

The Magellanic Stream as a Laboratory for Gas Stripping and Dark Matter Halo Evolution in Dwarf Irregular Galaxies

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ABSTRACT

Spanning more than 140° in the southern hemisphere, the Magellanic Stream is a huge filament of neutral and ionized hydrogen. It is an excellent example of a laboratory for studying gas stripping and dark matter halo evolution. The aim of this paper is to analyze the formation of the Magellanic Stream, the Large and Small Magellanic Clouds (LMC and SMC) orbital and interaction histories and the proposed competing theories for the formation of the Magellanic Stream. High 21-cm observations, UV observations, metallicity, proper motion data, and the results of numerous hydrodynamic and N-body simulations are reviewed to form a consolidated approach for the Stream's formation. It is argued that no single mechanism can entirely explain the observed properties of the Magellanic Stream and that the model that is most consistent with observations is a hybrid one in which tidal stripping of SMC gas is followed by ram-pressure acceleration and shaping within the Milky Way's circumgalactic medium (CGM). The results of this study can be, and likely will be, applied to the general evolution of dwarf irregular galaxies. The Magellanic interaction reveals that environmental effects can redistribute and truncate dark matter halos and alter the gas morphologies before a satellite galaxy even completes one pericentric passage. These changes may occur and alter the structure and regulation of star formation, before a satellite galaxy completes a single pericentric passage. Addressing the existing uncertainties regarding the mass of the Milky Way or the Magellanic orbital histories, combined with estimations of the Magellanic Stream gas densities, the CGM densities, and interactions between the Milky Way galaxy and the Magellanic Stream, will be important for building better models.

Keywords: Magellanic Stream; Large Magellanic Cloud (LMC); Small Magellanic Cloud (SMC); tidal stripping; ram pressure stripping; circumgalactic medium (CGM); dwarf irregular galaxies; dark matter halos; galaxy interactions; Magellanic System; neutral hydrogen (HI); galaxy evolution.

1. INTRODUCTION

The Magellanic Clouds are important for extragalactic astronomy for good reason. The LMC and SMC are the nearest gas-rich, dwarf irregular satellite galaxies of the Milky Way and, as such, provide a unique opportunity for natural experiments of disparate methods of study in knowing the various environmental processes involved in dwarf irregular galaxy evolution—mutual gravitational heating, tidal interactions and ram pressure loss. The Magellanic Stream is the most well-known example of the effects of these processes and it was first described by Mathewson et al. (1974) when they discovered a coherent trailing gas filament in HI 21 cm emission extending from the Clouds to the south Galactic pole (Mathewson et al., 1974). More recent studies have shown a complicated system that is morphologically diverse and contains more than just the trailing Stream such as the Leading Arm in orbit ahead of the Clouds (Putman et al., 1998) and an HI bridge linking the LMC and SMC (Hindman et al., 1963).

The Magellanic Stream is a crucial area of study in the study of dwarf galaxies. Gas stripping in the form of Tidal stripping and Ram pressure stripping are important factors in the transforming of field dwarf irregular galaxies into gas-poor dwarf spheroidal and dwarf elliptical galaxies. The Magellanic System provides an area of study to measure different theories. The Magellanic Stream is unique in its ability to study the distribution of matter and morphology of the dark matter halos of the Magellanic Clouds and the Milky Way's hot gaseous halo.

For over 20 years, the Magellanic System has been the focus of new interest in astrophysics. Measurements of their proper motion via Hubble Space Telescope have overturned the idea of multiple Milky Way passages for the Magellanic Clouds (Kallivayalil et al., 2013; Kallivayalil, Van Der Marel, & Alcock, 2006; Kallivayalil, Van Der Marel, Alcock, et al., 2006). Now the first-infall scenario is more plausible (Besla et al., 2007). This has created challenges to how we understand the evolution of the Magellanic Stream. The first-infall Stream model argues that the Clouds have not been subject to multiple orbits and also does not allow for pure tidal processes. This model has been validated by the effects of Magellanic Cloud interactions on the formation of the Stream and has been complemented by the effects of ram pressure in the circumgalactic medium of the Milky Way (Besla et al., 2010, 2012). A culmination of this is the interaction of the Magellanic System and the Milky Way Galaxy with the new constraints on the structure of dark matter haloes and the effects of stellar kinematics and new developments in cosmological simulations. These studies have the potential to describe the effects of tidal and hydrodynamic forces and the structure of irregular dwarf galaxies in group or cluster environments.

2. PHYSICAL CHARACTERISTICS OF THE MAGELLANIC SYSTEM

2.1 The LMC and SMC as Dwarf Irregular Galaxies

The LMC is an intermediate mass irregular galaxy with a stellar mass of about $2-3 \times 10^9 M_{\odot}$ and a total dynamical mass of about $10^{10} M_{\odot}$ (Van Der Marel et al., 2002) within its optical bounds. Based on the measurements of the eclipsing binary stars, the distance of the LMC is 49.97 ± 1.11 kpc (Pietrzyński et al., 2013) determined with high precision. The LMC has an asymmetric bar and is actively forming stars in giant HII regions including 30 Doradus. Its current HI mass is about $4-5 \times 10^8 M_{\odot}$ (Kim et al., 1998). The young stellar populational metallicity of the LMC is 0.3 to 0.5 $Z_{\odot}$ (Russell & Dopita, 1992) and is therefore higher than the SMC.

The SMC has a stellar mass of about $3-7 \times 10^8 M_{\odot}$ and lies at a distance of about 60–65 kpc (Graczyk et al., 2013). The SMC is an irregular galaxy that lacks a coherent disk structure, has a large depth along the line of sight of about 20 kpc (Subramanian & Subramaniam, 2012) and has an HI gas mass of about $4-5 \times 10^8 M_{\odot}$ (Stanimirovic et al., 1999). The stellar metallicity of the SMC is about 0.1–0.2 $Z_{\odot}$ (Russell & Dopita, 1992). Morphological irregularity, a large gas supply, ongoing star formation and low metallicity are the characteristics of dwarf irregular galaxies and therefore make the Magellanic Clouds a prototypical laboratory to study environmental effects on that morphological galaxy class.

