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IDENTIFICATION OF A-COLORED STARS AND STRUCTURE IN THE HALO OF THE MILKY WAY FROM SLOAN DIGITAL SKY SURVEY COMMISSIONING DATA[1]

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ABSTRACT

A sample of 4208 objects with magnitude $15 < g^* < 22$ and colors of main-sequence A stars have been selected from 370 deg^2 of Sloan Digital Sky Survey (SDSS) commissioning observations. The data is from two long, narrow stripes, each with an opening angle of greater than 60°, at Galactic latitudes $36° < |b| < 63°$ on the celestial equator. Relative photometric calibrations good to 2% and consistent absolute photometry allows this uniform sample to be treated statistically over the large area. An examination of the sample's distribution shows that these stars trace considerable substructure in the halo. Large overdensities of A-colored stars in the north at $(l, b, R) = (350°, 50°, 46$ kpc) and in the south at (157, −58, 33 kpc) and extending over tens of degrees are present in the halo of the Milky Way. Ivezic et al. have detected the northern structure from a sample of RR Lyrae stars in the SDSS.

Using photometry to separate the stars by surface gravity, both structures are shown to contain a sequence of low surface gravity stars consistent with identification as a blue horizontal branch (BHB). Both structures also contain a population of high surface gravity stars 2 mag fainter than the BHB stars, consistent with their identification as blue stragglers (BSs). The majority of the high surface gravity stars in the Galactic halo may be BS stars like these. A population of F stars associated with the A star excess in the southern structure is detected (the F stars in the northern structure at 46 kpc would be too faint for the SDSS to detect). From the numbers of detected BHB stars, lower limits to the implied mass of the structures are $6 \times 10^6\ M_\odot$ and $2 \times 10^6\ M_\odot$, although one does not yet know the full spatial extent of the structures. The fact that two such large clumps have been detected in a survey of only 1% of the sky indicates that such structures are not uncommon in the halo.

Simple spheroidal parameters are fit to a complete sample of the remaining unclumped BHB stars and yield (at $r < 40$ kpc) a fit to a halo distribution with flattening ($c/a = 0.65 \pm 0.2$) and a density falloff exponent of $\alpha = -3.2 \pm 0.3$.

Subject headings: blue stragglers — Galaxy: halo — Galaxy: structure — stars: early-type — stars: horizontal-branch

1. INTRODUCTION

1.1. *Halo Structure*

Observations of distinct populations of stars in the Milky Way (young, metal-rich stars in the disk and older, metal-poor stars in the halo) led Eggen, Lynden-Bell, & Sandage (1962) to propose that the Galactic halo formed before the disk during the rapid collapse of a gas cloud. In this picture, the stars in the halo are approximately the same age, with abundances that increase toward the center of the Galaxy. The model predicts a relatively smooth form and shape for the halo. Simple models, for instance, parameterize the distribution of matter in the Galactic halo as a flattened spheroid, where the flattening is given by an axial ratio $c/a \leq 1$ (and $b/a \leq 1$ if triaxiality is considered), with a power-law density profile $\rho(r) \sim r^\alpha$.

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As the positions and motions of luminous objects in the Galactic halo in principle provide tracers of mass within the halo potential, study of these objects is important for understanding the distribution of dark matter as well as providing clues to the formation of the Galaxy.

Model parameters for this simple description of the halo have been obtained by empirical fits to the distributions of such astronomical objects as Galactic globular clusters, K dwarfs, and A-colored stars. Here the term "A-colored stars" includes all types of stars, including blue horizontal branch (BHB) and blue straggler (BS) stars, that have colors and spectra similar to those of the bright, nearby, main-sequence A stars on which the spectral classification was defined. The distribution of Galactic globular clusters yields a fit to the structure parameters of $c/a \sim 1$ and $\alpha \sim -3.5$ (Harris 1976; Zinn 1985). Saha (1985) used RR Lyrae stars to find $\alpha \sim -3$ out to distances of 25 kpc, with a steeper decline thereafter. Ivezic et al. (2000) also measured a distribution of RR Lyrae stars with $\alpha \sim -3$ to at least 50 kpc. *Hubble Space Telescope* counts of K dwarfs by Gould, Flynn, & Bahcall (1998) yield $c/a = 0.8 \pm 0.1$ and $\alpha = -3.06 \pm 0.22$ Larsen & Humphreys (1994), using blue stars, obtain $c/a = 0.6$.

It is, of course, not required that c/a remain constant with Galactocentric radius. Preston, Shectman, & Beers (1991) counted BHB stars and found evidence that c/a increases from 0.5 to 1 as one moves out to $R > 20$ kpc with $\alpha = -3.5$. Using this changing c/a, Wetterer & MacGraw (1996) find $\alpha = -3.53 \pm 0.077$ for RR Lyrae stars. Sluis & Arnold (1998) find a flat c/a but less evidence for changing flattening with Galactocentric radius. As part of an extensive kinematic analysis of several hundred nearby halo stars with $[\mathrm{Fe/H}] \leq -1.8$, Chiba & Beers (2000) find that the axial ratio increases from 0.65 at $R < 15$ kpc to 1.0 at $R \sim 20$ kpc. Most of these studies use a few hundred objects at most on which to base their results, and only a few, such as Chiba & Beers (2000), have kinematic information.

In contrast to the Eggen et al. (1962) model, recent research suggests that some or all of the halo may have been formed through accretion of smaller dwarf galaxies (see Johnston et al. 1999; Majewski 1999 and references therein). One example of a dwarf galaxy thought to be in the process of accreting has been discussed by Ibata, Gilmore, & Irwin (1995). As these smaller galaxies fall into the Milky Way, they may be tidally disrupted and break up into long streams of stars that can persist for 1–10 Gyr (Lynden-Bell & Lynden-Bell 1995; Johnston 1998; Helmi et al. 1999).

1.2. *The Nature of A-colored Stars in the Galactic Halo*

A-colored stars at faint magnitudes are usually assumed to be halo population (Population II) stars and hence BHB stars. However, it has become clear that many distant blue stellar objects have hydrogen line widths indicative of main-sequence gravity A stars rather than the less massive BHB stars (Rodgers, Harding, & Sadler 1981; Sommer-Larsen, Christensen, & Carter 1989; Beers et al. 1992; Preston, Beers, & Shectman 1994; Wilhelm et al. 1999).

Why cannot all of these high-gravity A-colored stars be normal main-sequence stars? The well-known arguments against this are twofold. First, except for dwarf irregular companions to the Milky Way, such as the LMC and the Sextans dwarf, there is no evidence that significant star formation has taken place in the far halo ($R > 30$ kpc) within the last billion years, which is greater than the main-sequence lifetime of an A star. Second, the stars are too far from the star-forming regions in the Galactic plane to have reached their present positions in the far halo with any reasonable assumed velocity (it takes 300 Myr to travel 30 kpc at 100 km s^{-1}).

BS stars in globular clusters, which have ages closer to 10 Gyr, are interesting examples of high surface gravity A-colored objects that are present in an old environment. These high surface gravity BS stars are generally thought to be main-sequence stars that result from mergers of, or mass transfer between, two lower mass stars (Stryker 1993; Sills & Bailyn 1999). Whatever their formation mechanism, they should also be present at some level in the field of the Galactic halo (Rodgers & Roberts 1993; Norris & Hawkins 1991).

1.3. *The Sloan Digital Sky Survey*

The Sloan Digital Sky Survey (SDSS) is a large, international collaboration set up to survey 10,000 deg^2 of sky in five optical passbands and to obtain spectra of 1 million galaxies, 100,000 quasars, and tens of thousands of Galactic stars. The data are being taken with a dedicated 2.5 m telescope located at Apache Point Observatory (APO) near Cloudcroft, New Mexico. The telescope has two instruments: a CCD camera with 30 2048 × 2048 CCDs in the focal plane and two 320-fiber double spectrographs. The imaging data are tied to a network of brighter astrometric standards (which would be saturated in the main imaging data) through a set of 22 smaller CCDs in the focal plane of the imaging camera. A 0.5 m telescope at APO will be used to tie the imaging data to brighter photometric standards.

