found around MW-type hosts (Boylan-Kolchin et al. 2011; Liu et al. 2011), it is natural that the LMC should have an anomalously high current SFR relative to the average analogue (which is more likely to be isolated). This theory can be tested by comparing the LMC’s colour/SFR to a sample of Magellanic Irregulars (LMC analogues) with known close companions.

The recent collision between the MCs in Model 2 results in a dramatic increase in the SFR in the SMC at that time. As discussed above, the exact timing of the true collision is quite uncertain. The magnitude of the simulated burst is inconsistent with observations of the SFH of the SMC (Harris & Zaritsky 2006). Furthermore, the modelled SFRs today are also higher in both MCs than those observed (see Table 3). This likely points to significant problems in our adopted star formation prescriptions.

The star formation prescription we have adopted in these simulations follows a Kennicutt–Schmidt volume density law with a local volume density cut-off for star formation of \( r_{\text{c}} = 0.13 \text{ cm}^{-3} \). Springel & Hernquist (2003) showed that when combined with appropriate star formation time-scales and typical scale heights, this gives a good match to the observed Kennicutt star formation surface density relation for relatively massive galaxies. However, in the regime where galactic gas is dominated by atomic hydrogen and where molecular, star-forming, gas constitutes only a fraction of the gaseous content, one has to properly account for the

![Figure 16](https://academic.oup.com/mnras/article-abstract/421/3/2109/1076211)
formation of local density enhancements and molecular hydrogen formation (Robertson & Kravtsov 2008; Krumholz, McKee & Tumlinson 2009; Hopkins, Quataert & Murray 2011; Kuhlen et al. 2011). In low-mass galaxies that tend to be metal poor, such as the SMC (Fox et al. 2010), molecular gas formation and therefore also the star formation are very inefficient. Theoretical models show that not accounting for the details of molecular gas formation and using global metallicity-independent, low-density, threshold for the ISM model can lead to serious overestimates of the SFRs of metal-poor galaxies (Kuhlen et al. 2011). While larger improvement can be made by accounting for metallicity-dependent molecular gas formation in subresolution models, direct modelling of processes that self-regulate formation of molecular clouds, their star formation and related feedback requires more a complex ISM model and resolution that is beyond the simulations used in this work (Hopkins et al. 2011).

Since the bulk of this study focuses on the morphological and kinematic properties of the simulated MCs and the dynamics of the Magellanic System, the detailed star formation prescription does not alter any of the main conclusions in this work. However, it does limit the predictive power of the models concerning the chemical evolution and SFHs of the MCs. Future detailed studies of star formation prescriptions/feedback in a repeated series of Model 2 collisions can be compared directly with the multiples observational data sets for the SFHs of the MCs. Such a study may be a powerful method for constraining the appropriate subresolution physics for Magellanic Irregulars and shed light on to the nature of bursts of star formation in the histories of the MCs.

6.2 Star formation in the Bridge and Stream

An additional check for our proposed models is the predicted locations of ongoing star formation in the simulated Magellanic Bridge and Stream.

Fig. 17 shows the instantaneous SFR density in the Magellanic System for Models 1 and 2; the SFR density is derived from the gas density. These plots indicate the location of gas with densities above the star formation threshold and should thus be forming stars. While these plots may not be quantitatively accurate (the results clearly depend on the star formation prescription), they do highlight the location of high-density gas that should be forming stars in any subgrid model.

In both cases, the gas densities in the MS are too low to form stars. This is consistent with observations; molecular gas has not been detected in the densest cloudlets of the Stream, suggesting that star formation is not actively occurring there (Matthews et al. 2009).

In Model 1, stars do not form in the Magellanic Bridge, whereas in Model 2 a well-defined bridge of star-forming gas is seen connecting both galaxies. Stars as young as 10–40 Myr have been detected in the Bridge (Demers & Battinelli 1998), indicating that star formation

**Figure 17.** The instantaneous SFR density for the simulated Magellanic System is plotted for Model 1 (top panel) and Model 2 (bottom) as a function of Magellanic Longitude. The SFR density is proportional to UV luminosity and identifies the location of gas that is currently forming stars. The white circle indicates the observed extent of the LMC’s disc and the solid white line denotes the observed location of the Stream. Blue solid (dashed) lines indicate the past orbits of centre of mass of the LMC (SMC).
is ongoing there, as these stars could not have migrated from the SMC during their lifetimes. Furthermore, Harris (2007) was unable to locate stars older than 300 Myr in the Bridge, lending support to the idea that the majority of young stars there were formed in situ. The different results between Model 1 and Model 2 indicate that a very close/direct encounter between the MCs may be required in order to trigger in situ star formation in the Bridge, otherwise gas densities in the tidal bridge should not be significantly different from the MS (i.e. the tidal tail). A close encounter has generally been invoked to explain the properties of the Bridge in previous studies (e.g. Yoshizawa & Noguchi 2003; Connors et al. 2006).

Clearly, shock-induced star formation is a relevant process in the direct collision scenario presented here and must be accounted for in order to characterize this environment accurately.

Note that, although these results seem to favour Model 2, ram pressure compression of the Bridge region may also lead to triggered star formation (e.g. Mastroiopietro, Burkert & Moore 2009). Although, in this case there likely should be stars forming in both the Leading Arm and the MS as well.

The SFR along the Bridge in Model 2 increases steadily towards the SMC; this should be testable observationally. Indeed, Harris (2007) showed that the distribution of blue stars is more dense in the Bridge towards the SMC. *Spitzer* observations also confirm the presence of young stars in the ‘wing’ of the SMC, which leads to the Bridge (Gordon et al. 2009). Furthermore, Hα measurements of the Bridge by the Wisconsin Hα Mapper survey indicate that the Hα emission in the Bridge increases steadily towards the SMC (Barger et al., in preparation).

In Fig. 17, the bar region of Model 1 is currently the dominant site of ongoing star formation in the LMC (contrary to observations). The distribution of star formation in the disc appears similar to an isolated galaxy with a number of spiral arms. On the other hand, in Model 2 the bar is not the most prominent site of star formation today. Fig. 18 provides a zoomed-in view of the Model 2 results in the line-of-sight frame for the LMC disc. The centre of mass of the stellar disc is located just to the right of an intense star-forming knot that indicates the impact location of the SMC–LMC collision. As discussed earlier, this occurs because the bar is warped with respect to the gas disc plane and is therefore inefficient at funnelling gas along it.

