Chapter 4

Omega Centauri

4.1 Introduction

The globular clusters of the Milky Way represent an important class of object in the study of the Galaxy. Searle & Zinn (1978) proposed that the Galaxy was largely formed through the accretion of small protogalactic fragments. In general, this concept is supported by current models of the universe; standard cold dark matter (CDM) simulations indicate that the first significant structures were somewhat smaller than the current dwarf galaxies, and these merged over time to produce the large scale structure visible today. Freeman (1993) suggested that globular clusters may be the remnants of accreted systems; that is, they are essentially stripped nuclei comprising a few percent of the progenitor mass. If so, then the globular clusters represent the original building blocks of the universe (Freeman & Bland-Hawthorn 2002).

The most promising candidate for this role is the globular cluster ω Centauri. At first glance, this object possesses several important characteristics which separate it from the general population of Galactic globular clusters (GGCs). Firstly, ω Cen is the most massive Galactic cluster (Harris 1996). It is significantly flattened (an ellipticity of approximately 0.12) which is associated with fast internal rotation (Meylan & Mayor 1986; Freeman 2001). The orbit of this system is highly eccentric ($e \approx 0.7$) with a perigalacticon of 1.2 kpc (Dinescu et al. 1999). Indeed, Dinescu et al. found that the cluster is never more than 1.0 kpc from the Galactic disk. Also, ω Cen follows a retrograde orbit, which is unusual compared to the Galactic cluster population.

However, the most important characteristic which separates ω Cen from a typical GGC is its stellar population. Dickens & Woolley (1967) first noted the wide red giant branch and suggested it may be due to chemical inhomogeneity. This was subsequently confirmed through the spectroscopic studies of Freeman & Rodgers (1975) and Norris & Bessel (1975), who found a range of metallicities
in the cluster. Recent abundance measurements have confirmed that \( \omega \) Cen has a significant internal metallicity spread (Norris & Da Costa 1995; Smith et al. 2000) in contrast with a typical GGC. Norris et al. (1997) demonstrated that the metal-rich tail comprises approximately 20% of the stellar population, and that these stars are more centrally concentrated and kinematically colder than the dominant metal-poor stars. Additionally, whereas the metal-poor population ([Fe/H] \( \leq -1.2 \)) possesses well-defined systemic rotation, the metal-rich stars do not rotate. Furthermore, the metal-rich stars display a mean proper motion discrepant from that of the total cluster (Ferraro et al. 2002). These discoveries imply that the metal-rich stars form a kinematically separate population.

Wide-field photometry has revealed at least three (possibly five) distinct red giant branches in \( \omega \) Cen (Lee et al. 1999; Pancino et al. 2000; Sollima et al. 2004). This implies a series of delineated star formation bursts. Pancino et al. (2000) matched their RGB stars with the spectroscopic observations of Norris et al. (1996), and found that those located redward of the main RGB, comprising the sparsely populated sequence labelled ‘RGB-a’, are comparatively metal-rich. This has since been confirmed by Pancino et al. (2002) and Origlia et al. (2003), who found the RGB-a stars possess a metallicity of [Fe/H] \( \approx -0.6 \). Deeper studies indicate that this anomalous sequence continues through the sub-giant branch (Ferraro et al. 2004) and down to the main sequence (Bedin et al. 2004). The morphology of the main sequence turnover region suggests the stars in \( \omega \) Cen have an age range of \( \sim 3 \) Gyr (Hughes & Wallerstein 2000; Hilker & Richtler 2000), which is supported by spectroscopic results (for example, Norris & Da Costa 1995). The chemical signatures of the metal-poor stars indicate the cluster has retained ejecta from supernovae type II and intermediate-mass AGB stars (Norris & Da Costa 1995; Smith et al. 2000). Also, high resolution spectroscopy of the metal-rich population indicates they contain contamination from supernovae type Ia (Pancino et al. 2002). Thus, \( \omega \) Cen demonstrates clear signs of star formation and chemical enrichment over an extended period, which separates it from the remainder of the Galactic globular cluster population.

Retention of stellar ejecta is a characteristic associated with galaxies, hence \( \omega \) Cen resembles an intermediate system between globular clusters and dwarf galaxies. Consequently, it has been suggested that \( \omega \) Cen had a different origin to the other globular clusters (for example, Norris et al. 1997), possibly the remnant of a dwarf galaxy destroyed by the tidal field of the Galaxy. The cluster orbit suggests an origin beyond the Milky Way: \( \omega \) Cen follows a strongly retrograde orbit, thus the progenitor would have followed a retrograde orbit which decayed due to dynamical friction. This level of dynamical friction would require a progenitor with a relatively high mass, such as a dwarf galaxy (Dinescu et al. 1999). If the cluster did originate in a now-defunct satellite galaxy, then this may be analogous to the bright globular cluster M54, which is situated at the centre of
the Sagittarius dwarf galaxy. However, further work is still required to trace the
dynamical history of \( \omega \) Cen.

### 4.1.1 Tidal Tails

In general, the dynamical evolution of globular clusters is regulated by two
mechanisms. Internally, encounters between stars cause them to exchange kinetic
energy in a process of two-body relaxation. Externally, the tidal field of the host
object influences the stellar motions, accelerating the dynamical evolution and
increasing the rate of mass loss from the cluster. Simulations of GCCs indicate
their structural evolution is dominated by gravitational shocks due to the bulge
and disk components of the Galaxy (for example, Oh & Lin 1992; Johnston et al.
1999a; Combes et al. 1999). If the interaction is strong enough, tidal tails can be
formed from the stripped stars. These predictions are substantiated by observa-
tions of the globular cluster Palomar 5, which displays significant tidal tails due
to the Galactic tidal field (Odenkirchen et al. 2001, 2003).

