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# One ring to encompass them all: a giant stellar structure that surrounds the Galaxy

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## ABSTRACT

We present evidence that the curious stellar population found by the Sloan Digital Sky Survey in the Galactic anticentre direction extends to other distant fields that skirt the plane of the Milky Way. New data, taken with the Isaac Newton Telescope Wide Field Camera, show a similar population, narrowly aligned along the line of sight, but with a galactocentric distance that changes from ∼15 to ∼20 kpc (over ∼100° on the sky). Despite being narrowly concentrated along the line of sight, the structure is fairly extended vertically out of the plane of the disc, with a vertical scaleheight of 0.75 ± 0.04 kpc. This finding suggests that the outer rim of the Galaxy ends in a low surface brightness stellar ring. Presently available data do not allow us to ascertain the origin of the structure. One possibility is that it is the wraith of a satellite galaxy devoured long ago by the Milky Way, although our favoured interpretation is that it is a perturbation of the disc, possibly the result of ancient warps. Assuming that the ring is smooth and axisymmetric, the total stellar mass in the structure may amount to $\sim 2 \times 10^8\,\mathrm{M}_\odot$ up to $\sim 10^9\,\mathrm{M}_\odot$.

**Key words:** Galaxy: disc – Galaxy: structure – galaxies: interactions.

## 1 INTRODUCTION

Owing to our location within the disc of the Milky Way, studies of the global structure of this Galactic component are hampered by projection problems, crowding, dust, and the presence of intervening populations (such as the bulge). Nowhere is this so problematic as in the study of the very outer edge of the disc. The advent of the recent wide-area infrared surveys (e.g. 2MASS and DENIS) have alleviated the extinction problem, but the other problems remain, with the distance ambiguity being particularly limiting. Even the future astrometric mission *GAIA* (Perryman et al. 2001) is unlikely to give us a full picture of the Galactic disc, owing to telemetry limits in regions of high stellar density.

Yet the outer regions of galactic discs are important regions to study, as they provide important clues to our understanding of the global structure and formation of galaxies (see e.g. van der Kruit 2001). These are the least self-gravitating regions of galactic discs, and the presence of the dark matter halo can begin to be felt at these radii. The flaring of the outer disc constrains the dark matter fraction in these regions (Olling & Merrifield 2000, and references therein). Perhaps the most interesting aspect of the very outermost edge of the disc is that it is expected to be young. In galaxy formation simulations that contain a gas component as well as cold dark matter, galaxy discs tend to grow from the inside out, with the most recently accreted gas settling down on to the end of the disc (Navarro & Steinmetz 1997). Ensuing star formation in regions of sufficient density produces young stars, leading to a primarily young, metal-poor stellar population in these galactic extremities, although radial mixing in the disc may smear this information out (Sellwood & Binney 2002). However, recent simulations (Sommer-Larsen, Gotz & Portinari 2002) show that some discs form outside-in as well as inside-out, in agreement with tantalizing new evidence which indicates that the outer disc of the Andromeda galaxy may well be old (Ferguson & Johnson 2001). Determining the age of disc populations at large radius will provide a good test of current disc formation models.

An interesting recent development in the study of the stellar populations of the outer disc has been presented by Newberg et al. (2002), based on Sloan Digital Sky Survey (SDSS) photometry of fields towards the Galactic anticentre direction. Newberg et al. (2002) find an overdensity of F-coloured stars close to the Galactic plane in the constellation Monoceros, with a narrow colour–magnitude sequence that belies a stellar population ∼11 kpc from the Sun and ∼18 kpc from the Galactic Centre. The narrow magnitude spread

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implies a distance spread of about ∼2 kpc, despite the fact that the structure is seen over a wide range above and below the Galactic plane stretching from $b \sim -25°$ to ∼20° (i.e. $-5.5 < z < 4.5$ kpc).

The analysis of Newberg et al. (2002) suggested that this stellar population was a very nearby orbiting Galactic satellite. Here we present evidence of similar colour–magnitude features in fields taken as part of a survey of the Andromeda galaxy with the Isaac Newton Telescope (INT), and as part of a public survey observed with the same telescope entitled the INT Wide Field Survey (WFS).

## 2 THE ISAAC NEWTON TELESCOPE WIDE FIELD CAMERA SURVEYS

The INT WFS is an initiative by the UK and Dutch communities to devote a large fraction of the INT to deep and wide-field surveys. Many fields have now been observed since 1998. However, the resulting coverage at the present time is patchy, with most time having been spent in large extragalactic surveys towards the Galactic polar caps. Table 1 is a listing of suitable WFS or Wide Field Camera (WFC) observations below $|b| \lesssim 50°$. In Fig. 1 we display an example of one of these fields, the Elais field N1, located at $\ell = 85°$, $b = +44°$, which shows the normal Galactic stellar population sequences. In contrast, Newberg et al. (2002) have shown that the anticentre (Monoceros) region shows an additional feature in colour–magnitude space (their fig. 12), with shape similar to a main sequence that has a turn-off at $g' - r' = 0.25$, $g' \sim 19.5$ (in the AB system).

In examining INT WFC survey fields, we have detected the presence of this unexpected feature in other distant fields. Fig. 2 displays the colour–magnitude diagram of the INT WFC field Mono-N (located at $\ell = 150°$, $b = +20°$); a population that follows a track similar to a narrow main sequence is seen in addition to the usual Galactic components. This sequence is shown more clearly in the right-hand panel of Fig. 3, in which we have used the Elais-N1 field as a 'background' to subtract the normal Galactic components.