The U.S. Naval Observatory 1 m telescope at Flagstaff, Arizona, has been used to define the photometric system, defining SDSS standard stars in u', g', r', i', and z' (Smith et al. 2000, in preparation). Since the precise calibration for the SDSS filter system is still in progress, magnitudes in this paper are quoted in the $u^*g^*r^*i^*z^*$ system, which approximates the final SDSS system. These systems differ absolutely (with negligible color terms) by only a few percent in $g^*r^*i^*z^*$ and no more than 10% in u^*. See York et al. (2000), Fukugita et al. (1996), and Gunn et al. (1998) for further information on the SDSS, the filter system, and the imaging camera.

The SDSS has imaged a large fraction of the celestial equator ($-1^\circ.25 < \delta < 1^\circ.25$) as part of telescope and imaging camera commissioning. Catalogs produced from nearly 400 deg^2 of these data contain thousands of A-colored stars suitable for probing the halo, with absolute photometry good to $\sim 5\%$ for objects with $g^* < 20$. For reference, blue stars with $0 < B-V < 0.2$ (including A stars) have an SDSS g^* magnitude approximately equal to their Johnson V magnitude.

2. THE SAMPLE OF A-COLORED STARS

2.1. *Photometric Observations and Data Samples*

The SDSS camera contains six columns of CCDs, each of which records data for a $0^\circ.23$ wide strip of the sky. The CCDs are continuously read out as the camera scans a great circle across the sky at the sidereal rate, so the length of an imaged strip grows at 15° hr^{-1}. The effective exposure time in each of the five filters is 54 s. A "run" generates six parallel continuous strips of sky with a gap of $0^\circ.2$ between columns. A second "run," offset slightly from the first, is obtained to fill in the sky between the first six scan lines and fully image a $2^\circ.5$ wide "stripe" on the sky.

Figure 1 shows u^*-g^* versus g^*-r^* for all stellar objects with $g^* < 21$ in 13.3 deg^2 of one column of SDSS data. Objects in different magnitude ranges are plotted in different colors. As discussed by Newberg et al. (1999), the position of the blue end of the Galactic stellar locus shifts as a function of magnitude as a result of the sampling of populations of stars with different characteristic metallicities at different scale heights in the disk. The temperatures as a function of color can be estimated by comparison with Lenz et al. (1998). The stars in the A box in the diagram are expected to contain nearly exclusively hot stars with a strong Balmer jump: BHB stars, BSs, and main-sequence stars with spectral type A. These bluer objects do not shift by large amounts in color with magnitude. Boxes for quasar candidates and F- and G-type stars are also indicated and will be discussed below.

All of the magnitudes used in this paper are point spread function (PSF)–fitted magnitudes for stellar objects, generated by summing the PSF-weighted flux for each object (R. H. Lupton et al. 2000, in preparation). Saturation sets in for A-colored objects brighter than $g^* \sim 15$. All magnitudes in this paper use the modified flux designation for faint magnitudes described in Lupton, Gunn, & Szalay (1999), although for the range of magnitudes relevant here, $15 < g^* < 22.5$, the distinction is negligible.

The boundaries of the A-colored star box were chosen to provide a sample of A stars, BHBs, and BSs free from contamination from other populations of objects even to magnitudes as faint as $g^* \sim 21$. The choice of a $g^*-r^* = 0$ red limit was conservatively chosen in order to ensure that the Gaussian tail of color measurement errors of the population of the very large numbers of F stars did not begin to scatter into the A star box at faint magnitudes.

All magnitudes and colors in the present work have been corrected for reddening using the maps of Schlegel, Finkbeiner, & Davis (1998). Since all of the A-colored objects sampled here are at distances $d \gg 1$ kpc from the plane of the Galactic disk, where most reddening-producing dust occurs, the full reddening correction of Schlegel et al. (1998) is applied to all objects.

For this analysis, two samples of A-colored stars are chosen from two stripes of data. The northern sample (north of the Galactic plane on the celestial equator) is a filled stripe from SDSS runs 752 and 756, obtained 1999 March 21 and 22. The stripe is 87° long ($145^\circ.5 < \alpha < 232^\circ.5$ [J2000]) and $2^\circ.52$ wide ($-1^\circ.26 < \delta < 1^\circ.26$), with 219 deg^2 of data. Data in the region $215^\circ.5 < \alpha < 216^\circ$ from run 752 was excluded, since the seeing increased sharply to 3″ in this region (compared to typical seeing of 1″.3 for the rest of the scan). In Galactic coordinates, the northern sample runs in a long arc from $[l, b] = [236, 37]$ up to $[303, 63]$ and then gradually back to $[4, 43]$.

The northern sample contains 3126 point sources (extended sources are rejected) in the runs 752 and 756 that

FIG. 1.—u^*-g^* vs. g^*-r^* color-color diagram for SDSS commissioning data on the celestial equator. The plot shows the colors of ~30,000 stars from 13.3 deg^2 of commissioning data in the range $165^\circ < \alpha < 225^\circ$, $-0^\circ.23 < \delta < 0^\circ.0$. This represents 4 hr of observations from one of six columns of CCDs in the imaging camera. Each column of CCDs images a strip of sky $0^\circ.23$ wide in five passbands. Objects in different magnitude ranges are shaded differently. The A-colored star selection box is identified, as are boxes for quasar candidates and F- and G-type colored stars.

have dereddened colors in the box in Figure 1 ($0.8 < u^* - g^* < 1.5$ and $-0.3 < g^* - r^* < 0.0$) and that have u^* errors smaller than 30% (corresponding to a limit of $g^* \sim 22.5$).

The southern sample (south of the Galactic plane on the celestial equator) is a filled stripe from SDSS runs 94 and 125, obtained 1998 September 19 and 25. The stripe is 60° long ($353° < \alpha < 53°$) and 2°.5 wide ($-1°.24 < \delta < 1°.27$), with 151 deg^2 of data. The southern sample contains 1082 stars, to $g^* \sim 22$, with the same selection criteria as the northern sample. The southern sample runs from $[l, b] = [85, -57]$ through $[125, -63]$ and then back to $[184, -43]$.

The SDSS has imaged the majority of these equatorial regions twice. SDSS runs 259, 273, and 745 (obtained 1998 November 17 and 19 and 1999 March 20, respectively) nearly completely overlap runs 94, 125, and 756 and are used to verify the findings in the primary runs.

The list of A-colored stars from runs 745 and 756 were matched (without the requirement that the error in u^* be smaller than 30%), based on position (within 1″, well in excess of typical 1 σ astrometric errors of 100 mas). In addition, objects from these overlapping scans were matched without regard to color in order to estimate completeness, detection limits, and reproducibility of the data. The upper curve in Figure 2 shows the fraction of objects matched as a function of g^* for all stellar sources. The lower and noisier curve is that for matched objects within the A-colored box only. The maximum level of ~80% matched in the lower curve is primarily due to objects in one sample or the other scattering out of the box. One can estimate this fraction by noting that most of the objects in the box are on the red side, giving the box an effective width of 0.15 mag in $g^* - r^*$. When combined with typical color errors of 2% for two measurements, one derives an expected fraction $f = 1 - 0.02\sqrt{2}/0.15 = 81\%$. The matched fraction decreases rapidly for $g^* > 20.0$. Here the requirement that the object fall within the box in $u^* - g^*$ becomes the determining factor. From Figure 2, one sees that the A-colored star sample is uniform (in the sense that it samples the same population of stars) to $g^* \sim 20$ and has detections to about $g^* \sim 22.5$ (50% limit) in the northern stripe. After $g^* \sim 20$ the population of stars includes an increasing fraction of stars slightly redward of the box whose photometric errors have scattered them into the box. The fact that the upper curve does not start to drop until $g^* \sim 22.5$ indicates that the uniform sample is not affected by the detection limit and is in that sense complete. A related procedure in the south yields a uniform sample to $g^* = 19.5$ and detections to $g^* \sim 22$.