Consequently, wide-field studies have attempted to detect tail-like structures
around nearby globular clusters to determine the dynamical evolution of these
systems, and thereby measure the potential well of the Galaxy. Grillmair et al.
(1995) analysed photographic photometry for twelve Galactic globular clusters,
selecting candidate cluster stars based on colour and magnitude. This method
reduced contamination from the Galactic stellar population, and they found evi-
dence for tidal extensions in several clusters. Similarly, Leon et al. (2000; herea-
fter LMC00) obtained two-colour photographic data for 20 GCCs, and conducted a
search for tidal tails similar to the Grillmair et al. (1995) process. LMC00 found
strong evidence for tidal tails in the majority of these systems. In the case of \( \omega \)
Centauri, they discovered tidal tails located in the regions to the North and South
of the cluster, and state that these extenstions represent \( \sim 1\% \) of the \( \omega \) Cen mass.

However, LMC00 noted that \( \omega \) Cen is located near the Galactic plane, and
hence the distribution of dust may have influenced this result. The IRAS 100 \( \mu m \)
map indicates a differential reddening of \( \Delta E(B-V) = 0.18 \) magnitudes across the
field of the cluster, thus the colour-magnitude selection technique of LMC00 may
have erroneously detected extra-tidal structure. Consequently, Law et al. (2003)
investigated the role of dust obscuration in the \( \omega \) Cen field using 2MASS data in
conjunction with the dust map provided by Schlegel et al. (1998). Although the
tidal tails were present in the raw data, these structures were no longer visible
after accounting for differential reddening. That is, the detected tidal tails in this
cluster are extremely sensitive to the column density of dust in this region of the
sky.

We have searched for extra-tidal structure around \( \omega \) Cen using a combined
photometric and spectroscopic survey. Firstly, we have collected two-colour pho-
tometry over a 2.4° × 3.9° area centred on the cluster, providing colour-magnitude data for approximately 2.8 × 10^5 stars. These data have a considerably higher photometric precision than the photographic data of Leon et al. (2000) and Law et al. (2003). The colours and magnitudes of these stars were adjusted using the Schlegel et al. (1998) dust maps. These data were used to select candidate cluster stars over the tidal tail region, similar to the analyses of LMC00 and Law et al. (2003). Secondly, we obtained G-type spectra (centred at ∼4200 Å) for approximately 4000 candidate cluster stars over the survey region. Radial velocities and chemical abundances were then used to distinguish cluster members from field stars. From this, we were able to calculate an upper limit for the amount of ω Cen extra-tidal material.

### 4.2 Photometric Survey

#### 4.2.1 Observations and Data Reduction

Photometry was obtained using the WFI instrument mounted on the 1-metre telescope at Siding Spring Observatory. Our aim was to survey the tidal tails extending in the North and South directions from ω Cen as described by LMC00 (see their Figs. 5 and 6). Consequently, we covered an area of 2.4° × 3.9° centred on the cluster with a mosaic of fifteen fields. The configuration of these fields is shown in Fig. 4.1. The observed region covered the vertical extent of the LMC00 observations. Each field has been labelled ωC1, ωC2, . . . , ωC15, and includes an overlap region (width ∼5′) with all adjacent fields. These overlap regions were used to compare the photometry from adjacent fields, resulting in a series of magnitude adjustments such that each field was standardised to the same photometric system. Also, the overlap regions provided an estimate of the photometric and astrometric accuracy achieved by these observations.

We observed the fields using the V and I filters over four nights in April 2002. Conditions were photometric, with a median seeing of 2.0″, and a full list of observations is given in Table 4.1. Our aim was to obtain complete photometry down to the main sequence turnoff (MSTO) stars which, at the distance of ω Cen (5.3 kpc; Harris 1996), have apparent magnitudes of V ≈ 17.5, I ≈ 16.6. Thus, the observations for each field consisted of 5 × 300s exposures in V and 5 × 240s in I (although one of the V band images of the field ωC4 was not used as the star profiles were slightly trailed; see Table 4.1). Features such as cosmic rays, bad pixels and satellite trails were removed by median combining these multiple exposures.

Image reduction was completed using the process described in §2.3.1. In summary, images were reduced using the mscred package in IRAF. Bias images were recorded at the start and end of each night, and these were median combined to
<table>
<thead>
<tr>
<th>Field</th>
<th>$\alpha$ (J2000.0)</th>
<th>$\delta$ (J2000.0)</th>
<th>Date Obs.</th>
<th>$V$ Images Exposure (s)</th>
<th>Seeing ($\arcsec$)</th>
<th>Date Obs.</th>
<th>$I$ Images Exposure (s)</th>
<th>Seeing ($\arcsec$)</th>
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<td>5 x 240</td>
<td>2.2</td>
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<td>-45:40:38.72</td>
<td>2002-04-15</td>
<td>5 x 300</td>
<td>2.3</td>
<td>2002-04-15</td>
<td>5 x 240</td>
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<td>2002-04-17</td>
<td>5 x 240</td>
<td>2.4</td>
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<td>2002-09-01</td>
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<td>2.6</td>
<td>2002-09-02</td>
<td>5 x 240</td>
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<td>-47:10:41.65</td>
<td>2002-04-17</td>
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<td>2.3</td>
<td>2002-04-17</td>
<td>5 x 240</td>
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<td>2.2</td>
<td></td>
<td>18000</td>
<td>2.0</td>
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Figure 4.1: Schematic diagram illustrating the region covered by this survey. This figure covers approximately the same area as Fig. 5 in Leon et al. (2000). The red lines trace the core and tidal radii of ω Cen (Harris 1996) and outer dashed line represents the survey limit. The 'boundaries' between fields are represented by dotted lines, although each field contains an overlap region (width ~5') with all adjacent fields. The fields are labelled ωC1, ..., ωC15.

provided a master bias image for the observing run. This image, combined with the overscan regions, was used to subtract the pedestal current from each science image. Flat field images in V and I were obtained during twilight at the start of each observing night, and these were combined to provide a master flat field in both filters. These flats were used to normalise pixel sensitivity over the science images. Finally, fourteen long exposures (one from each ω Cen field, excluding ωC8) were median combined to produce a dark sky flat field image in both filters, and the science frames were divided by these to remove residual features. Each ω Cen frame was then divided into its eight CCD component images. The eight CCD images were aligned with the other exposures for that field, and these were median combined to produce a final image.

