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Towards a complete understanding of the Magellanic Stream Formation

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ABSTRACT

The Magellanic Clouds (MCs) have lost most of their gas during their passage by the Milky Way, a property that has never been successfully modelled. Here, we use accurate and mesh-free hydrodynamic simulations to reproduce the Magellanic Stream and the MCs in the frame of a ‘ram-pressure plus collision’ model. This model reproduces many of the observed properties of the H I Stream including most of its density profile along its length and its dual filamentary structure. Besides this, ram-pressure combined with Kelvin–Helmholtz instabilities extracts amounts of ionized and H I gas consistent with those observed. The modelled scenario also reproduces the Magellanic Bridge, including the offset between young and old stars, and the collision between the Clouds, which is responsible of the very elongated morphology of the Small Magellanic Cloud along the line of sight. This model has solved most of the mysteries linked to the formation of the Magellanic Stream. The Leading Arm is not reproduced in the current model because it requires an alternative origin.

Key words: Galaxy: halo – Galaxy: structure – galaxies: evolution – galaxies: interactions – Magellanic Clouds.

1 INTRODUCTION

If one was wearing special glasses to see the H I 21cm line, one would see the Milky Way (MW) disc and as the second largest structure in the sky, the Magellanic Stream (hereafter **MS**; Mathewson, Cleary & Murray 1974), which subtends an angle of more than 200 deg (Nidever et al. 2010, 2013). The Stream is linked to the Magellanic Clouds (MCs) and its formation is still challenging to explain. The MCs are likely at their first passage by the MW according to their proper motions from *Hubble Space Telescope* (*HST*; Kallivayalil et al. 2013) and *Gaia* Data Releases 2 (DR2; Gaia Collaboration 2018b). In the meantime, Fox et al. (2014) estimated to $2 \times 10^9 M_\odot$ the total mass released by the progenitors of both Magellanic Stream (**MS**) and Leading Arm (LA), assuming both structures at 55 kpc. Observation from H α emission (Barger et al. 2017) also leads to a similar amount of ionized gas mass. Further analysis by Richter et al. (2017) leads to an even larger value, $3 \times 10^9 M_\odot$. Since the **MS** is likely reaching higher distances than the LA, it is quite conservative to consider $1\text{--}2 \times 10^9 M_\odot$ for the sole contribution of the **MS**. Multiple photoionization and collisional ionization processes that might lead to the ionization of the gas have been explored in the literature, e.g. extragalactic background, hot gas, shock, conductive heating,

turbulent mixing (D’Onghia & Fox 2016; Barger et al. 2017). It has been also suggested by Bland-Hawthorn et al. (2013) that the Stream region below the South Galactic Pole (SGP) could be related to the past AGN activity at the Galactic Centre. Orbital calculations from proper motions of the MCs indicate that they experienced a strong collision a few hundreds Myr ago (Kallivayalil et al. 2013), which formed the Magellanic Bridge (MB) linking them together.

Explanations of the **MS** can be classified into two broad families. One is the ‘tidal’ model (Besla et al. 2012; Pardy, D’Onghia & Fox 2018) assuming that the **MS** is a tidal tail extracted from the Small Magellanic Cloud (SMC) after a collision with a very massive, $1.5\text{--}2.5 \times 10^{11} M_\odot$, Large Magellanic Cloud (LMC). The other is the ram-pressure models with moderate mass for the LMC, $3\text{--}20 \times 10^9 M_\odot$ (Mastropietro et al. 2005; Hammer et al. 2015), which consider ram-pressure effects and may also account for a recent collision between the Clouds.

The circumgalactic medium (CGM) plays a crucial role on the infalling gas by producing ram-pressure and Kelvin–Helmholtz (K–H) instabilities. The CGM extends to hundreds of kpc and is made of multiphase gases (Lehner et al. 2012; Richter et al. 2017), hot (Gupta et al. 2012; Miller & Bregman 2013; Nakashima et al. 2018) and warm phases (Zheng et al. 2019) showing similarities with MW-mass galaxies studied by Werk et al. (2014) and Prochaska et al. (2017). Indirect evidences that the H I Magellanic System is affected by the CGM gas are among others, provided by the exceptionally shrunk H I LMC disc (Salem et al. 2015) and the pressure confined

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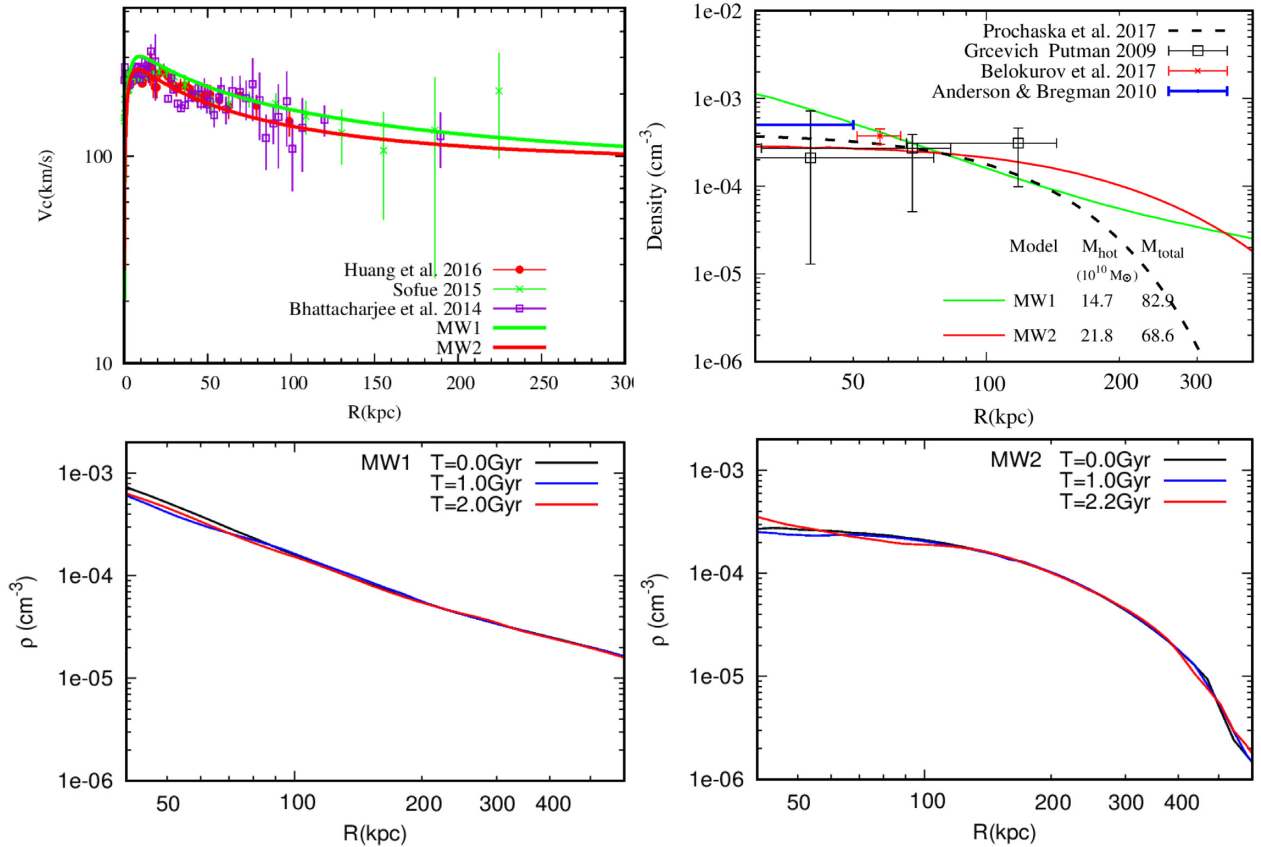


