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The Metallicity Distribution Function of ω Centauri

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Abstract. We explore the metallicity distribution function (MDF) of red giant stars in ω Centauri from a catalogue of Washington M, T_2 and $DDO51$ photometry covering over 1.1 deg^2 outside the cluster core. Using updated calibrations of giant branch isometallicity loci in this filter system, photometric metallicities, guided by previously published spectroscopic abundances, are derived. Several methods are employed to correct the MDF for contamination by Galactic stars, including: (1) use of the surface gravity sensitivity of the $(M - DDO51)$ color index to eliminate foreground dwarf stars, (2) radial velocities, and (3) membership probabilities from proper motions. The contamination-corrected MDF for ω Cen shows a range of enrichment levels spanning nearly 2 dex in [Fe/H], and with peaks at [Fe/H]$=-1.6$, -1.2, and -0.9.

1. Introduction

The large abundance spread seen in the red giant branch (RGB) of ω Cen has long been recognized as one of the unique features of this peculiar Milky Way globular cluster. Recent photometric analyses of the ω Cen RGB (e.g., Lee et al. 1999; Pancino et al. 2000, PFBPZ hereafter; Majewski et al. 2000a, M00a hereafter) indicate a metallicity distribution function (MDF) stretching from [Fe/H]~ -2.0 to perhaps as high as [Fe/H]$=-0.4$. This spread, together with clear evidence for a 2-4 Gyr age spread (Hughes & Wallerstein 2000) as well as other unusual characteristics relating to its large mass, elongated shape, and internal and external dynamics (see summary in M00a), suggests that ω Cen may represent an important transitional link between globular clusters and dwarf galaxies. Here we revisit the M00a analysis of the ω Cen MDF with the addition of new membership data for correcting sample contamination and an improved photometric metallicity calibration.

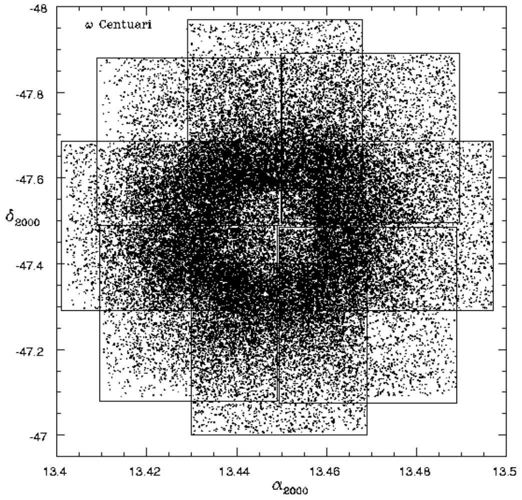

Figure 1. Stars detected in our eight pointings of ω Cen.

2. Photometric Analysis

We have imaged eight pointings of ω Cen in the Washington M, T_2 and $DDO51$ filters with the Swope 1-m telescope and a SITe CCD (Fig. 1). The data were reduced using standard routines, and DAOPHOT II and ALLFRAME (Stetson 1994) was used for PSF photometry. Our resulting catalogue of stars is not complete in the core (see Fig. 1) due to crowding and a conservative cut on stellar profile shape. Analysis was further limited to stars with σ_M, σ_{T_2}, and $\sigma_{DDO51} < 0.05$ mag, reducing the catalogue of 223,110 photometered stars to 52,923 stars. Outside the core ($8' < r < 25'$), our data are complete to past the main sequence turnoff (Fig. 2).

To create an ω Cen MDF, we first isolate its upper giant branch ($M < 14.5$, $M - T_2 > 1.40$) in the color-magnitude diagram (CMD) to limit our analysis to where we have the greatest resolution in photometric metallicities, and to reduce contamination from asymptotic giant branch stars (Fig. 2). This cut and the photometric error cut above combine to make the present analysis much more conservative than what we presented in M00a – our goal here is to search for MDF peaks that would tend to be washed out under the more liberal criteria used previously. While the selected CMD region is dominated by ω Cen RGB stars, we want to remove contamination by Milky Way field stars. The $DDO51$ filter samples the strength of the MgH+Mgb feature at 5150Å, which is greatly enhanced in dwarf stars (Fig. 3). Via the ($M - T_2$, $M - DDO51$) diagram (Fig. 3b), we can eliminate most foreground dwarf stars from the giant star sample (Majewski et al. 2000b). Remaining field giants are removed statistically (§3).

