THE ABSENCE OF EXTRATIDAL STRUCTURE IN THE SCULPTOR DWARF SPHEROIDAL GALAXY

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ABSTRACT

The results of a wide-field survey of the Sculptor dwarf spheroidal galaxy are presented. Our aims were to obtain an accurate map of the outer structure of Sculptor and to determine the level of interaction between this system and the Galaxy. Photometry was obtained in two colors down to the magnitude limits of $V = 20$ and $I = 19$, covering a $3\:\times\:3\:\text{arcmin}^2$ area centered on Sculptor. The resulting color-magnitude data were used as a mask to select candidate dwarf-spheroidal (dSph) and red giant branch stars for this system. Previous work has shown that the red HB stars are more concentrated than the blue HB stars. We have determined the radial distributions of these two populations and show that the overall Sculptor density profile is well described by a two-component model based on a combination of radial velocity and Ca ii triplet strength. The final list of Sculptor members contains 148 stars, 7 of which are located beyond the nominal tidal radius. Both the photometric and spectroscopic data sets indicate no significant extratidal structure. These results support at most a mild level of interaction between this system and the Galaxy, and we have measured an upper mass limit for extratidal material to be $2.3\% \pm 0.6\%$ of the Sculptor luminous mass. This lack of tidal interaction indicates that previous velocity dispersion measurements (and hence the amount of dark matter detected) in this system are not strongly influenced by the Galactic tidal field.

Key words: galaxies: dwarf — galaxies: individual (Sculptor) — galaxies: interactions — galaxies: photometry — galaxies: stellar content — Galaxy: halo — Local Group

Online material: color figures, machine-readable table

1. INTRODUCTION

The dwarf spheroidal (dSph) satellites of the Galaxy provide an important test of dark matter dynamics. Simulations of hierarchical merging indicate that dwarf galaxies were the first structures to form in the early universe, and the merging and accretion of these objects created the galaxies and clusters of galaxies that exist today. It is the collapse of dark matter that has driven the development of large-scale structure. Observations indicate that the local dSph galaxies are potent repositories of dark matter (see Mateo 1998 and references therein) in which the luminous material resides at the center of a large dark halo. However, these measurements of mass-to-light ratio ($M/L$) assume that the system is in virial equilibrium. Kuhn & Miller (1989) proposed that the interaction of a satellite within the tidal field of its host galaxy may result in an artificially inflated estimate of the virial mass. However, the simulations of Piatek & Pryor (1995) imply that the central $M/L$ is not substantially affected by tidal forces. In contrast, Kroupa (1997) and Klessen & Kroupa (1998) have created models of satellite systems without dark matter yet with characteristics apparently similar to those observed in the Galactic satellites. Thus, tidal disruption by the Milky Way may be producing the appearance of dark matter in dSph galaxies. The subsequent analysis of the Draco dSph by Klessen et al. (2003) did not detect the predicted line-of-sight depth in this system; however, a quantitative measurement of the gravitational influence of the Galaxy on its satellites is yet to be achieved.

Consequently, there have been attempts to detect evidence of interactions between large galaxies and their satellites in the nearby universe. Perhaps the best example of this process is the Sagittarius dwarf galaxy (Ibata et al. 1994; Majewski et al. 2003 and references therein), a satellite currently being torn apart by the gravitational potential of the Galaxy. The simulations of Law et al. (2005) have reproduced the general appearance of this disrupted system, and they find that it is on a highly eccentric polar orbit ($e \approx 0.75$). However, the structure of a satellite during the initial interaction with its host is still not understood. Numerical simulations by Helmi & White (2001), Mayer et al. (2001), and Johnston et al. (2002) predict that during the early phase of interaction with the Galaxy, energy is injected into the outer regions of the satellite, resulting in a slightly inflated structure. Also, depending on the level of interaction, the internal structure may be distorted. An example of this initial stage may be the Ursa Minor dSph, which has a structure that displays significant asymmetries and extratidal stars (Martinez-Delgado et al. 2001; Palma et al. 2003).

The Sculptor (Scl) dSph lies at a galactocentric distance of 80 kpc (Mateo 1998). Previous studies have attempted to detect the initial stage of Galaxy-satellite interaction by examining the radial profile of the Sculptor system. For example, wide-field photometric surveys in a single color (Eskridge 1988a, 1988b; Irwin & Hatzidimitriou 1995; Walcher et al. 2003) have identified possible substructure and found evidence for extratidal stars in this dSph. Indeed, Walcher et al. (2003) claim the possible detection of tidal tails aligned with the Scl major axis. However, the effect of foreground and background sources becomes...
accurate photometry was required to magnitudes of 

velocities studies by Armandroff & Da Costa (1986) and Queloz in Scl using traditional velocity dispersion measurements. Radial certain in the outer regions, and it has therefore been difficult to 

first, we collected wide-field photometry in 

For examples of this process, see the analyses by Grillmair et al. (2002). In the second stage, we obtained spectra 

...&...&...&...&...&...&...&...&...

...&...&...&...&...&...&...&...&...

| FIELD | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | Date Obs. | Exposure (s) | Seeing (arcsec) | Date Obs. | Exposure (s) | Seeing (arcsec) |
|-------|------------------|------------------|-----------|--------------|----------------|-----------|--------------|----------------|
| 1     | 01 05 30.3       | −32 35 05        | 2002 Nov 8 | 4 × 600     | 1.8            | 2002 Nov 3 | 4 × 480     | 1.7            |
| 2     | 01 01 56.2       | −32 35 06        | 2002 Nov 5 | 4 × 600     | 2.6            | 2002 Nov 5 | 4 × 480     | 2.0            |
| 3     | 00 58 21.7       | −32 35 05        | 2002 Nov 8 | 8 × 300     | 1.6            | 2002 Nov 6 | 7 × 240     | 1.7            |
| 4     | 00 54 26.8       | −32 35 00        | 2002 Nov 8 | 4 × 600     | 1.5            | 2002 Sep 29| 5 × 500    | 3.1            |
| 5     | 01 05 29.8       | −32 20 06        | 2002 Sep 29| 5 × 600     | 3.5            | 2002 Sep 29| 5 × 500    | 3.2            |
| 6     | 01 01 56.3       | −33 19 57        | 2002 Sep 28| 5 × 600     | 2.8            | 2002 Sep 28| 5 × 500    | 2.7            |
| 7     | 00 58 21.5       | −33 19 59        | 2002 Sep 30| 4 × 600     | 2.2            | 2002 Oct 1 | 4 × 400    | 1.4            |
| 8     | 00 54 46.7       | −33 20 04        | 2002 Oct 1 | 4 × 500     | 1.9            | 2002 Oct 2 | 5 × 400    | 1.7            |
| 9     | 01 05 29.6       | −34 05 09        | 2002 Oct 2 | 5 × 500     | 1.6            | 2002 Oct 1 | 5 × 400    | 1.7            |
| 10    | 01 01 55.7       | −34 04 52        | 2002 Oct 1 | 5 × 500     | 1.5            | 2002 Oct 1 | 5 × 400    | 1.7            |
| 11    | 00 58 22.3       | −34 04 59        | 2002 Oct 1 | 5 × 500     | 1.6            | 2002 Oct 1 | 4 × 400    | 2.0            |
| 12    | 00 54 46.6       | −34 04 57        | 2002 Oct 2 | 4 × 500     | 1.9            | 2002 Oct 2 | 4 × 400    | 2.0            |
| 13    | 01 05 30.4       | −34 50 07        | 2002 Oct 2 | 9 × 600     | 1.8            | 2002 Oct 28| 5 × 500    | 1.8            |
| 14    | 01 01 56.1       | −34 49 59        | 2002 Oct 28| 7 × 300     | 1.5            | 2002 Oct 29| 4 × 480    | 1.5            |
| 15    | 00 58 21.7       | −34 49 51        | 2002 Oct 30| 8 × 300     | 1.5            | 2002 Oct 30| 4 × 480    | 1.4            |
| 16    | 00 54 47.5       | −34 50 15        | 2002 Oct 31| 9 × 300     | 2.6            | 2002 Oct 31| 4 × 480    | 2.5            |
| Total | ...             | ...             | ...       | ...         | ...            | ...       | ...         | ...            |
|       | ...             | ...             | 42100     | 2.0         | ...            | 32480     | 2.0         | ...            |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

important in the outer regions of this system because of the relatively small number of Scl stars compared to foreground Galactic stars. As such, the existing radial profiles are highly uncertain in the outer regions, and it has therefore been difficult to accurately measure any possible inflation of the dSph structure. Without a clear understanding of the level of Milky Way–Scl interaction, and hence whether this system is in virial equilibrium, it is not possible to accurately constrain the amount of dark matter in Scl using traditional velocity dispersion measurements. Radial velocity studies by Armandroff & Da Costa (1986) and Queloz et al. (1995) of K giants found a central $M/L$ of $13 \pm 6$. If the system is undergoing substantial distortion due to the Galactic tidal field, then this $M/L$ may be overestimated.