Each frame was matched to the world coordinate system using the first USNO CCD Astrograph Catalogue (UCAC1) described by Zacharias et al. (2000). The overlap regions between fields were used to test the accuracy of this calibration.
Stars were matched in these regions using a search radius of 1.0". The coordinate differences are shown in Figs. 4.2 and 4.3. The mean difference in RA and Dec was approximately zero arcsec in both filters, and from the standard deviation of the coordinate differences we inferred the astrometric uncertainty to be $\sim0.12$ arcsec.

### 4.2.2 Photometry

Stellar magnitudes were measured using the DAOPHOT package (Stetson 1987) within IRAF. A full description of the techniques used can be found in Chapter 2. In summary, each image was searched for sources with a peak flux at least $4\sigma$ above the mean background level, where $\sigma$ is the standard deviation of the background flux in electrons. An initial measurement of the stellar magnitude was made using aperture photometry. However, in crowded regions such as globular clusters, PSF fitting provides a more accurate measurement of the total stellar flux. Thus, the light profiles of the twenty brightest stars in each image were individually examined to ensure they were not contaminated by close neighbours or bad pixels. Those with a smooth profile were median combined to produce an empirical PSF for that CCD image. This function was fitted to all stars in the image to measure the stellar magnitude.

A full description of the photometric calibration techniques applied to the WFI
Figure 4.3: (a) RA differences of multiply detected objects in the range $11 \leq I \leq 16$. (b) Frequency distribution of $\Delta$RA values. The dotted line shows the best Gaussian fit, centred at 0.0203$''$ with a standard deviation of 0.1223$''$. (c) Same as (a) for $\Delta$Dec. (d) Same as (b) for $\Delta$Dec. This distribution is centred at $-0.0056$ with a standard deviation of 0.1084$''$.

Table 4.2: Magnitude shifts to adjust all magnitudes to the F8 photometric system.

<table>
<thead>
<tr>
<th>Field</th>
<th>$\Delta Z_V$</th>
<th>$\Delta Z_I$</th>
<th>Field</th>
<th>$\Delta Z_V$</th>
<th>$\Delta Z_I$</th>
</tr>
</thead>
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<td>-0.0083</td>
<td>0.0016</td>
</tr>
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<td>-0.0055</td>
<td>10</td>
<td>-0.0465</td>
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</tr>
<tr>
<td>3</td>
<td>0.0120</td>
<td>0.0131</td>
<td>11</td>
<td>-0.0165</td>
<td>-0.0265</td>
</tr>
<tr>
<td>4</td>
<td>0.3988</td>
<td>-0.3265</td>
<td>12</td>
<td>-0.0215</td>
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</tr>
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</tr>
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<td>14</td>
<td>-0.0162</td>
<td>-0.0308</td>
</tr>
<tr>
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<td>-0.0041</td>
<td>15</td>
<td>-0.0497</td>
<td>-0.0320</td>
</tr>
<tr>
<td>8</td>
<td></td>
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</tr>
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</table>

data can be found in §2.4.1. In summary, the calibration proceeded in three stages. Firstly, a series of standard star observations on each CCD were used to internally calibrate the WFI photometry, such that each CCD occupied the same photometric system. Secondly, stars were matched in the overlap regions between fields to provide a set of inter-field photometric shifts. The mean difference resulted in a simple factor to adjust the photometry of each field to be consistent with that of the central field, $\omega$C8. The conversion factors for each field are listed in Table 4.2. The photometric accuracy was tested by comparing the magnitudes of these multiply observed stars. Fig. 4.4 displays the magnitude difference for these matched stars in the range $12 \leq V \leq 17$ and $11 \leq I \leq 16$. The standard deviation of these values from the mean gave an internal photometric precision of approximately 0.05 mag in both filters.
Figure 4.4: (a) $V$ magnitude differences of all fields in the range $12 \leq V \leq 17$. (b) Frequency distribution of $\Delta V$ values. The dotted line shows the best Gaussian fit, centred at $\Delta V = 0.004$ with a standard deviation of 0.048 mag. (c) Same as (a) for $\Delta I$ in the range $11 \leq I \leq 16$. (d) Same as (b) for $\Delta I$. This distribution is centred at $\Delta I = 0.000$ with a standard deviation of 0.057 mag.

The third and final calibration stage used several standard field observations made in conjunction with $\omega$C8, which provided an overall shift to the standard photometric system in $V$ and $I$. For each standard star, we defined $\Delta V$ and $\Delta I$ to be the difference between our instrumental magnitude and the standard magnitude listed by Graham (1982) and Landolt (1992). Fig. 4.5 shows these parameters as a function of colour for several standard stars observations. From these (and including the DAOPHOT zeropoint correction of 23.5) we derived the following solution to the transformation equations,

\[
V = v + 22.724 - 0.16X + 0.005(v - i),
\]

\[
I = i + 22.184 - 0.086X - 0.024(v - i),
\]

where $v$ and $i$ are the instrumental magnitudes, $X$ represents the airmass of the observation, and $V$ and $I$ are the resulting standard magnitudes. These functions are represented by the dashed lines in Fig. 4.5. The $\omega$ Cen photometry was adjusted using these solutions, resulting in two maps of the cluster region in $V$ and $I$.

Stars in the overlap regions were matched as described in the previous section.
Figure 4.5: The difference between instrumental and standard magnitudes against colour for the standard field observations of April 2002.

For each multiply observed star, its final magnitude and coordinates were set to be the mean value from all observations. We then combined the $V$ and $I$ maps by matching stars based on coordinates, resulting in a $(V - I)$ colour for all stars common to the two datasets. Fig. 4.6 (left panel) shows the colour-magnitude data for all stars in the radial range $6' \leq r \leq 24'$, where $r$ is measured from the centre of $\omega$ Cen. The blue horizontal branch population in $\omega$ Cen is centred approximately at $(V - I) = 0.25$, $V = 15$, while the lower red giant branch (RGB) stretches from $(V - I) = 1.2$, $V = 13.5$ (effectively the bright limit of our survey) down to $V \approx 17$. Below this luminosity are the main sequence turnoff (MSTO) and main sequence (MS) stars. Also, the cluster is located near the Galactic plane, hence we see significant contamination in the form of Galactic disk and halo stars, starting at $(V - I) = 0.7$, $V = 13.5$ and crossing the $\omega$ Cen sub-giant branch at $V \approx 17$. The right hand panel in Fig. 4.6 illustrates the error in $V$ and $V - I$ as a function of magnitude for the field $\omega$C8.

