ω Centauri as a Disrupted Dwarf Galaxy: Evidence from Multiple Stellar Populations

Young-Wook Lee, Soo-Chang Rey, Chang H. Ree, Jong-Myung Joo, Young-Jong Sohn, and Suk-Jin Yoon

Center for Space Astrophysics, Yonsei University, Seoul 120-749, Korea

Alistair Walker
National Optical Astronomy Observatories/Cerro Tololo Interamerican Observatory (NOAO/CTIO), Casilla 603, La Serena, Chile

Abstract. Our recent CCD photometry (Lee et al. 1999) has shown, for the first time, that ω Cen has several distinct stellar populations, which is reminiscent of the Sagittarius dwarf galaxy. Here we present more detailed analysis of the data along with the population models. We confirm the presence of several distinct red-giant-branches (RGBs) with a red metal-rich sequence well separated from other bluer metal-poor ones. Our population models suggest the red clump associated with the most metal-rich RGB is about 4 Gyr younger than the dominant metal-poor component, indicating that ω Cen was enriched over this timescale. These features, taken together with this cluster’s other unusual characteristics, provide good evidence that ω Cen was once part of a more massive system that merged with the Milky Way, as the Sagittarius dwarf galaxy is in the process of doing now. Mergers probably were much more frequent in the early history of the Galaxy and ω Cen appears to be a relict of this era.

1. Introduction

As part of our investigation of the luminosity-metallicity relation of the RR Lyrae stars in ω Cen, we have obtained BV and Ca & Strömgren CCD frames with the CTIO 0.9m telescope that cover $40 \times 40 \text{arcmin}^2$ in a $3 \times 3$ grid centered on the cluster. As a byproduct of this investigation, we obtained high-quality homogeneous BV color-magnitude (CM) data for more than 130,000 stars in the field toward ω Cen, which represents the most extensive photometric survey to date for this cluster as far as the stars brighter than the main-sequence (MS) turnoff are concerned. This study (Lee et al. 1999) has shown, for the first time, that ω Cen has several distinct stellar populations, which is reminiscent of the Sagittarius dwarf galaxy (Layden & Sarajedini 1997). This feature was later confirmed by Pancino et al. (2000) from their independent photometry. In this paper, we present our progress in more detailed analysis of the data along with the population models.
2. Multiple Stellar Populations in ω Centauri

Figure 1 presents $BV$ CM diagram for all stars in our program field including RR Lyrae variable stars. We were able to remove some foreground Galactic disk star contamination, as they are well discriminated from more metal-poor member stars of ω Cen in the analysis based on our $Ca$ & Strömgren by photometry (see Rey et al., this volume). Here we confirm our previous discovery that the red-giant-branch (RGB) of ω Cen has four distinct populations: the most metal-poor sequence, metal-poor sequence, metal-rich sequence, and the most metal-rich sequence well separated from others. We believe this is a clear evidence for the multiple stellar populations in ω Cen.

The horizontal-branch (HB) distribution is also consistent with the discrete nature of RGB. We have the blue HB and RR Lyrae variables mainly associated with the two metal-poor RGBs, some red HB stars associated with the metal-rich population, and finally the red clump superimposed on the RGB, which must be associated with the most metal-rich population.
3. Population Models

The presence of multiple stellar populations in ω Cen is confirmed by our population models (Figure 2; see also Ree et al., this volume). Our models are constructed based on the $Y^2$ isochrones (Yi et al. 2001) and corresponding HB evolutionary tracks (Yi, Demarque, & Kim 1997) calculated with updated input physics. The reader is referred to Lee, Demarque, & Zinn (1994) and Park & Lee (1997) for the details of model constructions. From the population models, we confirm four distinct populations with different metallicities can reproduce the observed discrete nature of the RGB. The models also confirm that the RR Lyrae variables are mainly produced by two metal-poor populations, with some contribution from the 2nd most metal-rich population.