3. Building the MDF

Our MDF is based on photometric metallicities derived for ω Cen stars as shown in Fig. 3. To the extent that magnesium tracks iron, we can derive rough [Fe/H] estimates for ω Cen giant stars due to the secondary sensitivity of ($M - DDO51$) to metallicity. Isometallicity curves in the two-color diagram (Fig. 3) are RGB

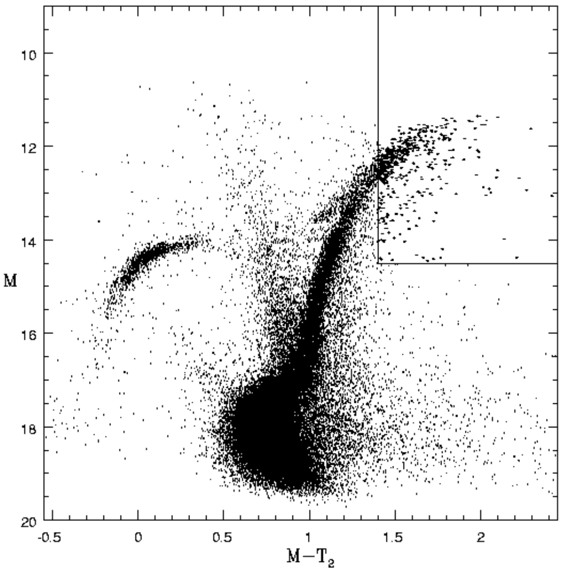

Figure 2. The complete photometric CMD for ω Cen using the Washington (M, $M-T_2$) system. The upper right portion is the area of the RGB isolated for the present MDF analysis.

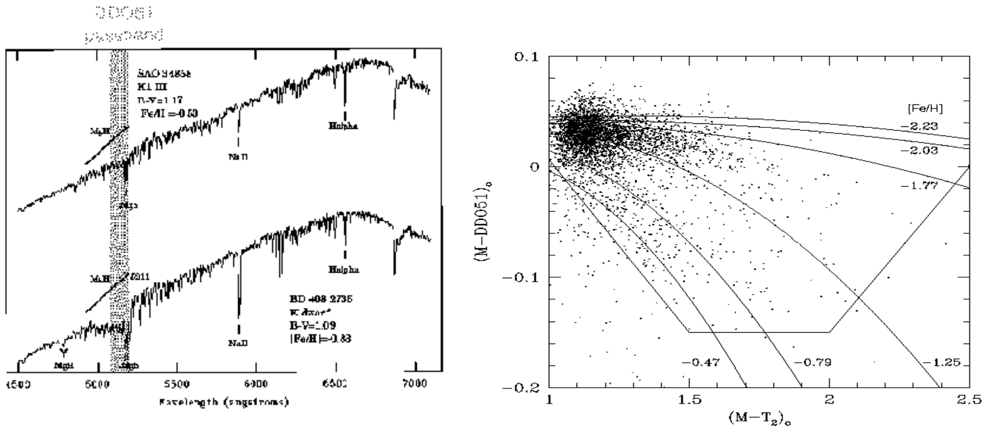

Figure 3. The $DDO51$ samples the strength of the MgH+Mgb feature which is primarily dependent on stellar surface gravity, as may be seen in the comparison of spectra for a K giant and K dwarf of similar metallicity and $(B-V)$ color (left). Thus, $(M-DDO51)$ allows us to separate most dwarf stars (which reside below the straight lines in the two-color diagram in the right panel) from the RGB sample. The $(M-DDO51)$ index's secondary dependence on metallicity for RGB stars is shown by the isometallicity curves. These curves, when calibrated with spectroscopic data, are used to determine the cluster MDF.