To be able to select various populations in the cluster and confidently plot their distribution, we first required a measurement of the completeness limit for
the survey. We determined this value by creating a luminosity function for each field and setting the completeness limit to be 0.2 mag brighter than the turnover magnitude. The luminosity function for each field in $V$ and $I$ is shown in Fig. 4.7. Artificial stars tests indicated at least 94% of stars down to the completeness limit were recovered. Consequently, the limiting magnitude of the survey was determined by the field with the least depth. This process was completed in both filters, resulting in the limits of $V = 18.0$ and $I = 17.0$. This limit is represented by the dashed line in Fig. 4.8.
Figure 4.7: Luminosity function for ω Cen fields 1 – 16 – the blue histograms refer to the V-band data, and the red to the I-band. The dashed line shows the measured limiting magnitude.
Figure 4.7 – Continued
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Figure 4.7 – Continued
4.2.3 Results

In a similar photometric survey of the Fornax dwarf spheroidal galaxy, we described a simple colour-magnitude selection technique which decreased contamination due to field stars (§2.5). This technique substantially increased the ‘signal’ from Fornax stars, and allowed an accurate structural map of the outer regions of the dwarf galaxy. However, whereas Fornax is located at a high Galactic latitude, ω Cen lies near to the Galactic plane, hence the level of field star contamination is substantially larger. Thus, a straightforward colour-magnitude selection was found to include a large number of unwanted Galactic stars. To demonstrate this point, we selected stars in the lower RGB and main sequence turnoff regions of the CMD using the selection ranges outlined in Fig. 4.8. The distribution of these CMD-selected stars is shown in Fig. 4.9. The outer dotted line describes the approximate area occupied by the tidal tails, and no clear structures are immediately visible.
Figure 4.9: Spatial distribution of stars selected in the lower RGB and main sequence turnoff regions of Fig. 4.8. The dashed lines mark the boundary of the survey, and the dotted lines represent the limits of the tidal tail region as defined by Law et al. (2003). The region within 20' of the centre (also marked as a dotted line) is defined to be the cluster core. The field star region is located outside these dotted lines and within the survey limit.

Grillmair et al. (1995) describe a more complex colour-magnitude selection process which has since been adapted by Leon et al. (2000), Odenkirchen et al. (2001) and Law et al. (2003). This method divides the CMD into a series of cells and maximises the ratio of cluster to field stars in the outer regions of the cluster. A full description can be found in Grillmair et al. (1995), however we include a summary of the process below, and detail how it was applied to our data.

Essentially, the area around ω Cen was divided into three areas; the core region ($r \leq 20'$), the region where we expected to find tidal tails ($50' \leq r \leq 100'$, $|\Delta \alpha| \leq 50'$) and the field star region (located outside the tidal region and within the survey limit). These regions are identical to those used by Law et al. (2003), and are outlined in Fig. 4.9. A grid was overlaid on the CMD, subdividing it into a series of cells with indices $(i, j)$. Each cell had a width of 0.05 mag in colour and a height of 0.10 mag. To minimise effects due to photometry errors, we only considered the magnitude range $13 \leq V \leq 17$, where the mean colour uncertainty
is less than 0.03 mag. For each colour-magnitude cell \((i, j)\), we counted the number of stars located in the core region \(n_C(i, j)\), the tidal tail region \(n_T(i, j)\), and the number in the field region \(n_F(i, j)\). Thus, the signal-to-noise ratio of core to field stars for each CMD cell is,

\[
s(i, j) = \frac{n_C(i, j) - gn_F(i, j)}{\sqrt{n_C(i, j) + g^2n_F(i, j)}},
\]

where \(g\) is the ratio of the core area to the field star area. In effect, the array \(s(i, j)\) listed which regions of the CMD contained a high signal-to-noise of \(\omega\) Cen stars.

Following the method of Law et al. (2003), we defined a limiting signal value \(s_{\text{lim}}\). Stars were then selected in those CMD cells with a signal-to-noise ratio greater than a limiting signal value: \(s(i, j) > s_{\text{lim}}\). Our aim was to determine which limiting signal maximised the density of stars in the tidal tail region compared to the field star region. Thus, we defined the parameters \(N_{\text{tail}} = \sum_{i,j} n_T(i, j)\) and \(N_{\text{field}} = \sum_{i,j} n_F(i, j)\), which are the total number of stars in the tail and field regions respectively. The best value of \(s_{\text{lim}}\) was that which maximised the ratio \(N_{\text{tail}}/gN_{\text{field}}\) (where \(g\) now represents the ratio in areas of the tidal tail region to the field star region). This quotient is the contrast in stellar density of the tidal tail region compared to the field region. This process was performed for the \(\omega\) Cen data, and stars were selected within those CMD cells whose signal \(s(i, j) > s_{\text{lim}}\). The optimal value for the limiting signal gave a density contrast of \(1.62 \pm 0.04\), where the uncertainty represents Poisson noise.

To examine the spatial distribution of these stars, we convolved each with a Gaussian of radius 40" and created a contour diagram, where the contour smoothing length was 3'. This contour diagram is shown in the left panel Fig. 4.10. Immediately apparent are the tail-like structures to the North and South of \(\omega\) Cen. These qualitatively match the contour diagrams of LMC00 (their Figs. 5 and 6) and Law et al. (2003; their Fig. 1(c)).