Both of these galaxies are surrounded by dark matter halos that are enormous in comparison to their baryonic components. For the Milky Way's LMC, which of these models is chosen leads to infall mass estimates that range between 10^{10} and $2.5 \times 10^{11} M_{\odot}$ (inside the 1σ range on mass estimates and 1σ error on the MC halo boundary value mass estimates) depending on the assumed halo profile and the adopted orbital model (Besla et al., 2012; Penarrubia et al., 2010). For the SMC, pre-infall mass estimates are in the range of 10 to 30 billion solar masses in dark matter. The ratio of dark matter to baryonic mass in both cases is in line with expectations of cosmology for field dwarf irregulars, which is also the likely class of both the LMC and SMC, although the stripping of their outer halos by the environment is likely to have progressed.

2.2 The Magellanic Stream, Leading Arm, and Bridge

Extending across about 140 degrees of the southern sky, the Magellanic Stream may contain an HI mass of $2-5 \times 10^8 M_{\odot}$ (Fox et al., 2014; Putman et al., 2002) depending upon the assumed distance and the fraction of ionized gas. The Stream was divided into two morphologically distinct filaments (Nidever et al., 2008) that possessed distinct kinematic identities by Nidever et al. (2008). This division has huge consequences for origin models. A bifurcated structure of this type that is divorced would very likely be the result of the different kinematic pathways of the gas expelled from the LMC and SMC. The most recent studies of UV absorption lines support this model by showing a differentiation of metallic content (Fox et al., 2013).

Leading Arm is a feature in HI of the Magellanic System that was first discovered by Putman et al. (1998) and later described Nidever et al. (2010). It is located 20–30° ahead of the Clouds and contains about 10% of the overall HI mass of the Stream. Its presence is of great theoretical value. In order to create a leading component, a process other than ram pressure must be responsible. This is the case because ram pressure acts opposite to the direction of motion and would thus create gas in the trailing wake. The Leading Arm serves as evidence for the Magellanic interaction as it is highly

likely that tidal forces are responsible and since tidal forces can torque gas into leading and trailing structures, this may be the case for the Magellanic System.

The Magellanic Bridge is a low-density neutral hydrogen structure interconnecting the LMC and SMC, and has about $1.5 \times 10^8 M_{\odot}$ of neutral gas (Miller & Bregman, 2016). The presence of young stars in this structure suggests the bridge (Kunkel et al., 1997) is a young structure that formed in the last 100 to 300 Myr, most likely after the LMC and SMC had a close encounter that tidally distorted the outer disk of the SMC.

3. ORBITAL HISTORY OF THE MAGELLANIC CLOUDS

3.1 Proper-Motion Constraints

Stream formation models hinge on the orbital history of Magellanic Cloud Streams boundary conditions. Traditionally (up until the mid-2000s) the dominant belief was that the Magellanic Clouds were in orbit around the Milky Way for multiple Gyr and had had multiple pericentric passages. As the Stream was interpreted to be comprised of material that had been stripped out of the Magellanic Clouds over successive close encounters with the Milky Way, these models were called Tidal stripping models (Gardiner & Noguchi, 1996; Lin & Lynden-Bell, 1982).

This theory was upended by the availability of the data on the proper motion of the Magellanic Clouds. The high precision data on the proper motion of the LMC were obtained by Kallivayalil et al. (2006a). They reported the first measurements of the proper motion of the LMC, by computing the motion of the LMC across the background quasars observed by HST/ACS, and reported a total proper motion of $\mu_W = -1.956 \pm 0.036 \text{ mas yr}^{-1}$ and $\mu_N = 0.435 \pm 0.036 \text{ mas yr}^{-1}$ (Kallivayalil, Van Der Marel, & Alcock, 2006). With the LMC parameters of distance and radial velocity, they reported three dimensional space velocity of $370 - 380 \text{ km s}^{-1}$, which is significantly higher than the previous estimates. The space velocity of the SMC, which was reported by Kallivayalil et al., was also on the same order of magnitude. With these new measurements, the space velocity of the Magellanic Clouds was among the highest observed for satellites of the Milky Way, and was reported to be on the order of, or in excess of the local escape velocity of the Milky Way.

In the third-epoch proper motion study, Kallivayalil et al. (2013) reported updated proper motion estimates of $\mu_W = -1.910 \pm 0.020 \text{ mas yr}^{-1}$ and $\mu_N = 0.229 \pm 0.047 \text{ mas yr}^{-1}$ for the LMC, which further confirmed the LMC's high velocity. With the updated estimates of the Milky Way mass, these new proper motion estimates have also been used to retro-integrate the orbits of the Clouds using N-body simulations (Kallivayalil et al., 2013).

3.2 First-Infall versus Multiple-Orbit Scenarios

The Magellanic Clouds' considerable space velocities, coupled with recent assessments of the Milky Way's virial mass, prompted Besla et al. (2007) to posit that the Clouds are on their initial approach to the Milky Way (Besla et al., 2007). In this model, the Clouds were gravitationally bound to one another and remained outside the Milky Way's virial radius prior to their first infall to the Milky Way, and crossed the virial radius of the Milky Way approximately 1-3 Gyr ago. Given this first-infall scenario, the Stream must have formed during that singular infall, and cannot be interpreted as the accumulated residue from multiple encounters with the Milky Way.

