ABSTRACT

We identify new structures in the halo of the Milky Way from positions, colors, and magnitudes of five million stars detected in the Sloan Digital Sky Survey. Most of these stars are within 1.26 of the celestial equator. We present color-magnitude diagrams (CMDs) for stars in two previously discovered, tidally disrupted structures. The CMDs and turnoff colors are consistent with those of the Sagittarius dwarf galaxy, as had been predicted. In one direction, we are even able to detect a clump of red stars, similar to that of the Sagittarius dwarf, from stars spread across 110 deg of sky. Focusing on stars with the colors of F turnoff objects, we identify at least five additional overdensities of stars. Four of these may be pieces of the same halo structure, which would cover a region of the sky at least 40 deg in diameter, at a distance of 11 kpc from the Sun (18 kpc from the center of the Galaxy). The turnoff is significantly bluer than that of thick-disk stars, yet the stars lie closer to the Galactic plane than a power-law spheroid predicts. We suggest two models to explain this new structure. One possibility is that this new structure could be a new dwarf satellite of the Milky Way, hidden in the Galactic plane and in the process of being tidally disrupted. The other possibility is that it could be part of a disklike distribution of stars which is metal-poor, with a scale height of approximately 2 kpc and a scale length of approximately 10 kpc. The fifth overdensity, which is 20 kpc away, is some distance from the Sagittarius dwarf streamer orbit and is not associated with any known Galactic structure. We have tentatively identified a sixth overdensity in the halo. If this sixth structure is instead part of a smooth distribution of halo stars (the spheroid), then the spheroid must be very flattened, with axial ratio \( q = 0.5 \). It is likely that there are many smaller streams of stars in the Galactic halo.

Subject headings: Galaxy: halo — Galaxy: structure

1. INTRODUCTION

There is a growing body of evidence which shows that at least part of the halo of the Milky Way was formed through the accretion of smaller satellite galaxies and is not a relic of the initial collapse of the Milky Way. In the last decade, studies have convincingly identified moving groups and substructure in the halo by identifying groups of stars which are coherent in velocity (Majewski, Munn, & Hawley 1996; Helmi et al. 1999). Simulations have predicted the existence of many halo streamers (Lynden-Bell & Lynden-Bell 1995; Johnston, Hernquist, & Bolte 1996; Johnston et al. 1999c; Johnston, Sigurdsson, & Hernquist 1999b). Most recently, studies have identified halo substructure and tidal stripping through spatial information alone (Ivezić et al. 2000; Yanny et al. 2000, hereafter Paper I; Odenkirchen et al. 2001). A striking example of substructure in the halo is the identification of the Sagittarius dwarf galaxy (Ibata, Gilmore, & Irwin 1994) and its associated stream of tidally stripped stars, which appears to circle the Galaxy (Johnston, Spergel, & Hernquist 1995; Ibata et al. 1997; Ibata & Lewis 1998; Johnston et al. 1999a; Helmi & White 2001; Martinez-Delgado et al. 2001).

The detection of substructure in the halo is important for our understanding of the formation of our galaxy and also as a test of cold dark matter (CDM) and hierarchical clustering scenarios for structure formation in the universe. For example, Bullock, Kravtsov, & Weinberg (2001) argue that the CDM scenario generically predicts large numbers of tidally disrupted streams in the halo of the Milky Way, perhaps enough to account for the stellar halo in its entirety. They also suggest that the amount of halo substructure could distinguish among proposed solutions to the “dwarf satellite problem,” the tendency of CDM N-body simulations to predict too many satellites in the halos of galaxies like the Milky Way and M31 (Klypin et al. 1999; Moore et al. 1999).

In Paper I we used a large sample of faint blue stars from the Sloan Digital Sky Survey (SDSS) to discover two diffuse structures of stars in the halo. Their inferred density indicated to us that these structures were disrupted rem-
nants of a previously bound structure, such as a dwarf galaxy. We were not able to see the full extent of either structure. Ibata et al. (2001a) explained these two structures as two slices through the same great stream which completely circles the galaxy. The positions and distances of the stars in our structures exactly matched those expected from the tidal disruption of the Sagittarius dwarf spheroidal galaxy. Other pieces of this same stream have been recently reported by Dohm-Palmer et al. (2001), and a simple model of the Sagittarius breakup is given in Helmi & White (2001).

In this paper we present additional observations of the equatorial (−1°26 < δ<0000 < 1°26) data from the SDSS which probe a significantly larger angle of right ascension along the equatorial ring than in Paper I. We extend the methods of Paper I, which used faint blue stars with A-type colors to trace structure, to include the much larger sample of turnoff or near-turnoff stars with F-type colors. These new data contain strong evidence for further halo substructure. The key figure in this paper is a two-dimensional polar density histogram (θ, ρ) = (R.A., γ) of stars in the plane of the celestial equator with F colors (primarily F dwarf stars) shown in Figure 1 and described in detail in §5.5.

We expect to detect these streams of stars in addition to, or as part of, the individual stellar components of the Milky Way. Bahcall & Soneira (1984) published the “standard galaxy model,” which contained two components: a thin disk modeled with a double-exponential profile with scale height 0.325 kpc, and a halo modeled with a slightly flattened power-law spheroid with axial ratio 0.80. In the solar neighborhood, the spheroid stars were outnumbered by the thin-disk stars by a factor of 1 in 500. An additional component, a thick disk, was proposed by Gilmore & Reid (1983). Since then, the popularity of models with a thick-disk component has grown. The thick disk is typically modeled as a double exponential with a scale height of about 1 ± 0.5 kpc and a stellar frequency, compared with the thin disk, in the solar neighborhood of between 1–8 and 1–50 (Reyle & Robin 2001; Reid & Majewski 1993; Ojha et al. 1996; Robin et al. 1996; Buser, Rong, & Karaali 1999; Chen et al. 2001; Kerber, Javiel, & Santiago 2001). Stars in the thick-disk component dominate the star counts 2–5 kpc above the plane and have chemical and kinematic properties intermediate to the thin-disk and halo populations. See Norris (1999) for a review of the status of the thick disk. See Gilmore, Wyse, & Kuijken (1989), Majewski (1993), and Wyse (1999) for reviews of Galactic components.

The literature on the subject of Galactic components is vast; studies include star count analyses, kinematics, chemical properties of stars, and comparisons with other galaxies. We have summarized only the most basic structures, which may themselves have substructure, and which some authors may break into parts or name differently. We have not discussed stellar populations in the Galactic center, such as the bulge population. See Frogel (1988, 1999) for reviews of the Galactic bulge.

2. OBSERVATIONS

The observations are from several time-delay and integrate mode CCD scans obtained under photometric conditions in good seeing (FWHM < 1.7") on 12 nights between 1998 September 19 (run 94) and 2001 February 20 (run 2126) with the SDSS mosaic imaging camera (Gunn et al. 1998). See York et al. (2000) for a technical overview of the survey.

A single “run” scans six 0°23 wide swaths of sky (“scan lines”) separated by gaps of about 0°2. The gaps are filled by a second “strip,” containing six scan lines, which completes a filled “stripe” on the sky. The SDSS survey area is divided into 48 numbered stripes, each 2°5 wide. Each stripe is an arc of 6–10 hr in length that follows a great circle which passes through the survey poles, (α, δ) = (275°, 0°) and (95°, 0°). Equinox J2000.0 is implied throughout this paper. Most of the survey area is in the north Galactic cap. The few stripes in the south Galactic cap have separate stripe designations from their northern counterparts on the same great circle. In particular, the celestial equator (δ = 0°) is designated stripe 10 above the Galactic equator and stripe 82 below. See Stoughton et al. (2002) for further details of the survey conventions.

The star count work of this paper requires that the sampling of stars be quite uniform over a large area of sky. Because of the way the SDSS map of the sky is obtained and pieced together in a mosaic fashion, it is important for the purposes of this paper to select a sample which does not unintentionally “double-count” objects in the boundary regions of overlapping survey pieces. The full SDSS database contains multiple copies of many objects. We select single copies of the objects using several flags stored with the object in the database. During image processing, objects are extracted from each scan line one “field” at a time, where the breaks between fields are imposed somewhat arbitrarily every 1361 rows. So that objects which lie on these break points are not lost, overlaps are processed with adjacent “fields.” Objects that fall in an overlap may be in the catalog twice. In addition, there are overlaps between the interleaved strips which make up a stripe. The flag “OK_SCANLINE” is assigned to only one copy of each object in an individual scan line and uses astrometric declination limits (on the equator) to flag only the nonoverlapping areas of the two strips in each stripe. If you take all objects from two interleaved runs which have OK_SCANLINE, you get one instance of each object from the combined two runs. Two instances of the same object may both have OK_SCANLINE set if they are in overlapping runs covering exactly the same part of the sky; however, since the data set used in this paper was constructed with only nonoverlapping portions of runs, selecting with the OK_SCANLINE flag produces only one instance of each object in a given stripe. Objects can also lie on overlaps between different stripes.

The flag “PRIMARY” is assigned to one copy of each object in the entire database. Each numbered stripe is assigned a region in the sky over which its objects will be PRIMARY. Each numbered run is assigned a region of the stripe over which it is PRIMARY. Since the stripes overlap more toward the survey poles, the area of sky over which the stripe is PRIMARY decreases toward its ends. To keep a sample of objects on a single stripe uniformly sampled in declination, one selects those with the OK_SCANLINE flag set (rather than the PRIMARY flag).

Most of the data used in this paper are located on stripes 10 and 82 on the celestial equator (−1°26 < δ < 1°26). We also use data from stripe 11, 2°5 above the equator, stripe 12, at δ ~ 5°, and stripe 37, which follows part of an arc of a great circle tilted 67°:5 relative to the equator. Table 1 presents details of the strips, the stripes, and the sky cover-
Fig. 1.—Two-dimensional $g^*$ and R.A.) polar density histogram of turnoff stars on the celestial equator with $0.1 < g^* - r^* < 0.3$. The shading of each cell indicates the relative number counts of stars in each (R.A., $g^*$) bin. Typical absolute magnitudes of stars with these colors are $M_r = 4.2$, and thus stars with $g^* = 19.4$ are at distances of 11 kpc from the Sun. The value $g^* = 22.5$ corresponds to objects 45 kpc from the Sun. The center of the Galaxy ($l = 0$) is toward the lower left at $\alpha = 228^\circ$. The intersection of the plane of the Celestial equator with the Galactic plane ($b = 0$) is indicated by the thick black line. Note the numerous high signal-to-noise ratio structures existing in the halo of the Milky Way. Boldface labels indicate positions of overdensities which are discussed in the text. The color cut excludes most thick-disk stars. The feature at $\alpha = 60^\circ$ is probably an artifact of the reddening correction applied to the data, since there is a large dust cloud at this position. The streak at $\alpha = 229^\circ$ is due to Palomar 5. The gray-scale bar at the bottom of the figure indicates relative star count density in each pixel.

