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Accretion relics in the solar neighbourhood: debris from ωCen's parent galaxy

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ABSTRACT

We use numerical simulations to investigate the orbital characteristics of tidal debris from satellites whose orbits are dragged into the plane of galactic discs by dynamical friction before disruption. We find that these satellites may deposit a significant fraction of their stars into the disc components of a galaxy, and use our results to motivate the search for accretion relics in samples of metal-poor disc stars in the vicinity of the Sun. Satellites disrupted on very eccentric orbits coplanar with the disc are expected to shed stars in 'trails' of distinct orbital energy and angular momentum during each pericentric passage. To an observer located between the pericentre and apocentre of such orbits, these trails would show as distinct groupings of stars with low vertical velocity and a broad, symmetric, often double-peaked distribution of Galactocentric radial velocities. One group of stars with these characteristics stands out in available compilations of nearby metal-poor stars. These stars have specific angular momenta similar to that of the globular cluster ωCen, long hypothesized to be the nucleus of a dwarf galaxy disrupted by the Milky Way tidal field. In addition to their kindred kinematics, stars in the ωCen group share distinct chemical abundance characteristics, and trace a well-defined track in the [α/Fe] versus [Fe/H] plane, consistent with simple closed-box enrichment models and a protracted star formation history. The dynamical and chemical coherence of this group suggests that it consists of stars that once belonged to the dwarf that brought ωCen into the Galaxy. The presence of this and other 'tidal relics' in the solar neighbourhood suggest an extra-Galactic origin for the presence of nearby stars with odd kinematics and chemistry, and implies that accounting for stars contributed by distinct satellite galaxies may be crucial to the success of models of Galactic chemical enrichment.

Key words: Galaxy: disc – Galaxy: formation – Galaxy: kinematics and dynamics – Galaxy: structure.

1 INTRODUCTION

Ever since Eggen, Lynden-Bell & Sandage (1962, hereinafter ELS) interpreted the correlations between metallicity and kinematics of 221 stars in the solar neighbourhood as evidence in favour of a monolithic collapse formation model of the Milky Way, the mode of assembly of the Milky Way has been one of the main goals of observational surveys of the chemistry, age and kinematics of stars in the Galaxy. Soon after the publication of ELS, it became clear that some data provided challenges to the ELS interpretation, paving the way to more complex formation scenarios for the Milky Way. For example, the properties of the stellar halo, as traced by the globular cluster system, deviate from the trends seen in the sample analysed by ELS (Searle & Zinn 1978, hereinafter SZ) and have long been viewed as consistent with a formation process that involves the merger of a number of smaller subunits rather than the gradual collapse envisioned by ELS.

The vigorous observational progress that followed the ELS and SZ papers (recently reviewed by Freeman & Bland-Hawthorn 2002) have led to the development of a Milky Way formation scenario that borrows from the basic tenets of both the ELS and SZ hypotheses. In this, the stellar spheroid is built through a number of early mergers, whereas the stellar disc is regarded as the outcome of the smooth, dissipative deposition (and transformation into stars) of

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gas cooling more or less continuously off the intergalactic medium. Although the disc is built smoothly in this scenario, it is not stationary, and may evolve as a result of internal inhomogeneities such as spiral arms and molecular clouds, as well as by the effect of minor mergers with external satellite galaxies. Indeed, the presence of two distinct components in the Galactic disc (the thin and thick discs, Gilmore & Reid 1983) is widely ascribed to the dynamical 'heating' of an early thin disc by a satellite roughly 10 Gyr ago (Quinn & Goodman 1986; Quinn, Hernquist & Fullagar 1993; Robin et al. 1996; Wyse 2005).

Various versions of this scenario have long guided the interpretation of newer data sets, which, thanks to dedicated observing campaigns, to the availability of accurate distance measurements from *Hipparcos*, as well as to exquisite spectroscopy possible from 8–10 m telescopes, have been expanded to include hundreds of stars with reliable three-dimensional kinematics and detailed chemical abundance information. Most of these stars, however, are in the immediate vicinity of the Sun, and therefore the analysis suffers from the subtle and inevitable biases that the Sun's location in the Galaxy brings about. The bias may be modest if the stellar distribution function is a smooth function of Galactic phase-space coordinates (May & Binney 1986), but it may imply severe limitations if a large number of coherent dynamical groups – relics from past accretion events – populate the Galaxy, as these may well be under- or over-represented in the vicinity of the Sun.

The relatively quiescent formation scenario of the Galaxy described above – the Galactic disc is after all the dominant stellar component of the Galaxy – has encouraged the interpretation of the abundance patterns of nearby stars in terms of global collapse models where enrichment proceeds according to the general scenario outlined by Tinsley (1979). Their success in reproducing the correlations between kinematics and chemistry of solar neighbourhood stars notwithstanding, such models have traditionally been less successful at accounting for the sizable scatter around the mean trends shown in the data, as well as by the presence of abundance oddities in stars with otherwise unremarkable kinematics (Carney et al. 1997; King 1997; Hanson et al. 1998; Fulbright 2002).

From a cosmological perspective, a slow and quiescent buildup of the Galaxy is at odds with the mode of assembly envisioned in currently popular hierarchical models of structure formation such as the ΛCDM scenario (Bahcall et al. 1999), where merging is expected to have contributed significantly to the various populations of the Galaxy (see, for example, Steinmetz & Navarro 2002). In particular, the presence of an old, extended stellar disc component (such as that hypothesized to be the progenitor of today's thick disc) is awkward to accommodate in such models, since the dynamical fragility of stars in disc-like orbits seems to pre-empt an active merging history.

Indeed, the presence of old stars in the disc components of the Galaxy is often used to argue that the Galaxy has not been disturbed by mergers throughout most of its life (see, for example, Wyse 2005); clearly an unusual assembly history in a universe where structure grows hierarchically. The precise age of the Galactic disc components is still somewhat controversial, given that ages of individual stars are notoriously difficult to measure accurately, but the thin disc of the Galaxy is known to contain a fair fraction of metal-poor (and presumably quite old) stars. For example, roughly 16 per cent of stars in the dynamically-unbiased catalogue of metal-deficient ([Fe/H] <-0.6) nearby stars compiled by Beers et al. (2000, hereinafter B00) have thin-disc-like angular momenta.

Numerical simulations of hierarchical galaxy formation have suggested a way to reconcile the presence of old, metal-poor disc stars with the hectic merging activity envisioned in hierarchical formation scenarios. Abadi et al. (2003a,b) report, for example, that ∼15 per cent of dynamically-selected thin-disc stars in their cosmological simulation of the formation of a disc galaxy are actually older than the epoch of the galaxy's last major merger. Essentially all ($\gtrsim$90 per cent) of these old stars are brought in at late times by satellite galaxies whose orbits are circularized and dragged into the disc by dynamical friction before disruption.

The core of satellites that disrupt after their orbits have been nearly circularized may thus contribute stars to the thin-disc component upon disruption. In contrast, satellites that are disrupted before their orbits are substantially eroded by dynamical friction (or whose orbits are roughly polar to the disc) will contribute most of their stars to the spheroidal component. More massive satellites are likely to see their orbits more severely affected by dynamical friction before disruption (they are typically denser and thus more resilient to disruption), and are therefore likely to shed their stars on to more rotationally supported orbits than those of less massive companions more prone to disruption.

This suggests that broad correlations between metallicity and rotation may arise without the need for progressive *in-situ* enrichment of gas cooling and settling into the disc. Indeed, most metal-poor stars in the solar neighbourhood may actually be the overlapping debris of numerous satellites disrupted in the past. In such a scenario, the trend for rotational support to increase with metallicity would just reflect the mass–metallicity relation of their progenitor galaxies, coupled with the more efficient orbital decay of massive satellites in the potential of the Galaxy.

If this scenario is correct, it should be possible to identify at least some of the relics of such accretion events as coherent groups in phase space. A number of such kinematically-distinct associations have been recognized in the stellar halo; for example, the Sagittarius dwarf (Ibata, Gilmore & Irwin 1994); the retrograde rotation of halo stars in the direction of the North Galactic Pole (Majewski 1992); and the identification of substructure in the outer halo by Helmi et al. (1999).

