First Chemical Abundances in the Outer Disk, Giant Stellar Stream, and Inner Stellar Halo of M31

Subaru 20th Anniversary
November 21, 2019

arXiv: 1909.0006

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Image credit: Torben Hansen
M31 is ideal for studies of galaxy formation in the Local Group

All three stages of the merger process:

(1) Intact satellite galaxies

(2) Stellar streams from the disruption of galaxies

(3) “Smooth” stellar halo
Chemical abundance patterns can reveal differences in formation history

Tolstoy et al. 2009
Previous methods cannot provide $[\alpha/\text{Fe}]$ in M31

Photometric metallicity estimates
- e.g. Kalirai+2006b, Tanaka+2010, Gilbert+2014, Ibata+2005

Spectroscopic calcium triplet equivalent width measurements
- e.g. Chapman+2006, Koch+2008

Spectral synthesis of medium resolution spectroscopy
- e.g. Vargas+2014a,b

Ibata et al. 2005

785 kpc
(McConnachie et al. 2005)
Moving to low-resolution spectroscopy increases the available abundance information.

Low-resolution => Higher signal-to-noise per pixel for the same exposure time and observing conditions.
Some low-resolution spectroscopic fields have deep HST photometry (Brown et al. 2009)

5 additional deep fields this fall!

Adapted from Escala et al. 2019b, submitted.
We measured abundances for 70 M31 RGB stars across the inner halo, Giant Stellar Stream, and outer disk*

*and an additional 21 stars in a 17 kpc GSS field (Gilbert et al. 2019)

Uniformly $\alpha$-enhanced: $\langle [\alpha/Fe] \rangle \gtrsim 0.35$ dex

Our abundance measurements in the Giant Stream will place constraints on major vs. minor merger models

Kirby, Gilbert, Escala et al., 2019, submitted; Kirby et al. 2013

$$\langle [\text{Fe/H}] \rangle_{\text{GSS}} \sim -0.8 - -0.7$$

$$M_* = 0.5 - 5 \times 10^9 \ M_\odot$$
A star formation episode induced by a major merger could explain the abundances of M31’s outer disk

\[ \langle [\alpha/Fe] \rangle_{M31\text{disk}} = 0.58 \pm 0.08 \]

(Escala et al. 2019b, submitted)

300 M31-like simulations
Merger ratios of 2:1 to 300:1 can make GSS
Observed M31 disk => 4:1 recent merger

Hammer et al. 2018
The metal-rich, inner halo of M31 could not have formed from present-day M31 satellite galaxies.

Metal-rich: \([\text{Fe/H}] > -1.5\) dex

Inner halo: \(r_{\text{proj}} \lesssim 26\) kpc


Vargas et al. 2014a
The Subaru Prime Focus Spectrograph will provide unprecedented spectroscopic coverage of M31

LRS blue arm
(380 - 650 nm)

MRS red arm
(710-885 nm)

PFS goal:
How does M31 differ from the MW in its merger history?

34 fields over 22 nights
Globally representative star formation histories for deep spectroscopic fields from HSC

Image credit: I. Escala

A holistic view of M31’s assembly history, in support of Keck/DEIMOS, Subaru/PFS, and Subaru/HSC

PI: E. Kirby, including I. Escala
Summary

Stellar chemical abundances provide detailed information about the formation history of a galaxy.

We measured abundances of 91 M31 RGB stars across the inner halo, Giant Stellar Stream, and outer disk.

M31 is relatively $\alpha$-enhanced. The abundances in the halo are distinct from present-day M31 satellites. The abundances in the disk and GSS may support a major merger in M31, but more data and follow-up modeling is required.

Spectral synthesis of low-resolution stellar spectra can be used to measure detailed elemental abundances in M31.
Abundances from low-resolution spectra agree with measurements from high-resolution spectra

\[ [\alpha/Fe]_{HRS} = 0.282 \times [Mg/Fe]_{HRS} + 0.136 \times [Si/Fe]_{HRS} + 0.582 \times [Ca/Fe]_{HRS}, \]
We identified 260 likely M31 RGB stars in our spectroscopic fields.

Membership criteria:
- Color-magnitude diagram position
- Presence of Na I 8190 absorption feature
- Heliocentric velocity

The velocity distributions for the low-resolution fields

The Giant Stellar Stream and other stellar features were likely produced by the merger of the GSS progenitor.
The difference between M31’s stellar halo and its satellite galaxies is also reflected in a simple $[\alpha/\text{Fe}]$ vs. $[\text{Fe/H}]$ diagram.

Kirby, Gilbert, Escala et al. 2019b, submitted.
Chemical abundance patterns similar to the MW disk are unlikely to reproduce the high $\alpha$-enhancement of M31’s outer disk.

\[
\langle [\alpha/Fe] \rangle_{\text{M31 disk}} = 0.58 \pm 0.08
\]
The 12 kpc substructure fits the spatial and kinematic profile of the Southeast shelf

Gilbert et al. 2007

Is the Southeast shelf associated with the GSS progenitor?

Answer: Need more data! But…

\[
\langle [\text{Fe/H}] \rangle_{\text{GSS}} - \langle [\text{Fe/H}] \rangle_{\text{SEshelf}} \gtrsim 0.1 \text{ dex}
\]

Dwarf galaxies: Kirby, Gilbert, Escala et al. 2019b, submitted; Vargas et al. 2014a
We do not find evidence of an [$\alpha$/Fe] gradient along the high surface brightness core of the GSS

This agrees with previous findings of no [Fe/H] gradient along the GSS core
The substructure of unknown origin: possibly related to the GSS?

Minor merger scenario: extension of W shelf?
Major merger scenario: Multiple wraps superposed along line-of-sight?
(e.g., Hammer+2018)

Gilbert et al. 2009b

Gilbert, Kirby, Escala et al. 2019, in press.
Modern theoretical studies are informative to place M31’s abundances in context

Escala et al., in preparation.