However, both these studies noted a strong correlation between these tail-like structures and the distribution of dust in the region of the cluster. Indeed, Law et al. (2003) noted that the signal from the tidal tails was substantially reduced after accounting for dust extinction. Therefore, we adjusted our \(\omega\) Cen photometry using the reddening and extinction values from the maps provided by Schlegel et al. (1998), which have a resolution of 6.1'. We conducted the same CMD selection technique described above, measuring the signal-to-noise of cluster stars to field stars across the colour-magnitude plane. As before, the value of \(s_{\text{lim}}\) was chosen to optimise the ratio of tidal tail to field stars. However, for this dataset, the maximum density ratio was \(1.21 \pm 0.04\), significantly less than the value derived above. Thus, the dust corrections significantly reduced the signal of the tidal tails. This effect is displayed in the right panel of Fig. 4.10, which contains the
Figure 4.10: Left panel: Contour diagram of the SGB-selected stars without correcting for reddening and extinction. Each star has been convolved with a Gaussian of radius 40 arcsec and the contour smoothing length is 3 arcmin. Tail-like structures are visible to the North and South of the cluster. Right panel: The corresponding diagram after applying the dust corrections. The tail structures are no longer visible.

contour map for the corrected photometry generated using the parameters given above. The tidal tails are no longer visible. We note that there is a general trend of increasing stellar density south of the cluster, and the same effect is visible in the dereddened data of Law et al. (2003). However, the Galactic plane is located almost due south of ω Cen, and given the low Galactic latitude of the cluster (b = 15°; Harris 1996) we would expect to see a significant stellar density increase over a declination range of 4°. Beyond this, there is little evidence of structural extensions from the cluster.

We created a radial profile for both the raw and dust-corrected datasets represented in Fig. 4.10. The profiles are shown in Fig. 4.11, and were created by placing a set of concentric circular annuli over the ω Cen RGB stars, and then calculating the stellar density in each annulus. The background level was determined as the mean stellar density beyond r = 50′, and is indicated by the dotted line in each diagram. The profile for the raw data (left panel) is not well described by a King (1966) model; beyond r ≈ 10′ the profile appears to follow a power law ρ ∝ r^−α where α ≈ 4. This effect was also noted by Leon et al. (2000). They measured α ≈ 5, however we note that our CMD-selection technique is significantly different to that of Leon et al. The star counts in the left panel of Fig. 4.11 appear to decrease out to r ≈ 50′, but then increase at further radii. This supports the results of Law et al. (2003), who observed a similar effect in the raw 2MASS data.

In contrast, the radial profile for the dust-corrected data follows a King (1966) profile. The dashed line represents the best-fitting King model, using the least-
Figure 4.11: Radial profiles generated from the (a) raw data and, (b) the dust-corrected data. In both panels, uncertainties represent Poisson noise, and the dotted line traces the background level subtracted from all data points. The dashed line in the right panel traces the best-fitting King model.

squares fit described in §2.5. There is little evidence of excess star counts in the outer regions. Law et al. (2003) found a similar result during their analysis of the corrected 2MASS data: a smooth profile with little indication of extra-tidal stars. Thus, the dust correction has substantially reduced the tidal tail signatures, and has resulted in an $\omega$ Cen structure which more closely matches a King model. It is worth noting that our photometric limit of $V = 18.0$ is approximately equivalent (at the colour of the main sequence turnoff) to the limit of $B = 19$ given for the LMC00 dataset.

To further investigate the extra-tidal regions of both datasets, we evaluated the probability density function using the method described in §2.6. Essentially, this function describes the probability of measuring a given density in the extra-tidal region. A uniform distribution of stars produces a Gaussian function, whereas a non-Gaussian function reflects substructure in the stellar distribution. The function was evaluated by placing $10^5$ circles at random positions in the extra-tidal region, and measuring the stellar density in each circle. Whereas the functions for Fornax and Sculptor were evaluated using a circle radius of 12', here we have used 6'. This was due to the relatively high density of field stars towards $\omega$ Cen, which allowed a refinement of the resolution without a significant increase in Poisson noise.

The probability density function for the raw dataset is displayed in Fig. 4.12(a). This function is non-Gaussian, and reflects the structured distribution of stars shown in the raw data contour plot (Fig. 4.10). In contrast, the dust-corrected photometry produced a Gaussian function, indicating the extra-tidal region con-
4.3 Spectroscopic Survey

Figure 4.12: (a) The probability density function evaluated for the extra-tidal region of the raw dataset. (b) The function for the extra-tidal region of the dust-corrected dataset. The dotted line traces the best-fitting Gaussian function to the data.

tains a uniform distribution of stars. The dotted line represents the best-fitting Gaussian function to the data, and is centred at 1153 stars/deg\(^2\) with a standard deviation of 280. In summary, our analysis of the photometric dataset supports the results of Law et al. (2003), who found that the tail-like structures are likely artefacts due to dust absorption.

4.3 Spectroscopic Survey

The 2dF instrument (Lewis et al. 2002) can obtain spectra for up to 400 objects simultaneously over a field two degrees in diameter. The system consists of two spectrographs, where each of these receive the signal from 200 fibres. That is, two CCDs each record 200 spectra. Additionally, a double buffered system allows the next field to be configured while observing the current field. We obtained G-type spectra for approximately 3800 candidate \(\omega\) Cen members over five nights in May 2003. Our aim was to minimise contamination due to the field population by
selecting those stars with a radial velocity and abundance pattern similar to the cluster members. The colour-magnitude selection range for these stars is outlined in Fig. 4.13. We required a minimum signal-to-noise ratio of 20 at $\sim 4300\AA$ to achieve a velocity accuracy of $\sim 15$ km s$^{-1}$. Thus, the faint selection limit was set to be $V = 16.7$, which optimised the number of observable stars within a single 2dF reconfiguration time. In order to reduce reddening variations, the candidates were selected based on their dust-corrected photometry. Also, to remove the effects of scattered light, we did not observe stars which had a bright neighbour within $\sim 10''$. Fiducial stars ($13.5 \leq V \leq 14.5$) and sky fibre positions were selected from our photometric dataset.

