THE POWER OF WIDE FIELD SURVEYS
FOR REVEALING THE MERGER HISTORY OF THE ANDROMEDA GALAXY

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Image credit: Robert Gendler
THE POWER OF WIDE FIELD SURVEYS FOR REVEALING ANDROMEDA’S MERGER HISTORY

SURVEYS OF RESOLVED STARS IN M31

PAndAs Starcount Map
(McConnachie et al. 2018)

M31

N185

N147

M33

30 kpc

90 kpc

150 kpc

60 kpc

Giants Southern Stream

M31 Halo Fields

Dwarf Galaxy Fields

SPLASH Fields

PHAT (Dalcanton et al. +KMG) 2012
Global Properties: Accretion History
- Luminosity Function, Time of Accretion of destroyed dwarf galaxy population
- Relative Importance of major/minor mergers over time

Inner Halo: In Situ Population
- Constraints on Formation Avenues
- Relative importance of in situ and accretion

Tidal Debris Features: Recent Accretion Events
- Stellar properties of recently accreted satellites
- Modeling of collision: time of accretion, mass of progenitor and host galaxy
- Orbits of satellites

Mass of Halo:
Comparing Observations with Simulated Halos

Key Observables:
stellar density, stellar velocities, chemical abundances, star formation histories
SPECTROSCOPY IS CRUCIAL FOR RECONSTRUCTING RECENT ACCRETION EVENTS

- ~10% of mass in Andromeda’s stellar halo is in photometrically identified tidal streams
- Imaging provides only tentative connections between substructures

McConnachie et al. 2018
Line of sight velocity distributions of stars
- resolve spatially overlapping streams
- discover faint streams
- identify connections between photometric substructures

CONSTRAIN THE ORBITS OF PROGENITORS
DECIPHERING ANDROMEDA’S MERGER HISTORY: RECENT ACCRETION EVENTS

SPECTROSCOPY ENABLES DETAILED MODELING OF TIDAL STREAMS

Key Observables

- Line of sight velocities in W Shelf, SE Shelf, GSS
- Stellar density distribution
- Line of sight distance along the GSS

Progenitor stellar mass:
~ LMC to M33
Disruption: ~ 750 Myr
M31’s mass:
$M_{200} \sim 2 \times 10^{12} \text{ Msun}$

DECIPHERING ANDROMEDA’S MERGER HISTORY: GLOBAL PROPERTIES

SURFACE BRIGHTNESS AND METALLICITY PROFILES TO 180 KPC

FROM SPECTROSCOPICALLY SELECTED M31 STARS

K. M. Gilbert et al. 2012
also Ibata et al. 2014 (PAndAS), Tanaka et al. 2009 (Subaru)

K. M. Gilbert et al. 2014
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Simultaneously modeled all known MW and M31 components.

MW halo dispersion profile also relatively flat over a large radial range.

Shallower profile than found in M31’s GC system.

**Also yielded full posterior probability distributions for tidal streams.**
Local Volume comparison points from the HST GHOSTS survey
Local Volume comparison points from the HST GHOSTS survey

Other Local Volume spirals have fainter surface brightness profiles, but similar power-law slopes

Stellar surface density profile of M31 consistent with accreted component of simulations
Observed and simulated halos show a strong trend of metallicity with accreted stellar halo mass.

Metallicity of accreted stellar halo dominated by most massive accreted progenitor.

The MW and M31 appear to be at opposite ends of the spectrum for \( L^*\) galaxies.
DECIPHERING ANDROMEDA’S MERGER HISTORY: INNER HALO AND DISK

TRACING THE STELLAR HALO INWARDS

- Combine contiguous spectroscopic and photometric datasets
  - SPLASH: spectra of > 5000 M31 Stars
  - PHAT: imaging of > 100 Million M31 stars
- Model M31’s structural components from 4 kpc
DECIPHERING ANDROMEDA’S MERGER HISTORY: INNER HALO AND DISK

FIRST EVIDENCE FOR AN IN SITU HALO COMPONENT

- Simultaneous modeling of stellar velocities, luminosity function, and surface photometry
  - **Observed**: Stars with spheroid-like kinematics and a disk-like luminosity function.
  - **Observed from velocities**: Significant rotation in inner spheroid.
  - **Implication**: Inner region of M31’s halo has a significant population of stars that once belonged to the disk.

