

Exploring the Mysteries of the Magellanic Stream: What We've Uncovered and What Remains Unknown

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Abstract. The Magellanic Stream is a lengthy, ribbon-like gas structure stretching 200 degrees across the sky and surrounding the Large and Small Magellanic Clouds. These two galaxies are the brightest dwarf galaxies orbiting the Milky Way (MW). The Stream is a major subject of study in galactic dynamics because it provides insights into the evolution of galaxies, including the MW and the Magellanic Clouds, its companion dwarf satellites, and the interstellar medium. Gas flows play a key role in galaxies' growth, evolution, and sustainability, but many questions related to the Stream remain unanswered. Here, I will review the main advance in this subject of the last decade and posit new questions that need to be addressed.

Keywords. Dynamics, Galaxies, Milky Way, Gas flows

1. Introduction

A fundamental problem in understanding galaxy formation is how gas accretion and large-scale outflows influence the evolution of galaxies. In particular, it is unclear whether the gas reservoir that maintains star formation in massive spiral galaxies like our MW is replenished predominantly by accreting filaments or via stripping from nearby dwarf galaxies. It is also unclear how the circum-galactic medium (CGM) gets enriched by metals. No studies have addressed the relative contribution of outflows versus gas tidally stripped by dwarf satellite galaxies to that enrichment. We know that the MW is accompanied by two dwarf galaxies, the Large and Small Magellanic Clouds (LMC and SMC, respectively, called the “Clouds” below), as well as a massive gaseous structure, the Magellanic Stream. This structure is an interwoven tail of filaments trailing the Clouds in their orbit around the Milky Way (Mathewson 1974; Bruns 2005; Nidever 2008, 2010). When considered in tandem with its Leading Arm (LA), the counterpart to the Stream on the opposite side of the Clouds leading their orbits, the Stream stretches over 200 degrees in the sky (as shown in Figure 1, colored in magenta).

Originally the Stream was detected in 21 cm observations of neutral hydrogen (Mathewson 1974) with a mass of $\approx 5 \times 10^8 M_{\odot}$. In addition to hundreds of head-tail clouds and intricate turbulent structures, data have shown that there are two spatially and kinematically distinct intertwined filaments in the Trailing Stream (Nidever 2008) (see Figure 2).

In early modeling (e.g. Gardiner 1996), the Clouds were thought to have completed multiple orbits around the Milky Way over a Hubble time. However, with the high astrometric precision of instruments such as the Advanced Camera for