Accretion on to the disc has also been recently recognized. One example is provided by the 'Monoceros ring' of stars in the outer disc of the Galaxy, which has been interpreted as material recently stripped from a dwarf galaxy that may still remain hidden in the disc (Newberg et al. 2002; Crane et al. 2003; Helmi et al. 2003; Ibata et al. 2003; Rocha-Pinto et al. 2003; Yanny et al. 2003; Martin et al. 2004). Further examples are provided by the 'Arcturus stream' – a group of stars at the apocentre of their eccentric disc-confined orbits that has been interpreted as debris from the disruption of a satellite in the plane of the Galactic disc (Eggen 1971; Navarro, Helmi & Freeman 2004) – as well as by the discovery of an unexpected, slowly rotating component above and below the plane of the disc (Gilmore, Wyse & Norris 2002).

We examine here the possibility that other solar-neighbourhood stars may have originated from material stripped from disrupted satellites. As with the analysis of the 'Arcturus group', we shall focus on stars with orbits confined to relatively small excursions from the plane of the disc (but not necessarily on circular orbits) and use numerical simulations to motivate and guide the search for common orbital characteristics in catalogues of nearby metal-deficient stars.

We describe briefly the numerical simulations and present our main results in Section 2. We use these to motivate the analysis of samples of nearby stars with accurate kinematics and chemical abundance measurements in Section 3. We conclude with a brief summary and discussion of our main conclusions in Section 4.

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2 TIDAL DEBRIS IN COSMOLOGICAL SIMULATIONS

2.1 Numerical experiments

We analyse the accretion and disruption of a satellite galaxy in the simulation of the formation of a disc galaxy presented by Abadi et al. (2003a,b). The simulation follows self-consistently the evolution in a ΛCDM universe of a small region surrounding a target galaxy, excised from a large periodic box and resimulated at higher resolution preserving the tidal fields from the whole box. The simulation includes the gravitational effects of dark matter, gas and stars, and follows the hydrodynamical evolution of the gaseous component using the smooth particle hydrodynamics (SPH) technique. Dense, cold gas is allowed to turn into stars at rates consistent with the empirical Schmidt-like law of Kennicutt (1998). The energetic feedback of evolving stars is included as a heating term on the surrounding gas, but its effectiveness in curtailing star formation is low. The transformation of gas into stars thus tracks closely the rate at which gas cools and condenses at the centre of dark matter haloes. Details of the simulation are given in Abadi et al. (2003a,b).

As discussed by these authors, at $z = 0$ the main galaxy resembles more an early-type spiral than the Milky Way. Although the luminosity of the disc component ($L_{\rm disc} \sim 2 \times 10^{10}$ $L_\odot$) and the circular speed at $R = 10$ kpc ($\sim$250 km s^{-1}) are comparable to those of our Galaxy, we emphasize that this is *not* a model of the Milky Way, and that our main goal is to understand *qualitatively* rather than quantitatively the nature of debris from tidally disrupted satellites.

2.2 Satellite orbital evolution

We choose to illustrate the analysis with the same satellite used by Helmi et al. (2003) in their discussion of the various formation scenarios of the 'Monoceros ring'. This is a 4.6×10^9 $M_\odot$ satellite that is accreted and disrupted at $z \sim 0.6$ by the main galaxy. The satellite turns around at $z \sim 1.2$ from a radius of 140 (physical) kpc, and first approaches the galaxy at $z = 0.94$, when it reaches a pericentric radius of 7.6 (physical) kpc. Its highly eccentric orbit is inclined by $\sim 40°$ relative to that of the disc of the galaxy. These orbital parameters evolve quickly, as dynamical friction breaks the satellite's orbit and steadily reduces its apocentric radius.

Fig. 1 shows the trajectory of the satellite in three orthogonal projections, chosen so that the z-axis coincides with the rotation axis of the disc of the main galaxy, which is located at the origin of the coordinate system. This trajectory follows the centre of mass of the self-bound stellar core of the satellite, computed by iteratively removing escapers using the procedure outlined in detail by Hayashi et al. (2003). For short, we shall use 'satellite' to denote this self-bound group of stars that track the surviving core of the satellite.

The orbit of the satellite decays steadily, gradually becoming more circular and more closely aligned with the plane of the disc. This is shown in Fig. 2, where we show the evolution of the satellite's distance to the galaxy (top panel); the inclination of the orbit relative to the disc (second panel); the orbital circularity[1] (third panel); and the self-bound stellar mass of the satellite (bottom panel).

[1] The circularity $J_z/J_c(E)$ is defined as the ratio between the orbital angular momentum and that of a circular orbit with the same binding energy, E.

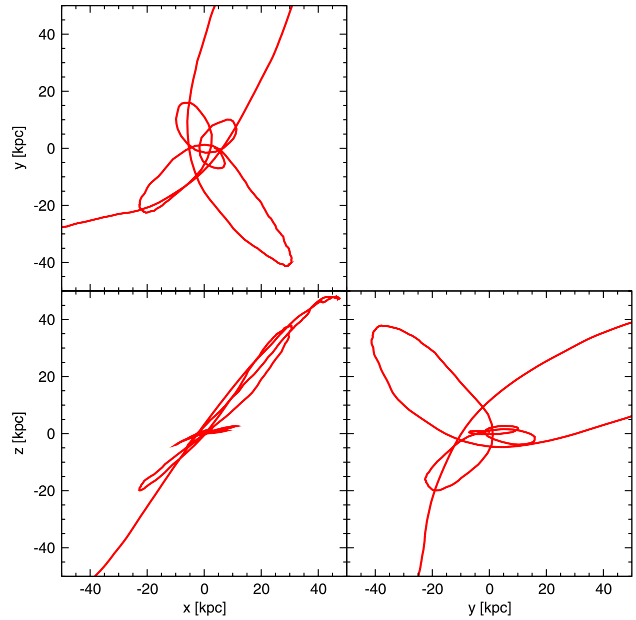

Figure 1. Orbital trajectory of the satellite's self-bound core in a reference frame where the main galaxy is at rest at the origin, and the z-axis is chosen to coincide with the rotation axis of the disc component. The orbital plane is initially seen approximately edge-on in the x–z projection and is inclined $\sim 40°$ relative to the plane of the disc. As the orbit of the satellite decays and approaches the disc, it is rapidly brought into the plane of the disc before disruption.

In the last few orbits, the satellite's core decays to an almost circular orbit coplanar with the disc. Although the orbital energy (as measured by the satellite's apocentre) declines gradually throughout the evolution, the inclination and circularity of the satellite change noticeably as the satellite approaches the disc of the main galaxy, which extends out to $\sim$10–15 kpc at this redshift. The fast decay into the plane seen after $z \sim 0.75$ is accompanied by rapid circularization of the orbit of the remaining self-bound core (Fig. 2), and is consistent with the results of previous work on satellite decay in disc-dominated or flattened systems (see, for example, Quinn & Goodman 1986; Peñarrubia, Kroupa & Boily 2002, and references therein).

2.3 Satellite debris

The stellar component of the satellite is disrupted mainly during the three last pericentric passages, between $z = 0.7$ and 0.6. The self-bound mass of the satellite core drops to zero after $z \sim 0.6$, and the satellite debris quickly phase-mixes into a torus-shaped configuration, as shown in Fig. 3. The well-mixed, relaxed configuration of the debris at late times hides the presence of several well-defined, dynamically coherent groups of well-defined (specific) binding energy (E) and angular momentum (J_z). This is shown in Fig. 4, where several distinct groups of particles are clearly apparent in the E and J_z histograms after disruption.

The 'peaks' in these histograms may be traced to particles lost during each of the last three pericentric passages prior to full disruption. This is illustrated by the dashed curve in Fig. 4, which correspond to stars lost at $z \approx 0.68$. The dot–dashed curve corresponds to stars lost during the last two pericentric passages, at $z \approx$ 0.64 and 0.62, respectively. In general, the satellite sheds two groups of particles at each pericentric passage, corresponding roughly to

