Mon. Not. R. Astron. Soc. **346,** L11–L15 (2003)

# Formation of $\omega$ Centauri from an ancient nucleated dwarf galaxy in the young Galactic disc

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Accepted 2003 October 9. Received 2003 September 21

## ABSTRACT

We first present a self-consistent dynamical model in which $\omega$ Cen is formed from an ancient nucleated dwarf galaxy merging with the first generation of the Galactic thin disc in a retrograde manner with respect to the Galactic rotation. Our numerical simulations demonstrate that during merging between the Galaxy and the $\omega$ Cen host dwarf with $M_{\rm B} \simeq -14$ mag and its nucleus mass of $10^7$ $\mathrm{M}_{\odot}$, the outer stellar envelope of the dwarf is nearly completely stripped, whereas the central nucleus can survive from the tidal stripping because of its compactness. The developed naked nucleus has a very bound retrograde orbit around the young Galactic disc, as observed for $\omega$ Cen, with apocentre and pericentre distances of $\sim$8 and $\sim$1 kpc, respectively. The Galactic tidal force can induce radial inflow of gas to the centre of the dwarf and consequently triggers moderately strong nuclear starbursts in a repetitive manner. This result implies that efficient nuclear chemical enrichment resulting from the later starbursts can be closely associated with the origin of the observed relatively young and metal-rich stars in $\omega$ Cen. Dynamical heating by the $\omega$ Cen host can transform the young thin disc into the thick disc during merging.

**Key words:** globular clusters: individual: $\omega$ Centauri.

## 1 INTRODUCTION

The most massive Galactic globular cluster, $\omega$ Cen, is observed to have unique physical properties, such as a very flattened shape for a globular cluster (e.g. Meylan 1987), broad metallicity distribution (e.g. Freeman & Rodgers 1975; Norris, Freeman & Mighell 1996), strong variations of nearly all element abundances among its stars (e.g. Norris & Da Costa 1995; Smith et al. 2000), kinematical difference between its metal-rich and metal-poor stellar populations (e.g. Norris et al. 1997), multiple stellar populations with different spatial distributions (e.g. Pancino et al. 2000; Ferraro, Bellazzini & Pancino 2002), star formation history extending over a few Gyr (Lee et al. 1999; Smith et al. 2000), and its very bound retrograde orbit with respect to the Galactic rotation (Dinescu, Girard & van Altena 1999). These unique characteristics have been considered to suggest that there are remarkable differences in star formation histories, chemical enrichment processes and structure formation between $\omega$ Cen and other Galactic normal globular clusters (e.g. Hilker & Richtler 2000, 2002).

The observed extraordinary nature of $\omega$ Cen has attracted much attention from theoretical and numerical works on chemical and dynamical evolution of $\omega$ Cen (e.g. Icke & Alcaino 1988; Carraro & Lia 2000; Gnedin et al. 2002; Zhao 2002). One of the most extensively discussed scenarios for $\omega$ Cen formation is that $\omega$ Cen is the surviving nucleus of an ancient nucleated dwarf galaxy with its outer stellar envelope almost entirely removed by tidal stripping of the Galaxy (Zinnecker et al. 1988; Freeman 1993). The observed atypical bimodal or multimodel metallicity distribution (e.g. Norris et al. 1996) and the metal-rich stellar population, which is 2–4 Gyr younger than the metal-poor population(Lee et al. 1999; Hilker & Richtler 2000; Hughes & Wallerstein 2000), have been suggested to support this scenario. However, because of the lack of extensive numerical studies on dynamical evolution of *nucleated* dwarf galaxies interacting/merging with the Galaxy, it remains unclear when and how an ancient nucleated dwarf galaxy loses *only* its stellar envelope without totally destroying its nucleus in its dynamical interaction with the Galaxy.