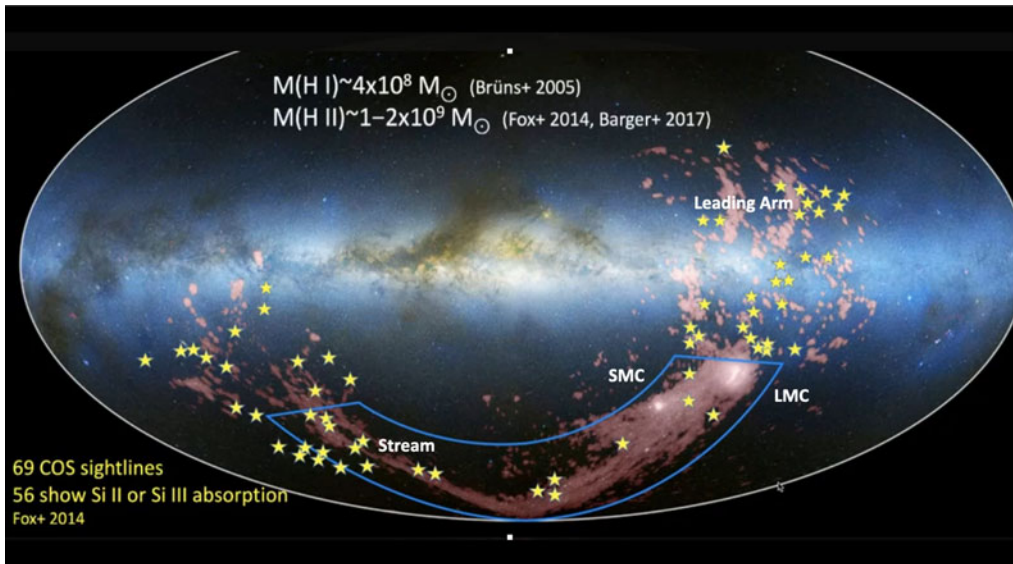


Figure 1. The Magellanic Stream in HI (magenta), credit (Nidever 2008). The bright blobs surrounded by the HI gas are the LMC and SMC, the HI gas ahead of the Clouds is the Leading Arm (LA) and the gas behind the Clouds is the Trailing Stream. The overlapping stars are the Cosmic Origins Spectrographs (COS) sightlines obtained with HST (Fox 2014). The total mass of the Stream is $\sim 5 \times 10^9 M_{\odot}$ consisting of HI ($\approx 5 \times 10^8 M_{\odot}$) and ionized gas ($\approx 5 \times 10^9 M_{\odot}$) (see D’Onghia & Fox 2016 for a recent review).

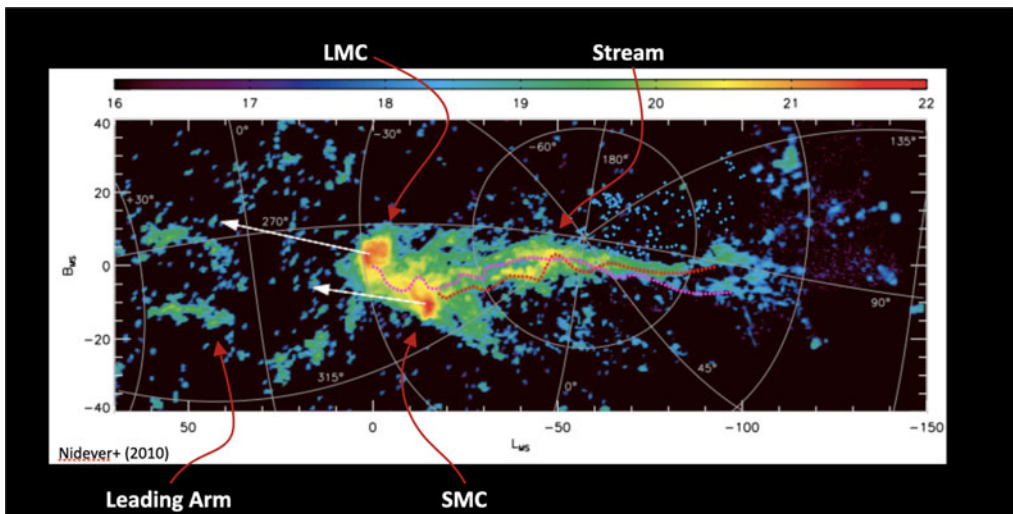


Figure 2. The Stream in Magellanic coordinates. There are two filaments, kinematically and chemically distinct indicating that both LMC and SMC gas are in the Stream (image adapted by Nidever (2010)).

Surveys (ACS) on the Hubble Space Telescope (HST) our knowledge of the Stream advanced significantly. Indeed, it was possible to measure accurate proper motions (Kallivayalil 2006a,b; Piatek 2008) and this showed that the Clouds have much higher orbital velocities than previously suspected, forcing a reconsideration of the conventional picture of their orbital history. Revised models thus had the LMC as a massive dwarf

galaxy falling into the Milky Way's potential for the first time (Besla 2010). Further, the discovery of dwarf galaxies that may be associated with the Magellanic Clouds suggested the possibility that the Clouds are being accreted onto the Milky Way as part of a group of dwarf galaxies (D'Onghia 2008).