Figure 1. *Top-left panel:* Comparison of the MW observed rotation data (Bhattacharjee, Chaudhury & Kundu 2014; Sofue 2015; Huang et al. 2016) and models used in this paper (red and green solid curves). *Top-right panel:* hot gas density profile used in models compared to several observational constraints, which are indicated on the top-right of the panel (see the text). The cool CGM density profile based on Prochaska et al. (2017) is obtained by fitting their mass distribution with a Hernquist density profile with a core. *Bottom panels:* Density profile evolution with time in isolation to test the stability of the two MW models.

clouds in the Stream (Fox et al. 2005; Kalberla & Haud 2006; For et al. 2014). As recalled by Fillingham et al. (2016), CGM gas at all temperatures contributes to strip and heat the infalling gas, and its density is in excess of a few 10^{-4} cm^{-3} , strongly affecting the MS. In such a condition, the low HI density LA, is unlikely to survive in the CGM as shown by Tepper-García et al. (2019), requiring another origin, such as stripped gas-rich dwarfs moving ahead of the MCs (Hammer et al. 2015).

Fillingham et al. (2016) convincingly showed that even large gas densities ($3\text{--}10 \times 10^{-4} \text{ cm}^{-3}$) in the CGM are unable to remove significant fractions of the gas in galaxies with total masses in excess to a few $10^{10} M_{\odot}$, i.e. masses of the MCs in the ‘tidal’ scenario. We then choose to follow the ‘ram-pressure plus collision’ modelling of Hammer et al. (2015). Here, we use a hydrodynamic solver GIZMO (Hopkins 2015), which accounts fairly for, e.g. K–H instabilities, conversely to GADGET2.

2 NUMERICAL SIMULATIONS AND INITIAL CONDITIONS

2.1 Initial conditions for the Milky Way and the Magellanic Clouds

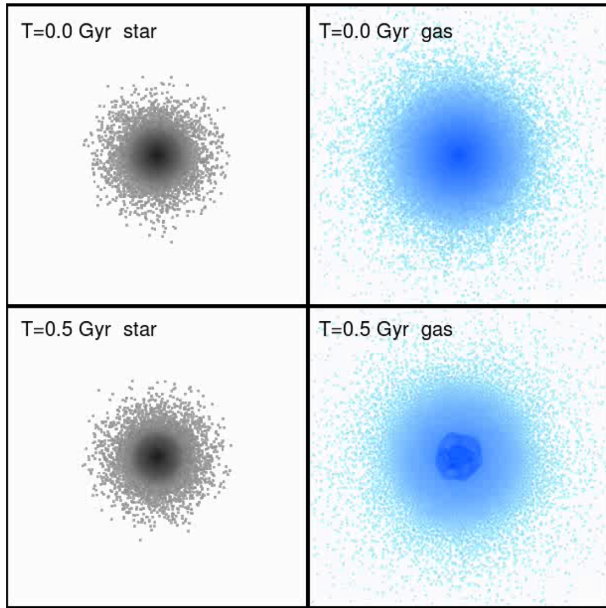
The MW model is set up including a stellar disc, gas disc, hot gas halo, and dark matter halo. The stellar and gas disc have the same properties as in Hammer et al. (2015). For the hot gas halo, we

use a core-profile similar to the halo profile of Hernquist (1993), which has large flexibility and well converging properties. Most constraints for the gaseous halo are indirect, based on observations at around 50 kpc as shown in the top-right panel of Fig. 1. In the current study, we use two types of hot gas halo profiles as shown by red and green lines (top-right panel of Fig. 1). Model MW1 shows a flatter profile since it includes the outskirts contribution of the IGM with a density of $\sim 2 \times 10^{-5} \text{ cm}^{-3}$ at virial radius. For comparison, the observed cool CGM density profile of MW-mass galaxies (Prochaska et al. 2017) is also shown in Fig. 1, with a dashed-black line. The density profile has been calculated from the projected mass density distribution from fig. 17 of Prochaska et al. (2017), assuming a core density profile (Hernquist 1993). For the MW dark matter halo, we use a core model as in Barnes (2002), and the dark matter profile is then adjusted to fit the observed rotation curve, which is shown in the left-hand panel of Fig. 1. Total and halo gas masses within the virial radius (260 kpc) are given in the top-right panel of Fig. 1 for the two adopted models. To reduce the particle number and numerical calculation in the simulation, the dark matter halo has been considered as causing a gravitational potential fully accounted by analytic formulae, such as: $\rho \propto (r + a_{\text{halo}})^{-4}$ with $a_{\text{halo}} = 6 \text{ kpc}$ and central density $\rho_0 = 0.7379$ and $0.4919 M_{\odot} \text{ pc}^{-3}$ for MW1 and MW2, respectively.

To test the stability of the MW gas halo model, we run it in isolation for 2 Gyr, which is similar to the time duration during which the MCs simulations are made. The two panels in the bottom

Table 1. Initial condition parameters.

Model components	Model-27		Model-28		Model-52	
	LMC	SMC	LMC	SMC	LMC	SMC
Stellar disc mass ($10^9 M_\odot$)	2.5	0.3	2.5	0.3	2.0	0.3
Gas disc mass ($10^9 M_\odot$)	2.5	2.4	2.5	2.4	2.0	2.4
Stellar spheroid mass ($10^9 M_\odot$)	0	0.3	0	0.3	0	0.3
Scale length of stellar disc (kpc)	1.4	1.5	1.4	1.5	1.4	1.5
Scale height of stellar disc (kpc)	1.0	0.8	1.0	0.8	1.0	0.8
Scale length of gas disc (kpc)	7.0	5.0	4.0	5.0	5.0	5.0
Scale size of spheroid (kpc)	0.0	1.5	0.0	1.5	0.0	1.5
Number of stellar particles	150 000	72 000	300 000	72 000	240 000	72 000
Number of gas particles	150 000	288 000	300 000	288 000	240 000	288 000


Figure 2. Projected density distribution of stars and gas for one model of the LMC at $T = 0.0$ Gyr and after an evolution in isolation after 0.5 Gyr. The size of each panel is 100×100 kpc.

row of Fig. 1 show the hot gas density profile evolution over a 2 Gyr time-scale. The two models of MW hot gas halo are stable enough for our studies.