FIG. 2.—Upper line indicates fraction of stars matched between runs 745 and 756 without any restrictions on color. This indicates a detection limit of about $g^* \sim 22.5$ (50%). The lower line shows the fraction of stars in the A star color-color box ($0.8 < u^* - g^* < 1.5$, $-0.3 < g^* - r^* < 0.0$) that are matched as a function of g^* magnitude. This indicates a uniform completeness limit of about $g^* \sim 20$ in the northern sample. The low matched fraction (80%) at bright magnitudes is due to color errors at the red end of the box ejecting one or another detection of a star from the matched pair out of the color box.

2.2. *Distribution of the A-colored Stars*

Horizontal branch stars, especially those in a restricted color range, are approximately standard candles. A BHB absolute magnitude of $M_{g^*} = 0.7$ can be used to infer approximate heliocentric distances from magnitudes for these objects. This absolute magnitude was calculated by converting the V absolute magnitude of halo RR Lyrae stars from Layden et al. (1996) into the g^* filter, using the transformations from Fukugita et al. (1996) for the colors of RR Lyrae stars. Since the g^* magnitudes of RR Lyrae stars in Pal 5 (Fig. 7) are similar to the BHB magnitudes in Pal 5, the assumption has been made throughout this paper that the absolute magnitudes of BHBs are the same. This approximation is dependent on the blue response of the filter used. Note, for example, that Preston et al. (1991) find that for objects with colors at the blue end of the A star selection box, BHBs are about 0.9 mag fainter in V than the RR Lyrae magnitude (this corresponds to a difference of 0.7 mag in g^*, given the transformations in Fukugita et al. 1996).

Figure 3 presents a wedge diagram with right ascension and g^* magnitude for all 4208 A-colored stars from both north and south samples. Significant structures are immediately apparent. The clump at $[l, b] = [242, 43]$, or $(\alpha, \delta) = (153, 0)$, and $20.50 < g^* < 20.55$ is the northern half of the Sextans dwarf irregular galaxy (van Dyk, Puche, & Wong 1998) at $d = 70$ kpc (the southern half of Sextans is at $\delta < -1°.25$ and is not covered in this data set). One also notes two dramatic arcs of structure at $g^* \sim 19$ and $g^* \sim 21$ in the north ($195° < \alpha < 230°$) and similar, although less pronounced, structure at $g^* = 18$ and $g^* \sim 20$ in the south ($20° <$ R.A. $< 45°$).

The large structure in the north was detected by Ivezic et al. (2000) in a search for variable RR Lyrae stars in the overlapping SDSS runs 745 and 756 taken two days apart. It contains a remarkable population of ~80 RR Lyrae stars clustered in the same way as the bluer A-colored stars in the northern sample.

There are numerous smaller apparent concentrations throughout this diagram. The Galactic globular cluster Pal 5, for example, has its horizontal branch at $g^* = 17.3$, $\alpha = 229°$ in the north. An enlargement of the 3° of arc in the Pal 5 area of sky is shown to the right in Figure 3. Along with the stars of Pal 5's BHB at $g^* = 17.3$, the narrow sequence of Pal 5 BSs (see § 4.1) is clearly visible from $18.5 < g^* < 20$, also at $\alpha = 229°$.

2.3. *Verification of the Halo Substructure*

A number of straightforward checks are performed to verify that the large structures in Figure 3 are not artifacts.

FIG. 3.—Polar wedge plot of right ascension vs. g^* magnitude for A-colored stars. Notice the parallel arcs at $195° < \alpha < 230°$ and the large structure at $20° < \alpha < 40°$ as well as the Sextans dwarf irregular galaxy at $\alpha = 153°$, $g^* = 20.5$ and the Pal 5 BHB at $\alpha = 229°$, $g^* = 17.3$. The Pal 5 BS sequence is visible as a thin line at $\alpha = 229°$, $18.5 < g^* < 20.5$. The intersection between the plane of the celestial equator and the plane of the Galaxy is indicated by a dark line. Galactic and celestial coordinates are indicated around the edge of the figure. g^* magnitude increases outward from the center. Pal 5 is notable in the enlarged small diagram to the right, rotated 90° counterclockwise from the main figure.

FIG. 5.—Number counts of quasars in the north and south samples. Densities of extragalactic candidate objects in the large quasar candidate color-color box of Figure 1 ($-0.05 < u^* - g^* < 0.35$, $-0.1 < g^* - r^* < 0.3$) in the north and south are overplotted. The close agreement between the two curves demonstrates the consistency of the SDSS photometric calibration for this isotropically distributed sample of objects. The magnitude limit in the north is about 0.5 mag fainter than that in the southern sample. The northern sample reaches about 0.5 mag deeper than the southern sample as a result of increased u^* errors for the somewhat lower quality southern sample data, leading to a brighter $u^*_{\rm err} < 0.30$ cutoff in the south.

In order to assess whether these structures could be due to selection effects, low-redshift quasar candidates are color-selected from the SDSS survey from a color box with boundaries $-0.05 < u^* - g^* < 0.15$, $-0.1 < g^* - r^* < 0.0$ (the small Q box in Fig. 1) and plotted in Figure 4. Figure 4 shows no significant magnitude (and thus implied spatial) structure to $g^* \sim 22$ except for the increasing density of quasar candidates to fainter magnitudes. While not every object in this color box is a quasar, other hot blue sources, which contaminate the low-redshift quasar population, such as white dwarfs and narrow emission line compact galaxies, also have population distributions that are expected to be isotropic, showing no structural signature of the Galactic disk, bulge, or halo (Fan et al. 2000). The uniformity of the distribution in Figure 4 demonstrates the uniformity of the photometry and calibration in the SDSS samples to magnitude limits of $g^* \sim 22$ for objects with

FIG. 4.—Wedge plot of right ascension vs. g^* magnitude for color-selected quasar candidates (objects in the small quasar box of Fig. 1 with $-0.05 < u^* - g^* < 0.15$, $-0.1 < g^* - r^* < 0.0$). This population of almost exclusively extragalactic objects is very uniformly distributed in right ascension to at least $g^* = 22$ (where there is contamination from F stars with large color errors). This demonstrates the uniformity of the SDSS data sample. The northern sample reaches about 0.5 mag deeper than the southern sample as a result of increased u^* errors for the somewhat lower quality southern sample data leading to a brighter $u^*_{\rm err} < 0.30$ cutoff in the south.

FIG. 6.—Wedge plot of right ascension vs. g^* magnitude for A-colored stars selected in independent SDSS runs. This plot is similar to Fig. 3, and the reality of clumped structures is independently verified. This data set does not cross the longitude of Sextans, and since it is only data for one-half of a filled stripe, it only has half the stellar density of the Fig. 3. However, the coverage makes the end of the northern structure more apparent than in Fig. 3.

colors similar to A stars. Fainter than $g^* \sim 22$, the errors in the u^* magnitudes of F stars become large enough that some of them scatter into the quasar color box. The distribution of F stars in the northern and southern sample areas is discussed in § 4.5.