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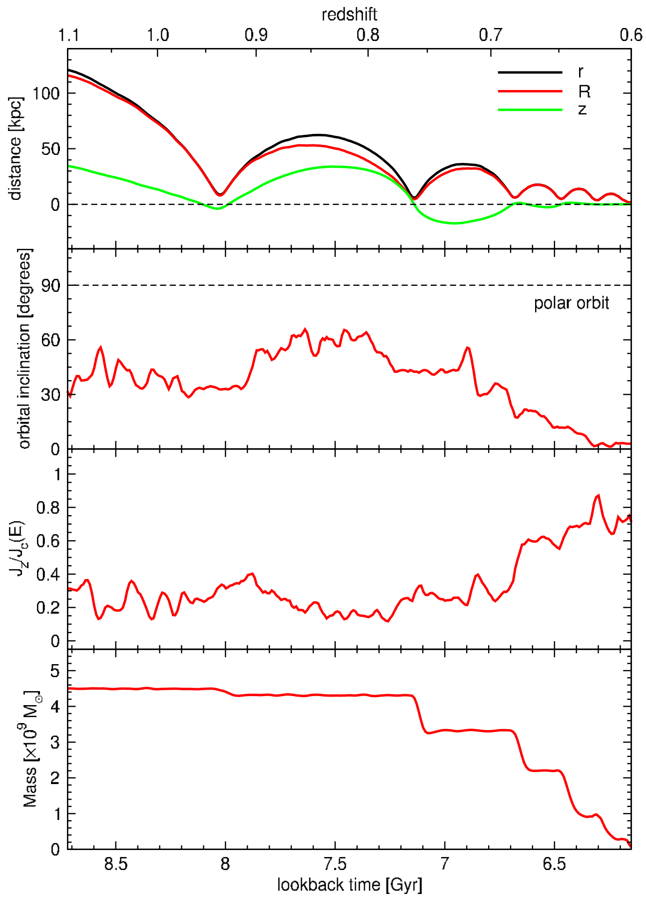

Figure 2. Evolution of the orbital parameters of the self-bound stellar core of the satellite in the same reference frame chosen in Fig. 1. Top panel shows the evolution of the distance to the centre of the main galaxy, r, the distance to the rotation axis of the disc, R, and the vertical distance to the plane of the disc, z, as a function of time. Second panel shows the evolution of the instantaneous inclination of the orbital plane of the satellite relative to the plane of the disc. Note that the satellite is brought on to an orbit nearly coplanar with the disc before disruption. Third panel shows the evolution of the circularity of the satellite's orbit, defined as the ratio between the z-component of its angular momentum and that of a circular orbit of the same binding energy. Note that the orbit becomes nearly circular before disruption. Bottom panel shows the evolution of the self-bound stellar mass of the satellite with time until disruption.

the 'inner' and 'outer' tidal arms seen in the $z = 0.67$ panel of Fig. 3, so we expect several distinct groups of particles in Fig. 4. Because of overlaps between groups, as well as the intrinsic spread in the E and J_z distributions due to the finite velocity dispersion of the satellite, roughly three prominent groups are clearly identifiable by their distinct energy and angular momentum after disruption.

The evolution of these groups in position–velocity space is shown in Figs 5 and 6, which show the rotation ($V_{\rm rot} = J_z/R$) and radial (V_R) velocity as a function of their distance (R) to the rotation axis of the disc. The solid curve in Fig. 5 shows the circular velocity on the plane of the disc of the main galaxy. Dashed hyperbolae in this figure are lines of constant specific angular momentum that indicate the location of the three prominent 'peaks' in the J_z distribution shown in Fig. 4.

These groupings are also seen in the V_R–R plane, as shown in Fig. 6. Solid line curves in the $z = 0.60$ panel of this figure indicate the average trajectory of particles with various energies and angular momenta. The innermost and outermost loops trace orbits with (E/km s^{-2}, J_z/km s^{-1} kpc) of order (-1.0×10^5, 1150) and (-1.5×10^5, 1150), corresponding roughly to two of the peaks in the distribution of stripped stars seen in Fig. 4. These groupings in E–J_z space are expected to be long lived, provided that the galactic potential remains relatively quiescent afterwards.

2.4 Debris identification strategy

As discussed by Abadi et al. (2003a,b), the disruption of satellites on coplanar orbits provides a mechanism for adding stars of various ages and metallicities to the disc components of a galaxy. These authors concentrate their analysis on the debris that contributes to the thin disc, and argue that accretion events are possibly responsible for the majority of old thin-disc stars in the solar neighbourhood. Satellites like the one we analyse here do not contribute substantially to the thin disc, as few particles in the debris of this satellite end up on nearly circular orbits. However, most of the debris is confined to a plane roughly coincident with that of the disc of the galaxy, as shown in Fig. 3, and might therefore be considered part of a thick-disc component.

To an observer in the disc, the local properties of the satellite debris will depend significantly on the position of the observer relative to the pericentre and apocentre of each of the groups mentioned above. Local detection of these groupings as recognizable features against the background of Galactic stars would be easier near apocentre, since stars tend to crowd there during their orbits. A possible debris detection strategy would thus be to search samples of nearby stars for groups with (i) modest vertical motions, (ii) negligible net Galactocentric radial velocity, and (iii) common angular momentum, and to probe them for corroborating traits suggestive of a common origin.

One example of such an approach is provided by the 'Arcturus group' reported by Navarro et al. (2004). These authors argue that the significant excess of disc stars with angular momentum similar to that of Arcturus seen in the B00 catalogue, together with other, more indirect, evidence (such as the tight correlation in the [α/Fe] versus [Fe/H] plane, and the discovery of an unexpected population with similar rotation speed above and below the Galactic plane by Gilmore et al. 2002), constitute persuasive evidence for the extra-Galactic origin of the bright star Arcturus and of other members of its namesake group.

On the other hand, for observers located *between* the apocentre and pericentre of a well-mixed group, the debris would show locally as groups of stars with a rather broad, symmetric (and at times 'double-humped') distribution of Galactocentric radial velocities. This is illustrated in Fig. 7, where we show the V_R histogram of stars chosen at various radii across the disc after disruption ($z = 0.6$). These radii are chosen to lie *between* the apocentres of the most prominent groups identified in Fig. 4. The relatively symmetric, double-peaked distribution of Galactocentric radial velocities is a tell-tale sign of a past accretion event that left a substantial fraction of stars on orbits more energetic than the observer's. We shall use this result below to motivate the search for coherent dynamical structures in samples of nearby stars that may have originated in the disruption of former satellites of the Milky Way.

3 TIDAL DEBRIS IN THE SOLAR NEIGHBOURHOOD

Given the clear trend for the metallicity of galaxies in the Local Group to increase with luminosity (van den Bergh 1999),

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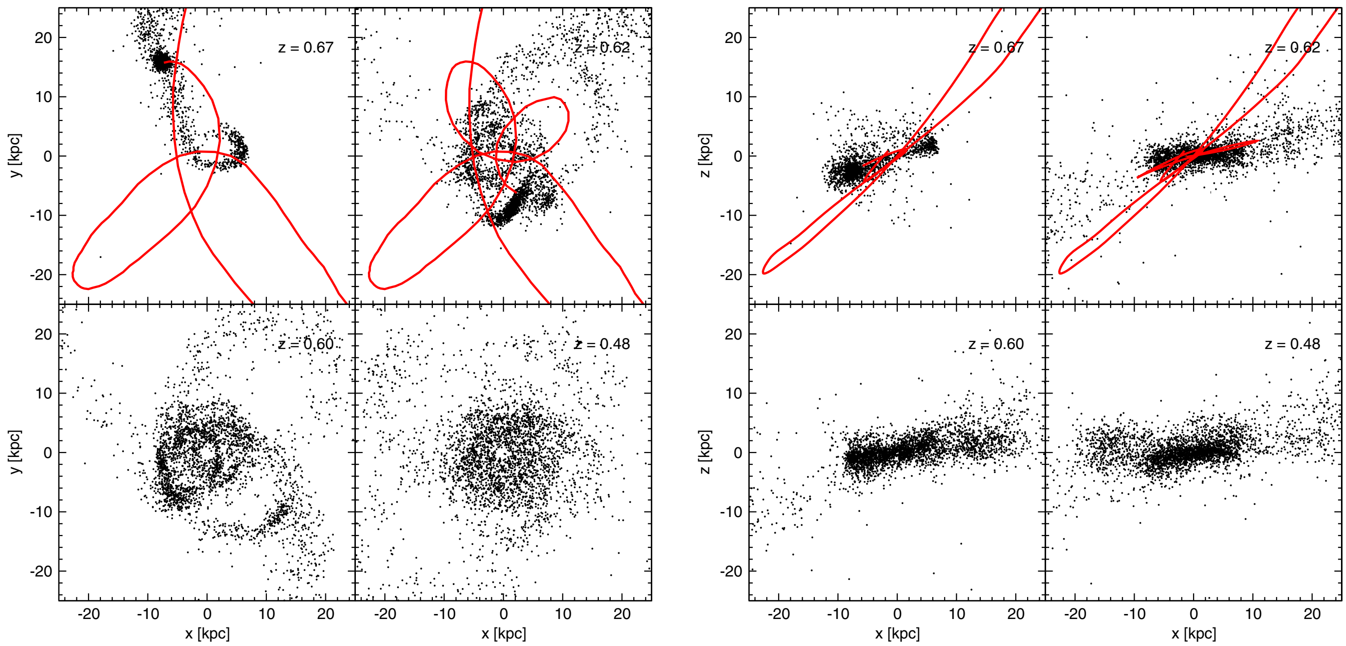

Figure 3. Evolution of the stellar component of the satellite seen 'face-on' (left panels) or 'edge-on' (right panels) relative to the plane of the disc. The curves in the top panels track the orbit of the self-bound core of the satellite up until the time shown in each panel. The satellite starts being stripped of stars after the pericentric passage that preceded the $z = 0.67$ panel. Each pericentric passage tears two tidal 'tails' from the satellite, an inner one more tightly bound and an outer one less tightly bound than the remaining self-bound core. Although these tails maintain their identity in phase-space, they quickly phase-mix, as the debris settles into a torus-shaped configuration. Most stars are lost after the satellite is brought on to the plane of the disc, and the symmetry axis of the torus is parallel to the rotation axis of the disc. Thus, much of the debris ends up on eccentric, disc-confined orbits (see text for further details).