While this is a reasonable proposition, there is an inherent contradiction. The Stream's length (over 140°) may appear to necessitate a long evolutionary process. In contrast to this general perception, however, Besla et al. (2010, 2012) argued that the Stream could be generated even in the first infall case if an adequate amount of gas was earlier left behind in the orbital wake as a result of an LMC–SMC interaction that occurred prior to the LMC and SMC's infall to the Milky Way. In the model they advanced, the LMC and SMC had a close encounter prior to Milky Way's infall at a distance of around 5–10 kpc, and the gravitational interaction between them disrupted the outer HI disk of the SMC.

Diaz & Bekki (2011, 2012) created N-body and SPH models postulating that the Clouds had experienced two or more Galactic pericenters. They defend the multiple-orbit scenario by explaining how the Stream's angular extent and bifurcated morphology can be accounted for without an LMC–SMC interaction being the primary driver (J. Diaz & Bekki, 2011; J. D. Diaz & Bekki, 2012). However, these models necessitate a Milky Way mass on the very high end of present-day estimates and are poorly constrained on the Milky Way's CGM density profile. The first-infall scenario has increased considerably in observational support, especially with the Gaia mission and its more recent proper motion data of the stars in the Clouds and the Stream. There is still substantial model degeneracy.

4. THEORETICAL MECHANISMS OF GAS STRIPPING

4.1 Tidal Stripping

Tidal stripping describes the phenomena when differential gravitational acceleration surpasses the self-gravity of a galaxy or gas cloud. Under such conditions the gas or the galaxy clusters begin losing their gravitationally bound material. The classical formulation defines the tidal radius as follows:

$$r_t = r \left(\frac{M_{sat}}{2M_{host}} \right)^{1/3}$$

Here r is the distance between the satellite galaxy and host galaxy, M_{sat} is the mass of the satellite and M_{host} is the mass of the host galaxy covering the distance r (Read et al, 2006). Material beyond the stripping radius are bound to get stripped. Along the subsequent orbits the gas of the satellite is eroded.

The original frameworks of Lin & Lynden-Bell (1982) and Gardiner & Noguchi (1996) utilized the stripping of the satellite galaxy in pericentric passages to explain the Stream. These models appeared to replicate the main features and the dynamics of the Stream in a multiple-orbit context. However, they struggled to account for the bifurcated filamentary structure and the metallicity distribution patterns depicted in the subsequent UV observations. The pericentric passage models of the satellite galaxy were further constrained by the high proper-motion observations conducted by Kallivayalil et al (2006).

Besla et al. (2010, 2012) provide a first-infall framework that reinterprets tidal stripping as primarily LMC-SMC interaction over Milky Way-SMC interaction. LMC's gravitational potential disturbs the outer HI disks and halos of the SMC as the two galaxies are brought into close proximity. This LMC-SMC interaction can account for the double filament structure of the Stream with one filament originating from each of the two encounter trajectories of SMC material. A notable strength of this interpretation is that it avoids the need of multiple Galactic pericentric passages and thus is in broad agreement with the elevated proper motion estimates.

4.2 Ram Pressure Stripping

Ram pressure stripping results from the hydrodynamic coupling of a galaxy's interstellar medium and the hot diffuse gas of the host halo in which it resides. Gunn & Gott (1972) first described the ram pressure condition for stripping as:

$$P_{ram} = \rho_{halo} v_{rel}^2 \geq 2\pi G \Sigma_{star} \Sigma_{gas}$$

Here, ρ_{halo} is for halo gas density and v_{rel} is the relative velocity of the galaxy through the halo. Σ_{star} and Σ_{gas} are the surface density of stars and gas in the satellite and G is the gravitational constant. This condition shows that stripping is relevant if the ram pressure of the surrounding medium exceeds the restoring force per unit area of the satellite's disk (Gunn & Gott, 1972).

Moore & Davis (1994) have suggested ram pressure stripping could be a mechanism for the formation of the Magellanic Stream. They suggested that the Clouds traveling through the Milky Way's hot gas halo at hundreds of km/s would be subject to ram pressure and lose outer HI gas (Moore & Davis, 1994). For this model to be correct, the Milky Way's hot halo would need to be relatively dense, of the order of 10^{-4} cm^{-3} , and at the distance of the Clouds ($\sim 50 - 60 \text{ kpc}$) and it produces a trailing wake with no leading structure, which is inconsistent with the observed Leading Arm.

Mastropietro et al. (2005) performed complex hydrodynamic simulations of ram pressure stripping focused specifically on the Magellanic System. These simulations were able to show that the combination of ram pressure with tidal forces results in complex stripped tails (Mastropietro et al., 2005). However, these simulations still struggled to reproduce the Leading Arm and needed the Clouds to be in relatively close orbits to the Milky Way for ram pressure to be impactful at those distances.

Bland-Hawthorn et al. (2007) noted the importance of Milky Way's ionizing radiation in ram pressure. They asserted that photoionization from the Galactic disk and a hot halo can explain a substantial fraction of the Stream's mass being dominantly in the ionized state rather than the neutral state. They claimed that the ionized gas in the Stream could be many times the currently observed HI mass, which was later shown to be the case with UV absorption-line studies (Bland-Hawthorn et al., 2007).

4.3 LMC–SMC Mutual Gravitational Interaction and Hybrid Models

The fact that LMC–SMC interaction could be the main tidal driver of a few hybrid models is a productive avenue of research. In such models, inter-Cloud tidal forces perturb and begin ejecting SMC gas, which is then accelerated, compressed and shaped by Ram pressure from the Milky Way CGM as the system travels to pericenter. The most developed examples of this line of research are from Besla et al. (2010, 2012). In their simulations, an LMC–SMC close encounter 1-2 Gyr ago caused the ejection of SMC gas into a trailing stream, which was then elongated and shaped by the interaction with the hot Milky Way Halo.

