A Keck/Deimos Survey of Red Giant Branch Stars in the Outskirts of M31

Annette M. N. Ferguson\textsuperscript{1}, Scott Chapman\textsuperscript{2}, Rodrigo Ibata\textsuperscript{3}, Mike Irwin\textsuperscript{4}, Geraint Lewis\textsuperscript{5}, and Alan McConnachie\textsuperscript{4}

\textsuperscript{1} Max-Planck-Institut für Astrophysik, Postfach 1317, 87541 Garching, Germany
\textsuperscript{2} California Institute of Technology, Pasadena, CA 91125, USA
\textsuperscript{3} Observatoire de Strasbourg, 11, rue de l’Université, Strasbourg F-67000, France
\textsuperscript{4} Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
\textsuperscript{5} School of Physics, University of Sydney, NSW 2006, Australia

Abstract. We are using the DEIMOS multi-object spectrograph on the Keck II 10 m telescope to conduct a spectroscopic survey of red giant branch stars in the outskirts of M31. To date, velocities have been obtained for most of the major substructures in the halo as well as at several positions in the far outer disk and inner halo. First results concerning the giant stellar stream and major axis substructures are presented here.

1 Introduction

Within the popular $\Lambda$CDM model for structure formation, massive galaxies are built up through the merger and accretion of smaller subsystems and through the smooth accretion of gas. Under the assumption that at least some of the accreted satellites contain significant stellar components, one expects observable signatures of this process in the form of tidal streams and other stellar inhomogeneities. While such features have been previously found in our Milky Way, little has been known, until recently, about their frequency in other galaxies. One of the main goals of the Isaac Newton Telescope Wide-Field Camera (INT WFC) survey of M31\cite{8,4,10} has been to search for signatures of satellite disruption in the outer halo of our nearest giant neighbour.

During the past four years, we have used the INT WFC to map \approx 40 sq. deg. (163 contiguous pointings) around M31 with 800–1200 sec exposures in the $V$ and $i$ passbands\cite{8,4,10}. This depth is sufficient to reach $V \sim 24.5$, $i \sim 23.5$, and hence probe the top three magnitudes of the red giant branch (RGB). Our current coverage extends to 4 degrees ($\approx 55$ kpc) and 2.5 degrees ($\approx 30$ kpc) along the major and minor axes respectively. Figure 1 shows the distribution of “blue” RGB stars across our survey area. As already apparent from our interim results\cite{8,4}, the distribution of giant branch stars at large radius is very far from uniform. Many of the clumpy features visible in the stellar distribution have effective surface brightnesses $\Sigma_V \gtrsim 28$ mag sq. arcsec – a value typically unobservable by traditional techniques but possible here due to the fact we are resolving individual stars at the bright end of the luminosity function.

The mere existence of stellar overdensities in the outskirts of M31 indicates an active accretion history, however many important questions remain. Are the
overdensities the result of many small accretions, or one large one? How much of the structure is simply the result of a warped/perturbed outer disk? What is the relationship between various stellar overdensities, such as a the giant tidal stream, and M31’s innermost satellites? To address these issues, we are pursuing a comprehensive follow-up program consisting of a large radial velocity survey with Keck II/DEIMOS and a detailed stellar populations study with HST/ACS.

2 Surveying the M31 Outer Halo with Keck/DEIMOS

Stellar kinematics at the distance of M31 can be probed directly through radial velocities of individual giant stars, or indirectly through tracer populations, such as planetary nebulae (PNe). While PNe have been used successfully to study the kinematics of the disk and inner halo (e.g. [13]), the efficiency of this technique declines rapidly in the low surface brightness outer regions. If one assumes the canonical $\alpha_{2.5} \sim 50 \times 10^{-9}$ PNe per unit V-band luminosity [3] then $\approx 50$ PNe would be expected per square degree at $\Sigma_V \sim 24$ mag sq. arcsec but only $\approx 1$ would be expected within the same area at $\Sigma_V \sim 28$ mag sq. arcsec.

We have been conducting our radial velocity survey using the DEIMOS multi-object spectrograph on the KeckII 10m telescope (see Figure 1 for the pointings observed to date). Our strategy involves both standard multi-slit masks, resulting in $\approx 100$ targets per $16.9^\prime \times 5.0^\prime$ DEIMOS pointing, as well as the use of a custom-built narrow-band filter to limit wavelength coverage and increase multiplexing in high density regions, typically allowing $\sim 400$ targets per mask. We exploit the near-IR Calcium II triplet lines ($\sim 8500A$) to provide information about both radial velocities (typical uncertainty here 5–10 km/s) and metallicities. Full details of our survey strategy and results so far are given in [9,12,2].