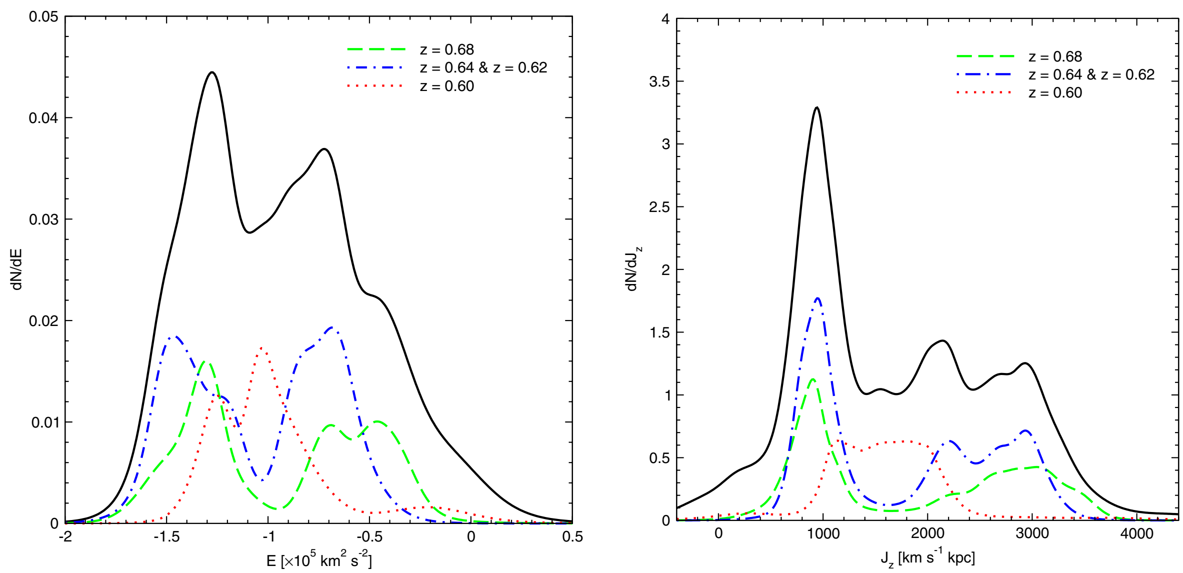

Figure 4. Specific energy (E) and z-angular momentum (J_z) distribution of satellite stellar debris soon after full disruption ($z \sim 0.60$). The thick upper curve corresponds to all satellite stars; the bottom curves show the E and J_z distribution of particles stripped from the galaxy during the last three pericentric passages: dashed curves correspond to stars stripped at $z = 0.68$, dot–dashed curves at $z = 0.64$ and $z = 0.62$, and dotted curves at $z = 0.60$. Stars stripped at each pericentric passage form long-lived, dynamically distinct groups in E–J_z space.

signatures of the accretion and disruption of dwarf galaxies are expected to be more prevalent in samples of metal-poor stars. B00 provide a catalogue of metal-deficient stars in the vicinity of the Sun, compiled with the specific aim of minimizing kinematic selection biases. This is the largest sample of metal-poor ([Fe/H] $\lesssim -0.6$) stars with available Fe abundances, distances and radial velocities. Proper motions are also available for many of these stars, making it a good sample to search for substructure (see, for example, Chiba & Beers 2000; Brook et al. 2003).

The top dot–dashed histogram in Fig. 8 shows the distribution of Galactocentric rotation speeds for all stars in the B00 sample. The full sample is dominated by the halo and the canonical 'thick-disc' component. A decomposition of the $V_{\rm rot}$ distribution into three Gaussians representing the 'canonical' components of the Galaxy

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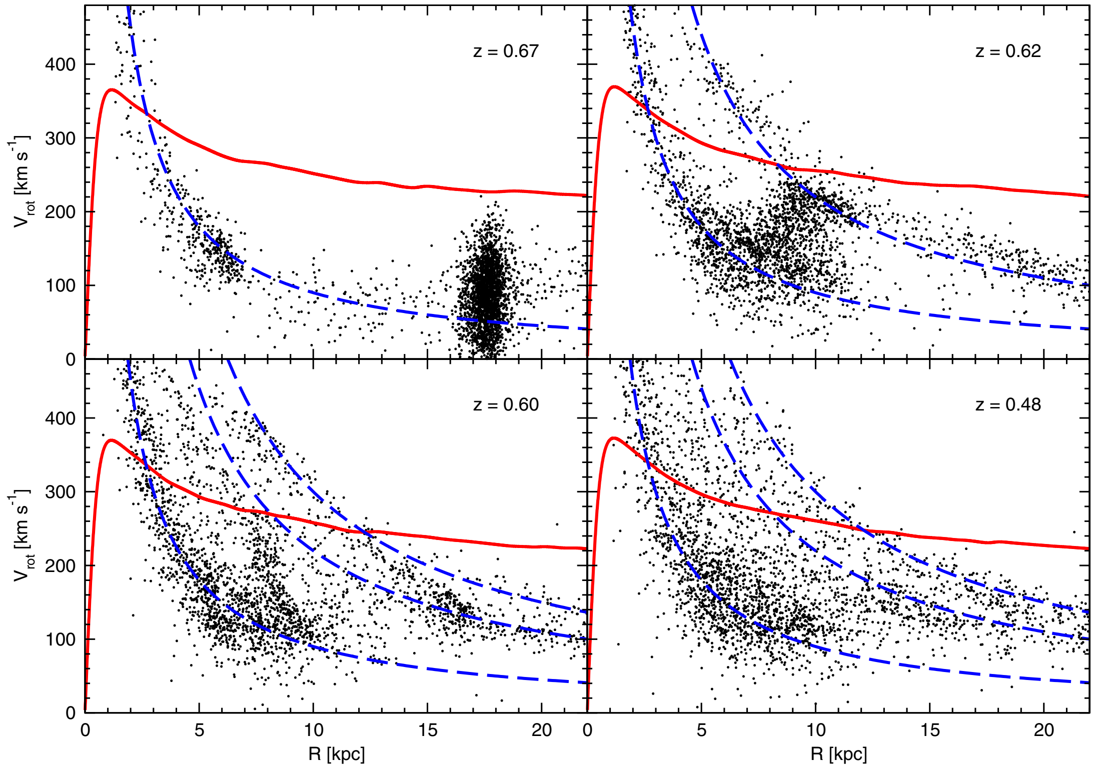

Figure 5. Evolution of satellite stars in the R–$V_{\rm rot}$ plane. R is the distance to the rotation axis of the disc, and $V_{\rm rot} = J_z/R$ is the rotation speed about that axis. Dashed curves are lines of constant (specific) angular momentum that mark the three most prominent 'peaks' in the J_z distribution shown in Fig. 4. From top to bottom, these correspond to $J_z = 900$, 2200 and 3000 km s^{-1} kpc. Solid curve is the circular velocity of the main galaxy, $V_c(R)$, measured on the plane of the disc.

is shown in Fig. 8. From left to right, the halo, thick-disc and thin-disc components are assumed to have $(\langle V_{\rm rot}\rangle, \sigma)$ equal to (0, 110), (160, 50) and (220, 25) km s^{-1}, and are found to contribute 56, 28 and 16 per cent of the sample, respectively.

The halo distribution is normalized to match the number of counter-rotating stars, whereas the relative contributions of the thick and thin discs are chosen to match the $V_{\rm rot}$ distribution of the remaining co-rotating stars. The fit obtained is shown by the thick solid curve in Fig. 8. Most random realizations are unable to account for the 'excess' of stars labelled as the 'Arcturus group' at $V_{\rm rot} \sim 90$ km s^{-1}; only 16 out of 1000 realizations give a value for the number of stars comparable to that observed (Navarro et al. 2004).

