The Selection of RR Lyrae Stars Using Single-epoch Data

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ABSTRACT

We utilize a complete sample of RR Lyrae stars discovered by the QUEST survey using light curves to design selection criteria based on SDSS colors. Thanks to the sensitivity of the $u - g$ color to surface gravity and of $g - r$ color to effective temperature, and to the small photometric errors ($\sim 0.02$ mag) delivered by SDSS, RR Lyrae stars can be efficiently and robustly recognized even with single-epoch data. In a 100\% complete color-selected sample, the selection efficiency (the fraction of RR Lyrae stars in the candidate sample) is 6\%, and, by adjusting color cuts, it can be increased to 10\% with a completeness of 80\%, and to 60\% with 28\% completeness. Such color selection produces samples that are sufficiently clean for statistical studies of the Milky Way’s halo substructure, and we utilize it to select 3,643 candidate RR Lyrae stars from SDSS Data Release 1. We demonstrate that this sample recovers known clumps of RR Lyrae stars associated with the Sgr dwarf tidal tail, and Pal 5 globular cluster, and use it to constrain the halo substructure away from the Sgr dwarf tidal tail. These results suggest that it will be possible to study the halo substructure out to $\sim 70$ kpc from the Galactic Center in the entire area imaged by the SDSS, and not only in the multiply observed regions.

Subject headings: Galaxy: structure — Galaxy: halo — Galaxy: stellar content — variables: RR Lyrae variable

1. Introduction

Studies of substructures, such as clumps and streams, in the Galactic halo can help constrain the formation history of the Milky Way. Hierarchical models of galaxy formation...
predict that these substructures should be ubiquitous in the outer halo, where the dynamical timescales are sufficiently long for them to remain spatially coherent (Johnston et al. 1996; Mayer et al. 2002, Helmi 2002). One of the best tracers to study the outer halo are RR Lyrae stars because

- They are nearly standard candles (dispersion of $\sim 0.13$ mag, Vivas et al. 2001) and thus it is straightforward to determine their distance, and
- They are sufficiently bright ($\langle M_V \rangle = 0.7-0.8$, Layden et al. 1996, Gould & Popowski 1998) to be detected at large distances ($5-100$ kpc for $14 < r < 20.7$).

RR Lyrae stars are typically found by obtaining well-sampled light curves. The QUEST survey is the largest such survey that is capable of discovering RR Lyrae stars in the outer halo. Using a 1m Schmidt telescope, the QUEST survey has so far discovered about 500 RR Lyrae stars in 400 deg$^2$ of sky (Vivas et al. 2003). Nevertheless, Ivezić et al. (2000, hereafter I00) demonstrated that RR Lyrae stars can be efficiently and robustly found even with two-epoch data, using accurate multi-band photometry obtained by the Sloan Digital Sky Survey (SDSS). The QUEST survey later demonstrated (Vivas et al. 2001) that most (>90%) of the SDSS candidates are real RR Lyrae stars, and also confirmed the estimate of the sample completeness ($\sim 35 \pm 5$%).

To extend the above surveys for RR Lyrae stars to a significant fraction of the sky (say, one quarter) is difficult. The QUEST survey will cover up to 700 deg$^2$, while the SDSS survey, which should observe close to one quarter of the sky, will obtain only single-epoch data for most of the scanned area. However, here we demonstrate that the distinctive SDSS colors of RR Lyrae stars allow their selection using only a single-epoch of data. We utilize a complete sample of RR Lyrae stars discovered by the QUEST survey and design optimal selection criteria based on SDSS colors. The data and the selection method are described in Section 2, in Section 3 we select and analyze candidate RR Lyrae stars from SDSS Data Release 1, and summarize and discuss the results in Section 4.

2. The Selection of RR Lyrae Stars Using SDSS Colors

2.1. The SDSS and QUEST Data

The Sloan Digital Sky Survey (SDSS; York et al. 2000) is revolutionizing studies of the Galactic halo because it is providing homogeneous and deep ($r < 22.5$) photometry in five passbands ($u, g, r, i, z$, Fukugita et al. 1996; Gunn et al. 1998; Smith et al. 2002; Hogg
et al. 2002) accurate to 0.02 mag (Ivezić et al. 2003a). The survey sky coverage of up to
10,000 deg$^2$ in the Northern Galactic Cap will result in photometric measurements for over
100 million stars and a similar number of galaxies. Astrometric positions are accurate to
better than 0.1 arcsec per coordinate (rms) for sources with $r < 20.5^m$ (Pier et al. 2003),
and the morphological information from the images allows reliable star-galaxy separation
to $r \sim 21.5^m$ (Lupton et al. 2001).