The photometric calibration within an individual stripe is accurate to a few percent because of the continuous drift scanning method of data collection and photometric observing conditions. Relative photometric accuracy of objects detected in multiple scans is good to $\sim 2\%$ for blue objects to $g^* \sim 20$ in the $g^*r^*i^*$ and z^* filters. The absolute calibration, and the calibration between runs observed in different seasons, relies on calibration patches obtained with a small photometric telescope and is not yet final.

To verify that the absolute calibration is essentially identical in the northern and southern stripes, the density of quasar candidates (chosen from the larger Q box in Fig. 1 to increase statistics) as a function of magnitude for the north and south is plotted in Figure 5. The excellent agreement between the two data sets to $g^* \sim 21.5$ is further evidence that the photometric calibration is uniform across the sky. One notes from the earlier falloff for southern quasar candidates in Figure 5 that the southern sample completeness limit is about 0.5 mag brighter than that of the northern sample. As the objects are selected in the bluest SDSS filters, and since the u' filter is the least sensitive filter, completeness limits and the magnitude limit for detections of objects in the present work are determined primarily by where the error in the u^*-band flux for objects becomes large. Note that although g^*-r^* colors for quasars and A stars are similar, the u^*-g^* colors of quasars are bluer than A stars by about 1 mag. Therefore, one expects to see a drop in A star counts 1 mag brighter than the drop in quasar counts.

The duplicate equatorial runs 745 and 273 were used to generate a plot similar to that shown in Figure 3. The structures noted in § 2.2 are also clearly visible in Figure 6, although there are fewer stars since only half of a filled stripe is plotted. Note that run 745 does not cover Sextans in right ascension, but does extend beyond the end of the northern structure and thus defines its full length more clearly than in Figure 3.

3. SPECTROSCOPIC FOLLOW-UP

3.1. *Observations*

While the SDSS continues commissioning of its spectrographs, which will obtain thousands of spectra of type A and BHB stars in addition to its main galaxy and quasar redshift survey, a small number of representative spectra have been obtained with other telescopes to investigate the nature of the selected A-colored objects.

The observations produced spectra for a sample of six A-colored stars selected from the SDSS samples, along with spectra of five A-colored reference stars with known surface gravities.

The Lick Observatory 3 m telescope was used to obtain reference stars—including CS 29516-0011, a BHB identified as a field horizontal branch star by Wilhelm et al. (1999); WD 0148+467, a DA white dwarf identified by Gliese & Jahreiss (1979); and HD 13433, a known A0V star classified by Houk & Smith-Moore (1988)—all with $8 < V < 12$. These spectra were obtained with exposures between 5 and 60 s on the night of 1998 December 19 at a resolution of about 6 Å, obtaining good signal-to-noise ratios (S/Ns) of about 50:1 in the continua.

Figure 7 shows the color-magnitude diagram of Pal 5, generated from reddening-corrected SDSS data. Stars of all colors within $\sim 9'$ of the center of the globular cluster Pal 5 were selected; note that there is significant field contamination here at $[l, b] = [1, 46]$. The vertical lines show the g^*-r^* limits of the A-colored star box. A 5400 s exposure of one BS and a 1800 s spectrum of a BHB star (marked with circled squares in Fig. 7) were taken at 3 Å resolution with the dual imaging spectrograph (DIS) on the Astrophysical Research Consortium (ARC) 3.5 m telescope at APO on the night of 1999 May 11. Proper motion studies confirm that both objects are members of the Pal 5 globular cluster (K. Cudworth 1999, private communication). The resolution of these spectra is approximately 3 Å at an S/N ~ 30 for the brighter object and 15 for the fainter. Wavelength calibrations were obtained, and standard flats and reductions were applied to all spectral data.

Six additional 30 minute spectra of $17 < g^* < 18$ A-colored stars selected from the SDSS were observed on the nights of 1999 May 8, 10, and 11 with the DIS at 3 Å resolution and an S/N ~ 20. The six spectra all confirmed that the A-colored star sample indeed consists entirely of blue stars with strong Balmer lines and is not contaminated by significant numbers of white dwarfs, quasars, or other extragalactic objects such as compact E+A galaxies.

3.2. *Spectroscopic Surface Gravity Indicator*

The primary diagnostic used to distinguish BHBs from A main-sequence (or BS) stars is the widths of the Balmer line profiles as indicators of stellar surface gravity (see Pier 1983 and references therein). Main-sequence A stars ($M \sim 2.5\ M_\odot$, $R \sim 2\ R_\odot$) have $3.5 < \log g < 5$, while horizontal branch stars, which have much smaller mass ($M \sim 0.7\ M_\odot$) and larger radii ($\sim 3\ R_\odot$) have $2.5 < \log g < 3.2$. This difference in surface gravities shows up clearly in the Stark pressure-broadened Balmer line profiles. White dwarfs, which have much higher surface gravities—typically

FIG. 7.—Color-magnitude diagram around the globular cluster Pal 5. The blue A-colored object box limits in g^*-r^* are indicated by two vertical lines. Note the five BHB stars and seven candidate BS stars, separated by about 2 mag in g^*. The circled objects indicate the BHB and BS objects. Objects with squared circles were followed up spectroscopically.

FIG. 8.—Spectra of a Pal 5 BHB and Pal 5 BS star. The upper panel shows the Balmer lines for a horizontal branch star in the cluster Pal 5. The width of the Hδ and Hγ lines are clearly better matched to the reference BHB star (a $V = 12$ field BHB) than to the reference field A0V star. The horizontal line marks 80% of the continuum of the stars, facilitating the quantitative width measurement. The lower panel shows a Pal 5 BS spectrum, which clearly fits the high-gravity reference A0V star.

$\log g > 7.5$—are easily distinguished from main-sequence A stars. Since white dwarf $u^* - g^*$ colors are significantly bluer than those of A and BHB stars, they are not present in the A star selection box in significant numbers. None of the spectra of A-colored stars presented here is consistent with a white dwarf identification.

The standard indicator that separates main-sequence gravity A stars from lower surface gravity BHB stars is the

FIG. 9.—Six ARC 3.5 m spectra of SDSS A-colored stars. The star in the lower left is best fit by a high-gravity model, while the other five are narrower and consistent with BHB gravities. The star in the upper left has a narrower line width, and the fluctuating continuum suggests a metal line–enhanced Am star classification.

width of the Hδ line at 80% of the continuum. One typically uses the Hδ line because the A star flux is higher here than in longer wavelength Balmer lines, and it is easier to fit the continuum at Hδ than at shorter wavelength Balmer lines. The width at 80% of the continuum is a measurement robust to the presence of metal lines, which can apparently widen the absorption lines near the continuum, and is insensitive to a range of instrumental resolutions, which can change the measured depth of the line.

IRAF was used to extract the one-dimensional spectra, select a region of the spectrum containing the Hδ and Hγ lines, divide the continuum by a best-fit sixth-order Legendre polynomial, and then boxcar smooth and wavelength shift the spectra to match the resolution and redshift of the Lick reference spectra. The difference in resolution between the sets of observations is not critical, since the broad Balmer lines typically have equivalent widths of 30 Å. It must be noted that with very wide Balmer lines it is difficult to uniformly fit the continuum in such a way that the lines themselves do not affect the fit.

The results are plotted in Figures 8 and 9. Figure 8 shows the Pal 5 stars compared to the blue reference templates.

