Wide-field High-precision CCD Photometry of ω Centauri and Its RR Lyrae Stars

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Abstract. We present wide-field and high-precision BV and Ca & Strömgren by photometry of ω Centauri and its RR Lyrae stars, which represents one of the most extensive photometric surveys to date for this cluster. The member stars of ω Cen are well discriminated from foreground Galactic disk stars from the different distributions in the hk [(Ca−b)−(b−y)] vs. b−y diagram. The color-magnitude diagrams show the presence of several distinct red-giant branches with a red, metal-rich, sequence clearly separated from other bluer metal-poor ones. Comparison with our population models suggests the most metal-rich population is few billion years younger than the most metal-poor population. From our new BV photometry and hk metallicity measurements for RR Lyrae stars in ω Cen, we also confirm that the luminosity of RR Lyrae stars depends on evolutionary status as well as metallicity. From the presence of several distinct populations and the internal age-metallicity relation, we conclude 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.

1. Introduction

From our CCD photometry with the CTIO 0.9m telescope, we have recently obtained high-quality homogeneous BV color-magnitude (CM) data for stars in ω Cen (Lee et al. 1999). For the first time, we found four distinct red giant-branchs (RGBs), with a red, metal-rich sequence well separated from other bluer metal-poor ones. An independent survey by Pancino et al. (2000) later confirmed the reality of our initial discovery. The most metal-rich ([Fe/H] ∼ -0.5) population in ω Cen appears to be few billion years younger than the most metal-poor ([Fe/H] ∼ -1.75) population in this system (Lee et al. 1999; Hughes & Wallerstein 2000; Hilker & Richtler 2000).

The multimodal metallicity distribution function and the apparent age-metallicity relation suggest that the protocluster of ω Cen was massive enough to undergo some self-enrichment and several early bursts of star formation. This
also suggests that ω Cen has evolved within a dwarf galaxy size gas-rich sub-

system until it merged with and was disrupted by our Galaxy few billion years
after the formation of its first generation metal-poor stars, leaving its core as
today’s globular cluster (GC) ω Cen (see also Majewski et al. 1999; Hughes &
Wallerstein 2000; Hilker & Richtler 2000). In this paper, we report our progress
in the detailed analysis of our photometric data.

2. Observations

All the observations were made using the CTIO 0.9m telescope and 2K CCD
during six nights in 1996 and three nights in 1997 for BV and Ca & Strömgren
by filter systems, respectively. Our observations covered 40 × 40 arcmin² in

a 3 × 3 grid centered on the cluster. In total, 40 - 42 and 2 - 4 frames were
taken in each filter and each field for BV and Ca & Strömgren by observations,
respectively. Photometry was accomplished using DAOPHOT II and ALLSTAR
(Stetson 1987). We obtained high-quality and homogeneous BV CM data for
more than 130,000 stars (Rey et al. 2001) and light curves for most RR Lyrae
stars (Joo et al. 2001) in ω Cen. From the Ca & Strömgren by observations,
[Fe/H] abundances for 131 RR Lyrae stars were also obtained (see Rey et al.
2000).

3. Color-Magnitude Diagram

Figure 1a shows a BV CMD for all stars in our program field with photometric
errors less than 0.05 mag in B and V. Note the presence of several distinct
RGBs with a red, metal-rich, sequence well separated from other bluer metal-

poor ones. Near $V \sim 14.7$ and $B - V \sim 0.95$, a red clump associated with the
most metal-rich population is superimposed by RGB bump, which is shaped as

an inclined sequence by metallicity spread (i.e., fainter as metallicity increases).
The presence of other interesting features on the CMD, such as the blue-tail
phenomenon of the HB and the prominent blue straggler stars, illustrates the

diversity of stellar populations in this cluster.

Because even the metallicity ([Fe/H] $\sim$ -0.5) of the most metal-rich stars
in ω Cen are relatively metal-deficient compared to the typical disk field stars,
it is possible to eliminate foreground field stars through the use of the $hk$
index (Anthony-Twarog et al. 1991; Twarog & Anthony-Twarog 1991, 1995). As
shown in Figure 2, at a given $b - y$, more metal-rich stars have larger $hk$
index, therefore an upper envelope line that cover field stars could be drawn. Any star
that lie below this envelope is tagged as a field star. This implies that the use
of the $hk$ vs. $b - y$ diagram is ideal for eliminating more metal-rich field stars
from the ω Cen, and the most Galactic GC stars as well. Figure 1b shows the
result of the decontamination. The resulting “cleaned” CMD has allowed us to
obtain more accurate distribution of HB and RGB stars.
Figure 1. (a) CMD of all stars in our program field with photometric errors less than 0.05 mag in $B$ and $V$. The RR Lyrae stars are represented by crosses. (b) Cleaned CMD. A subset of the Galactic field stars have been subtracted using the $hk$ vs. $b - y$ diagram.
4. Evidence for Multiple Stellar Populations from Red-Giant Branches

In order to investigate the discrete nature of the RGB, we have plotted in Figure 3 a histogram of the distribution of color difference between each RGB star and the RGB fiducial of the most metal-poor component. The RGB stars are selected in a relatively narrow magnitude range $12.4 < V < 12.9$, so that the field star and RGB bump contamination is minimized, and which also avoids artificial mixing in the histogram stemming from metallicity dependence of the RGB slope. The presence of several distinct RGBs is confirmed, although the most metal-rich component is not as well distinguished as in Fig. 1 because of the small sample size of such stars in this magnitude range.

