Clouds in Arms

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ABSTRACT
We use astrometry and broad-band photometry from Data Release 2 of the ESA’s Gaia mission to map out low surface-brightness features in the stellar density distribution around the Large and Small Magellanic Clouds. The LMC appears to have grown two thin and long stellar streams in its Northern and Southern regions, highly reminiscent of spiral arms. We use computer simulations of the Magellanic Clouds’ in-fall to demonstrate that these arms were likely pulled out of the LMC’s disc due to the combined influence of the SMC’s most recent fly-by and the tidal field of the Milky Way.

Key words: Milky Way – galaxies: dwarf – galaxies: structure – Local Group – stars

1 INTRODUCTION
Stellar discs are fragile and even a quick, low mass-ratio encounter with a neighboring galaxy can cause plenty of damage. The blockbuster by Toomre & Toomre (1972) provides a gallery of salient moments of such interactions as well as a comprehensive analysis of plausible outcomes. Let us provide a digest of their findings as to the formation of arms and bridges between companion galaxies. First, Toomre & Toomre (1972) point out that the damage is inflicted via tidal forces, which are roughly symmetric with respect to the disc’s host. Thus, a single passage will always produce two arms (whose relative strengths depend on the perturber’s orbit) on opposite sides of the disc. No slow interaction is needed, relatively fast (parabolic) orbits will also lead to arm formation. Naturally, smaller perturbers pull out tidier, i.e. more coherent arms as the fly-by of a massive neighbor causes a messier debris splatter. However, smaller perturbers take more time to pull out long arms and have to come closer to the disc compared to the massive ones. Toomre & Toomre (1972) highlight repeatedly how narrow the tidally-induced arms are, but take care to point out that this thinness is quite often the result of the perspective, in fact most arms are “ribbons”, not “strings”. While arm production can be thought of as a resonance phenomenon (see aslo D’Onghia et al. 2010), even highly inclined encounters produce dramatic arms. In the latter case, arms usually twist considerably in 3D, and while appearing face-on for some viewing angles are clearly pulled out of the disc plane.

While the study of Toomre & Toomre (1972) is motivated by such iconic images as that of e.g. M51, one can find several very local examples of low mass-ratio galaxy conflicts with dramatic consequences. Most notably, as described in Laporte et al. (2017, 2018), the Sagittarius (Sgr) dwarf - itself barely a twentieth of the Milky Way’s (MW) mass - has likely wrought plenty of havoc in the Galaxy’s disc. The dwarf is now held responsible for inducing a large-scale spiral structure in the Galaxy (see e.g. Purcell et al. 2011), creating a warp in the gaseous disc (see e.g. Gibbons et al. 2017) and sending large-amplitude waves through the stellar disc (e.g. Widrow et al. 2012; Schönrich & Dehnen 2017; Xu et al. 2015). Most interesting are the long thin streams of stars likely pulled out of the Galactic disc (see Grillmair 2006, 2011; de Boer et al. 2018; Deason et al. 2018) that do look remarkably similar to the tidal arms described in Toomre & Toomre (1972) and that can now be used for a variety of chemo-dynamical studies of both the MW and the Sgr dwarf (see Laporte et al. 2018).

It so happened that the most striking example of a nearby binary interaction was only just being discovered at the time of the writing of Toomre & Toomre (1972) and hence could not be included in their analysis. Wannier & Wrixon (1972) and van Kuijlenburg (1972) detected long streams of HI in the Southern sky, and some two years later these were shown to connect to the Magellanic Clouds by Mathewson et al. (1974). The Magellanic Stream (MS, as it is known today) has since been mapped across the sky (see e.g. Putman et al. 2003; Nidever et al. 2008, 2010) and is today unambiguously demonstrated to have originated in the interaction between the Large and the Small Clouds (LMC and SMC, Besla et al. 2007, 2010; Diaz & Bekki 2011, 2012). While the stellar counterpart to the MS is yet to be discovered, the last two years have seen a marked increase in the number of reported detections of low surface-brightness stellar substructure in the vicinity of the Clouds (see e.g. Mackey et al. 2016; Belokurov & Koposov 2016; Belokurov et al. 2017; Deason et al. 2017; Pieres et al. 2017; Mackey et al. 2018; Nidever et al. 2018). In particular, Mackey et al. (2016, 2018) concentrate on the perturbations in and around the LMC’s stellar disc. They uncover a

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wealth of sub-structure, some of which (such as the long stream-like feature in the North of the LMC) they tentatively attribute to the tidal influence of the MW (Mackey et al. 2016). They also detect prominent stellar debris over-densities in the Southern parts of the LMC and put forward two formation scenarios: one to do with the disruption of the LMC’s disc and one linked to the episodic stripping of the SMC (see also Besla et al. 2016, who argued for the importance of repeated interactions with the SMC).