A significant benefit of hybrid models is that they can, by their nature, account for the trailing Stream and Leading Arm simultaneously. The Leading Arm is created by the tidal interaction (the gas ahead of the Clouds in their orbital frame), while the Stream's extension and fine structure are shaped by Ram pressure. The relative contribution of each mechanism remains a matter of debate and the models are sensitive to parameters that are not well defined. This includes the CGM and the Magellanic dark matter halos' densities, temperatures, and their internal profiles.

5. OBSERVATIONAL EVIDENCE AND MODEL DISCRIMINATION

5.1 HI 21-cm Observations

Mathewson et al. (1974) pioneered identifying the Magellanic Stream using the HI 21-cm signal at Parkes. Later studies using Putman et al. (2003) and Brüns et al. (2005) improved upon the studies and revealed the Stream with its full spatial and kinematic detail (Brüns et al., 2005). It has been estimated that the Stream contains around 2 to $5 \times 10^8 M_{\odot}$ in HI. However, this study had considerable uncertainties attributed to distance and the possible contribution of ionized gas (Fox et al., 2014; Putman et al., 2002).

Nidever et al. (2008) identified a bifurcated morphology, which has become an important piece of evidence. Stream MS-I and MS-II were designated as two morphologically and kinematically distinct filaments. Nidever et al. (2008) used the Green Bank Telescope (GBT) to follow the Stream to its origins. Bifurcated morphology does not support a single stripping event hypothesis of a single galaxy. It is more favored by two separate stripping events or two separate source galaxies, consistent with LMC–SMC inter-Cloud tidal stripping. Nidever et al. (2010) applied this study to the Leading Arm, studying its HI column-density distribution and kinematic structure (Nidever et al., 2010).

A study provided an ATCA study with an high angular resolution. It reported HI detected in the Leading Arm, including clumps in a lower column density envelope (Kim et al., 2003). The presence of such clumps is relevant in the argument of ram pressure to tidal stripping. Ram pressure stripped gas is expected to be more diffuse and extended. In contrast, tidal debris is expected to be more coherent and retain clumps.

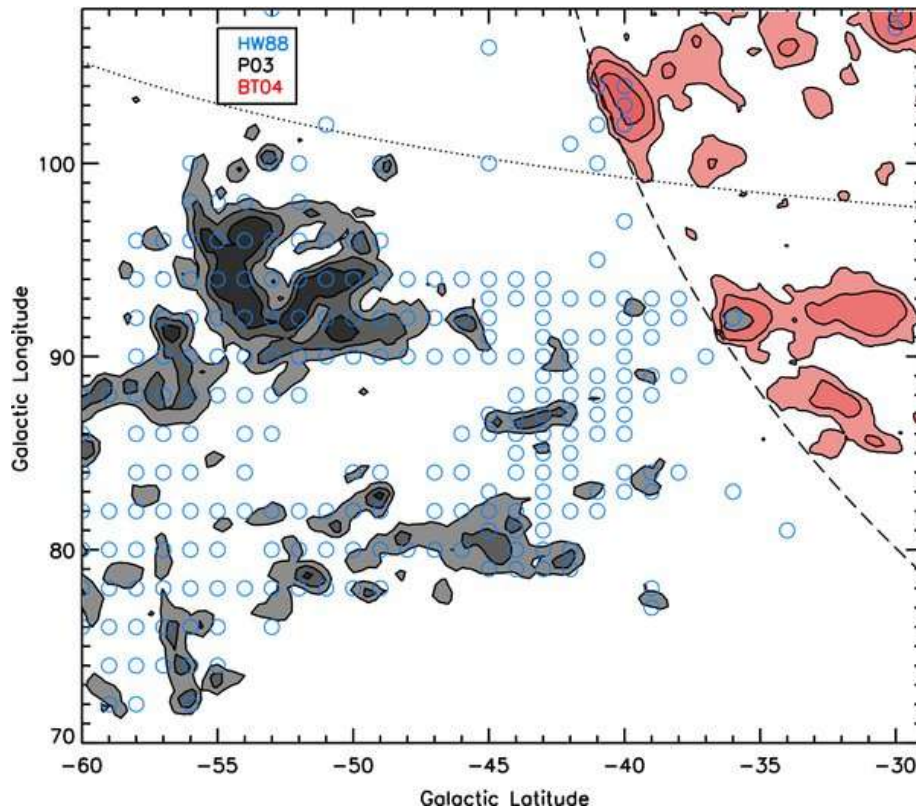


Figure 1: Full-sky HI 21-cm map of the Magellanic Stream system; Nidever et al. (2010), *The Astrophysical Journal*, 723, 1618.

5.2 Ultraviolet Spectroscopy and Metallicity

The Magellanic Stream's chemical composition provides insight into its galaxy of origin. The Stream's metallicity would be expected to reflect SMC abundances with Stream stripping as primarily from the SMC. However, if the stripping was mainly from the LMC, the Stream's metallicity will be greater. The primary method to measure the metallicity of the Stream is through UV absorption lines of background quasars located behind the Stream.

Fox et al. (2013) performed a systematic study of the Magellanic Stream absorption in the UV for which they obtained multiple HST/COS spectra of background AGN. They estimated the metallicity of these spectra from the sulfur abundance and found sulfur abundances of approximately -1.0 dex (roughly $0.1 Z_{\odot}$) along several Stream sightlines. A minority of sightlines exhibited higher metallicities and were between -0.5 and -0.3 , indicating an LMC contribution in these regions.

In a follow-up study, Richter et al. (2013) extended these studies and provided several new measurements by performing high-resolution UV spectroscopy on a Magellanic Stream sightline. Richter et al. (2013) found that the Stream absorption was consistent with the findings of Fox et al. (2013) and that absorption of molecular H_2 was present. These findings suggest that at least some regions of the Stream contain cold, partially shielded neutral gas which provide important constraints on the Stream's density structure and its pressure equilibrium with the surrounding circumgalactic medium (Richter et al., 2013).

