Local Group cosmology with ngCFHT

Nicolas Martin
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Cosmology on galaxy scales

the new frontier

“observed” halo

Large scale cosmology is now largely understood

• Λ Cold Dark Matter universe

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

• hierarchical build-up (stars, globular clusters, gas…)

Copper et al. (2009)
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*observed* halo

<table>
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<tr>
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<td>75</td>
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Copper et al. (2009)
Where the Local Group comes into play

SDSS (2004–2011)
Pan-STARRS (2010–2014)

MW plane

PAndAS (2008–2011)
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 $\sim$400 deg$^2$ now observed
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PAndAS data

- 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

Chapitre 6 – Un relevé du halo de la galaxie d’Andromède

Diagramme couleur-magnitude des étoiles (à gauche) et de ses galaxies (à droite) du champ M01. La contamination des étoiles Galactiques vient principalement des étoiles du halo ((g−i)_0 < ∼ 1.0) et de celles du disque ((g−i)_0 > ∼ 2.2) mais ne se superposent qu’avec les étoiles de M31 de métallicité élevée. Les isochrones de Girardi et al. (2004) pour des métallicités [Fe/H] = −2.3, −1.7, −1.3, −0.7, −0.4, 0.0 et +0.2 à la distance de M31 (m−M = 24.47) sont superposées, de même que la boîte de sélection utilisée pour isoler les étoiles RGB de M31 (en rouge). Les incertitudes sur la magnitude i sont indiquées à gauche du CMD des étoiles.
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).
Different causes produce different halos

\[ \mu \text{ (mag/arcsec}^2) \]

38 \rightarrow 23

\[ [\text{Fe/H}] \]

-2.0 \rightarrow -0.5

Fig. 17.—Same as Fig. 14, but for our "artificial" halo constructed from the highest (left) and lowest (right) luminosity accretion events.

Highest luminosity accretion events
Different causes produce different halos

\[ \mu \text{ (mag/arcsec}^2) \quad 38 \rightarrow 23 \]
\[ [\text{Fe/H}] \quad -2.0 \rightarrow -0.5 \]

Highest luminosity accretion events

Lowest luminosity accretion events

Johnston et al. (2008)
Different causes produce different halos

Johnston et al. (2008)

\[ \mu \text{ (mag/arcsec}^2\text{)} \]
\[
\begin{array}{c cc c}
38 & \rightarrow & 23 \\
\end{array}
\]

\[ [\text{Fe/H}] \]
\[
\begin{array}{c cc c}
-2.0 & \rightarrow & -0.5 \\
\end{array}
\]

\[ [\alpha/\text{Fe}] \]
\[
\begin{array}{c cc c}
-0.1 & \rightarrow & +0.2 \\
\end{array}
\]

\[ v_r \text{ (km/s)} \]
\[
\begin{array}{c cc c}
-200 & \rightarrow & +200 \\
\end{array}
\]

\[ \sigma \text{ (km/s)} \]
\[
\begin{array}{c cc c}
0 & \rightarrow & +150 \\
\end{array}
\]

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Highest luminosity accretion events

Lowest luminosity accretion events
A complete survey of M31’s surroundings?

Projected density of RGB candidates around M31 [ 0.5<(g−i)<2.0 ]
Figure 26: Radial distribution of stars surrounding M31 with colours in the range $0.5 < (g-i) < 2.0$. Densities have been averaged over circular annuli, and results are shown for a range of limiting $g$-band magnitudes. Note that red giant branch stars in M31 have $g & 22.5$. The bump at $R \approx 7.5$ is due to the NGC147/185 subsystem.

In Figure 25, the effective surface brightness of the faintest visible features is of order 32–33 mag arcsec$^{-2}$. This corresponds literally to a few RGB stars per square degree. Note that the disk of the Milky Way is located to the North so there is increasing contamination in the colour-magnitude of the RGB locus by foreground dwarfs; the reddest RGB stars are particularly affected by this source of contamination. Young, blue stellar populations — and even intermediate-age populations such as asymptotic giant branch (AGB) stars — are not present in the outer regions of M31 in any significant numbers. Thus, any spectroscopic study of the outer regions of the M31 halo will necessarily concentrate on the older, evolved, RGB population. For this reason, we consider separately surveys of the outer halo (characterized by a low surface density of evolved, giant star candidates) and the inner galaxy (with a high surface density of targets from a mixture of stellar populations).