Without appropriate feedback prescriptions, the appearance of the impact site today is difficult to assess. The thickness of the gas disc near the impact site has increased relative to the rest of the disc (see where the SMC’s trajectory crosses the LMC disc plane in Fig. 13). Intriguingly, this is also true for the active 30 Doradus star-forming region (Padoan et al. 2001), which is located at roughly the same location. However, the SFH of the true 30 Doradus region indicates that it has only been an active site of star formation for the past 12 Myr (Harris & Zaritsky 2009). Without accurately capturing star formation induced by shocks and including feedback, it is unclear whether the initial collision (100–300 Myr ago) is related to the triggering of star formation in 30 Doradus today or whether its remnant is related to any of the supergiant shells in the LMC disc (Kim et al. 1998; Book, Chu & Gruendl 2008; Book et al. 2009).

### 6.3 Mass breakdown

The initial and final mass contained within characteristic radii of the simulated LMC and SMC and the resulting mass of the simulated stream are listed in Table 4 and compared with observations. Quoted gas mass estimates are for the total gas component; the neutral H1 content will be lower than these values. We do not include a UV ionization model in these simulations and thus cannot accurately estimate the neutral gas fraction.

In general, the mass estimates for the LMC and SMC agree with the observations within a factor of 2. However, the final gas mass estimates for the MCs are lower than those observed and the simulated stream is about a factor of 5 lower.

| Galaxy | Property | Initial ($10^8 M_\odot$) | Model 1 ($10^8 M_\odot$) | Model 2 ($10^8 M_\odot$) | Observed ($10^8 M_\odot$) |
|--------|----------|--------------------------|---------------------------|---------------------------|---------------------------|
| LMC    | Stars (<9 kpc) | 2.5 | 3.1 | 3.1 | 2.7 (1) |
|        | Gas (<5 kpc)    | 0.87 | 0.17 | 0.26 | 0.441 (2) |
|        | Total (<9 kpc)  | 18 | 21 | 21 | 13±3 (3) |
|        | Total (<4 kpc)  | 6.9 | 7.3 | 7.1 | 5 (4) |
| SMC    | Stars (<3 kpc)  | 0.20 | 0.26 | 0.20 | 0.31 (5) |
|        | Gas (<3 kpc)    | 0.20 | 0.16 | 0.18 | 0.42 (5) |
|        | Total (<3 kpc)  | 2.1 | 1.8 | 1.1 | 2.7–5.1 (6) |
| Stream | Total (<1.6 kpc) | 0.84 | 0.70 | 0.49 | 1.4–1.9 (6) |
|        | Gas | 0.12 | 0.10 | 0.10 | 0.5 (7) |
|        | Stars | 0.6 | 0.4 | 0.4 | 0.4 |

*The Stream is defined as material at Magellanic Longitude less than −30. We have also accounted for the distance in our simulated stream in order to properly compare to the observed mass, which is computed modulo the distance squared.*

**Notes.** (1) van der Marel et al. (2002): the outermost data point lies at 9 kpc; (2) Brüns et al. (2005); (3) van der Marel, Kallivayalil & Besla (2009); (4) Kim et al. (1998); (5) Stanimirović et al. (2004); (6) Harris & Zaritsky (2006); (7) here we have accounted for the average distance to the simulated streams. The measured value is $1.25 \times 10^3 (d/55 \text{ kpc})^2$ (Brüns et al. 2005) + $2.0 \times 10^7 (d/120)^2$ (Nidever et al. 2010). The quoted simulated gas mass refers to the total mass, not just that of the neutral H1, whereas the observed values refer to H1 gas only.
As discussed in Section 6.1, given the adopted star formation prescriptions, the SFR in the MCs is being overestimated in the simulations. As a result, the gas consumption time-scale is also overestimated. The adoption of different prescriptions and/or changes in model parameters so that the SMC does not lose as much gas at early times (e.g. by reducing the scale length of the SMC’s gas disc) may allow for the SMC to retain its gas for longer, allowing more material to be removed at later times.

The mass budget of the Stream is also likely underestimated because ram pressure stripping has not been modelled here; the bulk of the missing material is in the region closest to the MCs, rather than the tip of the tail. However, this still means that more gas needs to be retained by the MCs themselves to provide a gas reservoir for this process to operate at late times. This suggests that the larger problem here is the adopted star formation prescriptions.

Probably more significantly, the total initial gas budget of the MCs has been underestimated in these simulations; the amount of gas initially modelled in both the LMC and SMC cannot explain the total gas budget (including both neutral and ionized components) of the Magellanic System. Although the neutral H\text{I} gas content of the observed Magellanic System has been well quantified, the ionized gas fraction is poorly understood. Fox et al. (2010) find that at the tip of the Stream as much as 95 per cent of the gas may be ionized. Along a similar line, Lehner et al. (2008) find that gas in the Magellanic Bridge is 70–90 per cent ionized. This means that the total gas mass budget of the Stream (and consequently of its progenitor) is significantly underestimated. Note that this statement implies that the LMC and SMC must have a significant amount of dark matter in order to make their initial baryon fractions consistent with cosmological expectations; this is the main motivation for the large total infall masses adopted in this study.

The fact that the stellar mass in the central regions of the SMC does not change substantially indicates that the bulk of the material being removed from the SMC via LMC tides is from the outskirts of the SMC. This explains why the stellar counterpart of the Stream is so faint. We will comment on the observability of this stellar stream counterpart in an upcoming paper.

6.4 Tidally captured SMC stars

In the presented models, there is a continual transfer of material from the SMC to the LMC. In particular, there is expected to be a population of stars that are tidally stripped from the SMC and captured by the LMC in both models.

Recently, Olsen et al. (2011) discovered a population of metal-poor RGB stars in the LMC field that have different kinematics from those of local stars in the LMC disc. Graff et al. (2000) have also identified a possible kinematically distinct collection of carbon stars and suggest that this population lies outside of the LMC. The discovery of such stars is a natural theoretical expectation from any tidal model for the LMC–SMC interaction. To date, no stars have been detected in the MS (Guhathakurta & Reitzel 1998) and only stars younger than 300 Myr have been identified in the Bridge (Harris 2007). Note that the Harris (2007) observations focused on the leading ridgeline (location of the highest gas density) of the Magellanic Bridge. This leading edge would currently be experiencing maximal ram pressure and so it is possible that the peak gas density in the bridge is displaced from the tidal stellar population theorized to be there. Harris (2007) constrained the stellar density of a possible offset stellar population using 2MASS observations, but the 2MASS sensitivity limit of 20 Ks mag arcsec$^{-2}$ is likely far too low to detect the expected faint stellar bridge (>30 Ks mag arcsec$^{-2}$; Besla et al., in preparation).

The potential identification of tidally stripped SMC stars in orbit about the LMC may be a key discriminant between various model interpretations of the origin of the MS, as they should not be present in a pure hydrodynamic model (Mastropietro et al. 2005) or one that relies on stellar outflows (Olano 2004; Nidever et al. 2008).