Here we use SDSS imaging data which are part of the SDSS Data Release 1 (Abazajian
et al. 2003, hereafter DR1). DR1 includes 2099 square degrees of five-band imaging data,
to a depth of $r \sim 22.6$. SDSS equatorial observing runs 752 and 756 overlap with the
QUEST observations in a 89 deg$^2$ large region defined by $-1^\circ < \delta_{2000} < 0^\circ$, and $09^h 44^m
< \alpha_{2000} < 15^h 40^m$. This region contains about 210,000 unique, stationary unresolved
sources with $14 < r < 20$, with mean galactic coordinates ($l = 290^\circ$, $b = 53^\circ$). In the same
region there are 162 RR Lyrae discovered by the QUEST survey, and described by Vivas
The discovery of these variables in this region of the sky was based on high quality light
curves, each containing 25 to 35 different epochs. This sample of RR Lyrae stars has a
high completeness (> 90%) for the ab-type variables (fundamental mode pulsators). The
completeness decreases for the low amplitude type c RR Lyrae stars to 55 – 75%, depending
on the magnitude of the star.

When computing the efficiency of the selection algorithms described below, we
exclude SDSS objects in the region $-0.58^\circ < \delta < -0.51^\circ$, which was not observed by
QUEST because it fell on a gap between the columns of CCDs in the QUEST camera.
All magnitudes have been corrected by interstellar extinction using the dust maps and
transformations given by Schlegel, Finkbeiner & Davis 1998.

2.2. The SDSS Observations of the QUEST RR Lyrae

We searched for the 162 QUEST RR Lyrae in the SDSS DR1 database\(^5\) within a circle
of radius 2 arcsec centered on the QUEST position, and found all of them. The distribution
of distances between the QUEST and SDSS positions has a median of 0.5 arcsec, and
root-mean-square scatter of 0.16 arcsec (the distributions of $\alpha_{2000}$ and $\delta_{2000}$ differences show
offsets of 0.3 arcsec for each coordinate).

The SDSS processing flags (for details see DR1 and Stoughton et al. 2002) indicated

\(^5\)Available from http://www.sdss.org
that 9 stars may have substandard photometry (complex blends, cosmic rays, bad pixels), with probable errors sometimes as large as 0.05 mag. Since the selection algorithm discussed here relies on accurate color measurements, hereafter we consider the sample of 153 stars with impeccable photometry.

The histogram marked by solid circles in the bottom panel in Figure 1 shows the distribution of differences between the mean $V$ magnitude measured by the QUEST survey, $V_{\text{mean}}^{\text{QUEST}}$, and a single-epoch synthetic SDSS-based $V_{\text{SDSS}}$ magnitude, computed from (Fukugita et al. 1996)

$$V_{\text{SDSS}} - r = 0.44 (g - r) - 0.02.$$  \hspace{1cm} (1)

Reassuringly, the mean value of the shown distribution is consistent with zero to within 0.02 mag. The distribution is skewed because RR Lyrae stars have asymmetric light curves (they spend more than 50% of their variability cycle fainter than their mean magnitude).

The top and middle panels show the correlations between the $u - g$ and $g - r$ colors measured by SDSS and the $V$ magnitude difference. As expected, RR Lyrae stars have bluer $g - r$ colors when brighter, while there is no discernible correlation for $u - g$ color, which may be due to shock wave related activity (Smith 1995). Note that the $g - r$ color spans twice as large a range as does the $u - g$ color.