The LMC is assumed to be the combination of an exponential stellar disc with a neutral gas disc, for which the scale length of the neutral gas disc is much larger than that of the stellar component as shown in Table 1 (van der Kruit 2007; Pardy et al. 2018; Tepper-García et al. 2019). For the SMC, we assume that there are two stellar components and one neutral gas disc. The stellar component consists of an exponential stellar disc and a spheroid, following Diaz & Bekki (2012). The stellar spheroid has a core density profile and is made of ancient stars, which is motivated by the recent observations of Ripepi et al. (2017), who found such a distribution using 3D mapping based on RR Lyrae stars. All the parameters used for the MCs are given in Table 1. The initial condition is created with a Schwarzschild orbit superposition method (Vasiliev 2013; Vasiliev & Athanassoula 2015). To test the stability of the initial model of the MCs, we let them evolve in isolation for 0.5 Gyr, without important changes as shown in Fig. 2. We have also tested cases after evolving MCs in isolation as progenitors, and the results do not change significantly. For both the MCs we have considered the possible presence of a dark matter halo. However, their masses

have been limited to be equal or up to 10 times the mass of the baryonic component that is few $10^9 M_\odot$, since the MW CGM gas would not be able to extract the cold gas from more massive galaxies (Fillingham et al. 2016).

2.2 The hydrodynamic code GIZMO

The numerical simulations were carried out with GIZMO (Hopkins 2015), which is based on a new Lagrangian method for hydrodynamics, and has simultaneously properties of both smoothed particle hydrodynamics (SPH) and grid-based/adaptive mesh refinement methods. It has considerable advantages when compared to SPH, for instances, proper convergence, good capturing of fluid-mixing instabilities, dramatically reduced numerical viscosity, sharp shock capturing, and so on. These features make GIZMO providing a considerable advance when compared to GADGET2, which was unable to properly account for K–H instabilities, considered by Hammer et al. (2015) as the main limitation for their study of the Magellanic Stream.

To use this code, we implemented into GIZMO star formation and feedback processes as in Wang et al. (2012) following the method of Cox et al. (2006). This code has been used for investigating the formation history of M31 (Hammer et al. 2018). For the radiative cooling process, we have used the updated version of Katz, Weinberg & Hernquist (1996). It assumes the gas as a primordial plasma, and ionization states of H and He are explicitly tracked under the assumption of collisional ionization equilibrium (Hopkins 2015).

2.3 Convergence of the simulation

All the simulations are using a softening of 40 pc, which is large enough to minimize discreteness noise and also small enough to sample a reasonable resolution. The particles mass ratio between the hot gas of the MW and cold gas of the MCs are important for ram-pressure, which can result in spurious enhancement of ram-pressure stripping when this ratio is too large (Abadi, Moore & Bower 1999; Mastropietro et al. 2005; Kazantzidis et al. 2017). In our simulations this ratio ranged from 2.4 to 12. To test convergence, we also run a high-resolution simulation for Model-28, this ratio changed from 12 to 1.2, but our result did not change significantly, which indicate that our results are not affected by artificial effects.

2.4 Definition of neutral gas and warm + hot gas

Since there is no radiative transfer used in the simulation, neutral and ionized gas cannot be directly distinguished properly (Marasco et al. 2015). To compare the properties of neutral H I and warm + hot

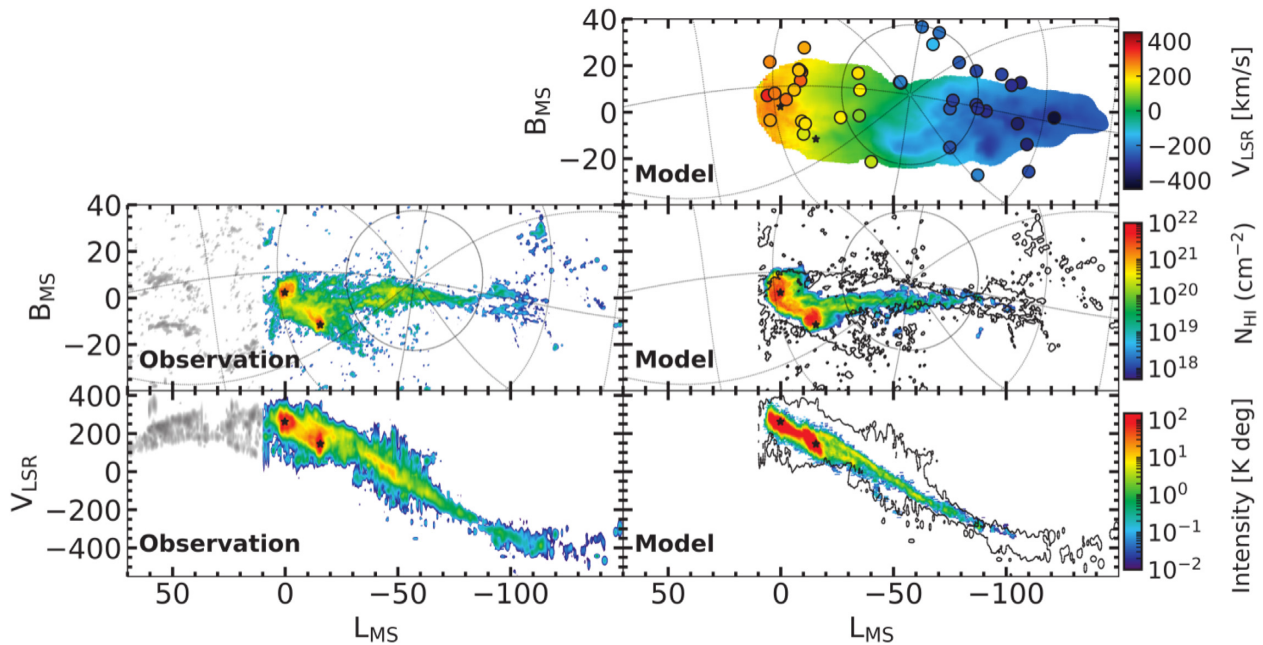


Figure 3. Comparing H I and warm + hot gas, from Model-28, distributions with observations in the Magellanic coordinate system (Nidever, Majewski & Butler Burton 2008). The top-right panel shows the sky distribution of the simulated warm + hot ionized gas with a colour coding for the line-of-sight velocity. Points represent QSOs absorption line observations by *HST*/COS (Fox et al. 2014). The simulated ionized gas mass ($0.81\text{--}0.94 \times 10^9 M_\odot$) is consistent with that observed $\sim 10^9 M_\odot$ (D’Onghia & Fox 2016). Most of them are lying in the same area as the simulations, though observations indicate an even larger area for the ionized gas. The bottom two rows compare observed H I distributions of the Magellanic Stream with that of simulations, of which the left column shows results of H I observations from Nidever et al. (2010), while the right column shows results from simulation of Model-28. The black stars in each panel indicate the position of LMC and SMC. The H I mass in the MS is in the range of $1.4\text{--}5 \times 10^8 M_\odot$, which is consistent with observations, $2.7 \times 10^8 M_\odot$ (D’Onghia & Fox 2016). In the simulation panels observations are marked by contours. The LA is shown with grey colour in the left-hand side of the observation panel to indicate that it is not reproduced by our models, because it is assumed to have another origin rather than the MC gas (Yang et al. 2014; Hammer et al. 2015; Tepper-García et al. 2019).

ionized gas stripped from the MCs with that from observations, we define particles with temperatures below 2×10^4 K as neutral gas and assume simple collisional ionization equilibrium (Sutherland & Dopita 1993), while particles with temperatures above 2×10^4 K are defined as warm + hot gas. The neutral hydrogen mass is derived by assuming that the gas has an universal hydrogen mass fraction of 0.76 (Sutherland & Dopita 1993). This simple definition between neutral and ionized gas is consistent with studies of gas properties in simulations (Marasco et al. 2015; Sokołowska et al. 2016), and with observational conventions (Putman, Peek & Joing 2012; Sokołowska et al. 2016).