3.1 The ωCen group

Of similar significance is the excess of stars on slightly retrograde orbits (-50 km s$^{-1} < V_{\rm rot} < 0$ km s^{-1}) labelled as the 'ωCen group' in Fig. 8. Stars in this group have specific angular momenta similar to that of the globular cluster ωCen, the most luminous and unusual of the Milky Way globular clusters. Although the typical metallicity of stars in ωCen is low (its distribution peaks at [Fe/H] ~ -1.6; see Smith 2004 for a review), there is convincing evidence for a long and complex star formation and enrichment history in the structure of the giant branch of cluster stars (Norris, Freeman & Mighell 1996; Lee et al. 1999), and in the unusual s-process element abundances, which point to the retention of elements fabricated in asymptotic giant branch (AGB) stars (Norris & Da Costa 1995).

These properties strongly suggest that the cluster did not form on its present orbit, which is rather bound (apocentre $\sim$6.2 kpc), confined to the disc ($z_{\rm max} \sim 1$ kpc), and mildly retrograde (Dinescu, Girard & van 1999). This orbit implies frequent passages through the disc, and may only be reconciled with significant gas retention and repeated episodes of star formation if ωCen formed elsewhere and its orbit has decayed substantially over time. Efficient decay requires more mass than presently attached to the cluster, implying that ωCen was probably much more massive in the past. Indeed, it has long been hypothesized that it was the nucleus of a rather massive and dense dwarf accreted and disrupted in the tidal field of the Milky Way (Freeman 1993).

Although the apocentre of ωCen's orbit lies at present within the solar circle, a substantial fraction of the stars of its parent galaxy may have been shed into orbits of higher energy that now intersect the solar neighbourhood. This has motivated several authors to search for debris from ωCen's parent galaxy in catalogues of nearby metal-poor stars. Dinescu (2002), for example, argues that the retrograde signature noted in Fig. 8 for stars with $V_{\rm rot} \sim -50$ km s^{-1} is most prevalent in samples with metallicities restricted to $-2.0 <$ [Fe/H] < -1.5 – a range that overlaps the metallicity distribution of ωCen stars.

Tidal debris tends to settle into a structure more vertically extended than the thin disc of the Galaxy, and therefore it may be detectable *in situ* above and below the plane of the Galaxy. Mizutani, Chiba & Sakamoto (2003; see also Chiba & Mizutani 2004) have recently argued that this may explain the presence of a high-velocity ($V_{\rm los} \sim 300$ km s^{-1}) peak in the line-of-sight velocities of stars in the direction against Galactic rotation recently presented by Gilmore et al. (2002).

Our analysis is complementary to that of these authors, but focuses instead on the Galactocentric radial velocity distribution of

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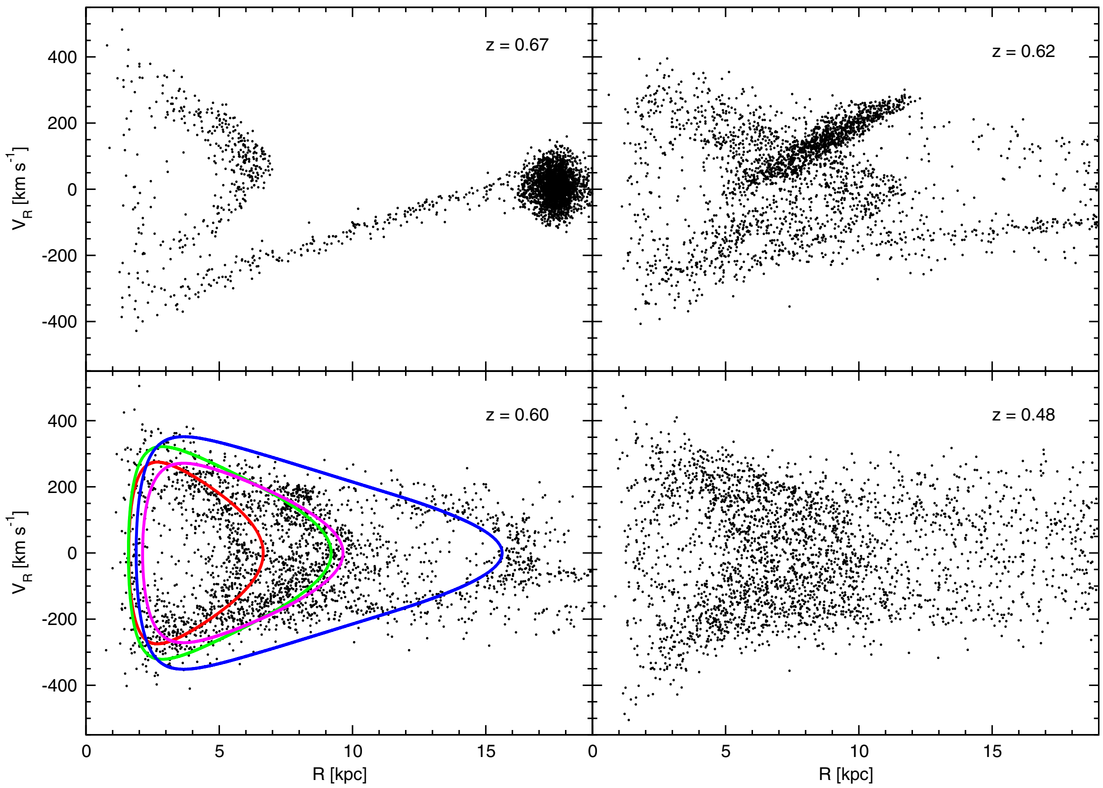

Figure 6. Evolution of satellite stars in the R–V_R plane. R is the distance to the rotation axis of the disc, and V_R is the galactocentric radial velocity. The solid curves are lines of constant (specific) energy and angular momentum that mark some of the characteristic 'peaks' in the J_z and E distributions shown in Fig. 4. From the inside out, $(E,\ J_z)$ for each curve is $(-1.5 \times 10^5, 900)$, $(-1.3 \times 10^5, 950)$, $(-1.25 \times 10^5, 1150)$ and $(-1.0 \times 10^5, 1150)$, respectively. E is in units of km^2 s^{-2} and J_z is in km s^{-1} kpc.

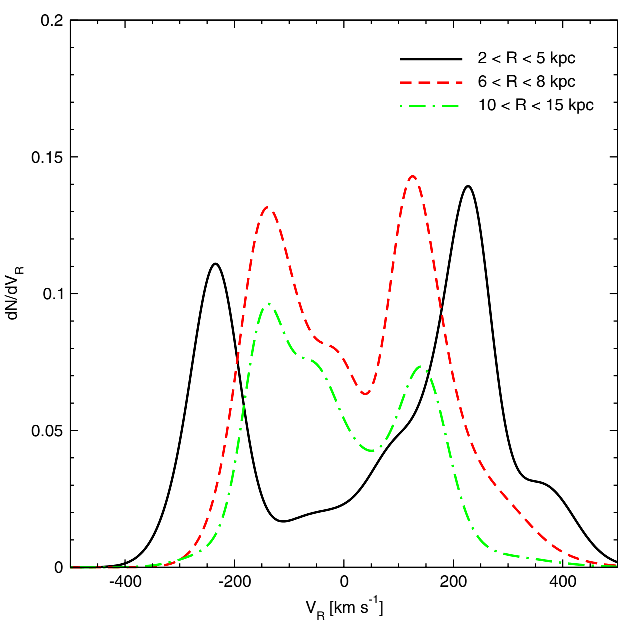

Figure 7. Distribution of galactocentric radial velocities of the satellite debris measured after full disruption ($z = 0.6$) at various radii. The solid curve is the histogram measured in the range (2,5) kpc, the dashed curve corresponds to the range (6,8) kpc, and the dashed curve to (10,15) kpc. These locations are chosen to bracket the apocentric radii corresponding to the three most prominent 'peaks' in the distribution of specific energies shown in Fig. 4, and are intended to illustrate the broad, symmetric, 'double-humped' velocity distribution measured by observers in the disc at radii intermediate between the characteristic apocentric radii of the debris.

disc-confined stars with angular momenta similar to ωCen's, as well as on the detailed abundance patterns of such stars.