3 Results To Date

3.1 The Giant Stellar Stream

Radial velocities for stars lying at four locations along the giant stellar stream were presented by [9] and used in combination with distance data [11] to place constraints on the orbit of the stream progenitor and on the total mass of M31. Figure 2 shows velocity histograms at these locations for stars with good S/N and good quality cross-correlation measurements. Gaussians distributions have been used to describe the components attributed to the stream (the dominant component in all fields significantly displaced from the inner halo (i.e. S01, S02, S06)) and the centroids and widths are indicated. Note that considerably more stars are now present in S08 than in [9] due to a reanalysis of the original data. A smooth gradient in both radial (heliocentric) velocity and line-of-sight velocity dispersion (uncorrected for the instrumental error) is apparent along the stream. The measurements of [7] for fields lying between S02 and S06 are fully consistent with these trends. The southern extent of the stream is essentially at rest with respect to M31 ($\Delta V_{M31} \sim -25$ km/s) and has the largest observed velocity
Fig. 1. The distribution of “blue” red giant branch stars in a ≈ 40 square degree (125 x 95 kpc) area centred on M31, as mapped with the INT WFC. Overlaid are the 30 Keck/DEIMOS pointings observed as of September 2003; these mainly target major regions of stellar substructure and a few locations in the far outer disk/inner halo. The three DEIMOS fields of Guhathakurta et al [7] are shown as dashed rectangles.

dispersion ($\sigma_v \sim 30$ km/s) – these observations suggest this location is close to apocentre [9,6].

The best-fitting progenitor orbit (in the best-fitting potential, see [9]) is highly radial and viewed close to edge-on. It passes near the centre of M31 before looping around to a position north-east of the galaxy centre (also supported by detailed studies of the stellar populations in these parts [4,5]). Before velocity data were available, a prime candidate for the progenitor was the compact dE, M32, which projects directly onto the stream, has a comparable line-of-sight distance and shares a similarly high metallicity. This association no longer appears likely however, since the radial velocity of M32 ($\Delta V_{M31} = +100$ km/s) is inconsistent with the expected velocity of the stream at this position in the current orbital phase ($\Delta V_{M31} \sim -280$ km/s). Similar arguments make an association with NGC 205, M31’s second closest luminous satellite, equally unlikely.
Fig. 2. Stellar radial (heliocentric) velocity distributions at four locations lying along the giant stellar stream (see [9]). The dashed-dotted lines represent gaussian fits to the components attributed to the stream stars. The measured velocity dispersion of the stream declines with distance to M31. The systemic velocity of M31 is $-300$ km/s.

3.2 Substructures Along the Major Axis

Significant substructure has been identified along both the north-eastern and south-western major axes (Figure 1), termed the “northern spur” and the “G1 clump” respectively. These stellar overdensities are unlikely to be related to each other – for e.g. representing debris from a satellite orbiting within the disk plane – given the different colours exhibited by their constituent stellar populations [4,5]. Figure 3 presents radial velocity histograms for these regions constructed from stars with good S/N measurements. The G1 clump, located at a radius of $\sim 35$ kpc, exhibits a clear velocity peak at $-455$ km/s (see also [14]). On the other hand, the G1 globular cluster, which is projected near the edge of the overdensity, has a sufficiently different radial velocity ($-331$ km/s), making it unlikely that the two are related. The northern spur region, located at a radius of $\sim 25$ kpc, exhibits a clear velocity peak at $-150$ km/s. While it is tempting to associate the major axis substructures with the outer disk, we note that simple expectations for the disk velocity (assuming $V_{\text{rot}} = 250$ km/s, based on HI observations [1]) are $-550$ km/s and $-50$ km/s respectively for the clump and the spur – velocities which differ from those observed by $\sim 100$ km/s (Figure 3).
Fig. 3. Radial velocity distributions for regions lying close to the north-eastern and south-western major axes. The dashed-dotted lines represent gaussian fits to the dominant component in these fields, while the vertical dashed lines indicate simple expectations for the disk rotation velocity at these locations along the major axis.

4 Summary

Our spectroscopic survey of RGB stars in the outskirts of M31 aims to constrain the nature and origin of the stellar substructure observed in these parts, and to quantify the kinematic and metallicity structure of the far outer disk and inner halo. Our results so far have enabled M32 and NGC 205 to be ruled out as the progenitors of the giant stellar stream; instead, they suggest an orbit which connects the stream to the diffuse overdensity located north-east of the galaxy centre. The kinematics of the substructure observed along the major axes defy easy interpretation at present. Future observations of radial velocities in unperturbed regions of the M31 outer disk will be crucial.

References

1. R. Braun: ApJ 372, 54 (1991)
2. S. C. Chapman et al.: in preparation (2004)
3. R. Ciardullo, G. H. Jacoby, H. C. Ford & J. D. Neill: ApJ 339 53 (1989)
4. A. M. N. Ferguson et al.: Astron. Journal 124, 1452 (2002)
5. A. M. N. Ferguson et al.: in preparation (2004)
6. A. Font et al.: ArXiv Astrophysics e-prints, astro-ph/0406146
7. P. Guhathakurta et al.: ArXiv Astrophysics e-prints, astro-ph/0406145
8. R. Ibata et al.: Nature 412, 49 (2001)
9. R. Ibata et al.: MNRAS 351, 117 (2004)
10. M. J. Irwin et al.: in preparation (2004)
11. A. W. McConnachie et al.: MNRAS 343, 1335 (2003)
12. A. W. McConnachie et al.: MNRAS 351, L94 (2004)
13. H. R. Merrett et al.: MNRAS 346, L62 (2003)
14. D. B. Reitzel, P. Guhathakurta, & R. M. Rich: Astron. Journal 127, 2133 (2004)