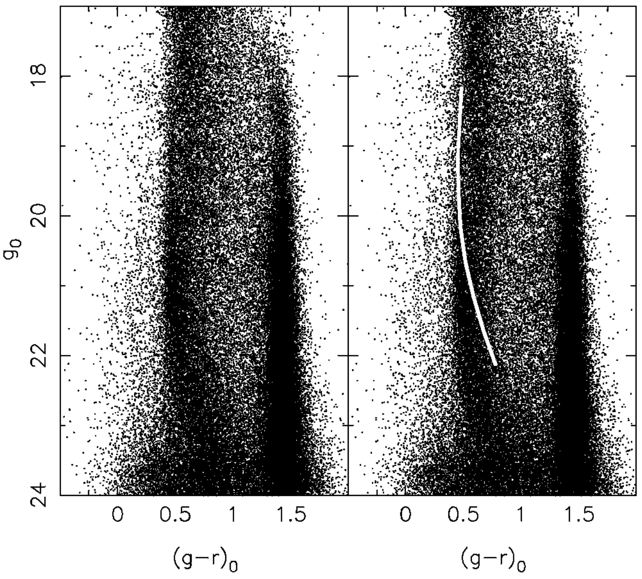

**Figure 1.** The colour–magnitude diagram of the Elais field N1 ($\ell = 85°$, $b = +44°$), which we will use as a control field. This comparison region shows the usual Galactic components. The Galactic disc dwarfs contribute to the well-populated red vertical structure at $(g - r)_0 \sim 1.4$, whereas the progressive main-sequence turn-offs of the thick disc and halo give rise to the blue vertical structure at $(g - r)_0 \sim 0.5$. Eventually, at magnitudes fainter than $g_0 \sim 22$, the halo sequence curves round to the red because of the rapidly falling density at large Galactocentric distance. [The photometry has been corrected for extinction using the maps of Schlegel, Finkbeiner & Davis (1998).] The right-hand panel shows the same data as the left-hand panel, but we have superposed the ridge-line of the structure of interest in Figs 2–5 to serve as a visual aid in the interpretation of those figures. Note that the narrow stellar sequence detected in fields Mono-N (Figs 2 and 3) and WFS-0801 (Figs 4 and 5), which lies close to the ridge-line, is not present in this comparison field. This figure is available in colour in the online version of the journal on *Synergy*.

**Table 1.** Summary of appropriate WFC observations, ordered in descending $|b|$. The final column lists whether the excess 'Monoceros' population is detected in the field. The significance of the detection is listed for those fields where it has been possible to calculate this parameter. (The significance cannot be calculated for all of the INT fields owing to a lack of suitable background fields, or of a sufficiently accurate Galaxy model.) We refrain from listing the stellar density in these fields, as the values cannot be compared in a simple manner, because of the different photometric systems used in the various surveys (Fig. 10 provides our current best estimate of the vertical structure of the population).

| Field | RA (J2000) | Dec. (J2000) | $\ell$ | $b$ | Area (sq. deg.) | Bands | Detection? |
|---|---|---|---|---|---|---|---|
| Equatorial survey | 22 to 3 | 0:00 | 60 to 180 | −40 to −60 | ∼20 | $g, r$ | No |
| WFS-2240 | 22:40 | +0:00 | 69 | −48 | 9.0 | $g, r$ | No |
| Elais-N1 | 16:13 | +55:16 | 85 | +44 | 9.0 | $g, r$ | No |
| Elais-N2 | 16:36 | +41:01 | 64 | +41 | 9.0 | $g, r$ | No |
| M33 | 1:34 | +30:40 | 134 | −31 | 4.8 | $V, i$ | No |
| WFS-0801 | 08:02 | +40:19 | 180 | +30 | 7.0 | $g, r$ | S/N >30 |
| M31 comparison 2 | 23:50 | +35 | 109 | −26 | 1.2 | $V, i$ | No |
| S200 − 24[a] | 5:00 | +0:00 | 199 | −25 | ∼5 | $g', r'$ | Yes |
| M31-S | 0:43 | +38:45 | 122 | −24 | 8.25 | $V, i$ | Yes |
| S183 + 22[a] | 7:22 | +35 | 183 | +22 | ∼5 | $g', r'$ | Yes |
| S218 + 22[a] | 8:16 | +6 | 218 | +22 | ∼5 | $g', r'$ | Yes |
| M31 comparison 1 | 22:27 | +31 | 90 | −21 | 1.2 | $V, i$ | Perhaps |
| M31-N | 0:47 | +43:22 | 123 | −19 | 6.5 | $V, i$ | S/N >30 |
| Mono-N | 6:03 | +64:43 | 149 | +20 | 1.2 | $g, r$ | S/N >20 |
| S223 + 20[a] | 8:00 | +0:00 | 221 | +15 | ∼10 | $g', r'$ | Yes |
| HVC[b] | 17:13 | −64:38 | 327 | −15 | 0.25 | $g, r$ | No |

[a] SDSS field (Newberg et al. 2002); [b] based on Anglo-Australian Telescope Wide Field Imager data (Lewis et al. 2002).

