The Magellanic Stream
Gas Circulation in the Galactic Halo

Nidever et al. 2010

Andrew Fox (STScI)
Bart Wakker, Philipp Richter, Joss Bland-Hawthorn, Nicolas Lehner, Chris Howk, Cora Fechner, Nadya Ben Behkti
Gas Flows in Milky Way Halo observed as High-Velocity Clouds (HVCs): non-co-rotating objects discovered at 21 cm
- HVC 21 cm sky covering fraction ~37% (down to \(N(\text{H} \ I)\)~3x10\(^{18}\) cm\(^{-2}\); Murphy + 1995)
- HVC \(Z/H\)\approx 0.1-1.0 solar; \(D\approx 5-15\) kpc (Lehner & Howk 2011, except MS & compact HVCs)
- Trace variety of physical processes (infall, fountain circulation, tidal stripping, condensation)
• Extended, bifurcated, 21 cm feature emanating from Magellanic Clouds
• Massive, $\sim1.5\times10^8 M_\odot$ in H I (if $d=55$ kpc; Brüns+ 2005) but no stars yet detected
• Result of triple-galaxy interaction (MW/LMC/SMC)
• Probe of multiphase Galactic accretion
The Magellanic Stream: Origin Mechanisms

- **Tidal Stripping** (explains LA but predicts stellar stream; e.g. Gardiner & Noguchi 1996)
- **Ram Pressure** (explains lack of stars, cannot explain LA; e.g. Moore & Davis 1994)
- **Supernova blowout** (following star formation in LMC; Nidever+ 2008)
- **Direct SMC/LMC collision** (and subsequent tidal evolution; Besla+ 2010, 2012)

Tidal (gravitational) models currently most favored; not mutually exclusive
Assuming MS tip is at ~120 kpc as in Besla+ 2012 models

RECENT MAP OF HI IN GALACTIC HALO (PUTMAN+ 2012)

Magellanic Stream – the dominant feature
QSO Spectroscopy of the MS

21 cm image from Parkes; credit CSIRO/Putman et al. 2003
Metallicity of MS toward NGC 7469 (tip of Stream)

\[
[\text{O/H}]_{\text{MS}} = -1.00 \pm 0.05 \text{ (stat)} \pm 0.08 \text{ (sys)} \quad [10\% \text{ solar}]
\]

Fox et al. 2010, HST/STIS
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\]

- Lower than current-day \((\text{O/H})_{\text{SMC}} \approx 20\% \text{ solar}\) and \((\text{O/H})_{\text{LMC}} \approx 50\% \text{ solar}\)
- But MS was formed \(~2 \text{ Gyr ago (in tidal models), when } (\text{O/H})_{\text{SMC}} \sim 10\% \text{ solar and (O/H)}_{\text{LMC}} \sim 30-40\% \text{ solar}\) (according to age-metallicity relations)
  \(\rightarrow\) tip of Stream has SMC origin

Fox et al. 2010, HST/STIS
Cycle 19 HST/COS program: The Magellanic Stream: A Case Study of Galactic Accretion

Extragalactic sight lines in yellow (our program) and green (archival programs)

First results:
NGC 7469
\([\text{O/H}] = -1.00 \pm 0.09\)

NGC 7714
\([\text{O/H}] = -1.24 \pm 0.20\)

PHL 2525
\([\text{O/H}] < -0.63 \ (3\sigma)\)

RBS 144
\([\text{S/H}] = -1.13 \pm 0.16\)

FAIRALL 9
\([\text{S/H}] = -0.30 \pm 0.04 \) (factor 5 higher!)
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Nidever et al. (2008), Figure 9

2I map of MS in Magellanic Coordinates
Nidever et al. (2008), Figure 9

21 map of MS in Magellanic Coordinates

position-velocity diagram
anomalous clouds

Nidever et al. (2008), Figure 9

Second filament

LMC filament
Two filaments of Stream have different abundances
Giant band of galactic gas likely has dual origin

Two satellites of the Milky Way contributed to the Magellanic Stream.

Ken Croswell

21 May 2013

The Magellanic Stream, a band of gas (pink in this false-color image) that sweeps across part of the sky around the Milky Way (horizontal light-blue band), originates in part from the interaction of the two Magellanic Clouds (white regions at bottom right).