The second advance in the knowledge of the Magellanic Stream came again from the Hubble Space Telescope. In fact, absorption line spectroscopy studies allowed us to characterize the Stream's chemical composition and ionization state along dozens of sightlines (Lu 1994; Fox 2010, 2013, 2014; Richter 2013). By analyzing the spectrum of background quasars, we can detect very low-density gas between us and the source based on how much light has been absorbed since it was emitted. Spectroscopy gives the intensity of detected light as a function of frequency, allowing us to identify what chemical elements exist along the line of sight by cross-matching the frequencies of absorbed light with known atomic transitions. In the case of the Magellanic System, these measurements have resulted in two critical discoveries: (1) the two filaments are also chemically distinct, indicating that there is both LMC and SMC gas in the Stream (Fox 2013); and (2) the Stream is mostly ionized (Fox 2014).

The Stream also consists of a Leading Arm (LA), which is the counterpart to the Trailing Stream comprised of clumpy clouds of gas out ahead of the LMC and SMC in their orbits (seen in Figure 1). Due to their very high velocities, consistent with the LMC and SMC, it was proposed that these features are tidal material thrown out during the interactions between the Clouds (Putman 1998; Besla 2012; Pardy 2018). Absorption line spectroscopy studies have also investigated the chemical composition of the LA structure, but the results cannot conclusively point to a Magellanic origin (Lu 1994; Sembach 2001). An alternate explanation involves the LA being gas stripped from other dwarf galaxies that fell into the Milky Way ahead of the Magellanic Clouds (Yang 2014). However, dwarf galaxy candidates with positions and velocities to make this a plausible scenario have yet to be found (Tepper-Garcia 2019).

The Magellanic Bridge is also part of the Stream. It is a gaseous and stellar structure connecting the LMC and the SMC (see Figure 1). Interestingly, it contains stars while the Stream does not, and the Bridge and the Stream likely formed at different times (D'Onghia & Fox 2016). The stars and the gas in the Bridge have been well studied, indicating an SMC-like metallicity (Lehner 2009), a flow of stars from the SMC to the LMC, and intricate tidal structures such as a counter-bridge. Based on the existence of this Bridge and its proper motions, as well as the observed velocities of the galaxies, it is very likely that the LMC and SMC experienced a direct collision within the past several hundred million years.

2. Modeling

Early on, it was assumed that the LMC and SMC were long-lived satellites of the Milky Way, and the Stream had been formed through repeated tidal encounters between the LMC and our Galaxy (Fujimoto 1976). A significant computational effort went into determining a model that could reproduce the observations. However, Fujimoto (1977) found that no parameters for the Clouds' masses and orbits could reproduce the Stream's high negative radial velocity. Moreover, ? discussed several alternative formation mechanisms and found that more than the proposed theories at that time were needed to explain the Stream. The next puzzle piece came with proper motion measurements for the Clouds. Using Hubble Space Telescope, Kallivayalil (2006a) determined that the LMC's velocity was very high (comparable with the Milky Way's escape velocity). Subsequent studies showed that these new data indicate that the Clouds are most likely on their first approach to the Milky Way (Besla 2007; Kallivayalil 2013). Therefore, previous tidal