To test whether the simulation results for the tidal debris are consistent with the Olsen et al. (2011) detections, we plot in Fig. 19 the expected distribution and kinematics of the stars captured by the LMC from the SMC for both Model 1 (top panel) and Model 2 (bottom panel). The box size and orientation is the same as in Figs 14 and 15, that is the field of view is centred on the LMC. The stellar line-of-sight velocities have been corrected for the centre-of-mass motion of the LMC. The SMC is located towards the south-west in this viewing perspective. Note that the SMC is actually present in this field of view for the Model 2 results, as this simulation resulted in the MCs being closer together than observed.

In Model 1, these transferred stars form a well-defined arc that is in orbit about the LMC: these stars are located behind the LMC disc. Comparing the velocity field to the bottom right-hand panel of Fig. 14, the kinematics of these stars appear to be offset by nearly 90° relative to the velocity gradient in the LMC’s disc. In Model 2, the stellar debris from the SMC exhibits a large range in velocities (±150 km s$^{-1}$). We made a velocity floor and ceiling of ±70 km s$^{-1}$ to better compare to the LMC stellar disc kinematics. In the north-west, there are stars that appear to be moving towards the observer and in the south-east there are stars moving away from the observer – this is opposite to the observed kinematics of the LMC stellar disc. Thus, in both models, stellar debris captured by the LMC from the SMC is expected to have kinematics that are distinct from those of the LMC disc stars – this is a generic prediction of the B10 model and is consistent with the Olsen et al. (2011) observations.

Olsen et al. (2011) estimate the mass of the observed SMC debris population to be 5 per cent of that of the LMC’s current disc mass (i.e. ∼1.4 × 10$^{6}$ M$_{\odot}$). In Model 1, only a modest amount of stars is transferred from the SMC to the LMC (∼0.2 per cent). As such, Model 1 cannot account for this population. On the other hand, in Model 2, the LMC accretes 1.5 per cent of its current disc mass from the SMC.

The exact distribution of SMC debris is certainly dependent on a number of parameters, but overall we can conclude that the Olsen et al. (2011) results support a model in which LMC tides have been actively distorting the SMC. Furthermore, in both models the acccreted stars are largely located behind the LMC disc and may provide a natural explanation for the origin of the observed MACHO microlensing events (Besla et al., in preparation).

6.5 The nature of Magellanic Irregulars

Dwarf galaxies are broadly referred to as galaxies with luminosities <0.1–0.3 of $L_{\odot}$. This definition encompasses a wide range of objects of varying morphology, including both the LMC and SMC. In this work, we have introduced a mass model for the LMC with a total mass of ∼10$^{11}$ M$_{\odot}$; it is questionable as to whether such a massive galaxy should be included in the same category as dwarf spheroidal or dwarf irregular galaxies. In particular, detailed analysis of the geometry (van der Marel & Cioni 2001) and kinematics (van der Marel et al. 2002) prove that the LMC is a disc galaxy. Furthermore, when looking at the distribution of intermediate-age and old stars out to large radii (i.e. ignoring the visible light in the bar region), the LMC does not look at all irregular, but clearly...

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The kinematics of SMC stars that are captured by the LMC in Model 1 (top panel) and Model 2 (bottom panel) are illustrated in the line-of-sight frame of the LMC’s disc. Only particles initially belonging to the SMC are plotted. The centre-of-mass velocity of the LMC’s stars has been subtracted from the velocity field of the transferred material. The left-hand panels show the stellar density map with the highest density contours overplotted. The size of each box is 11 kpc per side, the same as that in Figs 14 and 15. The slits along the major and minor kinematic axes of the LMC are overplotted for reference. The colour gradient ranging from blue to red indicates material moving towards (blue) and away (red) from the observer.

resembles a spiral galaxy with an asymmetric one-armed spiral (van der Marel 2001).

de Vaucouleurs & Freeman (1972) suggested that Magellanic Irregulars have more in common with spiral galaxies than dwarfs, referring to the LMC as an asymmetric, late-type SB galaxy. They argue that Magellanic Irregulars represent an extension of the Hubble spiral sequence (Sa, Sb, Sc, Sd, Sm, Im), where the subscript m denotes ‘Magellanic’ (see also section 4.1.1 of Binney & Merrifield 1998). Spiral structure ‘decays’ along the sequence, with Sc having irregular spiral patterns and Im none at all. This is true also for the SB sequence, with asymmetry referring also to the appearance/location of the bar. Magellanic Irregulars encompass the late stages of both barred and unbarred spirals (e.g. Sd–Im, SBd–SBm); the LMC is classified as SBm under this scheme and the SMC an Im.

This work postulates that many barred Magellanic Irregulars may be perturbed versions of symmetric low-mass, bulgeless, barred galaxies, such as Sbc-type galaxies, where the bar is typically well centred. We further illustrate a mode of inducing such perturbations, namely interactions with lower mass companions. In this picture, the LMC should not be thought of as a ‘dwarf’ galaxy except in the sense that it is less luminous than the MW.

Asymmetric bars are typically not seen in massive galaxies, making them a defining characteristic of Magellanic Irregulars. This might be explained by noting that Sc/Sbc-type galaxies and Magellanic Irregulars (Sd–Im) are low-mass systems compared to MW-type galaxies and, correspondingly, they sample very different environments. Such galaxies do not have bulges, have shallower central potentials, are more dark matter dominated, have different halo concentration parameters, higher gas fractions and different ratios between the ISM temperature and virial temperature of their haloes: all of these differences will influence the response of the system to tidal perturbations. As such, even if the physical scenario is similar (mass ratio and orbital configuration), the response of an MW-type galaxy to a 1:10 mass ratio direct collision is expected to be different than an LMC–SMC (∼1:10 mass ratio) encounter.

It is possible, for example, that the presence of a bulge may aid in stabilizing the bar of a high-mass galaxy, preventing comparable asymmetries in the bar from arising. However, a detailed numerical study of such parameter space to test such conjectures is beyond the scope of the presented study.

Magellanic Irregulars are ubiquitous in our Local Volume. In light of the theory presented here, it must also be true that interactions between low-mass barred galaxies and smaller companions are a relatively frequent occurrence. From Hopkins et al. (2010), the expected galaxy major merger (mass ratio > 1/3) rate is relatively flat as a function of host galaxy mass at z = 0, so it is not expected that such encounters would be more likely for low-mass systems. Stewart et al. (2008) find that 25–40 per cent of hosts with mass of the order of ∼10^{11} M⊙ h^{-1} have accreted a 1:10 mass ratio subhalo within the past 6–8 Gyr, which is the time-scale for our isolated LMC–SMC interaction. This scenario is thus not at odds with cosmological expectations.