The purpose of this Letter is to demonstrate that $\omega$ Cen can be formed from an ancient nucleated dwarf galaxy interacting/merging with the young Galactic disc ($\sim$10 Gyr ago). We consider that if $\omega$ Cen is formed from merging between a massive, compact nucleated dwarf and the Galaxy, the merging epoch should be well before the formation of the present-day thin disc, because such a massive dwarf can significantly heat up the thin Galactic disc (e.g. Quinn, Hernquist & Fullagar 1993). Our fully self-consistent numerical simulations demonstrate that the stellar envelope of the nucleated dwarf with $M_{\rm B} \sim -14$ can be nearly completely stripped by the strong tidal

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field of the first generation of the Galactic thin disc with the stellar mass only ∼10 per cent of the mass of the present-day Galactic thin disc (i.e. the same as that of the present-day thick disc), whereas the central nucleus can remain intact owing to its compactness. Recently Mizutani, Chiba & Sakamoto (2003) and Tsuchiya, Dinescu & Korchagin (2003) have discussed the formation of $\omega$ Cen in terms of tidal disruption of a dwarf by *the present-day* Galaxy. We discuss the origin of the relatively metal-rich and young stellar populations of $\omega$ Cen in terms of the star formation history of the dwarf, which is strongly influenced by tidal interaction with the first generation of the Galactic thin disc.

## 2 THE MODEL

### 2.1 The Galaxy

We construct the dynamical model of the Galaxy embedded in a massive dark matter halo by using the Fall & Efstathiou (1980) model with a total mass of $M_{\rm t}$. The exponential disc of the Galaxy is assumed to have the radial scalelength ($a_{\rm d}$) of 3.5 kpc, the size ($R_{\rm d}$) of 17.5 kpc, the mass of $M_{\rm d}$ and the ratio of the total Galactic mass to the disc mass ($M_{\rm t}/M_{\rm d}$, hereafter referred to as $F_{\rm d}$). These $M_{\rm d}$ and $F_{\rm d}$ values are considered to be important parameters for the young Galactic disc. In the adopted Fall–Efstathiou model, the rotation curve becomes nearly flat at 1.75 $a_{\rm d}$ and the dark matter halo is truncated at 8.0 $a_{\rm d}$, which is beyond the region reached by adopted orbit of $\omega$ Cen. If we assume that $M_{\rm d} = 6.0 \times 10^{10}$ M$_{\odot}$ [hereafter referred to as $M_{\rm d}(0)$] and $M_{\rm t} = 3.0 \times 10^{11}$ M$_{\odot}$ [hereafter $M_{\rm t}(0)$], the maximum circular velocity is 220 km s$^{-1}$. In addition to the rotational velocity associated with the gravitational field of disc and halo component, the initial radial and azimuthal velocity dispersion are given to disc component according to the epicyclic theory with Toomre's parameter (Binney & Tremaine 1987) $Q$ = 1.5. The vertical velocity dispersion at given radius are set to be 0.5 times as large as the radial velocity dispersion at that point, as is consistent with the observed trend of the Milky Way (e.g. Wielen 1977).

In the present study, we consider that merging between the $\omega$ Cen progenitor and the young Galaxy happened when the *stellar disc mass* of the Galaxy is only 10 per cent of the mass of the present-day Galactic thin disc [$M_{\rm d}(0)$]. The *total mass* of the young Galactic disc is highly likely to be larger than 0.1 (because of the possibly gas-rich nature of the disc) and we mainly present the results of the models with $M_{\rm d} = 0.2 \times M_{\rm d}(0)$. Because there are no observational constraints on the dark matter content of the young galaxy, we mainly investigate the models with $F_{\rm d} = 10.0$ [$M_{\rm t} = 0.4 \times M_{\rm t}(0)$] and 20.0 [$M_{\rm t} = 0.8 \times M_{\rm t}(0)$]. For comparison, we also investigate the model with a Galactic bulge with the $R^{1/4}$ density profile, the effective radius of 0.7 kpc and the mass ($M_{\rm b}$) of $10^{10}$ M$_{\odot}$.