In this Letter, we use a combination of Gaia’s (Data Release 2, or GDR2) photometry and astrometry to produce an uninterrupted panorama of the Magellanic Clouds. We focus on the density fluctuations between 10 and 30 degrees away from the LMC’s centre. While our maps do not attain the same level of detail achievable using deep imaging with instruments such as DECam, they help to fill in the gaps in the Magellanic puzzle. Moreover, Gaia’s astrometry has the unprecedented power to remove the bulk of the intervening MW’s disc population and thus extend the study of the Clouds to regions not accessible even with the deepest imaging surveys.

2 GAIA DR2 VIEW OF THE MAGELLANIC CLOUDS

In what follows we use the photometry and astrometry provided as part of the Data Release 2 (Gaia Collaboration et al. 2018a) of the Gaia mission (Gaia Collaboration et al. 2016). We correct the $G$, $G_{BP}$ and $G_{RP}$ magnitudes for the effects of extinction using the first two terms in the Equation 1 of Gaia Collaboration et al. (2018b) and the dust maps of Schlegel et al. (1998). Additionally, we remove the foreground dwarf stars from our sample by culling all objects with parallax $\varpi < 0.2$ mas and exclude stars with Galactic latitudes $|b| < 5^\circ$. We note that this is not the first attempt to use GDR2 to study the LMC (and the SMC): the kinematic view of the inner portions of each Cloud can be found in Gaia Collaboration et al. (2018c), while Vasiliev (2018) presents the first results of dynamical modelling of the inner LMC.

Figure 1 shows the behavior of stars with $\varpi < 0.2$ mas in the vicinity of the Clouds in color-magnitude and proper motion (PM) spaces. More precisely, the left panel displays the density of stars within 12 degrees of the LMC’s center in $G$ vs $G_{BP} - G_{RP}$ plane (Hess diagram). Here we assumed that the center of the dwarf is located at $\alpha, \delta = 80.89375^h,-69.7561^\circ$. The CMD signal of the LMC can be compared to that of the Galactic foreground shown in the second panel of the Figure. We give the difference of the two in the third panel. In this Hess difference plot, the LMC’s Red Giant Branch (RGB) and the Red Clump (RC) are easily discernible (their envelope is traced by black-and-white dashed line). Note that the tip of the RGB runs horizontally (i.e. at constant $G$) for colors redder than $G_{BP} - G_{RP} < 2$. While the RC is the most densely populated CMD feature, it is also the one that suffers the highest Galactic foreground contamination, especially at $G_{BP} - G_{RP} < 0.9$ and $G > 19$. Therefore, to select the likely Magellanic stars we choose objects with $\varpi < 0.2$ mas that fall within the CMD mask (broad enough to accommodate the heliocentric distance range across the Magellanic system) shown in panels 2 and 3 of Figure 1 and have $G_{BP} - G_{RP} < 0.9$ and $G < 19$. Finally, to further improve the purity of our selection we apply PM cuts chosen to delineate the motion of genuine LMC and SMC stars as shown in the fourth (rightmost) panel of the Figure. Here, stars within $15^\circ$ of the LMC and $7^\circ$ of the SMC are shown in $\mu_L, \mu_B$ PM space aligned with the gaseous MS (see Nidever et al. 2008, for the definition of the $L_{MS}, B_{MS}$ coordinate system). Note that to clarify the over-densities corresponding to the Clouds, for this panel only, we additionally limit the stars to those with $G_{BP} - G_{RP} > 1.3$.

The density of the likely Magellanic RGB candidate stars selected using a combination of parallax, $|b|$, CMD and PM cuts described above is shown in Figure 2. The same density map is displayed twice, in the middle and right panels of the Figure, albeit with different saturation levels to help study features across a wide range of surface brightness values. Note that even at astonishingly low Galactic latitudes, $|b| < 10^\circ$, very little disc contamination is visible thanks to the power of Gaia’s astrometry. Comparing the stellar density patterns in panels 2 and 3 with the dust distribution shown in panel 1, we conclude that the only noticeable correlation between the two maps can be seen in the very cores of each Cloud, where the star counts are depleted by high values of extinction. Figure 2 reveals an intricate and spatially extended system of narrow stream-like structures emanating from the LMC’s disc. A large portion of the Northern arm was already discussed in Mackey et al. (2016), where it was traced out to $\sim 20^\circ$ away from the LMC’s center. Here we show that this structure continues to higher $L_{MS}$ for (at least) some $5^\circ$ to $10^\circ$, passing right under the Carina dwarf, where, as pointed in Mackey et al. (2016), the LMC’s stars have been detected before (see Majewski et al. 2000; McMonigal et al. 2014). In the Southern regions of the LMC, a more complicated
web of sub-structures can be seen. There are two “claw”-like overdensities, identified as “Substructure 1” and “Substructure 2” in Mackey et al. (2018). Curiously, in the maps presented here, “Substructure 2” appears to be curving clockwise, continuing as far as \((L_{\text{MS}}, B_{\text{MS}}) = (10^\circ, -5^\circ)\). One of the most striking new features is a thin stellar stream which appears to be connecting to the SMC at around \(L_{\text{MS}} \sim -8^\circ\). This narrow tail, one of the longest structures discussed here, wraps around the Southern edge of the LMC’s disc, tracing an arc of \(\sim90^\circ\) in clockwise direction. As gleaned from Figure 2, the LMC appears to have two long arms, one in the North and its counter-part in the South.

