Disk Destruction and (Re)-Creation in the Magellanic Clouds

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Abstract. Unlike most satellite galaxies in the Local Group that have long lost their gaseous disks, the Magellanic Clouds are gas-rich dwarf galaxies most-likely on their first pericentric passage allowing us to study disk evolution on the smallest scales. The Magellanic Clouds show both disk destruction and (re)-creation. The Large Magellanic Cloud has a very extended stellar disk reaching to at least 15 kpc (10 radial scalelengths) while its gaseous disk is truncated at ∼5 kpc mainly due to its interaction with the hot gaseous halo of the Milky Way. The stellar disk of the Small Magellanic Cloud, on the other hand, has essentially been destroyed. The old stellar populations show no sign of rotation (being pressure supported) and have an irregular and elongated shape. The SMC has been severely disturbed by its close encounters with the LMC (the most recent only 200 Myr ago) which have also stripped out large quantities of gas creating much of the Magellanic Stream and the Magellanic Bridge. Amazingly, the SMC has an intact, rotating H I disk indicating that either the inner HI was preserved from destruction, or, more likely, that the HI disk reformed quickly after the last close encounter with the LMC.

Background: Essentially no Local Group (LG) dwarfs within 270 kpc of their host galaxy (Milky Way or M31) currently have HI (<10^5 M⊙, Greveich & Putman 2009). The lone exceptions are the Magellanic Clouds (MCs). It is thought that the gas was ram pressure stripped from the inner galaxies, but it is complicated to study now. Fortunately, the MCs can be used to study these gas-dynamical effects right now in great detail because the MCs still have a lot of gas (likely falling into the Milky Way for the first time; Besla et al. 2007) and are quite nearby.

One of the most striking features of the Magellanic system is the 200°–long Magellanic Stream (MS; Nidever et al. 2010). The MCs have lost lots of gas (∼ 5 × 10^8 M⊙; Bruns et al. 2005) to the MS and Leading Arm in the last couple of Gyrs due to their interaction with the MW and each other. The MS is spatially bifurcated into two filaments (Putman et al. 2003) and one of the filaments can be traced back to its origin in the LMC using its velocity coherence (Nidever et al. 2008). HST absorption line metallicities show that the MS has a dual origin with one filament coming from the LMC and the other from the SMC (Fox et al. 2013; Richter et al. 2013). Recent models indicate that the SMC gas was tidally stripped by the LMC in its most recent incounters (Besla et al. 2010; Diaz & Bekki 2012).

The Large Magellanic Cloud: The Large Magellanic Cloud (LMC) has an inclined, exponential, rotating stellar disk (van der Marel 2001, van der Marel et al. 2002, van der Marel & Kallivayalil 2013). It also has an off-center stellar bar (van der Marel 2001), a high star formation rate (Smecker-Hane et al. 2002), and a rotating HI disk (Kim et al. 1998). The LMC stellar and gaseous distributions are quite differ-
The stellar disk is regular, exponential and slightly elliptical, while the gaseous disk is smaller, rectangular, has a (morphological center that is offset from the stellar center, and also has a high column density on the leading edge (see Fig. 1 left panel). The Outer Limits Survey (OLS) used deep photometry of old MSTO stars to trace the LMC disk to $R=16^\circ$ and showed that it still followed an exponential out to these large radii (Saha et al. 2010). Spectroscopically-detected LMC giants have been traced to $R\approx20^\circ$ over $180^\circ$ in position angle (Muñoz et al. 2006; Majewski et al. 2009) and in some regions out to $R\approx27^\circ$ (Muñoz et al. 2013). However, the density profile and radial velocities of these stars are more consistent with a halo than a disk. Nevertheless, the current HI disk ($8^\circ$) is puny compared to the stellar disk ($32^\circ$) and it appears as if the gaseous disk has been whittled away. But by what? Whatever the cause it can’t have affected the stars that much because the LMC hosts an intact extended stellar disk.