### 2.2 The $\omega$ Cen progenitor: a nucleated dwarf

In estimating the initial stellar mass of the nucleated dwarf (i.e. the host galaxy of $\omega$ Cen), we consider the following two points: (i) the mass fraction of the nucleus (hereafter referred to as $f_{\rm n}$) is observed to range from 2 to 20 per cent for nucleated dwarfs in nearby clusters (e.g. Binggeli & Cameron 1991) and (ii) given the observationally estimated small pericentre ($r_{\rm peri}$) and apocentre distance ($r_{\rm apo}$) of the present-day orbit of $\omega$ Cen with respect to the Galaxy (Dinescu et al. 1999), stripping of some fraction of stars through long-term (∼10 Gyr) tidal interaction with the Galaxy (e.g. Combes, Leon & Meylan 1999) is highly likely for $\omega$ Cen. We therefore consider that the initial stellar mass $m_{\rm dw}$ of its host is equal to $(1.0 - f_{\rm lost})^{-1} f_{\rm n}^{-1} m_{\omega}$, where $m_{\omega}$ is the present-day mass of $\omega$ Cen (=5.0 × $10^6$ M$_{\odot}$; Meylan et al. 1995). If we adopt an $f_{\rm lost}$ of 0.2 and an $f_{\rm n}$ of 0.05, $m_{\rm dw}$ is 1.25 × $10^8$ M$_{\odot}$. The nucleated dwarf with $M_{\rm B}$ (*B*-band absolute magnitude) is assumed to consist of dark matter halo, stellar envelope, and nucleus. The stellar nucleus is modelled by the Plummer model with the scalelength of $a_{\rm n}$. Although we investigated both dwarf disc and spheroidal/elliptical models for the stellar envelopes, we show only the results of the dwarf disc models. We use the Fall & Efstathiou (1980) model for the dwarf disc models with $M_{\rm t} = 10 \times M_{\rm d}$ and the central *B*-band surface brightness ($\mu_0$) of 22 and 24 mag arcsec$^{-2}$.

### 2.3 The orbit of the dwarf

The centre of the Galaxy is set to be $(x, y, z) = (0, 0, 0)$ and the initial position and velocity of a dwarf are $(x, y, z) = [(\cos\theta)\, r_{\rm in}, 0, (\sin\theta)\, r_{\rm in}]$ and $(v_{\rm x}, v_{\rm y}, v_{\rm z}) = (0, v_{\rm in}, 0)$, respectively, where $r_{\rm in}$, $\theta$ and $v_{\rm in}$ are the distance from the Galactic centre, the inclination angle of the orbit of the dwarf with respect to the Galactic plane, and the velocity of the dwarf, respectively. The positive sign of $v_{\rm in}$ represents a prograde orbit with respect to the Galactic rotation. We present the results for the models with $r_{\rm in} = 1.5\, R_{\rm d}$ (=26.25 kpc), in which the dwarf can intrude into the Galaxy from well outside the disc component.

### 2.4 The fiducial model

We first searched for a collisionless model in which the end product satisfies the following two conditions: (i) only the nucleus of the dwarf can survive with the envelope being almost completely stripped and (ii) the developed 'naked nucleus' has an orbit similar to that observed for the present-day $\omega$ Cen (i.e. strongly retrograde orbit nearly confined within the Galactic plane; e.g. Dinescu et al. 1999). We found that the model with $M_{\rm B} \sim -14$ mag, the mass fraction of the nucleus of the dwarf of ∼ 0.05, $\mu_0 = 24$ mag arcsec$^{-2}$, $\theta \sim 30^{\circ}$ and $v_{\rm in} \sim -60$ km s$^{-1}$ (i.e. $e_{\rm p} \sim 0.63$) can satisfy the two required conditions above in the bulgeless Galaxy model with $M_{\rm d} = 0.2 \times M_{\rm d}(0)$ and $F_{\rm d} = 10$. We mainly show this fiducial results of the model. Fig. 1 shows the orbital evolution for the fiducial model as well as for those which did not succeed in satisfying the two conditions. These unsuccessful collisionless models suggest that (i) it is the density of the satellite that determines at which galactiocentric radius it will disrupt, whereas it is the mass of the satellite that determines the rate of orbital decay, and (ii) the more massive young Galaxy and the Galaxy with the bulge can prevent the survival of $\omega$ Cen-like clusters with the pericentre of <5 kpc.