The spatial distribution of those stars for which we obtained spectra is shown in Fig. 4.13. The dashed circle outlines the central exclusion zone: we obtained spectra only for those candidate stars greater than 20" from the cluster centre. This excluded the crowded inner regions, and included enough members to calibrate the expected radial velocity and equivalent width values for $\omega$ Cen. The four 2dF fields are represented as dotted circles in Fig. 4.13. The east and west fields each contained approximately 1200 stars, while approximately 2100 stars were located in each of the north and south fields. The 2dF instrument is capable of observing up to 400 stars at a time, thus multiple configurations were required for each field to obtain a spectrum for every star. We observed six configurations for both the north and south fields, and two for the east and west fields. Fifteen stars were allocated in each field to be common to all configurations, and these were also located in the overlap regions between fields. Additionally, multiple
spectra were obtained for another \( \sim 100 \) stars. These requirements had a twofold purpose. Firstly, the multiply observed stars allowed us to determine possible inter-configuration and inter-field radial velocity offsets. Secondly, they provided an internal test of accuracy achieved for the radial velocity and equivalent width measurements.

Spectra were obtained for the selected stars using the 1200B gratings. The wavelength range was approximately 3900 – 4800\( \text{Å} \) with a scale of 1.1\( \text{Å} \)/pixel. The observation sequence for each configuration consisted of three 1800s exposures, two arc frames and a fibre flat field. Thus, approximately two hours were required for each configuration. Offset sky exposures were collected throughout each night. We also obtained spectra of six bright stars to be used as radial velocity standards.

### 4.3.1 Data Reduction and Analysis

The data were reduced using the 2dfdr program. A tram line map was generated for both CCDs from a fibre flat field frame. This map tracked the pixel position of each spectrum, and was rotated and shifted to match each individual exposure. The arc frames provided a wavelength calibration for each fibre, and a throughput calibration was achieved using a median combination of the offset sky exposures. Each configuration included 42 sky fibres, 21 for each CCD. Thus, these were combined to produce a sky spectrum, which was scaled by the relative throughput for each fibre to ensure an accurate sky subtraction. Finally, each exposure was reduced, sky-subtracted and fit-extracted. The three exposures for each configuration were median combined to remove possible contaminating sources such as cosmic rays.

**Radial Velocities**

Radial velocities were calculated by cross-correlating spectra with that of the bright star HD 162396. This star is of a similar spectral type to the \( \omega \) Cen stars, and hence provided a consistent match with the spectral features. The radial velocity of this template star was measured using the \texttt{rvlines} routine in IRAF, which determines the offset of a given set of spectral features from their rest wavelength. Also, the radial velocities of the remaining five standard stars provided a velocity zeropoint.

The spectra of the candidate \( \omega \) Cen stars were cross-correlated with the template spectrum using the IRAF routine \texttt{fxcor}. Only those stars which had at least 400 counts at the G-band (\( \sim 4300 \text{ Å} \)) were included in this process. The spectra were correlated in the wavelength range \( \lambda \lambda 3800 - 4700 \text{ Å} \), which encompasses the Ca II H and K lines and the G-band amongst its strong spectral features. The resulting velocities were adjusted for the motion of the Earth, resulting in
Figure 4.14: The difference in radial velocity from the multiply observed stars. The dashed line traces the mean difference, and the standard deviation of these points indicates the mean velocity error is \( \sim 15 \text{ km s}^{-1} \).

<table>
<thead>
<tr>
<th>Feature</th>
<th>Line Bandpass (Å)</th>
<th>Blue Continuum Bandpass (Å)</th>
<th>Red Continuum Bandpass (Å)</th>
</tr>
</thead>
<tbody>
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<td>Ca II K</td>
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<td>3909 – 3921</td>
<td>4010 – 4057</td>
</tr>
<tr>
<td>G-band</td>
<td>4294 – 4316</td>
<td>4230 – 4248</td>
<td>4352 – 4373</td>
</tr>
<tr>
<td>H(_\gamma)</td>
<td>4332 – 4349</td>
<td>4230 – 4248</td>
<td>4352 – 4373</td>
</tr>
<tr>
<td>H(_\delta)</td>
<td>4093 – 4109</td>
<td>4035 – 4060</td>
<td>4120 – 4131</td>
</tr>
</tbody>
</table>

heliocentric velocities for 3822 candidate member stars over the survey region.

An estimate was made of the mean velocity uncertainty by comparing measurements from the multiply observed stars. Over 150 stars were observed more than once, and the velocity difference from these is shown in Fig. 4.14. The mean velocity difference was found to be \( \sim 3 \text{ km s}^{-1} \), with a standard deviation of 15.9 km s\(^{-1} \). Thus, the mean radial velocity uncertainty for the \( \omega \) Cen observations was \( \sim 15 \text{ km s}^{-1} \).

**Line Strengths**

Equivalent widths of the two hydrogen lines, H\(_\gamma\) and H\(_\delta\), were measured using the Gaussian fitting technique described in §3.3.2. The rest wavelength ranges of these features are listed in Table 4.3. A bandpass to either side of the features were used to measure the continuum level, and these ranges are also listed. The equivalent widths of the Ca II K line and the G-band were measured using a numerical integration technique, and the requisite values are given in Table 4.3.

The internal accuracies of these line strengths were obtained by comparing measurements of the multiply observed stars. Comparisons were made between 82 such stars, and the resulting equivalent width differences are shown in Fig. 4.15. The dashed line traces the mean difference for each line, which are all within 0.2 Å of zero. For the Ca II K line and the G-band, the standard deviations were
Figure 4.15: The difference in line strength indices for 36 multiply observed stars, where each value is in Å. A total of 82 comparisons have been made. The dashed line in each panel represents the mean difference.