The $g - r$ color is correlated with $V_{\text{SDSS}} - V_{\text{mean}}^{\text{QUEST}}$. The best-fit relation, shown in the middle panel by the dashed line is

$$g - r = 0.4 (V_{\text{SDSS}} - V_{\text{mean}}^{\text{QUEST}}) + 0.15.$$  \hspace{1cm} (2)

This relation can be used to correct a bias in single-epoch SDSS measurements due to unknown phase, such that

$$V_{\text{SDSS}}^{\text{RRLyr}} = r - 2.06 (g - r) + 0.355,$$  \hspace{1cm} (3)

where all measurements have been corrected for ISM reddening. The histogram marked by open squares in the bottom panel in Figure 1 shows the distribution of $V_{\text{SDSS}}^{\text{RRLyr}} - V_{\text{mean}}^{\text{QUEST}}$. The root-mean-square scatter is significantly decreased compared to the scatter in $V_{\text{SDSS}} - V_{\text{mean}}^{\text{QUEST}}$ (0.12 mag. vs. 0.18 mag., as marked in the figure). This is a relation that produces unbiased RR Lyrae distances with a minimal scatter (0.12 mag.) from single-epoch SDSS measurements. It is remarkable that the scatter in mean magnitude estimated from single-epoch SDSS measurements is as small as the intrinsic uncertainty in RR Lyrae absolute magnitudes. We note that assuming a constant $M_r$ (instead of $M_V$) to determine distances results in practically no bias, but the scatter is increased to 0.20 mag. (for constant $M_g$ the bias is 0.23 mag. with a comparable scatter).
2.3. The Colors of RR Lyrae in SDSS Photometric System

Figure 2 shows the distribution of all point sources with $r < 20$ in the SDSS color-magnitude and color-color diagrams as linearly spaced contours. In color-color diagrams, red is always towards the upper right. For a detailed description of stellar colors in the SDSS photometric system see Finlator et al. (2000) and references therein. The 153 QUEST RR Lyrae stars are shown as symbols. The symbol size corresponds to 3-5 times the photometric errors, depending on the scale of individual panels (for a detailed analysis of SDSS photometric errors see Ivezić et al. 2003a). That is, the scatter of points is due to intrinsic differences among RR Lyrae stars and the variation of colors with phase. Nevertheless, RR Lyrae stars span a very narrow range of SDSS colors. The color limits for the sample discussed here are

\begin{align*}
0.99 < u - g < 1.28 \\
-0.11 < g - r < 0.31 \\
-0.13 < r - i < 0.20 \\
-0.19 < i - z < 0.23
\end{align*}

In particular, both the range ($\sim 0.30$ mag) and the root-mean-square scatter ($\sim 0.06$ mag) are the smallest for $u - g$ color.

The RR Lyrae fraction is 1 in 1,300 amongst all SDSS stars with $r < 20$. In a subsample selected using the above color cuts, the RR Lyrae fraction is 6%. We show next how this fraction can be increased to over 60% by optimizing the color selection boundaries.

2.4. The Optimization of the Color Selection

RR Lyrae stars are found furthest from the locus of other stars in the $g - r$ vs. $u - g$ color-color diagram. The relevant part of this diagram, outlined by the small rectangle in Figure 2, is shown magnified in Figure 3. The small dots show all SDSS point sources with $14 < r < 20$, and the symbols are confirmed RR Lyrae stars (solid circles are $ab$ type RR Lyrae stars and triangles correspond to the $c$ type stars). The photometric errors are comparable to the radius of the large circles, except for objects in the top left corner which have faint $u$ band magnitudes ($\gtrsim 21.5$).

Most of the contamination in a sample of candidate RR Lyrae stars selected using simple color cuts listed above comes from the main stellar locus visible in the top left corner.
The second most significant source of contamination is the A star locus running from the main locus towards the bottom right. This motivates a revised selection boundaries shown as the polygon outlined by solid lines. The edges with positive \( \frac{d(g-r)}{d(u-g)} \) slope have a constant distance from the main stellar locus

\[
D_{ug} = (u-g) + 0.67(g-r) - 1.07,
\]

and the edges with negative slope have a constant distance from the A star locus

\[
D_{gr} = 0.45(u-g) - (g-r) - 0.12.
\]

The QUEST RR Lyrae span the ranges \(-0.05 < D_{ug} < 0.35\) and \(0.06 < D_{gr} < 0.55\), resulting in a selection efficiency (the fraction of RR Lyrae stars among the selected candidates) of 6%.

The selection efficiency can be further increased by increasing the lower limits on \(D_{ug}\) and \(D_{gr}\), \(D_{ug}^{\text{Min}}\) and \(D_{gr}^{\text{Min}}\), respectively (of course, the sample completeness then becomes less than 100%), and keeping the restrictions in colors \((u-g)\), \((r-i)\) and \((i-z)\). For example, the dashed lines show a restricted selection boundary obtained with \(D_{ug}^{\text{Min}} = 0.15\) and \(D_{gr}^{\text{Min}} = 0.23\), which results in a completeness of 28% and 61% efficiency\(^6\).