Gratton et al. (2003, hereinafter GCCLB) have compiled element-to-element abundance ratio measurements for about 150 stars in the solar neighbourhood with accurate kinematical data, bringing together their own measurements with literature data from the work of Nissen & Schuster (1997), Fulbright (2000) and Prochaska et al. (2000). The angular momentum distribution of these stars is presented in Fig. 9. The 'excess' of stars in the B00 catalogue corresponding to the ωCen and Arcturus groups noted in Fig. 8 are also clearly seen in this compilation, underscoring the robustness of these kinematic features to various selection techniques.

Following the motivation outlined in Section 2, we analyse the Galactocentric radial (U) and vertical (W) velocity[2] distribution of ωCen group stars in Fig. 10. Open circles show the vertical and radial velocities of all stars in the GCCLB compilation, whereas the filled circles highlight those with angular momenta in the 'peak' associated with ωCen in Fig. 9, i.e. J_z between -600 and 300 km s^{-1} kpc. We choose to focus on those stars which, like ωCen, have their orbits roughly confined to the disc, and restrict the candidate list further to stars with $|W| < 65$ km s^{-1} in order to weed out unrelated halo stars.

Thirteen stars are selected by these two criteria as candidate members of the group, and their U distribution is shown by the dashed

[2] We use U, V and W to denote radial, tangential and vertical velocities in Galactic coordinates, measured relative to the LSR. U is positive outwards, V in the direction of the Sun's rotation, and W towards the North Galactic Pole. We assume that the Sun's (U,V,W) velocity is $(-9,12,7)$ km s^{-1}.

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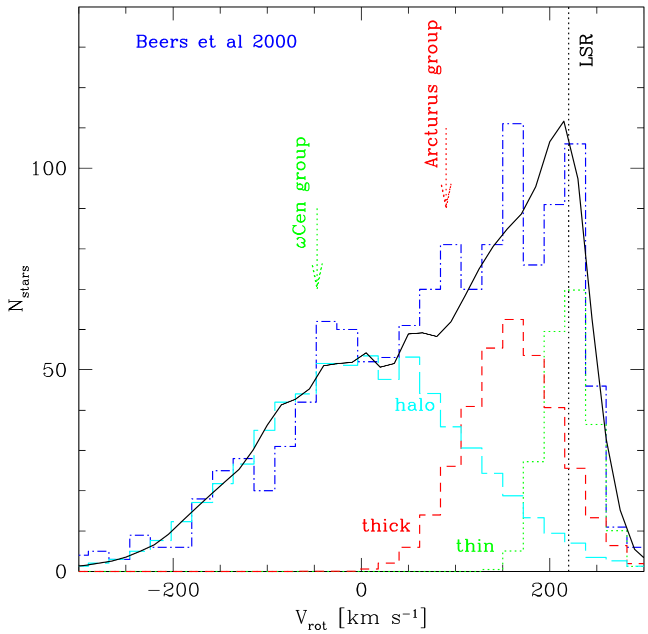

Figure 8. Rotational velocity distribution of all stars in the dynamically unbiased catalogue of metal-poor ([Fe/H] $\lesssim -0.6$) stars of Beers et al. (2000) (dashed histogram), decomposed into three canonical Galactic (Gaussian) components: halo, thick disc and thin disc, as labelled. The solid curve denotes the sum of all three components. Note the excess of stars lagging the local standard of rest (LSR) rotation by $\sim$120 km s^{-1}, coincident with the Arcturus group, as well as that for mildly retrograde orbits labelled as the ωCen group. See text for full details.

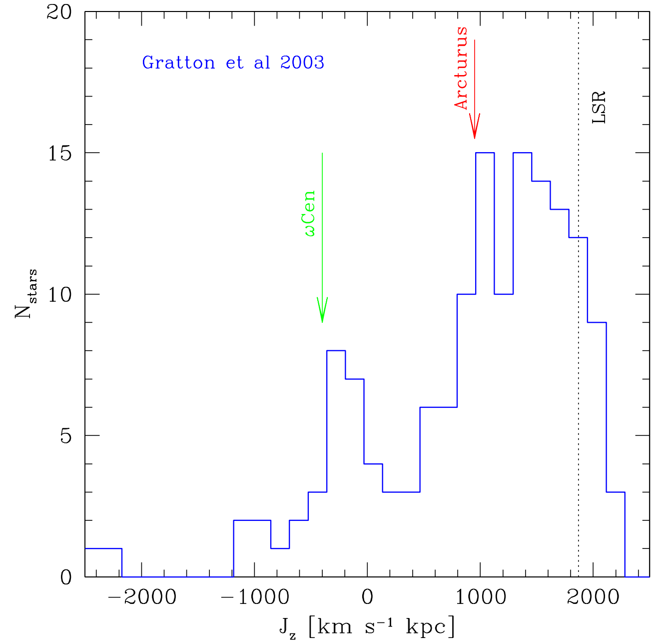

Figure 9. Distribution of specific angular momenta of all stars in the metal-poor compilation of Gratton et al. (2003). These $\sim$150 stars have accurate kinematics and distances, as well as reliable element-to-element abundance ratios. The excess of stars corresponding to the Arcturus and ωCen groups noted in the Beers et al. (2000) catalogue (Fig. 8) is also clearly seen here in this independent compilation.

histogram in Fig. 10 (for clarity, the number of stars in each bin is multiplied by four relative to the scale on the right axis). The radial velocity distribution of these stars is in obvious contrast with those of all stars in the GCCLB compilation, which is well described by a Gaussian of zero mean and dispersion 125 km s^{-1} (solid histogram in Fig. 10), as expected for stars selected preferentially near the apocentre of their orbits. The ωCen group candidates, on the other hand, span a large symmetric range in U, from -300 to 300 km s^{-1}, with no obvious central tendency (i.e. few stars near their apocentre) and a velocity dispersion exceeding 200 km s^{-1}. Indeed, only three out of thirteen candidates have $|U| < 100$ km s^{-1}, whereas one would have expected three times as many had their U distribution been similar to that of the whole ensemble.

With the obvious caveat that the number of candidates is rather small, one is tempted to interpret the broad, roughly symmetric U distribution as evidence that some of the candidate stars are part of a dynamically coherent group shed by ωCen's dwarf prior to disruption. The apocentre of this group is outside the solar circle, and therefore group stars are only seen moving towards their apocentre with high positive U velocity or coming from their apocentre with high negative U.

Support for the common origin of this group comes from analysing the abundances of candidate stars. Fig. 11 shows the abundance of α elements and iron for stars in the GCCLB sample. As is customary, the α-element abundance is expressed as the logarithm of its abundance relative to Fe in solar units, [α/Fe], and the iron abundance is given as a logarithmic measure of its ratio to H also in solar units, [Fe/H]. Open circles correspond to all stars in the GCCLB compilation, whereas the filled circles indicate the ωCen group candidates, as in Fig. 10. Remarkably, the ωCen group

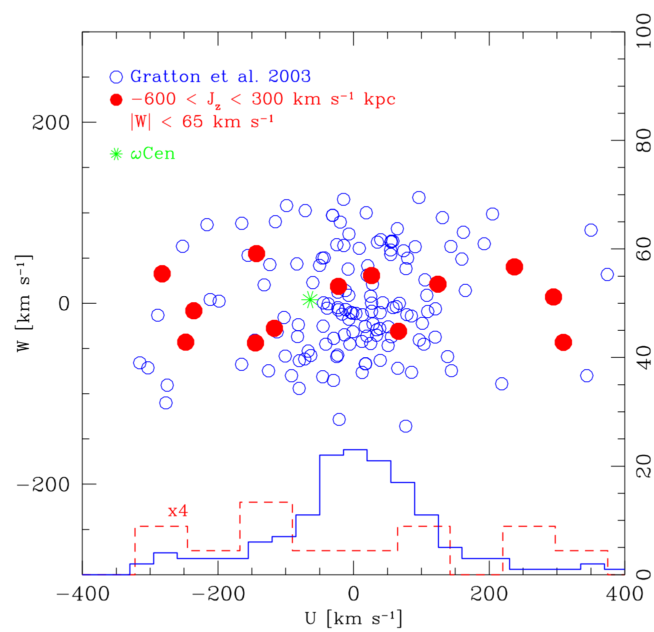

Figure 10. Vertical (W) versus radial (U) velocities of metal-poor stars in the Gratton et al. (2003) compilation (open circles). Filled circles are used to highlight ωCen group candidates. These are stars with angular momenta similar to ωCen's (starred symbol), and with relatively low vertical velocity (see conditions as labelled in the figure). The U distribution of the 13 candidate stars (dashed histogram, multiplied by four for clarity, scale on right axis) differs markedly from that of the rest of the stars in the compilation (solid histogram). Only three candidate stars have $|U| < 100$ km s^{-1}, whereas nine would be expected from the overall distribution.