The LMC star formation histories provide further evidence of the gaseous disk destruction. The right panel of Figure 1 shows the star formation histories for three intermediate radius LMC fields ($R=4.0^\circ$, $5.5^\circ$, and $7.1^\circ$; Gallart et al. 2009; Meschin et al. 2013). Stars were forming in all three fields within the last few Gyrs. However, recently there has been a severe drop in the star formation rate (SFR) starting with the outermost field and then moving inward over time. The innermost field (at the edge of the HI disk in a supergiant shell) has current ongoing star formation but if the decline in SFR continues this star formation will cease with less than one Gyr. The outer two fields where star formation has essentially ceased are outside the current HI disk. The rate at which the cutoff is moving inward is $\sim2.8^\circ$/Gyr$=2.4$ kpc/Gyr. At this rate, star formation in the LMC will completely cease within $\sim0.8$ Gyr and, presumably, also the HI disk will be gone.
The six mechanisms could that be destroying the LMC gaseous disk are: 1) star formation (gas $\rightarrow$ stars), 2) stellar feedback (gas), 3) MW tidal stripping (gas/stars), 4) MW ram pressure stripping (gas), 5) SMC tidal stripping (gas/stars), and 6) SMC ram pressure stripping (gas). The LMC has had continuous star formation for $\sim 12$ Gyr even though the gas depletion rates for dwarfs are normally $\sim 2$ Gyr (Bigiel et al. 2008). Gas accretion is required to keep the star formation going for this long, and it is quite unlikely that this would all stop right now (rules out #1). As previously mentioned, the stellar disk is basically unaffected, so the mechanism needs to be something that only affects gas. This rules out tidal forces (#3 and #5). How about the LMC/SMC interaction? The LMC and SMC have had a recent ($\sim 200$) close encounter (Růžička et al. 2010) and Besla et al. (2012) even suggest that there was a direct collision that can explain the LMC off-center bar. could this explain the outer LMC HI disk destruction? The collision was too recent (100–300 Myr ago) to explain the outer disk destruction ($\sim 2$ Gyr ago to present) and it also can’t explain the LMC gas in the MS downstream. So although a direct collision might have occurred, it isn’t the whole story. There must be something else affecting the LMC HI disk (rules out #6). Finally, we are left with two mechanisms: MW ram pressure stripping, and stellar feedback. Ram pressure is consistent with the boxy shape of the HI disk, large column density gradient on the leading edge, the timescale of LMC recent falling into the MW, as well as the Mastropietro et al. (2005) result showing you can get significant ram pressure stripping from the LMC. Furthermore, stellar feedback and outflow is consistent with the large number of supergiant shells in the LMC (Kim et al. 1998), gaseous outflow in the northeast of the LMC (Kim et al. 1998; Nidever et al. 2008), and the shut off of star star formation after a “burst” as seen in the 4.0$^\circ$ field.

The Small Magellanic Cloud: Gardiner & Hatzidimitriou (1992) used photographic plate photometry to study the SMC periphery and showed that the distribution of young stars is very irregular and elongated towards the LMC. This elongated distribution is also seen in HI, the Magellanic Bridge (Muller et al. 2003), that was recently tidally stripped from the SMC (Muller & Bekki 2007). The distribution of the red (and older) stars is much more regular and symmetric extending to $R\sim 4-5^\circ$ (Gardiner & Hatzidimitriou 1992). Nidever et al. (2011) used data from the MAgellanic Periphery Survey (MAPS) to trace photometrically-selected SMC giant stars to $R\sim 11^\circ$ and showed that they follow a slightly elliptical exponential profile out to $R\sim 8$ kpc. It is well known that the SMC has a large line-of-sight depth (Hatzidimitriou & Hawkins 1989). Nidever et al. (2013) derived distances for red clump stars in eight fields at $R=8^\circ$ and found a bimodality in distance in the eastern fields with a new structure at $\sim 55$ kpc on the near-side of the SMC. The most likely interpretation of this new structure is that it is the stellar counterpart of the tidally stripped Magellanic Bridge.

There is no detected rotation in the SMC stellar distribution either in radial velocities (Kunkel et al. 2000; Harris & Zaritsky 2006) or proper motions (Piatek et al. 2008), instead the stars appear to be pressure supported. Furthermore, the line-of-sight depths of red clump stars with radius on the western side of the SMC are more consistent with a spheroidal distribution than a disk distribution (Gardiner & Hawkins 1991). The evidence, therefore, points to the SMC having a spheroidal-like (or ellipsoidal) structure rather than an exponential disk. If there was a SMC stellar disk before (which is likely) then it was severely disturbed by the recent encounter with the LMC. On the other hand, rotation is seen in the SMC HI distribution (Stanimirović et al. 2004). How is it possible for the stars to be so perturbed (with no rotation) but the gas to be rotating? Recollapse into a disk. The stars are collisionless and non-dissipational and once the
stars are stirred up and perturbed they can’t easily relax to a disk again. The gas, on the other hand, is collisional and dissipational and can recollapse to a rotating disk even after being disturbed. The SMC free-fall timescale is \( \sim 50 \) Myr. Since the LMC/SMC collision happened 100–300 Myr ago that should give the gas enough time to collapse.

In the near future, the Survey of the MAgellanic Stellar History (SMASH, PI:Nidever), an approved community DECam project to perform deep imaging of the MCs and their periphery, will provide exquisite spatially-resolved star formation histories that will shed new light on the complex history and evolution of the Magellanic Clouds.

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