# The Unique History of the Globular Cluster $\omega$ Centauri

Oleg Y. Gnedin[1], HongSheng Zhao[2], J. E. Pringle[1,2], S. Michael Fall[1],
Mario Livio[1], and Georges Meylan[1]

## ABSTRACT

Using current observational data and simple dynamical modeling, we demonstrate that $\omega$ Cen is not special among the Galactic globular clusters in its ability to produce and retain the heavy elements dispersed in the AGB phase of stellar evolution. The multiple stellar populations observed in $\omega$ Cen cannot be explained if it had formed as an isolated star cluster. The formation within a progenitor galaxy of the Milky Way is more likely, although the unique properties of $\omega$ Cen still remain a mystery.

*Subject headings:* globular clusters: individual (NGC 5139), Galaxy: formation

## 1. Omega Centauri, the most massive globular cluster in the Galaxy

Omega Centauri is unique among globular clusters in the Milky Way in that its member stars exhibit a wide spread in metallicity (Freeman & Rodgers 1975; Freeman & Norris 1981; Mallia & Pagel 1981). This has led to the general belief that $\omega$ Cen was chemically self-enriched, while the other clusters were not (Suntzeff & Kraft 1996; see Meylan & Heggie 1997 for a review). In this context, it is often noted that $\omega$ Cen is the most massive globular cluster in the Milky Way and thus possibly the most capable of retaining its own stellar ejecta (e.g., Ikuta & Arimoto 2000). The globular cluster G1 in the halo of the Andromeda galaxy has similar properties; it appears to be self-enriched and is also one of the most massive clusters in its host galaxy (Meylan et al. 2001).

Omega Centauri has several other intriguing and potentially related properties. The metal-rich stellar population is more centrally concentrated and has a lower velocity dispersion than the metal-poor population (Norris et al. 1997). Moreover, the metal-rich population has no detectable rotation, while the metal-poor population rotates relatively rapidly ($\sim 7$ km s$^{-1}$), consistent with the apparent flattening of the cluster, which is among the highest

---

[1]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; ognedin@stsci.edu

[2]Institute of Astronomy, Cambridge CB3 0HA, UK

of all globular clusters in the Galaxy (Frenk & Fall 1982). The metal-rich stellar population also appears to be younger than the metal-poor population, consistent with the idea of self-enrichment over a period $\Delta\tau = 3-5$ Gyr (e.g., Hughes & Wallerstein 2000; Hilker & Richtler 2000; Lee et al. 1999). This is supported by the large enhancement in s-process elements in the metal-rich population relative to that in globular clusters with similar metallicities (Norris & Da Costa 1995; Vanture, Wallerstein & Brown 1994). These properties have led to the suggestion that $\omega$ Cen managed to retain the ejecta from the first generation of stars in the asymptotic giant branch (AGB) phase, which then formed a centrally concentrated, metal-enriched, younger generation of stars (e.g. Norris et al. 1996; Smith et al. 2000).

In this paper we demonstrate that $\omega$ Cen is not special in the ability to retain its own stellar ejecta. The escape speed in $\omega$ Cen is not the highest among the Galactic globular clusters. We find that more than half of the clusters could retain at least 20% of their AGB winds. It is therefore surprising that $\omega$ Cen is the only globular cluster in the Milky Way to show signs of self-enrichment.[3] We conclude that this cluster could not have evolved in isolation on its present orbit in the Galaxy and that it must have been substantially different in the past. We discuss other models suggested previously, including the idea that $\omega$ Cen is the nucleus of a dwarf galaxy that lost its outer envelop by tidal stripping (Zinnecker et al. 1988; Freeman 1993).

## 2. The escape velocity from the cluster

To compute the escape velocities of Galactic globular clusters, we use the photometric data from the catalog by Harris (1996). Out of 147 clusters in the catalog, we choose 141 for which the data are available on the distance, integrated magnitude, core radius, and concentration parameter. All clusters are fit by single-mass isotropic King models with a constant mass-to-light ratio, $M/L_V = 3$ in solar units.

First, we check that the photometric models are consistent with the directly measured central velocity dispersions for a sample of 56 clusters from Pryor & Meylan (1993), their Table 2. The most reliable estimates of the dispersion are based on individual stellar radial

[3]Sarajedini & Layden (1995) have inferred a dispersion of metallicity of 0.16 dex in M54, a globular cluster projected in the center of the Sagittarius dwarf galaxy. Also, Ree et al. (2001) have suggested that two other massive globular clusters (NGC 6388 and NGC 6441) may have an age and/or metallicity spread of 1.2 Gyr and 0.15 dex, respectively. These estimates, however, are not as large as those for $\omega$ Cen and may result from differential reddening or other systematic errors. Until these are confirmed, we assume that $\omega$ Cen is the only Galactic globular cluster with multiple stellar populations.

velocities, but these estimates depend on the position of stars relative to the cluster center. The core velocity dispersion of $\omega$ Cen is 17 km s$^{-1}$ (Merritt, Meylan & Mayor 1997), with the indication that it rises in the center up to 25 km s$^{-1}$ (van Leeuwen et al. 2000).