The top panel in Figure 4 shows a detailed dependence of the completeness (solid lines) and efficiency (dashed lines) as functions of \(D_{gr}^{\text{Min}}\) for three different values of \(D_{ug}^{\text{Min}}\), as indicated. The largest possible selection efficiency using single-epoch data is about 65%. The remaining contaminants are probably dominated by quasars (Richards et al. 2001) and non-variable horizontal branch stars.

The restricted color criteria preferentially select type \(c\) RR Lyrae stars because they have bluer \(g-r\) colors than \(ab\) type stars (see Figure 3). The bottom panel in Figure 4 compares the completeness estimates for the two different types of RR Lyrae variables for a color cut with \(D_{ug}^{\text{Min}} = 0.15\). When \(D_{gr}^{\text{Min}} > 0.16\), type \(c\) RR Lyrae stars have a higher selection efficiency. For example, in the region enclosed by the dashed lines in Figure 3, we recover 45% of all QUEST type \(c\) RR Lyrae stars but only 25% of the more common types \(ab\).

To summarize, the proposed selection criteria are

\[
14 < r < 20
\]
0.98 < u − g < 1.30 \quad (11)
\begin{align*}
D_{ug}^{Min} &< D_{ug} < 0.35 \quad (12) \\
D_{gr}^{Min} &< D_{gr} < 0.55 \quad (13)
\end{align*}
-0.15 < r − i < 0.22 \quad (14)
-0.21 < i − z < 0.25, \quad (15)

where $D_{ug}^{Min}$ and $D_{gr}^{Min}$ can be chosen using Figure 4 to yield desired selection completeness and efficiency, depending on a specific purpose.

3. Candidate RR Lyrae Stars in SDSS Data Release 1

We apply the color selection method discussed in the preceding Section to SDSS Data Release 1. DR1 includes sky regions with known halo substructures traced by RR Lyrae, and can thus be used to test the performance of the method for discovering such structures. DR1 also includes areas for which variability data does not exist (either from QUEST, or from repeated SDSS scans), and which may exhibit previously uncharted substructure.

The condition $D_{ug}^{Min} = 0.10$ and $D_{gr}^{Min} = 0.20$ results in a sample of 3,643 candidate RR Lyrae stars selected from SDSS DR1 database. Here we require that the processing flags SATURATED and BRIGHT are not set, and use un-derreddened magnitudes for the $14 < r < 20$ condition (of course, the color selection must be done with dereddened magnitudes). A subsample satisfying $D_{ug}^{Min} = 0.15$ and $D_{gr}^{Min} = 0.23$ contains 896 stars. The completeness and efficiency, determined using Figure 4, for the first selection criteria are $C = 50\%, E = 35\%$, and for the second selection criteria $C = 28\%, E = 60\%$. The distribution of selected candidates on the sky is shown in Figure 5 (which closely outlines the SDSS DR1 area).

3.1. A Self-consistency Test

The mean density of RR Lyrae stars can be estimated from

$$
\rho_{RRLyr} = \frac{N_s E_s}{A_{DR1} C_s},
$$

where the area included in DR1 is $A_{DR1} = 2099 \text{deg}^2$, and $N_s$ is the number of selected stars using particular values of $D_{ug}^{Min}$ and $D_{gr}^{Min}$. The estimate $\rho_{RRLyr}$ should be nearly the same for both samples, and should agree with the value of $\rho_{RRLyr} \sim 1.3 \text{deg}^2$, determined from the QUEST data for their first 400 deg$^2$ of sky (Vivas et al. 2003). The values obtained
here, $1.21 \, \text{deg}^2$ and $0.91 \, \text{deg}^2$, are in good agreement with each other, indicating that the selection method is robust (the training sample included data for a 24 times smaller area).

We estimate that SDSS DR1 contains $\sim 2200$ RR Lyrae stars, and that 1,170 are included in our sample of 3,643 candidates. The smaller, more restrictive, sample of 896 stars contains 540 probable RR Lyrae stars.