2.5 Orbital parameters

Determination of orbital parameters is a three-body problem (interaction between the two MCs and the MW), which is further complicated by gas dissipation properties. To calculate the initial position and velocity of the MCs before entering the MW hot medium, we use the solver defined by Yang & Hammer (2010) that has been improved in Hammer et al. (2015), and which can provide the final position and velocity of MCs at the current observing time and can match that of observations as shown in Section 3.

3 RESULTS OF MODELLING

3.1 Gas modelling

In the current model, the MCs enter the gas corona of the MW and their H I content is stripped by ram-pressure effects, which result in

the formation of the H I MS. Fig. 3 shows the H I sky distribution and its velocity along the Magellanic longitude. As in Hammer et al. (2015) the simulated H I Stream reproduces well the observations, including the two ram-pressure tails lagging behind each MC that mimic the MS structure with its two twisting filaments (Nidever et al. 2010). Observations of H I kinematics (Nidever et al. 2008) and chemical abundances (Fox et al. 2013; Richter et al. 2013) show that one of the two main filaments has LMC-like chemistry and kinematics, whereas the other has SMC-like properties. This indicates that one filament originates in the LMC, whereas the other originates in the SMC. This observed dual filamentary features is naturally formed by the ram-pressure stripping scenario, as ram-pressure acts separately on each Cloud, stripping gas to form two trailing stream tails of MCs (for a detailed comparison, see Hammer et al. 2015 and Fig. 5). The H I gas mass of the MS ranges from 1.4 to $5 \times 10^8 M_\odot$, to be compared to the observed value, $2.7 \times 10^8 M_\odot$ (D’Onghia & Fox 2016). The two values are in good agreement, since the latter is likely underestimated by assuming a 55 kpc distance for all the MS extent. Moreover, the column density profile of the H I gas is well reproduced (see Section 3.4).

The main difference with Hammer et al. (2015) modelling is the use of the GIZMO (Hopkins 2015, 2017) hydrodynamic solver instead of GADGET2. The former code accounts for K–H instabilities far much better than GADGET2 (Hopkins 2015), that do not only strips the MC gas but also dissolves the H I phase, helping it to be heated and then ionized. The high density of hot gas results in high ram-pressure (Gunn & Gott 1972), which strips H I gas of the MCs and then heats it up. It has led us to assume much higher initial gas mass than in Hammer et al. (2015) as well as higher density of hot

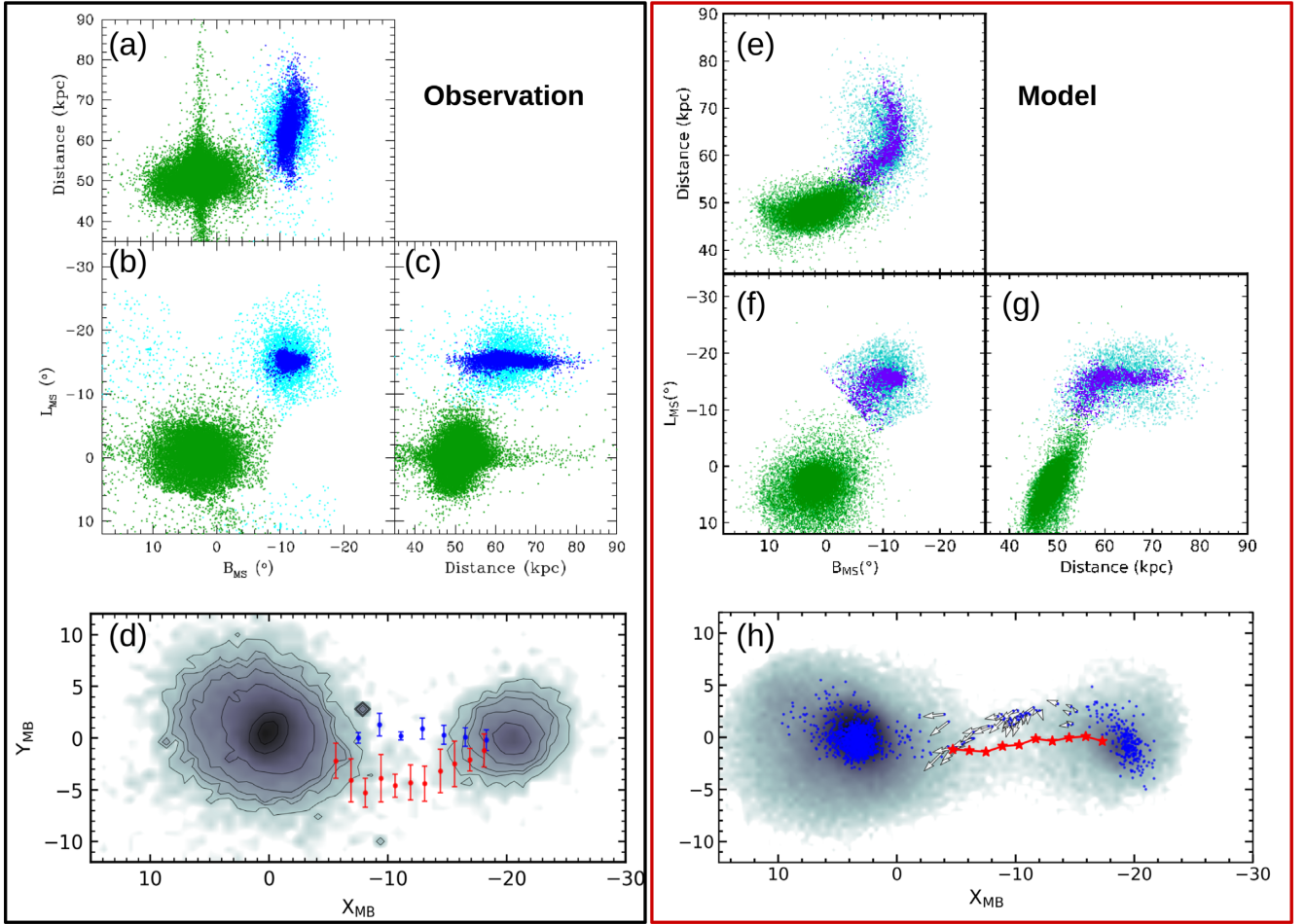


Figure 4. Comparison of the observed stellar distribution (the left-hand panels enclosed within rectangle a black box) of the MCs with that of simulations from Model-52 (the right-hand panels enclosed within a red box). In the observation panels (a, b, c), the observed stars are separated into ancient stars (green for LMC and cyan for SMC) and young stars (blue, age < 300 Myr). The former are traced by RR Lyrae stars and the latter by Classical Cepheids (Ripepi et al. 2017). The top-right panels (panels e, f, g, h) particles in ancient stars (green and cyan) are randomly selected to reach the same number as in the observations. In both observations and simulations young stars follow an elongated shape distribution along the line of sight, which is well explained by the interaction of the gas from which they formed with the LMC. The bottom-left panel (panel e) shows RR Lyrae stars from *Gaia* DR2, overlapped with the results from Belokurov et al. (2017): ancient star (red, RR Lyrae) and young stars (blue, main sequence). The bottom-right panel (panel h) shows results from Model-52 (blue points are stars with age < 150 Myr). The offset between the young and ancient stars in the Bridge occurs in both observations and simulations. In the bottom-right panel (panel h) the relative velocity of Bridge young stars are shown with vectors, for which the systematic motion of the SMC has been removed. They indicate that young stars are leaving the SMC, which is fully consistent with recent observations (Oey et al. 2018).