### TABLE 1

| Run | Stripe | Strip | Date          | Start R.A. (deg) | End R.A. (deg) | Seeing (arcsec) | Multiplicity |
|-----|--------|-------|---------------|-----------------|----------------|-----------------|--------------|
| 94.. | 82     | N     | 1998 Sep 19   | 350             | 56             | 1.7             | 1            |
| 125..| 82     | S     | 1998 Sep 25   | 350             | 77             | 1.9             | 1            |
| 752..| 10     | S     | 1999 Mar 21   | 145             | 233            | 1.4             | 1            |
| 752..| 10     | S     | 1999 Mar 21   | 234             | 250            | 1.4             | 2            |
| 756..| 10     | N     | 1999 Mar 22   | 117             | 121            | 1.4             | 2            |
| 756..| 10     | N     | 1999 Mar 22   | 122             | 235            | 1.4             | 1            |
| 1239.| 10     | S     | 2000 Mar 04   | 124             | 145            | 1.4             | 1            |
| 1350.| 37     | S     | 2000 Apr 06   | 112             | 125            | 1.5             | 1            |
| 1402.| 37     | N     | 2000 Apr 27   | 112             | 125            | 1.5             | 1            |
| 1462.| 11     | S     | 2000 May 05   | 120             | 137            | 1.5             | 1            |
| 1752.| 82     | N     | 2000 Oct 01   | 56              | 77             | 1.5             | 1            |
| 1755.| 82     | S     | 2000 Oct 02   | 319             | 350            | 1.4             | 2            |
| 1907.| 11     | N     | 2000 Nov 30   | 120             | 137            | 1.4             | 1            |
| 2125.| 12     | S     | 2001 Feb 20   | 122             | 142            | 1.5             | 1            |
| 2126.| 12     | N     | 2001 Feb 20   | 122             | 142            | 1.5             | 1            |
age of the data used in this paper. Not all sections of the
equator scanned have both strips filled. In particular, the
data from the ends of runs 752, 756, and 1755 do not have a
corresponding filling strip. In order to have uniform star
count statistics at all azimuths in these cases, double copies of
the single strips were made to normalize the number
counts to those areas of sky where two filled stripes were
available. This is indicated by a “2” in the multiplicity col-
umn of Table 1.

The photometric system for the SDSS includes five filters:
$u', g', r', i'$, and $z'$ (Fukugita et al. 1996). The system is
approximately AB, normalized, with central wavelengths
for the filters of 3543, 4770, 6231, 7625, and 9134 A, respec-
tively, and effective widths of typically 1000 A. 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 (Smith et al. 2002).
These systems differ absolutely (with small color terms)
by only a few percent in $g'r'i'z'$ and no more than 10% in $u'$. The data were reduced with PHOTO (R. H. Lup-
ton et al. 2002, in preparation), versions 5.1 and 5.2,
and astrometrically calibrated with the ASTROM pipeline
described in J. Pier et al. (2002, in preparation).

3. DATA REDUCTION

The SDSS software generates a database of measured
object parameters and flags, including information on
deblended “children” of sources whose profiles overlap.
One must select from this database a list of interesting
objects to be used as input to analysis routines. We selected
from the photometric catalog only those objects which were
marked as stellar, unsaturated, and not too near the edge of
the frame (too near is generally about 8°). In order to ensure
that only one instance of each object appears in the final
object tables, we selected objects which were marked as
OK_SCANCODELINE as explained above.

Using these criteria, we generated a catalog of 4.3 million
stars to $g^* \sim 23.5$ on the equator. The total area covered is
approximately 560 deg². Data on equatorial strips add
an additional 0.7 million stars over approximately 70 deg².
Completeness versus magnitude is discussed below, but we
note here that for objects with $g^* > 22.5$, the star-galaxy
separation results in most stellar objects being classified
as galaxies, and thus these are not prominent in our
subsample.

The SDSS software measures object flux in a variety of
ways. Since we are measuring stars only, we use magnitudes
calculated from a fit of modeled stellar profiles (point-
spread function [PSF] magnitudes) to each object. We correct
these magnitudes for reddening using $E(B-V)$ from
Schlegel, Finkbeiner, & Davis (1998), which has spatial
resolution of 0.1, and the standard extinction curve
(Cardelli, Clayton, & Mathis 1989), which for SDSS
filters yields $A_{u'} = 5.2E(B-V)$, $A_g = 3.8E(B-V)$, and
$A_r = 2.8E(B-V)$.

The fluxes of objects are presented in the inverse hyper-
bolic sine (asinh) representation of Lupton, Gunn, & Szalay
(1999). This definition has the feature (unlike a magnitude)
that it is well defined for zero or negative fluxes, which can
result from measurement of no flux at the position of an
object detected in a different filter. The asinh numbers and
magnitudes are the same to better than 0.1% for objects with
$g^* < 21$ but differ by 0.1 mag at $g^* = 23.9$. At zero flux, the
asinh numbers go through $g^* \sim 25$. The $r^*$ asinh flux shifts
in the same way as that of $g^*$, and thus there is negligibly lit-
tle change in $g^* - r^*$ color as a result of using these asinh
numbers instead of magnitudes. For the magnitude ranges
of interest here ($g^* < 22.5$), the difference is unimportant.
In the remainder of this paper we will refer to asinh numbers
as magnitudes.

Figure 2 shows reddening [$10E(B-V)$ in mag] from
Schlegel et al. (1998) around the celestial equator. We also
plot number counts in 100 bins for a sample of color-selected
stellar objects with $18 < g^* < 21.5$, $0 < u^* - g^* < 0.3$, and
$0.1 < g^* - r^* < 0.3$ versus right ascension around the equa-
tor. These objects, which are primarily quasars (see Figs. 1,
4, and 5 of Paper I), should have a constant number density
dependent of Galactic latitude. Figure 2 shows that the
selection of stars of similar colors and magnitudes as a func-
tion of $\alpha$ around the sky is mostly unbiased. Near $\alpha = 60°$
the amount of intervening interstellar dust is quite large and
the errors in the reddening-corrected magnitudes are larger
than at most other $\alpha$. For $310° < \alpha < 350°$, only one of two
SDSS strips of data is present, and thus the counts have
lower signal-to-noise ratio than the rest of the equatorial
data. The counts have been normalized upward by a factor
of 2 in the figure and the error bars appropriately increased.
Even with this normalization, it is apparent that the counts
fall systematically slightly below those at, for example,
$150° < \alpha < 230°$. We are uncertain of the reason for this.

From intercomparison of objects detected twice in over-
lapping scans, we find that the rms error for stellar sources
with $g^* < 19$ is typically $\sim 2%$. For objects with
$20 < g^* < 21$, typical errors are 5%, growing to 20% at
$g^* = 23.5$ near the detection limit. For reference, blue stars
with $0 < B-V < 0.2$ have an SDSS $g^*$ magnitude approxi-
mately equal to their Johnson $V$ magnitude. A theoretical
color transformation is given by Fukugita et al. (1996):

$g^* - r^* = 1.05(B-V) - 0.23$.

We plot in Figure 3 the rms dispersion of the difference in
$g^* - r^*$ color for matched objects between two runs as a
function of magnitude. For bright magnitudes this dispersion reflects the photometric errors of 2% in \(g\) and \(r\) (about 2\(\sqrt{2} \approx 3\%\) in uncorrelated color). The photometric error increases to nearly 20% for objects near \(g^* \approx 22.5\).

For some of our analyses, it is crucial to know the limiting magnitude, or more precisely the magnitude limit at which the survey can be considered complete, as a function of color and position in the sky. In Figure 3 we show the fraction of stars matched between two overlapping runs which make up the equatorial stripes. The matched fraction is calculated at two positions around the equator. One segment of matched data is at lower latitude, averaging \(b \approx 30^\circ\) with \(125^\circ < \alpha < 145^\circ\), while the other is at higher latitude, averaging \(b \approx 50^\circ\) with \(145^\circ < \alpha < 230^\circ\). Stars in three color ranges, \(0.1 < g^* - r^* < 0.3\), \(0.3 < g^* - r^* < 0.4\), and \(0.6 < g^* - r^* < 0.7\) (all with \(r^* - g^* > 0.4\)), in one strip are matched to the full list of stars in the overlapping strip. The fraction which are matched is recorded as a function of \(g^*\) magnitude. Figure 3 shows that for all three color bins of the high-latitude matched set (the low-latitude set is identical within the errors) the matched fraction is constant to about \(g^* \approx 22.5\), after which it drops off steeply, and somewhat more quickly for objects of bluer color.

One notes that for bright objects the matching fraction is not 100%. This is due in part to the fact that edge overlaps were used between the interleafing stripes (so that the same exact area of sky is not sampled by each overlapping patch). In addition, the reduction software does not resolve all objects around bright stars into separate detections. Independent matches against external catalogs indicate that the detection software detects over 99% of objects at these magnitudes (18 < \(g^* < 22\)).

Both segments of data at higher and lower latitudes give the same results for \(g^* < 22.5\). Thus, any selection we do based on magnitude \(g^* < 22.5\) is free of significant color or completeness bias to this limit. The variation in density of objects with quasar colors indicates that there is possibly some small variation in completeness limits or problems with reddening corrections at \(60^\circ < \alpha < 76^\circ\) and \(318^\circ < \alpha < 325^\circ\).

The imaging pipeline separates detected objects into stars and galaxies based on goodness of fit to PSFs and model galaxy profiles. For the seeing conditions under which these data were obtained, this separation produces excellent results to \(g^* \approx 21\).

We show in Figure 4 a color-magnitude image of \(\approx 100,000\) objects typed as galaxies, selected around the celestial equator, and binned as a Hess diagram (Hess 1924). Nearly all galaxies have colors redder than \(g^* - r^* > 0.4\), significantly redder than the turnoff stars we are interested in at \(g^* - r^* \approx 0.3\). There is some leakage of stars into the galaxy population for \(g^* - r^* > 0.3\) at \(g^* > 22.5\), again below the limits set by Figure 3. The galaxy population’s localization in color-magnitude space affects none of the conclusions made here about turnoff color star counts.

4. THE GHOST OF SAGITTARIUS

Since the positions and colors of the giant branches and horizontal branches of dwarf galaxy companions to the Milky Way differ considerably as a function of the dwarf’s metallicity, age, and stellar population mix, these features can be used as identifying signatures of a given dwarf galaxy or cluster. In this section we explore the color-magnitude distribution of stars in previously detected clumps. This discussion will motivate our use of F-colored stars to detect spatial structure in the next section.

Using a technique similar to that of Majewski et al. (1999), we will construct a color-magnitude diagram (CMD) of the two concentrations of stars from Paper I. To avoid confusion in referencing overdensities of stars, we will name them S1 \(+ b, g\), where \((l \pm b)\) are the Galactic coordinates of the approximate center of the structure (where it intersects an SDSS stripe) and \(g\) is the approximate \(g^*\) magnitude of the “turnoff” F dwarf stars in that structure. If the structure is identified with a known halo component, such as the Sagittarius dwarf, then the identification may appear in parentheses after the structure name. Under this naming convention, the two structures identified in Paper I are given the names S341+57−22.5 and S167−54−21.5 and may be clearly seen in Figure 1.

For structure S341+57−22.5, we used stars marked as “PRIMARY” in stripes 10 and 11 with \(200^\circ < \alpha < 225^\circ\) and \(u^* - g^* > 0.5\). The cut in \(u^* - g^*\) eliminates blue quasars which would otherwise dominate the faint blue edge of the CMD. The PRIMARY stars come from nonintersecting portions of stripes. Since the stripes are parts of great circle arcs, the nonoverlapping portion of the stripe is thinner toward the survey poles than it is on the survey equator. On the celestial equator at \(\alpha = 200^\circ\), the width of stripes 10 and 11 together is 4\(\frac{1}{2}\). On the celestial equator at \(\alpha = 225^\circ\), the width of the two stripes is 3\(\frac{1}{2}\). The total area covered is 110 deg\(^2\).