We have searched the Sculptor dSph for structural and kinematic distortion. First, we collected wide-field photometry in two colors covering a 10 deg$^2$ area centered on Scl, well beyond the nominal tidal radius of this galaxy. The color-magnitude diagram (CMD) obtained from the inner parts of the system was used to select candidate Scl stars over the data set area, thereby increasing their contrast relative to field sources in the outer parts. For examples of this process, see the analyses by Grillmair et al. (1995), Martinez-Delgado et al. (2001), Piatek et al. (2001), and Majewski et al. (2002). In the second stage, we obtained spectra for ~700 of the brightest candidate members. This allowed a further refinement of the data set by selecting stars based on radial velocity and metal abundances. This paper describes our search for substructure in Sculptor based on the combined photometric and spectroscopic data set. A companion paper (Coleman et al. 2005, hereafter C05) presents the results for a similar wide-field photometric survey of Fornax.

2. PHOTOMETRIC SURVEY

The observational strategy for this system followed that of the Fornax dSph (C05). Images of the Sculptor region were obtained at the Siding Spring Observatory 1 m telescope equipped with the Wide Field Imager (WFI). Sixteen fields were observed in two filters ($V$ and $I$), thereby covering a $31' \times 31'$ area on the sky using a $4 \times 4$ mosaic of WFI fields. Similar to the Fornax observations, accurate photometry was required to magnitudes of $V = 20$ and $I = 19$, encompassing the range of the Sculptor red giant branch (RGB). A full list of observations, including the atmospheric seeing, is given in Table 1. The data were reduced using the IRAF program, and the stellar magnitudes were measured using the DAOPHOT program within IRAF. An astrometric calibration of this data set was made using the first USNO CCD Astrograph Catalog (Zacharias et al. 2000). A full description of the data reduction and photometric calibration techniques can be found in C05.

Multiply detected stars in the $V$ and $I$ maps were removed by matching sources in the overlap regions with a search radius of 0.5'. The same search algorithm was used to combine the $V$ and $I$ data sets, thus producing a $(V - I)$ color for all stars in common between the two maps. Figure 1 shows the resulting CMD from the region within 30' of the center of Sculptor. To measure the photometric completeness of the survey, a luminosity function was generated for each of the 16 Sculptor fields in both the $V$ and $I$ bands. We then assumed the completeness limit of each field to be 0.2 mag brighter than the turnover in the luminosity function. To ensure this method provided an accurate measurement of the completeness limit, we created a data set of ~5000 artificial stars with a distribution resembling the Scl RGB. These stars were placed in each field and then recovered using the photometry routines described above. It was found that 94%–96% of the artificial stars were recovered from each field to their respective photometry limits. Thus, the luminosity function allowed an adequate measurement of the photometric limit for each field. The overall magnitude limit of the survey is then defined by the field with the least depth: field Scl5, which is complete to $I = 19$ and $V = 20$.

3. SPECTROSCOPIC SURVEY

3.1. Observations

The 2dF instrument at the prime focus of the Anglo-Australian Telescope allows the simultaneous spectroscopy of up to 400...
targets over a field of view 2° in diameter. A full description of 2dF is given by Lewis et al. (2002). Our aim was to collect spectra at 850 nm for candidate Scl stars and to use the Ca II triplet spectral features to separate the Scl members (the "signal") from foreground/background sources (the "noise"). We chose 1408 candidate Scl stars from the photometric survey (described in § 2) using the CMD selection range displayed in Figure 1. Spectra were obtained for 893 of these candidates; however, only 764 yielded spectra with the required signal-to-noise ratio (S/N). The majority of the stars for which spectra were not obtained lie close to or within three core radii, where the limit on fiber-to-fiber spacing of 2dF restricts the object selection. For the 527 stars in the sample beyond the tidal radius, however, 62% have acceptable signal strengths provided a second constraint to select members of the Scl system. Approximately 100 stars located in the overlap regions between 2dF fields were observed more than once to ensure we obtained consistent velocities and Ca II line strengths.

The selected stars were observed with the 1200R gratings, and the resulting spectra were centered near the Ca II IR triplet with a wavelength range of 8100–9100 Å and a scale of 1.07 Å pixel⁻¹. Although the red spectral region is dominated by sky emission lines, we reduced such contamination using the slow-beam switching method, which intersperses object exposures with offset sky frames containing the same fiber configuration; that is, object and sky were observed through the same fiber. In addition, each configuration included 42 fibers assigned to sky positions. Hence, the observation sequence for each Scl field consisted of 6 × 20 minute exposures and three offset sky images. Each sequence also included three wavelength calibration frames (arcs) comprising four CuAr and two CuHe lamps with an exposure time of 30 s. An arc frame at the start, middle, and end of the sequence accounted for possible instrumental wavelength shifts. Approximately 3–4 hr were required to completely observe each field. A list of observations is given in Table 2.

We also obtained spectra for 16 and 13 red giants in the globular clusters NGC 1904 and NGC 2298, respectively, to be used as radial velocity standard stars. In addition, the metallicities of these clusters (NGC 1904, [Fe/H] = −1.57; NGC 2298, [Fe/H] = −1.85; Harris 1996) are approximately equal to that of Scl (−2.8 ≤ [Fe/H] ≤ −1.0; Tolstoy et al. 2004). For old, metal-poor stars (such as those in Scl and the globular clusters) the individual equivalent widths of the calcium lines can be related to the metal abundance, and we can use the globular cluster observations to calibrate this relation. Thus, in addition to selecting stars based on radial velocity, the Ca II line strengths provided a second constraint to select members of the Scl system.

### 3.2. Data Reduction and Analysis

The spectra were reduced using the 2dfdr program in an interactive mode. In the 2df setup, 400 spectra are divided between two CCDs, including 21 sky fibers per CCD. As a first step in the data reduction process, a tram-line map was generated for both CCDs. This map tracked the output spectra on each CCD and was obtained from the fiber flat-field images as a result of their high S/N. The tram-line map was then shifted and

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**TABLE 2**

| Field          | Date       | Exposure (s) | Air Mass | Seeing (arcsec) |
|---------------|------------|-------------|---------|-----------------|
| Scl northeast | 2003 Sep 25| 5 × 1200    | 1.04    | 1.4             |
| Scl northwest | 2003 Sep 26| 6 × 1200    | 1.26    | 1.8             |
| Scl southwest | 2003 Sep 26| 6 × 1200    | 1.08    | 2.0             |
| Scl southeast | 2003 Sep 28| 6 × 1200    | 1.15    | 1.5             |
| Scl central   | 2003 Sep 28| 6 × 1200    | 1.11    | 1.5             |
| NGC 1904      | 2003 Sep 26| 750         | 1.02    | 2.0             |
| NGC 2298      | 2003 Sep 28| 600         | 1.11    | 1.5             |
rotated to fit each individual data frame, and the signal for each fiber was extracted. The arc frames then provided a wavelength calibration for each fiber by matching the pixel position of the observed lines with the spectral line list.

An accurate sky subtraction is dependent on a reliable fiber throughput calibration, since the relative throughputs of individual fibers can vary by ~10%. The offset sky exposures were used to measure the relative fiber throughput. These were taken with the same configuration as the object field, and multiple offset sky exposures at dithered positions ensured each fiber was accurately sampling the sky. The offset sky frames were median-combined to ensure the sky spectrum was not accidentally contaminated by sources or cosmic rays. The Scl frames were then reduced and fit-extracted, and the combined sky spectrum (from the 21 sky fibers), scaled by the individual fiber throughputs, was subtracted to remove the night-sky features. The six exposures for each field were then median-combined to produce the final set of spectra.

3.2.1. Radial Velocities

Because of less than favorable observing conditions (seeing $>2\arcsec$), only 14 of the 29 globular cluster stars in the observed configurations had spectra with sufficient S/N to be used as radial velocity standard stars. Six of these were recorded on CCD 1 and eight on CCD 2. To ensure these spectra were adequate templates, we used them to independently measure the mean systematic velocity of the two clusters, which were then compared to the known values. The stellar radial velocities were measured using the \textit{rvidlines} routine in IRAF. Each velocity was calculated as the mean value determined from the three Ca \textsc{ii} lines. These were corrected for the motion of the Earth, and we removed the CCD dependence of these velocities using the $\Delta v_r$ values determined below. Thus, we calculated a mean radial velocity of 205.3 $\pm$ 2.2 km s$^{-1}$ for NGC 1904 (from six stars) and 152.7 $\pm$ 1.4 km s$^{-1}$ for NGC 2298 (from seven stars, after removing a star whose radial velocity of 71 km s$^{-1}$ indicated that it was not a cluster member), where the errors are the standard deviation of the mean. These compare well to the values listed in the online catalog’s 723 stars.