We thus avoid a direct comparison and show instead in Figure 1 two separate histograms of the central velocity dispersions as inferred from the photometric models and as measured directly. The distributions are qualitatively similar. Also, the photometric model of $\omega$ Cen predicts a central velocity dispersion of about 17 km s$^{-1}$, the same as the observed value.

We note that in the past 20 years there has been only one study (Dubath et al. 1997) providing homogeneous velocity dispersion measurements for a significant number of clusters. Now, with the availability of large-field survey spectrographs such data should be easier to obtain and would provide a very useful constraint on the mass models of globular clusters.

Having calibrated the photometric models, we can use them to determine the escape velocity. This is calculated using the reduced gravitational potential, $v_{\rm esc} \equiv (2\Phi_t - 2\Phi)^{1/2}$, in the center (giving the maximum escape velocity) and at the half-mass radius (providing a threshold for most stars). Here, the tidal potential $\Phi_t$ accounts for truncation at the tidal radius.

Figures 2 and 3 demonstrate that $\omega$ Cen is not special in its escape velocity. There are 11 clusters with higher $v_{\rm esc,0}$ and 8 clusters with higher $v_{\rm esc,h}$.

We also find that the ratio of the central escape velocity to the central velocity dispersion can be fit by a simple relation

$$v_{\rm esc,0}/\sigma_0 = 3.7 + 0.9\,(c - 1.4), \tag{1}$$

where $c$ is the concentration of the King models. The fit is accurate to 3% in the range $c = 0.4 - 2.8$.

We now calculate the fraction of AGB winds retained by a cluster as a function of the wind velocity $u_w$. We integrate the distribution function of stars, $f(E)$, over the phase space volume within which the total velocity of the wind particles is below the escape speed at the star's position:

$$f_w = \frac{1}{M} \int f(E) d\mathbf{r} d\mathbf{v} \frac{1}{4\pi} \int d\Omega_u \, h(v_{\rm esc}(r) - |\mathbf{v} + \mathbf{u}_w|), \tag{2}$$

where $\Omega_u$ is a solid angle of the wind velocity $\mathbf{u}_w$, and $h(x)$ is a unit step function.

Figure 4 shows the result for clusters of various concentration parameters, from $c = 0.6$ to 2.4. The fraction $f_w$ declines gradually and even the clusters with $u_w \sim 3\sigma_0$ can retain 10 to 20% of their winds. Since according to Loup et al. (1993) the characteristic terminal