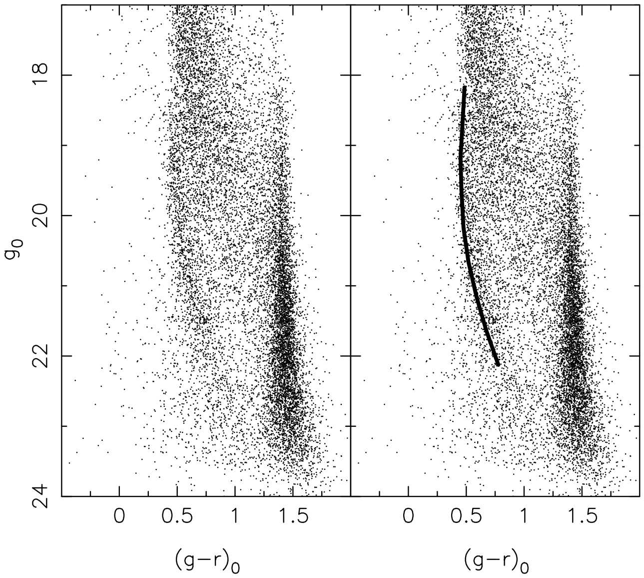

**Figure 2.** The colour–magnitude diagram of a field (Mono-N) at $\ell = 150°$, $b = +20°$. An additional colour–magnitude feature is present here over the expected disc, thick disc and halo components, and is seen as a narrow colour–magnitude diagram structure, similar to a main sequence with turn-off at $(g - r)_0 \sim 0.5$, $g_0 \sim 19.5$ (in the Vega system). Correcting for the difference between the AB and Vega photometry, we see that the peculiar main sequence detected by Newberg et al. (2002) in SDSS data towards the Galactic anticentre is also clearly present in this field. We used the colour transformations outlined in the text to convert the ridge-line of the feature in the SDSS S223 + 20 field; an offset of −0.4 mag was needed to match up the sequences, implying that the structure in the S223 + 20 field is more distant. The right-hand panel shows this ridge-line overlaid on the colour–magnitude diagram. The similarity in the turn-off colour of this feature and that of the Galactic thick disc and halo shows that its stellar population is of comparable age to those ancient Galactic components. This figure is available in colour in the online version of the journal on *Synergy*.

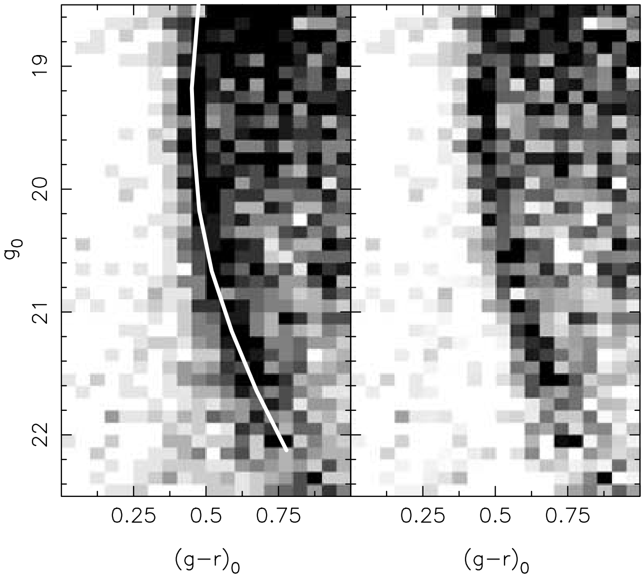

**Figure 3.** The left-hand panel shows a (zoomed-in) Hess diagram of the Mono-N field previously presented in Fig. 2 (the ridge-line of Fig. 2 has been reproduced here as well). The right-hand panel shows the result of subtracting the Hess diagram of the Elais-N1 comparison region from these data. The halo contribution, which lies primarily at fainter magnitudes than the ridge-line, is similar in the two fields, so the subtracted Hess diagram is relatively well cleaned of halo contaminants. However, the comparison field (which is located at $b = +44°$) has a substantially lower surface density of thick disc stars than the Mono-N field, so the thick disc contribution is only slightly reduced in the subtracted Hess diagram. Nevertheless, the narrow colour–magnitude sequence can be clearly perceived. The colour distribution around the sequence shows a narrow peak with signal-to-noise ratio >20 (see Fig. 9, later). This figure is available in colour in the online version of the journal on *Synergy*.

Owing to the difference in Galactic latitude between the target and control fields, the thick disc is not subtracted cleanly; this poor subtraction of the thick disc is seen as a smear to brighter magnitudes and redder colours than the narrow sequence that delineates the abrupt faint end of the right-hand panel of Fig. 3. Another INT WFS field that displays this excess population is the field named WFS-0801 ($\ell = 180°, b = +30°$), the colour–magnitude diagram of which is displayed in Fig. 4. Subtracting a background estimated from the Elias-N1 field gives the Hess diagram displayed in the right-hand panel of Fig. 5. As the 'background' field is closer in Galactic latitude to the WFS-0801 field, this statistical subtraction is much cleaner, allowing us to show the unexpected excess population relatively free of contamination from the expected Galactic components.