To clarify the origin of the stellar over-densities described above, Figure 3 gives the PMs of the selected LMC’s candidate RGB stars. Note that these PMs have been corrected for the Solar reflex assuming a constant heliocentric distance of 49.9 kpc. The pattern of the median PM values (left column of the Figure) across the inner 10\(^\circ\) (smaller dashed circle) is dominated by the gradient associated with the Cloud’s rotation (see also Vasiliev 2018). Note, however, that the stellar motions preserve coherence well outside the central LMC. More fascinating still, all of the narrow arm-like features at distances beyond \(\sim 15^\circ\) also display coherent systematic motions. Overall, the kinematics of the Northern and Southern arms resembles that of the outer LMC’s disc but offset in orbital phase. Note that the bulk of the Southern sub-structure shares the PM of the LMC. This is especially evident in the lower left panel, where the stellar streams have colors from green to red, similar the LMC’s disc, while the SMC is dark blue. While not the main focus of this Letter, it is worth commenting briefly on the PM pattern of the SMC. According to Figure 3, the SMC’s systemic motion is in the direction away from the LMC, i.e. towards negative \(L_{\text{MS}}\) and negative \(B_{\text{MS}}\), consistent with previous measurements (see e.g. Kallivayalil et al. 2013). Also visible are clear proper motion gradients, whose direction is roughly aligned with the line connecting the centers of the two Clouds. While this gradient could be modelled as an intrinsic rotation signal (see e.g. Gaia Collaboration et al. 2018c), we suggest it could also be the result of the strong tidal stretching of the SMC by the LMC (see also Zivick et al. 2018).

The right column of the Figure presents dispersions around the median values of PM components \(\mu_L\) and \(\mu_B\) for each pixel of \(L_{\text{MS}}\) and \(B_{\text{MS}}\). Strong perturbations of the inner LMC’s disc have recently been reported in the literature (see Choi et al. 2018), but here, we offer a much more complete map of kinematically cold (blue) and hot (red) regions across the entire Cloud. The regions of elevated dispersion are clearly different for the longitudinal and latitudinal PM components. For \(\mu_L\), the hottest region is on the rim of the LMC’s disc facing the SMC and in between the Clouds, where one naturally expects a mixture of stars from both dwarfs. In \(\mu_B\), there are two extended regions with high PM dispersion, one in the North and one in the South, located radially inward from the locations of each arm. The arms themselves are distinctly cold as judged by their dark blue color.
3 SIMULATIONS, CAVEATS AND CONCLUSIONS

In order to investigate how the MW and SMC affect the LMC’s disc and whether they can induce the spiral features shown in Figure 2, we have run a series of simulations in the spirit of Toomre & Toomre (1972). In particular, we simulate the disc of the LMC as a series of particles in concentric rings which are initially on circular orbits. While this ignores the initial non-circular motions, it captures the overall behavior of the disc over the relatively short timescales considered here. The system is then evolved in the presence of the MW and the SMC. We model the LMC’s potential as a Hernquist profile (Hernquist 1990) which satisfies the rotation curve measurement at a radius of 8.7 kpc from van der Marel & Kallivayalil (2014) (for each LMC mass, the scale radius is fixed by this constraint). The initial orientation and rotation sense of the LMC are chosen to match the observations from van der Marel & Kallivayalil (2014). The SMC is also modelled as a Hernquist profile satisfying the rotation curve measurement at a radius of 3 kpc from Stanimirović et al. (2004). The MW is modelled as the 3-component potential, MWPotential2014, from Bovy (2015). Starting from their present day positions, the LMC and SMC are wound around 1 Gyr (in the presence of each other and the MW), at which point particles are placed on circular orbits around the LMC. For each simulation, we place 5000 particles on 50 separate concentric circles with radii evenly spaced from 1 to 20 kpc. The simulation is then evolved to the present. For the LMC’s present day position and velocity, we use a distance of 49.97 ± 1.126 kpc (Pietrzyński et al. 2013), a radial velocity of 262.2 ± 3.4 km/s (van der Marel et al. 2002), and PMs of \((\mu_\alpha \cos \delta, \mu_\delta) = (1.91 \pm 0.02, 0.229 \pm 0.047) \text{ mas/yr} \) (Kallivayalil et al. 2013). For the SMC, we use a distance of 62.1 ± 1.9 kpc (Graczyk et al. 2014), a radial velocity of 145.6 ± 0.6 km/s (Harris & Zaritsky 2006), and PMs of \((\mu_\alpha \cos \delta, \mu_\delta) = (0.772 \pm 0.063, -1.117 \pm 0.061) \text{ mas/yr} \) (Kallivayalil et al. 2013). For each choice of the LMC and SMC masses and scale radii, we sample their present day position and velocity and simulate 100 realizations to explore the variety of outcomes.

