PAndAS mining the stellar halo of Andromeda

Stellar streams, dwarf galaxies, globular clusters et al.

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Cosmology on galaxy scales

the new frontier

- Large scale cosmology is now largely understood
  - $\Lambda$ Cold Dark Matter universe
- How do baryons condense at the center of dark matter halos?
  - hierarchical build-up (stars, globular clusters, gas...)

Aquarius simulation, Springel et al. (2009)
Cosmology on galaxy scales

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How do baryons condense at the center of dark matter halos?

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Figure 6. $V$-band surface brightness of our model haloes (and surviving satellites), to a limiting depth of 35 mag/arcsec$^2$. The axis scales are in kiloparsecs.

Cooper et al. (2009) "observed" halo

see also Kathryn’s talk
Massive galaxies contain the majority of the universe’s stellar mass

Is there a faint end to galaxy formation?
  • sensitive to star-formation-suppression mechanisms
  • “missing satellite crisis”?

Which dark matter halos contain stars?
  • What sets their numbers? their properties (luminosity, size, shape)?

Why study the faintest galaxies?

Springel et al. (2009)
PAndAS
The Panoramic Andromeda Archaeological Survey

PI: Alan McConnachie

Arif Babul, Mike Barker, Pauline Barmby, Edouard Bernard, Crystal Brasseur, Scott Chapman, Robert Cockcroft, Michelle Collins, Anthony Conn, Pat Côté, Tim Davidge, Anjali Doney, Aaron Dotter, John Dubinski, Greg Fahlman, Mark Fardal, Annette Ferguson, Jurgen Fliri, Bill Harris, Avon Huxor, Rodrigo Ibata, Mike Irwin, Geraint Lewis, Dougal Mackey, Nicolas Martin, Mustapha Moucine, Julio Navarro, Jorge Peñarrubia, Thomas Puzia, Mike Rich, Jenny Richardson, Harvey Richer, Arnaud Siebert, Nial Tanvir, David Valls-Gabaud, Kim Venn, Larry Widrow, Kristin Woodley...
PAndAS

The Pan-Andromeda Archaeological Survey (2008–2011)

_building on pilot M31 CFHT surveys_ (Ibata, Martin et al. 2007, McConnachie et al. 2008)

_CFHT large program_

- 220 hours over 3 years
- 3.6m telescope on Mauna Kea

_MegaCam/MegaPrime_

- 1 deg$^2$ field of view
- 2 bands ($g$ & $i$)

_all ~400 deg$^2$ now observed_
Observing 3 mag. below the tip of RGB
• 0.5–0.8” seeing
• ~20 min integration in g & i
• S/N=10 depths
  • g ≈ 25.5
  • i ≈ 24.5

96 million sources

~10 million stars in M31
RGB selection box
Stellar halo of M31
Different stellar populations → age/metallicity/distance differences
Let us assume metallicity differences...
$[\text{Fe/H}] = -0.9$

@ M31 distance

150 kpc

50 kpc
Measuring Shape/Lumpiness of the halo

- Ibata et al. (2012)
- McConnachie et al. (2012/13)

Figure 6. V-band surface brightness of our model haloes (and surviving satellites), to a limiting depth of 35 mag/arcsec$^2$. The axis scales are in kiloparsecs.

Only stars formed in satellites are present in our particle model; there is no contribution to these maps from a central galactic disc or bulge formed in situ (see Section 3.3)
Fig. 2.—The distribution of HI gas (red contours), drawn from the survey of Braun & Thilker (2004), overlaid on a surface density map of stars identified as being on the RGB within M31 and M33 in the entire PAndAS footprint (see McConnachie et al. 2009; Richardson et al. 2011). The logarithmic contours are drawn at integrated column densities of HI, with \( N_{\text{HI}} = 10^{17} \) to \( 10^{20} \) cm
\(^2\) in steps of 0.5 dex.

The annotations indicate the heliocentric radial velocity of HI features.

This study focuses upon Red Giant Branch (RGB) stars at the distance of M31 and M33, selected with a cuts in color and magnitude (e.g. Ibata et al. 2001, 2007; McConnachie et al. 2009). Figure 1 presents the distribution of metal-rich RGB stars, overlain by a schematic map of the prominent stellar substructure; note that a non-linear scaling has been applied to the RGB density, to bring out faint substructure. The thick solid line is the entire PAndAS footprint, with stellar substructure as labelled thin solid lines. The dashed curve represents a significant over-density of globular clusters, identified as the NW Group by Mackey et al. (2010). The dot-dashed line corresponds to a circle of radius of 150 kpc from the center of M31. It is very apparent that accompanying M31 and M33 is a wealth of substructure consisting of extensive streams and dwarf galaxies [these will be discussed in more detail in Section 3.1.2, and see Richardson et al. (2011)].

