The Magellanic System: What have we learnt from \textit{FUSE}?

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\textbf{Abstract.} I review some of the findings on the Magellanic System produced by the \textit{Far Ultraviolet Spectroscopic Explorer (FUSE)} during and after its eight years of service. The Magellanic System with its high-velocity complexes provides a nearby laboratory that can be used to characterize phenomena that involve interaction between galaxies, infall and outflow of gas and metals in galaxies. These processes are crucial for understanding the evolution of galaxies and the intergalactic medium. Among the \textit{FUSE} successes I highlight are the coronal gas about the LMC and SMC, and beyond in the Stream, the outflows from these galaxies, the discovery of molecules in the diffuse gas of the Stream and the Bridge, an extremely sub-solar and sub-SMC metallicity of the Bridge, and a high-velocity complex between the Milky Way and the Clouds.

\textbf{Keywords:} galaxies: interaction — Magellanic Clouds — intergalactic medium — galaxies: halos — galaxies: kinematics and dynamics

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1. INTRODUCTION

The interactions of galaxies and the nearby intergalactic medium (IGM) through the accretion of matter onto galaxies or the expulsion of matter and energy in winds from galaxies are crucial for the evolution of both the galaxies and the IGM [e.g., 3, 34, 27]. Interactions between galaxies often produce long tails of gaseous matter and galaxy mergers, where starbursts can be triggered [e.g., 13]. Galactic winds, driven by the energy and momentum deposited into the interstellar medium (ISM) by massive stars and supernovae or by active galactic nuclei, are the primary mechanism by which energy, gas, and metals are injected into the IGM [e.g., 34].

Observational information of galactic interaction and winds comes in part from the observation of emission lines of hydrogen and metals [e.g., 3, 34, 31]. While, these observations yield crucial information, such as the multiphase nature (from very hot ionized gas to cold neutral gas) and large-scale morphology of these features, the detailed physics remain largely unknown. Because of their density-squared dependence, emission line observations are heavily biased toward the highest-density regions, which may only trace a relatively small fraction of the total mass and energy [e.g., 34, 32]. Measurements that rely on absorption lines are less biased to the highest densities, but they require strong background sources. Absorption line observations of outflows beyond the Clouds probe only directions toward the brightest stellar clusters, losing detail as the stars are integrated in the spectrograph slit. The Magellanic System is near enough to allow absorption line measurements to individual background objects.

The Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC), and Milky Way (MW) have long been suspected to have influenced each other. Large-scale mapping
in H I 21-cm emission of these clouds have revealed several large gaseous structures, signatures of such interactions [24, 2]. From the H I maps of the Magellanic System, many other distinct H I features are visible: the Magellanic Bridge linking the SMC and LMC, the Magellanic Stream, a $10^\circ \times 100^\circ$ H I filament that trails the Clouds, and the Leading Arm that leads the Clouds in their orbit [24]. Thus the Magellanic System is an excellent laboratory for studying outflow (see below), accretion, tidal effects, and coronal gas in and around low mass, low metallicity galaxies.

Over the last 8 years, FUSE has collected over 230 spectra of early-type stars in the Small and Large Magellanic Clouds (SMC and LMC) as well as a handful of QSOs behind the Stream and Bridge, providing a high-quality FUV LMC-SMC database. This database is extremely important because the multiphase nature of these features. The FUV bandpass provides diagnostics of a wide range of gas phases, from the molecular clouds, to the neutral atoms, to low-, intermediate-, and highly-ionized gas. In particular the importance of the ionized component has been truly revealed by FUSE. Although the spectral resolution of $FUSE (R \sim 15,000, \delta \nu \approx 20 \text{ km s}^{-1})$ is not so great for interstellar studies, it is high enough to estimate the column density and kinematics in many of these features and to decipher blueshifted or redshifted absorption relative to systemic velocities of the SMC and LMC (i.e., to find signatures of outflow or accretion).

