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Exploring Andromeda's Halo with the INT

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The structure of the outer regions of galaxies is a key area in which to look for fossil remnants of the accreted masses from which the galaxies that we see today are thought to be built (Searle, 1978, White, 1978). The importance of these regions has increased in recent years as cosmological theories of structure formation become more exact in their predictions, and the observational instrumentation required to conduct these detailed analyses becomes more sophisticated. Currently composed of 165 individual pointings of the Isaac Newton Telescope Wide Field Camera (INT WFC), the M31 halo survey consists of photometry for over 7 million sources, on a photometric system accurate to 2% over ~40 square degrees on the sky, in some places probing the halo of Andromeda out to 6° (~80 kpc). Observations of 800–1000 seconds in the Johnson V (V′) and Gunn i (i′) passbands are deep enough to detect individual RGB stars down to V′= 0 and Main Sequence stars down to V′=−1. This unique dataset has provided, for the first time, a panoramic deep view of the stellar halo of a giant galaxy *thought* to be similar to our own Milky Way (Irwin, 2004).

The initial results of this survey could not have been more surprising: despite exhibiting a near pristene disk, M31's halo is full of substructure and points to a history of accretion and disruption (Ferguson, 2002). Figure 1 shows an image of M31, constructed from the WFC photometry, which shows the inhomogeneity of this system. Metal-poor/young stars are coded blue whilst metal rich/older stars are coded red. This spectacular image shows in amazing detail the wealth of information that the INT is helping to reveal about the structure of this previously invisible region of galaxies. The most obvious piece of substructure visible in Figure 1 is the giant stellar stream (visible in the south-east). This extends to near the edge of our survey — a projected distance of some 60 kpc (Ibata, 2001). In fact, by examining the systematic shift in the luminosity function of the stream as a function of galactocentric radius, we find its actual length is much greater than 100 kpc (McConnachie, 2003). The similarity of the colour of this feature with the loop of material at the north of the survey suggests a connection: deep follow-up imaging using HST/ACS confirms that they possess the same stellar population (Ferguson, 2004a). It seems likely that the northern feature is an extension of the stream, after it has passed very close to the centre of the potential of M31 (Font, 2004; Ibata, 2001).

A second large stellar stream candidate has also been identified with the INT WFC photometry (McConnachie, 2004c). The visible part of this feature

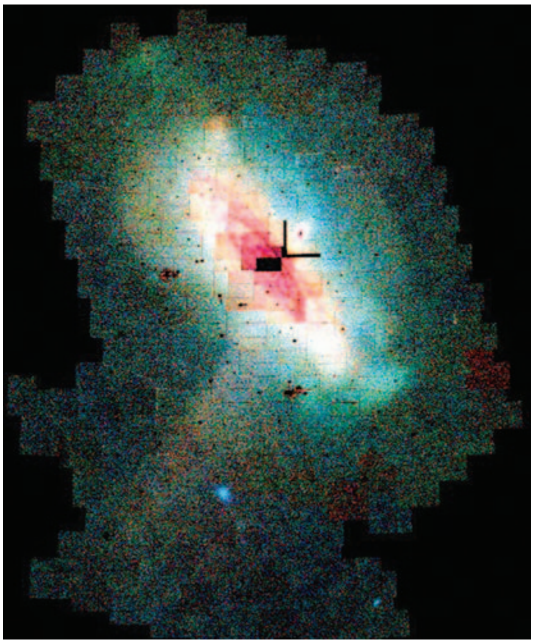

Figure 1. A multi-colour mosaic of the INT WFC survey of M31, involving 165 individual pointings over 40 square degrees of the sky. North is at the top, and East is to the left of this image. Metal poor/young stars are coloured blue, while metal rich/old stars are coloured red. The (colour-dependant) substructure is obvious, and surprising given the pristene nature of the Galactic disk. The dwarf galaxies Andromeda I & III are visible at the bottom left of this figure; the newly discovered dwarf spheroidal, Andromeda IX, is just visible at the top left as a small blue dot. NGC 205 is also visible in this figure, at the right-hand side of the disk.

is some 15 kpc long and Figure 2 shows a cartoon of its location. The progenitor of this feature appears to be the satellite galaxy NGC 205, although this awaits spectroscopic confirmation. This object has long been known to be tidally perturbed (Choi, 2002; Hodge, 1973) but it is only now that the full extent of its disruption is becoming clear. Considerable amounts of other substructure exists in addition to these streams. For example, near the position of the famous M31 globular cluster, G1, lies a large blue clump of stars (bottom right of Figure 1) and opposite this across the minor axis, near the position of the famous HI warp, lies a redder one. The origin of both these features is currently undecided, as is the origin of the curiously sparse cloud of stars at the far north of our survey region.