It has been pointed out by Wilcots & Prescott (2004) that many Magellanic Irregulars do not currently have companions, despite earlier claims of a high frequency of pairs by Odewahn (1994).
However, the number of observed interacting dwarf systems is steadily increasing. Recently, Martinez-Delgado et al. (2011) have discovered a stellar stream about the Magellanic Irregular galaxy NGC 4449, which is an LMC analogue in terms of its absolute magnitude. Although the stellar mass ratio of the disrupted object and the host is 1:50, the inferred dynamical mass ratio is between 1:10 and 1:5, making this system an analogue of the late stages of an LMC–SMC-type tidal interaction. NGC 4449 was long thought to be an isolated Magellanic Irregular until observations of associated HI streams indicated that it likely had an encounter with an unseen companion (Hunter et al. 1998). Moreover, an unusual globular cluster exists in this galaxy with properties consistent with the nucleus of a disrupted galaxy (Annibali et al. 2011, 2012); such observations indicate that NGC 4449 may also have had more ancient accretion activity, which may partially explain the significant amount of mass in the HI streams surrounding the system. Signatures of earlier accretion events in dwarf galaxies have also been presented by Geha, Guhathakurta & van der Marel (2005), who find evidence for a counter-rotating core in the elliptical dwarf galaxy NGC 770 that they attribute to a minor merger event.

Such observations clearly illustrate that LMC-mass objects do cannibalize smaller companions; however, the hallmarks of these encounters, such as faint tidal streams, are challenging to observe. The Wilcots & Prescott (2004) conclusions may thus indicate that the perturbing companion has already been cannibalized, causing most Magellanic Irregulars to appear as isolated objects. Moreover, the $M_{\text{baryon}}/M_{\text{total}}$ ratio is a steep function of mass for these low-mass systems; many dwarfs in the Local Group have extremely large mass-to-light ratios. As such, a 1:10 total mass ratio companion may have a very discrepant stellar mass ratio, making the identification of such a companion challenging observationally.

In the context of the work presented here, Magellanic Irregulars are therefore key targets for deep HI and optical follow-up observations as they are expected to be associated with tidal HI and stellar streams. Particular attention should be paid to Magellanic Irregulars with high current SFRs, such as NGC 4449 and the LMC, which may point to ongoing tidal interactions with a low-mass companion. Furthermore, there is clearly need for future observational and theoretical studies to better statistically quantify the frequency of interactions between LMC-mass galaxies and smaller companions in order to assess the ubiquity of the theory presented here for the nature of Magellanic Irregulars.

### 6.6 Assessment of the models

In this study, we have explored the consequent large-scale structure of the Magellanic System, the internal structure, kinematics of the LMC and the recent SFHs of the MCs in a first infall scenario, i.e. without strong tidal torques from the MW. We focus on two different models for the interaction history of the LMC–SMC, one of which invokes a direct recent collision (Model 2), whereas in the other the MCs never get closer than 20 kpc (Model 1). The ability of the presented models to reproduce key observed features of the Magellanic System is summarized in Table 5.

Both models are able to reproduce the global large-scale structure of the Magellanic System. Overall, however, Model 1 provides better agreement with the properties of the MS, whereas Model 2 provides significantly better agreement with the structure and kinematics of the LMC.

While neither model reproduces every one of the features listed in Table 5 (and indeed the real answer is probably somewhere in between the two presented models), it is still rather remarkable that a single self-consistent model (namely Model 2) can simultaneously reproduce a large number of these features. Generally, where the models fail (e.g. the column density gradient or location of the Leading Arm), the likely missing ingredients are ram

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### Table 5. Observed properties of the Magellanic System and how the models fare.

| Object                  | Property                        | Model 1 | Model 2 | Alternative             |
|-------------------------|---------------------------------|---------|---------|-------------------------|
| Large-scale structure   | A Leading Arm                   | Yes     | Yes     | Ram pressure            |
|                         | Location of Leading Arm         | No      | No      |                         |
|                         | A 150' Stream                   | Yes     | Yes     |                         |
|                         | Stream location offset from orbit | Yes   | Roughly | I.C.: SMC disc inclination |
|                         | Stream velocity gradient        | Yes     | Roughly | I.C.: SMC disc inclination |
|                         | Stream bifurcation              | Roughly | No      | Hydro instabilities     |
|                         | Stream column gradient          | No      | No      | Ram pressure            |
|                         | Stream total mass               | No      | No      | I.C. SMC gas mass       |
|                         | A Bridge                        | Yes     | Yes     | I.C. SMC gas mass       |
|                         | SF in Bridge                    | No      | Yes     |                         |
|                         | No SF in Stream                 | Yes     | Yes     |                         |
| LMC                     | Rotation curve                  | Yes     | Yes     |                         |
|                         | Offset gas and stellar          | No      | Yes     |                         |
|                         | Kinematics                      |         |         |                         |
|                         | Offset bar                      | No      | Yes     |                         |
|                         | Bar not seen in gas             | No      | Yes     |                         |
|                         | Warped stellar disc             | Yes     | Yes     |                         |
|                         | Elliptical stellar disc         | Roughly | Yes     |                         |
|                         | Current SFR                     | No      | No      | SF details, feedback    |
| SMC                     | Increasing SFR < Gyr             | No      | Yes     |                         |
|                         | Current SFR                     | No      | No      | SF details, feedback    |

Notes. SF stands for star formation. I.C. stands for initial conditions. The column marked ‘Alternative’ indicates other possible factors that may help fix discrepancies between the observations and the models.
pressure stripping owing to the passage of the galaxies through the ambient hot gaseous halo of the MW or a detailed search of model parameters (e.g. initial gas mass or orbital parameters). Inconsistencies with the current SFR and recent SFHs are almost certainly a result of the star formation prescriptions employed and the lack of stellar feedback.

A number of the discrepancies with the orbital model (e.g. the SMC’s position and velocity) can likely be addressed by a complete parameter search of, e.g., plausible mass ratios between the two galaxies (we chose a fixed mass ratio of 1:10) and different orientations of the SMC disc relative to the LMC–SMC binary orbital plane. The inclination of the SMC’s disc can dramatically alter the location and properties of the Stream, e.g. a retrograde coplanar configuration would inhibit the formation of a stream entirely. It can also change the way LMC torques affect the SMC’s motion. This is likely the explanation for why the Model 2 results do not reproduce the exact velocity field or location of the Stream.