Below I briefly touch on some of the $FUSE$ successes. Because of space I do not discuss the details (but I invite the reader to check out the various papers mentioned here) or other important results on the SMC and LMC interstellar disk or stellar work that $FUSE$ provided over the years [e.g., 21, 36, 5, 33, 20].

2. CORONAL GAS IN THE LMC, SMC, AND BEYOND

Prior to $FUSE$, little was known about the existence, not to mention the characteristics and distribution, of the coronal gas about the LMC. Early $IUE$ observations presented by [26] were not conclusive because the low data quality and owing to possible stellar contamination. First non-controversial evidence was through the detection of C IV toward a couple of B-type stars [35]. However, it is with the advent of $FUSE$ that the hot halo about the LMC was established using the O VI coronal diagnostic [12]. Further evidence of outflow feeding the coronal gas of the LMC was recently presented by [17] who found a systematic similarity in the O VI/C IV ratio between the LMC and blueshifted high-velocity components at 100–150 km s$^{-1}$ (incompatible with those of the LMC disk) seen in the UV absorption, suggesting that the blueshifted component has its origins in the LMC. Since the velocities of the blueshifted component relative to the LMC disk are larger than the escape velocity of the LMC, this material may be escaping the LMC, polluting the intergalactic space between the LMC and the Milky Way or serving as fuel for the Magellanic Stream [23]. Independently, [28] also found that the relatively high H I column density clouds at $v_{\text{LSR}} \sim 100–160 \text{ km s}^{-1}$ are often seen projected onto H I voids in the LMC disk and are connected to the disk with spatial and kinematic bridges in position-velocity plots, suggesting outflows as well (see also below).

In the SMC, early $IUE$ observations allowed to provide some evidence for a global component of highly ionized gas in the SMC [7], but [11] truly established the presence of a substantial and extended component of O VI coronal gas in the SMC. They also
found that the large star-forming regions in the SMC strongly affect the distribution of hot gas, and more so than in the LMC [12, 17, but see also Blair et al., these proceedings]. Possible origins for the coronal gas include superbubbles and galactic fountains.

Finally, [30], and see also [8], show that some high-velocity O VI clouds were associated with the Magellanic Stream. This indicates that the stream extends further out in space than the regions sampled by H I 21 cm emission, suggesting coronal gas up to 50 kpc [see also 4, 9]. Hence while it was often assumed before the FUSE results, it is now established that these galaxies are surrounded by hot coronal gas on large scale.

3. THE MAGELLANIC STREAM AND LEADING ARM

Unfortunately, there are not many QSOs or AGNs behind the Stream, and most of our knowledge in the UV came from GHRS and STIS observations [e.g. 10]. Nevertheless one notable exception was the FUSE observation of NGC 3783, which probes gas in the leading Arm of the Stream [29]. Thanks to a large number of spectral diagnostics, these authors show that ionization corrections were small and the abundance pattern suggests that the Leading Arm contains dust grains that have been processed significantly. The most important finding was the discovery of H₂ associated with this high-velocity cloud (HVC). This is the only HVC where molecules have been found so far, further supporting that the gas from the stream was tidally pulled or ejected from a galaxy based on H₂ formation time-scale [29].

4. THE MAGELLANIC BRIDGE

Although only two lines of sight could be observed with FUSE, our knowledge of the conditions in the Bridge has expanded thanks to these observations. In a series of papers, my collaborators and I show that the diffuse gas in the Bridge is multiphase, consisting of neutral, weakly, and highly ionized gas using a combination of STIS and FUSE data [19, 15, 16]. FUSE observations toward one star embedded in the Bridge show that a small amount of molecular hydrogen exists in this very much ionized environment (see below). Detection of CO molecules were also subsequently found [22], but in a much denser region of the Bridge, a.k.a. the SMC wing [see 16].