For the fiducial model, we also investigate the star formation history of the dwarf disc by assuming the gas mass fraction of 0.1 and by adopting the Schmidt law (Schmidt 1959) with an exponent of 1.5. An isothermal equation of state is used for the gas with a temperature of 2.5 × $10^3$ K. We first describe the results of the collisionless fiducial model and then describe the model including star formation. The total number of particles used for each model are 30 000 for the Galactic dark matter, 20 000 for the Galactic stellar disc, 10 000 for the dark matter of the dwarf, 20 000 for the stellar envelope of the dwarf, 10 000 for the gas of the dwarf and 5000 for the nucleus of the dwarf (all of these are 'live'). All the calculations related to the evolution of collisionless models have been carried out on the GRAPE board (Sugimoto et al.

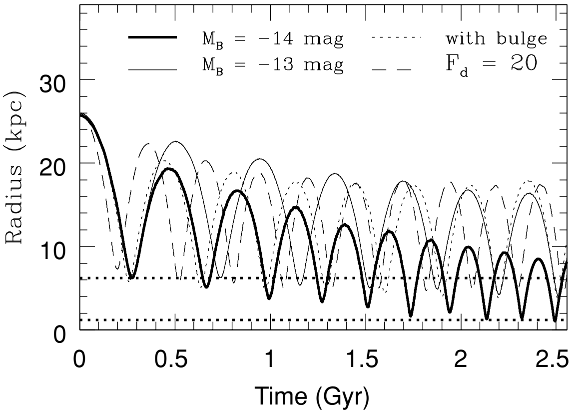

**Figure 1.** Orbital evolution of the nucleated dwarf for four different models with initial $e_{\mathrm{p}} \sim 0.63$: the fiducial model with $M_{\mathrm{B}} = -14.0$ mag, $F_{\mathrm{d}} = 5$ and $M_{\mathrm{b}} = 0$ (thick solid line); the less luminous one with $M_{\mathrm{B}} = -13.0$ mag, $F_{\mathrm{d}} = 5$ and $M_{\mathrm{b}} = 0$ (thin solid line); the bulge model with $M_{\mathrm{B}} = -14.0$ mag, $F_{\mathrm{d}} = 5$ and $M_{\mathrm{b}} = 10^{10}$ $\mathrm{M}_{\odot}$ (thin dotted line); and the more massive Galaxy model with $M_{\mathrm{B}} = -14.0$ mag, $F_{\mathrm{d}} = 20$ and $M_{\mathrm{b}} = 0$ (dashed). The upper and lower thick (horizontal) lines represent the observed apocentre (6.2 kpc) and pericentre distance (1.2 kpc) of the orbit of ω Cen's (Dinescu et al. 1999). Note that only the nucleus of the more luminous dwarf can reach the central region of the Galaxy within a few Gyr. Note also that the dwarfs in the latter two models can not approach the inner region of the Galaxy because the dwarfs are completely destroyed before dynamical friction cause significant orbital decay of the dwarf.

1990) and the models including star formation and hydrodynamical evolution are investigated by using TREESPH codes described in Bekki (1995, 1997). Different gravitational softening lengths are allocated for different components (e.g. nucleus) so that we can investigate the dynamical scale on both the Galaxy-scale and the dwarf-scale.

## 3 RESULTS

Figs 1 and 2 summarize the dynamical evolution of the stellar component of the dwarf in the collisionless fiducial model. As the dwarf sinks into the inner region of the Galactic disc, owing to dynamical friction, the outer low surface brightness stellar envelope is efficiently stripped by the Galactic strong tidal force ($T = 0.93$ Gyr). The compact prolate bar-like structure can be formed when the dwarf passes by its orbital pericentre because of the tidal perturbation. The dwarf finally lose most of its initial stellar (and dark matter) mass within ∼2.6 Gyr. The stripped stars forms an inner stellar halo with the total mass of $\sim 10^8$ $\mathrm{M}_{\odot}$ (corresponding to less than 10 per cent of the present-day Galactic stellar halo mass) and the initial Galactic thin disc finally become significantly thickened owing to the vertical heating by the dwarf (See Fig. 3).