TABLE 1

SPECTROSCOPICALLY TARGETED A-COLORED STARS

Identification	g^*	u^*-g^*	g^*-r^*	Hδ(0.8) (Å)	l (deg)	b (deg)	Class
CS 29516-0011[a]	12.24[b]	1.30[b]	−0.17[b]	21	71	−42	BHB
HD 13433	8.16[b]	1.10[b]	−0.14[b]	35	184	−68	A0V
WD 0148p467[c]	12.44[b]	0.20[b]	−0.17[b]	60	134	−15	DA WD
SDSSp J151610.80−000745.0	17.20	1.13	−0.20	25	1	46	BHB[d]
SDSSp J151608.00−000821.0	18.88	1.12	−0.13	36	1	46	BS[d]
SDSSp J154256.50−005609.0	17.55	0.99	−0.29	31	6	40	BHB
SDSSp J162341.10+000926.0	17.52	1.18	−0.24	26	14	32	BHB
SDSSp J160326.10+005104.0	17.49	1.18	−0.12	27	11	37	Am
SDSSp J162520.10+000223.0	17.49	0.96	−0.26	33	15	32	A/BS
SDSSp J162025.50−004537.0	17.82	1.11	−0.23	26	13	33	BHB
SDSSp J162532.10−011215.0	17.54	1.11	−0.20	26	13	31	BHB

[a] Wilhelm et al. 1999.
[b] Magnitudes and colors converted from measured values of U, B, and V.
[c] Gliese & Jahreiss 1979.
[d] These objects are in the globular cluster Pal 5.

The BHB star in Pal 5 is a good match to the template BHB star. The spectrum of the Pal 5 BS has much larger line widths consistent with the template A0V star. The six additional representative A-colored objects were spectroscopically confirmed with spectra shown in Figure 9. For these six brighter ($17 < g^* < 18$) SDSS northern sample targets observed from APO in Figure 9, four have narrow widths, one has a broad width (*lower left panel*), and one is apparently a metallic-lined Am star (*upper left panel*).

Table 1 summarizes the spectroscopic targets, listing SDSS identification (or other identification, such as HD number), dereddened g^* magnitude, u^*-g^*, g^*-r^*, Hδ(0.8), l, b, and classification determined from the Balmer line widths in the spectrum.

The radial velocities of the stars were only approximately measured (with typical error of 30 km s^{-1}) and ranged from −120 to 120 km s^{-1}, consistent with halo objects. The resolution of the observations and uncertainties in the wavelength calibrations made it difficult to draw conclusions about clustering of this small sample of objects from radial velocities. Kinematic information will of course be an important future diagnostic of SDSS A-colored stars in continuing searches for coherent halo structures.

4. THE NATURE OF THE A-COLORED STAR SAMPLE

4.1. *The Example of Pal 5*

As previous authors (Preston et al. 1991, 1994; Norris & Hawkins 1991; Wilhelm et al. 1999) have noted, and as the spectroscopy in this paper also shows, one must be careful drawing conclusions about Galactic structure from color-selected A stars in the halo of the Milky Way, since the blue star population is not homogeneous; it includes at least two types of objects.

One gains insight into the nature of the A star sample by examining the appearance of the globular cluster Pal 5 in the star distribution in Figure 3 at $\alpha = 229°$. Pal 5, located about 20 kpc from the Sun, contributes five BHB stars at $g^* \sim 17.3$ and at least seven BS stars at $18.5 < g^* < 20.0$ (see Fig. 7). On an absolute scale, the BHBs in Pal 5 have $M_{g^*} \sim 0.7$, and the BSs are thus at absolute magnitudes of $1.9 < M_{g^*} < 3.4$.

The large parallel arcs of A-colored stars present in Figure 3 are also separated by about 2 mag, suggesting that they might represent associated BHB and BS stars at a common distance. If this assumption is correct, then one can use the location of the BHB in g^* and the absolute magnitude of BHB stars to determine a distance to the stars in the arcs. For example, the northern arc, with an implied BHB magnitude of $g^* \sim 19$, is then approximately 45 kpc from the Sun.

4.2. *Photometric Determination of Surface Gravity*

In order to support the identification of the stars in the overdensities, one would like to be able to separate all of the high surface gravity stars from the low surface gravity stars. Presently lacking individual spectra for such a large sample, one turns to photometric multicolor indicators of surface gravity in the SDSS filters. From a sample of 1121 A-colored stars, Wilhelm et al. (1999) show that they can separate (although not perfectly) high surface gravity stars from low surface gravity stars in $U-B$, $B-V$ color-color diagrams. As a result of the lack of a single-valued transformation between the U and u^* (they have different behavior around the Balmer jump), a simple conversion between u^*-g^* and $U-B$ is not well defined. Thus, although one cannot precisely convert the $U-B$, $B-V$ color separation criteria to the SDSS filter system, a similar idea is applied to approximately separate the populations; extreme Balmer jump BHB stars are in general slightly bluer in g^*-r^* and redder in u^*-g^* than those with higher gravities.

The other SDSS filters available (i^*, z^*) may be considered for color separation of gravities. For instance, Lenz et al. (1998) show that in synthetic A stars derived from Kurucz model spectra (Kurucz 1991), different gravities separate well in the z' filter, and they derive a direction in SDSS color space that results in maximum separation. Since z^* magnitudes accurate to 2% are lacking for most of the faint A star sample considered here, the stars were separated in u^*-g^* and g^*-r^* only. (The r^*-i^* color contributes little to surface gravity separation for objects with A star effective temperatures.) Figure 10 shows the colors of the Lenz et al. (1998) models along with the colors of the six stars for which spectra exist, and the colors of the BSs and horizontal branch stars in Pal 5. The positions of the Pal 5 stars plotted in Figure 10 are circled in the Pal 5 color-magnitude diagram in Figure 7. One star that appears to be on the horizontal branch of Pal 5 and also in the A

FIG. 10.—u^*-g^* vs. g^*-r^* color-color plot for stellar models and stars with measured surface gravities. Models from Lenz et al. (1998), valid for stars with 6500 K $< T_{\rm eff} <$ 10,000 K, are plotted in small filled circles (low-gravity BHB models) and small open circles (high-gravity BS/A models). The range of colors for each model represents a range of metallicities. The eight stars for which spectra were obtained plus other Pal 5 BHBs and BSs are plotted on the diagram as triangles and squares. The thick black line then represents an empirical separation curve between stars of high and low gravity and is used to separate the SDSS A-colored star sample into BS candidates and BHB candidates based on colors alone. A few (low-gravity) variable RR Lyrae stars from Ivezic et al. (2000), put on the color system of this paper, are also indicated.

FIG. 11.—Wedge plot of right ascension vs. g^* magnitude for stars with colors of candidate BHBs. The well-defined horizontal branches of the arcs at $g^* = 19$ in the north and $g^* = 18$ in the south, as well as Pal 5's BHB, clearly stand out in this selection of photometrically selected BHB candidates.

star box is far enough from the center of the globular cluster that its membership is questionable, so it was not included in Figure 10. The adopted separation between BHBs and high-gravity stars (Fig. 10, *thick line*) in $u^*g^*r^*$ colors was based empirically on the spectra and photometry obtained here, guided by Lenz et al. (1998) and Wilhelm et al. (1999). The models are valid for stars with 6500 K $< T_{\rm eff} <$ 10,000 K. A few candidate RR Lyrae stars, selected as in Ivezic et al. (2000), are also indicated.

4.3. *Subsamples of A-colored Stars*

Applying the color separation in Figure 10, the 3126 stars in the northern sample are split into 2041 candidate BS stars and 1085 candidate BHB stars. The southern sample split into 674 candidate BS stars and 408 candidate BHB stars. The wedge diagrams for these separated stars are shown in Figure 11 (BHBs only) and Figure 12 (BSs only). These plots separate and enhance the contrast of the structures found in Figure 3, supporting the identifications in § 4.1. The structures are interpreted as an elongated arc of BHB stars at $g^* \sim 19$ in the north and an arc of BS stars about 2 mag fainter in the same direction in the north. In addition, an arc of BS stars at about $g^* \sim 20$ is apparent in the south. Both the northern and southern structures extend over 30° or more of the sky. The SDSS stripe is 2°.5 wide in declination, and so these large structures may extend well beyond the narrow stripes observed here.