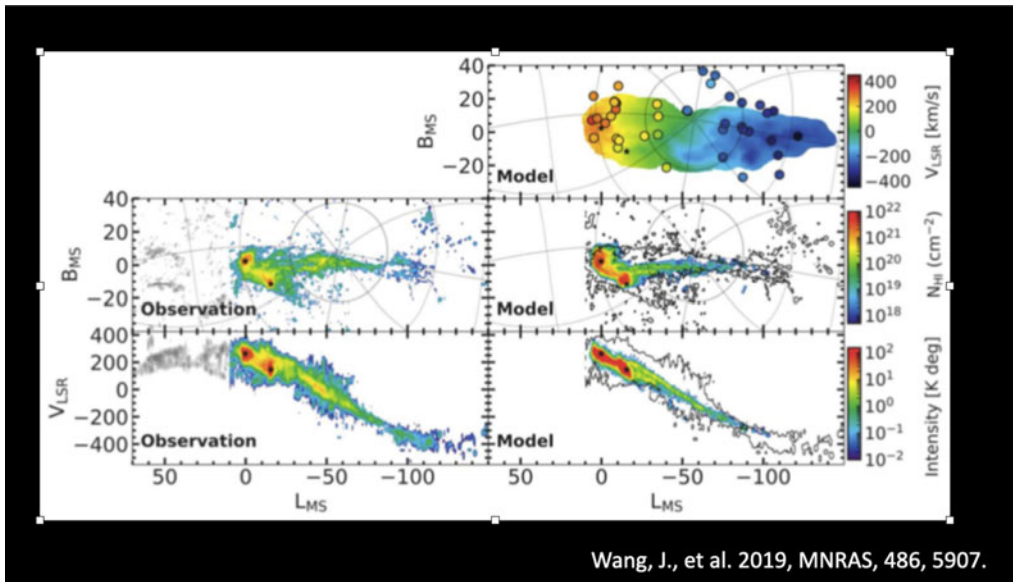


Figure 3. The ram pressure model proposes that the Stream material is pushed out of the disks of the Magellanic Clouds through hydrodynamical interactions with the Milky Way’s hot gaseous halo. This model can also reproduce many of the features of the Trailing Stream (credits: Wang (2019)).

models were no longer viable. Besla (2010) proposed a new paradigm for the tidal formation of the Stream in which the material is stripped out of the SMC through interactions with the LMC before they approach our Galaxy (Besla 2012; Pardy 2018). This model has been widely considered a benchmark for forming the Stream.

Another significant development has been the inclusion of gas physics and hydrodynamic effects in the numerical experiments of the Stream. Several studies explored the effects of “ram-pressure” on the Stream’s formation. In these models, the trailing material is pushed out of the Magellanic disks through interactions with an extended gaseous halo around the Milky Way (Moore 1994). The development of hydrodynamics simulation codes allowed for the whole, self-consistent exploration of both the tidal and ram pressure models for the Stream’s formation. With advanced new codes and increases in computation power, modern simulations have come a long way (Besla 2012; Hammer 2015; Pardy 2018; Tepper-García 2019; Wang 2019).

Currently, there are two leading theories for forming the Magellanic Stream. The original tidal model has evolved into a scenario in which the LMC and SMC are orbiting around each other, and the gravitational forces between the Clouds tidally strip material before they fall into the Milky Way (Besla 2012; Pardy 2018). In addition, the ram pressure model proposes that the Stream material is pushed out of the disks of the Magellanic Clouds through hydrodynamical interactions with the Milky Way’s hot gaseous halo. This model is also able to reproduce many of the features of the Trailing Stream (Hammer 2015; Wang 2019) (see Figure 3). Just as the measurement of the proper motions of the Clouds ruled out multiple-passage models of the formation of the Stream, recent observations have been shown to conflict with these two existing models - (1) the Magellanic System is mostly ionized, and (2) the LMC has a total mass $> 10^{11} M_{\odot}$. While the tidal model requires a high LMC mass, it alone cannot explain the ionized gas mass; and the