The nucleus, on the other hand, can survive tidal destruction by the Galaxy owing to its initial compact configuration (See Fig. 3). The developed 'naked nucleus' still follows the decayed dwarf orbit at the time of the destruction of the dwarf so that it has orbital eccentricity of 0.78 ($r_{\mathrm{peri}} = 1.0$ kpc and $r_{\mathrm{apo}} = 8$ kpc for the final 0.2 Gyr) similar to the observationally suggested one (∼0.7). The total mass within the central 100 pc of the dwarf is $6.2 \times 10^6$ $\mathrm{M}_{\odot}$ for the nucleus, $3.4 \times 10^6$ $\mathrm{M}_{\odot}$ for the stellar envelope, and $0.4 \times 10^6$ $\mathrm{M}_{\odot}$ for the dark matter at $T = 2.6$ Gyr, which means that the surviving nucleus is dominated by baryonic components. Thus a ω Cen-like stellar cluster with the mass of $10^7$ $\mathrm{M}_{\odot}$ and almost no dark matter can be formed from the dwarf galaxy dominated by dark matter. We expect that this cluster will further decrease its apocentre distance and its stellar mass slowly, owing to dynamical friction and tidal stripping (e.g. Zhao 2002).

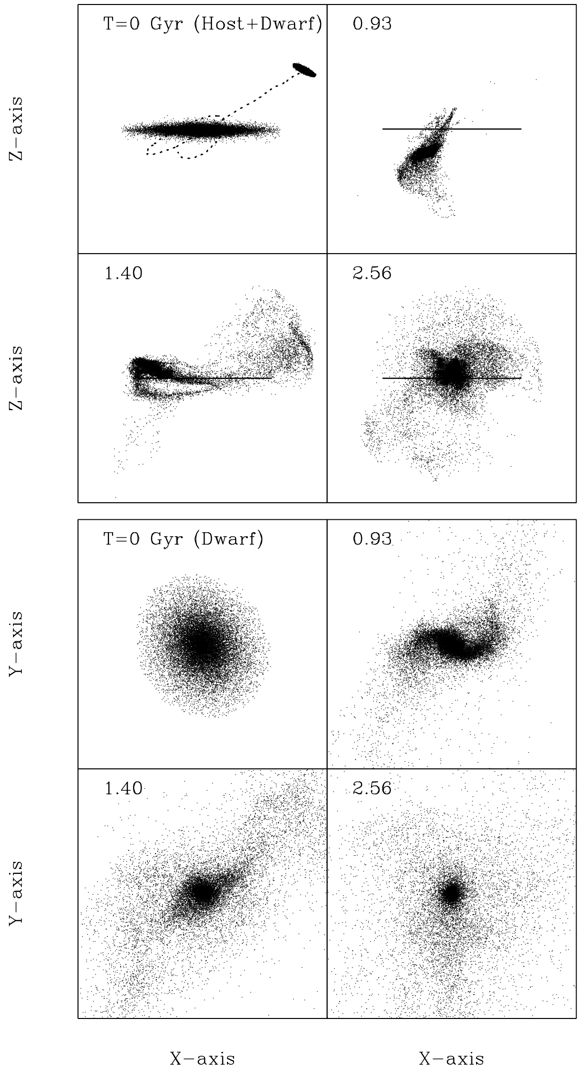

**Figure 2.** Morphological evolution of stellar components of the nucleated dwarf galaxy projected on to the $x$–$z$ plane (upper four) and on to the $x$–$y$ one (lower four) in the fiducial model. For clarity, the Galactic plane is represented as a solid line in the three of the upper four panels. The time $T$ (in our units) represents the time that has elapsed since the simulation started. Each frame in the upper (lower) four panels measures 54.6 (9.4) kpc on each side. For comparison, we plot the initial Galactic disc stars at $T = 0$ and the orbit for the first 0.93 Gyr (dotted line) in the left-most of the upper four panels.