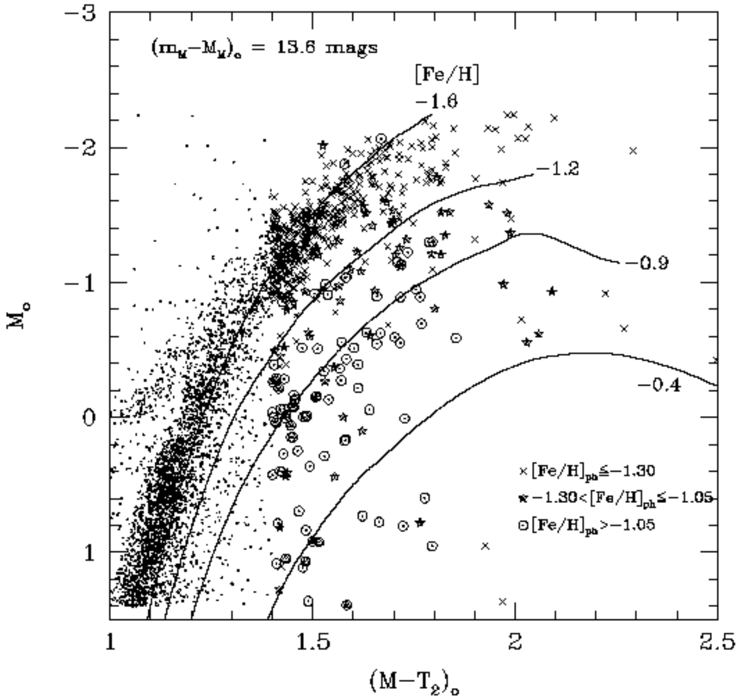

Figure 4. ω Cen RGB stars with assigned photometric [Fe/H] values (indicated by different symbols) from the analysis in Fig. 3. Y^2 isochrones (Yi et al. 2001) at 15 Gyr (for [Fe/H]=-1.6 and -1.2) and 13 Gyr (for [Fe/H]=-0.9 and -0.4) are provided for comparison.

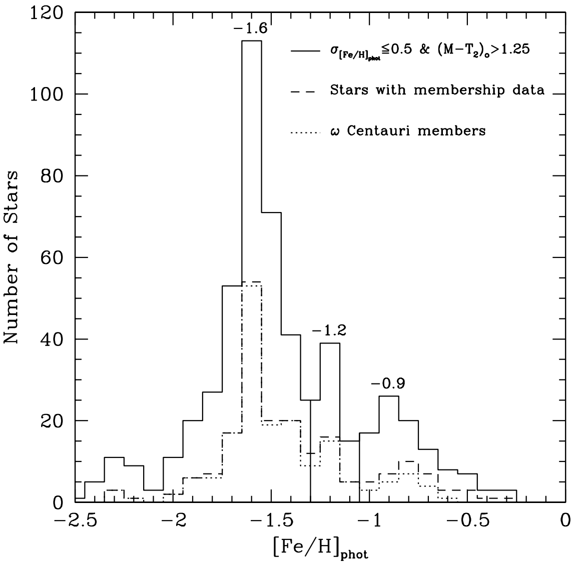

Figure 5. The preliminary MDF derived from our photometric data (solid line). Also plotted are the distribution of stars having membership data (dashed lines) and those stars that are found to be members according to these membership data (dotted lines). Vertical lines demarcate the three abundance ranges shown in Fig. 4.

loci from synthetic colors (Paltoglou & Bell 1994) calibrated to fit stars with spectroscopically determined [Fe/H] from Suntzeff & Kraft (1996) as discussed in Majewski et al. (2000b). Stars coded by these photometric metallicities are plotted in the RGB CMD of ω Cen in Fig. 4. Y^2 isochrones (Yi et al. 2001) for old (13-15 Gyr) giants, converted to the Washington system by matching the output T_{eff} and log g from Y^2 to the corresponding values in the tabulated synthetic Washington colors by Bessell (2001), are also provided for comparison (Fig. 4). The initial MDF is constructed using these derived photometric metallicities (Fig. 5). The Y^2 isochrones shown in Fig. 4 match metallicities that correspond to major MDF peaks in Fig. 5. In general, the derived photometric abundances for stars track the position of isochrones of corresponding metallicity in the CMD, but of course there is scatter. Some scatter is due to inherent limitations of photometric abundances combined with observational errors, but a significant source of scatter may derive from the intrinsic 1 dex spread in [Mg/Fe] in ω Cen giants (Smith et al. 2000). Nevertheless, we believe the data to be sufficiently reliable to reveal gross characteristics of the MDF.