One also detects the candidate BHB stars associated with the candidate BS stars in the southern structure. Figure 13 shows histograms of the candidate BS and BHB stars in the right ascension ranges of the northern and southern structures as a function of magnitude. While there are no significant structures apparent at $\alpha < 200°$ in the north (*left panels*), the plot clearly shows an overdensity of BHB stars at $g^* \sim 19$ in the north at $\alpha > 200°$ (*middle panels*) and also shows the overdensity in BHBs at $g^* \sim 18$ in the south (*right panels*).

The BS/BHB color-color separation is far from razor sharp. Figure 11, for example, which should show the absence of the second fainter arc from the candidate BHB star set and leave only the brighter arc in the north, does not do this completely. This is expected, since the color separation technique does not definitively separate the two populations of stars (see Fig. 10). The separation is less effective at fainter magnitudes, where the errors are larger,

FIG. 12.—Wedge plot of right ascension vs. g^* magnitude for stars with colors of BSs. The distant (fainter) clumps are defined in intrinsically fainter BS candidate A-colored stars, photometrically separated from the BHBs.

FIG. 13.—Magnitude histograms for candidate BHB and BS stars in the northern and southern structures. The northern diagrams include all blue stars with R.A. $< 200°$ (*left panels*) and R.A. $> 200°$ (*middle panels*), and the southern diagrams include all stars with R.A. $> 0°$. There are clearly clustered horizontal branch objects at $g^* = 19$ in the north at R.A. $> 200°$ and at $g^* = 18$ in the south.

and at redder colors, where the populations overlap in color-color diagrams.

The g^*-r^* color distribution of candidate BS and BHB stars in the large structures in the north and south is histogrammed in Figure 14. In the upper panel, candidate BSs with $\alpha > 200°$ and $g^* > 20$ in the northern structure are indicated with a thin line against g^*-r^* color, while candidate BHBs ($18.8 < g^* < 19.4$) in the same area are histogrammed with a thick line. The lower panel shows the southern structure objects with $19.0 < g^* < 20.5$ BSs and $17.7 < g^* < 18.3$ BHBs. In this color system, an A0V main-sequence star has $g^*-r^* = -0.25$, whereas a somewhat cooler A5V star will have $g^*-r^* \sim -0.05$. The distribution of BS stars in Figure 14 shows that the BS candidate stars are consistent with intermediate (A3–A5) A star colors, and the population is not dominated by the hottest A0 colored objects. The BS candidate sample is also notably consistent with the Pal 5 BS objects of Figure 7, which also does not contain any BS stars as hot as an A0 dwarf.

One might naively expect the A-colored stars in the Sextans dwarf irregular galaxy to represent its horizontal branch. However, van Dyk et al. (1998) show that this galaxy has a young very blue main sequence; if there is a horizontal branch, it contains very many fewer stars. The ratio of the number counts of BS to BHB candidates is 36:19 for the Sextans dwarf. This ratio is similar to the ratio of the excess of BS candidates at $g^* \sim 20$ to the excess of BHB candidates in the same magnitude range in the southern structure. In both cases, we assume that the candidate BHBs are misidentified high surface gravity stars. Thus, for Sextans nearly all the BS and BHB candidates are simply young main-sequence stars.

4.4. *Simulation of a Spheroidal Halo*

The tight concentration of BHB magnitudes in Figure 13 and the existence of associated BS candidate stars are strong evidence that the northern and southern structures are real halo substructure. However, one must explore the possibility that these structures could be artifacts of a smoothly varying Galactic structure combined with the magnitude limits of the SDSS samples. One is concerned with the possibility that the northern structure might be associated with the bulge of the Milky Way, since it occurs at a Galactic longitude of 0°.

Figure 15 shows a simulated halo density distribution expected for a smooth spheroidal distribution of BHB stars, assuming $M_{g^*}(\mathrm{BHB}) = 0.7$, $\alpha = -3.0$, and $c/a = 1.0$. One can see from this figure that the highest density of BHBs is closer to the Galactic plane in the equatorial stripe (indicated by the line of nodes in Fig. 15) than to Galactic longitude of zero. This is because the plane of the celestial equator passes closer to the center of the Galaxy at the Galactic plane than at Galactic longitude of zero. The halo density distribution depends only on the distance from the Galactic center for a spherically symmetric halo population.

One must resort to an extremely unlikely model to reproduce an overdensity such as that seen in Figure 3 within a smooth spheroid. For example, assuming an unrealistic absolute magnitude of $M_V \sim 4$ for the A-colored stars and

FIG. 14.—g^*-r^* color histogram of all objects in the northern structure (*upper panel*) with BHB candidate colors and $18.8 < g^* < 19.4$ (*thick line*) and BS candidate colors and $g^* > 20$ (*thin line*). The southern structure histograms (*lower panel*) are objects in the clump with $17.7 < g^* < 18.3$ for BHB candidates (*thick line*) and $19 < g^* < 20.5$ for BS candidates (*thin line*). Note that most of the BS candidates are on the red side of the diagram.

an extremely prolate ($c/a = 3$) bulge, one can obtain an overdensity near $l = 0$, but it will be much more spread out in magnitude than the tight BHB locus seen at $g^* \sim 19$. In addition, such an exercise can in no way reproduce the observed overdensity in the south with the same smooth model. The southern structure is nearly directly opposite the Galactic center.

4.5. *Distribution of Redder Galactic Stars*

Figure 16 shows a wedge plot, similar to Figure 3, but for F star candidates (objects with $0.6 < u^*-g^* < 1.0$, $0.1 < g^*-r^* < 0.3$), which are intrinsically about 3 mag fainter than BHB stars. One sees here the familiar overdensity in the southern sample, but the typical magnitude, $g^* \sim 21$, is about 1 mag fainter than that of the presumed BSs of Figure 12. This indicates that one may be detecting F stars associated with the southern structure ($g^*_{\rm BHB} = 18$). Note that although the density of the F star concentration appears to fall off near $\alpha = 49°$, the density of quasi-stellar objects in Figure 4 also drops off in this region at about $g^* \sim 21$, indicating that the sample is less complete in that region.

The rest of the F star distribution is consistent with a smooth Galactic model. (Imagine shifting the model distribution in Fig. 15 3 mag fainter.) The halo F stars associated with the northern structure are too faint to be unambiguously detected with the SDSS.

A magnitude versus right ascension wedge plot for color-selected G stars for the same SDSS samples is presented in Figure 17. It is reassuring to see no signs of the northern or the southern structures in this wedge plot; the G stars ($M_V \sim 5$) associated with these structures are too faint to appear above the SDSS magnitude limits. This population may prove valuable for studies of Galactic structure at closer distances than those probed by the BHB/BS stars. A slight leak of F stars into the G star box may be manifesting itself as structure in the south at $g^* \sim 21.5$.

5. PROPERTIES OF THE LARGEST STRUCTURES

As horizontal branch stars have $M_{g^*} \sim 0.7$ and BS stars have $M_{g^*} \sim 2.7 \pm 1.0$, one can estimate the heliocentric distances to the largest structures using the simple magnitude-distance relation, $m - M_{g^*} = 5 \log (d_{\rm pc}) - 5$. Assuming the Sun is 8 kpc from the Galactic center, one can then use $[l, b]$ for each object and calculate a Galactocentric distance for each star. The resulting Galactocentric distance estimates are plotted as (α, $R_{\rm GC}$) polar wedge diagrams in Figure 18 (for the BHB subsample) and Figure 19 (for the BS subsample). The implied distance of the large clump of stars in the north is 46 kpc from the Galactic center, with Galactic rectangular coordinates extending from $(X, Y, Z) = (12, -13, 41)$ to $(26, 1, 34)$ centered at $(X, Y, Z) = (21, -5, 38)$ [units are kiloparsecs, where the Sun is at $(-8, 0, 0)$]. The most significant clump in the south is inferred to be about 33 kpc from the GC extending from $(X, Y, Z) = (-18, 9, -25)$ to $(X, Y, Z) = (-25, 3, -22)$ centered at $(-22, 6, -24)$. The significance of other smaller clumps seen in Figures 18 and 19 is tantalizing and merits kinematic follow-up to determine if they are moving groups or streamers. In this coordinate system, Sextans is at $(-36, -53, 58)$ and Pal 5 is at $(7, 0, 16)$.