As a result of the large number of stars in this area of sky, we generated an image of counts-in-cells of the CMD, with a bin width of 0.02 in \(g^* - r^*\) and 0.05 in \(g^*\). In order to reduce the number of field stars in the image, we subtracted a similarly generated color-magnitude image of stars in a similar portion of the sky which does not contain the Sagittarius dwarf. The subtracted stars are from stripes 10 and 11, \(170^\circ < \alpha < 180^\circ\), plus twice stripe 10, \(230^\circ < \alpha < 235^\circ\).
Fig. 4.—CMD of objects typed as galaxies in the SDSS sample. Normally, CMDs are shown with one dot plotted for each star observed. Since we have too many stars to be effectively plotted in this way, we instead histogram the number of counts in each two-dimensional binned cell. The horizontal bin width in \( g^* - r^* \) color is 0.02 mag, and the vertical bin width in \( g^* \) is 0.05 mag. The image is plotted with square root density scaling. The galaxies are localized in color-magnitude space redward of the turnoff in such a way that they do not contaminate blue star counts at \( g^* < 22.5 \).

For stars at \( \alpha = 341 + 57 - 22.5 \), the resulting Hess CMD image (with a gray-scale stretch proportional to the square root of the number of stars in each bin) is shown in Figure 5. One can clearly see the turnoff at \((g^* - r^*, g^*) = (0.2, 22.5)\), the giant branch at \((g^* - r^*, g^*) = (0.5, 22)\) running to \((g^* - r^*, g^*) = (0.6, 20.5)\), blue stragglers at \((g^* - r^*, g^*) = (0.1, 21.5)\), a blue horizontal branch at \((g^* - r^*, g^*) = (0.15, 19.2)\), and a clump of red stars at \((g^* - r^*, g^*) = (0.55, 19.6)\). For comparison, we show in Figure 6 the identical plot for the Sagittarius dwarf itself, with data from Marconi et al. (1998). Since these Sagittarius dwarf data were taken with \( V \) and \( I \) filters and the dwarf is much closer than the dispersed clump (23 vs. 45 kpc), we arbitrarily aligned the clump of red stars and applied a linear correction in the color direction so that the distance between the clump of red stars and the point where the horizontal branch and the upper main sequence (as traced by blue stragglers) meet is the same in each image. The adopted transformation equations are \( g^* = V + 1.39 \) and \( (g^* - r^*) = 0.9(V - I) - 0.41 \). The relation between \( g^* \) and \( V \) includes both the difference in distance modulus and the filter transformation. Any differences in reddening or errors in reddening correction for either data set are implicitly included in the transformation. We then compared this empirical transformation with one derived from theoretical SDSS filter curves as given in Fukugita et al. (1996) and find that they match to within about 5%. The distance compensation, \( g^* = V + 1.39 \), is also within a few percent of the expected theoretical value, \( g^* = V + 5 \log(45/23) = V + 1.45 \).

The similarity of CMDs can be judged from the color of the turnoff, the distance from the horizontal branch to the turnoff, the slope and degree of population of the red giant branch, the presence or absence of blue stragglers, and the color distribution of stars along the horizontal branch. Though there are some differences (most notably, the Sagittarius dwarf photometry shows few if any blue horizontal branch stars), the agreement between the CMDs for the Sagittarius dwarf and our 110 deg\(^2\) patch of sky on the equator is striking and leaves little doubt that the tidally disrupted clumps of stars discovered in Ivezic et al. (2000) and Paper I are in fact pieces of the Sagittarius dwarf stream, in exactly the positions predicted by Ibata et al. (2001b).

It is interesting to estimate the fraction of the Sagittarius dwarf which is present in our observed piece of its orbit. One measure is the number counts in the clump of red stars. We estimate that there are 500 ± 50 stars in the 110 deg\(^2\) patch of sky with \( 19.30 < g^* < 19.65 \) and \( 0.52 < g^* - r^* < 0.66 \). For this estimate, we measured the clump of red stars in the unsubtracted color-magnitude image to reduce the statistical noise in the measurement (the background was determined by linear interpolation). Ibata, Gilmore, & Irwin (1995) find 17,000 horizontal branch stars in a patch of sky thought to contain half the mass of the Sagittarius dwarf. We detected about 500/34,000 = 1.5% as many red stars in the clump as are present in the dwarf itself in a portion of its orbit extending 4.7 on the sky. The orbit is roughly perpendicular to our scan line and presumably...
extends over 360° on the sky. If the stellar density along the stream is constant (admittedly a naive assumption) and the stream only wraps around on itself (so as not to produce multiple streams at other positions on the sky), then this implies about as many stars (1.2 times as many in this calculation) in the stream as in the undisrupted dwarf. This number is interesting but has a large error bar as the fraction of stars in the clump of red stars could easily differ between or within the dwarf and the stream.

Using exactly the same procedure as for S341+57−22.5 (Sagittarius), we generate a color-magnitude image for S167−54−21.5, which has also been tentatively identified as a piece of the Sagittarius stream by Ibata et al. (2001a). Since we have no data adjacent to stripe 82, we used the full width of the collected data (there is no change in the -width of the stripe on the sky as a function of right ascension). We used all stars with to make the clump color-magnitude image. We then subtracted a color-magnitude image of all stars with and double-counted all of the stars with and . The resulting color-magnitude image is shown in Figure 7. One can see a clear turnoff, a giant branch, and blue straggler stars. The horizontal branch and clump of red stars, though possibly faintly present, are not compelling. There are definitely blue horizontal branch stars present, since this clump was originally detected in A-colored stars in Paper I. The number of blue horizontal branch stars in the Sagittarius southern stream is only one-third of the number in the northern stream. This CMD is consistent with that of the Sagittarius dwarf but does not present as strong a case for identification as that in the north.

5. HALO STRUCTURE IN F STARS

5.1. Distribution on the Celestial Equator

Our detection of halo structure in Paper I relied on the standard candle characteristics of A-colored blue horizontal branch stars. The results of the previous section demonstrate our ability to examine the structure of the Milky Way using stars as faint as F dwarfs. If it is possible to use the much larger numbers of these main-sequence stars, one anticipates that much more tenuous halo structures could be discerned, though not as far out into the halo. We pursue such a path.

From stripes 10 and 82, we generate a catalog of 4,270,645 stars with and . The color range is wide enough to include essentially all stars. In this section we will be using not just the PRIMARY flagged stars but all of the OK_SCANLINE flagged stars from the runs used to fill in stripes 10 and 82 as detailed in Table 1. This way, the width of the stripe in declination does not change as a function of right ascension. The color cut removes primarily low-redshift QSOs.

In Figure 8 we show a color-magnitude image of all of the stars centered in the direction ( , ) = (6°, 41°), 230° < < 240° in stripe 10. The stars with and are thought to be associated with the thick disk of the Milky Way. The stars with are M stars
in the thin disk, the thick disk, and, at $g^* > 22$, the halo. The bluer stars ($g^* - r^* \sim 0.3$) are generally ascribed to the halo. The clear separation in turnoff color between the "thick disk" and "halo" was described by Chen et al. (2001). The stars we are interested in are the bluer stars with $g^* > 19$, which are associated with the halo population. It is important to note that using a color separation to distinguish between "thick-disk" and "halo" populations, though it appears to work well, is an empirical method and is distinct from a kinematic separation of the populations.

To separate the thick-disk stars from halo stars, we select 334,066 stars in stripes 10 and 82 (which are both on the celestial equator) with $0.1 < g^* - r^* < 0.3$, keeping the $u^* - g^* > 0.4$ color cut. This cut includes only the bluer "halo" stars; we have so many stars that we have the luxury of throwing half of them away to reduce thick-disk contamination and keep a much smaller range of dwarf star absolute magnitudes in the sample. We plot this sample of stars in a two-dimensional polar density histogram in Figure 1. This figure is similar to the wedge plots of Paper I (see Fig. 3 of that paper) but is displayed in an image by binning all the stars that would have appeared as individual dots within each pixel. The Sun is located at the center of the plot. Stars of the same apparent magnitude are at the same radial distance from the center of the plot, with $g^* = 11$ at the center of the plot and $g^* = 24$ at the edge (though the data cut off at $g^* = 23.5$). If each star has the same intrinsic magnitude (roughly the magnitude of an F main-sequence star), then the radius from the center of the diagram scales as the logarithm of the distance from us. Typical distances probed with turnoff stars range from a few to about 60 kpc at the edge of the plot ($g^* = 23$).

The shading of each box indicates the relative number of F stars within the pixel's azimuth and magnitude ranges, with 7.69 pixels mag$^{-1}$. It is generated by calculating the $(x, y)$ position in Figure 1 for each star in the sample and then incrementing the count in the pixel which covers that spot.

Figure 1 does not show the smooth distribution of stars expected from a power-law spheroid or exponential disk stellar density distribution. The overdensities of stars at $(\alpha, g^*) = (210^\circ, 22)$ and $(40^\circ, 21)$ are F dwarfs associated with S341+57–22.5 and S167–54–21.5 (Sagittarius). The dark radial line at $\alpha = 229^\circ$ is the main-sequence turnoff of the globular cluster Palomar 5.

The feature at $\alpha = 60^\circ$ is exactly coincident with a large interstellar dust cloud at that position in the sky and does not represent halo structure. When the reddening correction is that large, one must worry about the distance to the source(s) of reddening and the accuracy of the maps. Small differences in applied reddening change the intrinsic colors of the selected objects. The counts in this direction are consistent with overcorrection for reddening, which moves redder stars into the color selection box. As is apparent in the color-magnitude Hess diagrams, the redder turnoff stars are more prevalent at brighter magnitudes.

**Fig. 6.** — Color-magnitude image of the Sagittarius dwarf. The stellar data used to create this color-magnitude image come from Marconi et al. (1998), who published photometry for two fields in the Sagittarius dwarf itself, using $V$ and $I$ filters on the 3.5 m ESO New Technology Telescope. In order to compare these data with Fig. 5, the photometry was converted to the SDSS filter system and the magnitude shifted to reflect the difference in distance between the Sagittarius dwarf stream (at this position) and the Sagittarius dwarf galaxy. The similarity between the CMD of the Sagittarius dwarf and that of the streamer in Fig. 5 is striking.
Locations of other interesting overdensities are labeled in Figure 1 and summarized in Table 2. These and other overdensities will be discussed in detail below.

5.2. Spheroid Models

What do typical Galactic stellar component models, such as an exponential thick disk or a power-law spheroid, look like in a wedge image such as that of Figure 1? We will use the term “spheroid” to describe any smooth distribution of stars (in excess of the known thin- and thick-disk populations) in the halo of the Milky Way, regardless of its density profile. The halo of the Milky Way is a region of space containing gravitationally bound matter. The halo stars of the Milky Way are a combination of dwarf galaxies, globular clusters, streamers, and a smooth component (spheroid).

The usual density profile for the Galactic spheroid is a power law or, alternatively, a flattened power law with flattening parameter $q$, given by

$$\rho = \rho_0 \left( X^2 + Y^2 + \frac{Z^2}{q^2} \right)^{\alpha/2},$$

where $X$, $Y$, and $Z$ are the usual Galactocentric coordinates, with $Z$ perpendicular to the Galactic plane, and $\rho_0$ sets the density scale. If $q = 1$, the model is spherically symmetric; $\alpha$ is thought to be about $-3.2 \pm 0.3$ (see Paper I).