_Dorman et al. (+KMG) 2012, 2013_
M31’S DISK HAS BEEN HEATED

- Combination of stellar velocities, precision stellar photometry, gas kinematics
  - Observed: Disk velocity dispersion increases with stellar age
  - Observed: Asymmetric drift increases with stellar age
  - Implication: M31’s stellar disk has continually experienced events which dynamically heated the disk

Dorman et al. (+KMG) 2015; Quirk et al. (+KMG) 2019
A recent major merger can reproduce multiple observed properties of M31’s stellar halo and disk.
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Observations best matched by simulations of a ~4:1 merger.

- First passage 7-10 Gyr ago,
- Coalescence ~2-3 Gyr ago.
A MAJOR MERGER SCENARIO CAN MATCH GLOBAL PROPERTIES

Minor Axis

Surface Brightness

$\log \frac{\Sigma_2}{M_\odot \, kpc^{-2}}$

Velocity Dispersion (km/s)

Projected Distance (kpc)

D’Souza and Bell 2018b

DECIPHERING ANDROMEDA’S MERGER HISTORY: A RECENT MAJOR MERGER?
DECRYPTING ANDROMEDA’S MERGER HISTORY: A RECENT MAJOR MERGER?

PLACING A MASSIVE PROGENITOR IN CONTEXT

ANALOGUES FROM THE LOCAL VOLUME
8 galaxies of similar mass found in a volume to 24 Mpc (S4G Survey)

IN A LOCAL GROUP LINEUP
D’Souza and Bell 2018b
Global Properties: Accretion History

• Bulk of stellar mass: one to a few relatively massive (>10⁹ M⊙) accretion events

• M31 likely experienced a prolonged accretion history. May require many recent low-mass accretions at large radii.

• M31 likely has a more massive dominant progenitor and larger accreted stellar halo than the typical MW-mass galaxy

Inner Halo: In Situ Population

• Inner region of M31’s halo has a significant population of stars that once belonged to the disk

• Multiple lines of evidence indicate an active recent accretion history impacting the disk

Tidal Debris Features: Recent Accretion Events

• Giant Stellar Stream related debris found throughout the inner halo

• Minor merger simulations indicate an LMC to M33 mass progenitor disrupted ~750 Myr ago

• Modeling full halo velocity distribution: improved constraints on substructure kinematics and uncertainties

SIMULATIONS HAVE NOW PRODUCED GSS MORPHOLOGY WITH MERGER MASS RATIOS RANGING FROM 2:1 TO 300:1
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Chemical Abundance measurements can break existing degeneracies

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ABUNDANCES CAN BREAK THE DEGENERACY

Stellar Surface Density
Stellar luminosity plus time since disruption

Metallicity [Fe/H]
Stellar luminosity

Alpha Element Abundances [$\alpha$/Fe]
Time of infall

LUMINOSITY FUNCTION OF ACCRETED SATELLITES

TIME OF ACCRETION

e.g., K. M. Gilbert et al. 2009a, Lee et al. 2015
BUILDING A STATISTICAL CENSUS OF CHEMICAL ABUNDANCES

- Existing SPLASH data
  - Coadd low SNR spectra
  - Mean [Fe/H], [α/Fe] abundances

- New Spectroscopic Campaign
  - Obtain deep data in strategic dSph and halo fields
  - Distributions of [Fe/H], [α/Fe] abundances

- Extension of spectral synthesis method to lower resolution (R~3000)
  
  Escala, Kirby, K. M. Gilbert et al. 2019

NSF AST-1614569 (PI K. M. Gilbert) and AST-1614081 (PI Kirby)
FIRST ALPHA ABUNDANCES IN GSS

- GSS experienced higher efficiency of star formation than surviving M31 dwarf satellites

![Graph showing chemical abundances and star formation efficiencies](image)
FIRST ALPHA ABUNDANCES IN GSS

- GSS experienced higher efficiency of star formation than surviving M31 dwarf satellites
- And than Sagittarius and the Magellanic Clouds

K. M. Gilbert et al., 2019
HINTS OF A GRADIENT IN ALPHA ENHANCEMENT AS WELL AS METALLICITY

At R > 40 kpc: 9 RGB stars with \([\alpha/\text{Fe}]\), 23 with \([\text{Fe/H}]\)
THE POWER OF WIDE FIELD SURVEYS FOR REVEALING TRIANGULUM’S HISTORY

TRIANGULUM (M33)

~200 kpc from M31, $M_\star \sim 3 \times 10^9 M_\odot$

from D’Souza and Bell 2018b
EXTENDING LARGE SCALE RESOLVED STELLAR POPULATION SURVEYS TO M33

THE POWER OF WIDE FIELD SURVEYS FOR REVEALING TRIANGULUM’S HISTORY

PAndAs Starcount Map
(McConnachie et al. 2018)
DOES M33 HAVE A HALO?