We could further limit the MDF to only known ω Cen members, but these are a small fraction of our data set and, moreover, this smaller subsample is not unbiased with respect to [Fe/H]. However, we can correct our MDF statistically by taking advantage of the available cluster membership data to scale each metallicity bin by the proportion of ω Cen members found among stars in that bin having membership data (Fig. 5). Spectroscopic membership data are derived from Suntzeff & Kraft (1996), Norris et al. (1996), and our own work. Our spectra, centered on the calcium infrared triplet, were obtained with the Las Campanas DuPont 2.5m + ModSpec (see M00a) and the CTIO 4-m + Hydra/Loral 3k. In total, we have obtained 68 new spectra of candidate RGB stars in the Fig. 4 sample, among which we identify 49 members. Additional membership data were obtained by matching our data to the proper motion catalogue of van Leeuwen et al. (2000), and adopting as members all stars with $> 80\%$ probabilities from that work. Using all membership criteria, a total of 176 stars out of 215 stars in our Fig. 4 sample were found to be ω Cen members (Fig. 5). The MDF corrected by fractional membership is shown in Fig. 6.

With the intention of reducing errors in derived [Fe/H], we have adopted a much more conservative sample selection here than we used in M00a. The result is an MDF that is less smoothly varying, with narrower, more defined peaks, than our previous MDF. No doubt the width of the peaks are still exaggerated by observational errors, but they have now been reduced sufficiently that the new corrected MDF (Fig. 6) shows three distinct peaks at [Fe/H] = -1.6, -1.2, and -0.9. These peaks agree well with peaks identified by PFBPZ at [Fe/H]=-1.7, -1.3, and -0.8, and by Lee et al. (1999) at [Fe/H]=-1.7, -1.3, and -1.0, and the overall range of [Fe/H] is consistent with the spread found by Norris et al. (1996). However, like Lee et al., while we also find evidence for ω Cen members as metal rich as [Fe/H]= -0.6, Fig. 6 does not show an additional MDF *peak* at [Fe/H] = -0.4, corresponding to the metal rich, "RGB-a" giant branch identified by PFBPZ. Surely some of the most metal rich RGB candidates from Fig. 5 may have been accidentally "corrected out" of the MDF in Fig. 6 as a result of bad luck in finding no members among the statistically small number of stars with these metallicities available for the membership correction analysis. Indeed, the impact that small number statistics can have on the cor-

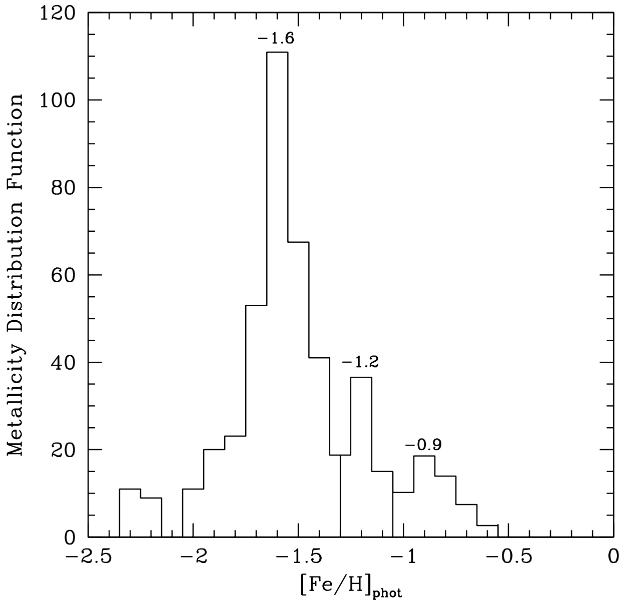

Figure 6. The corrected MDF derived from our data normalized using membership functions in Fig. 5. The MDF shows the photometric [Fe/H] peaks at −1.6, −1.2, and −0.9. Vertical lines are as in Fig. 5.

rection process is demonstrated by the results of our previous analysis (M00a) in which we had found almost *no* ω Cen members among any star with derived photometric [Fe/H] > -1.10, which resulted in a corrected MDF terminating near *that* abundance limit and completely eliminating the now obvious −0.9 dex peak from that previous analysis. But even given the lesson of this experience, the more likely reason that we do not see as high a relative frequency of metal rich stars in the Fig. 6 MDF compared to the frequency identified in the PFBPZ survey is because, as these authors point out, their metal-rich "RGB-a" stars are concentrated to the inner 6 arcmin of the cluster, a radius within which the present analysis faces severe incompleteness. However, we have found that in a less conservatively selected subsample that admits more stars in the cluster core we can see the "RGB-a" in the CMD (indeed, a trace of it can be seen in Figs. 2 and 4), and we have even confirmed radial velocity membership for eight of these metal-rich stars (almost all within 9 arcmin) – unfortunately they are not admitted to the subsample under discussion here. Thus, the MDF we have constructed in Fig. 6 must not be taken to represent the MDF of the core of ω Cen, but rather it more closely approximates the MDF outside the core.