In order to use these spectra as radial velocity standard spectra, we first needed to measure the velocity offset between each globular cluster star. For each CCD, the star with the highest S/N spectrum was defined as the master star, and the remaining globular cluster spectra were cross-correlated with the master spectrum to measure velocity offsets. This resulted in six and eight template spectra on CCD 1 and CCD 2, respectively, with a known velocity offset from the master star. Radial velocities for the candidate Scl stars were then measured by cross-correlating the spectrum with all templates from the appropriate CCD and shifting the resulting velocity by the appropriate offset such that they were measured relative to the master star for that CCD. The spectra were cross-correlated in the wavelength range 8380–8820 Å, which encompasses the Ca \textsc{ii} triplet lines ($\lambda\lambda$8498, 8542, and 8662) and reduces the number of strong sky features that may not have been completely removed from the stellar spectra (see Fig. 1 in Armandroff & Da Costa 1986). This was accomplished using the \textit{fixcor} routine in the IRAF radial velocity package.

Consequently, each star whose spectrum was recorded on CCD 1 and CCD 2 was cross-correlated with six and eight globular cluster spectra, respectively, resulting in multiple radial velocity measurements. Since the velocities of the candidate Scl stars were measured relative to the two master stars, an adjustment was required to transform these to heliocentric velocities. The heliocentric velocities of both master stars were previously measured using the \textit{rvidlines} routine, as described above. Also, we calculated the heliocentric conversion for the Scl frames. The difference between these values was added to the velocities of the candidate Sculptor stars, resulting in a set of radial velocity measurements relative to the Sun. We combined these values to give a mean radial velocity for each potential Scl member, and the velocity uncertainty was calculated as the standard deviation from the mean.

A final velocity zero-point shift was achieved by comparing our measured radial velocities with those in a previous catalog, which includes the observations of Armandroff & Da Costa (1986). High-resolution spectra for 38 stars were recorded over three seasons (1985–1987) at the CTIO 4 m telescope; the stars were selected from the Hodge (1965) and Kunkel & Demers (1977) photographic surveys of Scl. Armandroff & Da Costa (1986) described the data reduction and velocity measurement techniques and estimated that the radial velocities had a mean error of $\sim$ 4 km s$^{-1}$. The current survey included 27 stars in common with this catalog, with 14 spectra recorded on CCD 1 and 13 on CCD 2. From these, the mean velocity difference between this program and the Armandroff & Da Costa (1986) catalog was found to be

\[
\text{CCD 1: } \Delta v_r = 5.3 \pm 2.1 \text{ km s}^{-1}, \\
\text{CCD 2: } \Delta v_r = 11.2 \pm 2.3 \text{ km s}^{-1},
\]

where the errors are the standard deviation of the mean. These $\Delta v_r$ values were added to the measured velocities to produce a final radial velocity for 764 stars.

To determine the mean uncertainty of the Scl radial velocities, we compared the measurements for multiply observed stars. During the 2dF observing run, multiple observations were obtained of 120 stars located in the overlap regions between 2dF fields. Of these stars, 92 yielded multiple radial velocities with an uncertainty less than 20 km s$^{-1}$, and these covered the full magnitude range of the survey. Approximately 60 of these were observed on both CCDs, and over half were obtained with significantly different fiber numbers. This allowed cross-CCD comparisons between spectra recorded at different positions in each CCD. The CCD velocity corrections listed above were applied to these values, and a comparison of these multiple observations yielded a mean velocity difference of 2.3 km s$^{-1}$, with a standard deviation of 14.9 km s$^{-1}$. Thus, dividing this value by $\sqrt{2}$, the Scl velocities have a mean uncertainty of approximately 10 km s$^{-1}$.

Some of the measured velocities contained a large uncertainty; hence, those with a velocity error greater than 20 km s$^{-1}$ were removed. This criterion removed 41 stars, resulting in a final catalog containing 723 candidate Scl stars. The majority of the rejected stars were located toward the faint end of the 2dF survey limit, where the mean velocity uncertainty was found to be $\sim$12 km s$^{-1}$, as compared with $\sim$2 km s$^{-1}$ at the bright end of the survey. Figure 2 shows the spatial distribution of the final catalog’s 723 stars.

3.2.2. Line Strengths

The lines comprising the Ca \textsc{ii} triplet are the strongest features in the far-red component of a stellar spectrum and are situated close to the peak of the spectral energy distribution displayed by red giant stars. Therefore, the pseudo-equivalent widths, or line...
strengths, of these three lines ($W_{8452}$, $W_{8542}$, and $W_{8662}$) in RGB stars can be easily measured by medium-resolution spectroscopy. A detailed description of the calcium triplet lines and their relation to red giant metallicities is given by Cole et al. (2004).

Armandroff & Da Costa (1991) first noted that if $\Sigma Ca = W_{8542} + W_{8662}$ is plotted against $V - V_{HB}$ (where $V_{HB}$ is the magnitude of the horizontal branch [HB]) for several stars in numerous globular clusters, then the resulting slopes are independent of cluster abundance. This relation has been further investigated by Sundozeff (1993), Da Costa & Armandroff (1995), Rutledge et al. (1997a, 1997b), and Cole et al. (2004). We refer the reader to Fig. 2 in Da Costa & Armandroff (1995), whose study of several Galactic globular clusters demonstrated that the best-fitting line for the $(\Sigma Ca, V - V_{HB})$ relation has a slope of $-0.62$ Å mag$^{-1}$. Consequently, this linear relationship can be used to remove the dependence of line strength on surface gravity by defining the reduced equivalent width to be $W' = \Sigma Ca + 0.62(V - V_{HB})$. An important feature of $W'$ is that it can be directly related to the iron abundance (Armandroff & Da Costa 1991). Da Costa & Armandroff (1995) analyzed several Galactic globular clusters with a large abundance range and demonstrated that the $W' - [Fe/H]$ relation can be split into two linear regimes. This relation was further investigated by Rutledge et al. (1997a), who found a similar result (albeit with a slightly different definition of the reduced equivalent width) using data for 52 Galactic globular clusters. Therefore, the strengths of the Ca ii lines provide an independent measure of metallicity for old, metal-poor stars.

In this survey, equivalent widths of the Ca ii lines at 8452 and 8662 Å were measured using the method described by Armandroff & Da Costa (1991). Two windows to either side of each feature were used to trace the continuum at the feature wavelength. The equivalent widths were then measured using a Gaussian fitting technique. The same rest-wavelength windows given in Table 2 of Armandroff & Da Costa (1991) were used to fit the Gaussian functions and continuum line; however, for the blue continuum bandpass of the Ca ii λ8662 line we used the wavelength range 8559–8595 Å. The weakest of the Ca ii triplet lines, centered at a rest wavelength of 8498 Å, generally does not have sufficient S/N in our spectra, especially at low metallicities, for accurate measurement of the equivalent width. Hence, this line was not included in the following line-strength analysis.

Figure 3a shows the sum of the two strongest Ca ii line strengths as a function of magnitude difference from the HB for the two globular clusters NGC 1904 (filled circles) and NGC 2298 (open circles). We have discounted one of the stars in the NGC 2298 data set, since its velocity and equivalent width data indicate that it is not a member of the cluster. Also, two of the stars have been removed from the set of NGC 1904 points, as their $\Sigma Ca$ values contained large uncertainties and differed significantly from the remaining four stars. The dashed lines in Figure 3a trace the best linear fit to the data with a slope of $-0.62$ Å mag$^{-1}$. This slope provided an adequate linear fit to the data points for both clusters.

To ensure these results are consistent with previous observations, we calculated the mean reduced equivalent width ($W'$) for both clusters. Rutledge et al. (1997a) list values for the two clusters that can be easily modified to the current system. From the transformation derived by Rutledge et al., we find their $W'$ values for the clusters NGC 1904 and NGC 2298 to be $3.24 \pm 0.12$ and $2.32 \pm 0.05$ Å, respectively. We calculated $W'$ for each star using the data shown in Figure 3a and found the following mean reduced equivalent width for each cluster:

$$\overline{W'} = \begin{cases} 
3.23 \pm 0.10 \text{ Å}, & \text{NGC 1904}, \\
2.51 \pm 0.17 \text{ Å}, & \text{NGC 2298},
\end{cases}$$

where the uncertainties are the standard deviation of the mean. These are consistent with the Rutledge et al. (1997a) values.

A second verification of these reduced equivalent widths was to ensure they satisfy the empirical $W' - [Fe/H]$ relation derived by Da Costa & Armandroff (1995) using the globular cluster metallicities provided by Zinn & West (1984). The dashed line in Figure 3b illustrates this relationship for metal-poor clusters, and the two data points represent the $W'$ values listed above. The [Fe/H] values are from Zinn & West (1984), to ensure consistency with the Da Costa & Armandroff study. The data points are adequately described by the abundance relation; hence, the mean reduced equivalent widths derived for these two globular clusters are consistent with previous observations.