At present, the best instrument with which to study M31 and M33 spectroscopically is Keck/DEIMOS. This multi-object spectrograph has a $5.00 \times 16.07 \approx 80$ arcmin$^2$ field of view, and can observe $\approx 200$ targets simultaneously in dense fields. At its highest resolution ($R = 6000$), it is capable of obtaining spectra at the Ca II triplet (850 nm) with $S/N = 10$ for stars within the brightest 1 mag of TRGB in a 1-hour exposure. Spectra of this quality are sufficient to measure accurate kinematics (i.e., better than $5\ km\ s^{-1}$) and also provide a rough estimate of the metallicity from the Ca II equivalent widths. The wide wavelength coverage of ngCFHT at a similar resolution will allow derivation of addition stellar parameters, as discussed earlier. Table 9 summarises the overall parameters of a survey of this subgroup, which we now discuss in more detail.

A. An Outer Halo Survey of M31/M33

Principal science aim: To obtain a complete, magnitude-limited, spectroscopic census of every star in the outer regions of an $L^?$ galaxy halo, to provide complete kinematics and metallicities for every star, and, ultimately, to deconstruct a nearby galactic halo into its accreted “building blocks”.

Area and number density: Figure 26 shows the number density of all potential evolved stars in the outer reaches of M31, averaged over circular annuli. These are very broadly defined as having colour in the range $0.5 < (g-i) < 2.0$, and magnitudes within the quoted limits. Within $\approx 0.5$ mag of the TRGB, there are typically $< 2000$ stars deg$^{-2}$ for $58$.
A complete survey of M31's surroundings?

Projected density of RGB candidates around M31 [ 0.5<(g−i)<2.0 ]

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What could ngCFHT do in 1h?

- DEIMOS
- Medium resolution
- 1h exposure
- Calcium triplet velocities
  - 8400–8700 Å
“Interesting” targets

- Dwarf galaxies
  - 1s–100s of stars
  - $\sigma_{vr} \approx 3–10$ km/s

$\rightarrow$ Metallicities
$\rightarrow$ Stacked $[\alpha/\text{Fe}]$
In what follows, it is convenient to separate the inner regions of M31 and M33 offer a high surface density of stellar targets for ngCFHT. Unlike their outer regions, there is a broad variety of stellar populations that span all ages. The first aim of this survey is to map velocity structures in the halo. These will generally arise from dwarf galaxies in various stages of disruption. Typical velocity dispersions of dwarf galaxies (and, hence, lower limits on the velocity dispersions of the streams) are \( \sigma \sim 200 \) km s\(^{-1}\). Thus, typical velocity accuracies should be \( \sigma_v \approx \frac{30}{R} \) km s\(^{-1}\), or better, in order to resolve low-mass structures kinematically.  

### Medium resolution imperative

The second aim of this survey is to obtain spectroscopic metallicities for a large fraction (and possibly all) of RGB targets. This is most easily done at intermediate resolution using the CaT feature at 850 nm. For these reasons, higher resolution is generally favorable at S/N \( S/N \gg 10 \) is required for \([Fe/H]\) estimates with accuracies of \( \sim 0.1 \) dex. At current specifications, exposures of 1 hour at \( R = 3,500 \) implies a survey area of \( 300 \) deg\(^2\) out to the limits of the PAndAS pointing per position (and would correspond to observations of more than a million stars). It is worth emphasizing the extreme multiplexing in order to identify the few genuine RGB stars over the strong foreground contamination. Even within 2 mag of the TRGB, the number density of target stars is \( \sim 0.3 \) per square degree. Thus, a complete survey of these regions necessitates \( N \gg 10^7 \) observations or typical velocity accuracies of \( \sigma_v \approx 0.2 \) km s\(^{-1}\), or possibly \( \sigma_v \sim 0.1 \) km s\(^{-1}\), at S/N \( S/N \gg 10 \). For high-S/N spectra and good wavelength coverage, spectral synthesis techniques should also be explored to extract maximal stellar parameter information.

#### Table 10: Signal-to-Noise Ratios and Velocity Accuracies for M31/M33 Surveys†

<table>
<thead>
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<th>( g )</th>
<th>( R = 1,500 )</th>
<th>( R = 3,500 )</th>
<th>( R = 5,000 )</th>
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<td></td>
<td>( (S/N, \sigma_v) )</td>
<td>( (S/N, \sigma_v) )</td>
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<td>22.5</td>
<td>(19, 10)</td>
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<td>(8, 11)</td>
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<td>(5, 8)</td>
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<td>(5, 17)</td>
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<td>24.0</td>
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<td>(1.8, 33)</td>
<td>(1.3, 31)</td>
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Needs

- Medium resolution imperative
- Large field of view (>deg$^2$)

Chapman et al. (2007)
Needs

- Medium resolution imperative
- Large field of view (>deg$^2$)
- Heavy multiplexing

Martin et al. (2013)
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