## 4 STAR FORMATION HISTORY

Fig. 4 shows that the star formation of the fiducial model with gas dynamics is moderately enhanced around $T \sim 1.2$ Gyr (0.025 $\mathrm{M}_{\odot}$ $\mathrm{yr}^{-1}$) and ∼2.2 Gyr (0.02 $\mathrm{M}_{\odot}$ $\mathrm{yr}^{-1}$; also at $T = 0.2$, 0.6, 0.8, 1.0 and 1.5 Gyr). This enhancement of star formation can result from the radial gas inflow induced by tidal torque of the developed prolate (bar-like) stellar structure in the dwarf. As a result of this, 40 per cent of the initial gas is consumed up by the triggered star formation, and mass fraction of new stars to the nucleus (old stars) within 200 pc becomes rather high (0.21) at $T = 2.6$ Gyr.

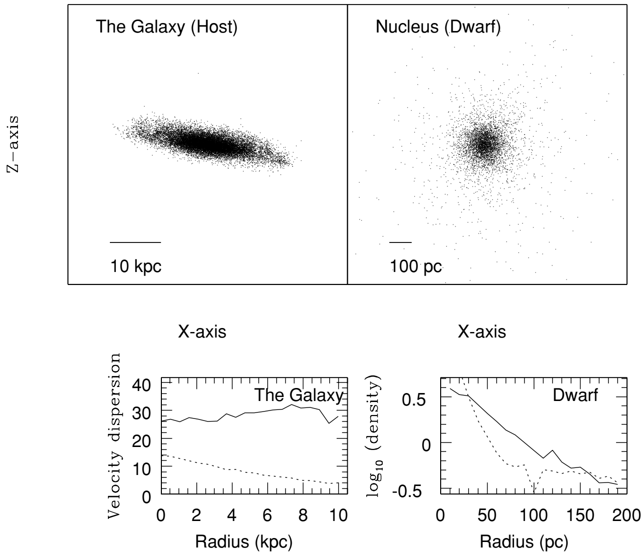

**Figure 3.** Upper two panels: final mass distribution of the Galactic stellar disc (left-hand panel) and the nucleus of the survived dwarf (right-hand panel) projected on to the *x–y* plane at = 2.56 Gyr. Note that the $\omega$ Cen host dwarf can cause significant dynamical heating (vertical thickening) of the first generation of the Galactic thin disc. Lower two panels: initial (dotted line) and final (solid, at $T = 2.56$ Gyr) radial dependences of the vertical velocity dispersion ($\sigma_z$) for the initial Galactic disc in units of km $\mathrm{s^{-1}}$ (left-hand panel) and the initial (dotted line) and final (solid line) density distributions of the dwarf projected on to the $x - y$ plane for the central 200 pc. The decrease of the central density of the dwarf is due mostly to numerical effects caused by the introduction of gravitational softening length.

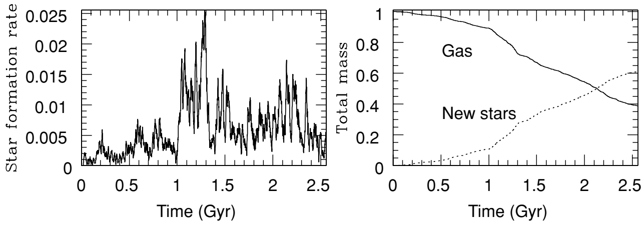

**Figure 4.** The time-evolution of star formation rate (in units of $\mathrm{M_{\odot}\ yr^{-1}}$) in the fiducial model (left-hand panel) and the time evolution of the mass (normalized by the initial gas mass) for the gas (solid line) and the new stars (dotted line) in the model (right-hand panel).