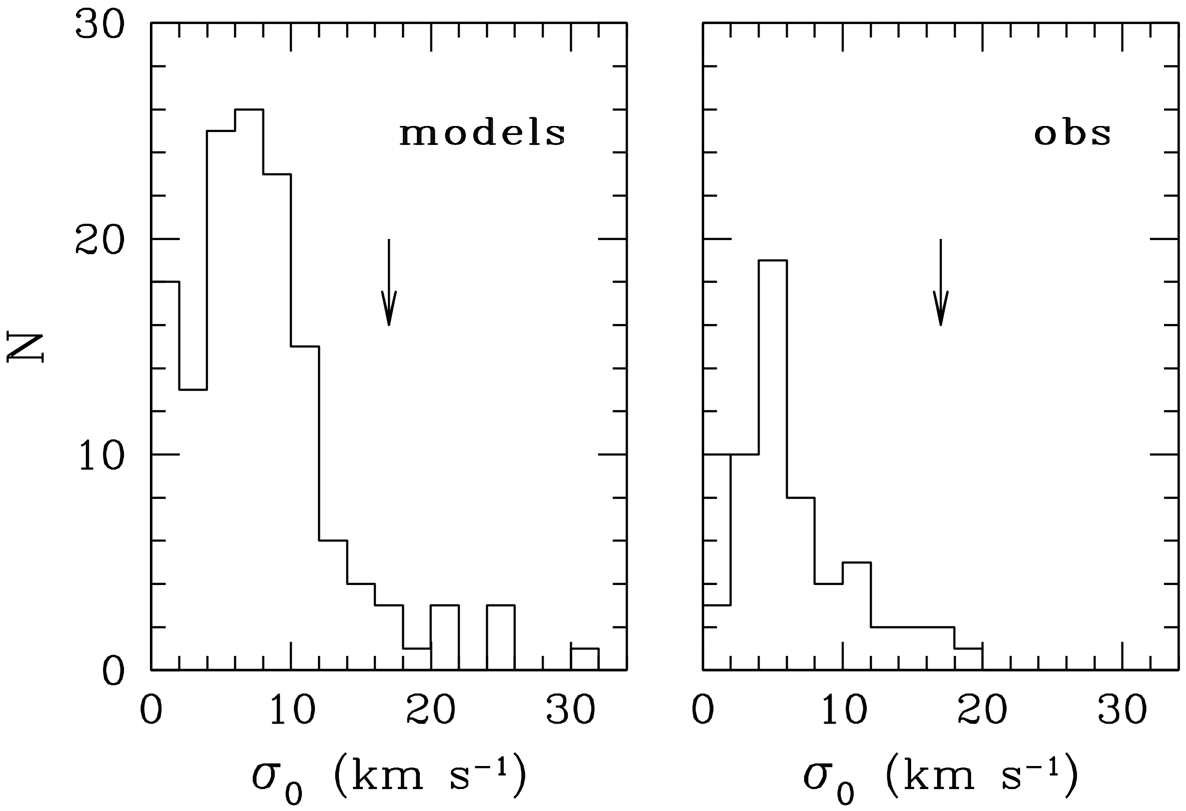


Fig. 1.— Distribution of the central line-of-sight velocity dispersion of the Galactic globular clusters, as inferred from the photometric models (left panel) and observed spectroscopically (right panel). The arrows point to the velocity dispersion of $\omega$ Cen.