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candidates are not distributed at random amongst the sample, but rather trace a well-defined narrow track in this plane, spanning a wide range in iron abundance ($-2.6 < [\mathrm{Fe/H}] < -0.9$) which is consistent with the spread in metallicity measured for individual stars in ωCen (Suntzeff & Kraft 1996).

This well defined track in the [α/Fe] versus [Fe/H] plane is roughly consistent with simple one-zone self-enrichment models (see, for example, Matteucci & Francois 1989), but where pollution by the iron-rich ejecta of type Ia supernovae becomes important at lower metallicity than for 'typical' stars in the halo, where [α/Fe] drops precipitously for $[\mathrm{Fe/H}] \gtrsim -1.5$. Intriguingly, two candidate stars appear to deviate from this trend, and are highlighted by starred symbols in Fig. 11. This is consistent with the above interpretation, as these two stars are dynamically quite distinct from the rest; although they share the angular momentum of ωCen, their low U velocity ($|U| < 50$ km s^{-1}) sets them apart from the rest as unrelated stars on much more tightly bound orbits.

The chemical coherence highlighted by the filled symbols in Fig. 11 is thus manifest only when stars of coherent kinematics (i.e. similar E and J_z) are considered part of the group. Overall, this pattern is consistent with that expected for a satellite system that self-enriched to a metallicity of order one-tenth of the Sun on a time scale somewhat longer than envisioned for the bulk of metal-poor stars in the vicinity of the Sun.

We conclude that the chemical and dynamical coherence of stars in the ωCen group is highly suggestive of a common origin, most likely a single dwarf system that was dragged and disrupted into the disc of the Galaxy early during its assembly history.

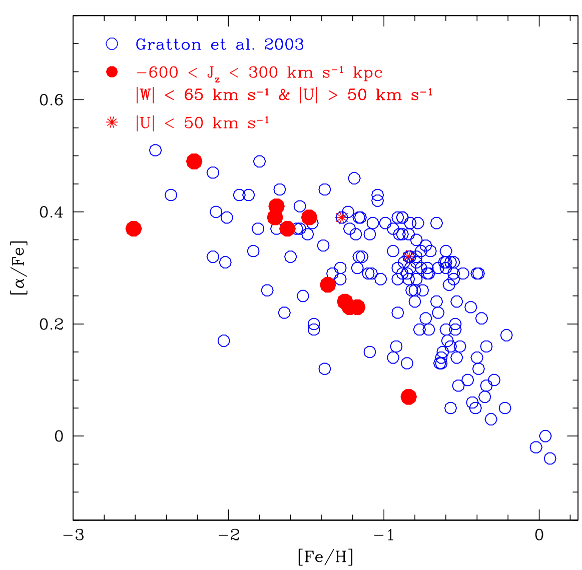

Figure 11. Abundance ratios for stars in the Gratton et al. (2003) sample. Open circles correspond to all stars in the sample, whereas filled circles indicate candidate stars of the ωCen group. Note that these stars delineate a well defined sequence in the abundance ratios that may be interpreted as resulting from a protracted episode of star formation where a system self-enriched to a metallicity of order one-tenth of solar. Two candidate stars deviate from the main trend, and are highlighted with starred symbols. These two stars, however, are kinematically distinct from the rest. Although they share the angular momentum of ωCen, they are at the apocentre of their orbits ($|U| < 50$ km s^{-1}) in sharp contrast with the rest of ωCen group candidates, which are moving through the solar neighbourhood to or from their apocentre at an average radial velocity of ~200 km s^{-1}. These stars are unlikely to be related to ωCen's progenitor.

4 SUMMARY AND DISCUSSION

We use numerical simulations to analyse the dynamical properties of tidal debris stripped from a satellite on a highly eccentric orbit roughly coplanar with the disc of the main galaxy upon disruption. Because of the small pericentric radius of the orbit, the stellar component of the satellite is disrupted by the tidal shocks that accompany the last few pericentric passages, splitting the bulk of stars into coherent groups of common energy and angular momentum on eccentric orbits roughly confined to the disc.

Observers located between the pericentre and apocentre of such groups would see the debris as stars of common angular momentum but with a wide, symmetric (and at times 'double-peaked') distribution of Galactocentric radial velocities. A group of stars with these characteristics stands out in catalogues of nearby metal-poor stars and shares the peculiar kinematics of the unusual globular cluster ωCen. These stars orbit the Galaxy on retrograde orbits but they are confined to relatively small vertical excursions from the plane of the disc, and show extremely well-correlated element-to-element abundance ratios. They span a range in [Fe/H] comparable to that of individual stars in ωCen, and follow closely the [α/Fe] versus [Fe/H] correlation expected for a simple closed-box self-enrichment model. The dynamical and chemical coherence of stars in this group is highly suggestive of a common origin, which we ascribe to the dwarf galaxy that brought ωCen into the Galactic disc.

The ωCen group thus shares some of the properties of the 'Arcturus group' – a group of stars of moderate velocity dispersion and singular metal abundance (Eggen 1971), that Navarro et al. (2004) have recently claimed to be part of the debris from another past accretion event. However, the ωCen and Arcturus groups also differ in a number of properties. For example, although Arcturus group members have negligible net radial motions and are thus near the apocentre of their orbits, ωCen group stars are passing by the solar neighbourhood at fairly high speeds to or from apocentric radii far outside the solar circle.

In addition, most Arcturus group members have highly enhanced [α/Fe] ratios relative to solar, and are in this regard similar to the majority of metal-poor stars in the solar neighbourhood (see fig. 3 of Navarro et al. 2004). On the other hand, the [α/Fe] ratio of ωCen group members approaches the solar value at relatively low metallicity ($[\alpha/\mathrm{Fe}] \sim 0.05$ at $[\mathrm{Fe/H}] \sim -0.9$; see Fig. 11). Thus, several stars in this group have unusually low [α/Fe] enhancement relative to typical halo stars of comparable metallicity. This is important, as it suggests an 'extra-Galactic' resolution for the puzzle surrounding stars with anomalously low [α/Fe] in the solar neighbourhood: namely, all such stars may come from disrupted dwarfs (Carney et al. 1997; King 1997; Hanson et al. 1998; Fulbright 2002). Indeed, low [α/Fe] ratios are consistent with those of stars in the dwarf satellites of the Milky Way (Draco; Sculptor; and Sagittarius; see, for example, Shetrone, Côté & Sargent 2001; Shetrone et al. 2003; Bonifacio et al. 2004; Venn et al. 2004).

The prominence of the Arcturus and ωCen groups in samples of metal-deficient stars (the two combined make up to ~16 per cent of the stars in the GCCLB sample) suggests that accretion events have probably contributed a significant number of the metal-deficient stars in the solar neighbourhood. These two examples demonstrate that at least some, and perhaps many, old stars on orbits confined to the disc did not form *in situ*, but were brought into the Galaxy by accretion events.

It is clearly important to search exhaustively for signatures of past accretion events in the solar neighbourhood in order to quantify properly the contribution of tidal debris to the inventory of

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metal-poor stars in the Galaxy, as this may seriously affect the validity and applicability of Galactic formation and evolution models. For example, ELS-inspired interpretations of the correlation between metallicity and rotational support for nearby metal-poor stars in terms of a global collapse rest on the assumption that their orbits have not evolved drastically over time.[3]

On the other hand, if most metal-poor stars in the solar neighbourhood have been brought into the Galaxy by accretion events, a drastically different scenario may be required to accommodate this correlation. One possibility is that this may just reflect the increasing efficiency of dynamical friction in circularizing the orbits of more massive satellites – the most effective contributors of stars relatively rich in metals.

Is it possible that the whole trend seen in Fig. 11 is caused by the overlap of stars stripped from numerous satellites, each of which may have self-enriched roughly as a closed box prior to accretion? It would be premature to argue that the data is fully consistent with such a scenario, but nor is it obviously ruled out by the data.

For example, the scarcity of metal-poor stars with low $[\alpha/\mathrm{Fe}]$ may be explained by arguing that they originate in the smallest and most metal-poor of all accreted satellites (i.e. the likes of Sculptor, Draco, or the progenitor of ωCen). Overall, few stars are locked up in such small satellites, and therefore it is not surprising that they contribute a relatively small fraction of all the metal-deficient stars in the solar neighbourhood. In this interpretation, the main trend in the $[\alpha/\mathrm{Fe}]$ versus [Fe/H] plane (Fig. 11) is dominated by the enrichment process of the few massive dwarfs whose debris dominates the metal-poor star counts in the solar neighbourhood. One example would be the progenitor of the Arcturus group, which probably self-enriched rapidly to $[\mathrm{Fe/H}] \sim -0.5$ before disruption, and therefore contributed mostly stars highly enhanced in $[\alpha/\mathrm{Fe}]$.