5. Age - Metallicity Relation of $\omega$ Centauri

In our previous analysis using synthetic HB models (Lee et al. 1999), we have made the relative age estimation from the location of the red clump (i.e., the most metal-rich RHB) associated with the most metal-rich RGB with respect to the blue HB associated with the most metal-poor component. More detailed analysis (Rey et al. 2001) indicates that this conclusion is somewhat affected by the presence of RGB bumps associated with several discrete RGBs, because of the overlapping of the red clump with RGB bumps at the same location on the CMD. Therefore, it is important to discriminate the red clump from metal-poor RGB bump stars for better estimation of relative ages.
Figure 3. Histogram of the distribution of color difference. Color difference between each RGB star and RGB fiducial of the most metal-poor component, $\Delta (B - V)$, is plotted in the range $12.4 < V < 12.9$. Note the presence of several distinct RGBs. The mean $[\text{Fe/H}]$ abundances (Zinn & West scale) for the four main components are indicated.

Figure 4 shows the CMD that highlights the RGB and RGB bump region. For the purpose of the analysis, RGB is divided into three sequences with different metallicities. A schematic band of RGB bump is shaped as an inclined sequence by metallicity difference. A smaller box indicates the predicted location of the red clump from our synthetic HB models which is younger ($\Delta t \sim 4 \text{ Gyr}$) than the most metal-poor population (see Ree et al., this volume). As shown in the upper panel, if $\Delta t \sim 4 \text{ Gyr}$, the red clump is predicted to be superimposed on the RGB bump of relatively metal-rich (-1.5 < $[\text{Fe/H}]$ < -1.0) population, and therefore we can expect the enhancement of stars on the relatively metal-rich RGBs by the red clump stars. In the lower panel, we compared normalized LFs for metal-poor and relatively metal-rich RGBs. Peaks of two LFs correspond to the RGB bumps. The LF of metal-poor RGB is shifted horizontally in order to coincide its RGB bump with that of metal-poor RGB. An arrow indicates the predicted location of the red clump from our model which is younger ($\Delta t \sim 4 \text{ Gyr}$) than the most metal-poor population. Note that the peak of the relatively metal-rich RGB bump is higher than that of metal-poor one, indicating the red clump stars enhance the feature of relatively metal-rich RGB bump due to their similar locations. This and the similar analyses under different assumptions regarding $\Delta t$ suggest that the most metal-rich population in $\omega$ Cen is some 4 Gyr younger than the most metal-poor population. This conclusion is in qualitative agreement with the results based on the Strömgren photometry of main-sequence stars (Hughes & Wallerstein 2000; Hilker & Richtler 2000). The internal age-metallicity relation is a clear evidence that $\omega$ Cen has enriched itself over this time scale.
Figure 4. (upper) CMD that highlights the RGB and RGB bump region. Three different RGB sequences with different metallicities are shown. A schematic band of RGB bump and the predicted location of the red clump from our synthetic HB models ($\Delta t \sim 4$ Gyr) are indicated. (lower) Normalized LFs for metal-poor (dashed line) and relatively metal-rich (solid line) RGBs. Peaks of two LFs correspond to the RGB bumps. An arrow indicates the predicted location of the red clump from our model which is younger ($\Delta t \sim 4$ Gyr) than the most metal-poor population.
6. RR Lyrae Stars

Figure 5a presents the observed $M_V$ (RR) - [Fe/H] relation for 64 RRab stars in ω Cen, from our new data for magnitude and metallicity. We adopted a distance modulus of $V - M_V = 14.1$ based on the recent evolutionary models of $M_V$ (RR) from Demarque et al. (2000). This distance modulus is in good agreement with the ones obtained by independent methods (see Kaluzny et al. and Kovács, this volume). The larger symbols represent stars with smaller observational errors ($\sigma_{[Fe/H]} < 0.2$ dex) in [Fe/H]. We have also superposed the model correlation of Lee (1991) with fixed mass loss and age. The sudden upturn in $M_V$ (RR) at [Fe/H] $\sim -1.5$ can be explained by a series of HB population models (see Fig. 5 of Lee 1993), where one can see how sensitively the population of the instability strip changes with decreasing [Fe/H]. As [Fe/H] decreases, there is a certain point where the zero age portion of the HB just crosses the blue edge of the instability strip. Then, only highly evolved stars from the blue HB can penetrate back into the instability strip, and the mean RR Lyrae luminosity increases abruptly. This model prediction is clearly visible in our observations.

If the relationship between $M_V$ (RR) and [Fe/H] is not linear as noticed above, we can expect a similar correlation between period-shift and [Fe/H]. In order to confirm this, we obtained the period-shifts of ω Cen RRab stars at fixed $T_{\text{eff}}$ from the deviations in the period of each ω Cen RRab star from the M3 fiducial line in the logP - log$T_{\text{eff}}$ plane. In Figure 5b, we present the result with the model locus by Lee (1993). Our new correlation between period-shift and [Fe/H] shows roughly the same trend as the $M_V$ (RR) - [Fe/H] relation, and is in good agreement with the model locus. All of these results suggest that the luminosity of RR Lyrae stars depends on evolutionary status as well as metallicity.
7. Conclusions

From our study, we draw the following conclusions:

1. The “cleaned” CMD of ω Cen shows the presence of several distinct RGBs with a red, metal-rich, sequence clearly separated from other bluer metal-poor ones.

2. Comparison with our population models suggests the most metal-rich (\([\text{Fe/H}] \sim -0.5\)) population is few billion years younger (\(\Delta t \sim 4 \text{ Gyr}\)) than the most metal-poor (\([\text{Fe/H}] \sim -1.75\)) population.

3. We present new \(BV\) photometry and \(hk\) metallicity measurements of RR Lyrae stars in ω Cen, which confirm that the luminosity of RR Lyrae stars depends on evolutionary status as well as metallicity.

4. From the presence of several distinct populations and the internal age-metallicity relation, we suggest 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.

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