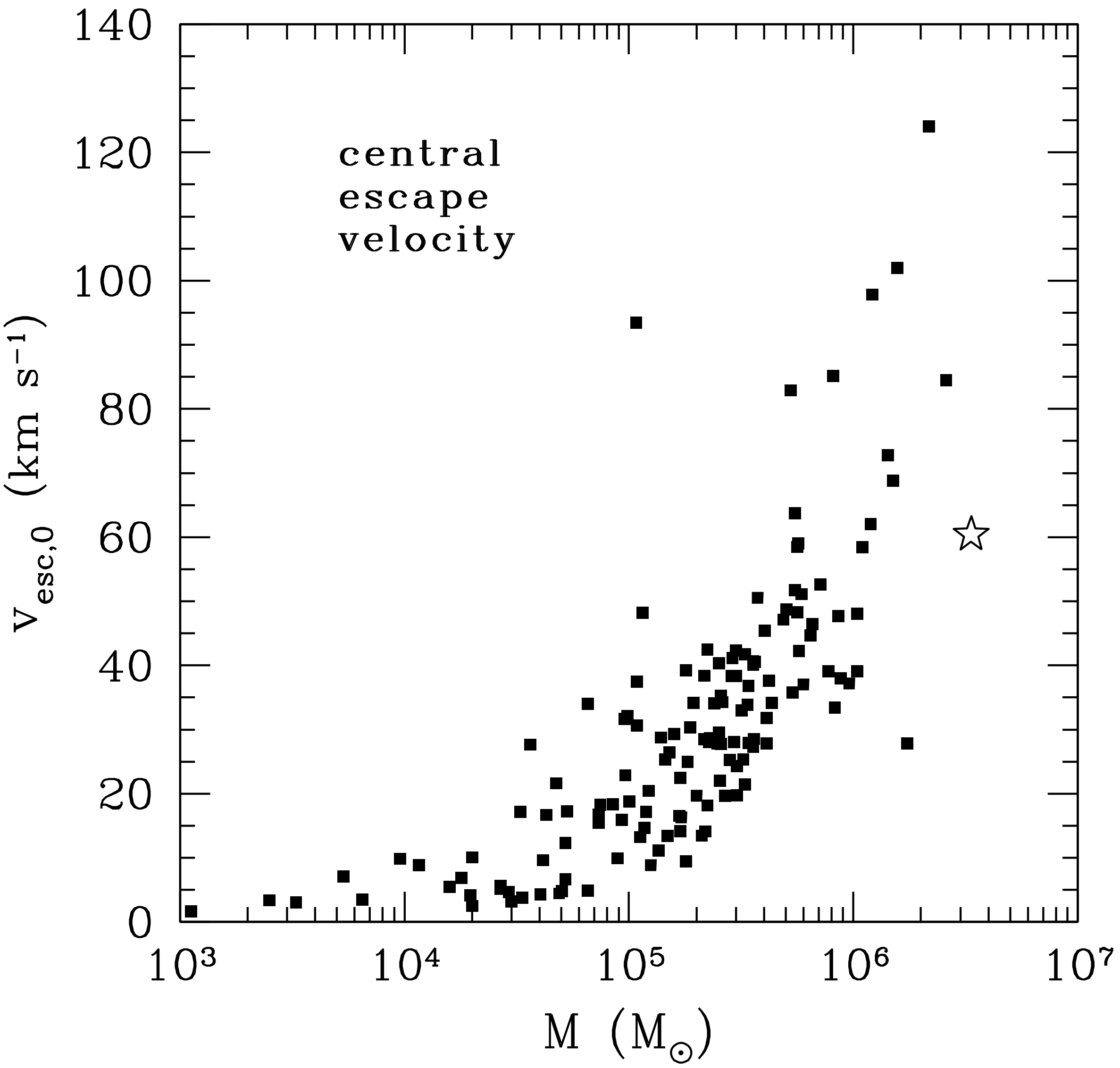


Fig. 2.— Central escape velocity for 141 Galactic globular clusters vs their mass $M$. Omega Centauri is denoted by an asterisk. The escape velocity is calculated from the photometric single-mass King models with $M/L_V = 3$.