0.78 Å and 0.73 Å respectively. The next section uses the mean hydrogen index, \([W(H_g) + W(H_b)]/2\), and we measured the uncertainty in this parameter to be 0.27 Å.
4.4 Results

From the 2dF survey we obtained radial velocities for 3822 stars in the vicinity of ω Cen with a mean radial velocity uncertainty of ~15 km s\(^{-1}\). The velocity of these stars as a function of \(V\) magnitude is shown in Fig. 4.16. The stars clearly define a bimodal population. The majority are clustered around a heliocentric velocity of zero with a velocity dispersion of approximately 30 km s\(^{-1}\), and these are the Galactic disk stars. Also, a small population is located near ~230 km s\(^{-1}\), and these represent the ω Cen population. To determine the mean velocity of the cluster, we selected those stars in the range \(200 \leq v_r \leq 260\) km s\(^{-1}\) and within 30\(\) of the cluster centre, which we are confident will have produced a subset dominated by ω Cen members. These criteria resulted in 110 stars, and we calculated a mean cluster velocity of \(\bar{v} = 230.3 \pm 1.2\) km s\(^{-1}\), where the error is the standard deviation of the mean. This value agrees with previously determined values (Harris 1996), and is marked as the dashed line in Fig. 4.16.

Towards ω Cen, the Galactic halo population is centred at a heliocentric velocity of ~160 km s\(^{-1}\), with a velocity dispersion of approximately 120 km s\(^{-1}\) (Binney & Tremaine 1987). Therefore, although velocity selection will remove the large majority of Galactic disk stars, we expect residual contamination in the form of halo stars. A useful method to determine the level of halo contamination is to examine the histogram in Fig. 4.16 as a function of radius. We divided the survey region at \(r = 50\)\(\), and evaluated the velocity distribution for both areas. These
Figure 4.17: Velocity histograms for a set of concentric annuli. Each histogram has been normalised to unit area. The dashed line represents the mean ω Cen velocity, and the dotted lines trace the selection range represented in Fig. 4.16. Each histogram has been labelled with its range in radius.

are shown in Fig. 4.17, where both histograms have been normalised to contain unit area. The dashed line represents the mean cluster velocity, and the dotted lines define the velocity selection envelope for ω Cen (derived in the next section). Although there are a few stars beyond r = 50′ which are within the velocity range, these do not appear to define an obvious sub-population. This would suggest that the majority of these stars are halo objects rather than a significant number of extra-tidal ω Cen stars.

4.4.1 Cluster Membership

Radial velocities provide a powerful selection parameter to remove the majority of foreground/background stars. Given that the mean radial velocity uncertainty was $\sigma_v \sim 15$ km s$^{-1}$, we selected those stars within $3\sigma_v$ of the mean cluster velocity, which is equivalent to the velocity range $185.3 \leq v_r \leq 275.3$ km s$^{-1}$. This range is marked as the dotted lines in Fig. 4.16. This criterion produced 193 probable cluster members, 25 of which were located beyond the tidal radius.
(where \( r_t = 57.03' \); Harris 1996). The remainder of this section describes the methods used to detect residual field stars based on their chemical signatures and proper motions.

For each of the 193 potential cluster members, we measured the equivalent widths of the G-band, Ca II K line, and the two hydrogen lines H\(_\alpha\) and H\(_\beta\). The first two lines trace the abundance of CH and Ca in the star, and the final two represent the surface temperature. To calibrate these line strengths for \( \omega \) Cen, we examined these values for the stars within 30' of the cluster centre (this radial limit is marked as the dotted line in Fig. 4.21). This yielded 117 probable members, and their G-band and Ca II K line strengths are shown as a function of the mean hydrogen line strength in Fig. 4.18. The dashed line represents the least-squares fit to the data points. We calculated \( \sigma \), the standard deviation of these points around the linear fit, and the two dotted lines represent the 2.5\( \sigma \) limit imposed for member selection.

Those stars with line strengths greater than the 2.5\( \sigma \) limit were retained as members, given that \( \omega \) Cen displays a long metal-rich tail in its inner regions (Norris et al. 1997; Pancino et al. 2000). Also, for a star with a small equivalent width to be rejected, it required both the G-band and Ca II K line strengths to be less than the 2.5\( \sigma \) limit. Thus, four stars in the inner region were rejected as cluster members.

The process was repeated for the velocity-selected stars beyond a radius of 30'. The right panel of Fig. 4.18 shows the line strength data for these stars. Using the same selection criteria given above, we have discarded three stars. Two of these displayed G-band and Ca II K line strengths below the selection limit. The other star had strengths significantly higher than the allowed range, and hence is probably a metal-rich field star in the Galactic disk.

Similar to the Sculptor survey (Chapter 3), the proper motion of each probable member was used as a final selection criterion. Proper motions were extracted from the SuperCOSMOS Science Archive\(^1\). Due to crowding effects towards the centre of the \( \omega \) Cen, we only examined the motions of those stars beyond 30' from the cluster centre. These values are displayed in Fig. 4.19. We measured the standard deviations from the mean motions in RA and Dec to be \( \sigma_{\mu,\alpha} = 7.30 \) milliarcsec/year and \( \sigma_{\mu,\delta} = 6.32 \) milliarcsec/year respectively. Thus, the proper motion limits for members were set to be \( 3\sigma_{\mu,\alpha} \) and \( 3\sigma_{\mu,\delta} \), and this is marked as the dashed ellipse in Fig. 3.32. Within the uncertainties, none of the stars were outside this limit, and hence all were retained as probable members.

These criteria removed seven of the 193 stars as probable members. The colour-magnitude data for the remaining 186 stars are shown in Fig. 4.20. Although the majority closely match the lower RGB, there is some indication of a

\(^{1}\) http://surveys.roe.ac.uk/ssa/index.html
sub-population with redder colours. At this magnitude, the mean colour error is approximately 0.03 mag, which cannot fully account for the observed colour dispersion. We infer that these redward stars are probably part of the RGB-a population, a metal rich subset of stars which can be seen as an anomalous sequence with redder colours than the cluster RGB (Lee et al. 1999; Pancino et al. 2000). Norris et al. (1997) have shown that the metal-rich stars are concentrated towards the centre of the cluster. However, the stars in the current program are located in the outer regions of ω Cen, hence it would be worthwhile to obtain high S/N spectra of these candidates to determine if the metal-rich sub-population is distributed throughout the entirety of the cluster.