The Stream is also known to be both spatially and kinematically bifurcated, leading Putman et al. (2003) to describe it as a ‘twisted helix’. The Stream in our Model 1 is not of constant column density along its width; between Magellanic Longitudes of ~50 and ~100, the simulated stream appears to split into two high column density filaments. This bifurcation is largely a result of the rotation of the SMC’s initial disc. Note also that because the Stream is seen in projection, the appearance of this bifurcation is highly dependent on the viewing orientation (which is model dependent). This is likely why similar structures are not seen as clearly in Model 2. However, it should be noted that in the GADGET simulations, the ISM is smoothed by an effective equation of state, whereas in reality inhomogeneities should be present in the real ISM (e.g. molecular clouds). Stripping from a clumpier SMC ISM would lead to differences in the distribution of the stripped material. We further expect that hydrodynamic instabilities, which are not modelled here, would capitalize on any initial density inhomogeneities and augment this bifurcation. It is clear from the significant observed turbulence (Nigra et al. 2010) and the existence of head–tail structures in cloudlets within the Stream (Putman et al. 2003; Putman, Saul & Mets 2011) that hydrodynamic instabilities are shaping its internal structure. Gas drag will operate differently on these clumps depending on their densities, naturally leading to a velocity bifurcation as well.

Although strong perturbations in the LMC disc are expected from a close encounter with a 1:10 mass ratio companion, without a large parameter study of impact parameters for the collision and mass ratios, it is unclear how generally these results can be applied to Magellanic Irregulars. A future study of these parameters will assess the robustness and longevity of the presented asymmetric structures (i.e. offset bars and one-armed spirals). In particular, it remains unclear as to whether a direct collision is always required to produce such structures. Regardless, the existence of Magellanic Irregulars with close pairs connected by gaseous bridges is certainly suggestive of a link to a similar interaction history as that of the MCs.

It is worth pointing out that while it has been speculated that many of the features listed in Table 5 were directly related to interactions with the SMC, most of these links have never been illustrated by numerical simulations which self-consistently reproduce the global large-scale features of the system. In this light, particular successes of the simulations presented in this work include the reproduction of a warped, off-centred bar that is detectable neither in the gaseous disc nor in actively forming stars, while simultaneously forming a Bridge, Leading Arm and trailing 150◦ long Stream. Furthermore, we have not yet discussed the remarkable agreement of the simulated SMC model with its observed structure and kinematics from this same Model 2. These results will be outlined in a subsequent paper.

7 CONCLUSIONS

We have explored two models for the possible interaction history of the LMC and SMC in an effort to simultaneously reproduce both the large-scale gaseous distribution of the Magellanic System and the internal structure and morphology of the LMC. Here we summarize our findings for the Magellanic System and the implications for the study of Magellanic Irregular galaxies more generally.

7.1 Conclusions for the Magellanic System

The resulting kinematics and structure of the LMC strongly favour a scenario in which the MCs have recently (100–300 Myr) experienced a direct collision (our Model 2). Orbital models where the SMC never gets closer than 20 kpc to the LMC (e.g. Model 1) are able to reproduce the large-scale structure of the Magellanic System, but poorly match the LMC’s internal properties. In particular, without a direct collision with the SMC, the LMC would be better described as a normal, symmetric SB galaxy. An upcoming paper will also illustrate that the observed internal kinematics and morphology of the SMC are also better described by this same collision model (Besla et al., in preparation).

This study illustrates that, surprisingly, the LMC’s disc can maintain a fairly smooth stellar velocity field despite a direct collision with the SMC and that such a scenario can explain a number of observed features of the LMC disc.

(i) The gas and stellar kinematic centres of the LMC disc are coincident; however, they are offset from the photometric centre (Cole et al. 2005).

(ii) The old stellar disc of the LMC is thick and warped. The warping at the edges may give it a flared appearance (Alves & Nelson 2000).

(iii) The bar is warped relative to the LMC disc plane by 10◦ and is off-centre relative to the dynamical centre of the gaseous disc. While an offset bar in the LMC has been suggested by numerous authors as being the result of collisions with the SMC (e.g. Subramaniam 2003; Bekki & Chiba 2007; Subramaniam & Subramanian 2009), this is the first time it has been modelled self-consistently.

(iv) The bar is not seen in the gas distribution (Kim et al. 1998) or as a site of ongoing star formation, likely because the bar is warped out of the plane, inhibiting efficient gas funnelling.

(v) Gaseous ‘arms’ similar to those seen in H1 maps of the LMC (Nidever et al. 2008, 2010) are stripped out of the LMC by the SMC in the direction of the Magellanic Bridge. This ‘arm’ was formed during a violent collision and may have signatures in polarization maps of the LMC’s magnetic field (Mao et al., in preparation). This result also implies that there should be a metallicity gradient along the Bridge, increasing towards the LMC owing to contamination by LMC gas.

(vi) A one-armed spiral is induced in the LMC’s disc and is a site of ongoing star formation.

(vii) Stellar debris from the SMC is expected in the same field of view as the LMC disc. These stars will have differing kinematics signatures from the local LMC disc velocity field (Olsen et al. 2011) and may be the source of microlensing events towards the LMC (Besla et al., in preparation). Such tidally stripped stars are not expected in a pure ram pressure stripping model for the Stream.
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The gaseous Bridge that connects the two galaxies is the site of ongoing star formation, where the SFR increases along its length towards the SMC.

The Leading Arm extends >70° ahead of the MCs and the MS extends 150° behind them, reproducing the full extent of the Magellanic System. The Leading Arm is a younger structure than the Stream since it formed as a tidal tail during the SMC’s most recent orbit about the LMC.

These listed properties are direct consequence of interactions with the SMC, confirming the suspicions of de Vaucouleurs & Freeman (1972) that the LMC’s peculiar morphology does not owe to interactions with the MW.

7.2 Implications for Magellanic Irregulars

There is potentially much to learn about Magellanic Irregular galaxies as a class by studying the Magellanic System in detail. In this work, we have shown that the off-centre bar and one-armed spiral arm of the LMC may be a product of close encounters with its smaller companion, the SMC. We conclude that interactions between a massive dwarf and a smaller companion, even 10 times smaller in mass, can significantly alter the morphology of an otherwise normal looking, low-mass spiral galaxy. This study thus indicates that dwarf–dwarf galaxy interactions can be important drivers of their morphological evolution, without relying on interactions with a massive host.

Given that off-centre bars and one-armed spirals are common characteristics of Magellanic Irregulars (de Vaucouleurs 1964), it is possible that such galaxies currently have or once had small companions. Known examples of Magellanic Irregulars with a close companion are thus prime candidates for follow-up H$^\alpha$ surveys to map the extended H$^\alpha$ distribution, as the bridges that connect them likely have tidal tail counterparts. We argue here that if such systems were accreted by a massive spiral, they could form an analogous Magellanic System, i.e. two interacting dwarfs surrounded by an extended H$^\alpha$ complex. A potential example could be the interacting dwarfs of the MS, which are surrounded by an extensive H$^\alpha$ envelope and are not in close proximity to a massive host (Clemens, Alexander & Green 1998). The recently identified stellar stream about the Magellanic Irregular galaxy NGC 4449 (Martinez-Delgado et al. 2011) gives further credence to this theory.