### 3.2. A Test of the Ability to Recover Halo Substructure

We analyze the spatial structure of selected candidates by examining their distribution in the $r$ vs. position diagrams, for narrow strips on the sky. The equatorial strip ($\text{Dec} \sim 0^\circ$) contains several known clumps of RR Lyrae stars (I00, Vivas et al. 2001).

The distribution of QUEST RR Lyrae stars in the $r$ vs. RA diagram along the Celestial equator is shown in the top panel in Figure 6. The $r$ range from 14 to 20 corresponds to distances of 5 kpc to 70 kpc (recall that the strip width in the Dec direction for the QUEST subsample is 1 deg). Three especially prominent features are the clump associated with the Sgr dwarf tidal tail ($\text{RA} \sim 215$, $r \sim 19$), Pal 5 globular cluster and associated tidal debris ($\text{RA} \sim 230$, $r \sim 17.4$), and a clump at ($\text{RA} \sim 190$, $r \sim 17$).

All these three features are recovered by the color-selected SDSS DR1 candidate RR Lyrae stars, whose $r$ vs. RA distributions are shown in in the middle and bottom panels in Figure 6. In particular, the feature at ($\text{RA} \sim 190$, $r \sim 17$), detected at a 5$\sigma$ level above the background by Vivas & Zinn (2002, 2003) using a complete sample of confirmed RR Lyrae stars is clearly visible.

The color-selected samples also recover the so-called “southern” clump at $\text{RA} \sim 30$ and $r \sim 17–18$, (associated with the Sgr dwarf tidal tail, see the great circle marked by long-dashed line in Figure 5) that was discovered using A-colored stars by Yanny et al. (2000). Furthermore, the faint clump at $\text{RA} \sim 30$ and $r > 19$ is present in a sample of candidate RR Lyrae stars selected from repeated SDSS observations (Ivezić et al. 2003b). Given these successful recoveries of known structure, we conclude that the color-selected samples of candidate RR Lyrae stars are sufficiently clean and robust to study halo substructure out to distances of $\sim 70$ kpc.
3.3. Is Sgr Tidal Stream the Most Prominent Halo Feature?

To reliably answer the question posed in the title of this subsection, one would need an all-sky survey of several halo tracers. While such data do not exist yet (the upcoming large scale synoptic surveys will eventually discover all halo RR Lyrae), a study of 2MASS data by Majewski et al. (2003) provided the first all-sky view of halo structure, traced by M giants. They did not find any features that would compete with the prominence of the Sgr tidal stream. Nevertheless, M giants are not as good standard candles as RR Lyrae stars, and are more sensitive to metallicity effects. It is therefore worthwhile to examine the distribution of candidate RR Lyrae stars in areas of sky that were not explored until now.

In Figure 7 we examine magnitude-angle diagrams for candidates selected using $D^M_{ug} = 0.10$ and $D^M_{gr} = 0.20$, along the great circle (within $\pm 5^\circ$) marked by short-dashed line in Figure 5, and defined by node=$95^\circ$ and inclination=$65^\circ$, relative to the Celestial Equator (for more details about great circle coordinates see Pier et al. 2003). The structure seen in this Figure is not nearly as prominent as that shown in the middle panel of Figure 6, where the candidate RR Lyrae stars were selected by the same criteria. Two possible overdensities are visible at the longitude of $\sim 225$ and $r \sim 16$, and the longitude of $\sim 150$–165 and $r \sim 19$–20. The latter is supported by the distribution of candidate RR Lyrae stars selected from repeated SDSS observations (and is probably associated with the Sgr tidal stream, Ivezić et al. 2003c), while such data are not available in the region of the former overdensity. We are currently investigating the distribution of candidate variable stars selected by comparing POSS and SDSS measurements (Sesar et al. 2003, in prep.) in order to derive more reliable conclusions about the halo substructure in that region.