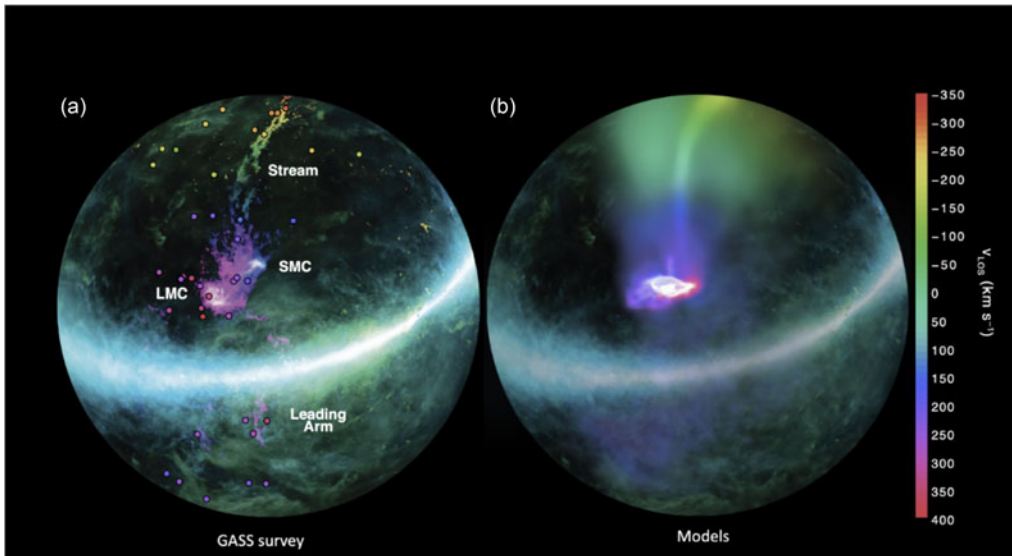


Figure 4. Hydrodynamic simulations of the Magellanic Stream with the inclusion of a Magellanic Corona (right panel) as compared to observations (McClure-Griffiths 2009) (left panel); credits: Lucchini (2020).

ram pressure model can form the ionized material, but it requires a very low mass for the LMC.

3. Understanding the Stream: the need for Galactic Coronae

A large fraction of all the ionized gas in the MW CGM is contained in the Stream (Fox 2014). All models of Stream formation via repeated encounters between the Magellanic Clouds underestimated its total mass, especially when considering the large ionized component. Even models that varied the gas fraction of the Clouds could not explain the large ionized mass (Pardy 2018). For the trailing Stream, ram-pressure stripping was suggested as the source of both the neutral material (Mathewson 1976; Moore 1994; Salem 2015; Hammer 2015; Wang 2019, 2022) and the ionized gas (Wang 2019; Bland-Howthorn 2017; Tepper-Garcia 2015). However, in a first-passage scenario, the Clouds are initially far from the MW where they encounter only low-density gas, which makes ram-pressure stripping inefficient.

The discovery of several ultra-faint dwarfs around the LMC (Bechtol 2015) suggests that the LMC and SMC approached the MW as part of a system of dwarf galaxies (the Magellanic Group), with the LMC as its largest member (D’Onghia 2008; Nichols 2011). Furthermore, cosmological simulations of MW-sized galaxies with LMC-like dwarf satellites (Pardy 2020) predict the existence of ionized halos surrounding those satellites (Hafen 2019; Jahn 2019). Thus, the LMC is expected to have an associated dark matter halo with a mass of $\sim 2 \times 10^{11} M_{\odot}$ (Penarrubia 2016), and a virial temperature of $\sim 5 \times 10^5 K$, a factor of 4–10 lower than that of the MW halo. It is likely kept warm via energy input from stellar feedback and outflows. Recent work (Lucchini 2020) has shown that including a Magellanic Corona in hydrodynamic simulations of Stream formation solves many open questions, including the existence of the LA and the mass budget of the Stream (see Figure 4). The Corona has been directly observed in high-ion absorption toward quasars (Krishnarao 2022) (see Figure 5) and in “down-the-barrel” spectroscopic observations of hot stars in the LMC (Wakker 1998; Lehner 2009).