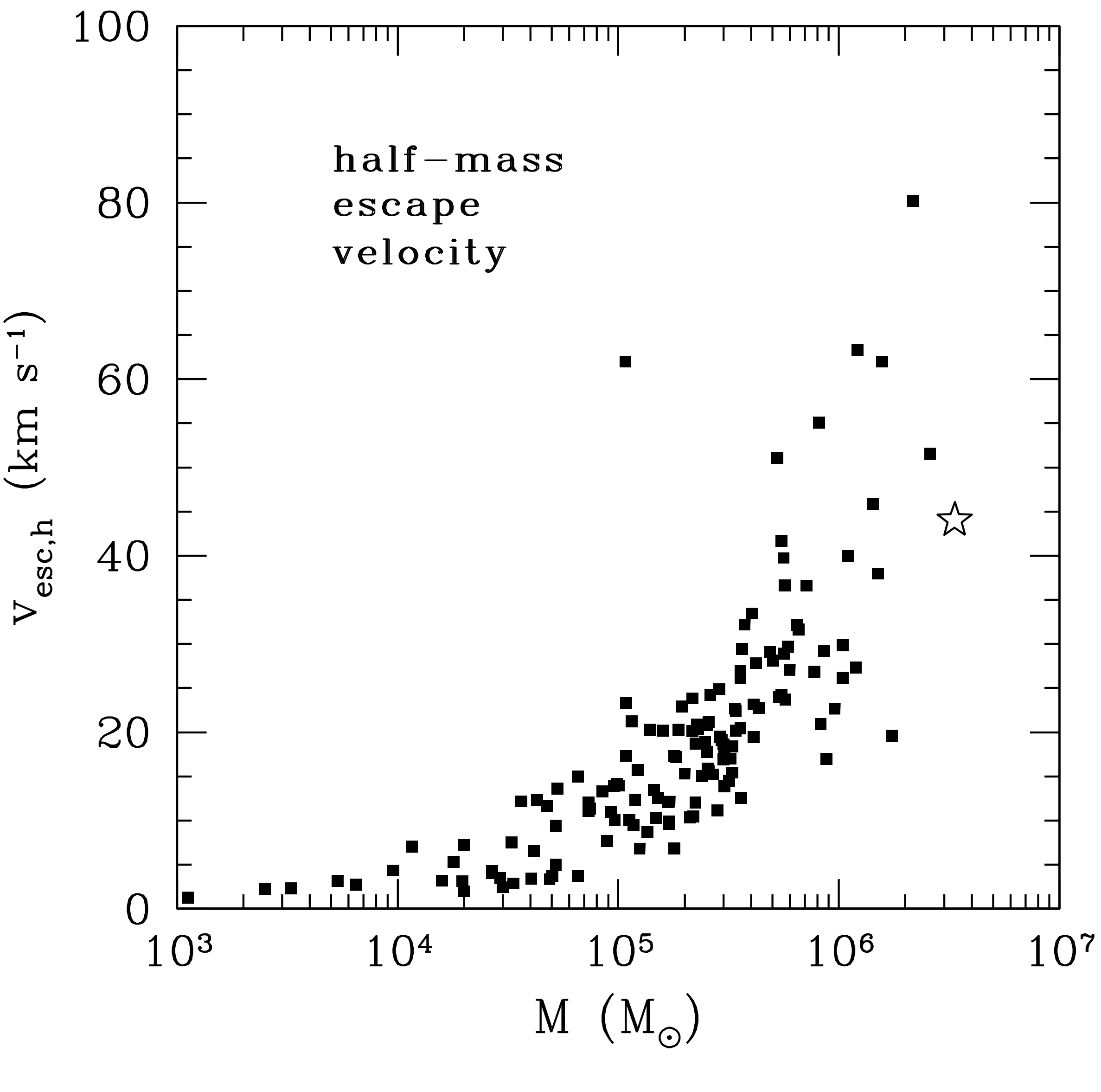


Fig. 3.— Escape velocity at the half-mass radius for the Galactic globular clusters vs their mass $M$. Omega Centauri is denoted by an asterisk.

velocity of AGB winds is $u_w \approx 15$ km s$^{-1}$ (although a velocity as high as 90 km s$^{-1}$ has been measured for a field red giant by Dupree, Sasselov & Lester 1992), more than half of the Galactic clusters should be able to retain a sizable fraction of their winds.

## 3. The orbit and the possibility of self-enrichment

The question now is: could $\omega$ Cen (and other clusters) retain the wind material throughout their evolution in the Galaxy? The oldest stars in the Galactic disk are dated to be at least $9.5 \pm 0.8$ Gyr old (Oswalt et al. 1996; Leggett et al. 1998). The age of the Universe is determined fortuitously well from the coincidental CMB correlation (Knox et al. 2001) to be $14.0 \pm 0.5$ Gyr. Thus, it is quite possible that the dense gaseous disk was already assembled when the Universe was about 4 Gyr old, equal to the age spread of stars in $\omega$ Cen. If this was the case, ram pressure of the disk would strip any gas left in $\omega$ Cen, as we show below.

The current Galactocentric velocity of $\omega$ Cen from the recently measured proper motion (Dinescu et al. 1999) is relatively low: $V_R = -31$ km s$^{-1}$, $V_\theta = -65$ km s$^{-1}$, $V_z = 4$ km s$^{-1}$, with the uncertainty $\pm 10$ km s$^{-1}$. The speed of only 70 km s$^{-1}$ makes the cluster strongly bound and thus, its present position at 6.3 kpc from the Galactic center is likely to be close to the orbital apocenter. Indeed, calculations of Dinescu et al. (1999) give the pericenter distance $R_p = 1.2$ kpc and the apocenter distance $R_a = 6.4$ kpc. Therefore $\omega$ Cen remains close enough to the Galactic center to pass through the disk twice in each orbital period, which is relatively short, $P_{\rm orb} = 1.2 \times 10^8$ yr.

We calculate the amount of gas that might have been present in $\omega$ Cen as follows. The total mass-loss rate of AGB stars depends on the slope of the IMF between 1 and 8 $M_\odot$, $dN/dm \propto m^{-\gamma}$, on the mass of the white dwarf remnant, $m_{wd}$, and on the main sequence lifetimes of stars, $t_{ms}$:

$$\frac{dM_w}{dt} = \frac{dN}{dm}\,(m - m_{wd}) \left(-\frac{dt_{ms}}{dm}\right)^{-1}, \qquad (3)$$

where $m = m_{ms}(t)$ is the inversion of the function $t_{ms}(m)$. We consider two cases, $\gamma = 2.2$ (following Kroupa, Tout & Gilmore 1993) and $\gamma = 3.3$ (Scalo 1986). Using the code of Hurley, Pols & Tout (2000), we calculate $t_{ms}(m)$ for the oldest stars in $\omega$ Cen, with the metallicity $[Fe/H] = -1.7$, and find that in the mass range of interest it is well fit by $t_{ms} \approx 5 \times 10^9\,(m/M_\odot)^{-2.4}$ yr. The masses of stellar remnants have been determined observationally in the nearby star clusters (Weidemann 2000), and the result can be accurately fit by $m_{wd} = 0.444\,M_\odot + 0.084\,m_{ms}$. Combining all these expressions, we find the mass-loss rate at the age of 4 Gyr: $dM_w/dt \approx 10^{-2}\,M_{cl}$ Gyr$^{-1}$. Here $M_{cl} \approx 3 \times 10^6\,M_\odot$ is the present mass of the cluster. (Interestingly, the mass-loss rate is almost the same for both values $\gamma = 2.2$ and