Detection of ionized gas in the Stream via $H\alpha$ emission (Barger et al., 2012) and UV metal-line absorption (Fox et al., 2014) indicates that the total gas mass of the System is far greater than the mass of neutral hydrogen, H I. In their study, Fox et al. (2014) derived estimates for the total gas mass (including the ionized component) in the Magellanic System of $\sim 4.9 \times 10^9 M_{\odot}$, which is about 10 times greater than the H I mass, and suggested that a significant portion of the gas in the Clouds was stripped to the halo and Stream. This suggests that a large fraction of the gas originally present in the Magellanic Clouds has already been stripped into the Stream and the Milky Way halo.

6. Hybrid Models and Model Comparison

The hot, diffuse, ionized gas that makes up the circumgalactic medium (CGM) extends to the virial radius and beyond, and has two important functions in the interaction with the Magellanic clouds. First, it makes up the surrounding medium that causes the ram pressure stripping, and second, it is the pressure that influences the structure and the survival of the stripped gas. Because of this, the CGM's density and temperature profiles are important when it comes to modeling the gas Stream formation.

The hot halo of the Milky Way is best studied by tracing gas in the Magellanic Cloud region (50–65 kpc) using X-ray emission and absorption. In one such study, Anderson & Bregman (2010) estimated the mass of hot halo gas in the Milky Way to be between $3.8 \times 10^{10} M_{\odot}$ and $5 \times 10^{10} M_{\odot}$, and located it within 200 kpc of the Milky Way with a halo gas density profile of $n_e \propto r^{-3/2}$ (Anderson & Bregman, 2010). Using OVII and OVIII observations of background AGN, Miller & Bregman (2015) estimated the density of the CGM to be on the order of 10^{-4} cm^{-3} at 50 kpc, but were careful to note that this predicted density also depended on the halo gas metallicity and temperature and had large associated uncertainties.

These CGM density estimates and the required ram pressure to strip gas from the Clouds correlate that the required density is at the order estimated with a large level of uncertainty. Densities lower by a factor of two to three would substantially reduce the efficiency of ram pressure stripping at distances of 50–60 kpc. The ram pressure values are quite sensitive and result in a lot of model uncertainty. The Besla et al. (2012) and Diaz & Bekki (2012) simulations both included hot halo components. However, the density profiles assumed in each of the simulations were different and were not easily determined from other observations.

Bland-Hawthorn et al. (2007) analyzed the H α surface brightness of the Stream to derive the CGM ionizing photon flux and pressure. Their results provided halo density constraints that were broadly consistent with X-ray estimates, although they did not tightly constrain the halo properties. The ionized gas mass of the Stream is sensitive to the density of the halo. A more dense CGM not only strips more gas but also more completely ionizes gas, which could support the findings of Fox et al. (2014) who found a higher ionized fraction.

The CGM also causes hydrodynamic Kelvin-Helmholtz and Rayleigh-Taylor instabilities at the interface between stripped gas and the surrounding halo medium. These instabilities gradually disrupt coherent gas streams into smaller cloudlets and diffuse gas. This may help explain the Stream's structure at low HI densities. Hydrodynamic simulations with sufficient resolution to capture these instabilities indicate that Kelvin-Helmholtz instabilities have growth times of tens of Myr on scales of hundreds of parsecs. Therefore, such simulations suggest that stripped SMC gas can survive for approximately 1–2 Gyr before becoming fully mixed into the hot halo (Sofue, 1994).