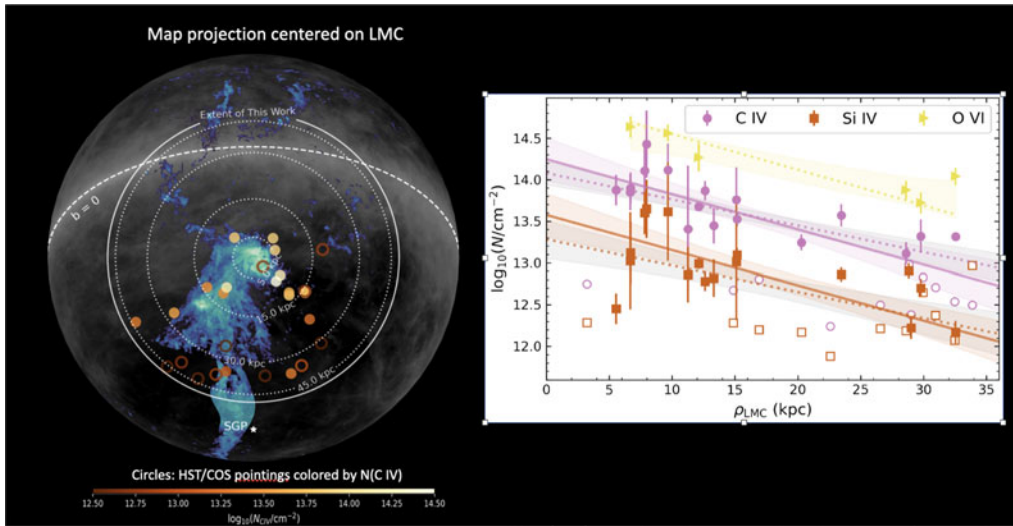


Figure 5. High-ion absorption toward quasars provides evidence for a corona around the LMC (pointings are shown in the left panel). The CIV and SiIV radial profile shows evidence of ionized coronal gas around the LMC. Credits: [Krishnarao \(2022\)](#)

The Magellanic Corona plays a dual role: it feeds the Stream and LA with ionized gas, thereby contributing to their mass budget, and it also *cocoons* them against disruption by the ram-pressure of the MW Corona ([Lucchini 2020](#)). The Corona therefore provides a shield around the Stream and LA allowing them to penetrate further into the MW Corona. While the MW Corona regulates the formation and morphology of the LA, the Magellanic Corona affects its spatial extent, so both Coronae have to be carefully modeled to fully explain the system. Even if the LA turns out to have a non-Magellanic origin, as recently suggested ([Tepper-Garcia 2019](#)), the inclusion of the Magellanic Corona still provides the bulk of the mass of the trailing Stream ([Lucchini 2020](#)).

4. A possible nearby Stream

The existence of a Magellanic Corona affects the orbital history of the Magellanic Clouds. As the SMC orbits around the LMC, it moves through the Corona, a warm gaseous medium, experiencing hydrodynamical drag. Hence, previous orbits of the Clouds are no longer consistent with their present-day positions and velocities. A new orbital model consistent with the locations and proper motions of the Clouds today was presented in [Lucchini \(2021\)](#). The model can reproduce the Trailing Stream, including the Magellanic Corona and a hot gas halo around the Milky Way. Intriguingly, these inclusions result in a Stream that is a factor of three to five closer to the Sun than previous models predicted.

5. Unsolved questions and validation tests

The existence of the LA poses a key challenge to models. If the MW corona is too dense, the infalling Magellanic gas stalls and no LA can form. Its formation is therefore tied to the properties of the MW and Magellanic Coronae. Recent models find that most (>50%) of the LA mass is contributed by the Magellanic Corona, with the remainder pulled out from both LMC and SMC ([Lucchini 2020](#)), but have not yet conducted a thorough parameter space study to determine what range of MW and Magellanic

coronal parameters are consistent with the formation of the LA. Recent observational studies have constrained the metallicity of the LA using Ultraviolet (UV) spectroscopy from HST/COS found values of 5-10% solar, slightly lower than the current-day SMC metallicity (20% solar), consistent with the LA being formed from SMC material two Gyrs ago (Fox 2018; Richter 2018). At present we cannot yet rule out a scenario where the LA is unrelated to the Magellanic System, instead representing a shredded “fore-runner” galaxy from the Magellanic Group (Tepper-Garcia 2019) or a complex of cool high-velocity clouds (HVCs) in the MW CGM. However, the LA origin remains uncertain.

While the recent models that include both Magellanic and Galactic Coronae break new ground and solve critical problems in Stream formation, they also pose new questions to address. If the Stream is so close, its stellar counterpart should be detectable. Furthermore, a key observational prediction of the nearby-Stream hypothesis is that the Stream should be detectable in absorption toward halo stars at known distances of 20–30 kpc (Lucchini 2021). A detection of Magellanic gas in absorption would provide the first direct distance constraint on the Stream since any gas seen in absorption in the stellar spectra must lie in front of the stars. Hence, this method offers a potential direct confirmation of the nearby-Stream hypothesis.

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