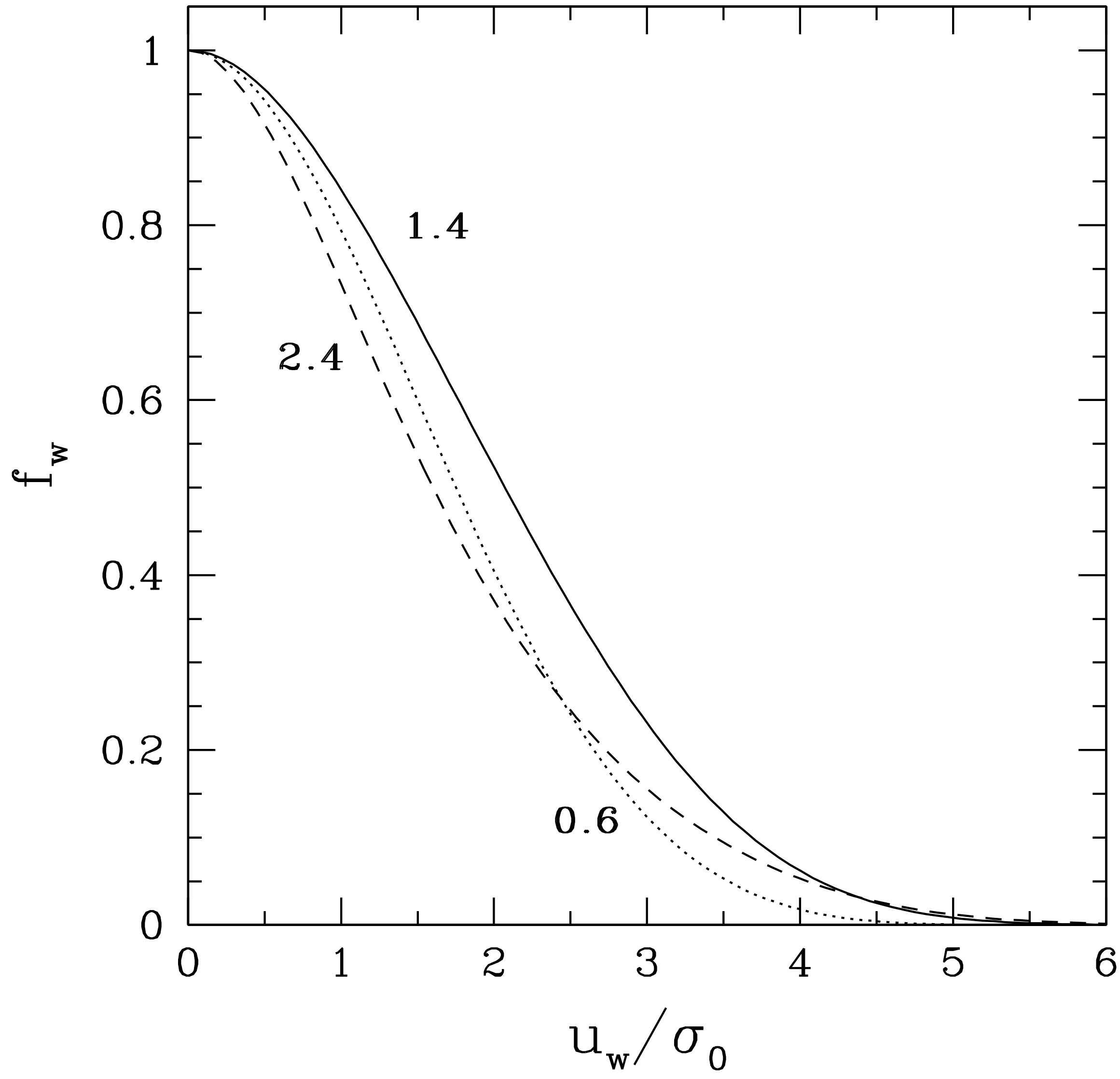


Fig. 4.— Fraction of AGB winds retained by clusters of concentration $c$ (marked by numbers) as a function of the wind velocity in units of the central velocity dispersion. The top solid line shows the model with the highest binding energy ($c = 1.4$), the dotted ($c = 0.6$) and dashed ($c = 2.4$) curves give the lower bounds. All models with intermediate concentrations fall between the plotted lines. For all concentrations, the fraction can be fit reasonably accurately by $f_w(x \equiv u_w/\sigma_0) = 1/[1 + (x/2)^2 + (x/4)^4 + (x/3)^8]$.

$\gamma = 3.3$.) Thus, in half the orbital period the cluster would accumulate $M_g = 2 \times 10^3\, M_\odot$ of gas.