Quantifying the efficiency with which such dwarf–dwarf tidal interactions can remove gaseous material is directly relevant to questions about how dwarf galaxies lose their gas and how gas is supplied to more massive galaxies. The frequency of such dwarf–dwarf encounters has not yet been quantified observationally or theoretically. As such, the relative importance of such encounters remains to be determined. However, by reproducing the large-scale structure of the Magellanic System in an LMC–SMC tidal scenario, we have shown here that at least 50 per cent of the original gas budget of a small dwarf can be easily removed by tidal interactions with a larger dwarf companion, making such encounters a potentially important mode of baryon loss on these mass scales.

While the accretion of an LMC+SMC analogue by an MW-type host is a relatively rare event today (Boylan-Kolchin et al. 2011; Liu et al. 2011), modern models for the cosmological assembly of galactic-scale structures suggest that the MW halo formed from the earlier accretion and disruption of LMC-mass objects (Stewart et al. 2008). As such, simulations of isolated Magellanic Irregulars (LMC analogues) with low-mass companions and the direct comparisons of such simulations to observed analogues, such as NGC 4027 (Phookun et al. 1992) and NGC 3664 (Wilcots & Prescott 2004), provide a logical testing ground for our understanding of the morphological, kinematic and chemical evolution of the fundamental building block of an MW-type galaxy.

ACKNOWLEDGMENTS

The simulations in this paper were run on the Odyssey cluster supported by the FAS Science Division Research Computing Group at Harvard University. We thank Knut Olsen, Alar Toomre, David Nidever, Crystal Martin, Patrik Jonsson, Mary Putman and Dennis Zaritsky for useful discussions that have contributed to this paper. GB acknowledges support from NASA through Hubble Fellowship grant HST-HF-51284.01-A.

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APPENDIX A: THE ROLE OF RAM PRESSURE STRIPPING IN THE FORMATION OF THE STREAM

Evidence for the existence of a hot gaseous halo component of our MW comes from absorption lines towards distant active galactic nuclei (Sembach et al. 2003). The MCs are therefore known to be moving through some ambient medium, and so the effects of ram pressure stripping and gas drag likely play some role in explaining the gas distribution of the Magellanic System. Our contention is that the impact of ram pressure is to modify the properties (velocity, location, mass) of the gas distribution, but does not in itself explain the existence of the Stream, Bridge and LAF.

Modelling the impact of ram pressure from a physical ambient medium representing the MW’s gaseous halo with either an SPH or Eulerian grid-based code would require extremely high numerical resolution, as the gaseous stream is very diffuse. Instead, we have created a toy simulation, where the GADGET3 code was modified to include a ram pressure acceleration term that is applied uniformly to all gas particles and operates opposite to the direction of motion of those gas particles. Following the Gunn & Gott (1972) prescription, the ram pressure experienced by a gas particle moving through the hot gaseous halo of the MW (density, $\rho_{\text{hot}}$) at a speed $v_{\text{gal}}$ is expressed as follows:

$$ P_{\text{ram}} = \rho_{\text{hot}} v_{\text{gal}}^2. \quad (A1) $$

The acceleration experienced by a gas cloud of surface density $\Sigma_{\text{gas}}$ owing to ram pressure is

$$ a_{\text{ram}} = P_{\text{ram}} / \Sigma_{\text{gas}}. \quad (A2) $$

Following Vollmer et al. (2001), we can describe an H I gas cloud as having a characteristic column density of $N_{\text{HI}} = 7.5 \times 10^2$ cm$^{-2}$ (Sanders, Scoville & Solomon 1985). Thus, $\Sigma_{\text{gas}} \sim N_{\text{HI}} \times m_{\text{HI}}$. For a given velocity component $v_i = y_i, z_i, 5$ the corresponding acceleration applied in that direction per time step is

$$ a_i = -\frac{n_{\text{hot}} v_i}{N_{\text{HI}}} v_i, \quad (A3) $$

where the volume density ($\rho_{\text{hot}}$) has been replaced by the number density of the MW’s ambient halo medium ($n_{\text{hot}}$) multiplied by the mass of the average particle in the halo, which we have assumed is $\sim m_{\text{HI}}$. The quantity $n_{\text{hot}}$ is largely unconstrained, although an upper limit of $5 \times 10^{-4}$ cm$^{-3}$ is estimated (Maloney & Bland-Hawthorn 1999; Rasmussen & Pedersen 2001). We consider three values for this parameter: 5 $\times 10^{-4}$, $10^{-3}$, and $5 \times 10^{-4}$ cm$^{-3}$. We further assume that this density is constant all the way to $R_{200} = 220$ kpc of the MW. The ram pressure acceleration is applied to all gas particles as soon as the MCs enter within $R_{200}$ of the MW. Note that this acceleration will not be constant as a function of time since the velocity of the particles changes as the MCs fall towards the MW.

We stress that this is a crude model, as there is no actual ambient gas density present and the force is applied uniformly to all particles. In reality, gas in the inner parts of the disc should be shielded by those on the outside. Moreover, other hydrodynamical instabilities, such as Kelvin–Helmholtz and Rayleigh–Taylor, will not be modelled in this set-up and we will therefore underestimate the amount of gas loss the galaxies may incur. This toy model will, however, give us a rough idea of how the position of the simulated Leading Arm, Bridge and Stream will evolve over time.

In Figs A1 and A2, the gas column density of the Magellanic System is mapped in Magellanic Coordinates for Model 1 and Model 2, respectively. As the background density is increased, the location of the Stream changes, and the gas begins to trace the orbit. In Besla et al. (2007), it was shown that the location of the LMC past orbit deviates from the location of the Stream on the plane of the sky. This result was further shown to be insensitive to the MW model and robust within 3$\sigma$ of the measured proper motions. The fact that ram pressure stripping works to align the stripped material and the past orbits suggests that it is not the main formation mechanism for the MS.

The Leading Arm also changes location and structure significantly in the toy model, particularly in Model 1. Facing gas densities larger than $10^{-4}$ cm$^{-3}$, it disappears entirely. Although the Bridge disappears in Model 1 at densities larger than $5 \times 10^{-4}$ cm$^{-3}$, it remains a strong feature in Model 2 at all densities. This is likely because, in Model 2, the Bridge is a young feature that formed in the most recent collision between the MCs. It has thus not had enough time to experience significant ram pressure effects. In Model 2, the Leading Arm also gets closer to the MW, falling to a line-of-sight distance of 30 kpc. These models do not predict that components of the Leading Arm should be interacting with the gaseous disc of the MW, although there are claims that such a situation has been observed (McClure-Griffiths et al. 2008).