The stellar catalog derived from PAndAS is supplemented with earlier observations with Isaac Newton Telescope Wide Field Camera (see Ibata et al. 2001) and CFHT/MegaCam & CFHT/CFH12k (see McConnachie et al. 2003; Ibata et al. 2007) provide the full survey coverage. In parallel, a number of fields, targeting prominent substructure and dwarfs, were targeted with DIEMOS \(^4\) on the 10m Keck-II Telescope (e.g. Chapman et al. 2008; Collins et al. 2011). With a moderate resolution (\( R \sim 6000 \)), observations of 60-90 mins around the prominent CaT absorption lines \( \sim 8600 \) \( \AA \) resulted in a S/N \( \sim 5 \) for targets of \( i \sim 21 \), with a corresponding velocity resolution of \( \sim 5 \) \( 10 \) km s\(^{-1}\); these will be described in more detail in Section 4.2.

3.1.2. Stellar Properties

Detailed analysis of the stellar substructure in PAndAS will be presented in Ibata et al. (2012) and McConnachie et al. (2012b), so here we focus on the key features. The most significant structure is an extensive stellar stream, the Giant Stellar Stream (GSS), in the halo of M31, initially discovered with the Wide Field Camera on DIEMOS \(^4\).
The M31 satellite systems

PAAndAS’ Cubs: Dwarf galaxies & globular clusters
6 dSphs (2004) → 28 dSphs (now; 4 SDSS + 16 PAndAS) + deep follow-up
Two examples

And XXI
$M_V = -9.9 \pm 0.6$
$r_h = 875 \pm 127 \text{ pc}$

And XXII
$M_V = -6.5 \pm 0.8$
$r_h \sim 220 \text{ pc}$
Bayesian TRGB distance analysis
A. Conn et al. (2011, 2012)
Bayesian TRGB distance analysis

A. Conn et al. (2011, 2012)
Bayesian distance analysis

Homogeneous distances
Automatic search & completeness limits

- Full statistical analysis of spatial + CMD information
  - Accounting for varying MW foreground contamination, very structured M31 "contamination"

Martin et al. (2012)
Automatic search & completeness limits

- Full statistical analysis of spatial + CMD information
  - Accounting for varying MW foreground contamination, very structured M31 "contamination"

- Automated search:
  - completeness function as $f(X,Y,r_h,[\text{Fe/H}],m-M,...)$
  - new candidate dwarf galaxies

→ comparison with simulations
Dwarf galaxy radial velocities

see Michelle Collins’ and Larry Widrow’s posters!

Dwarf galaxy radial velocities

Collins et al. (2011, 2012)

Chapman et al. (2012)

Tollerud et al. (2012)
Globular clusters

Huxor et al. (2011, 2012)
Mackey et al. (2009, 2012)

see Dougal Mackey’s and Avon Huxor’s posters!
Some other results
The M33 stellar halo

McConnachie et al. (2010)
Cockcroft et al. (2012)

Tidal material from the M31/M33 interaction

Genuine M33 stellar halo
Milky Way foreground “contamination”

$D_{GC} \sim 30$ kpc

Martin et al. (2012)
Fardal et al. (2012)
The remnants of galaxy formation from a panoramic survey of the region around M31

PAndAS cubs: Discovery of two new dwarf galaxies in the surrounding of the Andromeda and Triangulum galaxies

Evidence for an accretion origin for the outer halo globular cluster system of M31

The photometric properties of a vast stellar substructure in the outskirts of M31

The M33 globular clusters with PAndAS data: the last outer halo clusters?

PAndAS progeny: Extending the M31 dwarf galaxy cabal

Density variations in the M31 north-west star stream

A Bayesian approach to locating the red giant branch tip magnitude I

A Bayesian approach to locating the red giant branch tip magnitude II

Unearthing foundations of a cosmic cathedral: searching the stars for M33’s halo

The PAndAS view of Andromeda’s dwarf galaxy system I: Automated search and structural properties of the dwarf galaxies

The non-universal dSph mass profile? A kinematic study of the Andromeda dwarf spheroidal system
Collins et al. 2012, to be submitted

Dynamics in the satellite system of Triangulum: Is And XXII a dwarf satellite of M33?
Chapman et al. 2012, to be submitted

The PAndAS survey catalogue
McConnachie et al. 2013