NIDEVER, ET AL., NRAO/AUI/NSF AND MELLINGER, LEIDEN-ARGENTINE-BONN SURVEY, PARKES OBSERVATORY, WESTERBORK OBSERVATORY, ARECIBO OBSERVATORY.
Ion Abundances

Fairall 9 (LMC filament):
- S/H=0.5 solar, N/H=0.07 solar
- N (AGB stars) released later than $\alpha$-elements (core-collapse SNe)
  - $\rightarrow$ gas stripped from LMC region <250 Myr after burst of SF

RBS 144 (SMC filament):
- S/H=0.1 solar, N/H<0.015 solar
- $\rightarrow$ gas also stripped before N enrichment

Gas is “chemically young” (low N/$\alpha$) in both filaments
Dust depletion levels (toward RBS 144):

\[ [\text{Fe}/\text{S}]=-0.6, \ [\text{Si}/\text{S}]=-0.6, \ [\text{Al}/\text{S}]=-0.7 \] (all sub-solar)

→ dust present in MS, grains survive ejection process

Gas-to-dust ratios:

RBS 144 G/D ~ SMC diffuse-gas G/D (Roman-Duval+ 2013)
Fairall 9 G/D ~ LMC diffuse-gas G/D

supportive of dual origin
Ionization I: Low ions photoionized

- Galactic ionizing radiation
- Extragalactic ionizing radiation
- corona
- disk
- MCs
- Leading Arm
- Stream
Model of Galactic radiation field
Fox+ 2005

Contours of log (photons cm$^{-2}$ s$^{-1}$) for ionizing (blue) and non-ionizing (red) radiation.
Ionization Corrections

*Cloudy* photoionization models

Ionization parameter \( U = \) ionizing photon density/gas density

Small ionization corrections for S, Si, Fe, Al, O for parts of Stream with \( N(\text{H I}) > 10^{19} \text{ cm}^{-2} \)

This means e.g. \([\text{S/H}] \approx [\text{S II/H I}]\)
Cloudy models also solve for the physical conditions in the low-ion phase.

Results for Mrk 335 (Outer-Stream):

\[
\log N(\text{H I}) = 16.67 \\
[\text{O/H}] = -1.0 \\
\log (\text{Si III}/\text{Si II}) = 0.52 \pm 0.08
\]

→ \( \log U = -3.45 \pm 0.10 \)
→ \( \log (n/\text{cm}^{-3}) \sim -2.2 \)
→ line-of-sight size \( \sim 0.9 \) kpc
→ ionization level \( x_H = 98.9 - 99.5\% \)
→ \( \text{H II}/\text{H I} \sim 100 \)
**Cloudy** models also solve for the *physical* conditions in the low-ion phase.

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\[\rightarrow \text{ionization level } x_H = 98.9 - 99.5\%\]

\[\rightarrow \text{H II/H I } \sim 100\]
Ionization II) High ions (C IV, O VI, Si IV) collisionally ionized
The high-ion phase: collisionally ionized in boundary layers

Recent turbulent mixing layer models (Kwak+ 2011) explain average HVC O VI column (log N ~14.0), high-ion ratios and kinematics. (Kelvin-Helmholtz shearing instability)

Simulations ran for several 100 Myr, O VI builds up over time
Takeaway:

Conductive interfaces (Gnat+) or turbulent mixing (Kwak+) viable for MS high ions

(more data needed)
Fate of the MS: feed the disk or feed the corona?

1. **UV metal lines:** MS has boundary-layer high-ion phase (Sembach+ 2003, Fox+ 2005, 2010)
2. **21 cm evidence** of fragmentation/disruptive interaction with the hot corona (below)
3. Cloud evaporation explored in simulations, timescale short (~100 Myr if $M\sim10^4 M_\odot$)

Stanimirovic+ 2008, Arecibo, 3.5' resol., fragmentation near MS tip
BUT…… MS has survived ~2 Gyr (→ stabilized against evaporation?)
Leading Arm has reached (crossed) disk
Summary

Recent observational results from *HST/COS* on the Stream

- **MS metallicity** ~10% solar in multiple directions but 50% solar in LMC filament
  - main body originated in SMC ~2 Gyr ago in tidal interaction
  - LMC filament chemically consistent with (recent) LMC origin
  - dual origin, with “double-helix” structure of interwoven strands

- **MS contains dust** (sub-solar Fe/S, Si/S, Al/S ratios), with dust-to-gas ratios supportive of dual origin for two filaments

- **High ions** in MS indicate interaction with hot corona
  - much of Stream will evaporate before reaching disk
  - gas must cool and recondense to be available for star formation