The Magellanic Stream — A Tail of Two Galaxies

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Interactions between spiral galaxies and their dwarf satellites are often spectacular, producing extended streams of stripped gas and triggering new generations of star formation. The most striking local example lies in the outer halo of the Milky Way in the form of the Magellanic Stream. Extending for over 140 degrees, the Stream is a giant ribbon of gas trailing the orbit of the Large and Small Magellanic Clouds. Since its discovery over 40 years ago, the Stream has puzzled observers and theorists alike and raised many questions. New spectroscopic observations with the Hubble Space Telescope and VLT/UVES are addressing these questions and finding the origin of the Stream to be surprisingly complex.

Discovery of the Magellanic Stream

Radio observations in the early 1970s discovered an extended stream of H I 21-cm-emitting neutral gas emanating from the Magellanic Clouds and passing over a wide swath of the southern sky (Dieter, 1971; Wannier & Wrixon, 1972). Dubbed the Magellanic Stream, this object has been studied extensively with successive generations of sensitive radio telescopes (e.g., Putman et al., 2003; Brüns et al., 2005), and has been the subject of many simulations exploring its existence and properties. The nature of the mechanism(s) producing the Stream is still debated; the two leading theories are tidal stripping and ram-pressure stripping. In the tidal scenario, gravitational forces exerted by the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) on each other pull gas out of their potential wells and create the Stream (e.g., Besla et al., 2010). In the ram-pressure model, drag forces exerted on the LMC and SMC as they pass through the extended gaseous halo of the Galaxy push gas out of their interstellar medium into the wake of their orbits (e.g., Mastropietro et al., 2005).

The Stream is split spatially into two principal filaments, which appear to wrap around each other, and is paired with a "Leading Arm" of material extending for ~ 60 degrees on the other side of the LMC and SMC. Since the Leading Arm lies in front of the direction of motion of the LMC and SMC, it cannot be created by ram-pressure forces, so at least this portion of the Magellanic System is thought to be tidally created. However, if the entire Stream were created by tidal forces, there ought to be a stellar component, yet such a stellar stream has never been observed, despite deep searches. Both origin mechanisms may therefore be at play.

Studying the Stream in absorption

While the radio data give exquisite quality maps of the neutral gas in the Stream, absorption-line spectroscopy of background targets is needed to reveal how much ionised gas and metal enrichment is present. Using ultraviolet (UV) spectra taken with the Cosmic Origins Spectrograph (COS) on board the Hubble Space Telescope (HST), together with optical spectra from VLT/UVES, we recently studied 14 active galactic nuclei (AGN) lying behind or near the Stream (a map of the Stream is shown in Figure 1, with the positions of several of the AGN marked). The resonance lines of the key elements for interstellar abundance measurements all lie in the UV, so the COS observations are necessary for constraining the Stream's metallicity. However, the UVES observations have the advantage of high velocity resolution (4.0 km s^{-1} full width at half maximum [FWHM] given the 0.6-arcsecond slit used), which allows the component structure of the cool gas in the Stream to be resolved. An example of the UVES data is shown in Figure 2, in which seven components of Ca II H and K absorption are seen in the velocity interval of the Stream toward the AGN

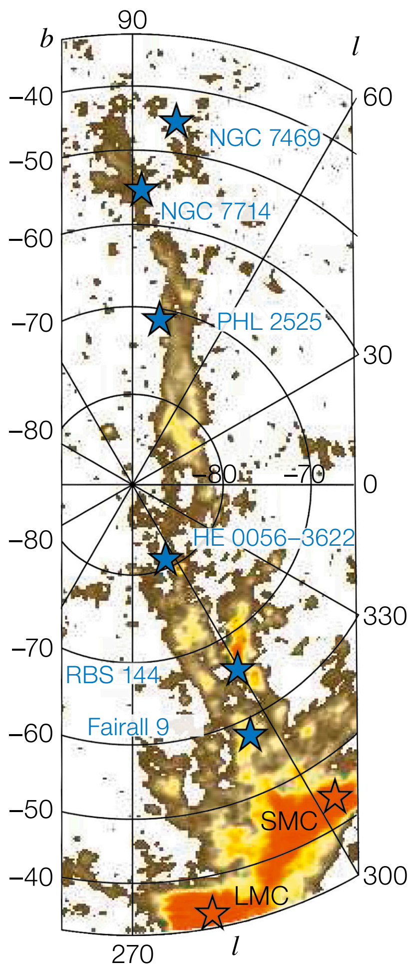

Figure 1. H I 21 cm map of the Magellanic Stream generated from the Leiden/Argentine/Bonn (LAB) survey, colour-coded by H I column density (from Fox et al., 2013). The map is shown in Galactic coordinates centred on the South Galactic Pole, with the LMC and SMC at the bottom. Background sources are indicated with stars. RBS 144 and Fairall 9 sample the two principal filaments of the Stream.

Fairall 9. This indicates that complex substructure and fragmentation is present in the gas. This substructure provides a valuable template for modelling the UV lines observed at lower resolution with COS (20 km s^{-1} FWHM).