To generate the wedge image, we must transform to a heliocentric coordinate system, $(l, b, R)$, where $R$ is the distance from the Sun. In this coordinate system, the number of stars per magnitude bin is given by

$$\frac{dN}{dm} = \frac{dR}{dm} \frac{dN}{dR} = \left( \frac{R}{5} \right) \left( \Omega R_0^2 \rho_0 r^\alpha \right),$$

where

$$r^2 = R_0^2 + Q R^2 - 2R_0 R \cos l \cos b,$$

$$Q = \cos^2 b + \frac{\sin^2 b}{q^2}.$$

In our simulations, we assume that the distance to the center of the galaxy, $R_0$, is 8.0 kpc. In our plots, the number

| Name            | Stripe | Stripe Azimuth (deg) | Turnoff $g^*-r^*$ | Thick-Disk Turnoff $g^*-r^*$ |
|-----------------|--------|----------------------|------------------|-----------------------------|
| S6 +41–20.0......| 10     | 235                  | 0.30             | 0.40                        |
| S167–54–21.5.....| 82     | 37                   | 0.22             | 0.40                        |
| S297 +63–20.0....| 10     | 190                  | 0.26             | 0.40                        |
| S200–24–19.8.....| 82     | 75                   | 0.25             | 0.32                        |
| S223 +20–19.4....| 10     | 125                  | 0.28             | 0.38                        |
| S183 +22–19.4....| 37     | 135                  | 0.28             | 0.39                        |
| S52–32–20.4......| 82     | 320                  | 0.26             | 0.40                        |
| S218 +22–19.5....| 12     | 125                  | 0.28             | 0.39                        |
| S341 +57–22.5....| 10     | 213                  |                  |                             |

Fig. 7.—Color-magnitude image of S167–54–21.5 (Sagittarius). We used data from stripe 82, $15^\circ < \alpha < 50^\circ$, to make a color-magnitude image, and then we subtracted suitable reference fields to decrease the contrast between the streamer stars and the other stars of the Galaxy. The southern streamer shows a clear turnoff, giant branch, and blue straggler stars. The horizontal branch at $g^* \sim 18$ is rather weak, and the clump of red stars is neither ruled out nor apparent. The CMD is consistent with its identification as a piece of the Sagittarius streamer, though we cannot make a positive identification from this diagram.
of pixels in a given apparent magnitude annulus of width \( dm \) is proportional to \( (m - 11) \), and the width of the data in declination is constant. Therefore,

\[
\Omega \propto (m - 11)^{-1},
\]
as \( dm \) is approximately constant for each pixel in the wedge image of Figure 1. In this way we correct for the angular size of each pixel.

In order to construct the simulation, we need to relate the distance \( R \) to the apparent magnitude \( m \). For this we need to know the approximate absolute magnitude of the stars in Figure 1. Clearly there will be a spread in stellar magnitudes, which should result in a broader distribution in the data than in the simulated image. We find an estimate of the magnitudes of turnoff stars by using the distance in magnitudes from the horizontal branch of S167–54–21.5 (Sagittarius; from Paper I) to the turnoff of the Sagittarius stars in Figure 1, stripe 82. Figure 9 shows the distribution of apparent magnitudes for stars with \( 30^\circ < \alpha < 45^\circ \). In each magnitude bin, we have subtracted the number of stars in a similar region of the equator that does not include the Sagittarius stream \( (20^\circ < \alpha < 25^\circ \text{ and } 45^\circ < \alpha < 55^\circ) \). The range of apparent magnitudes at the peak of the distribution is \( 21.1 < g^* < 21.8 \). Assuming a horizontal branch absolute magnitude \( M_{g^*} \sim 0.7 \) and \( g^* = 18 \) (Paper I), the absolute magnitudes of the stars in the image are estimated to be in the \( 3.8 < M_{g^*} < 4.5 \) range, quite typical for F dwarfs. We adopt \( M_{g^*} = 4.2 \) as the typical magnitude of a turnoff star. This value is consistent with that estimated from SDSS magnitudes and known distances of the globular cluster Palomar 5.

We would like to draw attention to some special azimuthal directions on the wedge plot of Figure 1. The Galactic plane intersects the plane of the plot at \( \alpha = 103^\circ \) and goes straight through the plot center to \( \alpha = 283^\circ \). The place where \( l = 0^\circ \) is at \( \alpha = 228^\circ \), almost in the direction of Palomar 5.
mar 5 at $\alpha = 229^\circ$. In the celestial equatorial plane, this is not the direction of the Galactic center, but above the Galactic center in the direction that will intersect the Z-axis of the Galaxy. If the Galactic spheroid were very prolate ($q \to \infty$), then the highest density of stars intersected by the celestial equator would be at $l = 0^\circ$. If the spheroid were flattened into a pancake ($q = 0$), the highest density of stars would be in the Galactic plane at $\alpha = 283^\circ$ ($b = 0^\circ, l = 32^\circ$); and there would be another high density of stars at $\alpha = 103^\circ$ ($b = 0^\circ, l = 212^\circ$); the relative densities would depend on how quickly the power law drops off. If the spheroid is spherical, the highest density will be in the direction of the closest approach to the center of the Galaxy. This direction does not depend on the slope of the power law or the inferred absolute magnitude of the stars. We show in Figures 10a, 10b, and 10c the wedge image simulations which result from $q = 0.5, 1.0,$ and 1.5 power-law spheroid models with $\alpha = -3.5$.

Using a similar procedure to that for the spheroidal models, we can generate a simulated exponential disk as seen in the cross section of the celestial equator. The relevant equations for the disk density profile models are

$$
\rho = \rho_0 e^{-r/s_l} e^{-|Z|/s_h},
$$

$$
\frac{dN}{dm} = \frac{dR}{dm} dN = \left(\frac{R}{s_h}\right)^2 \left(\Omega R^2 \rho_0 e^{-r/s_l} e^{-|Z|/s_h}\right),
$$

where $r^2 = X^2 + Y^2$ and $X$, $Y$, and $Z$ are standard Galactocentric coordinates with the Sun at $(X, Y, Z) = (-8.0, 0, 0)$. $\Omega$ is the same as in the spheroid model. A simulated exponential disk with scale length $s_l = 3$ kpc and scale height $s_h = 1$ kpc is shown in Figure 10d. We used the same absolute magnitude for the simulated stars. Exponential disks generally put concentrations of stars at $b = 0$ ($s_h \ll s_l$). They result in concentrations of stars at $l = 0$ if $s_h \gg s_l$.

5.3. Overdensity at $\alpha = 190^\circ$: S297+63–20.0

Armed with these results, we turn our attention again to the data in the wedge plot of Figure 1. Neither an exponen-
tial disk model nor a power-law model can put a density peak at $180^\circ < \alpha < 195^\circ$, where $(l, b) = (297^\circ, 63^\circ)$. We tentatively identify the concentration at about $g^* = 20.5$ in Figure 1 as a stream or other diffuse concentration of stars in the halo, and we name it S297+63−20.0. Figure 11 shows the CMD for stars with $180^\circ < \alpha < 195^\circ$. Vivas et al. (2001) present corroborating evidence for this stream from observations of five clumped RR Lyrae stars at $\alpha = 197^\circ$, at a similar inferred distance from the Sun (20 kpc).

5.4. Overdensity near $\alpha = 125^\circ$: S223+20−19.4

We now turn our attention to the concentration of stars near $\alpha = 125^\circ$ at $g^* \sim 19.5$. As we noted above, it is possible to put concentrations of stars near the Galactic plane near the anticenter ($l \sim 180^\circ$) with either an exponential disk or a flattened spheroidal power-law model ($q < 0.6$). These stars are too faint to be produced by thin-disk or thick-disk stars from the double-exponential profiles of any standard models. As we will show in § 5.7, it would be necessary to postulate an unusually flattened power-law distribution, or an unusually large scale length exponential disk distribution, to put enough stars this far away from the Galactic center and still fit the number counts toward the Galactic center.

A color-magnitude image for stars in this direction is shown in Figure 12. Most of the brighter, bluer stars ($g^* < 18.5, 0.4 < g^* - r^* < 0.6$), presumably thick and thin disk, are part of a distribution with a redder turnoff than the fainter stars at $g^* > 20$. What is stunning about the color-magnitude image in this direction is that the fainter, bluer stars appear to follow a main sequence, as if the stars are all at about the same distance from the Sun. In any kind of exponential disk or power-law distribution, one expects a much broader distribution of distances, which spreads the stars in the vertical direction on the CMD. See Figure 6a of Layden & Sarajedini (2000) for an example of how a dwarf spheroidal in the field looks in such a CMD.

We show the shallow depth of the structure quantitatively in Figure 13. Figure 13a shows power-law models for a variety of slopes and flattenings in the direction $(\alpha, \delta) = (125^\circ, 0^\circ)$. Figure 13b shows a variety of exponential disks in the same direction. Compare the widths of the peaks of these models with the width (in magnitude) of the main sequence at $\alpha \sim 125^\circ$ shown in Figure 13c. The black line gives star counts versus magnitude in the color range $0.1 < g^* - r^* < 0.3$. Note the peak centered at $g^* = 19.4$.

If the data were broader than the model, we might expect that the data represented stars with a range of absolute magnitudes. Since the data are narrower than all of the models, no power-law or exponential disk model is a good fit to the data. The spheroid models are all very poor fits to the data. The only exponential model with any hope of fitting the data has a scale height of 2 kpc and a scale length of 10 kpc. Even this model produces a peak that is a little wide for comfort.

The red line in Figure 13c shows the magnitude distribution of all stars with $117^\circ < \alpha < 130^\circ, u^* - g^* > 0.4$, and $0.44 < g^* - r^* < 0.48$. The peak in this plot occurs at fainter magnitudes, since at the redder colors the stars are intrinsically fainter. The peak is narrower because these stars are on the main sequence rather than at the turnoff, where there is a broader range of intrinsic brightnesses of stars. The actual width of the stellar group must correspond to significantly less than 1 mag in distance modulus. Figure

Fig. 11.—Hess diagram for stars in stripe 10 with $180^\circ < \alpha < 195^\circ$ (spheroid)
13c also shows sample model counts of a dwarf spheroidal galaxy at the distance of the stellar excess, offset from the Galactic center, at \((l, b, R_{GC}) = (212^\circ, 0^\circ, 18 \text{kpc})\). The fact that this model nominally fits the SDSS star counts allows the possibility of a newly discovered dwarf galaxy in the Galactic plane, though this is not the only possible interpretation (see §5.7).

One also verifies that incompleteness at the faint end as a function of color is not responsible for the turnoff-like feature in Figure 12. The tests of §3 indicate that this is not the case for stars with \(g^* < 22\), well below the turnoff and main sequence seen here at \(19.4 < g^* < 21.5\). We adopt the name S223+20−19.4 for this structure.

5.5. Overdensity near \(\alpha = 75^\circ\): S200−24+19.8

Now we look at stars at \(\alpha = 75^\circ\) in Figure 1 and see if those stars can be explained by smooth components. See Figure 14 for evidence that the excess on this side of the plane is also thinner than expected for a power-law or exponential disk model. For this figure, we tightened up the color range plotted, to reduce contamination from the thick disk. As was evident in Figure 2, the data in this region are of lower quality. In §5.9 we will show that the measured thick-disk turnoff is much redder in these data and may indicate a calibration error or incorrect reddening correction applied here. Although the absolute photometry is suspect in this region, we still detect an unexpectedly tight magnitude peak at \(g^* \sim 19.8\). Figure 15 shows a CMD of stars in stripe 82, \(70^\circ < \alpha < 77^\circ\). This structure is named S200−24−19.8.

5.6. Other SDSS Data near the Galactic Plane: S218+22−19.5, S183+22−19.4

We looked through other SDSS data sets to see if the excess of stars near the plane showed up in other runs. We have data at low Galactic latitude in stripes 12 and 37. These data include 153,286 stars of all colors in stripe 12 with \(122^\circ < \alpha < 135^\circ\) and 252,099 stars in stripe 37 with \(112^\circ < \alpha < 125^\circ\). Figure 16 shows wedge plots for the ends of stripes 12 and 37.