gas. This is to warrant a sufficient amount of residual MS H I gas, and large quantities of ionized gas as found by Fox et al. (2014) and confirmed by Richter et al. (2017). In fact K–H instabilities are so efficient that the modelling of the MS naturally leads to a much larger fraction of ionized gas than of H I gas. The extent of the simulated hot gas associated with the MS (see top panel of Fig. 3) is far larger than that of the H I and matches quite well the large extended area where quasistellar objects (QSOs) absorption lines reveal the presence of the MS ionized gas (Fox et al. 2014; Richter et al. 2017). In total the gas mass associated with the MS ranges from 0.8 to $1.5 \times 10^9 M_{\odot}$, and these numbers can be increased by using models with progenitors having larger gas fractions and shallower gas distributions.

3.2 The SMC morphologies

The recent collision between the MCs has a strong effect on the SMC, particularly on the young, ≤ 300 Myr stars, which formed

from the gas during the most violent phases of interactions. The young stars identified by Classical Cepheids (CCs) with ages less than 300 Myr indeed show a very unusual 3D shape heavily elongated to about 30 kpc along the line of sight (Ripepi et al. 2017). Fig. 4 compares the 3D stellar distributions of the MCs. Simulations shows that the SMC gas is pressurized by LMC gravitational tides, leading to a strongly elongated 3D shape in which star formation is favoured. Fig. 4 shows that young, ≤ 300 Myr stars formed during the interaction have shapes with similar elongations along the line of sight than that observed. In both simulations and observations, old stars linked to the initial disc and spheroid have a much less elongated distribution.

There are some apparent differences between the model and data in the distribution of stars. In the observation panel (panel a) of Fig. 4, there are RR Lyrae stars with vertical (distance) distribution which is absent in the simulations (panel e). The large majority of these stars are true Galactic RR Lyrae variables along the line of sight, the rest are pulsators with large distance errors (Ripepi

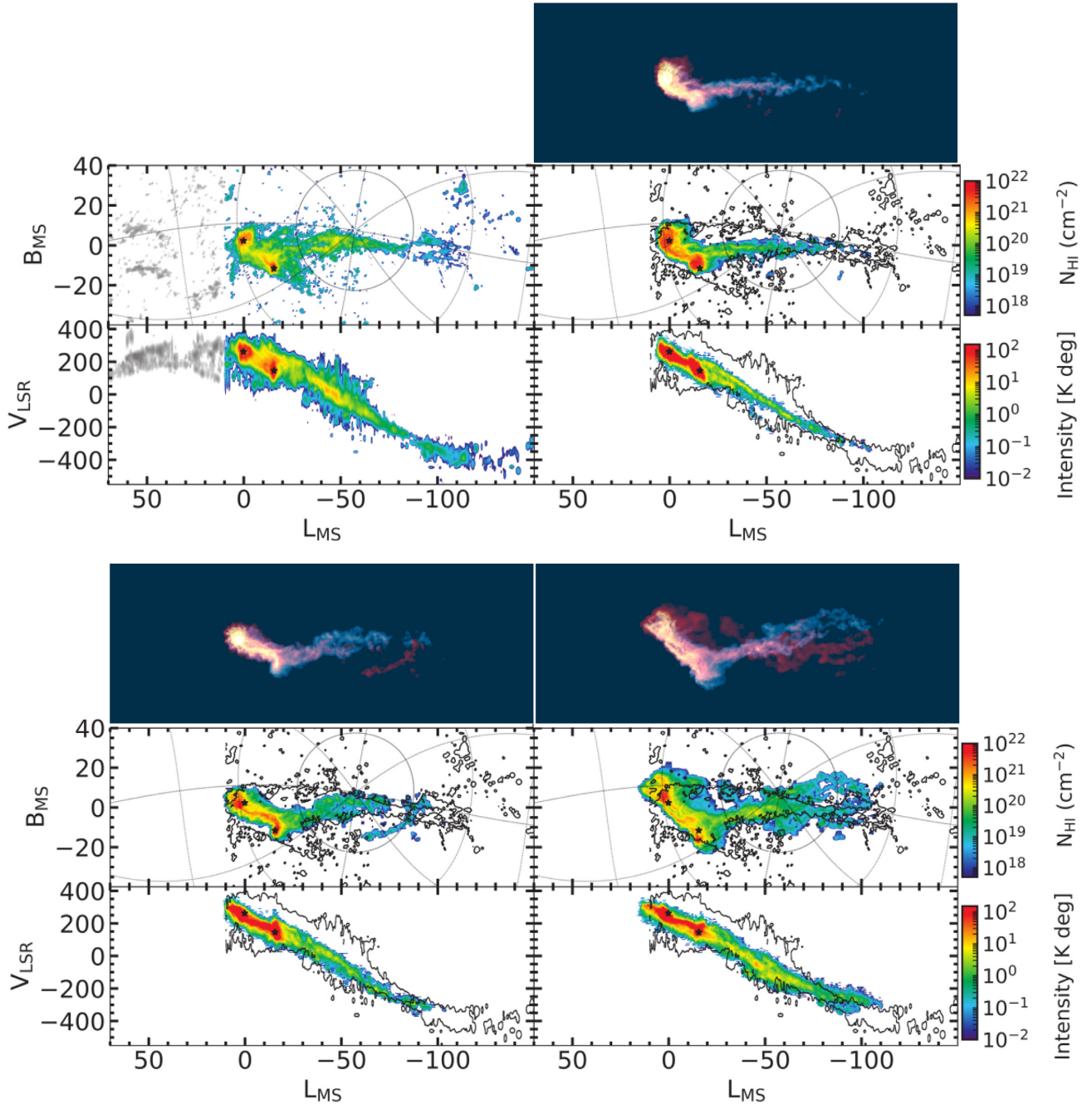


Figure 5. Comparison of three simulated models of Magellanic Stream H I gas distribution with observations (top-left) from Nidever et al. (2010). The simulations refer to Model-28 (top-right), Model-52 (bottom-left), and Model-27 (bottom-right). On the top of each simulation panel, a colour image shows the distribution of particles, which have been separated into LMC (red) and SMC (blue) according to their origins.

et al. 2017). The differences with respect to the morphology traced by young stars (blue points) can be resolved by fine-tuning of the collision parameters between the MCs, e.g. the mass ratio of progenitors, the relative inclination of the SMC disc, and the pericentre distance. The collision affects the disc of LMC too. Section 3.4 shows the results of three different models with slightly different parameters. Because the parameter space is huge, finely tuning the parameters will further imply optimizing the match between observations and modelling.

3.3 The Magellanic Bridge for gas and stars

The model reproduces well the H I Bridge as shown in Fig. 3. Young, intermediate-age and old stars have been identified in the Bridge (Irwin, Demers & Kunkel 1990; Bagheri, Cioni & Napiwotzki 2013; Noël et al. 2013; Skowron et al. 2014). Belokurov et al. (2017) has discovered an offset between young main-sequence stars and old stars (traced by RR Lyrae from *Gaia* Data Release 1, DR1) as shown in the bottom-left panel of Fig. 4.