We integrate the orbit of $\omega$ Cen backward in time using an accurate Galactic potential that fits most observational constraints of the Milky Way (model $A_1$ of Klypin, Zhao & Somerville 2002). We model the evolution of the Galaxy starting with a spherical halo 14 Gyr ago, compress the baryons into the disk and the bulge over an exponential timescale of 3 Gyr and then turn them into stars over the next 3 Gyr. The bulge is gradually converted into the present flattened shape.

We find the locations where the cluster crosses the plane of the disk and then compare the ram pressure of the disk gas with the restoring gravitational force per unit area at the half-mass radius of $\omega$ Cen. In many passages $\rho_{\rm disk} v_{\rm rel}^2 > G M_{cl} M_g / (4\pi R_h^4)$ and therefore the AGB ejecta should be stripped from the cluster. Also, the current mass of $\omega$ Cen is too small for dynamical friction to affect the orbit.

To summarize, we have shown that if (1) $\omega$ Cen had formed in isolation with its present mass, and (2) the Galactic disk was in place prior to the formation of the metal-rich stars, then the cluster would encounter the disk gas in its orbital motion and lose the gas accumulated from the enriched AGB winds. The same argument applies to all globular clusters within 10 kpc from the Galactic center. They could not have formed stars from the material enriched by s-process elements.

Alternatively, if all the stars in the oldest globular clusters form prior to the assembly of the Galactic disk, then $\omega$ Cen must be unrealistically special. Why did it retain its enriched gas and formed new populations of stars over 4 Gyr whereas a few dozen other clusters, capable of doing so, did not. As we have shown, even though $\omega$ Cen is the most massive cluster its potential well is similar to many others. So we are left again with the puzzle of why $\omega$ Cen is different from all other Galactic globular clusters.

*We conclude that it is highly unlikely that $\omega$ Cen formed and evolved in isolation and enriched itself with heavy elements of the AGB winds.*

## 4. In Closing: Towards a correct story of $\omega$ Cen

In light of the unusual properties of $\omega$ Cen, it is becoming a popular scenario that the cluster may be the core of a disrupted dwarf galaxy (e.g., Freeman 1993). The attraction is that a continuous infall of gas to the center of the dwarf galaxy may lead to a variable star formation history. Kormendy (1985) has shown that dwarf galaxies split on the plot of the central surface brightness vs core radius into dense dE galaxies (like M32) with the central velocity dispersion $\sigma_0$ in excess of 50 km s$^{-1}$, and diffuse dSph galaxies (like Draco) with $\sigma_0 < 20$ km s$^{-1}$. Tidal stripping of the outer envelope would decrease the total luminosity of the dwarf galaxy but would not significantly change its core properties, $\mu_0$ and $R_c$. Thus, the cores of dE would have too high a velocity dispersion and the cores of dSph would have too low density to count as globular clusters.

The counter-examples to this rule are nucleated dSph galaxies, sometimes classified as dE,N (Peterson & Caldwell 1993). NGC 205 (Meylan 2001) has a core velocity dispersion of 30 km s$^{-1}$, dropping to 15 km s$^{-1}$ in the bright compact nucleus (Carter & Sadler 1990). The recently discovered Sagittarius galaxy apparently has a globular cluster M54 positioned at its center (Ibata, Gilmore & Irwin 1994). Also, Drinkwater et al. (2000) detected five Ultra-Compact Dwarf galaxies in the Fornax cluster of galaxies, which are brighter than globular clusters but almost as compact. They could be the result of mergers of young star clusters, as suggested by Fellhauer & Kroupa (2002). It remains to be seen if the nuclei of these galaxies, when stripped of their envelopes, would have similar kinematic and chemical properties to $\omega$ Cen. Also, detailed orbital calculations are necessary to determine if the cluster can be brought in to its present location near the Galactic center (see Zhao 2001).

The uniqueness of $\omega$ Cen among the Galactic globular clusters still poses unanswered questions. In the hierarchical formation scenario we expect a few dozen progenitor galaxies to make up the Milky Way. If $\omega$ Cen did in fact form at the center of one of them, why did not other almost as massive clusters form in the other progenitors and have similar chemical enrichment? Were they entirely disrupted or was the history of $\omega$ Cen completely different? We intend to address these issues in forthcoming work.

We thank Chris Tout for discussions. OG is supported by the STScI Institute Fellowship, and JEP acknowledges the continuing support by the STScI visitors program. The electronic tables of the escape velocities, velocity dispersions, and main-sequence lifetimes are available at `http://www.stsci.edu/~ognedin/gc/`.