The large increase in stars near the Galactic plane at Galactic latitude about \(20^\circ\) and \(g^* \sim 19.5\) is apparent in stripes 12 and 37 as well. The magnitudes of the stars near the ends of stripes 12 and 37 are similarly as narrow, and peaked at a similar magnitude, as those at the end of stripe 10. We adopt the labels S218+22−19.5 and S183+22−19.4 for these apparent overdensities.

Figure 17 shows a CMD of stars in stripe 37, separated by \(40^\circ\) in Galactic longitude from those of Figure 12 (at about the same \(b = 20^\circ\)). The similarity between Figures 17 and 12 is remarkable. The CMD for S218+22−19.5 looks the same as well.

5.7. Fits to the Galactic Spheroid

Now that we have identified several large features in the data which are not consistent with a smooth distribution of stars, we will attempt to constrain spheroid models. In Figure 18 we show the distribution in magnitude for stars with \(0.1 < g^* - r^* < 0.3\), \(u^* - g^* < 0.4\), and \(230^\circ < \alpha < 240^\circ\). We would be very surprised if these stars were not consistent.
Fig. 13.—Model fits to the data at $122^\circ < \alpha < 130^\circ$ ($S223+20=19.4$). In the top panel six power-law models are plotted. In the middle panel six exponential disk models are plotted. Models and data are arbitrarily normalized. Note how broad in magnitude these distributions are compared to the peak of the distribution of observed stars in the bottom panel. None of the models of the top or middle panel fit the data well, though an exponential disk model with scale height $\sim 2$ kpc and scale length $\sim 10$ kpc might be made to work by postulating brighter and fainter peaks in the star counts from other populations. In the bottom panel we also show a distribution of redder stars. The redder color cut includes thick-disk stars at the bright end and an even narrower peak (the peak is fainter because the selected stars are intrinsically fainter). A model spheroid offset from the center of the Galaxy by about 18 kpc in the direction of the excess stars is fitted to the data. One expects the broader peak in the data than in the model as a result of intrinsic spread in the absolute magnitudes of the stars, plus photometric error.
Fig. 14.—Model fits to the data at $70^\circ < \alpha < 77^\circ$ ($S200-24-19.8$). Same as Fig. 13, except on the other side of the Galactic plane. Again, the power-law models look nothing like the data. Exponential disk models are better but have a somewhat broader distribution and require larger scale lengths than typically assumed for the thick disk.
with a spheroid population. The figure shows a very broad distribution in magnitude, most consistent with a flattened \( q \approx 0.5 \) power law with slope of \( -3 \), though one could imagine fitting other power-law distributions. Notice that the magnitude distribution in this direction is not consistent with an exponential disk with large scale lengths, especially for \( g > 20 \).

We selected all of the stars with \( u - g > 0.4, \, 19.0 < g < 20.0, \) and \( 0.1 < g - r < 0.3 \). The number of these stars as a function of right ascension is shown in black in Figure 19. We then attempted to fit spheroid models (also shown in Fig. 19) to the data. We do not expect many thick-disk stars in this plot, since we have selected only stars bluer than the nominal turnoff. We expect very few thin-disk stars at these faint magnitudes. The models are generated by integrating the models of \( x \) over our apparent magnitude range, \( 19 < g < 20 \). With only angular information, there is very little difference between models with different power-law slopes or different assumed absolute magnitudes for the stars. There is greater sensitivity to the flattening of the spheroid. The only way to fit the star counts on both sides of \( \alpha = 280^\circ \) is with a very large flattening, such as \( q = 0.5 \).

More spherical models can fit the slope near \( \alpha = 250^\circ \) but do not put enough stars at \( \alpha = 320^\circ \). Note that we did not attempt to fit a triaxial halo, which has been used by other authors (Larsen & Humphreys 1996) to explain an interesting asymmetry in the blue star counts around the Galactic center.

As a class, the power-law models cannot put enough stars around \( \alpha \approx 100^\circ \) to explain the high counts there. We already encountered difficulty fitting this feature with a power law in Figures 13 and 14, but it is good to see the discrepancy in this plot as well. In order to produce anything close, one would need a flattening more like \( q = 0.2 \), which is quite a bit lower than anyone has previously considered and still does not fit well.

Since a power-law spheroid does not seem to be a good fit to these stars, we look to other proposed Galactic components to fit the data. Evidence for a metal-weak thick disk (MWTD) has been given by Morrison, Flynn, & Freeman (1990) and Norris (1994). Chiba & Beers (2000), using kinematics of faint blue stars, find a scale length for this component of 4.5 kpc. An exponential disk with a scale height of 2 kpc and a scale length of 10 kpc produces our best fit to the angular data near the Galactic plane. We need the large scale length to put enough stars out at \( \alpha \approx 100^\circ \). This model gives a surprisingly good fit to the data. It is important to remember that the stars fitted here are not the ones routinely assigned to the thick disk; they have a bluer turnoff. This would imply that we are seeing an “even thicker disk” of different metallicity (or age) from the “thick disk.” The only data that this model contradicts are the narrow magnitude profiles in Figures 13 and 14. The model does not explain the fainter star counts in Figure 18. The center of the peak near the anticenter is slightly shifted between the exponential disk model and the data. This shift cannot be reduced by small changes in the scale lengths, assumed stellar absolute magnitudes, or the Sun’s distance from the Galactic center. It could be reduced by moving the Sun to 0.2 kpc above the Galactic plane (or by tilting or lowering the extended exponential disk model below the plane of the thin disk by a similar amount). We placed the Sun 20 pc above the Galactic plane in our standard model, in keeping with recent estimates of this parameter (Hammersley et al. 1995; Cohen...
We have proposed two possible explanations for the over-density S223+20/C0/19.4. The first possibility is that it is a previously undiscovered dwarf galaxy (probably in the process of tidally disrupting) or a stream from a dwarf galaxy. The other is that it is part of a smooth, metal-poor Galactic component with a double-exponential profile with about 2 kpc scale height and 10 kpc scale length. One cannot produce this many star counts near the Galactic anticenter with a power-law distribution of stars. Based on the results of Chen et al. (2001), we do not expect stars with these blue colors in the thick disk. We will now show that the star counts do not fit exponential density models with the previously measured scale heights and scale lengths of the thin and thick disks.

There are two issues that were not addressed in the previous model fits in Figure 19. We did not consider that the metallicity of the thick disk could have changed as a function of scale height. We also did not use our knowledge of the local normalization of stars from the various Galactic components to check whether the stellar distributions could be reasonably attributed to a known and measured disk component.

To address these issues, we selected all of the stars in a broader color range (0.2 < g* - r* < 0.5) and in five magnitude ranges: 15.5 < g* < 16.5, 16.5 < g* < 17.5, 17.5 < g* < 18.5, 18.5 < g* < 19.5, and 19.5 < g* < 20.0. This should contain nearly all turnoff stars in the thick disk and halo populations, and at the bright end the older turnoff stars in the thin disk. The densities of these distributions as a function of right ascension are shown in Figure 20. We can now fit models to these data plots as a set. Since the stars are redder than in the previous plot, we assume that they are fainter, using M_g* ~ 5.0, which is about the absolute magnitude of the Sun. First, we fit the standard thin disk (scale height 0.25 kpc and scale length 2.5 kpc) and thick disk (scale height 1.0 kpc and scale length 3.0 kpc, with a local ratio of turnoff stars of 1:30 of the thin-disk stars), shown as a black line in Figure 20. The models are empirically normalized to the data at only one point. They are forced to match the data at α = 240° for stars near g* = 17. This fit sets the number of stars in this color range in the thick disk in the solar neighborhood to a reasonable value.

The star counts for standard thin- and thick-disk models do not fit. The discrepancy is most pronounced for the fainter star counts, where we see too many stars near the Galactic center and too few stars near the anticenter. We cannot move stars from the center to the anticenter by tweaking the assumed absolute magnitudes of the stars, the distance from the Sun to the center of the Galaxy, or the ratio of thin-disk to thick-disk stars. Adding a power-law component will also not help add star counts near the anticenter. As we saw in Figure 19, the...
way to significantly increase the number of stars at faint magnitudes is to add a component with larger scale height and scale length.

We could take the thin- and thick-disk models and add an additional exponential disk model to attempt to fit the data. Since we now have so many adjustable parameters, we decided to fit only a thin disk and an MWTD and were able to fit the data about as well as if standard thick-disk or spheroid components were also included in the mix. We used a thin disk with a scale height of 300 pc and a scale length of 2.8 kpc, an MWTD with a scale height of 1.8 kpc and a scale length of 8 kpc, and a thin disk/MWTD ratio of 100:1 in the solar neighborhood (for stars of this color range). We also used separate assumed absolute magnitudes for the two components: $g^* = 5.0$ for the thin disk and $g^* = 4.2$ for the MWTD. Note that the brighter stars, assumed to be part of the thinner disk, have $g^* - r^* \approx 0.25$, while the fainter stars associated with the MWTD structure have $g^* - r^* \approx 0.40$. Although one might expect the absolute magnitude of a more metal-poor population to be fainter at the same color, the color difference (i.e., the thin disk samples stars farther down the main sequence) is more important in this case. The models are fairly insensitive to our assumed absolute magnitudes. Figure 20 shows the model in red, with the thin-disk and MWTD components in green and blue, respectively. With this model, the brighter star counts are dominated by the thin disk and the fainter star counts are dominated by the MWTD.

We do not claim to show from this demonstration that a thick disk is ruled out. We have done the exercise of adding the third, thick-disk exponential to the model, and it makes little difference. If we adjust slightly all of the parameters, a thick disk with reasonable properties can easily be added to the model. We refrain from quoting numbers for this, since there are so many correlated parameters in this model that the individual values of each parameter may have little meaning. The thick disk may help adjust the relative numbers of redder and bluer turnoff stars in detail. For example, look at the relative number of redder and bluer turnoff stars at $\alpha \sim 235^\circ$, $g^* = 17$ in Figure 8. Most of them are the redder population. Now look at the model for $16.5 < r^* < 17.5$ in Figure 20. At $\alpha \sim 235^\circ$, somewhat more than half of the stars are MWTD, or the bluer population. We do note that qualitatively in the CMDs we see only two distinct turnoff colors, except in Figure 12 where there is a set of very bright stars with a very blue turnoff. We do not see a turnoff that gets steadily redder with increasing magnitude or that widely varies as a function of position in the Galaxy (see, e.g., stars with $0.2 < g^* - r^* < 0.5$ in Fig. 8).

As with our model fits to Figure 19, the peak near the anticenter is not well centered on the model fits near $g^* = 18.5$. If we attempt to adjust our height above the plane to center the model, then the model becomes a very poor fit at the bright end. One could imagine that adding a warp to the MWTD might fix this discrepancy. Note in Figure 1 that there are multiple apparent overdensities of stars near the Galactic plane at the anticenter. At $\alpha \sim 125^\circ$, the overdensities are near $g^* = 15.5$ and 19.5. At $\alpha \sim 77^\circ$, the overdensities are near $g^* = 18$ and 20. We have no ready explanation for this.