The other two proprietary large surveys (Ibata et al. 2001; Ferguson et al. 2002, and in preparation) were conducted by our group to reveal the structure and stellar populations in the halo of the Andromeda galaxy ($\ell = 122°$, $b = -21°$) and M33 ($\ell = 134°$, $b = -31°$). A further two fields were observed for use as comparison regions for these surveys. Table 1 also lists these fields. In Figs 6 and 7 we display the $(V - i)_0$, $V_0$ colour–magnitude diagram in our M31 survey, where we have plotted separately the northern (lower $|b|$) and southern quadrants of the survey. These colour–magnitude diagrams show that the structure seen in the SDSS Monoceros field is also present in our 30 deg$^2$ field around M31. The left-hand panel of Fig. 8 shows the Hess diagram of the northern M31 field

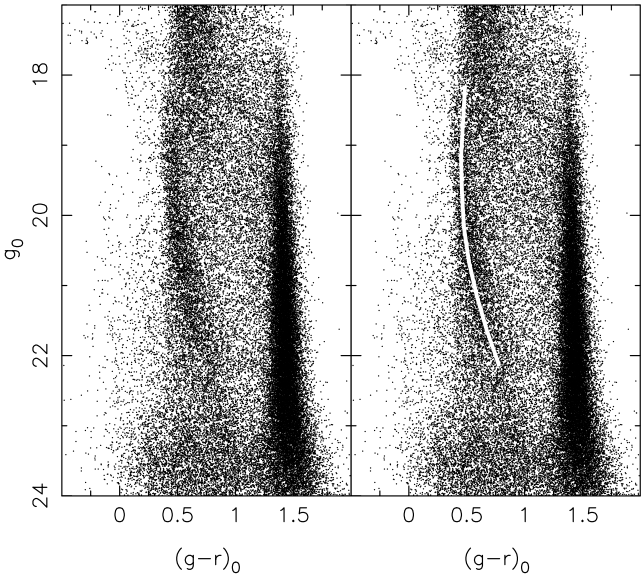

**Figure 4.** As Fig. 2, but for the INT WFS-0801 field at $\ell = 180°$, $b = +30°$. An offset of −0.4 mag is needed to match up this sequence to that of the S223 + 20 field. This figure is available in colour in the online version of the journal on *Synergy*.

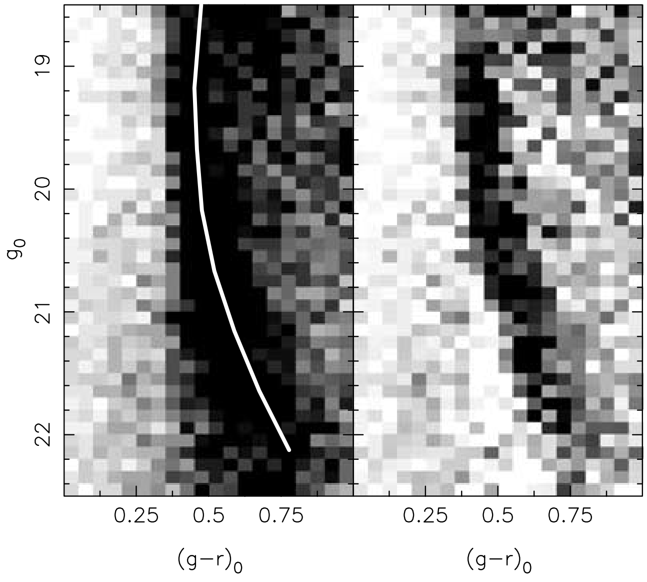

**Figure 5.** In a similar manner to Fig. 3, the right-hand panel shows the Hess diagram of the INT WFS-0801 field at $\ell = 180°$, $b = +30°$. The left-hand panel displays the result of subtracting the Elais-N1 comparison region from the data in the right-hand panel. Owing to the smaller difference in Galactic latitude between the WFS-0801 field and the Elais-N1 field, the subtraction of the thick disc component is cleaner than in Fig. 3, and the excess population stands out very clearly. Fig. 9 (later) shows that the excess is detected at signal-to-noise ratio >30. This figure is available in colour in the online version of the journal on *Synergy*.

(note that this is a zoomed-in view of Fig. 6). Lacking an appropriate background field in *V* and *i* passbands, we have been forced to use the southern M31 field as a comparison region. The result of subtracting the southern M31 field from the northern M31 field is displayed in the right-hand panel of Fig. 8; the excess population is again clearly seen as a narrow sequence.

The high statistical significance of the detection of the excess population in the different fields is demonstrated in Fig. 9, where we show the distribution of stars as a function of their displacement in colour from the ridge-lines. Owing to the lack of a suitable background field, we are unable to provide a similar estimate of the significance of the detection in the southern M31 field, although the population is clearly present in that field, as we show in Fig. 10.

## 3 RESULTS AND CONCLUSIONS

The detection of a stellar population almost identical to that seen in the SDSS Monoceros fields shows that this structure is immense. The M31 field is ~100° away in longitude from the S223 + 20 field, towards the diametrically opposite side of the Galaxy. The structure is also seen both below the Galactic plane (in the M31 field and in S200 − 24) and above it (in fields Mono-N, WFS-0801, S183 + 22, S218 + 22 and S223 + 20), covering a vertical range of more than 50°. The fields at higher Galactic latitude than $|b| \sim 30°$ did not show up a similar colour–magnitude diagram feature, and neither was the feature detected in the lower latitude ($b = -31°$) M33 field. The structure appears to be confined close to the Galactic plane.