Note that as the ram pressure increases, the SMC’s orbit changes; the SMC is clearly not in the same location in the lower panel of Figs A1 and A2 as in the respective upper panel. This occurs because ram pressure decreases the velocity of the SMC. The LMC, on the other hand, is too massive for its motion to be affected. A strong ram pressure headwind is thus likely at odds with the high relative velocity observed between the MCs ($\sim 100$ km s$^{-1}$; K2).
The structure of the LMC gas disc changes even with a mild ram pressure headwind. The gas disc is rotating clockwise, and so the lower half is rotating into the head wind and gets stalled. Gas therefore builds up in the lower left corner of the LMC's disc. This is in fact where the 30 Doradus star-forming region is situated. de Boer et al. (1998) suggested that the H\textsc{i} overdensity seen in the south-east is a direct result of the interaction between the rotating LMC gaseous disc and a headwind from the ambient medium. Here, we can indeed see that this process occurs generically in both Models 1 and 2. The LMC’s gaseous disc is observed to be truncated (i.e. it is not as extended as the stellar disc). The simulated LMC gas disc is truncated if the ambient gas density is at least of the order of $5 \times 10^{-5}$ cm$^{-3}$.

Note that the column density along the Stream also changes as ram pressure becomes more important. The column density increases in the regions closest to the MCs, indicating that ram pressure may be the solution for the mismatch between the observed maximal column density gradient along the Stream and the simulation results presented in Fig. 8.

From this simple toy model, we can conclude that ram pressure and other hydrodynamic instabilities will change the mass budget in the various components of the system and change their locations.
on the plane of the sky. In particular, ram pressure works to align the Stream with the past orbits, contrary to expectations from the proper motions (Besla et al. 2007). We estimate that if the background halo gas densities are in excess of $10^{-4}$ cm$^{-3}$, the gas distribution of the simulated Magellanic System will be irreconcilable with observations. This estimate is in accord with observational upper limits (Rasmussen & Pedersen 2001).

A recent study by Diaz & Bekki (2011b) suggests that ram pressure at the ambient densities required by the Mastropietro et al. (2005) study ($5 \times 10^{-5}$ cm$^{-3}$) would be too large for the survival of the MS. In a first infall scenario, where the Magellanic System would be interacting with the ambient halo medium for a shorter period of time ($<1$ Gyr), we find that the Stream can indeed survive such densities and that ram pressure stripping likely plays a very important role in shaping the MS (particularly the Leading Arm) and increasing its mass budget. It should also be noted that Faraday rotation has been detected in at least one high-velocity cloud (HVC) in the Leading Arm (McClure-Griffiths et al. 2010); magnetic fields may protect the cloudlets from evaporation and hydrodynamic instabilities, increasing the chance of survivability of the Stream in the face of a ram pressure headwind.

**APPENDIX B: THE ROLE OF STELLAR FEEDBACK IN THE FORMATION OF THE STREAM**

There is evidence of stellar feedback in the vicinity of the MCs. Lehner, Staveley-Smith & Howk (2009) have detected HVCs...
between the MCs and the MW, moving at a velocity with respect to the local standard of rest \( (v_{lsr}) \) as high as 150 km s\(^{-1}\). Using Far Ultraviolet Spectroscopic Explorer (FUSE), they find on average that these HVCs have metallicities of \([O/H] = -0.51 \pm 0.12\) and \(H\) masses of \((0.5 - 1) \times 10^7 M_\odot\), although these HVCs are predominantly ionized. Such material is thus, on average, enriched relative to the LMC and SMC. Furthermore, Lehner & Howk (2007) have detected a highly ionized \((O\,vi, C\,iv, Si\,iv, N\,vi)\) corona of high-velocity gas surrounding the LMC, suggestive of outflows. Staveley-Smith et al. (2003b) also report similar observations, and find some of this high-velocity gas to be projected on \(H\) voids in the LMC. Data from FUSE indicate that the SMC appears to also have an \(O\,vi\) corona (Hoopes et al. 2002). These detected structures are in close proximity to the MCs, and so may be indicative of mass loss processes that are currently ongoing, rather than a long duration process that would be required to build the MS.

Recently, Nidever et al. (2008) found a coherent \(v_{lsr}\) gradient from the LMC along one of the filaments in the Stream and in the Leading Arm. They also claim to detect sinusoidal velocity patterns in the Stream, which they interpret as signatures of the LMC’s disc rotation. They thus conclude that as much as half of the mass within the Stream originates from the LMC and that the sinusoidal velocity pattern indicates that the bulk of this material is emanating from the south-east \(H\) overdensity region of the LMC’s \(H\) gaseous disc as a stellar outflow over the past 1.7 Gyr. The idea that the MS was formed from stellar outflows was also suggested by Olovo (2004). The LMC is pick-marked with giant superbubbles, indicating locations of strong stellar feedback/winds. If the column density were constant across the disc, then each superbubble would have originally contained roughly \(10^7 M_\odot\) worth of material (Kim et al. 1998, 1999). Nidever et al. (2008) determine that two to three superbubbles losing \(10^6 M_\odot\) worth of material every 10 Myr over 1.7 Gyr would be sufficient to explain the mass budget of the Stream.

A stellar feedback model for the Stream is attractive in that it does not rely on strong MW tides to remove material from the LMC, making it consistent with a first infall scenario (although the leading component would still be an issue).

However, it is unlikely that outflows generated by supernovae (SNe) feedback would be sufficiently energetic to be unbound from the LMC’s gravitational potential. In our first infall LMC models (\(M_\text{LMC} = 1.8 \times 10^{11} M_\odot\)), the escape speed is of the order of 250 km s\(^{-1}\) at 10 kpc. Martin (2005) finds that terminal velocities expected from galaxies with maximum circular velocities of 100 km s\(^{-1}\) should also be of the order of 100 km s\(^{-1}\), well below the escape speed at 10 kpc. Moreover, galaxies with star formation rates as low as 0.1 M_\odot yr\(^{-1}\) (i.e. the value in the 30 Doradus region today; Harris & Zaritsky 2009) generally have outflow velocities less than 30 km s\(^{-1}\) (fig. 6 of Martin 2005).

However, it is certainly possible that a ram pressure headwind can exploit the stellar feedback processes to aid in the removal of material from the deepest parts of the LMC’s potential. This theory is testable by observations of the metallicity in the Stream: not only do the LMC and SMC have different metallicities, but any feedback scenario will result in the removal of enriched material (Mac Low & Ferrara 1999).