Fig. 17.—Hess diagram for stars on the end of stripe 37, with $\alpha < 125^\circ$ (S183+22−19.4). Note the similarity to Fig. 12. The horizontal branch at $g^* \sim 20.5$, $g^* - r^* \sim -0.2$ is from the globular cluster NGC 2419.
Fig. 18.—Model fits to the data at $230^\circ < \alpha < 240^\circ$ (spheroid). Here the flattened power-law model $q = 0.5$ is a good fit to the data (the normalization of the models is arbitrary). Note in particular that no exponential disk model is a good fit. If we wish to explain the structure in Fig. 13c with a smooth, exponential disk distribution of spheroid stars, we must modify the functional form of the spheroid or add a separate component in the general direction of the Galactic center.
Could all of this be explained without a disrupted dwarf galaxy or MWTD, but by warps or flares of the thick (or thin) disk? A warp in the disk means that the highest density of disk stars, which is generally in the Galactic plane \((b = 0)\), shifts a little—to higher or lower Galactic latitude, depending on the direction. Such a warp has been detected in HI (Burton & te Lintel Hekkert 1986) and possibly in stars as well (Carney & Seitzer 1993; Alard 2002). The measured shifts amount to less than half a kiloparsec deviation from the \(b = 0\) plane. Shifting the thick disk up or down by this amount could throw more or fewer stars into our data set at any given location but would not explain why the stars had a bluer turnoff than the supposed thick-disk stars.

Disk flaring occurs if the scale height of the disk increases with cylindrical radius from the center of the Galaxy. This effect has also been seen in the Milky Way (Alard 2002) and perhaps in Andromeda (Guhathakurta, Choi, & Reitzel 2000). But again, increasing the scale height with Galactocentric radius also does not put stars all at the same distance from us and does not explain the bluer turnoff of these stars. We would expect to see the flare putting stars into our sample at even larger scale heights at slightly higher Galactic latitudes. We do not see an excess of stars at \(g^* > 20\) and \(b > 20^\circ\) near the anticenter. The excess stops at \(g^* \sim 19.5\).

What we would need is a thick (or thin) disk which goes out to 14–18 kpc from the center of the Galaxy, warps sharply perpendicular to the plane, goes up to about 20° Galactic latitude, and then ends abruptly. This would put stars all at the same distance from us (since we would be looking straight through the “disk”). The stars in this “disk” must also have a turnoff with the same color as the spheroid population of stars in order to match the observations discussed in §5.9. Alternatively, one could construct a flare model which flares up 18 kpc from the center of the Galaxy and then decreases in scale height with distance.

5.8. S52–32–20.4

A look at Figure 19 in directions near the Galactic center shows that one could not fit the observed density of stars at \(\alpha = 240^\circ\) and \(320^\circ\) without assuming a very flattened spheroid \((q = 0.5)\). The exponential model is also a very flattened structure. The only way to avoid a very flattened spheroid is to postulate a large structure around \(\alpha = 300^\circ\) which accounts for the star counts in this direction. A look at the distribution of magnitudes in this direction (Fig. 21) shows that the magnitude distribution does not match our expectations for a power-law spheroid, and thus there is the possibility of yet more structure at \(\alpha = 320^\circ\). We identify this possible structure as S52–32–20.4.

We see below and in Table 2 that the stars in S52–32–20.4, which were originally assumed to be part of the spheroid population as well, appear to have significantly bluer turnoff stars than those of S6+41–20.0. This is a further indication that at least some of the stars in this direction are members of another Milky Way structure and would
Fig. 20.—Thin-disk plus extended MWTD model of the Galaxy. We show F/G turnoff star counts as a function of right ascension, on the celestial equator, for five magnitude ranges. The stars were color selected, with $0.2 < g^* - r^* < 0.5$. The data are indicated by black dots (which show up as a thick black line at zero counts where there are no data). The solid lines show theoretical exponential disks fitted to the data. The standard (black) and proposed (red) thin-thick exponential disk models are normalized to match the star counts at $\alpha = 240°$ in the $16.5 < g^* < 17.5$ plot. A standard model for the thick and thin disks, with thin-disk scale height 250 pc, thin-disk scale length 2.5 kpc, thick-disk scale height 1.0 kpc, and thick-disk scale length 3.0 kpc, is shown in black. The assumed ratio of thin-disk stars to thick-disk stars at the solar position is $30 : 1$. This model does not account for the large number of faint stars near the Galactic anticenter. Adding a power-law spheroid to this would only make the disagreement larger. In red we show a model with a thin disk with scale height 200 pc and scale length 2.8 kpc, plus a proposed MWTD with scale height 1.8 kpc and scale length 8 kpc. The ratio of thin-disk to MWTD stars at the solar position is $100 : 1$. The thin-disk and MWTD components of this model are shown in green and blue, respectively. One could achieve a similar fit to the data if a third double exponential, representing a standard thick disk, is included in the model. It is difficult to fit the peaks near the center and anticenter by including both standard power-law and MWTD components. The power law inserts too many stars near the Galactic center (and very few toward the Galactic anticenter) at faint magnitudes.
Fig. 21.—Disk and halo models vs. data at $320^\circ < \alpha < 330^\circ$ (S52–32–20.4). Note that this distribution is not consistent with a power-law spheroid. To fit this distribution with an exponential disk would require large scale lengths.
runs were removed. By a decrease in the data quality in this region. The very low points occur where the data quality was so low that the data in close to half a degree of one of the identified structures, selection criteria were chosen to highlight stars in each of the detected overdensities (S167−54−21.5 [ Sagittarius]; red; S223+20−19.4: black; S297+63−20.0: green; S341+57−22.5 [ Sagittarius]; blue). Curves were scaled so that they match in height at $\alpha = 240^\circ$. Notice that each detected overdensity produces a strong peak in this plot. There is an additional overdensity apparent in this plot at $\alpha = 10^\circ$. One could imagine other smaller overdensities that could help fill in the plot between the theoretical curves and the data curves. The dip in star counts in the center of the structure at $\alpha = 213^\circ$ is artificially caused by a decrease in the data quality in this region. The very low points occur where the data quality was so low that the data in close to half a degree of one of the runs were removed.

release us from the need for a very flattened spheroid population. If there is a stream at S52−32−20.4 that is not part of a smooth spheroidal distribution, then it is possible that we could fit a rounder $q = 0.8$ model, also shown in Figure 19.

5.9. Properties of the Halo Structures

From positions of the turnoffs in CMDs in the vicinity of the identified structures, selection criteria were chosen which were intended to favor each of the structures mentioned above. The specific selections shown in Figure 22 are S223+20−19.4 [black; 7.05($g^*−r^*+17.24 < g^* < 21$ and $g^*−r^* > 0.1]$], S341+57−22.5 ( Sagittarius) (blue; $21.5 < g^* < 23.5$ and $0.1 < g^*−r^* < 0.7$), S167−54−21.5 ( Sagittarius) (red; $20.5 < g^* < 22.5$ and $0.0 < g^*−r^* < 0.6$), and S297+63−20.0 (green; $20.0 < g^* < 21.5$ and $0.1 < g^*−r^* < 0.4$). The star counts per area as a function of right ascension for each of the selected boxes is artificially caused by a decrease in the data quality in this region. The very low points occur where the data quality was so low that the data in close to half a degree of one of the runs were removed.

Fig. 22.—Selected F star counts along the celestial equator. We show the relative distribution of stellar densities along the celestial equator. Four boxes in color-magnitude space were chosen to highlight stars in each of the detected overdensities (S167−54−21.5 [ Sagittarius]; red; S223+20−19.4: black; S297+63−20.0: green; S341+57−22.5 [ Sagittarius]; blue). Curves were scaled so that they match in height at $\alpha = 240^\circ$. Notice that each detected overdensity produces a strong peak in this plot. There is an additional overdensity apparent in this plot at $\alpha = 10^\circ$. One could imagine other smaller overdensities that could help fill in the plot between the theoretical curves and the data curves. The dip in star counts in the center of the structure at $\alpha = 213^\circ$ is artificially caused by a decrease in the data quality in this region. The very low points occur where the data quality was so low that the data in close to half a degree of one of the runs were removed.

of the red curve in the plot is at 1000 stars. Subtracting off a background of 400 stars, we are left with 600 stars at the peak. However, the curve has been multiplied by a scale of 2, so there were only really 300 stars at the peak. The width of the structure is about 30', or 100 bins. Multiplying $0.5 \times 100 \times 300$ for the area of a triangle gives 15,000 turnoff stars spread over a $2.5 \times 50 = 125$ deg² area of sky.

The data curves in Figure 22 also show a possible peak in the stellar density at $\alpha \sim 10^\circ$. This is faintly evident in Figure 1 but is not distinguished from an extension of S167−54−21.5 ( Sagittarius).

In addition to counting stars in stellar streams, it is interesting to look for directional information on the angle at which the streams cross the celestial equator. We split the equatorial data into three roughly equal declination bins: $\delta < −0^\circ.4$, $−0^\circ.4 < \delta < 0^\circ.4$, and $\delta > 0^\circ.4$. The star counts in these bins are plotted as a function of right ascension in Figure 23. The center of S167−54−21.5 ( Sagittarius) moves from $\alpha = 33^\circ$ to $36^\circ$ when the average declination goes from $\delta = −0^\circ.8$ to $0^\circ.8$. The slope of this shift, $\Delta \delta/\Delta \alpha = 1.6/3 = 0.53$, is in excellent agreement with that predicted for the orbit of a Sagittarius stream at this position by Ibata et al. (2001b), where $\Delta \delta/\Delta \alpha \sim 0.5$. The northern Sagittarius stream structure, S341+57−22.5, appears to move toward lower right ascensions as the declination increases, which is the expected sign, though the magnitude of the shift is

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We can use this plot to estimate the number of turnoff stars in S167−54−21.5 ( Sagittarius), for example. The peak of the red curve in the plot is at 1000 stars. Subtracting off a background of 400 stars, we are left with 600 stars at the peak. However, the curve has been multiplied by a scale of 2, so there were only really 300 stars at the peak. The width of the structure is about 30', or 100 bins. Multiplying $0.5 \times 100 \times 300$ for the area of a triangle gives 15,000 turnoff stars spread over a $2.5 \times 50 = 125$ deg² area of sky.

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Fig. 23.—Stream direction. The SDSS data are obtained in stripes of width $2^\circ$ in declination. To examine the direction that a stream of stars makes with a stripe, we divide each stripe up into three substripes, each with width $0^\circ.8$ in declination. The histogram of star counts within each substripe is shown for (a) S167−54−21.5 (Sagittarius), (b) S341+57−22.5 (Sagittarius), (c) S297+63−20.0, and (d) S223+20−19.4. Each plot shows the stars which have colors and magnitudes consistent with the clumped population (see § 5.9). For the S167−54−21.5 (Sagittarius) structure a shift is apparent from south to north and indicates that the stream crosses the celestial equator at P.A. $\sim 30^\circ$. A shift in the opposite direction (as would be expected for the stream) is observed in S341+57−22.5. The peak at $\alpha = 229^\circ$ is due to the globular cluster Palomar 5. In this figure, the counts in a single $3^\prime$ bin have been divided by 0.925 to compensate for missing data in right ascension range $215^\circ.5 < \alpha < 215^\circ.95$. These data were flagged as bad data and removed from our data set. Data near this right ascension have poorer than average seeing. The density of stars in S223+20−19.4 decreases for increasing declination. Since we do not detect a peak for structure S223+20−19.4, we cannot tell whether this is a shift or a density change in the declination direction. If it is a shift, it is consistent with a structure which is aligned more along the Galactic plane than along the celestial equator.
smaller than predicted, suggesting that some overlapping of streams may be present here. The direction of S297+63–20.0 cannot be distinguished from a track perpendicular to the equator. The structures S223+20–19.4 and S200–24–19.8 shift slightly toward lower right ascensions as the declination increases.