To investigate the difference in heliocentric distance between the fields, we compared the colour–magnitude sequence detected by

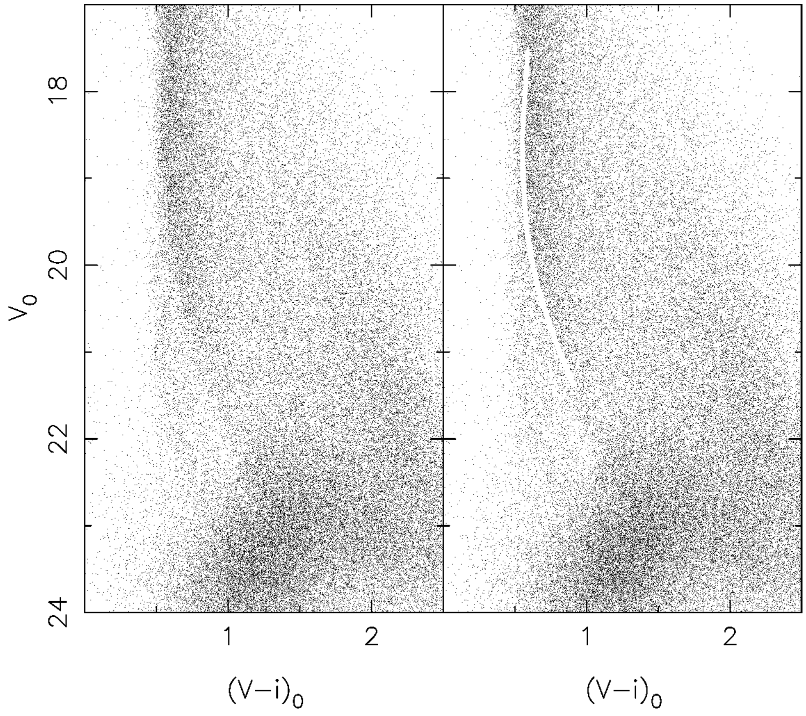

**Figure 6.** The colour–magnitude diagram of the northern M31 field ($\ell = 123°$, $b = -19°$). A well-populated main-sequence-shaped colour–magnitude structure is seen from $(V - i)_0 \sim 0.5$, $V_0 \sim 19$ curving redwards to $(V - i)_0 \sim 1.0$ at $V_0 \sim 21.5$. Although this diagram cannot be compared directly to Fig. 2 or 4, or to the SDSS colour–magnitude diagram of the Monoceros population, owing to the different photometric passbands, its behaviour is strikingly similar. The additional stars with $V_0 \gtrsim 22$ are the top two magnitudes of the red giant branch in the halo of M31. The ridge-line of the SDSS S223 + 20 feature, converted to $(V, i)$, requires a significant offset of $\sim -0.8$ mag to make the two sequences coincide. The right-hand panel shows this ridge-line. This figure is available in colour in the online version of the journal on *Synergy*.

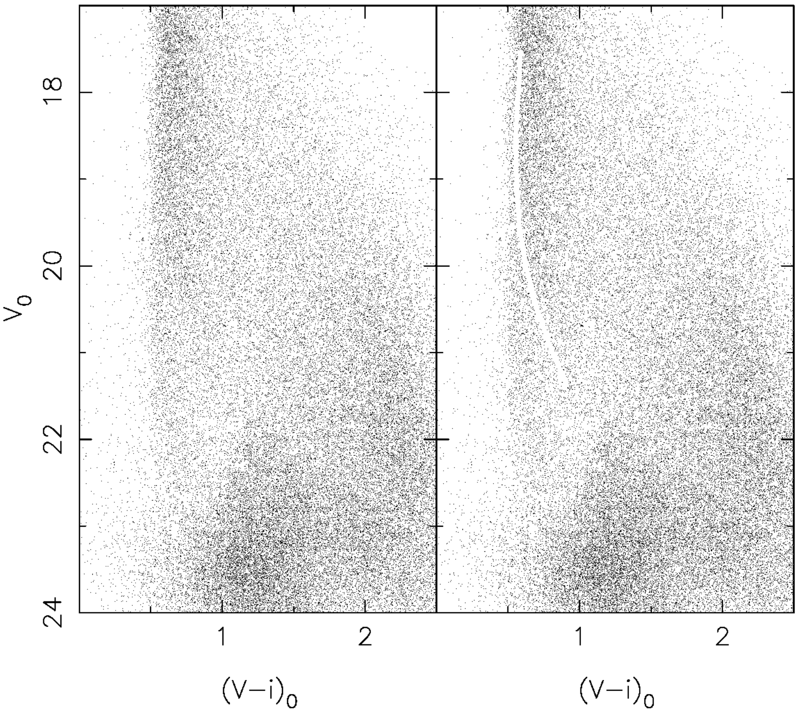

**Figure 7.** As Fig. 6, but for the southern M31 field which lies further from the Galactic plane ($\ell = 122°$, $b = -24°$). The 'Monoceros-like' population is still present, although much less numerous than in the northern field (which is displayed in Fig. 6). To guide the eye, the location of the ridge-line in Fig. 6 is shown in the right-hand panel. This figure is available in colour in the online version of the journal on *Synergy*.