As well as these and many other obvious substructures, the INT WFC is allowing the identification of previously unknown globular clusters in the halo of M31 (Huxor, 2004). These include some of the most distant so far discovered, at projected radii of

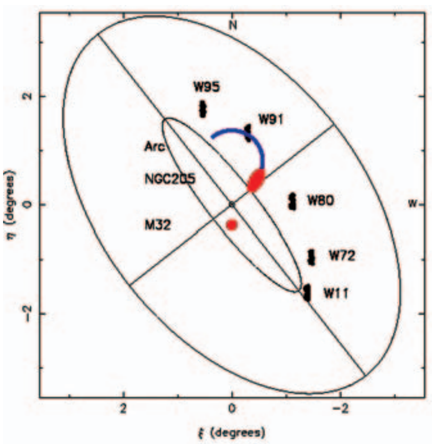

Figure 2. Cartoon showing the path of the new stellar steam candidate, the progenitor of which is thought to be NGC 205 (large red ellipse). Also highlighted are the location of several fields being used to probe the kinematics of the halo, as well as the dwarf elliptical galaxy M32. The stellar arc is some 15 kpc in length and may be able to shed light on the dynamical evolution of NGC 205, and provide a useful probe of the potential of M31. Although previously known to have been tidally perturbed, this is the first detection of a probable significant extra-tidal component of NGC 205.

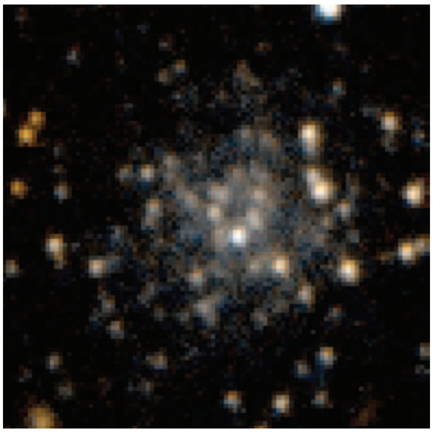

Figure 3. An example of a new class of globular cluster around M31, much sparser than typical globular clusters, being discovered by the INT WFC survey. Fourteen new globular clusters have so far been discovered, many at large projected radii. Three of these objects have morphologies similar to the above. The half- light radii of these clusters are significantly larger than normal. Follow-up spectroscopic observations should yield important information as to their true nature.

~80 kpc. So far 14 have been found, including a whole new class of cluster, much sparser than typical globulars. These objects, of which three candidates have currently been identified, are far less concentrated and have larger half-light radii than normal, making their appearance fuzzy and diffuse. A colour image of one of these objects, created from our photometry, is shown in Figure 3. The identification and quantification of the globular cluster system provides yet another valuable handle on the accretion history of this giant galaxy.

The other spiral in the Local Group, the Triangulum Galaxy (M33), has also been surveyed with the INT WFC (Ferguson, 2004b). The structure of this galaxy is striking in comparison to M31. Figure 4 shows the distribution of stars in this object and the *lack* of substructure is immediately obvious. It appears that not all spiral galaxy haloes need look like M31, and it raises the question: is there such a thing as a 'typical' stellar halo?

There is then the question of the M31 dwarf satellite galaxies, several of which are visible in Figure 1. In total, we now have INT WFC photometry for all of M31's satellites visible from La Palma. A three dimensional map of the Andromeda subgroup, created from our measurements, is shown in Figure 5. The homogeneous nature of our data has allowed accurate and internally self-consistent distances and metallicities to be measured for each of these galaxies(McConnachie, 2004a, 2004b). This allows us for the first time to reliably probe the three dimensional spatial distribution of these objects, revealing that far from being isotropically distributed and unbiased indicators of the potential of Andromeda, there are strong indications that these objects are preferentially located on the near side of Andromeda, towards the Galaxy. This result is unexpected, and intriguing.