For the RR Lyrae stars in ω Cen, we have new metallicity measurements from our Ca & Strömgren by photometry (see Rey et al., this volume), and therefore more detailed comparison with the models is possible. From the luminosity-metallicity relation and the period-shift – metallicity correlation of the RR Lyrae variables in ω Cen, we confirm that our models reproduce even the fine details within the instability strip, including the sudden upturn of the RR Lyrae lumi-
The models illustrate the estimation of age difference between the red clump associated with the most metal-rich population and the blue HB associated with the most metal-poor component.

Figure 3. The models illustrate the estimation of age difference between the red clump associated with the most metal-rich population and the blue HB associated with the most metal-poor component.

Hassity and corresponding increase in period-shift at [Fe/H] ∼-1.5, which is a result of redward evolution from the blue HB (see Rey et al., this volume; Yoon & Lee, this volume). This suggests we have a very good understanding of what is happening in the instability strip of ω Cen.

Our models also reproduce the red clump associated with the most metal-rich RGB, but only when the age of the most metal-rich population is some 4 Gyr younger than the most metal-poor population. This is illustrated in Figure 3, where we can see the variation of the red clump location in the CM diagram under different assumptions regarding the age difference between the most metal-rich and the most metal-poor populations. By comparing these models with the observed color of the red clump, which is estimated from the analysis of the luminosity functions of the RGBs superimposed on the red clump (see Rey et al., this volume), we conclude that the Δt of ∼ 4 Gyrs is our best estimate for the age spread within the ω Cen, in the sense that the metal-rich population is younger. This is in qualitative agreement with the results obtained directly from the Strömgren photometry of main-sequence stars (Hughes & Wallerstein 2000; Hilker & Richtler 2000), although these results are subject to large errors associated with the photometry and metallicity groupings.

These unusual characteristics of ω Cen are very similar to the case of Sagittarius dwarf galaxy, which is in the process of disruption with the Milky Way (Ibata, Gilmore, & Irwin 1994). In Figure 4, we have compared our population models with the observations centered on the M54 (Layden & Sarajedini 2000),
Figure 4. Comparison of observation and population model for the Sagittarius dwarf galaxy.

which is believed to be the nucleus of the Sagittarius dwarf galaxy. Note again that the blue HB is from the most metal-poor (and older) population, the red HB is from the intermediate metallicity population, and finally the red clump is from the most metal-rich (and younger) population. We confirm here that the Sagittarius dwarf galaxy also has several distinct stellar populations with the internal age-metallicity relation that spans \(\sim 7\) Gyrs. Other Local Group dwarf galaxies are also known to have similarly complex star formation histories (Mateo 1998).

4. Discussion

4.1. The Origin of \(\omega\) Centauri

The multiple populations and the internal age-metallicity relation found in our work (and also suggested by others in this workshop), which resemble the characteristics of Sagittarius dwarf galaxy, suggest \(\omega\) Cen was massive enough for self-enrichment and several bursts of star formation. The relatively extended enrichment period of \(\sim 4\) Gyrs then indicates that the initial evolution of \(\omega\) Cen occurred away from the dense central regions of young Milky Way, because, near the Galactic center like the current location of \(\omega\) Cen, we would expect the gaseous materials to have been stripped from the proto \(\omega\) Cen on a much shorter timescale as a result of disk shocking and/or similar processes. This view is not inconsistent with \(\omega\) Cen’s rather unusual kinematics and orbit (Dinescu, this volume).
From the discrete nature of RGB, some may suggest that the $\omega$ Cen could be a merger of several globular clusters. But mergers of (at least) four clusters are very unlikely, if not impossible, in the Milky Way, considering the rather high velocities between the clusters in the halo. We can not rule out this scenario in dwarf galaxies, however, because internal velocity dispersion is much lower in dwarf galaxies (van den Bergh 1996).

All of these information strongly suggest that the $\omega$ Cen is a relict or a nucleus of a disrupted dwarf galaxy. The case of $\omega$ Cen and that of the Sagittarius dwarf system therefore provide direct evidence for past and continuing accretion of protogalactic fragments, which suggest that similar accretion events may have continued throughout the history of Milky Way formation.