The overall uncertainty of the line-strength measurements was obtained by comparing 71 multiply observed stars in the overlap regions between 2dF fields that have the same approximate luminosity distribution as the total set of ScI candidates. For the $W_{8542}$ and $W_{8662}$ lines, we measured the standard deviation from the mean to be 0.31 and 0.38 Å, respectively. The total uncertainty for $\Sigma Ca$ was measured to be $\sigma_{\Sigma Ca} = 0.42$ Å. This uncertainty is dominated by instrumental and sky noise and is only weakly dependent on magnitude.

4. RESULTS: PHOTOMETRIC SURVEY

The early photographic studies of Hodge (1961, 1965, 1966) established many of the fundamental structural parameters of
Scl and did not detect any significant deviations from a smooth stellar density profile. However, later analyses (Demers et al. 1980; Eskridge 1988a, 1988b) found that the region within the core radius is almost circular, yet the ellipticity increases with radius. These analyses also detected possible extratidal stars. More recently, Irwin & Hatzidimitriou (1995) conducted a structural analysis of Scl based on a “blue” (IIIaJ) photographic plate and found that its structure closely resembles the numerical simulations of tidally distorted galaxies by Piatek & Pryor (1995). Irwin & Hatzidimitriou also found some evidence for extratidal stars. The CCD survey of Walcher et al. (2003) detected possible tidal tails extending along the major axis of Scl in the east-west direction and concluded that the outer structure of Scl is strongly influenced by the Galactic tidal field. Consequently, to further address these claims, we have investigated the structure of Scl using a variety of methods applied to the photometric data set.

The CMD provides a filter to select candidate Scl stars, thereby decreasing the number of field stars. In a similar photometric survey of the Fornax dSph galaxy, we described a simple color-magnitude selection technique that decreased contamination due to field stars (C05). For the Scl survey we applied a more complex CMD-selection process based on that of Grillmair et al. (1995), which has since been adapted by Odenkirchen et al. (2001). This method required the CMD to be divided into an array of cells and provided a “signal” value of Scl stars throughout color-magnitude space. Those cells with a signal greater than the limiting value were then used to select candidate Scl stars, maximizing the ratio of Scl to field stars in the outer regions of the dwarf galaxy. A full description can be found in Grillmair et al. (1995); however, we include a summary of the process below, detailing how it was applied to our data.

To determine the signal of Scl stars over the CMD, we divided the photometric data into two spatial regions: the core region (within three core radii of the Scl center), which is dominated by Scl stars, and the field star region (located outside the tidal radius and within the survey limit). 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 color and a height of 0.10 mag. To minimize the effects of photometry errors, we only considered the magnitude range \(16 \leq V \leq 20\), where the mean color uncertainty is less than 0.03 mag. For each color-magnitude cell \((i, j)\), we counted the number of stars located in the core region \(n_c(i, j)\) and the number in the field region \(n_F(i, j)\). Thus, the S/N of core stars 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

| Population | Central Density (stars arcmin\(^{-2}\)) | \(r_c\) (arcmin) | \(r_{lim}\) (arcmin) | \(c\) | Background (stars arcmin\(^{-2}\)) |
|------------|------------------------------------------|-----------------|---------------------|-----|----------------------------------|
| RGB        | 12.0                                     | 6.8 ± 1.2       | 72.5 ± 4.0          | 1.028 | 0.0893 ± 0.0104 |
| RGB-a      | 9.4                                      | 7.6 ± 1.4       | 40.5 ± 2.5          | 0.727 | 0.0893 ± 0.0104 |
| RHB        | 5.9                                      | 4.9 ± 0.7       | 35.5 ± 2.0          | 0.860 | 0.0186 ± 0.0069 |
| BHB        | 2.6                                      | 7.3 ± 1.1       | 81.5 ± 4.0          | 1.048 | 0.0030 ± 0.0002 |
high S/N of Sculptor stars. Following the method of Grillmair et al. (1995), we defined a limiting signal value $s_{\text{lim}}$ to optimize the cumulative S/N of core stars to field stars. Stars were then selected in those CMD cells with a signal greater than a limiting signal value, $s(i, j) > s_{\text{lim}}$. A contour plot showing the signal $s(i, j)$ over color-magnitude space is given in Figure 4. The outer contour outlines those cells with a signal greater than $s_{\text{lim}}$. This region encompasses the Scl RGB down to the photometric limit and hence was used to select candidate RGB stars.

Thus, we selected 4355 candidate Scl RGB stars, and the spatial distribution is displayed in Figure 5, where the ellipses represent the core and tidal radii of the RGB population (see Table 3). At first glance, there is no obvious substructure in the distribution of Scl RGB stars. The radial profile of this stellar population is displayed in Figure 6. The best-fitting King (1966) model to all data points is represented as a dashed line, from which we derive a nominal tidal radius of 72.5 ± 4.0, which is...
Section 4.3 contains a full analysis of the blue and red HB star distributions, from which we have derived their spatial extents; the King parameters for both populations are given in Table 3. We have used these distributions to examine the overall density profile of the RGB stars, finding that a two-component fit gives an excellent representation of the data. This is shown by the dashed line in Figure 7; the dotted lines represent the two components. These two components have the core and limiting radii listed for the blue and red HB populations, respectively. Also, to reduce the number of free parameters, the ratio of the central densities of these two components is the same as the blue HB/red HB ratio taken from Table 3. The resulting model provides a significantly better fit to the data than a single-component model.

4.1. Extratidal Structure

4.1.1. Density Probability Function

In the companion paper (C05) we describe two methods to detect structure beyond the nominal tidal radius of a stellar system. The first of these, a density probability function, is created by measuring the stellar density in a large number of randomly

![Figure 10](https://example.com/figure10.png)

**Fig. 10.—** Density probability functions for simulated tidal tails. The mean stellar density of the tails above the background is given in the top right corner of each panel. [See the electronic edition of the Journal for a color version of this figure.]

comparable to the Irwin & Hatzidimitriou (1995) value of $r_t = 76.5 \pm 5.5$. However, there is some deviation from this curve beyond $r \approx 30'$. Consequently, we fit a King profile to the inner 40', which is represented by a dotted line. This profile has a limiting radius of $40.5 \pm 2.5$, and the data shown in Figure 6 imply significant extratidal structure. This is consistent with the results of Walcher et al. (2003), who found a tidal radius of 44' and claimed a large population of stars beyond this radius. We have found that an oversubtraction of the field population in our data can reproduce the results of Walcher et al., giving a detection of extratidal structure. It is clear that neither model provides an adequate description of the Sculptor system; however, the King parameters for both models are listed in Table 3, where the entries for RGB-a refer to the profile for the inner 40' of Scl.

In this context it is worth considering the results of Tolstoy et al. (2004), who found that the red giants of Sculptor apparently consist of two populations that are kinematically and chemically distinct. These two populations are probably related to the fact that the red and blue HB stars in Sculptor have different radial distributions, with the red HB stars being more centrally concentrated (Kaluzny et al. 1995; Da Costa et al. 1996; Harbeck et al. 2001; Majewski et al. 1999; Hurley-Keller et al. 1999).
placed circles over the survey area. In this way we were able to find the probability of measuring a given density of stars outside the nominal tidal radius. A uniform distribution of stars (for example, the field star population) is expected to display a Gaussian density function, while substructure will produce a non-Gaussian function. This function was measured for the distribution of RGB-selected stars outside the nominal tidal radius of Scl, where the stellar density was measured within $10^6$ circles of radius $12'$. The circle size was chosen to be large enough to include a reasonable number of stars, yet not too large to miss the detection of medium-scale ($\sim 20'$) structures. Figure 8 shows the density function; the dashed line represents the best-fitting Gaussian to the data. This function indicates that the mean background stellar density is $237$ stars deg$^{-2}$ with a standard deviation of $65$. Unlike the corresponding result for Fornax (C05), the extratidal region of Scl does not display any significant substructure; the function appears to be consistent with a uniform distribution of sources, which implies a population comprising only field stars.

If the stars beyond the tidal radius are not part of the Scl system, then they must be foreground and background sources. The background source population is made up of distant galaxies; however, the majority of these would not be interpreted as stellar sources by the DAOPHOT program because of their noncircular morphology. Although a complete star-galaxy separation cannot be made given an average seeing of $2''$ for the survey, we estimate the total number of background galaxies to be less than $25\%$ of the number of objects detected. Also, the CMD selection range shown in Figure 4 further prejudices this population. Hence, assuming that the extratidal population of Scl is negligible, the field population is almost entirely assembled from foreground Galactic stars. Ratnatunga & Bahcall (1985) estimated the density of the field star population toward Sculptor using the Galactic models of Bahcall & Soneira (1980). In the color-magnitude range $17 < V < 21$, $0.8 < (B - V) < 1.3$, they estimated $252$ stars deg$^{-2}$ in the Scl field, with an approximate error of $25\%$. Although these color and magnitude limits do not exactly correspond with our CMD selection range (Fig. 4), the Ratnatunga & Bahcall (1985) estimate agrees (within the uncertainties) with our mean field star density measurement of $237$ stars deg$^{-2}$ represented in Figure 8. This supports our inference that the candidate RGB stars beyond the nominal tidal radius correspond to the field star population, and there is no substantive evidence for Scl RGB stars in this region.