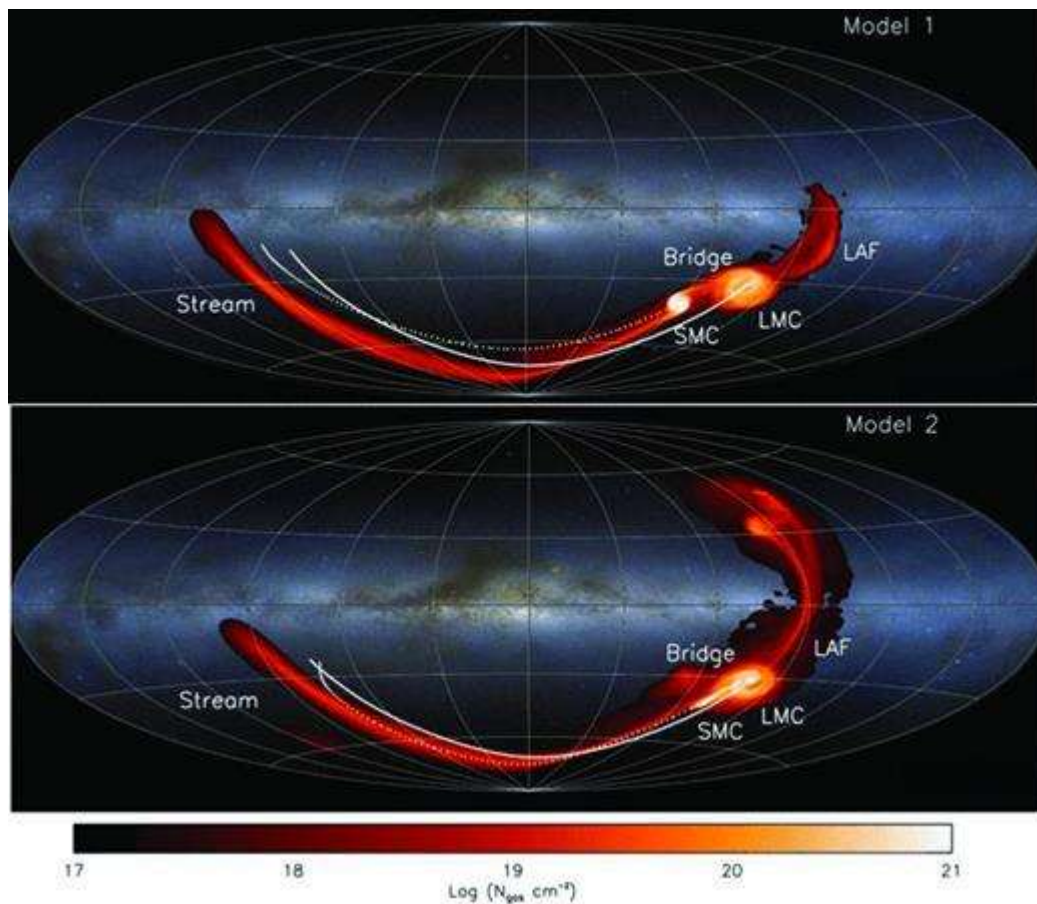


Figure 2 The Hammer-Aitoff (all-sky) projection showing the simulated total gas distribution for Model 1 and Model 2, overlaid on a Milky Way background; Source: Besla et al. (2012), *Monthly Notices of the Royal Astronomical Society*, 421, 2109

7. DARK MATTER HALO MORPHOLOGY AND CONSTRAINTS

7.1 Theoretical Framework and Halo Profiles

The dark matter halos of the Magellanic Clouds sit in an important part of parameter space for the potential for testing constraints on cosmology and the structure of halos. The standard paradigm, built upon Navarro et al.'s (1996, 1997) N-body cosmological simulations, proposes the existence of a universal density profile for dark matter halos. Dark matter halos are expected to possess a central cusp ($\rho \propto r^{-1}$) and an outer profile that is expected to decline ($\rho \propto r^{-3}$):

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right) \left(\frac{1+r}{r_s}\right)^2}$$

where ρ_s is the characteristic density and r_s is the scale radius. The profile as well as the concentration parameter $c = r_{\text{vir}}/r_s$, defines the response of the halo to perturbations tidal and hydrodynamic stripping (Navarro et al., 1996, 1997).

Tidal stripping removes mass from the outer regions of the halo and decreases the tidal radius which may alter the density profile at intermediate radii (Peñarrubia et al., 2008, 2010). Using N-body simulations, Read et al. (2006) showed that within a tidal environment, stripping a satellite's halo progressively removes the outer regions of the halo and preserves the inner cusp. This prediction can be tested by measuring the stellar velocity dispersion in the outer regions of the Magellanic Clouds (Read et al., 2006). However, highly concentrated halos make the inner cusp more resistant to stripping.

An essential difficulty in astrophysical modeling is the core-cusp problem. Cosmological models usually produce cusp-like dark matter density profiles for inner galaxy structures consistent with the NFW framework, while observations of dwarf irregular galaxies show generally core-like density profiles with structures of the form $\rho \propto r^0$ at small values of r (De Blok, 2010). The Magellanic Clouds are large enough that stellar kinematic data provide sufficient constraints on

the inner dark matter profiles, likely consistent with cuspy NFW-type structures. However, the SMC's irregular structure coupled with the extended line-of-sight depth (Subramanian & Subramaniam, 2012) makes precise profile determination difficult.

7.2 Observational Constraints on Halo Truncation and Shape

In principle, the spatial distribution of the Magellanic halos' stellar populations can place limits on the extent of tidal stripping. As the SMC interacts with the LMC, stars are stripped off of the outer LMC disk, forming tidal streams that encircle the LMC, which should be observable in photometric surveys. Stellar overdensities in the LMC's northern and northeastern regions have been reported by Mackey et al. (2016) and are suggestive of tidal distortions, extending 20 to 30° from the center of the LMC (Mackey et al., 2016). These regions constrain the extent of LMC's outer stellar disk and provide an estimate of the outermost portions of its dark matter halo during the most recent interaction with the SMC.

The internal kinematics of LMC is described by van der Marel et al. (2002) and is kinematically defined by the line-of-sight velocities of carbon stars and later refined with proper-motion data from Gaia by van der Marel & Kallivayalil (2013), it is reasonable to conclude that the inner LMC has been relatively undisturbed by the SMC and the Milky Way. This is consistent with the notion that tidal stripping is largely restricted to the LMC's outer halo and gas disk, as opposed to its stellar disk (Kallivayalil et al., 2013; Van Der Marel et al., 2002).

For the SMC, the situation is even more dramatic due to its disturbed stellar morphology. The long line-of-sight depth shows significant tidal disruption that includes disturbance of not only stellar, but also dark matter distribution. According to Besla et al. (2012), the SMC could have lost a considerable amount (20-50%) of its total mass during the LMC interaction and may have lost a large portion of its outer dark matter halo which would weaken the gravitational restoring force on its gas disk.

Another factor influencing the efficiency of stripping and the evolution of the system is the shape of the Magellanic halos. Specifically, whether the Magellanic halos are the shape of a sphere, prolate, triaxial or oblate. Most of the cosmological simulations predict dwarf galaxy halos being triaxial with moderate ellipticity (Allgood et al., 2006). An oblate or triaxial halo can funnel tidally stripped material preferentially along specific geometric directions, contributing to the bifurcated Stream morphology. However, there is a lack of observational constraints on the three-dimensional shape of the Magellanic halos which is one of the foremost uncertainties of most of the models.

7.3 Implications of Halo Stripping for the Stream Mass Budget

A major question in analyzing the Magellanic Stream is if the SMC has lost enough gas to explain the inferred ionized mass and the observed mass of the Stream. Fox et al. (2014) estimate that the total Stream mass is $4 - 5 \times 10^9 M_{\odot}$. If the present SMC has $4 - 5 \times 10^8 M_{\odot}$ of HI, then the mass lost to the Stream is about 10 times more than the gas currently in the SMC. This means that either that the pre-stripping SMC was substantially more gas-rich than previously assumed or the mass estimate by Fox et al. (2014) is too high, or the LMC has contributed more gas to the Stream than the low-metallicity observations have indicated.