Newberg et al. (2002) in the S223 + 20 field with the three INT fields Mono-N, WFS-0801 and M31. Owing to the difference in the photometric systems between the surveys, conversions need to be made to shift measurements in the SDSS ($g'$, $r'$) system to Vega-normalized ($g$, $r$) and ($V$, $i$). For the ($g$, $r$) fields we used a South Galactic Pole region where there are overlapping INT and SDSS data (the latter from the Early Data Release: Stoughton et al. 2002); we find $(g - r) = 0.21 + 0.86(g' - r')$ and $g = g' + 0.15 - 0.16(g - r)$. The resulting transformed track of the S223 + 20 field requires an offset of −0.4 mag to match the Mono-N and WFS-0801 fields (i.e. stars in the Mono-N and WFS-0801 features are brighter). To convert to ($V$, $i$) we took $V = g - 0.03 - 0.42(g - r)$ (Windhorst et al. 1991), and used the WFS photometry in the WFS-2240 field to find the following necessary transformation: $(g - i) = 0.09 + 1.51(g - r)$. The offset of the S223 + 20 ridge-line was found to be −0.8 mag for the northern M31 field (the feature in the southern M31 field has too low a signal-to-noise ratio to fit). Assuming that the S223 + 20 feature is 11 kpc distant (Newberg et al. 2002), and interpreting these magnitude offsets as being due to distance variations, puts the structure in the Mono-N, WFS-0801 and M31 fields at a distance of ∼9, ∼9 and ∼8 kpc respectively. The corresponding galactocentric distances, in order of increasing Galactic longitude,[1] are ∼14 kpc in M31 (at $\ell = 123°$), ∼16 kpc in Mono-N (at $\ell = 149°$), ∼16 kpc in WFS-0801 (at $\ell = 180°$), and 17.7 kpc in S223 + 20 (at $\ell = 221°$).

The substantial area of our M31 field allows a first estimation of the scaleheight of this unexpected population. To this end we selected stars in a banana-shaped region in the range $20.5 < V_0 < 21.5$ and $0.5 + 0.02(V_0 - 17.0)^2 < (V - i)_0 < 0.8 + 0.02(V_0 - 17.0)^2$. The density of these sources is displayed as filled circles in Fig. 10, and shows a rapid rise towards the Galactic plane. After subtracting a 'background' level measured from the same colour–magnitude region in the M33 field ($b = -31°$), we performed a straight-line fit to the logarithm (base 10) of the counts per square degree, which yields a slope of 0.081 ± 0.004 per degree of Galactic latitude. Taking the distance of 8 kpc derived above, this implies a scaleheight of 0.75 ± 0.04 kpc. The open circles in Fig. 10 show a similar selection, just slightly bluer, which picks out Galactic halo stars. In contrast, this second selection gives an almost flat distribution, consistent with our preconceptions of the halo as an almost spherically distributed component.

The nature of this structure remains a puzzle. It is clear that it cannot be related to the normal thin disc, as it lies several magnitudes below the expected thin disc sequence. The rapid decline in the density of the feature away from the Galactic plane also rules out a direct connection to the halo. This leaves the thick disc as the only normal Galactic option. We used the Galaxy star counts model of Ibata (1994) to predict the $B - V$, $V$ colour–magnitude diagram of the thick disc in all of the fields investigated ($B - V$ colours are close to $g - r$). For the thick disc, we find that the spread in $V$ magnitude at constant colour has a FWHM exceeding 3 mag in all of our fields (we chose to sample 0.05 mag about $B - V = 1.0$ which gives the minimum spread in magnitude). The detected feature therefore cannot be the standard thin disc, halo or even thick disc, in agreement with Newberg et al. (2002). Several possibilities present themselves.

(i) One option is that the various surveys probe small areas of a gigantic ring that encompasses the disc. The ring has a radius of 15–20 kpc, a radial thickness of ∼2 kpc, and a vertical scaleheight of ∼0.75 kpc. Owing to the presence of the Magellanic Clouds and

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[1] Please note that the photometric conversions, especially the extrapolation from ($g'$, $r'$) on the AB system to ($V$, $i$) on the Vega system, may have significant systematic errors. The estimated distances are therefore only indicative.

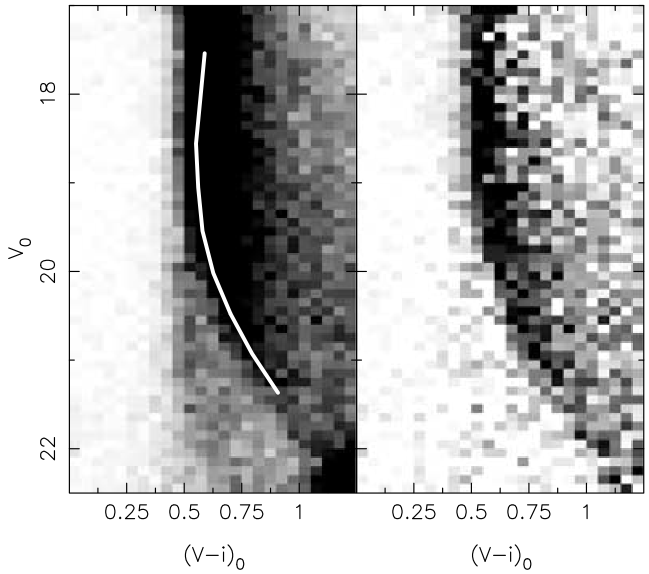

**Figure 8.** The left-hand panel shows the Hess diagram of the northern M31 field ($\ell = 123°$, $b = -19°$). This is a zoomed-in view of Fig. 6; the ridge-line of Fig. 6 is also reproduced here to guide the eye. The right-hand panel is the result of subtracting the southern M31 field ($\ell = 122°$, $b = -24°$) from these data. Given that these two fields are so close on the sky, the halo and thick disc populations are similar, so the contamination of the halo and thick disc in the Hess diagram in the right-hand panel has been substantially reduced by the subtraction. The narrow colour–magnitude sequence stands out with signal-to-noise ratio >30 (see Fig. 9, later). Note, however, that the southern M31 field is not a good 'background' region, since the excess population is also detected in that field (as seen in Figs 7 and 10, later), although in lower numbers. This means that the excess population is over-subtracted in the right-hand panel, leading to an underestimate of its significance. This figure is available in colour in the online version of the journal on *Synergy*.