A number of critical enquiries should be pursued before one may elevate this speculation into a working hypothesis to guide the interpretation of future data sets. These enquiries will soon become possible, as the completion of large-scale surveys such as those planned by the RAVE collaboration (Steinmetz 2003) or by *GAIA* (Perryman et al. 2001) promise to provide a comprehensive appraisal of the importance of kinematical substructure in the dynamics of the Galaxy.

Detailed abundance studies of stars selected from such surveys to belong dynamically to either the Arcturus or ωCen groups may corroborate the 'closed-box' evolutionary sequence outlined for the progenitors of these stellar groups. (We note, however, that this may only apply to the low-mass end of accreted dwarfs, as large satellites like, say, the LMC, may themselves have been built through the assembly of smaller subunits.) The discovery of further dynamically and chemically coherent groups associated with stars of anomalous chemistry in the solar neighbourhood would be especially helpful to confirm the extra-Galactic origin of such stars.

Finally, ongoing studies of the kinematics of thick discs in external galaxies (see, for example, Dalcanton, Yoachim & Bernstein 2004) hold the promise of extending these studies beyond the unique environment of the Milky Way and to unravel the cosmological role of accretion events in the formation of the various galactic components.

[3] We note that Chiba & Beers (2000) argue against the presence of such correlation in reference to the work of ELS. However, this applies only to the most metal-poor tail of the halo distribution, i.e. to stars with $[\mathrm{Fe/H}] \lesssim -2.2$ (see also Bekki & Chiba 2000 for further discussion). Our comment, on the other hand, refers to all stars in the Beers et al. (2000) sample, i.e. those with $[\mathrm{Fe/H}] \lesssim -0.6$.

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REFERENCES

Abadi M. G., Navarro J. F., Steinmetz M., Eke V. R., 2003a, ApJ, 591, 499
Abadi M. G., Navarro J. F., Steinmetz M., Eke V. R., 2003b, ApJ, 597, 21
Bahcall N. A., Ostriker J. P., Perlmutter S., Steinhardt P. J., 1999, Sci, 284, 1481
Beers T. C., Chiba M., Yoshii Y., Platais I., Hanson R. B., Fuchs B., Rossi S., 2000, AJ, 119, 2866 (B00)
Bekki K., Chiba M., 2000, ApJ, 534, L89
Bonifacio P., Sbordone L., Marconi G., Pasquini L., Hill V., 2004, A&A, 414, 503
Brook C. B., Kawata D., Gibson B. K., Flynn C., 2003, ApJ, 585, L125
Carney B. W., Wright J. S., Sneden C., Laird J. B., Aguilar L. A., Latham D. W., 1997, AJ, 114, 363
Chiba M., Beers T. C., 2000, AJ, 119, 2843
Chiba M., Mizutani A., 2004, PASA, 21, 237
Crane J. D., Majewski S. R., Rocha-Pinto H. J., Frinchaboy P. M., Skrutskie M. F., Law D. R., 2003, ApJ, 594, L119
Dalcanton J. J., Yoachim P., Bernstein R. A., 2004, ApJ, 608, 189
Dinescu D. I., 2002, in van Leeuwen F., Hughes J. D., Piotto G., eds, ASP Conf. Ser. Vol. 265, Centauri: a Unique Window into Astrophysics. Astron. Soc. Pac., San Francisco, p. 365
Dinescu D. I., Girard T. M., van Altena W. F., 1999, AJ, 117, 1792
Eggen O. J., 1971, PASP, 83, 271
Eggen O. J., Lynden-Bell D., Sandage A. R., 1962, ApJ, 136, 748 (ELS)
Freeman K. C., 1993, in Smith G. H., Brodie J. P., eds, ASP Conf. Ser. Vol. 48, The Globular Clusters–Galaxy Connection. Astron. Soc. Pac., San Francisco, p. 608
Freeman K., Bland-Hawthorn J., 2002, ARA&A, 40, 487
Fulbright J. P., 2000, AJ, 120, 1841
Fulbright J. P., 2002, AJ, 123, 404
Gilmore G., Reid N., 1983, MNRAS, 202, 1025
Gilmore G., Wyse R. F. G., Norris J. E., 2002, ApJ, 574, L39
Gratton R. G., Carretta E., Claudi R., Lucatello S., Barbieri M., 2003, A&A, 404, 187 (GCCLB)
Hanson R. B., Sneden C., Kraft R. P., Fulbright J., 1998, AJ, 116, 1286
Hayashi E., Navarro J. F., Taylor J. E., Stadel J., Quinn T., 2003, ApJ, 584, 541
Helmi A., White S. D. M., de Zeeuw P. T., Zhao H., 1999, Nat, 402, 53
Helmi A., Navarro J. F., Meza A., Steinmetz M., Eke V. R., 2003, ApJ, 592, L25
Ibata R. A., Gilmore G., Irwin M. J., 1994, Nat, 370, 194
Ibata R. A., Irwin M. J., Lewis G. F., Ferguson A. M. N., Tanvir N., 2003, MNRAS, 340, L21
Kennicutt R. C., 1998, ApJ, 498, 541
King J. R., 1997, AJ, 113, 2302
Lee Y.-W., Joo J.-M., Sohn Y.-J., Rey S.-C., Lee H.-C., Walker A. R., 1999, Nat, 402, 55
Majewski S. R., 1992, ApJS, 78, 87
Martin N. F., Ibata R. A., Bellazzini M., Irwin M. J., Lewis G. F., Dehnen W., 2004, MNRAS, 348, 12
Matteucci F., Francois P., 1989, MNRAS, 239, 885
May A., Binney J., 1986, MNRAS, 221, 857
Mizutani A., Chiba M., Sakamoto T., 2003, ApJ, 589, L89
Navarro J. F., Helmi A., Freeman K. C., 2004, ApJ, 601, L43
Newberg H. J. et al., 2002, ApJ, 569, 245
Nissen P. E., Schuster W. J., 1997, A&A, 326, 751
Norris J. E., Da Costa G. S., 1995, ApJ, 447, 680
Norris J. E., Freeman K. C., Mighell K. J., 1996, ApJ, 462, 241
Peñarrubia J., Kroupa P., Boily C. M., 2002, MNRAS, 333, 779

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Perryman M. A. C. et al., 2001, A&A, 369, 339
Prochaska J. X., Naumov S. O., Carney B. W., McWilliam A., Wolfe A. M., 2000, AJ, 120, 2513
Quinn P. J., Goodman J., 1986, ApJ, 309, 472
Quinn P. J., Hernquist L., Fullagar D. P., 1993, ApJ, 403, 74
Robin A. C., Haywood M., Creze M., Ojha D. K., Bienayme O., 1996, A&A, 305, 125
Rocha-Pinto H. J., Majewski S. R., Skrutskie M. F., Crane J. D., 2003, ApJ, 594, L115
Searle L., Zinn R., 1978, ApJ, 225, 357 (SZ)
Shetrone M. D., Côté P., Sargent W. L. W., 2001, ApJ, 548, 592
Shetrone M. D., Venn K. A., Tolstoy E., Primas F., Hill V., Kaufer A., 2003, AJ, 125, 684
Smith V. V., 2004, in McWilliam A., Rauch M., eds, Carnegie Obs. Astrophys. Ser. Vol. 4, Origin and Evolution of the Elements. Cambridge Univ. Press, Cambridge, p. 186
Steinmetz M., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy: Science and Technology. Astron. Soc. Pac., San Francisco, p. 381
Steinmetz M., Navarro J. F., 2002, New Astron., 7, 155
Suntzeff N. B., Kraft R. P., 1996, AJ, 111, 1913
Tinsley B. M., 1979, ApJ, 229, 1046
van den Bergh S., 1999, A&ARv, 9, 273
Venn K. A., Irwin M., Shetrone M. D., Tout C. A., Hill V., Tolstoy E., 2005, AJ, 128, 1177
Wyse R. F. G., 2004, in Livio M., ed., Proc. 2003 May Symposium of the Space Telescope Science Institute, The Local Group as an Astrophysical Laboratory. Cambridge Univ. Press, Cambridge, in press (astro-ph/0402636)
Yanny B. et al., 2003, ApJ, 588, 824

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