Metallicities for various components of the Magellanic System are summarized in Table B1. The current day LMC’s metallicity is \([O/H]_{\text{LMC}} = -0.34 \pm 0.06\) (Russell & Dopita 1992; updated to the latest solar abundances by Fox et al. 2010). However, chemical enrichment models of Pagel & Tautvaisiene (1998) suggest that 2 Gyr ago the LMC’s metallicity could have been as low as \([O/H]_{\text{LMC}} \sim -0.5\) (their fig. 3). 1–2 Gyr is the relevant time-scale for the formation of the Stream (Gardiner & Noguchi 1996; Nidever et al. 2008); given the measured He emission along its length (Weiner & Williams 1996) and the corresponding expected ablation time-scale for the neutral \(H\) component of the Stream (Bland-Hawthorn et al. 2007), it is unlikely that the Stream could have survived for much longer.

Recently, Fox et al. (2010) have determined the oxygen abundance for a region near the tip of the Stream from absorption lines towards the background quasar NGC 7469. Observed \([O/H]\) abundances are a close indication of the true oxygen abundance, \([O/H]\), since oxygen is not strongly depleted on to interstellar dust (Jensen, Rachford & Snow 2005). They find

\[
\frac{[O]}{H} \sim \left[ \frac{O}{H} \right] = \log \left( \frac{N(0)}{N(H)} \right) - \log \left( \frac{O}{H} \right) \tag{B1}
\]

\[
= \log \left( \frac{10^{14.32+0.04}}{10^{18.63+0.13}} \right) - (-3.31) \quad \tag{B2}
\]

\[
= -1.00 \pm 0.05 \text{(stat) } \pm 0.08 \text{ (syst).} \tag{B3}
\]

In an outflow or ram pressure stripping scenario, the metallicity of the Stream must be at least that of the original ISM. These measurements make it improbable that the Stream could have solely originated in the LMC, regardless of the formation mechanism. The SMC interstellar oxygen abundance is a better match to these observations (see Table B1), especially since it was also less enriched 1–2 Gyr ago (Pagel & Tautvaisiene 1998). Interestingly, such low abundances are also measured in the Bridge connecting the MCs (Table B1; Lehner et al. 2008), suggestive of a common origin for both structures.

Closer to the MCs, the metallicity measurements derived from absorption lines towards background quasars are larger by a factor

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**Table B1. Oxygen abundances.**

| Object                  | \([O/H]^{a}\) | Reference                          |
|-------------------------|---------------|-----------------------------------|
| LMC (today)             | -0.34 ± 0.6   | Russell & Dopita (1992); Fox et al. (2010) |
| LMC (2 Gyr ago)         | -0.5          | Pagel & Tautvaisiene (1998)       |
| SMC (today)             | -0.66 ± 0.1   | Russell & Dopita (1992); Fox et al. (2010) |
| Stream                  | -1.0 ± 0.13   | Fox et al. (2010)                 |
| Stream (Upper limit)\(^{b}\) | -0.4          | Gibson et al. (2000); Lu et al. (1998); Sembach et al. (2001) |
| Bridge                  | -0.96\(^{+0.13}_{-0.11}\) | Lehner et al. (2008)             |
| HVCs near LMC           | -0.5\(^{+0.12}_{-0.16}\) | Lehner et al. (2009)             |

\(^{a}\)Log of the oxygen abundance relative to solar, as defined in equation (B2).

\(^{b}\)Upper limit is defined by increasing the observed oxygen column density of the Stream by a factor of 4.
of 2–4 (Lu et al. 1998; Gibson et al. 2000; Sembach et al. 2001). However, these other measurements also have much larger error bars, as they use tracers that are more sensitive to ionization corrections than the O/H ratio. If we take an upper limit of a factor of 4 increase in the oxygen abundance in the Stream relative to the Fox et al. (2010) values, we can assess whether this material could have once (∼2 Gyr ago) originated in a stellar wind from the LMC. We follow the methodology of Martin, Kobulnicky & Heckman (2002), who estimate the expected metallicity of outflows from the starbursting dwarf NGC 1569. The total mass of the ejected wind $M_w$ is given by

$$M_w = M_{ej}(1 + \chi), \quad (B4)$$

where $M_{ej}$ is the mass in SNe ejecta and $\chi$ is the mass loading of the wind. We consider first the required mass loading from the ISM of the LMC needed to dilute the metallicity so as to not violate the upper limits for the Stream. The oxygen abundance of the wind can be expressed as

$$Z_{O,w} = \frac{M_{ej}(Z_{O,SN} + \chi Z_{O,ISM})}{M_w}. \quad (B5)$$

Written in terms of the solar values, the abundance of the ISM 2 Gyr ago is $Z_{O,ISM} = 10^{-0.5} = 0.32$. Following Martin et al. (2002), the initial mass function (IMF) averaged metallicity of SNe ejecta is $Z_{O,SN} \sim 8$ times solar for oxygen. We choose three values for $Z_{O,SN} = 4, 8$ and 12. We can rewrite equation (B5) to solve for $\chi$ in a mass-independent way using equation (B4):

$$\chi = \frac{Z_{O,SN} - Z_{O,w}}{Z_{O,w} - Z_{O,ISM}}. \quad (B6)$$

Given that we know the current upper limit for the metallicity of the wind, $Z_{O,w} = 10^{-0.4} = 0.4$, the required mass loading is $\chi(Z_{O,SN} = 4, 8, 12) = (45, 95, 145)$.

Mass loadings in excess of factors of 10 are not observed. The wind from M82 is expected to be mass loaded by a factor of 3–6 (Suchkov et al. 1996), and Martin et al. (2002) find a value of $\chi = 9$ to be favoured for NGC 1569. Furthermore, numerical simulations by Mac Low & Ferrara (1999) find it difficult to accelerate any ambient cool gas that is swept up with the expanding outflow; instead, much of that material remains bound to the galaxy.

Ram pressure stripping might be the key missing ingredient that could help entrain ambient gas and explain such high mass loading factors. Assuming the addition of ram pressure stripping results in mass loading in excess of a factor of 45, the resulting total wind mass (equation B4) over a time-scale of 1.7 Gyr (the lifetime of the Stream according to the Nidever et al. 2008 model) would be of the order of $M_w \sim 10^9 M_\odot$.\(^2\) While this appears to be more than enough material to explain the total amount of neutral H I observed in the Stream ($5 \times 10^8 M_\odot$; Table 4), it would imply that the entire Stream should be metal enriched, contrary to observations. This scenario thus overpredicts the mass budget of the Stream and requires mass loading factors that are more extreme than observed.

\(^2\) $M_{ej} = \Gamma M_\star T_{MS}$ is determined assuming an SFR of $M_\star = 0.1 M_\odot \text{yr}^{-1}$ (the current rate in 30 Doradus), an SNe formation rate of $\Gamma = 0.12$ determined from STARBURST99 (Leitherer et al. 1999) with a Kroupa IMF, over a time-scale of $T_{MS} = 1.7$ Gyr.