This mass budget imbalance has led to the need to evaluate the mass the LMC has contributed to the Stream. While the main metallicity of the Stream is SMC-like ($[S/H] \approx -1.0$; Fox et al., 2013), portions with higher metallicity ($[S/H] \approx -0.3$ to -0.5) may be LMC gas. If a major portion of the ionized gas of the Stream is mostly from the LMC, then the mass budget is reasonable. This is also supported by the observed morphology of the Stream: if one filament (MS-I) is SMC gas and the other (MS-II) is LMC gas, then both Clouds have to be contributing to the mass of the Stream.

The mass budget also places limits on the SMC's pre-stripping dark matter halo. Following the suggestion of Besla et al. (2012), if the SMC is thought to have lost about 50% of its mass, its pre-infall halo mass would have been much higher than the current estimates, derived from the stellar kinematics of the post-stripping remnant. This would affect the SMC's contributions to the local satellite luminosity function and the semi-analytic models of the evolution of groups of dwarf galaxies.

8. IMPLICATIONS FOR DWARF IRREGULAR GALAXY EVOLUTION

The Magellanic interaction offers a local case study of a process thought to be more common: the transformation of gas-rich dwarf irregular galaxies into gas-poor galaxies via environmental stripping that occurs when these galaxies fall into the potential wells of larger halos. There are many ways the Magellanic System can be useful.

First, the Large and Small Magellanic Clouds illustrate that substantial gas stripping can take place 50 to 100 kpc away from a host galaxy. At these distances, the Milky Way's hot halo will be less dense, therefore ram pressure stripping may be inadequate at these distances. This supports the idea that inter-satellite tidal interactions are the first triggers of gas stripping. Thus, in a galaxy group, dwarf-dwarf gravitational encounters may play a role in gas stripping before the larger galaxy does.

Second, the interaction shows the Clouds have likely experienced inter-satellite interactions prior to entering the virial radius of the Milky Way (Besla et al. 2007, 2012). This pre-conditioning of the SMC's gas disk likely made the outer gas disk of the SMC more vulnerable to ram pressure stripping. This is similar to the galaxy preprocessing that occurs in a group of galaxies prior to an interaction with a cluster of galaxies (Fujita, 2004). The Magellanic System is an example of a galaxy group undergoing a hierarchical gas stripping process.

Third, there are consequences to the gas versus stellar stripping efficiency of the Magellanic interactions with regards to the morphological changes of the dwarf irregulars. Consider the LMC's stellar disk, which remains relatively untouched and organized, despite the large gas deficit (Kallivayalil et al., 2013; Van Der Marel et al., 2002). This observation supports the claim that gas can be removed more efficiently than stars because the outer gas is less gravitationally bound. This pressure may provide a pathway that allows dwarf irregulars to shift toward a gas-deficient and passive state while still retaining an ordered structure in their stellar components. This would also explain the presence of dwarf lenticulars found in groups (Boselli & Gavazzi, 2006).

Fourth, with regards to the CGM of the Milky Way in the formation of the Stream, the variation of CGM density within the different host halos requires consideration into the stripping efficacy of their satellites. More massive host halos with denser CGMs will strip gas more efficiently. Less massive hosts will rely more on inter-satellite tidal interactions. Because of the properties in the host CGMs, this will introduce a variation in the time scale of star formation quenching for the satellite dwarf irregulars, which will account for the variation of satellite quenching within Milky Way-sized galaxies (Wetzel et al., 2015).

9. CURRENT UNCERTAINTIES AND UNRESOLVED QUESTIONS

The last 20 years have yielded significant insights related to the Magellanic Stream and its associated interactions, some major challenges to understanding this phenomenon remain.

9.1 Milky Way mass and virial radius

Estimates for the total mass of the Milky Way ($0.5 - 2 \times 10^{12} M_{\odot}$, (Bland-Hawthorn & Gerhard, 2016)- which have a large inherent uncertainty - are bound to the situation of the Magellanic Clouds and the Milky Way's CGM. Estimates are also required for the CGM mass and density, the Clouds' escape velocity, and the SMC's tidal radius, which specifies the SMC's LMC encounter, as well as the LMC's own mass. The Milky Way mass estimate can change the assumptions regarding the Clouds' approach history, including whether they have made previous close peri passages.

9.2 Circumgalactic medium density profile

The density and temperature profiles of the Milky Way's hot halo at distances of around 50-100 kpc, are poorly constrained. Their temperature and density distribution are poorly constrained, and existing constraints are dominated by assumptions of the gas' metallicity and its filling factor. $H\alpha$ emission surfaces of the Stream, and UV absorptive observations, also provide some distributional constraints of CGM gas, but mainly at close ranges of 50-100 kpc. These estimates show a gas density range of $\sim \text{cm}^{-3} 10^{-5} - 10^{-4}$. Improved measurements of low gas density in the Milky Way's halo, with less reliance upon arbitrary assumptions, are anticipated with planned future X-ray missions and enhanced UV gas absorption studies (Bland-Hawthorn et al., 2007; Miller & Bregman, 2016).

9.3 Magellanic Cloud masses and pre-infall conditions

The pre-infall masses and internal structures of the LMC and SMC are largely uncertain. This is because of the remnants left of their post-stripping. Given the SMC's irregular structure and the extended line-of-sight depth (Subramanian & Subramaniam, 2012), many regional mass estimates also suffer from large and undetermined systematic uncertainties. We have no knowledge of the pre-infall SMC dark matter halo shape, and because of this, we can only make educated guesses about the stripping efficiency of the dark matter halo and the mass of the Stream.