Because of the small declination coverage currently available, the full extent of these large halo structures is not known. However, an extent of 30° in right ascension at 46 kpc, with a "depth" of up to 10 kpc (from the spread in magnitudes in Fig. 13), suggests a structure of extent at least 20 kpc by at least 2 kpc by up to 10 kpc. A significant fraction of the assumed width from the magnitude spread could be due to the intrinsic spread in the absolute magnitudes of BHB stars, and the actual structures could in fact be extremely long and narrow "streams." One can estimate the implied total mass for the large structures in the northern and southern samples from the number of BHB stars observed. From the data associated with Figure 13, one estimates that there are 200 BHB stars (above background) in the northern structure. To arrive at this estimate, one uses the counts per square degree of BS and BHB stars in the left-hand panel in Figure 13 to estimate the background; the counts above background are assumed to be associated with the structures. Excess counts at $g^* \sim 19$ in the northern sample and at $g^* \sim 18$ in the southern sample were assumed to be BHB stars. Likewise, excess counts at $g^* \sim 21$ in the northern sample and at $g^* \sim 20$ in the southern sample were assumed to be BSs.

In Pal 5, there are five BHB stars in the sample. From comparisons of the total magnitude of Pal 5 to other globular clusters as tabulated in Djorgovski & Meylan (1993), we estimate the mass of Pal 5 to be $1.5 \times 10^5\ M_\odot$. Scaling up

from a globular cluster mass, a lower limit on the inferred mass in the part of the northern structure detected is then $6 \times 10^6\ M_\odot$. This is roughly consistent with estimates of the mass from extrapolations from the number of RR Lyrae stars. Ivezic et al. (2000) detect nearly 80 RR Lyrae variables at $\sim 50\%$ efficiency within the northern clump, as compared to five in Pal 5, giving a ratio of 160:5 as compared with the above ratio of 200:5. An estimated 60 BHB stars in the southern structure implies a lower limit for the mass of $2 \times 10^6\ M_\odot$. There is, of course, no way to tell what fraction of the structure is detected; more data from the SDSS survey will eventually be able to map out the full extent of such structures.

It is interesting to calculate the ratio of BS to BHB stars in the large structures. In the globular cluster Pal 5, in the color range $-0.3 < g^* - r^* < 0$, there are seven BS stars and five BHBs for a ratio of 1.4:1. In the northern clump, an estimate of 450 BSs is made by assuming a background similar to that in the upper left-hand panel of 13, giving a ratio of 2.2:1 when combined with the 200 BHBs seen. The BSs are near the limit of detection in the north, and the sample is incomplete, so the ratio may be considerably larger. For the southern structure, about 380 BSs are estimated, compared with about 60 BHBs, for a ratio of 6:1, with considerable uncertainty. For A-colored stars in the field not associated with the clumps, a ratio of about 2:1 is estimated by the same technique. Preston et al. (1994) explore the populations of blue stars located at $d < 2$ kpc and find a relatively large specific ratio of blue metal-poor to field horizontal branch objects (which are similar to the BS and BHB categories characterized here, although based on somewhat different selection criteria). This apparent variation in the BS-to-BHB ratio between globular clusters, in the field and in the northern and southern structures, while still somewhat uncertain, appears to be a significant effect, indicating different populations of stars populate different regions of the halo.

The large angular extent and relatively low surface brightness of these structures leads one to believe that these may be tidally disrupted streamers in the halo. The fact that two such structures were detected in 370 deg^2 of data ($\sim 1\%$

FIG. 16.—Wedge plot of right ascension vs. g^* magnitude for F star candidates (objects in the box $0.6 < u^* - g^* < 1.0$, $0.1 < g^* - r^* < 0.3$. Because of the high relative density of these objects, a randomly selected subsample of 1 in 10 points is actually plotted. The F stars in the south at $20° < \alpha < 40°$ at $g^* = 21.5$ are apparently associated with the A-colored star clump. In the north, the Galactic halo distribution overwhelms any clumps. Clump-associated F stars in the north would have magnitudes $g^* \sim 22$–23.

FIG. 15.—Wedge plot of right ascension vs. g^* for a simulated smooth galaxy halo of $M_{g^*} = 0.7$ BHBs with $\alpha = -3$ and $c/a = 1$. The entire celestial circle is shown (not just for regions where SDSS data exists). The maximal density of stars is nearly, but not exactly, at $b = 0$. Such a density maximum is a poor fit to the clump seen in Fig. 3, with maximum density at $l \sim 0$, and no equivalent maximum is seen in the south at $l = 180$. This is further evidence that the structures seen in Fig. 3 are real halo substructures.

FIG. 17.—Wedge plot of right ascension vs. g^* magnitude for G star candidates ($0.9 < u^* - g^* < 1.3$, $0.3 < g^* - r^* < 0.4$). Because of the relative density of these objects, a randomly selected subsample of 1 in 5 points is actually plotted. The structure of the disk is becoming manifest as one moves to lower Galactic latitudes. No trace of the clumps visible in A-colored objects remains for G stars of similar magnitudes. Clump-associated G stars would be at $g^* > 24$. A few F stars may be leaking into the G star box, as indicated by the presence of excess stars near $g^* = 21.5$ in the south.

of the sky) leads one to ask how common these structures might be in the Galactic halo. If the distribution of these objects is uniform across the sky, there may be as many as 200 of these to mag $g^* = 20$. Since the size of the structures parallel to the line of sight could be as large as 10 kpc, the area effectively surveyed may be up to 5 times larger than the survey area (since the width of the stripe is approximately 2 kpc at mag $g^* = 19$). In this case, the total expected number of such structures in the halo would be 40, or fewer if the length of each streamer is much greater than 20 kpc. The existence of such structures lends strength to the argument that some or all of the halo of our Galaxy has been formed through the accretion, or at least the disruption, of smaller stellar systems (Majewski 1994). Numerous studies have found evidence for coherent structures in the halo using kinematic information. Majewski, Munn, & Hawley (1994) found a clump of six to nine halo stars about 4–5 kpc above the north Galactic pole, with very similar radial velocities and proper motions, and identified a moving group. Helmi & White (1999) simulate satellite galaxy disruption and phase-space diffusion in the halo and suggest that the halo could consist of 300–500 streams with components that pass close to the Sun, a number consistent with that estimated above. Earlier, Doinidis & Beers (1989) noted a group of seven field horizontal branch stars with similar radial velocities all within 1 deg^2 on the sky and furthermore noted a positive signal in the 2-point star-star correlation function of A-colored objects on scales of 10′.

A cross-check against 21 cm emitting high-velocity clouds (Wakker & van Woerden 1997) does not show any obvious positional matches with these large structures in the north and south, but if even small amounts of gas are associated with the structures, a scenario such as that described in York et al. (1986) could hold, where the halos

FIG. 18.—Wedge plot of right ascension vs. inferred Galactocentric radius for candidate BHB stars. An average absolute magnitude of $M_g = 0.7$ is assumed to infer distances to the BHB photometrically selected sample. Horizontal branch concentrations are visible at $R = 46$ kpc in the north and $R = 33$ kpc in the south. Sextans is visible at about 80 kpc. Other structures, such as the one at $\alpha = 194°$, $R = 50$ kpc remain to be confirmed. The limiting magnitude ($g^* \sim 22.5$) allows detection of BHBs out to 150 kpc, but the sample at the faintest limits is contaminated by intrinsically fainter BSs, and so the objects apparently out at $R > 75$ kpc are not confirmed to actually be at these great distances.