the Sagittarius dwarf galaxy, the ring is warped and non-circular, explaining the variation in galactocentric radius between some of the survey fields. The stellar mass of the structure can be estimated by taking the surface density in the M31 field as representative of the whole ring, and assuming axisymmetry and some vertical profile. If the vertical profile is exponential, as is suggested by the data displayed in Fig. 10, we find that the total stellar mass of the structure is $M = 10^9\ \mathrm{M_\odot}$ , whereas if the surface density remains constant below $|b| = 18°$, the mass is $M = 2 \times 10^8\ \mathrm{M_\odot}$ [for these estimates we have taken the luminosity function of Jahreis & Wielen (1997) and the mass–luminosity relation of Henry & McCarthy (1993)]. A possible mechanism to form such a ring may be repeated warpings of the outer disc. In the Andromeda galaxy (seen almost edge-on), the outer stellar disc has a complicated non-axisymmetric shape Ferguson et al. (2002), with large vertical deviations suggestive of ancient warps which now no longer follow the warp seen in the gas. The possible ring seen in the outer disc of the Milky Way may be of similar origin. One would expect such structures eventually to mix entirely, leaving a flared outer disc, rather than a radially thin ring. Either there is another factor at play, such as, for instance, a strong interaction with the Sagittarius dwarf galaxy (Ibata & Razoumov 1998) or the Magellanic Clouds (e.g. Tsuchiya 2002), or the ring is a recent phenomenon (note, however, that the stellar constituents could be older than the structure). If the structure is a perturbation, the wave may have been amplified to the current large vertical extent (in the manner of a whip) in passing outwards through the disc to regions of progressively lower density.

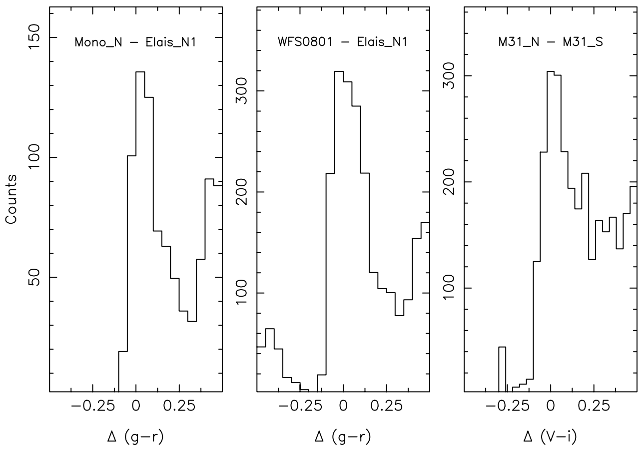

**Figure 9.** The three panels display the distribution of counts in the subtracted Hess diagrams shown in the right-hand panels of Figs 3, 5 and 8. Stars were selected in the magnitude ranges $20.5 < g_0 < 22.0$ (for the left-hand and middle panels) and $20.5 < V_0 < 22.0$ (for the right-hand panel), which are ranges in which the excess population in the subtracted Hess diagrams is relatively uncontaminated. The abscissa displays the difference between the colour of the stars and the colour of the ridge-line. These narrow peaks, centred at a colour difference close to zero, show that the excess stellar population closely follows the ridge-line. Fitting these narrow peaks with a Gaussian function (in the range $-0.25 < \Delta\mathrm{Colour} < 0.25$) gives a colour dispersion smaller than $\sigma = 0.12$ mag for all three cases. Summing under these peaks, we find that the excess population is detected with signal-to-noise ratio >20 in the Mono-N field and with signal-to-noise ratio >30 in the fields WFS-0801 and M31-N.

The low-latitude HVC field (Lewis et al. 2002), located at ($\ell = 327°$, $b = -15°$), is not in contradiction with the interpretation of the structure as a Galactic ring. Assuming that the ring has a radius of 18 kpc implies a distance of 24 kpc in this direction, more than twice the distance to the fields in which the 'Monoceros-like' colour–magnitude diagram structure has been detected. The HVC field may simply lie too far below the Galactic plane (in that direction) to detect the ring (the field also covers a relatively small solid angle of sky).

The reason why the ring may not have been discovered before is due to its low surface density. Very large areas need to be surveyed to detect it. It would also be difficult to detect with, for instance, the poorer photometry available from photographic plates.