In Figure 4 we isolate the effect of the MW (left-most column) and the SMC (middle two columns) on the LMC. The two rows show two different realizations of the LMC and SMC’s present day position and velocity. The top row shows an LMC with a closer encounter with the SMC (\(r_{peri} \sim 10 \text{ kpc}\)), while the bottom row shows a more distant encounter (\(r_{peri} \sim 15 \text{ kpc}\)). The tidal field of the MW is primarily responsible for bending the Northern half of the LMC, similar to what was found in \(N\)-body simulations in Mackey et al. (2016), and creates a spiral arm feature similar in position and orientation to what is seen in the data. The SMC can create one or two spiral arms, depending on how strong of an interaction it has with the LMC during its most recent pericenter. While this is in seeming contradiction to the results of Toomre & Toomre (1972), we stress that we are observing the LMC disc only ∼ 150 Myr after its most recent passage with the SMC and that it takes time for the spiral features to form. If the LMC was simulated for longer, the second spiral would form in the lower panel of Figure 4. Interestingly, we find that the SMC creates a strong spiral arm in the South which matches the observed Southern stream. We found that changing the SMC mass from \(5 \times 10^9 \text{ M}_\odot \) to \(10^{10} \text{ M}_\odot \) resulted in only a modest change in the spiral features. Our simulations do not contain the “claw”–like features visible in the data in the Southern part of the LMC. We conjecture that these density features are remnants of much earlier interactions between the two Clouds. The fourth column of the figure shows the effect of both the MW and the SMC. This demonstrates that their combined effect is needed to create the two spirals observed in the LMC. It also illustrates how a close encounter with the SMC can truncate the Western portion of the LMC’s disc (top, second from the right panel) similar to what it seen in the data. Taken together, this shows that morphology of the LMC’s disc and the associated spiral structure can be used to reveal its rich dynamical history.
In a similar vein, we also explore the effect of the LMC’s mass on its morphology in Figure 4. While the first four columns show a $2 \times 10^{10} M_\odot$ LMC, the final column shows a $2 \times 10^{11} M_\odot$ LMC. Note that the final column should be compared with the fourth column since these have the same setup. As the LMC mass is increased, we find that the LMC is deformed less by the MW. This is because the increased LMC mass results in a larger tidal radius and hence a larger region where the effect of the MW is negligible. Interestingly, only the lowest mass LMC we consider ($2 \times 10^{10} M_\odot$) can match the tightly wound spiral seen in the North (see Fig. 2). Since this mass is only slightly higher than the mass constraint within 8.7 kpc from van der Marel & Kallivayalil (2014), this could suggest that the LMC has already been significantly stripped. However, we stress that these simulations are only meant to be the first step in showing that the morphology (including spirals) of the LMC’s disc can provide useful constraints on the properties of the LMC, SMC, and on the tidal effect of the MW. With this aim in mind, the rich PMs in Figure 3 will also be useful in future modelling efforts.

In summary, we have used the exquisite data from Gaia DR2 to unveil a global view of the perturbations to the LMC’s disc. In particular, there are two clear spiral features, as well as some complex substructure to the South of the LMC (see Fig. 2). While some of this structure was seen before (e.g. Mackey et al. 2016, 2018), the uninterrupted view afforded by Gaia allows us to better understand how these features arose. We simulated the combined effect of the MW and SMC on the LMC’s disc and found that both are important for creating the spiral features seen in the data. Namely, the MW is responsible for deforming the Northern part of the LMC while the most recent passage of the SMC creates the strong spiral feature in the South. A close passage with the SMC can also truncate the Western side of the LMC’s disc. Finally, we showed that the distant Magellanic Red Giants detected here can be used to map out the LMC’s mass distribution at unprecedentedly large distances.

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