9.4 Stream ionization and total mass

The Stream's composition is also problematic. Fox et al. (2014) proposed a mass of roughly $4.9 \times 10^9 M_{\odot}$ for the whole system, but this relies on a framework that uses H α and is dependent on the local conditions of the ionizing photons and the recombination rate, which the Stream's ionization structure and total mass are highly sensitive to. Its also sensitive to the local ionizing radiation field and recombination rates. If the Stream has regions that are largely shielded from ionizing radiation, then the total mass could greatly vary from Estimates.

9.5 Leading Arm origin

The morphology and metallicity of the Leading Arm are not characterized as thoroughly as the trailing Stream. Existing models disagree about the origin of the Leading Arm where some think its because of the tidal debris from the LMC–SMC interaction and others invoking a combination of tidal effects and Milky Way gravitational influences. The leading material appears to have a higher metallicity than the trailing Stream in some sightlines (Fox et al., 2013), possibly indicating a higher contribution from the LMC, but these are few.

9.6 Numerical simulation resolution and gas physics

The state-of-the-art hydrodynamic simulations of the Magellanic System cannot, for the moment, resolve the structure of the gas streams that have been stripped, model the multiphase CGM accurately, or incorporate magnetic fields and cosmic rays, and simulate the system for a number of Gyr. Gas streams and clouds stripped from the CGM are not well represented, and the gas clouds are likely to have a substantial degree of instability when trapped in the CGM. Adaptive mesh refinement and smoothed particle hydrodynamics codes have complementary strengths and weaknesses, and the differences in the predicted Stream structure between the codes is as much a reflection of the limitations of the numerical methods as the underlying physics (Sparre et al., 2019).

9.7 Degeneracy of orbital reconstruction

Even with the accurate proper-motion measurements of Kallivayalil et al. (2013), backward orbital integration of the Clouds remains degenerative due to the mass of the Milky Way, the mass of the LMC (which influences dynamic friction and the LMC's gravitational influence on the Milky Way potential (Steele et al., 2024), and the marginalization of the LMC and Clouds dark matter halo geometry. Orbital reconstruction becomes even more problematic with possibility that the LMC is massive enough to induce a response in the Milky Way halo, producing the so-called “LMC wake” (Garavito-Camargo et al., 2019).

9.8 SMC Core-Cusp Problem

The Core-Cusp Problem is also unsolved in the Magellanic Clouds. Feedback processes do cause fluctuating potentials that eventually create cores due to supernovae in dwarf galaxies (Pontzen & Governato, 2012), but the SMC's highly irregular and disturbed state dynamically, makes it difficult to differentiate feedback between the cored and tidally disturbed. The answer to this problem directly relates to the NFW profile and the nature of dark matter, and bears important implications in both areas.

10. CONCLUSION

The Magellanic Stream serves as one of the most important case studies for observing tidal stripping, ram pressure stripping, and the effects of dark matter halo evolution in dwarf irregular galaxies. Using an array of available tools, this paper attempts to resolve competing models of the Magellanic Stream's formation and address the structural implications of irregular dwarf galaxies and dark matter halos.

The available evidence supports the hybrid model most clearly. Specifically, the clear inter-Cloud tidal stripping of the SMC by the LMC, gas ejection, and the ram pressure from the Milky Way's halo, which accelerates and shapes the ejected gas, explains the Stream's morphology and the Leading Arm formation, and the high velocity of the Clouds. This

is consistent with SMC-like metallicities and the connection of the bifurcated filaments to the Clouds. Contrary to the aforementioned models, pure ram pressure (Moore & Davis, 1994) and tidal models based on several close passages (Gardiner & Noguchi, 1996) fall short of describing several important aspects of the Stream and the Clouds of the Magellanic System.

The interaction places numerous constraints on the evolution of dark matter halos in dwarf irregulars. Tidal stripping occurs in the outer halos of the Clouds, which truncates dark matter while the inner disk and stellar body remain intact. This is consistent with the disk kinematics of the LMC (Kallivayalil et al., 2013; Van Der Marel et al., 2002) and the structure of the SMC. Based on the Stream mass budget, the mass stripping efficiency suggests that the pre-infall SMC halo was more massive and extended than the current remnant and also agrees with the NFW prediction, which states that halos have cuspy and concentrated profiles that resist stripping in the inner regions, but are susceptible to stripping in the outer regions.

Other effects on dwarf irregular galaxy evolution are that the inter-satellite preprocessing prior to the infall into the host-halo is relevant; that the density of the CGM is a factor in determining ram-pressure stripping at great distances from the center of the Galaxy; that gas is preferentially stripped over stars during early stripping, which enables the development of gas-poor but more morphologically regular descendants; and that the properties of the host halo have an effect on the gas-poor and morphologically regular descendants and the duration of the phenomena.

Uncertainties continue to persist with regards to the complete mass of the Milky Way, the CGM density profile, Clouds pre-infall masses, the total ionized gas mass of the Stream, and the mass of the required numerical resolution required to model small-scale hydrodynamic instabilities. More extensive future developments of UV absorption studies with the next-generation UV satellites, deeper HI studies with the Square Kilometre Array, more accurate proper motion measurements with subsequent Gaia data releases, and high resolution cosmological simulations, among others, will aid in addressing these issues.

The Magellanic System will be foundational in our attempts to understand the restructuring of baryonic and dark matter from dwarf irregular galaxies, as they traverse the circumgalactic environments of large hosts from the perspective of the active and massive hosts. The CGM Stripping is hierarchical and will also operate multiple mechanisms simultaneously. As an active participant, the CGM is not passive and these will be true for all group and cluster environments where dwarf galaxy transformation is known to take place.

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