The colors of the turnoffs of the various overdensities provide an illuminating check on their identities. Figure 24 shows the number of stars near the turnoff as a function of color for stars in the various identified structures. The structures plotted are S167–54–21.5 (Sagittarius; magenta) and S341+57–22.5 (Sagittarius; not shown) both have turnoffs well to the blue of \( g^* - r^* = 0.25 \) and are probably of the same origin. S297+63–20.0 stars (blue) and S52–32–20.4 stars (green) also have similar turnoff colors \( g^* - r^* \sim 0.26 \). The turnoff stars of the spheroid S6+41–20.0 (black), S183+22–19.4 (red), S218+22–19.5 (red), and S223+20–19.4 (red) all have similar distributions, while that of the S200–24–19.8 structure (cyan) has a bluer turnoff. This bluer color of S200–24–19.8 might be the result of calibration errors or too much reddening correction applied here (see Fig. 25).

S167–54–21.5 is blue, further evidence that this overdensity is a part of the tidal stream of the Sagittarius dwarf galaxy. None of the other identified structures have turnoffs as blue as these.

S223+20–19.4, S218+22–19.5, and S183+22–19.4 have the same color turnoffs as the spheroid distributions. However, S200–24–19.8, which might belong to the same halo structure as S223+20–19.4 and S183+22–19.4, has a much bluer turnoff. We believe the reason for this can be found in Figure 25, which shows the number counts of stars near the thick-disk turnoff (16.0 < \( g^* < 16.75 \)). Note that the turnoff \( g^* - r^* \) color of presumed thick-disk stars in all directions is within a couple of tenths of 0.4, except in the direction of S200–24–19.8, which is much bluer than the rest. (There are very few thick-disk stars in the field of the Sagittarius dwarf itself, which accounts for the apparently poor statistics of this curve.) If one adjusted the colors of the S200–24–19.8 turnoff stars by the amount needed for the thick-disk turnoff in this direction to match all other directions, then the turnoff of S200–24–19.8 would more closely match the spheroid (S6+41–20.0) and S223+20–19.4 and S183+22–19.4. We are uncertain as to the reason for the discrepancy, but we believe that either there is a calibration error in these data or the reddening correction could have been overapplied. If it is an error in the reddening correction which produced too blue a color by 0.05 mag, then the \( g^* \) and \( r^* \) magnitudes should be shifted fainter by 0.15 and 0.10 mag, respectively.
It is interesting that S297+63/C0 20.0 appears to be intermediate in color between Sagittarius and the spheroid, as does S52/C0 32/C0 20.4. The latter is also a candidate for a flattened spheroid population.

6. DISCUSSION

What have we learned about the halo of the Milky Way? The most important lesson is that at distances of 20 kpc from the center of the Galaxy, the stellar density is not at all smoothly varying, as a power-law density distribution would be. It includes dwarf galaxies, globular clusters, and streamers of tidally stripped stars. With sufficiently large sky coverage and good color photometry, these streamers can be identified by their density in space, and not just by kinematic techniques which have been previously used to identify moving groups in the solar neighborhood.

The prevalence and ambiguity of clumped stars in our data frustrate our attempts to fit any smoothly varying “spheroidal” distribution. The only direction in the sky in which the stellar distribution looks at all like our expectations for a power-law distribution is at right ascension 240° < α < 250°, where the stars are less than 10 kpc from the Galactic center. In all other directions, the stellar distribution appears to be dominated by large structures with scale lengths of 10 kpc or greater, or by stars that do not fit neatly into the standard Galactic components. Even the stars near α = 245° may not be identified as part of a presumed smooth power-law distribution in the halo.

All of our attempts to fit a power law to the spheroid population of stars, both in magnitude and right ascension, produced best fits for a very flattened (q ~ 0.5) spheroid. We do not rule out a q = 0.8 spheroid, however, since we cannot be sure which of our data, if any, represent the spheroid distribution. We would also like to be clear that even if the spheroid is flattened, that does not imply a flattened halo dark matter distribution. One expects that stars and their associated dark matter are falling into the Galaxy from all directions.

Kinman, Suntzeff, & Kraft (1994) found evidence for a flattened distribution of blue horizontal branch stars among other more spherically distributed populations of objects in the halo. This effect is discussed in Chiba & Beers (2001 and references therein) and suggests that a flattened halo dominates at R < 15 kpc, while the outer halo is spherical. We imagine that if one averaged over all of the streams, the distribution could be spherical at large Galactocentric radii. Close to the plane the MWTD or a flattened spheroid could dominate, and the distribution would appear to be flattened.

The overdensities which we have so far identified, and the smooth distributions of stars which we have assigned to some of the overdensities, do not account for all of the stars in the data set. For example, look at the star counts in Figure 22 at α ~ 160°. There are significantly more stars here than in any smooth model fit in Figure 19. We could try to construct a stream profile for S297+63–20.0 that put stars out this far. The spreading of tidal streams in the disruption process is not unexpected, especially if the mass distribution of the halo is not spherical. However, in this case the profile...
would seem contrived to fill in gaps between the assumed spheroid distribution at $\alpha \sim 250^\circ$ and the structure at $\alpha \sim 75^\circ$.

There are enormous streams of stars in the halo. The tidal stream from the Sagittarius dwarf galaxy is one of them. We may have found additional large streams as described in this paper. Since our color cut is relatively blue, we are biased against finding older or more metal-rich streams with redder turnoff stars. We are also less sensitive to smaller, lower stellar density streams. One might expect that there are streams from smaller infalling stellar associations or more disbursed streams from dwarf galaxies which were consumed by our Galaxy at earlier times in its history. These smaller or more disbursed streams might more naturally explain the difference in star counts between the models and the data at, for instance, $\alpha \sim 160^\circ$.

6.1. Debris from the Sagittarius Dwarf

We have shown evidence supporting the identification of S341+57−22.5 and S167−54−21.5 with the tidal stream of the Sagittarius dwarf galaxy. The CMDs for the stars in these structures match that of the dwarf itself. In addition, the $g^* - r^*$ color of the turnoff is consistent with that of the Sagittarius dwarf. We find no reason to doubt the identification of the structures at $\alpha \sim 210^\circ$ and $35^\circ$ as pieces of the stream of the Sagittarius dwarf galaxy. One might ask whether any of the other structures identified in this paper could be part of the Sagittarius stream as well.

We assume from its low stellar density that the structure S297+63−20.0 has undergone tidal disruption in the Milky Way. It is possible that it could be a part of the tidal stream of the Sagittarius dwarf galaxy. Figure 2 of Ibata et al. (2001a) shows how debris from the Sagittarius dwarf is found off the main Sagittarius streamer orbit. If the F stars in S297+63−20.0 are related to this off-stream debris, it implies a more disbursed stream than their $g = 0.9$ model predicts. A model closer to $q = 0.7$ is needed to explain the star density relative to that of S341+57−22.5 (Sagittarius) in terms of a single tidally precessed stream. Note, however, that the turnoff color of the stars in S297+63−20.0 does not support the idea that they originated in the Sagittarius dwarf galaxy. The turnoff color also does not rule out an identification with the Sagittarius stream; if they are associated, it would imply that the stellar populations changed along a stream. It is also noteworthy that the S297+63−20.0 structure lies exactly on the plane of the Fornax-Leo-Sculptor dwarf galaxies (Majewski 1994), though it is much closer to the Galactic center than any of these dwarfs.

6.2. The Monoceros–Canis Major Structure

The most tantalizing structures we have identified are S223+20−19.4, S218+22−19.5, and S183+22−19.4, which may be two sides of the same contiguous structure. S200−24−19.8 could also belong to this structure, but its relationship is more difficult to establish, as a result of the lower data quality in this region. Though it is possible that we have found three independent, similar structures of stars in the halo, we find that possibility unlikely. In $\frac{x}{y}$ we explored the possibility that this structure was part of an MWTD. In this section we explore the possibility that it is a tidally disrupted dwarf galaxy spread across 45$^\circ$ on the sky and 11 kpc from us (18 kpc from the center of the Galaxy). We believe that this would not have been identified previously because it is so large and close and hidden by the plane of the Milky Way. Figure 26 shows our knowledge of the edge of this stellar structure.

Since we do not probe the full extent of any structure in this area of the sky as a result of the intervening Galactic plane, it is difficult to distinguish a disrupted galaxy residual stream from a dwarf galaxy. Without kinematic information it is difficult for us to identify streams with possible parent dwarf galaxies. Since we do not see much of the perimeter of this structure, we cannot distinguish very easily between a dwarf galaxy and a gravitationally unbound streamer which circles the entire Galaxy at an inclination $i < 20^\circ$ to the Galactic plane (or something in between). Most other orbital directions are ruled out because it is only evident at the ends of stripes 10, 11, 12, 37, and 82.

A dwarf galaxy or disrupted galaxy stream of stars in the Galactic halo provides a simpler model which produces stars all at about the same distance from us. With a distance modulus of about 15.2 (from Fig. 13 and an assumed absolute magnitude of $g^* = 4.2$), the distance to S223+20−19.4 is 11 kpc from the Sun. The same distance is derived for S183+22−19.4. These two overdensities are separated by 40$^\circ$ on the sky. If they indeed belong to the same structure, the structure is at least 8 kpc across. This is of the same scale as other large structures identified in the halo, including the Sagittarius dwarf spheroidal galaxy and the Sagittarius dwarf streamer. If S200−24−19.8 is part of the same structure, it is 8 kpc in the declination direction.

The width of the main sequence of S223+20−19.4 (see Fig. 13) is only about 1 mag wide at $g^* = 21.1$. From the errors in color alone (multiply the expected dispersion in $g^* - r^*$ color at $g^* = 21.1$, from Fig. 3, by the slope of the main sequence in Fig. 8), we could explain this entire width. To gain an upper limit on the thickness of the structure, we assume that the entire 1 mag dispersion is due to depth of the structure and obtain an upper limit for the depth of the
structure of 6 kpc. We obtain a similar measurement for the depth of S183+22 − 19.4.

We now ask what the mass of a satellite in the Galactic plane would have to be in order to remain tidally bound. A simple tidal analysis can be done following, for example, equation (7.84) in Binney & Tremaine (1987). The mass of the satellite within the tidal radius is given by

\[ m_{\text{sat}} = 3 M_{\text{MW}} \left( \frac{r_{\text{tidal}}}{D} \right)^3, \]

where \( r_{\text{tidal}} \) is the tidal radius of the dwarf, \( D \) is the distance of the satellite from the center of the Milky Way, and \( M_{\text{MW}} \) is the mass of the Milky Way within a radius of \( D \). This equation holds for \( m_{\text{sat}} \ll M_{\text{MW}} \) and \( r_{\text{tidal}} \ll D \). Plugging in \( r_{\text{tidal}} = 4 \) kpc and \( D = 18 \) kpc, we find that the satellite would have to have a mass equal to 3% of the mass of the Milky Way. Estimating the mass of the Milky Way interior to \( D \) from \( M_{\text{MW}} = r_{\text{MW}}^2 D / G \) with \( r_{\text{MW}} = 220 \) km s\(^{-1} \), we find \( M_{\text{MW}} \approx 2 \times 10^{11} M_\odot \) and an inferred satellite mass of \( 6 \times 10^9 M_\odot \).

For reference, the dynamically estimated initial mass of the Sagittarius dwarf galaxy is between \( 10^9 \) and \( 10^{11} M_\odot \). (Ibata & Lewis 1998; Jiang & Binney 2000), and it is currently about \( 10^9 M_\odot \). (Johnston et al. 1999a). Sagittarius is located 16 kpc from the Galactic center and prolate with axis ratios 3 : 1 : 1 and a major axis of at least 9 kpc (Ibata et al. 1997). So far, our observations could be explained by a dwarf galaxy, similar in size to the Sagittarius galaxy, and hiding in the plane of the Milky Way, 18 kpc from the Galactic center. We have asked whether the star counts support the existence of so massive a structure in the halo. For stars of this turnoff color, \( g^* - r^* = 0.28 \), a relatively metal-poor, spheroidal-type population with [Fe/H] = −1.7 ± 0.3 is implied. An isochrone analysis like that for the Sagittarius stream of §4 then indicates that these turnoff stars typically would have masses near 0.75 \( M_\odot \) and approximate ages of 13 Gyr.