(ii) Another possibility is that the surveys probe different regions of the disrupted tidal stream of an accreted satellite galaxy. Halo satellites are expected to have high-eccentricity orbits, with apocentre to pericentre ratio of ∼4 (van den Bosch et al. 1999). For sufficiently massive satellites ($\gtrsim 10^9\ \mathrm{M_\odot}$), the continual braking effect of dynamical friction with the Galactic halo and disc can eventually lead to the decay of the orbit. However, simulations show that satellite orbits are not readily circularized by dynamical friction (van den Bosch et al. 1999; Colpi, Mayer & Governato 1999), so it is hard to explain the near-circular orbit required by this scenario. A second problem relates to the small distance spread along the line of sight. As the orbit of the satellite decays, constituent stars will be lost by tidal disruption. Over time, the tidally removed stars become phased-mixed, spreading out over the orbit, and occupying the region between the orbit pericentre and apocentre. The fact that the 'Monoceros-like' population is seen confined in a narrow distance interval along the line of sight therefore also argues against this scenario. The problem may be alleviated if the progenitor satellite disrupted only recently. A further concern with this scenario comes

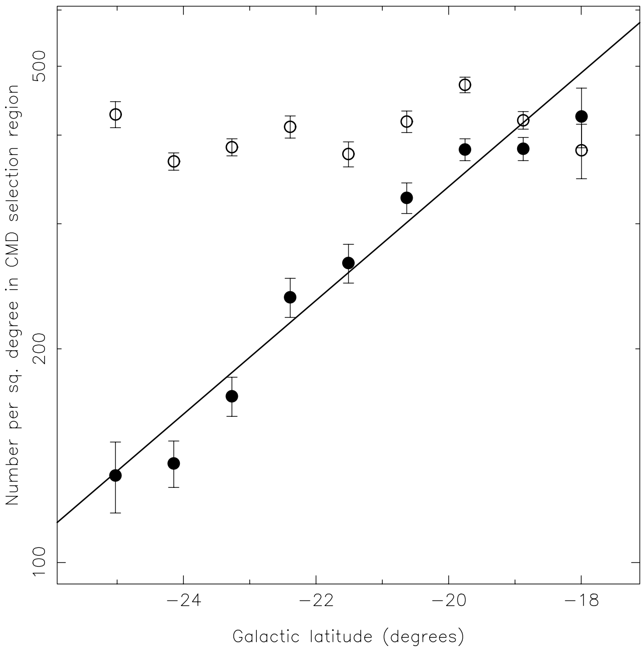

**Figure 10.** The filled circles show the density of sources (plotted on a logarithmic scale) as a function of Galactic latitude $b$ in the M31 field that belong to the 'Monoceros-like' main-sequence feature that is shown in Figs 6 and 7. These sources have been selected in the range $20.5 < V_0 < 21.5$, and with colours lying in the range $0.5 + 0.02(V_0 - 17.0)^2 < (V - i)_0 < 0.8 + 0.02(V_0 - 17.0)^2$. The 'background' ($133.0 \pm 5.3$ counts per square degree, estimated from the M33 field) has been subtracted from the counts of this 'Monoceros-like' population. A straight-line fit through these data is shown. The open circles show the corresponding density of normal halo sources, selected with $21.0 < V_0 < 22.0$, and with colours lying in the range $0.5 < (V - i)_0 < 0.4 + 0.02(V_0 - 17.0)^2$. (No background has been subtracted from this 'halo' population.)

from the disruptive effect of the satellite on the Milky Way. Current cosmological simulations suggest that galaxy satellites have their own massive dark matter mini-haloes (Stoehr et al. 2002), a possibility that is supported by the high mass-to-light ratios inferred from small Galactic dwarf spheroidals (Mateo 1998), and from the survival requirement of the Sgr dwarf galaxy (Ibata et al. 1997; Ibata & Lewis 1998). Including the dark matter halo of a satellite that has a stellar mass in the range $2 \times 10^8$ to $10^9$ $\mathrm{M}_\odot$ increases significantly the potential damage to the disc of the Milky Way, and raises the question of whether the thin disc would survive such an encounter (see e.g. (Tóth & Ostriker 1992; Velazquez & White 1999).

(iii) Another possibility is that we are seeing part of an outer spiral arm, or various arm fragments. Davies (1972) has identified a variety of spiral features in the outer Galaxy via 21-cm emission, extending out to a radius of ~25 kpc. Many of these structures lie in directions where we have also detected an anomalous stellar component, leading one to speculate if these could be associated stellar arms. Indeed, if an underlying global mode were responsible for driving the spiral structure, it would not be unexpected to find an older stellar population tracing out the same pattern as the gas (e.g. Rix & Rieke 1993; Thornley & Mundy 1997). The narrow line-of-sight thickness of the structures stands in favour of this hypothesis. The thickness of the stellar component may be problematic for the spiral arm hypothesis, however, although one might be able to appeal to warping to bring the bulk of the stars out of the plane.

(iv) The beating motion of an asymmetric Galactic component (such as the bar) induces resonances in the disc component. However, these resonances occur very close to the plane of the disc, and stars with significant vertical motions are unlikely to partake in a strong resonance. It seems implausible, therefore, that a resonance is the cause of the detected structure.

The photometric information presented here is not sufficient to discriminate between the first three scenarios. Further photometry, especially at low Galactic latitude, will be invaluable if we are to be able to follow the structure properly, and ascertain whether it is a Galactic ring, an inhomogeneous mess arising from ancient warps and disturbances, or part of a disrupted satellite stream. If this manifestly old population turns out to be the outer stellar disc, it will pose a very interesting challenge to galaxy formation models that predict inside-out assembly. Alternatively, if it transpires that the structure is due to a disrupted satellite whose orbit has been circularized and accreted along with its cargo of dark matter on to the disc, it will provide a unique first-hand opportunity to understand the effect of massive accretions on to the inner regions of galaxies.

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