- M33’s disk has a break in surface density - transition to a stellar halo, or large extended disk?
  
  Barker et al. 2011, Cockcroft et al. 2013

- PAndAS resolved stellar photometry places an upper limit of $10^6 \, L_\odot$ on a spatially smooth stellar halo

  McMonigal et al., 2016
THE POWER OF WIDE FIELD SURVEYS FOR REVEALING TRIANGULUM’S HISTORY

PHAT + SPLASH EXTENSION TO M33: RESOLVED STELLAR SPECTROSCOPY AND HST IMAGING

- Disk kinematics as a function of stellar age
- Quantitative comparison with tracers of gas disk
- Chemo-dynamical analysis of older stellar populations
- Does M33 have a stellar halo?
- What forces have driven the disturbances in the stellar and gas disks?

NSF AST-1909066 (PI K. M. Gilbert) and AST-1909759 (PI P. Guhathakurta)
FIRST RESULTS: DEFINITIVE EVIDENCE OF A WIDESPREAD KINEMATICALLY HOT COMPONENT

>450 RGB stars; ~30% in a 50 km/s component

K. M. Gilbert et al., in prep.
WIDE FIELDS AND EXPANDED SURVEY VOLUMES

THE FUTURE OF STELLAR HALO STUDIES
THE FUTURE OF STELLAR HALO STUDIES: WIDE FIELDS

WIDE FIELD SPECTROSCOPY IN ANDROMEDA

K. M. Gilbert & E. Tollerud, Astro2020 white paper

Current Spectroscopic Coverage

McConnachie et al. 2018

-2.5 < [Fe/H] < -0.7 dex

150 kpc
100 kpc
50 kpc

Degrees from M31’s Center

Degrees from M31’s Center

PAndAs Starcount Map
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PAndAs Starcount Map

Degrees from M31’s Center

PAndAs Footprint

M31 Halo Stellar Mass Budget

McConnachie et al. 2018

Globular Clusters (0.1%)

“Smooth Halo” (27%)

Amorphous Substructure (59%)

Dwarf Galaxies (4%)

Named substructures (10%)

Giant Stellar Stream +
Associated Features (93%)

NGC147 (54%)

NGC185 (41%)

K. M. Gilbert & E. Tollerud, Astro2020 white paper

150 kpc

100 kpc

50 kpc

Degrees from M31’s Center

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PLANNED PFS M31 SURVEY COVERAGE

CURRENT SPECTROSCOPIC COVERAGE
THE FUTURE OF STELLAR HALO STUDIES: WIDE FIELDS

WIDE FIELD SPECTROSCOPY IN ANDROMEDA

K. M. Gilbert & E. Tollerud, Astro2020 white paper

Pan-Andromeda Archaeological Survey
(McConnachie et al. 2009)
(Figure adapted from Martin et al. 2014)

MSE Survey Strategy
for M31 and M33

PAndAs Starcount Map

McConnachie et al. 2018

CURRENT SPECTROSCOPIC COVERAGE

POTENTIAL WIDE FIELD MOS SURVEY COVERAGE
Contiguous deep imaging to ancient Main Sequence turnoff will be enabled over significant areas of halo with WFIRST.
THE FUTURE OF STELLAR HALO STUDIES: EXPANDED SURVEY VOLUMES

M81 Group
3.5 Mpc

WFIRST Resolved RGB imaging of halos

LUVOIR 15m PHAT
LUVOIR 9m PHAT
30-m MOS

Fig. from Weisz & Boylan-Kolchin, Astro2020 white paper
Mergers have played a significant role – at all radii – in crafting Andromeda’s present-day morphology.

Observations of resolved stars enable reconstruction of the build-up of individual stellar halos - and chemical abundances and deep star formation histories provide key observational constraints.

Future wide field spectroscopy and deep imaging will revolutionize our understanding of Andromeda’s halo and greatly increase the N_{halos} we can characterize.