It is difficult to estimate the total number of stars in the proposed structure. If it is a dwarf galaxy, we have only detected the tails of the distribution. Star counts must be estimated by extrapolation. The highest detected stellar density is about 1500 F and G stars above background in a 1.25 deg\(^2\) region of the sky (Fig. 22). A structure with constant stellar density over a \( 40' \times 40' \) area of the sky would contain \( 2 \times 10^6 \) stars. This is a lower limit.

If, instead, one fits to a model power-law distribution (\( \alpha = -3.5 \)) of stars centered halfway between our two detections, such as that shown in Figures 13c and 22, we calculate \( 1 \times 10^7 \) F and G stars in the whole structure. If we put the center of the dwarf galaxy in the plane of the Milky Way, the inferred star count is several times higher. One could increase or decrease the inferred mass in stars by suitably adjusting the axial ratios or density profiles of the models. A mass in stars of a few times \( 10^7 M_\odot \) is feasible, though by no means proven.

The total number of stars in the structure could easily be larger than these estimates if it is part of a stream which circles the Galaxy. If the stream contains at least \( 2 \times 10^8 \) stars in the \( 40' \) section of sky where we detected it, and if it extends all the way around the Galaxy with similar density, it must contain at least \( 2 \times 10^9 \) stars. The actual stellar and dynamical masses are likely to be much higher, since these estimates use the lowest possible extent and stellar densities.

Thus, the overdensity could indicate a dwarf galaxy in the constellation Monoceros or in nearby Canis Major to the south. However, even if it is a dwarf galaxy, the high tidal mass calculated above suggests that it would be in the process of disrupting, just as the Sagittarius dwarf galaxy is. One could go a step further and suggest that what we have detected is not a dwarf galaxy at all, but instead a gravitationally unbound stream of stars. This conclusion might be preferred, since it frees us from explaining the coincidence of having found the very ends of the structure by chance in stripes 10, 82, and 37. Figure 22 shows that even as a stream, this structure is significantly denser than the Sagittarius stream where it crosses zero declination. It is not only denser where we detect it, but it is also steeply rising as we run out of data.

If it is the result of the complete disruption of a gravitationally bound group of stars, the original mass of the infalling matter was probably quite large. The stream must contain at least \( 1 \times 10^7 \) stars in the \( 40' \) section of sky where we detected it. If it extends all the way around the Galaxy with similar density, it must contain at least \( 1 \times 10^7 \) stars.

7. Conclusions

From stars in the SDSS, we have shown that we can detect large (\( ~10 \) kpc) structures of stars in the halo of the Milky Way. In Paper I we showed that substructure in the Galactic halo could be identified from photometric data for blue stars. In this paper we extended the technique to identify large structures directly from turnoff stars. The CMDs of the stars in the structures should resemble the CMDs of the original dwarf galaxies or clusters which fell into the Milky Way. Features of the diagrams can be used to constrain the origins of each detected overdensity.

As more data are collected from the SDSS, we will be able to trace each structure through space and connect the overdensities in each stripe to each other to build up a large-scale map of large stellar streams in the halo of our Galaxy. For now, we must content to identify and name each overdensity and only to estimate their full extent and origin. In this paper we studied the \( g^* - r^* \) colors and \( g^* \) magnitude distributions of seven overdensities of halo stars in the equatorial plane. We also show overdensities in three off-equatorial stripes, since they appear to be associated with the equatorial structures.

We emphasize these conclusions:

1. We show additional evidence that the overdensities S341 + 57 − 22.5 and S167 − 54 − 21.5 are in fact part of the tidal stream of the Sagittarius dwarf galaxy. These structures were discovered in Paper I and were interpreted by Ibata et al. (2001a) as two slices through the tidal stream of the Sagittarius dwarf galaxy.

The CMD of S341 + 57 − 22.5 bears striking resemblance to the CMD of the Sagittarius dwarf, including similar clumps of red stars. The CMD of S167 − 54 − 21.5 is consistent with that of the Sagittarius dwarf galaxy. In addition, the two overdensities are shown to have the same color turnoff stars as the Sagittarius dwarf galaxy; the turnoff of the Sagittarius dwarf is 0.08–0.1 mag bluer in \( g^* - r^* \) than the assumed Galactic spheroid stars and substantially bluer than any other structure we have identified.

A comparison of the number of stars detected in the clump of red stars of S341 + 57 − 22.5 and S344 + 58 − 22.5
CMDs for S223+20

off colors, and inferred distances. The similarity between the
from the Sun. S223+20 is consistent with stars all at the same distance, about 11 kpc
larly striking. The narrow main sequence seen in the CMDs
gated by 40

3. We observe many more stars at low Galactic latitudes
near the Galactic anticenter than standard models predict at
g° ~ 19.5. These stars were selected to be bluer than the
turnoff of the thick-disk stars. Several of our identified
structures lie in this general direction and may be part of the
same physical structure in the Galaxy. The structures
S223+20–19.4, S218+22–19.5, S183+22–19.4, and (with
less significance) S200–24–19.8 have similar CMDs, turn-
of colors, and inferred distances. The similarity between the
CMFs for S223+20–19.4 and S183+22–19.4 is parti-
cularly striking. The narrow main sequence seen in the CMDs
is consistent with stars all at the same distance, about 11 kpc
from the Sun. S223+20–19.4 and S183+22–19.4 are sepa-
rated by 40° in right ascension. These are both separated
from S200–24–19.8 by 40° in declination. The inferred spa-
tial extent of the structure is 8 kpc in declination, centered
approximately on the Galactic plane, by at least 8 kpc in
right ascension. Since it would seem coincidental to have
detected the structure exactly at its ends, we expect that the
structure is substantially longer than 8 kpc. The inferred dis-
tance from magnitudes of turnoff stars is 11–16 kpc from
the Sun. From the magnitude distribution, the structure
is less than 6 kpc thick along the line of sight. The turnoff
stars of this structure have colors of spheroid stars
(g° – r° = 0.28) rather than colors of thick-disk stars
(g° – r° = 0.40).

We propose two possible explanations for the unexpect-
edly high concentrations of blue stars near the Galactic anti-
center. One of the possibilities is that they are stars
associated with a tidally disrupted dwarf galaxy. The other
is that these stars are part of an “even thicker disk” popula-
tion which has a bluer turnoff than the thick disk, a scale
height of about 2 kpc, and a scale length around 10 kpc.
Though neither explanation explains all of the data, either
model could be reasonably extended to work. We do not
propose that these possibilities exclude all other models;
they are merely the most reasonable explanations we could
find.

The tidally disrupted dwarf galaxy model neatly explains
a distribution of stars all at the same apparent distance. The
presence of the disrupted Sagittarius dwarf galaxy proves that
such structures can and do exist in the Milky Way halo and
that they can be detected by these techniques. The
inferred physical parameters for such a structure, though
large, are not prohibitive; the projected mass of the original
dwarf galaxy could be of similar size to the Sagittarius dwarf
galaxy. This model does not explain why the stars we see
toward the Galactic center show an unexpectedly large flat-
tening (other additional streams or Galactic components
are required to explain this), or why the turnoff of this pro-
posed dwarf has the same color as the stars toward the
Galactic center.

The “even thicker” double-exponential disk model uses
large scale lengths to put the peak of the stellar density at
faint enough magnitudes. This model is appealing because it
naturally explains why such a structure is found over at least
40° of right ascension in the Galactic plane, and it may
correspond to the MWTD proposed by previous authors. The
negatives of this model are that it does not fit the faint star
counts near the Galactic center (Fig. 18) and consumes all
of the stars brighter than 20th magnitude which we expected
were part of the power-law spheroid part of the halo. It also
is rather broader in magnitude, spreading stars over a larger
distance range, than the data suggest. This model would
reduce the significance of, or eliminate, a power-law distri-
bution of halo stars. The distribution in magnitude of the
concentration of stars near the anticenter is somewhat nar-
rower than expected for an exponential disk (Fig. 13).

Neither of these models explains the excess of stars at
15th and 17th magnitude near the plane at the Galactic anti-
center. A stream model might introduce additional streams
to explain this, whereas a disk model might introduce warp-
ing to explain this.

4. On the other side of the Milky Way at (l, b) = (52°, −32°), in a direction not far from the Galactic
center S52–32–20.4, there is evidence for stars distinct
from a smooth spheroidal distribution of stars at g° = 20.8.
The distribution in magnitude is not consistent with a
power-law spheroid, although it could be fitted with an
exponential disk with large scale length. This is in contrast
to the structure S6+41–20.0, which is the only observed
concentration of halo stars that shows the spatial distribu-
tion, both in right ascension and apparent magnitude,
expected for a power-law Galactic spheroid. Additionally,
the turnoff color of the stars in S52–32–20.4 is not the same
as that of the presumed spheroid stars at S6+41–20.0, but
rather intermediate between the spheroid and the Sagittari-
uus dwarf.

If we try to fit a power law to the stars in both
S6+41–20.0 and S52–32–20.4, then we must have q < 0.6
(and there is a poor fit with distance in the direction of
S52–32–20.4). If this structure is regarded as distinct from
the spheroid, then the remaining spheroidal stars toward
the Galactic center could be fitted with a rounder model,
q = 0.8.

We do not present a single, coherent proposal for the
components of the Milky Way, since it is not clear to what
component each identified overdensity should be assigned.
As more SDSS data are analyzed, and the extent of each
structure is better known, we hope to generate a more coher-
ent, defendable model.

5. Aside from the obvious large overdensities in the halo,
two is tantalizing evidence for further, smaller structures,
for example, at α = 10°. One could imagine that there are
even smaller structures which are not spatially resolved,
which make up the difference between the observed star
counts and the model fits to the spheroid population.
In this paper and in Paper I we identified seven or eight large overdensities which we believe might be associated with three or more halo structures. In view of these results, one must take seriously the possibility that there are many such previously unidentified structures in the halo. It is also probable that there are many smaller or more disrupted structures which might be better detected from kinematics than spatial information. Models of structure formation which have produced "too many galaxies per halo" may actually be predicting correct numbers of smaller halo structures. It appears we may be able to solve the problem by observationally finding more disrupted satellites in each halo.

One cannot help but wonder many things about the results presented in this paper. We conclude our discoveries with a list of questions for which we do not yet have answers. Is there a previously undiscovered dwarf galaxy hidden in the plane of the Milky Way? If there is a massive streamer or dwarf galaxy which orbits our Milky Way in the Galactic plane, could this disrupt the disk at about 18 kpc from the Galactic center? Would it cause disk warping or flaring? Are there any dynamical models that could put a sheet of stars in a ring around the Galaxy without an infalling dwarf? If there is a structure with a scale length of many kiloparsecs which is only 11 kpc from us, can we detect any stars from this structure in the solar neighborhood kinematically or photometrically? Is there an MWTD? Is there a model for the MWTD which could explain why the stars seem to be shifted toward lower Galactic latitudes at $g^* \sim 18$? Why do we not see a break, or at least a gradient, in the turnover color between stars which would nominally be assigned to the thin disk and those which would be assigned to the thick disk? Finally, are there any halo stars which form a well-mixed, smooth, spheroidal distribution, and were any of them formed during the initial collapse of our Galaxy, as was proposed by Eggen, Lynden-Bell, & Sandage (1962)?

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