The Stream's metallicity was derived in each direction by comparing the strength of the O I 1302 Å, S II 1250 Å or S II 1259 Å UV absorption lines to the strength of the H I (atomic hydrogen) 21 cm emission line measured from radio telescope observations. Neutral oxygen (O I) and singly ionised sulphur (S II) are chosen for these measurements since, in interstellar envi-

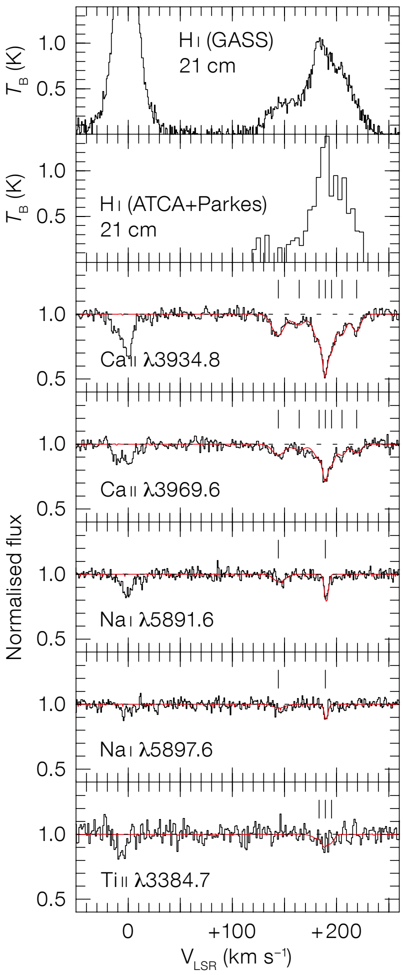

Figure 2. High-resolution VLT/UVES spectra of Ca II, Na I, and Ti II absorption lines in the direction of Fairall 9 (from Richter et al., 2013). Magellanic Stream absorption is visible in multiple components at local standard of rest (LSR) velocities between +130 and +240 km s^{-1}. The red lines indicate our Voigt-profile fit to the data. In the top panel, the Galactic All Sky Survey (GASS) 21 cm profile is included for comparison.

ronments, they are largely unaffected by ionisation and dust-depletion effects, so their ratios with H I provide robust metallicity indicators. We found the Stream's metallicity to be only ≈ 10 % of the Solar value in three separate directions sampling most of its length (Fox et al., 2010; 2013; see Figure 3 upper panels), considerably lower than the current-day average metallicity of the SMC (≈ 20 % Solar) and the LMC (≈ 50 % Solar). However, the age of the Stream is estimated from tidal models to be around 2 Gyr (e.g., Besla et al., 2010), and to determine its parent galaxy, we need to know the LMC and SMC metallicity at that time in the past.

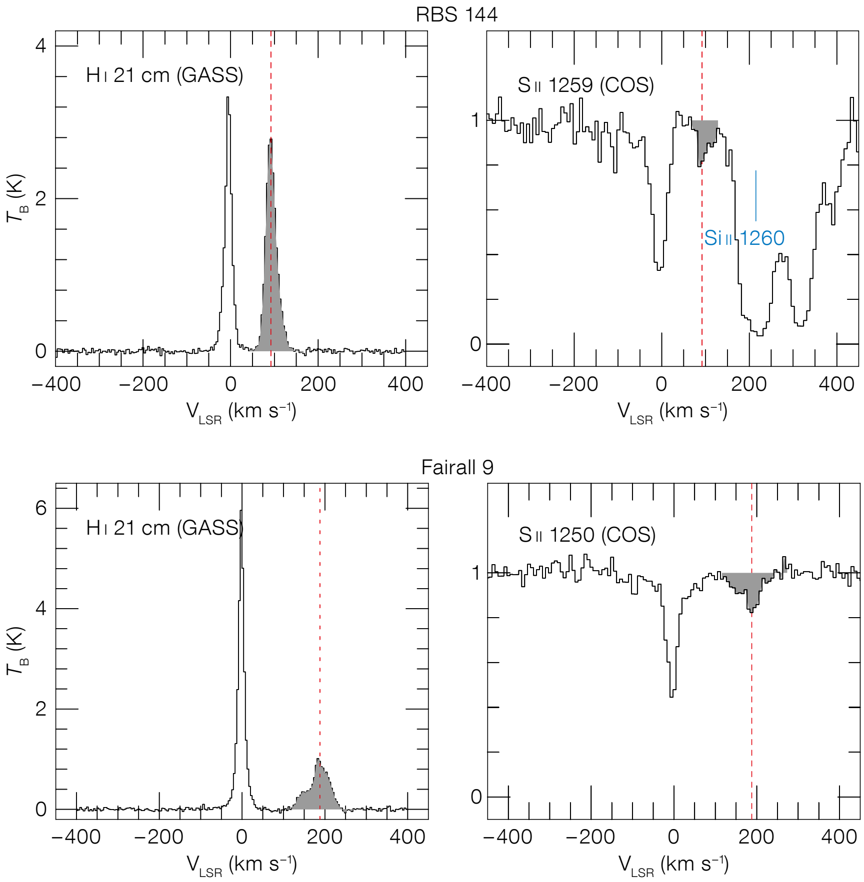

Figure 3. UV and radio spectra used to derive the metallicity of the Magellanic Stream towards RBS 144 (upper) and Fairall 9 (lower), two directions that lie only 8.4 degrees apart on the sky, yet trace two separate filaments of the Stream. The shaded regions show the Stream component, with the Milky Way component visible near 0 km s^{-1}. The abundance of sulphur in the Stream is only 10 % Solar toward RBS 144, but 50 % Solar toward Fairall 9.