To determine how effectively the density probability function can detect structures in an otherwise random distribution of stars, we simulated a series of overdensities in the extratidal region of Scl. The Monte Carlo algorithm was applied to a data set consisting of the candidate Scl RGB stars and two synthetic tidal tails extending in the north and south directions from the center of the system. We created six artificial data sets in which the mean stellar density of the synthetic tidal tails was $\rho = 0.5$, $1.0$, $\ldots$, $3.0\sigma$ above that of the field population. The tails uniformly occupied the region $-0.5 \leq \Delta \alpha \leq 0.5$ over the declination range of the survey, both inside and outside the nominal tidal radius. For example, a spatial plot of the RGB data set with artificial tidal tails of density $2.0\sigma$ is shown in Figure 9; the tails (from the aggregate stellar luminosity over this sky area) have a surface brightness of $30.4$ mag arcsec$^{-2}$ above that of the field population.

Figure 10 shows the density functions measured from the six tidal tail simulations. In each panel the dashed line traces the density function measured from the true extratidal population. The $0.5\sigma$ overdensity population is barely visible in the density function; however, a second peak becomes more prominent as the density of the synthetic tidal tails increases. For tidal tails of this type, we find evidence for substructure when the density is a factor of $\sim 1.5$ above the background population. This corresponds to $\sim 100$ extratidal RGB stars per square degree, or approximately $10\%$ of the light from all Sculptor RGB stars. The simulations were repeated using tidal tails of various widths (greater than $\sim 0.3'$) aligned at several position angles relative to Sculptor, and we found that the density probability function was able to detect features with a surface brightness greater than $\mu_V \sim 31$ mag arcsec$^{-2}$ above the background population, assuming they have the same luminosity function as Scl.

4.1.2. Angular Correlation Function

A second method to search for extratidal structures is to measure the angular correlation function for the stellar population beyond the nominal tidal radius. The angular correlation function is generally used in cosmology to examine whether galaxies in a sample are clustered or, alternatively, follow a Poissonian distribution (Peebles 1980). For a given sample of data points covering a finite area, this function is measured by placing a large number of random points in a two-dimensional area with the same shape as the data set. The number of data-data pairs ($DD(\theta)$), data-random pairs ($DR(\theta)$), and random-random pairs ($RR(\theta)$) is then determined at a given scale length $\theta$. The observed angular correlation function is then calculated as

$$w_{\text{obs}}(\theta) = 1 + \frac{DD(\theta)}{RR(\theta)}W_1 - 2\frac{DR(\theta)}{RR(\theta)}W_2. \quad (1)$$

The parameters $W_1$ and $W_2$ are determined from the number of data and random points ($N_{\text{data}}, N_{\text{ran}}$) using the relations

$$W_1 = \frac{N_{\text{ran}}(N_{\text{ran}} - 1)}{N_{\text{data}}(N_{\text{data}} - 1)}, \quad (2)$$

$$W_2 = \frac{N_{\text{ran}} - 1}{N_{\text{data}}}. \quad (3)$$

FIG. 11.—Observed angular correlation function for the extratidal region of the Sculptor data set. Error bars are measured from Poisson noise, and a factor of 0.3 has been added to all points. The dashed line represents $w_{\text{obs}}(\theta) = 0$. 
This provides a solution for a survey of infinite extent; however, for a finite survey the function must be adjusted by a constant called the integral constraint, defined as the product $A_wB$ (Roche & Eales 1999). The parameter $B$ is determined numerically from the number of random-random pairs, and the values of $A_w$ and $\beta$ (defined below) are determined to be those that provide the best-fitting function to the observed data points. After correcting for the integral constraint, the angular correlation function takes the form

$$w(\theta) = \frac{A_w}{C_{18}} \theta^{-\beta};$$

where $A_w$ is the function amplitude and $\beta$ defines the slope. A purely random distribution of points will produce a flat angular correlation function ($A_w$ and $\beta$ are both equal to zero; hence, $w(\theta) = 0$), while a sloped function ($A_w$ and $\beta$ greater than zero) reflects a clustered sample.

Accordingly, we measured the angular correlation function for all stars beyond the nominal tidal radius of Scl. We placed $10^5$ points randomly throughout the survey region and measured the distance between all data-data, data-random, and random-random pairs. These were placed in logarithmic bins of width $\Delta \log \theta = 0.05$, where $\theta$ is in arcminutes. Figure 11 shows the data points for the observed angular correlation function, calculated using equation (1). The error bars were calculated from the Poisson noise of the number of data points in each bin of $\theta$. The dashed line defines $w_{\text{obs}}(\theta) = 0$, which is the expected function for a randomly distributed set of stars. This line accurately traces the data points, especially at large scales at which a large number of data-data pairs in each bin results in small uncertainties. Hence, this test indicates that there is no significant structure in the distribution of RGB candidate stars beyond the nominal tidal radius of Scl.

To test the effectiveness of this function, we repeated the process for the six synthetic tidal tail data sets described in §3. Figure 12 displays the resulting angular correlation functions, where the parameter at the top right corner of each panel is the density of the tidal tails in terms of the standard deviation of the field population ($\sigma$). The error bars represent Poisson noise, and the dashed lines trace $w_{\text{obs}}(\theta) = 0$, the expected function for a normal distribution of points. Similar to the density function above, we have found that an overdensity of $\sim 1.5 \sigma$ is easily discernible, while structures with a density less than this value are
difficult to distinguish from the background noise. Hence, the angular correlation function was able to detect extratidal structures with a surface brightness greater than $\mu_V \sim 31$ mag arcsec$^{-2}$. That is, in order for an extratidal structure to have been detected around Scl, it required a surface brightness approximately 30% greater than the background.

### 4.1.3. Contour Map

Both tests indicated that there was no substructure in the extratidal distribution of stars shown in Figure 5. To further investigate the possibility of extratidal structure, we created a contour map of Scl (Fig. 13) from the RGB-selected stars. Each star was convolved with a Gaussian of radius 40", and the contour smoothing length was 3". The first contour traces all structure with a density 1 $\sigma$ above the field population, and the second contour level represents a 3 $\sigma$ density, where $\sigma = 65$ stars deg$^{-2}$ is the standard deviation of the field population. The first contour is highly sensitive to statistical variations in the field star density; hence, we define the 3 $\sigma$ level as the significance limit of this survey. The red ellipse in Figure 13 represents the Scl tidal radius.

There are some signs of structure in the outer regions of Sculptor: for instance, the two small 3 $\sigma$ density peaks located in the southwest quadrant. Schweitzer et al. (1995) measured the absolute proper motion of Scl to be directed toward the northeast; thus, it is possible that the southwest "blobs" represent tidally stripped stars trailing the Sculptor system. It is also possible, however, that these structures are simply density spikes in the field star population and are therefore not associated with Sculptor. Either way, they represent only a small fraction of the stars in this system.

A second feature is the small "hook" structure centered at approximately $\Delta \alpha = -0.2$, $\Delta \delta = -0.6$, within the tidal radius. There is some evidence that this structure also exists in the Walcher et al. (2003) study, but only at the 1–2 $\sigma$ level in their diagram. It points toward the southwest quadrant and possibly to the small 3 $\sigma$ density peaks mentioned above. This structure may represent tidal distortion, or it may also be a random fluctuation in the field star density.

### 4.2. Inner Structure

We investigated whether the structure of Scl RGB stars is dependent on radius by fitting a series of ellipses to the stellar density, following the method described in C05. The best-fitting center, position angle, and ellipticity were calculated at each major axis radius value of $r = 5\', 6\', \ldots, 60\'$. Beyond $r = 60\'$, the number of stars was too low to accurately fit an ellipse to the data. Figure 14 shows the mean values in radial bins of 5\', where the uncertainties represent the standard deviation from the mean and the dashed lines indicate the central coordinates, ellipticity, and position angle listed by Mateo (1998). Figures 14a and 14b demonstrate that the center of Scl remains constant out to a radius of approximately 40' and then moves north for all subsequent radii. Although the position angle of these ellipses effectively remains constant at all radii, the ellipticity plot in Figure 14d indicates that the structure of the inner regions is almost circular and then becomes more elliptical as the radius increases (see Fig. 13). This reinforces the results of Demers et al. (1980), Eskridge (1988a), and Irwin & Hatzidimitriou (1995).

Hence, there is some evidence for Scl distortion. A visual examination of the contour diagram in Figure 13 does indicate that the outer region has a significantly higher ellipticity compared to the inner region. Walcher et al. (2003) reported the possibility of tidal extensions along the east-west axis (see their

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**Fig. 2.** Although Walcher et al. state a limiting magnitude for their survey of $V \sim 23.5$, they also point out that the claim of tidal extensions is subject to nonuniform limiting magnitudes throughout the survey and is dependent on the level of galaxy separation. We confirm that the structure of Scl appears stretched along this axis in the outer regions, but there is little evidence to support the existence of well-defined tidal tails.