We note the existence of at least one further bias in our MDF, which relates to age/metallicity differences in the fractional lifetime of RGB stars beyond our $M - T_2$ color limit. We hope to address this in future work.

4. Discussion: What is Omega Centauri?

It is well known that ω Cen does not conform with most globular clusters in a variety of ways (see M00a): It is the most massive cluster, it shows substantial rotation and flattening, and, of course, it has a large metallicity spread. Several theories about the origin of ω Cen have been proposed, including that it is a rare cluster that (for some reason) encountered substantial self-enrichment, that it is the product of the merger of two stellar systems, that it is the remains of a disrupted dwarf spheroidal, and even that it derived from some amalgam of these possibilities. That ω Cen seems to have at least *three* primary enrichment peaks and an overall [Fe/H] spread from at least -0.4 to -2.0 dex, coupled with claims for an age spread of up to 4 Gyr in the cluster's main sequence turn-off (Hughes & Wallerstein 2000), makes a simple two cluster merger hypothesis unlikely (see also Norris et al. 1997). Confronted by the difficulties of multiple metallicity populations and motivated by the relative spatial distributions of these populations, PFBPZ propose a more complicated scenario – the merger of two systems with at least one of the systems having undergone self-enrichment and sinking into the center of ω Cen. For the merged, self-enriched entity, which is intended to account for the two intermediate as well as the most metal rich populations, PFBPZ propose a giant molecular cloud or a gas-rich protocluster.

However, a number of aspects of ω Cen lead one to suspect its closer association with dwarf galaxies. For example, the "peaky" MDF of ω Cen bears great resemblance to the burst-like, multiple populations seen in dwarf spheroidal (dSph) galaxies (Grebel 1997). Interestingly, the Sagittarius (Sgr) dwarf galaxy shows a similarly large (and punctuated) spread in [Fe/H] to ω Cen (Layden & Sarajedini 2000). For a variety of reasons, including the similarity in MDFs as well as the fact that the mass of ω Cen is comparable to that of the globular M54, which appears to be the core of Sgr, it has been proposed (e.g., Lee et al. 1999, M00a) that ω Cen may be the remnant nucleus of a tidally disrupted dwarf galaxy analogous to the Sgr system. As pointed out by Shetrone et al. (2001), for this model of ω Cen formation to work, the cluster would have to be a daughter product of a large dwarf galaxy like Sgr, since the heavy-element abundance patterns of smaller, dSph systems like Ursa Minor, Draco and Sextans differ from that of ω Cen, which shows a large enhancement of s to r-process elements with increasing metallicity (Smith et al. 2000). On the other hand, the apparent greater concentration of more metal rich stars observed in ω Cen by PFBPZ mimics a trend seen in dwarf galaxies both great (like Fornax – Grebel & Stetson 1998) and small (like Sculptor – e.g., Majewski et al. 1999).

Apart from the actual difficulty of two clusters merging, which requires relative velocities of $<\sim 1$ km s^{-1} (Thurl & Johnston, this proceedings), the merger hypothesis suffers from at least one other unlikelihood: If ω Cen were the result of the merger of two cluster-like systems, the parent clusters would *each* have to have been among the largest clusters in the Galaxy, and even if only the metal poor part of ω Cen began its life as a traditional cluster, it too would be at the extreme end of the Galactic cluster mass scale. Somehow it is easier to accept that the peculiar properties of ω Cen are the *result* of its large mass, rather than that its large mass and other peculiar properties were accumulated as the result of a series of unlikely occurences. Indeed, the present orbit of ω Cen (i.e., barreling retrograde within and through the Galactic plane – Dinescu et al. 1999) is one that undoubtedly subjects it to substantial tidal stripping. Therefore, not only was ω Cen almost certainly larger and even more like a dwarf galaxy in the past, but there is every expectation that it has led a battered life much like its Sgr counterpart. Evidence for tidal tails extending from ω Cen have been reported by Leon et al. (2000).

We have attempted to present a more accurate representation of the MDF for ω Cen. However, as pointed out by Majewski et al. (2001), if a system has endured substantial mass loss over its lifetime, one must be wary of interpreting the presently observed MDF to represent the true enrichment history of that stellar system. Older (and more extended) populations will have had more time to have been stripped, and especially in the case of ω Cen, whose planar orbit has almost certainly evolved considerably, that mass loss rate may have been highly variable over the enrichment timescale.

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