Fortunately, information on the metallicity evolution of the Magellanic Clouds is available from their age–metallicity relations (Pagel & Tautvaisiene, 1998); these indicate that 2 Gyr ago, the SMC abundance was ~ 10 % Solar, matching the value we measure in the Stream, whereas the mean LMC abundance at that time was much higher, at ~ 30–40 % Solar. Our results thus support a scenario in which most of the Stream was stripped from the SMC (not the LMC), and has not self-enriched since its formation, because there is no evidence for ongoing star formation in the gas. In a sense, we have measured a fossil record of the Stream at the time of its birth in the SMC about 2 Gyr ago.

A second filament connected to the LMC?

However, a fourth sightline we studied (toward the AGN Fairall 9) tells a very different story (Richter et al., 2013; see also Gibson et al., 2000). In this direction, which lies close to the Magellanic Clouds on the sky, the sulphur abundance in the Stream is found to be 50 % solar (Figure 3 lower panels), five times higher than the value measured in the other directions, and much higher than expected for gas that has been stripped from the SMC. Furthermore, the Fairall 9 direction traces a filament of the Stream that appears to connect kinematically to the southeastern corner of the LMC (Nidever et al., 2008). Our measurement of a higher metal abundance in this direction supports this claim, and points towards a dual origin for the Stream, with two interwoven strands of material, one pulled out of the SMC ~ 2 Gyr ago and another pulled out of the LMC more recently.

In both strands of the Stream, we measure a low nitrogen abundance relative to sulphur: in the LMC filament toward Fairall 9, we derive an N/S ratio of only 14% of the Solar value (Richter et al., 2013), and in the SMC filament toward RBS 144, we derive an upper limit of N/S < 17% Solar based on a non-detection in the N I 1200 Å triplet (Fox et al., 2013). Since nitrogen and sulphur have different nucleosynthetic origins, with nitrogen primarily produced in the asymptotic giant branch (AGB) phase of intermediate-mass stars, and sulphur largely released by core-collapse supernovae, the N/S ratio can be used as a clock, gauging how much time has passed since a burst of star formation occurred. The low N/S ratios measured in the Stream therefore indicate that both strands were stripped from their parent galaxy within ≈ 250 Myr of the initial burst of star formation, before the gas had time to become enriched in nitrogen.

Fuel for the halo or fuel for the disc?

A key remaining open question on the Stream concerns its fate — will it survive its journey through the Galactic halo to reach the disc, or evaporate into the million-degree corona? Continued star formation in spiral galaxies like the Milky Way is dependent on the replenishment of their fuel supplies, so the survival of gaseous tidal streams is of relevance to galaxy evolution in general. The strength of the evaporative interaction between the Stream and the hot corona depends on the density contrast between the two phases, which is poorly constrained observationally.

However, three separate lines of evidence indicate that the Stream is in the process of being evaporated: the presence of a highly ionised phase of gas seen in the UV absorption lines of C IV and O VI (Fox et al., 2010), which appear to trace the conductive or turbulent interfaces between the cool gas and the corona; the filamentary head–tail structures seen in radio data that are the hydrodynamic signatures of gas interaction (e.g., Nidever et al., 2008); and the results of simulations that explore the lifetime of the Stream to evaporative interactions (Bland-Hawthorn et al., 2007). Unless the evaporated material finds a way to re-cool and condense into the neutral phase, the eventual fate of the Stream may be to feed the halo, not the disc, of our Galaxy. The hot halo therefore plays an important role in controlling the passage of fuel supplies into the Milky Way.

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References

Besla, G. et al. 2010, ApJ, 721, L97
Bland-Hawthorn, J. et al. 2007, 670, L109
Brüns, C. et al. 2005, A&A, 432, 45
Dieter, N. H. 1971, A&A, 12, 59
Fox, A. J. et al. 2010, ApJ, 718, 1046
Fox, A. J. et al. 2013, ApJ, 772, 110
Gibson, B. K. et al. 2000, AJ, 120, 1803
Mastropietro, C. et al. 2005, MNRAS, 363, 509
Nidever, D., Majewski, S. R. & Burton, W. B. 2008, ApJ, 679, 432
Pagel, B. E. J. & Tautvaisiene, G. 1998, MNRAS, 299, 535
Putman, M. E. et al. 2003, ApJ, 586, 170
Richter, P. et al. 2013, ApJ, 772, 111
Wannier, P. & Wrixon, G. T. 1972, ApJ, 173, L119

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Night landscape and skyscape of the Paranal Observatory from the north. In the sky over the Observatory, the Large and Small Magellanic Clouds are clearly visible.