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### 4.3. Horizontal-Branch Stars

Kuhn & Miller (1989) proposed that the interaction between a satellite system and the host galaxy may artificially increase the velocity dispersion, thereby increasing the measured $M/L$. However, in order to increase the radial velocity dispersion, the satellite galaxy must be positioned such that its long axis is aligned along the line of sight. Klessen & Kroupa (1998) stated that the resulting distance distribution of the stars should produce a HB width of $\sim$1 mag. Klessen et al. (2003) previously searched for this line-of-sight depth in the Draco dSph, without success. In Scl we find the HB vertical dispersion to be approximately 0.15 mag, which does not support a line-of-sight inflation of this system. For the remainder of this section, we investigate the morphology of the Scl HB in relation to the second parameter (2P) effect.

The HB constitutes core He-burning stars with ages greater than $\sim$10 Gyr. Studies of globular clusters indicate that metallicity is the first parameter governing the HB morphology; metal-poor populations tend toward a blue horizontal branch (BHB), while metal-rich populations often form the red horizontal branch (RHB). However, some systems exhibit a 2P effect, in which the HB morphology is not wholly dependent on metallicity. The early photometric analyses of Scl revealed a surprisingly red HB given its mean abundance (Kunkel & Demers 1977; Da Costa 1984, 1988), implying that Scl is a 2P object.

More recently, deeper photometry over a wide field has revealed that the HB morphology in Scl is radially dependent (Light 1988; Kaluzny et al. 1995; Da Costa et al. 1996) such that the
RHB stars are more centrally concentrated than the BHB stars. This has been verified by Harbeck et al. (2001). The results of Majewski et al. (1999) and Hurley-Keller et al. (1999) indicate that the stellar population of Scl is bimodal; that is, the inner region displays the 2P effect and contains a mixture of RHB and BHB stars, while the outer region is dominated by BHB stars. The spectroscopic study by Tolstoy et al. (2004) showed that Sculptor contains two distinct stellar populations represented by either side of the HB, and that these populations are offset from each other in metallicity and kinematics. The population gradient in Scl may indicate that residual gas from the first star formation burst was concentrated at the center of the system, resulting in a younger and/or more metal-rich central stellar population (for a full discussion, see Harbeck et al. 2001).

To investigate the radial dependence of the HB morphology, we selected stars using the color-magnitude ranges outlined in Figure 1. The selection range for both components of the HB was chosen to minimize contamination effects due to stars in the RGB and instability strip. First we examine the RHB stars. The dashed line represents the completeness limit (\(V = 20.4\) and \(I = 19.6\)) of the four inner fields. Hence, the corresponding spatial distribution of RHB stars displayed in Figure 15 is essentially complete for all values of \(\Delta \alpha\) and \(\Delta \delta\) between \(0^\circ.6\) and \(0^\circ.6\). A radial profile of the RHB candidate stars was assembled by selecting stars within a set of annuli of constant center, ellipticity, and position angle (listed by Mateo 1998). The background stellar density was calculated as the mean value beyond \(r = 40'\) (Table 3). This value was subtracted from the stellar density measurements, and the resulting radial profile is shown in Figure 16a, where the dashed line represents the best-fitting King profile. The resulting core and limiting radii are represented by the solid ellipses in the RHB-selected spatial map (Fig. 15), while the dashed line represents the limiting radius of the Scl RGB stars (see Table 3).

Now we turn to the BHB stars. The BHB selection box shown in Figure 1 lies beyond the photometric limit of the four inner fields. Hence, to determine which fields contain a near-complete sample at this luminosity, we placed \(\approx 5000\) artificial BHB stars in each field and attempted to recover these using the same photometry routines described in § 2. The artificial stars were clustered around \(V = 20.35, (V - I) = 0.3\) with a dispersion of 0.15 mag in both \(V\) and color, resembling the appearance of the BHB as seen in Figure 1. The recovery statistics for each field are listed in Table 4. For each artificial star we measured the difference between the input and output magnitudes. The values \(\sigma_V\) and \(\sigma_I\) are the standard deviations from the mean difference and hence
indicate the level of photometric accuracy achieved by each field at the depth of the BHB.

An examination of Table 4 reveals that 7 of the 16 fields recovered significantly less than 80% of the artificial BHB stars. Therefore, BHB stars were selected only in the remaining nine fields, and their spatial distribution is shown in Figure 17. The dotted line outlines the seven incomplete fields, which are also labeled. We constrained the best-fitting BHB radial profile from the nine complete fields using the same technique described above for the RHB population. Figure 16b shows the BHB profile; the errors are the Poisson noise for each annulus, and the dashed line represents the best-fitting King model. We subtracted a background density from the profile, measured to be $(2.97 \pm 0.20) \times 10^{-3}$ stars arcmin$^{-2}$ in the area beyond a major axis radius of 80'. The resulting King profile parameters are listed in Table 3, while the core and limiting radii are displayed in the BHB-selected spatial map (Fig. 17). A comparison of the radial profiles for the RHB and BHB stars is shown in Figure 16c. We have thus

| Field | Recovery (%) | $\sigma_V$ (mag) | $\sigma_I$ (mag) |
|-------|-------------|-----------------|-----------------|
| 1     | 57.6 ± 1.8  | 0.053           | 0.110           |
| 2     | 74.9 ± 1.6  | 0.077           | 0.128           |
| 3     | 48.8 ± 1.9  | 0.287           | 0.137           |
| 4     | 21.8 ± 2.9  | 0.152           | 0.573           |
| 5     | 2.34 ± 8.8  | 0.037           | 0.428           |
| 6     | 21.7 ± 2.8  | 0.058           | 0.122           |
| 7     | 97.9 ± 1.4  | 0.064           | 0.077           |
| 8     | 88.7 ± 1.4  | 0.048           | 0.094           |
| 9     | 95.8 ± 1.4  | 0.065           | 0.145           |
| 10    | 85.5 ± 1.4  | 0.103           | 0.185           |
| 11    | 95.0 ± 1.4  | 0.061           | 0.105           |
| 12    | 79.2 ± 1.5  | 0.058           | 0.089           |
| 13    | 97.0 ± 1.4  | 0.053           | 0.101           |
| 14    | 94.7 ± 1.4  | 0.059           | 0.084           |
| 15    | 99.1 ± 1.4  | 0.056           | 0.105           |
| 16    | 55.3 ± 1.8  | 0.074           | 0.106           |
confirmed the HB gradient in Scl and measured the spatial extent of the two populations described by Tolstoy et al. (2004).

5. RESULTS: SPECTROSCOPIC SURVEY

The Scl spectroscopic data set contained 723 candidate RGB stars with radial velocity errors less than 20 km s$^{-1}$. The velocity distribution of these stars is shown in Figure 18. The population is clearly bimodal in velocity, with the Scl population clustered around $v_r/\pm100$ km s$^{-1}$ and the field population around $\sim0$ km s$^{-1}$. To determine the mean Scl radial velocity, we selected 188 stars in the radial velocity range $76.5$ km s$^{-1} \leq v_r \leq 137.5$ km s$^{-1}$ and calculated the mean velocity using the relation from Armandroff & Da Costa (1986),

$$v = \frac{\sum_{i=1}^{N} w_i v_i}{\sum_{i=1}^{N} w_i},$$

where the weight ($w_i$) is defined as the inverse square of the individual velocity uncertainty for each velocity $v_i$. The mean heliocentric velocity of Scl was then measured to be $v_{Scl} = 106.9 \pm 1.1$ km s$^{-1}$, where the error is the weighted standard deviation of the mean. This value is represented by the dashed line in Figure 18 and agrees well with the previous measurements by Armandroff & Da Costa (1986) and Queloz et al. (1995).

5.1. Sculptor Membership

In this section we describe several methods used to eliminate foreground Galactic stars from the Scl member list. The primary method was provided by a radial velocity selection range. We measured the velocity dispersion around the Scl mean to be $\sigma_{obs} = 15.2 \pm 0.6$ km s$^{-1}$. Assuming that the average global velocity dispersion of the Scl system is approximately 10 km s$^{-1}$ (Tolstoy et al. 2004), this $\sigma_{obs}$ value agrees with the overall velocity uncertainty of $\sim10$ km s$^{-1}$. This allows us to define the velocity selection range for the Scl members.