Because such efficient star formation can naturally cause rapid chemical enrichment due to metal ejection from supernovae, the new stars are highly likely to be more metal-rich than the old nucleus component and form a secondary peak of the metallicity distribution of the nucleus. These results suggest that the observed unique chemical evolution history of $\omega$ Cen can be understand in the context of the repetitive radial gas inflow to the nucleus of the dwarf (and the resultant moderate starbursts and chemical enrichment there) triggered by tidal interaction with the Galaxy. We also suggest that the observed spatial distribution and kinematics of relatively metal-rich populations with $-\ 1.2 \leqslant$ [Fe/H] $\leqslant -0.6$ in $\omega$ Cen (Norris et al. 1997; Pancino et al. 2000; Ferraro et al. 2002) can reflect the detail of the radial gaseous inflow processes in the dwarf nucleus. The new stellar populations in the nucleus might well be classified as new clusters rather than field stars, because star clusters are more likely to be formed in the central regions of interacting/merging galaxies because of very high gas pressure (Bekki et al. 2002). The merging of these young clusters with the nucleus of the dwarf can cause flattening (by rotation) of the shape of the nucleus and thus be responsible for the observed flattened shape and unusual rapid rotation of $\omega$ Cen.

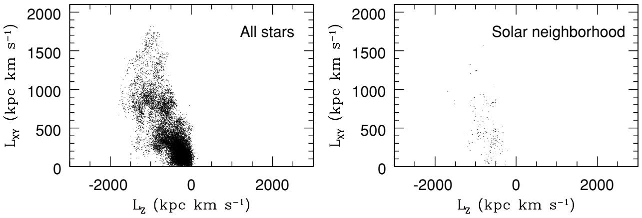

**Figure 5.** The distribution of stars stripped from the $\omega$ Cen host dwarf on the $L_z - L_{xy}$ plane for all stars (left-hand panel) and those within 5 kpc from the solar neighborhood (right-hand panel). Here $L_z$ ($L_x$, $L_y$) and $L_{xy}$ are the angular momentum component in the *z* (*x*, *y*) direction and $(L^2{}_x + L^2{}_y)^{1/2}$, respectively, and this $L_{xy}$ is not strictly a conserved quantity. The right panel can be directly compared with observations shown in fig. 15 of the paper by Chiba & Beers (2000).

## 5 DISCUSSIONS AND CONCLUSIONS

If $\omega$ Cen was previously the nucleus of a nucleated dwarf galaxy, what fossil evidences for this can be seen in the Galactic halo region? Fig. 5 demonstrates that the tidally stripped stellar envelope of the $\omega$ Cen host shows a characteristic distribution in the $L_z - L_{xy}$ plane, where $L_z(L_x,\ L_y)$ and $L_{xy}$ are the angular momentum component in the *z* (*x*, *y*) direction and $(L_x^2 + L_y^2)^{1/2}$, respectively. These stars around the solar neighbourhood also show some crowding around $L_z \sim -500$ and $L_{xy} \sim 300$ kpc km $\mathrm{s^{-1}}$, which reflects the orbital evolution of the dwarf. If we adopt the observed luminosity–metallicity relation $[\mathrm{Fe/H}]_* = -3.43(\pm\,0.14) - 0.157(\pm\,0.012)\,M_V$ (Côta et al. 2000) for dwarfs, we can expect that the stellar halo formed from the $\omega$ Cen host with $M_B \sim -14$ mag has the likely peak value of [Fe/H] $\sim -1.2$ (or somewhere between $-1.5$ and $-0.84$ in [Fe/H]) in its metallicity distribution for $B - V = 0.5$. Thus we suggest that the Galactic halo stars with [Fe/H] $\sim -1.2$ and $L_z \sim -500$ and $L_{xy} \sim 300$ kpc km $\mathrm{s^{-1}}$ can originate from the host of $\omega$ Cen. $\omega$ Cen-like objects have been already discovered in other galaxies and environments: G1 in M31 (e.g. Meylan et al. 2001) and very bright G1-like cluster in NGC 1023 (Larsen 2001). We suggest that if $\omega$ Cen-like objects in disc galaxies are formed from ancient nucleated dwarfs merging with discs, there should be some correlations between the existence of $\omega$ Cen-like objects and the structural properties of the discs, because galaxy interaction/merging can be responsible not only for the formation of thick discs and bars but also for the formation of starbursts and active galactic nuclei (e.g. Noguchi 1987). For example, it is an interesting observational question whether or not disc galaxies with $\omega$ Cen-like objects are more likely to have thick discs.