4. Discussion

The robust recovery of the known halo substructures with the color selection proposed here suggests that it will be possible to constrain the halo structure out to $\sim 70$ kpc from the Galactic Center in the entire area imaged by the SDSS, and not only in the multiply observed regions. This method may result in discoveries of more Sgr dwarf debris in currently unexplored parts of sky, which would be important to understand the evolution of the disruption of this galaxy. If events similar to the accretion and disruption of Sgr dwarf have occurred with other galaxies, this technique has a good chance of discovering their signatures. Therefore, before large-scale variability surveys, such as Pan-STARRS and LSST become available, the candidate RR Lyrae stars selected using SDSS colors can be used for statistical studies of the halo substructure. The selection efficiency of $\sim 60\%$, with a completeness of $\sim 30\%$, should be sufficient to uncover the most prominent features.
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Fig. 1.— The top and middle panels show the correlations between the single-epoch $u-g$ and $g-r$ colors measured by SDSS, and the difference between the mean $V$ magnitude measured by the QUEST survey ($V_{\text{QUEST}}^{\text{mean}}$) and a single-epoch synthetic $V$ magnitude measured by the SDSS ($V_{\text{SDSS}}$), for 153 RR Lyrae stars observed by both surveys. Note that RR Lyrae stars have bluer $g-r$ colors when brighter, while there is no discernible correlation for $u-g$ color. The dashed line in the middle panel shows a best-fit relation between the $g-r$ color and $V_{\text{SDSS}}-V_{\text{QUEST}}^{\text{mean}}$. The bottom panel compares the distribution of $V_{\text{SDSS}}-V_{\text{QUEST}}^{\text{mean}}$ differences (solid circles) to the distribution of differences when $V_{\text{SDSS}}$ is corrected for this correlation (open squares, see eq. 3).
Fig. 2.— The comparison of the distribution of point sources in the SDSS color-magnitude and color-color diagrams (linearly spaced contours) and the distribution of RR Lyrae stars (symbols). The symbol size corresponds to 3-5 times the photometric errors, depending on the scale of individual panels. The rectangle shown by the dashed lines in the top right panel is the region which is shown magnified in Figure 3. Note that RR Lyrae stars span a very narrow range of $u - g$ color ($u - g \sim 0.3 \pm 0.06$).
Fig. 3.— The selection criteria for RR Lyrae stars. The small dots show all SDSS point sources with $r < 20$, and the large symbols are confirmed RR Lyrae stars (solid circles are stars of the type $ab$ and triangles are $c$ type). The photometric errors are comparable to the radius of the large dots. The solid polygon is a suggested boundary for the 100% completeness, with efficiency of 6%. The dashed lines are an example of a restricted selection boundary which results in a completeness of 28% and 61% efficiency. The dot-dashed lines are the selection boundary from a variability study by Ivezić (2000), shown here for reference.
Fig. 4.— The panel shows the dependence of the selection completeness (solid lines) and efficiency (dashed lines) as a function of $D_{ug}^{Min}$ (different curves, as labeled) and $D_{gr}^{Min}$. The bottom panel compares the completeness estimates for the different types of RR Lyrae variables for a color cut with $D_{ug}^{Min} = 0.15$. The dotted line marks a cut with $D_{gr}^{Min} = 0.23$. Type c RR Lyrae stars have a higher selection efficiency for $D_{gr}^{Min} > 0.16$ than type ab RR Lyrae.
Fig. 5.— The distribution of color-selected RR Lyrae candidates from SDSS Data Release 1, shown in Aitoff equatorial projection. The long-dashed line indicates the position of the Sgr dwarf tidal stream, and the short-dashed line is a great circle that tracks a large fraction of the SDSS DR1 region (node=95°, inclination=65°). The r vs. RA distribution of stars along the latter great circle is shown in Fig.7.
Fig. 6.— The comparison of the $r$ vs. RA distribution of QUEST RR Lyrae stars (top panel) and color-selected candidates using SDSS single-epoch measurements (middle and bottom panels). The QUEST sample of confirmed RR Lyrae stars is practically complete (in the region $150 < $ RA $< 240$, while the estimated completeness and efficiency for SDSS samples are 50%/35% and 28%/60%, for the middle and bottom panels, respectively (in the sampled RA range). Note that the clumps associated with the Sgr dwarf tidal tail (RA $\sim 215$, $r \sim 19$) and Pal 5 globular cluster (RA $\sim 230$, $r \sim 17.4$), as well as a clump at (RA $\sim 190$, $r \sim 17$), are recovered by color-selected SDSS samples. The clump at (RA $\sim 35$, $r \sim 17.5$) is also associated with the Sgr dwarf tidal tail.
Fig. 7.— The $r$ vs. great circle longitude distribution of SDSS color-selected candidates (selection 0.10/0.20), along a great circle marked by the short-dashed line in Fig. 5. The structure is not as pronounced along this great circle, as it is along the Celestial Equator (see the middle panel of Fig. 6, note different scale for x axis).