5.1.1. Velocity Selection and the Field Population

The dotted lines in Figure 18 illustrate the velocity range for the selection of Scl stars. We have chosen a width of $2.5 \sigma_{obs}$ to either side of the mean Scl velocity ($81.9$ km s$^{-1} \leq v_r \leq 131.9$ km s$^{-1}$). This velocity range gives 157 likely members of Scl.
the Scl system. An important concern in this selection criterion is residual background noise from Galactic stars; Figure 18 shows the distribution in velocity of these foreground stars included in the Scl observations, and clearly some portion of the Galaxy’s population extends into the Scl velocity range. The color selection range for these stars illustrated in Figure 1 allows two possible populations of stars to contribute to the field population; halo RGB stars or Galactic (thin and/or thick) disk main-sequence stars. Assuming that the field population comprises giant stars, the apparent magnitude selection range implies a distance of at least 45 kpc (from the Yonsei-Yale isochrones; Yi et al. 2001; Kim et al. 2002). The stellar halo contains ~1% of the stellar mass of the Galaxy and has a power density distribution $\rho \propto r^{-n}$, where $n = 2.5–3.5$, depending on the stellar population (Chiba & Beers 2000; Chen et al. 2001; Vivas et al. 2001); thus, we expect the contribution of halo stars to the field population to be negligible.

In contrast, if we assume that the field population comprises dwarf stars occupying the Galactic disk, the color-magnitude selection range implies that these stars are located at a distance of 350 pc $\leq d \leq 1600$ pc. Now, the thin disk displays a scale height of ~300 pc (e.g., Gilmore 1984; Bahcall & Soneira1984; Chen et al. 2001), whereas the scale height of the thick disk (Gilmore & Reid 1983) is approximately 1000 pc (Chen et al. 2001; see Norris 1999 for a recent review). Therefore, we expect a negligible contribution from the thin disk, and hence the field population is composed almost entirely of Galactic thick-disk stars.

The Scl dSph is located near the south Galactic pole (SGP); hence, the width in velocity space of the field stars is determined almost exclusively by the vertical velocity dispersion of the Galactic thick disk. Recent measurements (Norris 1987; Layden et al. 1996; Chiba & Beers 2000) have found this value to be 30–35 km s$^{-1}$. We calculated the observed velocity dispersion of the field stars toward Scl to be 34.1 km s$^{-1}$.

Assuming an instrumental uncertainty of 10 km s$^{-1}$ gives the true velocity dispersion of these stars as 32.6 km s$^{-1}$, which agrees with previously determined values. There were 364 stars in the velocity range $-50 \leq v_\phi \leq 50$ km s$^{-1}$; hence, we deduce that the data set includes approximately 430 Galactic stars overall. Assuming that the velocity distribution follows the Gaussian function illustrated in Figure 18, the 2.5 $\sigma_{\text{obs}}$ star selection criterion is expected to include approximately eight high-velocity Galactic thick-disk stars.

### 5.1.2. Equivalent Widths

A second test for the membership status of the candidate Scl stars was provided by abundance measurements. From the pseudo-equivalent widths we were able to calculate $\Sigma$Ca for the 157 candidate Scl stars, which can be directly related to [Fe/H] for red giants. Given that any residual field objects would be foreground dwarf stars, we expect that their surface gravities may provide a Ca triplet measurement markedly different from the range seen in Sculptor. The resulting $\Sigma$Ca values are plotted against magnitude in Figure 19. Based on Ca $\Pi$ triplet observations of approximately 300 RGB stars in Scl, Tolstoy et al. (2004) observed an abundance range in Scl of $-2.8 \leq [\text{Fe/H}] \leq -0.9$. The upper abundance limit is shown by the dashed line in Figure 19. However, the line-strength index has an uncertainty of $\sigma_{\text{W}} = 0.42$ $\AA$; therefore, we extended the $W$ selection limit by a factor

### TABLE 5

**Candidate Extragalactic Scl Stars: Photometric Properties**

| Star | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $I$ | $V - I$ | $\mu_\alpha$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) |
|------|-----------------|-----------------|-----|--------|-----------------|-----------------|
| 1_1_240 | 01 07 22.81 | -32 21 13.99 | 16.64 ± 0.02 | 1.41 ± 0.03 | 11.0 ± 8.4 | -16.4 ± 8.3 |
| 1_4_548 | 01 06 02.01 | -32 59 42.36 | 15.64 ± 0.02 | 1.65 ± 0.03 | 20.0 ± 8.6 | -9.5 ± 8.1 |
| 1_8_249 | 01 04 27.87 | -32 14 43.56 | 17.40 ± 0.02 | 1.13 ± 0.03 | 11.9 ± 8.4 | -13.4 ± 8.0 |
| 2_3_289 | 01 02 23.29 | -32 42 57.54 | 16.62 ± 0.02 | 1.26 ± 0.03 | 11.1 ± 8.9 | -7.3 ± 8.4 |
| 4_3_158 | 00 55 37.52 | -32 41 58.09 | 16.93 ± 0.02 | 1.26 ± 0.03 | -6.0 ± 15.7 | -7.2 ± 14.6 |
| 13_5_446 | 01 03 40.85 | -35 09 10.23 | 16.32 ± 0.02 | 1.32 ± 0.03 | 2.9 ± 8.8 | -13.7 ± 8.2 |
| 16_2_265 | 00 55 21.21 | -34 42 12.65 | 16.70 ± 0.02 | 1.23 ± 0.03 | 28.8 ± 14.0 | -24.2 ± 13.2 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

### TABLE 6

**Candidate Extragalactic Scl Stars: Spectroscopic Properties**

| Star | $v_\phi$ (km s$^{-1}$) | [Fe/H] | $\Delta \alpha$ (deg) | $\Delta \delta$ (deg) | $d_{\text{Scl}}$ (deg) |
|------|-----------------|--------|-----------------|-----------------|-----------------|
| 1_1_240 | 89.1 ± 1.9 | -1.67 ± 0.17 | 1.50 | 1.35 | 2.02 |
| 1_4_548 | 84.0 ± 0.7 | -1.89 ± 0.11 | 1.22 | 0.71 | 1.42 |
| 1_8_249 | 86.6 ± 7.8 | -1.66 ± 0.08 | 0.90 | 1.46 | 1.72 |
| 2_3_289 | 91.3 ± 7.1 | -1.70 ± 0.21 | 0.47 | 0.99 | 1.10 |
| 4_3_158 | 95.8 ± 11.8 | -1.86 ± 0.36 | -0.94 | 1.01 | 1.38 |
| 13_5_446 | 126.6 ± 3.8 | -1.66 ± 0.29 | 0.73 | -1.45 | 1.62 |
| 16_2_265 | 112.9 ± 3.7 | -1.40 ± 0.22 | -1.00 | -1.00 | 1.41 |

![Fig. 22.—Spatial distribution of the 148 Sculptor members. The triangles represent stars beyond the nominal tidal radius (including the tidal radius uncertainty). [See the electronic edition of the Journal for a color version of this figure.]](image-url)
of 2 \sigma_{B}, and this limit is shown by the solid line in Figure 19. In order for a star to be included as a Scl member, its line strength must lie below this value. The open circles represent the two stars that do not fulfill this criterion and have been discarded as Scl members.

Tolstoy et al. (2004) revealed that Scl contains a metallicity gradient such that the mean [Fe/H] value of the inner region is higher than that of the outer region. We found a similar result in our data. Figure 20 shows the metallicity of these stars as a function of (major axis) radius, under the assumption that Scl has an ellipticity of e = 0.32 (Mateo 1998). The two dotted lines indicate the core and nominal tidal radii. We subdivided these data at the core radius (r_c) and found the mean metallicity for both data sets to be

\[ \langle [\text{Fe/H}] \rangle = \begin{cases} -1.56 \pm 0.04; & r \leq r_c, \quad N = 8, \\ -1.92 \pm 0.03; & r_c < r < r_t, \quad N = 135, \end{cases} \]

where the errors are the standard deviation of the mean. That is, we have confirmed the metallicity gradient noted by Tolstoy et al. (2004).

5.1.3. Proper Motions

Scl is located toward the SGP; hence, we expect many of the field stars to display a high proper motion. Proper motions of all stars in the refined Scl member list were extracted from the SuperCOSMOS Science Archive, which makes use of observations at up to four different epochs. The astrometry from this catalog is described by Hambly et al. (2001). The proper motions of the potential members are shown in Figure 21. We measured the standard deviations from the mean motions in right ascension and declination to be \( \sigma_{\mu, \alpha} = 14.4 \) and \( \sigma_{\mu, \delta} = 18.3 \) mas yr\(^{-1}\), respectively. Thus, the proper motion limits for Scl stars were set to be 3 \( \sigma_{\mu, \alpha} \) and 3 \( \sigma_{\mu, \delta} \), represented by the dashed ellipse in Figure 21. The four stars with a proper motion (within their uncertainties) beyond this value were discarded as Scl members and are represented by open circles.

5.2. Extratidal Candidates

The \( \sigma \)-clipping processes above removed six contaminating objects, two based on calcium triplet measurements and four based on proper motion. This reduced the number of possible Scl members to 151 stars, of which 10 are located outside the nominal tidal radius. Three of these extratidal candidates have relatively large velocity errors, which makes it difficult to be certain of membership, and colors that place them \( \sim 0.05 \) mag too red of the definite Scl RGB members in the CMD (see Fig. 23). For these reasons they were discarded from the Scl member sample. Consequently, we have seven candidate extratidal members.