The spatial distribution of the candidates is shown in Fig. 4.21, where the green points represent the seven rejected stars. The red circle represents the tidal radius.

Figure 4.18: Left panel: The line strengths for those stars within 30′ of the centre of ω Cen, and within 3σ_v of the mean cluster velocity. The dashed line in each panel traces the best-fitting relation, and the dotted lines represent the 2.5σ selection limits to remove field stars. Given the high-metallicity tail of the cluster, we have not removed those stars with relatively strong spectral features. However, the stars with a weak Ca II K line and a weak G-band have been removed as cluster members. These are represented by open circles. Right panel: The line strengths for those stars outside a radius of 30′, and within 3σ_v of the mean cluster velocity.
Figure 4.19: Proper motions (in milliarcsec/year) of all stars within the radial velocity ranges, and beyond the $r = 30'$ limit displayed in Fig. 4.21. The dashed ellipse outlines the selection range for $\omega$ Cen stars, and has a minor (major) axis radius of $3\sigma_{\mu,\alpha}$ ($3\sigma_{\mu,\delta}$). The parameters $\sigma_{\mu,\alpha}$ and $\sigma_{\mu,\delta}$ are the standard deviations from the mean proper motion values $\overline{\mu}_\alpha$ and $\overline{\mu}_\delta$ respectively. All stars passed this selection criterion.

listed by Harris (1996); $r_t = 57.03'$. Thus, of the 186 probable member stars, 24 are located beyond the tidal radius. The properties of these stars are summarised in Table 4.4. To determine what fraction of the cluster mass this represents, we re-applied the CMD selection range displayed in Fig. 4.13, which was originally used to obtain the 2dF candidates. This resulted in 7930 stars over the survey region, with a field population density of 603 stars/arcmin$^2$. Given that the photometric survey covered an area of 9.36 deg$^2$, we infer that approximately 5650 of these stars are field stars, while the remainder ($\sim 2280$) belong to the cluster. Thus, assuming the 24 extra-tidal stars trace an underlying population with the same mass distribution as $\omega$ Cen, then the extra-tidal candidates represent $\sim 1\%$ of the cluster.
Figure 4.20: Colour-magnitude data of the ω Cen member stars overlaid on the CMD data from Fig. 4.13. Stars rejected based on chemistry are not shown.
Figure 4.21: Spatial distribution of the probable cluster members. The dashed line represents the limit of the photometric survey, and the red circle represents the tidal radius of $\omega$ Cen, from Harris (1996). The dotted line traces the $r = 30'$ limit, dividing the spectroscopic survey into the 'inner' and 'outer' datasets. Stars within the velocity selection range, and rejected as members based on chemistry, are represented as green points.
### Table 4.4: Properties of the candidate \( \omega \) Cen extra-tidal stars

<table>
<thead>
<tr>
<th>Star</th>
<th>( \alpha ) (J2000.0)</th>
<th>( \delta ) (J2000.0)</th>
<th>( \Delta \alpha ) (°)</th>
<th>( \Delta \delta ) (°)</th>
<th>( V )</th>
<th>( V - I )</th>
<th>( v_r ) (km s(^{-1}))</th>
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<td>15.869</td>
<td>1.093</td>
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<td>15.888</td>
<td>1.128</td>
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<td>1.53</td>
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<td>1.025</td>
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<td>15.814</td>
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<td>-48:49:43.1</td>
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<td>15.898</td>
<td>1.101</td>
<td>201.9</td>
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<td>13:27:49.72</td>
<td>-49:06:53.5</td>
<td>0.18</td>
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<td>16.697</td>
<td>1.048</td>
<td>246.2</td>
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<td>13:25:36.47</td>
<td>-48:44:40.1</td>
<td>-0.20</td>
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<td>0.960</td>
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<td>0.65</td>
<td>-1.76</td>
<td>16.658</td>
<td>1.051</td>
<td>219.3</td>
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</table>
4.5 Conclusion

The wide-field photometry obtained for \(\omega\) Cen allowed an independent analysis of the tidal tails which are possibly associated with the cluster. The original studies by Leon et al. (2000) and Law et al. (2003) were based on photographic plates, hence the CCD-based survey described in this chapter provided photometry of a higher precision. Leon et al. observed significant tidal tails to the north and south of the cluster, however they noted that these structures were correlated with the distribution of dust. Subsequently, Law et al. demonstrated that accounting for dust absorption removed the tail-like features. Section 4.2.3 contained the details of a similar analysis. Applying the reddening and extinction corrections of Schlegel et al. (1998) was found to remove the tidal tails, and adjust the structure of \(\omega\) Cen to more closely match a King model. These results, in conjunction with those of Law et al. (2003), present strong evidence that the \(\omega\) Cen tidal tails are probably artefacts of dust obscuration.

To further pursue the possibility of extra-tidal structure, G-band spectra were obtained for almost 4000 candidate cluster members over the survey region. Radial velocities provided a useful tool to remove the large majority of the field stars. Similarly, the Ca \(II\) K line and G-band strengths were used to remove residual contaminants. Of the initial candidate list of 3822 stars, 186 were found to be probable members of \(\omega\) Cen, and 24 of these were located outside the tidal radius. However, the \(\omega\) Cen stars overlap with those of the Galactic halo in both velocity and abundance distributions, hence it is difficult to determine the remaining level of field star contamination. Thus, a high signal-to-noise spectroscopic analysis of these candidate extra-tidal stars is required to determine if they display the same chemical signature observed in the cluster.

In conclusion, these data present evidence for 24 probable members in the extra-tidal region of \(\omega\) Cen. Assuming these stars are associated with the cluster, and they represent an underlying structure with a similar luminosity function, then these stars correspond to 1% of the \(\omega\) Cen mass. This is equivalent to the tidal tail mass estimated by Leon et al. (2000). However, given that these extra-tidal candidates may include contamination from the Galactic halo, the value of 1% represents a strong upper limit for the mass of these tails. This analysis needs to be extended to the eastern and western extra-tidal regions to determine if these stars trace the tidal tail structure, or if they are predominately field stars.