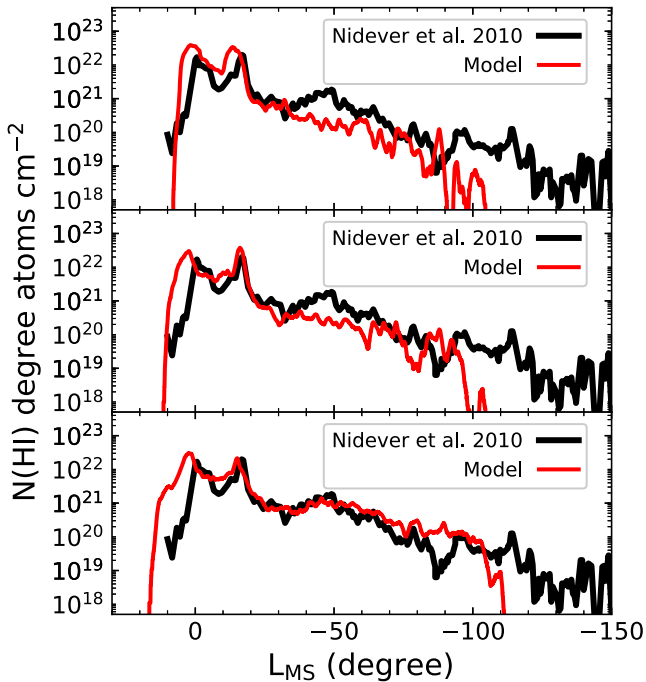


Figure 6. Comparison of the observed H I column density projected along the Magellanic longitude with that provided by three simulation models: Model-28 (top), Model-52 (centre), and Model-27 (bottom). The black line is from observational data (Nidever et al. 2010) and red lines are from simulations.

In this section we are verifying whether our modelling of the Bridge is consistent with the discovery by Belokurov et al. (2017) that there is an offset between the distribution of young and old star locations in the Bridge. However Belokurov et al. (2017) used *Gaia* DR1 data, and in the Appendix A we have used a larger sample from *Gaia* DR2 to select RR Lyrae stars for analysing the old population in the Bridge. Here, we compare the resulting observed distributions of old and young stellar populations with our simulation. In the right-hand panel of Fig. 4, simulations also show a similar offset between young and old stars, though less pronounced, between the young and old stars. Thanks to *Gaia*, proper motions of OB stars in the Wing region of the SMC indicate a systematic peculiar motion away from the SMC of $64 \pm 8 \text{ km s}^{-1}$ (Oey et al. 2018; Schmidt et al. 2018). The bottom-right panel of Fig. 4 shows a similar trend: young, $< 150 \text{ Myr}$ stars (motions indicated by white arrows) are leaving the SMC towards the LMC. Young stars within the $-16 < X_{\text{MS}} < -10$ range have a mean velocity of 19 km s^{-1} in the simulation, which is around a third of that observed. We also recover the observed fact (Zivick et al. 2019) that Bridge stars are moving faster when they lie closer to the LMC (see increasing arrow sizes).

3.4 Model variance

We have explored a total of ~ 200 different models to compare with observed properties. A comparison between 3 of them is given in Figs 5, 6, and 7 for the H I distribution on the sky, the projected column density distribution, and the 3D star distribution for both MCs. The final results of our models are listed in Table 2.

In Fig. 5, we have distinguished gas particles from LMC and SMC progenitors, which are shown with different colours on the top of each subpanel of Fig. 5. The MS is composed from both LMC and SMC particles, which form two filaments as observed (Nidever et al. 2010; Hammer et al. 2015). All models reproduce well the main properties, though with some differences.

3.5 Limitations of the modelling

Our model has some weaknesses, linked to the complexity of the problem and to observational uncertainties. The most important one is our choice to model the MW halo gas by a single hot gas component in equilibrium with the MW mass distribution ($T \sim 10^6 \text{ K}$). Simulations are also not accounting for gas cooling that is metal dependent, or for shielding and UV background. Although ram-pressure depends only on gas-density, a high temperature helps to heat the MS gas, rendering easier the formation of a large ionized gas fraction. It is however likely that the MW halo gas is multiphased (Lehner et al. 2012; Prochaska et al. 2017; Richter et al. 2017), and this may affect the global balance between ionized and neutral gas in the MS. However, uncertainties about the different components of the multiphase gas in the MW are too large to improve our modelling of the MW halo gas. Moreover, while it is well known (Fox et al. 2014; Richter et al. 2017) that the MS is dominated by the ionized gas, its density along the MS longitude (or distance) is far from being well known, leading to large uncertainties on the total density deposited by the MC, from 1 to $5 \times 10^9 \text{ M}_{\odot}$ according to Richter et al. (2017). The above weaknesses are then not affecting the conclusion of the paper: it is the first time the release of more than 50 per cent of the initial gas from the MCs has been modelled.

The series of simulations reproduce all features, but not always at the same time (e.g. for a single model). Of more concern is the fact that a few features are not reproduced by any model. For example, the simulated H I velocity along the Magellanic longitude is not as broad as observed. This could be due to an insufficient account of shocks, or perhaps of contamination by background structures such as H I emission from the Sculptor group. Most other discrepancies (e.g. number of young stars in the Bridge) can be solved by fine-tuning orbital parameters or the star formation efficiency.

4 CONCLUSION

The recent infalling of the MCs into the MW gaseous halo and their mutual interaction have formed the gigantic MS and the Bridge, which are fully reproduced by a simulation based on a very precise hydrodynamic solver. This includes detailed properties such as the two filamentary structures of the MS (see Fig. 5). Accounting for K-H effects automatically generates large amounts of ionized gas. It is the first time that a physical modelling is able to explain and reproduce the enormous quantities of gas stripped from the MCs, i.e. more than 50 per cent of their initial content. This adds another challenge to the ‘tidal’ scenario, which is unable to provide such large gas amounts extracted from a single tidal tail (Diaz & Bekki 2012; Pardy et al. 2018; Tepper-García et al. 2019). Masses in excess of $10^{11} \text{ M}_{\odot}$ for the LMC are then likely excluded, while we verified that our modelling may accommodate for masses up to $2 \times 10^{10} \text{ M}_{\odot}$.