### 4.2. Other Globular Clusters with Multiple Populations?

It is interesting to note that two globular clusters, now identified as the nuclei or parts of disrupted dwarf galaxies, are among the most massive globular clusters in the Milky Way. $\omega$ Cen is, of course, the most massive globular cluster, and M54, the nucleus of the Sagittarius dwarf, is the 2nd most massive globular cluster. Then, how about the other massive globular clusters? There are several Galactic globular clusters that resemble $\omega$ Cen, but among them, we found the cases of NGC 6388 and NGC 6441 are the most interesting. They are 3rd and 5th most massive globular clusters, respectively, and they all have very peculiar bimodal HB distributions. Our population models for these unusual clusters show that the adoption of two distinct populations within the systems and very mild internal age-metallicity relations between the two populations can reproduce the observed features on the HB and RGB (see Ree et al., this volume). This conclusion is also supported by the fact that the mean period of RR Lyrae variables in these clusters are too long for their high metallicities, which is understood in two populations scenario, where the RR Lyraes are highly evolved stars from the older and metal-poor blue HB population (see Ree et al., this volume).

This suggests some massive globular clusters in the Milky Way are probably not genuine globular clusters, but in fact relicts of disrupted dwarf galaxies like $\omega$ Cen and M54.

### 4.3. Classification of Galactic Globular Cluster System

Our conclusion on the origin of $\omega$ Cen and other massive globular clusters, when combined with other recent findings on the origin of Galactic globular cluster system, suggest that the present day Galactic globular clusters are in fact subdivided into three different types:

(a) Clusters formed in a collapsing proto-Galaxy (e.g., Eggen, Lyndel-Bell, & Sandage 1962). They are mostly in the inner halo and are only genuine Galactic globular clusters.

(b) Clusters originally formed in satellite dwarf galaxies later accreted to the Milky Way. They include globular clusters (Pal 12, Ter 7, Ter 8, & Arp 2) belong to Sagittarius dwarf galaxy, and young outer halo clusters with retrograde motion (Zinn 1993; van den Bergh 1993). Yoon & Lee (this volume) also reported very compelling evidence that metal-poor ([Fe/H] $\lesssim -2.0$) Oosterhoff II
clusters have the positional and orbital characteristics fully consistent with the hypothesis that they were originated from a satellite galaxy.

(c) Nuclei (or relics) of disrupted dwarf galaxies. ω Cen and M54, the nucleus of the Sagittarius dwarf, are undoubtedly belong to this type. Our population models (Ree et al., this volume) suggest other massive globular clusters with bimodal HBs (e.g., NGC 6388 and NGC 6441) may also belong to this category.

References

Eggen, O. J., Lynden-Bell, D., & Sandage, A. 1962, ApJ, 136, 748
Ibata, R. A., Gilmore, G. & Irwin, M. J. 1994, Nature, 370, 194
Hilker, M., & Richtler, T. 2000, A&A, 362, 895
Hughes, J., & Wallerstein, G. 2000, AJ, 119, 1225
Layden, A. C., & Sarajedini, A. 1997, ApJ, 486, L107
——. 2000, AJ, 119, 1760
Lee, Y. -W., Demarque, P., & Zinn, R. 1994, ApJ, 423, 248
Lee, Y. -W., Joo, J. -M., Sohn, Y. -J., Rey, S. -C., Lee, H. -c., & Walker, A. R. 1999, Nature, 402, 55
Mateo, M. 1998, ARA&A, 36, 435
Pancino, E., Ferraro, F. R., Bellazzini, M., Piotto, G., & Zoccali, M. 2000, ApJ, 534, L83
Park, J. -H., & Lee, Y. -W. 1997, ApJ, 476, 28
van den Bergh, S. 1993, ApJ, 411, 178
——. 1996, ApJ, 471, L31
Yi, S., Demarque, P., & Kim, Y. -C. 1997, ApJ, 482, 677
Yi, S., Demarque, P., Kim, Y. -C., Lee, Y. -W., Ree, C. H., Lejeune, T., & Barnes, S. 2001, ApJS, 136, 417
Zinn, R. J. 1993, in The Globular Cluster–Galaxy Connection, ed. G. Smith & J. Brodie (San Francisco: ASP), 38