The characteristics of these stars are listed in Tables 5 and 6. Figure 22 shows the spatial distribution of the 148 Scl members, with the triangles representing the seven extratidal stars. Note that those stars within the tidal radius uncertainty of this limit are not considered to be extratidal. To aid the reader in matching the data in Tables 5 and 6 with the data points in Figure 22, we have also listed their \( \Delta \alpha \) and \( \Delta \delta \) coordinates and their distance from the center of Scl, \( d_{\text{Scl}} \). The color-magnitude distribution of the final member star list is shown in Figure 23, with the asterisks representing the three stars rejected based on colors. The parameters we have measured for all Sculptor members are given in Table 7.

**TABLE 7**

| Star   | \( \alpha \) (J2000.0) | \( \delta \) (J2000.0) | \( V \)     | \( V - I \)     | \( v_r \) (km s\(^{-1}\)) | [Fe/H] |
|--------|------------------------|------------------------|------------|---------------|-----------------|--------|
| 16_2_265 | 00 55 21.20            | -34 42 12.6            | 17.934 ± 0.005 | 1.232 ± 0.009 | 112.9 ± 3.7    | -1.40 ± 0.22 |
| 12_2_332 | 00 55 21.98            | -34 01 42.4            | 18.498 ± 0.006 | 1.097 ± 0.008 | 118.7 ± 14.8    | -2.38 ± 0.17 |
| 8_3_296  | 00 55 23.44            | -33 24 09.9            | 18.639 ± 0.006 | 1.173 ± 0.008 | 101.7 ± 6.7    | -1.78 ± 0.26 |
| 4_3_158  | 00 55 37.52            | -32 41 58.0            | 18.186 ± 0.006 | 1.260 ± 0.007 | 95.8 ± 11.8    | -1.86 ± 0.36 |
| 8_4_235  | 00 55 55.74            | -33 51 53.3            | 18.351 ± 0.005 | 1.146 ± 0.007 | 95.1 ± 19.0    | -2.00 ± 0.19 |
| 12_3_139 | 00 56 12.09            | -34 16 17.7            | 18.012 ± 0.004 | 1.199 ± 0.006 | 140.4 ± 2.5    | -2.27 ± 0.21 |
| 7_7_306  | 00 56 20.23            | -33 09 20.9            | 18.551 ± 0.007 | 1.158 ± 0.012 | 108.6 ± 19.4    | -1.24 ± 0.13 |
| 11_8_435 | 00 56 46.94            | -33 48 20.6            | 17.235 ± 0.003 | 1.480 ± 0.005 | 116.2 ± 3.4    | -2.06 ± 0.10 |
| 3_5_175  | 00 57 15.38            | -32 59 28.4            | 18.046 ± 0.006 | 1.277 ± 0.010 | 89.9 ± 5.3     | -1.46 ± 0.09 |
| 7_5_285  | 00 57 19.67            | -33 36 38.0            | 18.525 ± 0.008 | 1.129 ± 0.001 | 126.6 ± 2.5    | -1.83 ± 0.20 |

Notes.—Table 7 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content. The uncertainties for \( V \) and \( V - I \) are relative only and do not include those from the photometric calibration. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

4 Available at http://surveys.roe.ac.uk/ssa/index.html.
6. DISCUSSION

6.1. Inner Structure

Demers et al. (1980) found that the ellipticity of Scl increased with radius, which has since been confirmed in subsequent photographic plate analyses (Eskridge 1988a, 1988b; Irwin & Hatzidimitriou 1995). We also noted this effect. In our analysis the position angle of these ellipses did not significantly change with radius (ΔP.A. ~ 10°). A possible indication of tidal distortion was the fluctuation of the central coordinates of Scl. That is, as the ellipse radius increased, the center shifted by approximately 10′ north. As such, the internal structure of Scl displays what may be the hallmarks of tidal distortion. However, it is worth noting that a triaxial structure can also produce these characteristics.

Walcher et al. (2003) described a feature extending south from the eastern lobe of Scl (see their Fig. 2). This feature was located near their tidal limit of the system (r_t = 44′), and they stated that it may indicate a tidal extension. We found no evidence of this feature in the current study. Also, Walcher et al. (2003) measured the tidal radius of Sculptor to be 44′ (significantly less than previous surveys), with clear signs of tidal structure. In contrast, we fitted a two-component King model to Sculptor with a limiting radius of 70′–80′ and found that it adequately described the system with little sign of tidal inflation. This reinforced the result of Tolstoy et al. (2004), who found that Sculptor contains two separate stellar populations.

Tidal distortion may also produce kinematic substructure (such as apparent rotation) in a satellite system. We have identified 148 Scl members through a spectroscopic analysis, and the spatial distribution of these is shown in Figure 22. An examination of the velocities of these stars as a function of position angle revealed no significant evidence for rotation, confirming the original result by Armandroff & Da Costa (1986). Kleyna et al. (2003) conducted a radial velocity analysis of the UMi dSph and discovered a kinematically cold population of stars toward the center of the system, which they hypothesize may represent an underlying clump of dark matter. To investigate the presence of kinematic substructure within Scl, we measured the offset in velocity of each star from the mean velocity of Scl and examined this offset as a function of position. There were no obvious kinematic substructures; however, the small number of stars in the outer regions of Scl for which we have radial velocities precludes a strong result, as do the relatively large velocity errors.

6.2. Extratidal Structure

Our analysis of the photometric survey set the upper limit for extratidal material to approximately 10% of the Sculptor mass. With the spectroscopic survey, we were able to strengthen this result. By selecting stars based on radial velocity, metallicity, and proper motion, we found seven extratidal candidates out of a total member list of 148 objects. These seven stars may include some residual Galactic thick-disk stars, thus corresponding to an upper limit for the total mass outside the Scl tidal radius. However, the spectroscopic survey was not complete; we obtained radial velocities for 723 of the 1408 CMD-selected stars. Thus, by examining the number of candidates surveyed beyond the tidal radius, we found that the seven extratidal candidates correspond to 13.6 stars in a complete survey of the RGB candidates. Similarly, the density of the field stars in this CMD selection range is ~80 stars deg⁻², from which we inferred that approximately 600 of the 1408 stars within the tidal radius are Sculptor members.

Therefore, assuming that the extratidal candidates represent a stellar population with the same luminosity function as Scl, we have measured the upper limit of extratidal luminous mass to be 2.3% ± 0.6% of the Scl total, where the uncertainty represents Poisson noise.

This result can be compared to the previous study by Innanen & Papp (1979), who analyzed 602 variable stars (mostly RR Lyrae type) in the Scl region using the catalog of van Agt (1978), described to be 75% complete. From an analysis of the stellar positions (see their Fig. 2) we find that ~10 of these are located beyond the nominal tidal radius of the RGB population determined in the current study, r_t = 72.5′. That is, only 1%–2% of these stars are extratidal. This result agrees with our upper mass limit for extratidal structure stated above.

Although there is little evidence of significant extratidal structure in our spectroscopic sample, it is worth referring to the work of Schweitzer et al. (1995), who measured the absolute proper motion of Scl to be toward the northeast. Four of the seven extratidal stars we have identified are located in this quadrant. If these stars are members of Sculptor, then they represent leading tidal material. It is difficult, however, to make any definite statement in this regard based on such a small data set. Also, there is no correlating northeast population of extratidal stars in the Innanen & Papp (1979) analysis.

7. CONCLUSION

We have conducted a combined photometric and spectroscopic survey of the Scl dSph to determine whether its structure and kinematics have been influenced by the tidal field of the Galaxy. In the first phase of the survey, we obtained photometry in two colors (V and I) over a 10 deg² area centered on Scl. The data set was complete to a magnitude of V = 20, encompassing the Scl red giant branch (RGB). Stars were selected in the RGB color-magnitude range, thereby increasing the contrast of Scl stars to the foreground Galactic population. The Sculptor structure appears to follow a two-component model in which each component is represented by the blue and red horizontal branch stars, respectively. Although there was no obvious extratidal structure, we determined that up to 10% of the light from Scl could be outside the tidal radius and still evade photometric detection.

Hence, to further probe the Scl extratidal region, we obtained far-red spectra for over 700 stars located in the upper RGB region of the Scl CMD. Stars were selected as Scl members based on three criteria: radial velocity, Ca ii triplet strength, and proper motion. The final Scl member list contained 148 stars, with seven located outside the tidal radius. Thus, if Scl does possess extratidal structure, then it makes up less than 2.3% ± 0.6% of the luminous mass in the system. Therefore, we have found little sign of tidal interaction between Sculptor and the Galaxy. This lack of tidal interaction makes it highly likely that velocity dispersion studies do provide a true measure of the dark matter mass of this dSph.

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