FIG. 19.—Wedge plot of right ascension vs. inferred Galactocentric radius for candidate BS stars. An average absolute magnitude of $M_g = 2.7$ is assumed to infer distance to the BSs. Loose concentrations at $R = 46$ kpc in the north and $R = 30$ kpc in the south are visible. The limiting magnitude cuts off the distribution at about 60–70 kpc.

of galaxies are full of small, complex, quasar absorption line–producing structures. If the structures are as numerous as 100 in the halo, then they could contain a few times 10^8 $M_\odot$, a significant fraction of the luminous halo. This is corroborated by Figure 13, from which one estimates that one in four of the BHB stars in the combined samples are in one of the two large clumps (using the color separation of stellar types for field stars and magnitude separation of the stellar types in the clumps).

In summary, for the structure in the north, one sees BHB and BS candidate stars and for the structure in the south, which is closer, one sees these related populations of stars: BHB candidates, BS candidates, and F stars in numerical proportions that are not completely out of line with expectations from globular clusters or that of known galactic populations. The rough mass estimates for the structures are somewhat above that for a massive globular cluster and only a factor of a few smaller than that of known dwarf companions to the Milky Way. Thus, galaxies like Ursa Minor or the Draco dwarf spheroidal at about 70 kpc from the Galactic center, which currently have central stellar densities much higher than those inferred for the extended structures in the north and the south, could provide progenitors of the low-density structures seen in Figure 3. It should be noted that the mass estimates from BHB stars is highly uncertain and assumes similar horizontal branch structure for all populations. If BS counts were used, the mass estimates would be several times higher.

6. FITS TO THE GALACTIC HALO MODEL

The discovery of extensive structures in the outer Galactic halo is extremely interesting, and the number of A-colored stars associated with structures is of the same order as that in a supposed smooth background distribution of halo tracers. This renders attempts to fit a smooth spheroid model with single values of α and c/a problematic. The approximate separation of BHB and BS stars in § 4.3,

however, can be used to try and isolate only BHB tracers, and if one restricts that sample further to avoid the obvious clumps, one may still attempt a significant fit to a smooth spheroid. Figure 20 shows a maximum likelihood fit to flattened spheroidal models of BHB candidate stars in the north and south. Fits were restricted to those BHB color candidates with implied $R < 40$ kpc to regions that avoided the clump at $g^*(\mathrm{BHB}) = 18$ in the south and to regions that avoided saturated detections of stars (which occurs in the SDSS at about $g^* \sim 15$, $d \sim 7$ kpc). Constraining the fit to match the numbers of objects seen in the north and south simultaneously helps greatly in restricting parameter space. The model fit uses $\rho \sim R^{\alpha}$, where $R^2 = (X^2/a^2 + Y^2/b^2 + Z^2/c^2)$ and X, Y, Z are Galactic rectangular coordinates. Setting $a = b = 1$, α and c are allowed to vary.

The maximum likelihood estimate of the halo structure parameters for 7 kpc $< d <$ 40 kpc is $\alpha = -3.2 \pm 0.3$, $c/a = 0.65 \pm 0.2$, in agreement with Larsen & Humphreys

FIG. 20.—Binned representations of the data and best-fit solutions for a simultaneous two-parameter fit (plus normalization to the total number of stars) to the stars in the northern and southern BHB candidate (color-selected) subsamples after the stars in the large structures have been removed. The upper left panel shows the northern sample star counts vs. distance from the Sun and a binned likelihood fit model. The upper right panel shows the fit and star count histograms vs. right ascension. The error bars on the fit represent Poisson statistics for the number of expected objects in the fitted bin. For display purposes, the bin size is 2 kpc in distance and 5° in right ascension. The southern subsample and fits are shown in the lower two panels. The maximum likelihood fit yields $\alpha = -3.2 \pm 0.3$ and $c/a = 0.65 \pm 0.2$.

(1994) Gould, Flynn, & Bahcall (1998) and many other authors. Models with $c/a = 1.0$ or $\alpha < -2.8$ yield significantly worse fits to the sample. After the numerous cuts placed on the input candidate sample, the number of stars fit is 527. The fit can be extrapolated to provide a local density for BHB stars at a distance of 8 kpc from the Galactic center. This normalization yields $\rho_{\rm BHB}(8\ {\rm kpc}) = 8\ {\rm kpc}^{-3}$, in reasonable agreement with earlier studies (Kinman, Suntzeff, & Kraft 1994).

More data and cleaner spectroscopic separation of BHB from BS stars will, of course, help improve the confidence in these numbers to $R > 40$ kpc, although if the presence of enormous structures in the outer halo at larger radii is pervasive, fitting a single set of parameters to the shape of the outer halo may not provide much insight into its overall mass distribution.

7. CONCLUSIONS

1. A sample of 4208 A-colored stars from the SDSS is uniform to $g^* = 19.5$ and extends to $g^* \sim 22$. This sample is used to probe halo structure at distances of up to 60 kpc from the Galactic center.

2. A plot of all A-colored stars in magnitude-angle space shows significant clumpiness, including a large structure in the north at $(\alpha, \delta) = (220°, 0°)$ extending over 30° in length and at least 2°.5 in width. The remarkable detection of a clump of 80 RR Lyrae stars in this same area of sky by Ivezic et al. (2000) demonstrates the coherence and existence of this structure. In the south, a second extended structure of over 20° in length is apparent. Numerous smaller structures, including the known dwarf irregular Sextans (at 75 kpc from the Galactic center) and the Globular cluster Pal 5 are also clearly visible.

3. The example of Pal 5, which has a BHB and a BS sequence 2 mag below its BHB, suggests an explanation for the parallel magnitude-angle space arcs seen in the larger blue star halo samples. Photometric separation of A star surface gravities supports this explanation. A majority of the high surface gravity A-colored stars in the halo may be BSs.

4. Based on follow-up spectroscopy of eight objects, there are at least two subpopulations of A-colored stars identified: BHB stars with low surface gravities and BS stars with high surface gravities and absolute magnitudes 1–3 mag fainter than the horizontal branch.

5. The assumption of $M_{g^*} \sim 0.7$ for the horizontal branch yields approximate distances to the large clumps in the north and south of 46 and 33 kpc from the Galactic center at positions $(X, Y, Z) = (21, -5, 38)$ and $(-22, 6, -24)$ kpc, respectively. The inferred masses of the detected structures is at least $6 \times 10^6\ M_\odot$ in the north and at least $2 \times 10^6\ M_\odot$ in the south, although it is not known what fraction of the total extent of these elongated structures has so far been detected. From estimates of the mass in these structures and the fraction of sample BHB stars they contain, one concludes that structures such as these could contain a significant fraction of the mass of the luminous halo.

6. Fitting the "field" BHB candidate stars (those that avoid the structures), while requiring a consistent normalization between northern and southern Galactic samples, yields a maximum likelihood fit to a spheroidal halo model of $\alpha = -3.2 \pm 0.3$ and flattening of $c/a = 0.65 \pm 0.2$ for 7 kpc $< R <$ 40 kpc, consistent with previous work. Since clumps of A-colored objects dominate the numbers of halo BHBs and BSs at distances greater than 30 kpc, however, simple parameter fits to single-spheroid models are not representative of the whole picture. The existence of enormous structures in the outer halo must be addressed.

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