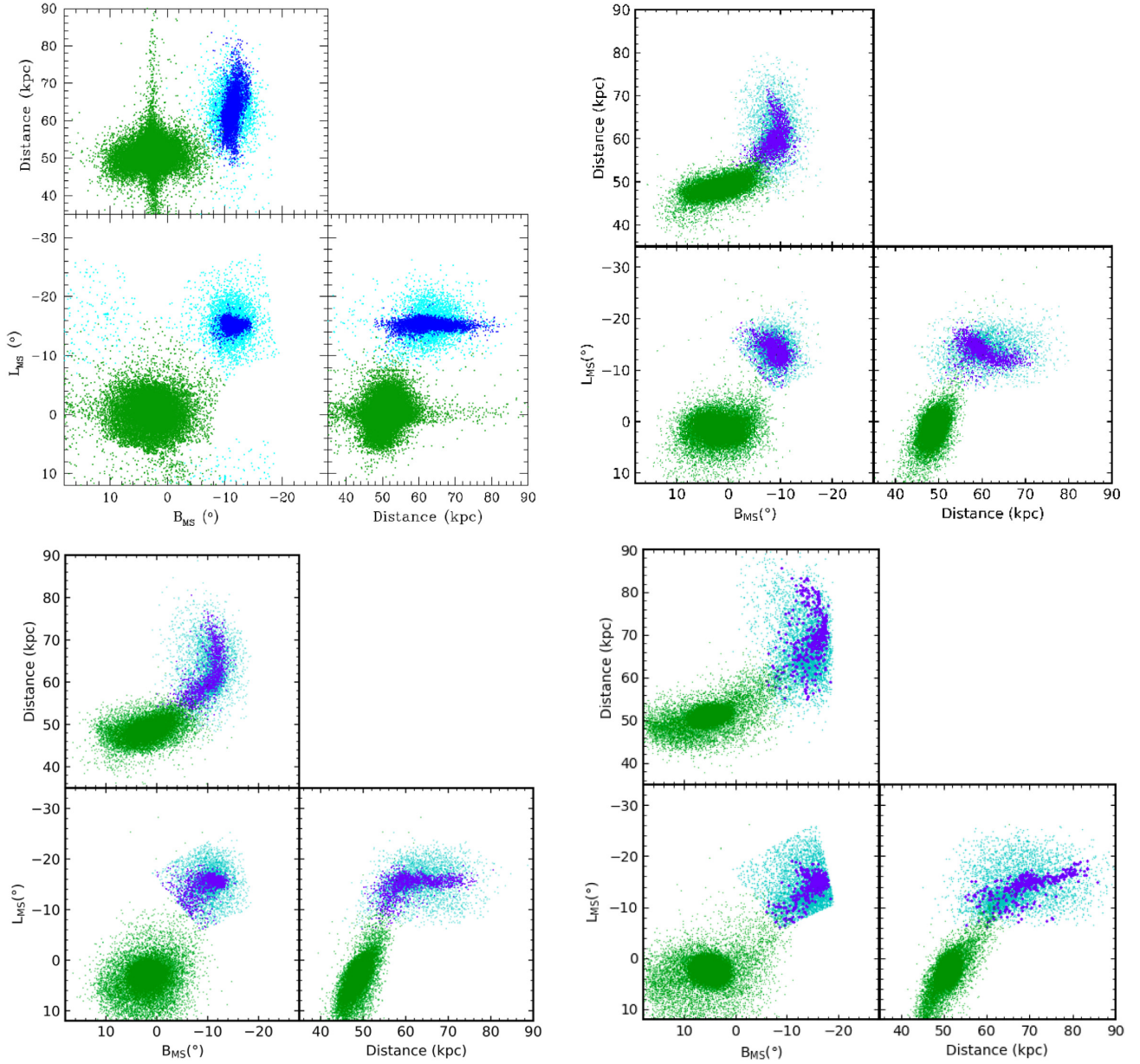


Figure 7. Stellar distribution in 3D for both observations by Ripepi et al. (2017) (top-left panel) and simulations of three models, Model-28 (top-right), Model-52 (bottom-left), and Model-27 (bottom-right). Observed data refer to RR Lyrae for ancient stars (green and cyan), and Classical Cepheids for young stars (blue). In the simulations young stars are selected with having ages lower than 300 Myr. The observing selecting box on the SMC stars (Ripepi et al. 2017) has been applied on the simulation images as it is shown in the sky plane (L_{MS} , B_{MS}) subpanels.

Table 2. Simulated Magellanic Clouds and Stream properties.

Model	MCs	Total Mass $10^9 M_{\odot}$ $R < 3.5 \text{ kpc}$	Magellanic Clouds		Gas fraction per cent $R < 3.5 \text{ kpc}$	Magellanic Stream	
			Gas mass $10^9 M_{\odot}$ $R < 3.5 \text{ kpc}$	Stellar mass $10^9 M_{\odot}$ $R < 3.5 \text{ kpc}$		H I mass $10^9 M_{\odot}$ $L_{\text{MS}} < -25 \text{ deg}$	Warm + hot gas $10^9 M_{\odot}$ $L_{\text{MS}} < -25 \text{ deg}$
Mod27	LMC	2.88	0.83	2.05	29	0.5	0.93
	SMC	0.40	0.22	0.18	55		
Mod28	LMC	3.05	0.93	2.12	30	0.14	0.81
	SMC	1.73	1.30	0.43	75		
Mod52	LMC	2.45	0.83	1.62	34	0.15	0.94
	SMC	0.81	0.50	0.31	62		