FUSE also provided several O I lines that were crucial for determining the first gas-phase metallicity of the Magellanic Bridge (combined with STIS), \([Z/H] = -1.02 \pm 0.07\) toward one sightline, and \(-1.7 < [Z/H] < -0.9\) toward another one [16]. These are in excellent agreement with B-type stellar abundances in the Bridge [25, 14]. If we believe current tidal models, then the Bridge is only 200 Myr old and was pulled from the SMC \((Z/H)_{SMC} = -0.6\), which implies that the diffuse gas was highly diluted with extremely low metallicity gas. On the other hand the very low present-day metallicity in the Bridge is similar to the SMC before its burst of star formation that occurred about 2.5 Gyr ago and a time that coincidentally corresponds as well to a close encounter between the SMC and LMC. This may not only be a pure coincidence since interaction between galaxies create bursts of star formation within the interacting galaxies. Although some chemico-dynamical models of the LMC-SMC-Galaxy interactions attempt to address
that question [e.g., 1], I do not think there is yet a satisfactory model that explains the stellar and interstellar results. Another issue is that current models only attempt to model the neutral component, while we find that 80% of the gas may be ionized, implying that the largest fraction of the gas mass of the Bridge may come from the ionized gas [16].

5. HVCS IN FRONT THE MAGELLANIC CLOUDS

Finally, I will conclude on the HVC complex observed between the MW and the Clouds at LSR velocities between about 90 and 150 km s\(^{-1}\), already mentioned in §2. Paradoxically, even though these HVCs have many background stars (> 230) that can be used to provide a detailed study of its abundances, distribution, etc., little is still known about this complex. My collaborators (Chris Howk and Lister Staveley-Smith) and I are working on a series of papers that should shed light on these HVCs. Toward the Bridge, we first reported the existence of an HVC that is fully ionized using STIS observations [18], at a time when HVCs were mostly known as neutral entities. When \textit{FUSE} came online it was realized that these HVCs were observed frequently in the spectra of LMC and SMC stars in the low and high ions [6, 11, 12].

Toward the LMC, independent results show that this HVC may be linked to outflows from the LMC (see §2). One way to further test this is to estimate the metallicities of these HVCs. Combining H I emission and O I absorption data toward about 80 sightlines, our preliminary results show that about 88% of our sample has an O abundance relative to solar between \(-0.8\) and \(-0.2\) dex, and peaking near \(-0.5\) dex. The average metallicity of \(-0.5\) dex relative to solar abundance seems to support the recent claims of [23] that massive outflow had to occur over 1.3 Gyr ago, since chemical evolution models of LMC predict it had a metallicity of \(-0.5\) dex approximately 2 Gyr ago. The scatter in the metallicities is also quite similar to those found in the Stream [10], and suggests that outflows are still ongoing and that part of the gas may also be mixed with a lower metallicity component. In the future, we will fully characterize the properties of this HVC complex.

6. CONCLUDING THOUGHTS

In summary, it has been a nice ride with many exciting results that will continue to grow thanks to the rich SMC/LMC \textit{FUSE} archive. Future UV observations with COS will provide new information, e.g. we will be able to probe the characteristics of the LMC/SMC halo throughout their coronal gas at much larger impact parameters. But I believe the \textit{FUSE} results already provide key information that models of the Magellanic Cloud-Milky Way system should attempt to reproduce and use.

Since the theme of this conference is also the future of UV and since the UV is at the core of astrophysical inference with uniquely rich spectral diagnostics, we need to think possibly not so much in terms of better resolution (although that is always good!), but to bigger and more sensitive instruments (even than COS) to go beyond the Clouds. As accretion and outflow are so important for our understanding galaxies and input physics in cosmological simulations, an unbiased sample of galaxies in the
Local Group where these processes may not be as entangled as in the LMC/SMC and where UV spectroscopy can be achieved toward individual background objects will be key for making more progress in our understanding of the influence of accretion/outflow in galaxy evolution and in modeling these processes. It is also important to realize that many of the FUSE observations relied on STIS E140M data (e.g., Ly$\alpha$, N V, C IV, etc...), so a future UV space mission will need somehow to combine the FUV and UV.

As a final word, I want to thank you the FUSE scientific, planning, and engineering teams for their dedicated and creative efforts that allow this telescope to exist and ran well beyond its nominal 3-year mission.

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