## REFERENCES

Carter, D., & Sadler, E. M. 1990, MNRAS, 245, 12P

Dinescu, D. I., Girard, T. M., & van Altena, W. F. 1999, AJ, 117, 1792

Drinkwater, M. J., Jones, J. B., Gregg, M. D., & Phillipps, S. 2000, PASA, 17, 227

Dubath, P., Meylan, G., & Mayor, M. 1997, A&A, 324, 505

Dupree, A. K., Sasselov, D. D., & Lester, J. B. 1992, ApJ, 387, L85

Fellhauer, M., & Kroupa, P. 2002, MNRAS, in press; astro-ph/0110621

Freeman, K. C. 1993, in Galactic Bulges (IAU Symp 153), eds. H. Dejonghe and H. J. Habing (Dordrecht: Kluwer), p. 263

Freeman, K. C., & Norris, J. E. 1981, ARA&A, 19, 319

Freeman, K. C., & Rodgers, A. W. 1975, ApJ, 201, L71

Frenk, C. S., & Fall, S. M. 1982, MNRAS, 199, 565

Harris, W. E. 1996, AJ, 112, 1487

Hilker, M., & Richtler, T. 2000, A&A, 362, 895

Hughes, J., & Wallerstein, G. 2000, AJ, 119, 1225

Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, MNRAS, 315, 543

Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Nature, 370, 194

Ikuta, C., & Arimoto, N. 2000, A&A, 358, 535

Klypin, A., Zhao, H., & Somerville, R. S. 2002, ApJ, in press; astro-ph/0110390

Knox, L., Christensen, N., & Skordis, C. 2001, ApJ, 563, L95

Kormendy, J. 1985, 0, 295, 73

Kroupa, P., Tout, C. A., & Gilmore, G. 1993, MNRAS, 262, 545

Lee, Y.-W., Joo, J.-M., Sohn, Y.-J., Rey, S.-C., Lee, H.-c., & Walker, A. R. 1999, Nature, 402, 55

Leggett, S. K., Ruiz, M. T., & Bergeron, P. 1998, 0, 497, 294

Loup, C., Forveille, T., Omont, A., & Paul, J. F. 1993, A&AS, 99, 291

Mallia, E. A., & Pagel, B. E. J. 1981, MNRAS, 194, 421

Merritt, D., Meylan, G., & Mayor, M. 1997, AJ, 114, 1074

Meylan, G. 2001, in Extragalactic Star Clusters (IAU Symp 207), eds. E. K. Grebel, D. Geisler & D. Minniti

Meylan, G., Heggie D. C. 1997, A&ARev, 8, 1

Meylan, G., Sarajedini, A., Jablonka, P., Djorgovski, S. G., Bridges, T., & Rich, R. M. 2001, AJ, 122, 830

Norris, J. E., & Da Costa, G. S. 1995, 0, 447, 680

Norris, J. E., Freeman, K. C., & Mighell, K. J. 1996, 0, 462, 254

Norris, J. E., Freeman, K. C., Mayor, M., & Seitzer, P. 1997, ApJ, 487, L187

Oswalt, T. D., Smith, J. A., Wood, M. A., & Hintzen, P. 1996, Nature, 382, 692

Peterson, R. C., & Caldwell, N. 1993, AJ, 105, 1411

Pryor, C., & Meylan, G. 1993, in Structure and Dynamics of Globular Clusters (ASP Conf Ser 50), p. 357

Ree, C. H., Yoon, S.-J., Rey, S.-C., & Lee, Y.-W. 2001, `astro-ph/0110689`

Sarajedini, A., & Layden, A. C. A. 1995, AJ, 109, 1086

Scalo, J. M. 1986, Fundam. Cosmic Physics, 11, 1

Smith, V. V., Suntzeff, N. B., Cunha, K., Gallino, R., Busso, M., Lambert, D. L., & Straniero, O. 2000, AJ, 119, 1239

Suntzeff, N. B., & Kraft, R. P. 1996, AJ, 111, 1913

van Leeuwen, F., Le Poole, R. S., Reijns, R. A., Freeman, K. C., & de Zeeuw, P. T. 2000, A&A, 360, 472

Vanture, A. D., Wallerstein, G., & Brown, J. A. 1994, PASP, 106, 835

Weidemann, V. 2000, A&A, 363, 647

Zhao, H. 2001, `astro-ph/0112094`

Zinnecker, H., Keable, C. J., Dunlop, J. S., Cannon, R. D., & Griffiths, W. K. 1988, in Globular Cluster Systems (IAU Symp 126), eds. J. E. Grindlay and A. G. D. Philip (Dordrecht: Kluwer), p. 603

---