## ACKNOWLEDGMENT

KB acknowledge the financial support of the Australian Research Council throughout the course of this work.

## REFERENCES

Bekki K., 1995, MNRAS, 276, 9
Bekki K., 1997, ApJ, 483, p. 608

Bekki K., Forbes Duncan A., Beasley M. A., Couch W. J., 2002, MNRAS, 335, 1176
Binggeli B., Cameron L. M., 1991, A&A, 252, 27
Binney J., Tremaine S., 1987, in Galactic Dynamics. Princeton Univ. Press, Princeton
Carraro G., Lia C., 2000, A&A, 357, 977
Chiba M., Beers T. C., 2000, AJ, 119, 2843
Combes F., Leon S., Meylan G., 1999, A&A, 352, 149
Côta P., Marzke R. O., West M. J., Minniti D., 2000, ApJ, 533, 869
Dinescu D. I., Girard T. M., van Altena W. F., 1999, AJ, 117, 1792
Fall S. M., Efstathiou G., 1980, MNRAS, 193, 189
Ferraro F. R., Bellazzini M., Pancino E., 2002, ApJ, 573, L95
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. C., Rodgers A. W., 1975, ApJ, 201, L71
Gnedin Oleg Y., Zhao H., Pringle J. E., Fall S. M., Livio M., Meylan G., 2002, ApJ, 568, L23
Hilker M., Richtler T., 2000, A&A, 362, 895
Hilker M., Richtler T., 2002, in van Leeuwen F., Hughes J. D., Piotto G., eds, ASP Conf. Ser. Vol. 265, Omega Centauri, a Unique Window into Astrophysics. Astron. Soc. Pac., San Francisco, p. 59
Hughes J., Wallerstein G., 2000, AJ, 119, 1225
Icke V., Alcaino G., 1988, A&A, 204, 115
Larsen S. S., 2001, AJ, 122, 1782
Lee Y.-W., Joo J.-M., Sohn Y.-J., Rey S.-C., Lee H.-C., Walker A. R., 1999, Nat, 402, 55
Meylan G., 1987, A&A, 184, 144
Meylan G., Mayor M., Duquennoy A., Dubath P., 1995, A&A, 303, 761
Meylan G., Sarajedini A., Jablonka P., Djorgovski S. G., Bridges T., Rich R. M., 2001, AJ, 122, 830
Mizutani A., Chiba M., Sakamoto T., 2003, ApJ, 589, L89
Noguchi M., 1987, MNRAS, 228, 635
Norris J. E., Da Costa G. S., 1995, ApJ, 447, 680
Norris J. E., Freeman K. C., Mighell K. J., 1996, ApJ, 462, 241
Norris J. E. et al., 1997, ApJ, 487, L187
Pancino E., Ferraro F. R., Bellazzini M., Piotto G., Zoccali M., 2000, ApJ, 534, L83
Quinn P. J., Hernquist L., Fullagar D. P., 1993, ApJ, 403, 74
Schmidt M., 1959, ApJ, 129, 243
Smith V. V., Suntzeff N. B., Cunha K., Gallino R., Busso M. Lambert D. L., Straniero O., 2000, AJ, 119, 1239
Sugimoto D., Chikada Y., Makino J., Ito T., Ebisuzaki T., Umemura M., 1990, Nat, 345, 33
Tsuchiya T., Dinescu D. I., Korchagin V. I., 2003, ApJ, 589, L29
van den Bergh S., 2000, The Galaxies of the Local Group. Cambridge Univ. Press, Cambridge
Wielen R., 1977, A&A, 60, 263
Zhao H. S., 2002, in van Leeuwen F., Hughes J. D., Piotto G., eds, ASP Conf. Ser. Vol. 265, Omega Centauri, A Unique Window into Astrophysics. Astron. Soc. Pac., San Francisco, p. 391
Zinnecker H., Keable C. J., Dunlop J. S., Cannon R. D., Griffiths W. K., 1988, in Grindlay J. E., Davis Philip A. G., eds, Globular Cluster Systems in Galaxies. Kluwer, Dordrecht, p. 603

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