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REFERENCES

- Abadi M. G., Moore B., Bower R. G., 1999, *MNRAS*, 308, 947
 Bagheri G., Cioni M.-R. L., Napiwotzki R., 2013, *A&A*, 551, A78
 Barger K. A. et al., 2017, *ApJ*, 851, 110
 Barnes J. E., 2002, *MNRAS*, 333, 481
 Belokurov V., Erkal D., Deason A. J., Koposov S. E., De Angeli F., Evans D. W., Fraternali F., Mackey D., 2017, *MNRAS*, 466, 4711
 Besla G., Kallivayalil N., Hernquist L., van der Marel R. P., Cox T. J., Kereš D., 2012, *MNRAS*, 421, 2109
 Bhattacharjee P., Chaudhury S., Kundu S., 2014, *ApJ*, 785, 63
 Bland-Hawthorn J., Maloney P. R., Sutherland R. S., Madsen G. J., 2013, *ApJ*, 778, 58
 Clementini G. et al., 2016, *A&A*, 595, A133
 Clementini G. et al., 2019, *A&A*, 622, A60
 Cox T. J., Jonsson P., Primack J. R., Somerville R. S., 2006, *MNRAS*, 373, 1013
 D’Onghia E., Fox A. J., 2016, *ARA&A*, 54, 363
 Diaz J. D., Bekki K., 2012, *ApJ*, 750, 36
 Fillingham S. P., Cooper M. C., Pace A. B., Boylan-Kolchin M., Bullock J. S., Garrison-Kimmel S., Wheeler C., 2016, *MNRAS*, 463, 1916
 For B.-Q., Staveley-Smith L., Matthews D., McClure-Griffiths N. M., 2014, *ApJ*, 792, 43
 Fox A. J., Wakker B. P., Savage B. D., Tripp T. M., Sembach K. R., Bland-Hawthorn J., 2005, *ApJ*, 630, 332
 Fox A. J., Richter P., Wakker B. P., Lehner N., Howk J. C., Ben Bekhti N., Bland-Hawthorn J., Lucas S., 2013, *ApJ*, 772, 110
 Fox A. J. et al., 2014, *ApJ*, 787, 147
 Gaia Collaboration, 2016a, *A&A*, 595, A1
 Gaia Collaboration, 2016b, *A&A*, 595, A2
 Gaia Collaboration, 2018a, *A&A*, 616, A1
 Gaia Collaboration, 2018b, *A&A*, 616, A12
 Gunn J. E., Gott J. R., III, 1972, *ApJ*, 176, 1
 Gupta A., Mathur S., Krongold Y., Nicastro F., Galeazzi M., 2012, *ApJ*, 756, L8
 Hammer F., Yang Y. B., Flores H., Puech M., Fouquet S., 2015, *ApJ*, 813, 110
 Hammer F., Yang Y. B., Wang J. L., Ibata R., Flores H., Puech M., 2018, *MNRAS*, 475, 2754
 Hernquist L., 1993, *ApJS*, 86, 389
 Hopkins P. F., 2015, *MNRAS*, 450, 53
 Hopkins P. F., 2017, preprint([arXiv:1712.01294](https://arxiv.org/abs/1712.01294))
 Huang Y. et al., 2016, *MNRAS*, 463, 2623
 Irwin M. J., Demers S., Kunkel W. E., 1990, *AJ*, 99, 191
 Kalberla P. M. W., Haud U., 2006, *A&A*, 455, 481
 Kallivayalil N., van der Marel R. P., Besla G., Anderson J., Alcock C., 2013, *ApJ*, 764, 161
 Katz N., Weinberg D. H., Hernquist L., 1996, *ApJS*, 105, 19
 Kazantzidis S., Mayer L., Callegari S., Dotti M., Moustakas L. A., 2017, *ApJ*, 836, L13
 Lehner N., Howk J. C., Thom C., Fox A. J., Tumlinson J., Tripp T. M., Meiring J. D., 2012, *MNRAS*, 424, 2896
 Marasco A., Debattista V. P., Fraternali F., van der Hulst T., Wadsley J., Quinn T., Roškar R., 2015, *MNRAS*, 451, 4223
 Mastropietro C., Moore B., Mayer L., Wadsley J., Stadel J., 2005, *MNRAS*, 363, 509
 Mathewson D. S., Cleary M. N., Murray J. D., 1974, *ApJ*, 190, 291 (MS)
 Miller M. J., Bregman J. N., 2013, *ApJ*, 770, 118
 Nakashima S., Inoue Y., Yamasaki N., Sofue Y., Kataoka J., Sakai K., 2018, *ApJ*, 862, 34
 Nidever D. L., Majewski S. R., Butler Burton W., 2008, *ApJ*, 679, 432
 Nidever D. L., Majewski S. R., Butler Burton W., Nigra L., 2010, *ApJ*, 723, 1618
 Nidever D. L. et al., 2013, American Astronomical Society Meeting Abstracts, #221, 404.04
 Noël N. E. D., Conn B. C., Carrera R., Read J. I., Rix H.-W., Dolphin A., 2013, *ApJ*, 768, 109
 Oey M. S. et al., 2018, *ApJ*, 867, L8
 Pardy S. A., D’Onghia E., Fox A. J., 2018, *ApJ*, 857, 101
 Prochaska J. X. et al., 2017, *ApJ*, 837, 169
 Putman M. E., Peek J. E. G., Joun M. R., 2012, *ARA&A*, 50, 491
 Richter P., Fox A. J., Wakker B. P., Lehner N., Howk J. C., Bland-Hawthorn J., Ben Bekhti N., Fechner C., 2013, *ApJ*, 772, 111
 Richter P. et al., 2017, *A&A*, 607, A48
 Ripepi V. et al., 2017, *MNRAS*, 472, 808
 Salem M., Besla G., Bryan G., Putman M., van der Marel R. P., Tonnesen S., 2015, *ApJ*, 815, 77
 Schmidt T., Cioni M.-R., Niederhofer F., Diaz J., Matijevic G., 2018, preprint([arXiv:1810.02701](https://arxiv.org/abs/1810.02701))
 Skowron D. M. et al., 2014, *ApJ*, 795, 108
 Sofue Y., 2015, *PASJ*, 67, 75
 Sokołowska A., Mayer L., Babul A., Madau P., Shen S., 2016, *ApJ*, 819, 21
 Soszyński I. et al., 2016, *Acta Astron.*, 66, 131
 Sutherland R. S., Dopita M. A., 1993, *ApJS*, 88, 253
 Tepper-García T., Bland-Hawthorn J., Pawłowski M. S., Fritz T. K., 2019, preprint([arXiv:1901.05636](https://arxiv.org/abs/1901.05636))
 Udalski A. et al., 2015, *Acta Astron.*, 65, 341
 van der Kruit P. C., 2007, *A&A*, 466, 883
 Vasiliev E., 2013, *MNRAS*, 434, 3174
 Vasiliev E., Athanassoula E., 2015, *MNRAS*, 450, 2842
 Wang J., Hammer F., Athanassoula E., Puech M., Yang Y., Flores H., 2012, *A&A*, 538, A121
 Werk J. K. et al., 2014, *ApJ*, 792, 8
 Yang Y., Hammer F., 2010, *ApJ*, 725, L24
 Yang Y., Hammer F., Fouquet S., Flores H., Puech M., Pawłowski M. S., Kroupa P., 2014, *MNRAS*, 442, 2419
 Zheng Y., Peek J. E. G., Putman M. E., Werk J. K., 2019, *ApJ*, 871, 35
 Zivick P. et al., 2019, *ApJ*, 874, 78

APPENDIX A: RR LYRAE STAR DISTRIBUTION IN THE INTRA-CLOUD REGION OF THE BRIDGE

Due to their typical variability, relatively easy detection and ubiquity, the RR Lyrae variables are important tracers of the old (age > 10 Gyr) population of the host galaxy. The OGLE group (Udalski et al. 2015; Soszyński et al. 2016) has identified tens of thousands such pulsators in the LMC and SMC, whereas the all sky survey carried out by the *Gaia* spacecraft (Gaia Collaboration 2016a), presented in DR1 and DR2 (Gaia Collaboration 2016b, 2018a) contributed to the detection of RR Lyrae variables in the outskirts of the MCs and in the intra-cloud region, beyond the OGLE survey footprint (Clementini et al. 2016, 2019).

The *Gaia* DR1 data were exploited by Belokurov et al. (2017), who found bona fide RR Lyrae candidate variables relying only on the *Gaia*'s mean flux and its associated errors. On these bases Belokurov et al. (2017) claimed the presence of a second old Bridge between the MCs, not aligned with the gaseous MB, and shifted by ~ 5 deg from the young main-sequence Bridge. Giving the limited information available, the Belokurov et al. (2017)'s RR Lyrae sample completeness and purity are low in comparison with surveys where light curve and colour data are available. This is the case of *Gaia* DR2 where light curves for ~ 140 K RR Lyrae were published in the *Gaia* *G* band and for ~ 83 K also in the G_{BP} and G_{RP} bands. These data, in conjunction with the OGLE data set, provide a reliable sample of RR Lyrae to study the distribution of old stars around and in-between the MCs. This data set can be used

to update the Belokurov et al. (2017) analysis and the result of this operation is shown in Fig. 4, where to select objects likely belonging to the Magellanic System, we displayed only RR Lyrae with $V > 18$ mag (diffuse grey regions). An inspection of the figure reveals that the old Bridge (red symbols) suggested by Belokurov et al. (2017) is substantially confirmed. There are also differences, such as a concentration of objects at $X_{MB}, Y_{MB} = -11, -2$ deg, where the distribution of the pulsators traced by the *Gaia* DR2 data set is displaced towards the north by ~ 2 deg with respect to Belokurov et al. (2017), lying very close to the young main-sequence Bridge (blue symbols).

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