The INT WFC survey of M31 and its environs has revealed, and continues to reveal, startling surprises about the faint surroundings of otherwise normal galaxies. Its tendency to raise more questions than answers seems to be continuing, and it offers a warning to studies of our own Galactic halo: given our position *inside* the Galaxy, how would we interpret our stellar halo if it looks in the least bit like M31? ¤

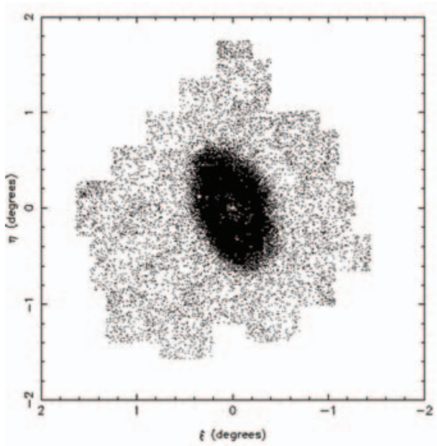

Figure 4. The spatial distribution of stellar sources in the INT WFC survey of M33, the Triangulum Galaxy. This is a small spiral, approximately one-tenth the size of Andromeda. The lack of substructure in this galaxy is in startling contrast to M31 —virtually no spatial inhomogeneities are present in this galaxy's outer regions.

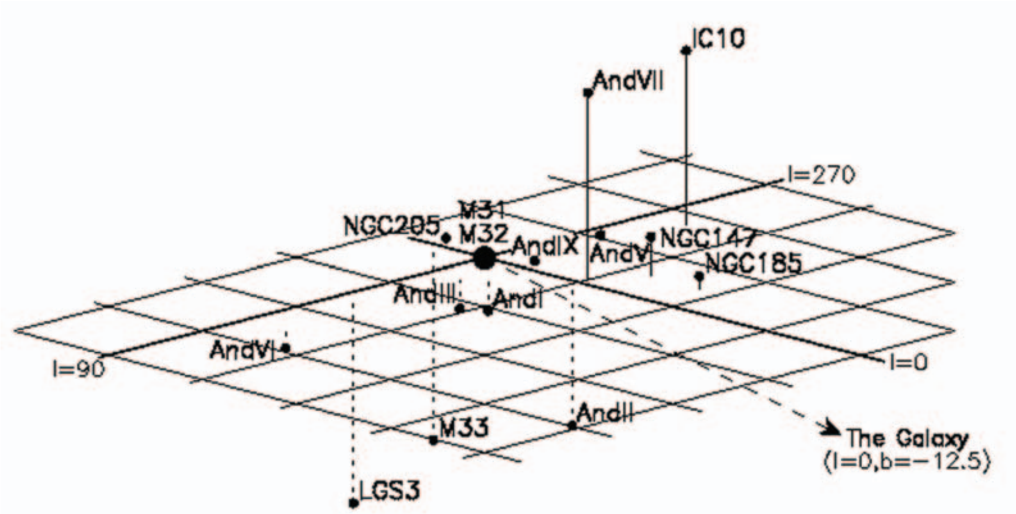

Figure 5. The distribution of the satellite galaxies of M31, as derived from our INT WFC photometry of these objects. The coordinate system is an M31–centric system. The plane is the plane of the disk of M31, and each cell corresponds to 100 kpc×100 kpc. l is a longitude measured around the disk of M31, such that l =0 is the longitude of the Galaxy. b is a latitude, measured from the disk of M31. Solid lines indicate objects located above the plane of the disk, while dashed lines indicate objects below the plane of the disk. A clear tendency for the satellites to lie on the near side of M31 can be observed, and suggests an intriguing correlation between the M31 satellites and our own Galaxy.

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The Bull's Eye Pattern in the Cat's Eye and Other Planetary Nebulae

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The end-point of the evolution of solar-type stars is essentially determined by the onset of a strong stellar wind, which, in a few hundred thousand years completely removes the star's gaseous envelope, thereby removing the fuel that has previously maintained the thermonuclear energy source in its interior. This phenomenon occur during a (second) phase in which the star becomes a red giant, the so-called the Asymptotic Giant Branch (AGB) stage. In the last million years of the AGB, the red giant is dynamically unstable and pulsates with typical periods of few hundred days: a prototypical star in this phase is Mira in Cetus. The mechanical energy of the pulsations pushes large amounts of material far away enough from the core of the star for it to cool down and condense into dust. This newly formed dust is further accelerated out of the gravitational bounds of the star by the pressure of the radiation coming from the hot stellar remnant. Gas, which is coupled to dust by collisions, also leaves the star in this process.

In the last hundred thousand years of the AGB, this mass loss process is so strong that the star is completely surrounded by a thick, expanding