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Galactic structure from photometric surveys

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Abstract. Seventeen of twenty known or suspected dwarf galaxy satellites of the Milky Way were discovered through photometric images. Six significant tidal streams are known in the Galactic spheroid, all of which were discovered through photometric surveys. At present, only photometric surveys provide enough sky coverage and depth to probe the shape of the Milky Way. We argue that the Virgo Stellar Stream, which might be a stream or a disrupting dwarf galaxy, has a center 14-19 kpc from the Sun in the direction $(l, b) = (300°, 64°)$, using photometry from the Sloan Digital Sky Survey (SDSS) and the Sloan Extension for Galactic Understanding and Exploration (SEGUE). In the process, we demonstrate the importance of large, deep, multi-color, public photometric sky surveys with precision color information. Currently, the most urgent need is for data in the southern hemisphere and at low Galactic latitude. Deeper surveys would also be useful.

Key words. Galaxy: fundamental parameters – Galaxy: halo Galaxy: stellar content – Galaxy: structure

1. Introduction

In 1999, I (HJN) submitted my first proposal to the National Science Foundation, entitled "Tracing the Galactic Halo with A Stars From the SDSS." It was rejected, of course. One of the reviewers summed up the review with the statement: "Also, because the BHB lifetimes are shorter than even those of evolving giants, they are relatively rare in the halo, and the chances of finding them grouped in a stream from spatial data alone are rather small." The second reviewer wrote: "It is also apparent that the preliminary engineering data is quite interesting, and gives a pretty good estimate of the halo axis ratio c/a in some lines of sight. These data already suggest that the measurement of the axis ratio has already been done: how well does this ratio have to be known? Regarding the question of detecting the effects of merger streams in the data: the best way, of course, is to obtain kinematics of these stars and to show that they occupy a relatively narrow part of the energy/angular momentum space (i.e., their orbits have not been equilibrized.)"

It is now seven years later. The use of photometrically selected BHB stars, RR Lyrae stars, F turnoff stars, M giants, K giants and other select populations to trace Galactic structure has been overwhelmingly demonstrated (see references below). The Galactic spheroid is now known to be so lumpy that I am not yet positive that I know how to construct a sam-

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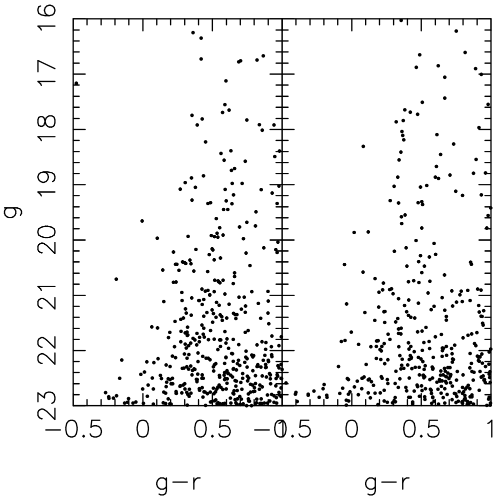

Fig. 1. Color-magnitude diagram (left) of the stars within 7 arcminutes of (RA,Dec) = (186.33°, 6.72°), showing a candidate Milkyway satellite in the constellation Virgo. Note the horizontal branch at $g \sim 20.4$ and $g - r \sim 0.3$, with a giant branch going from $g \sim 21.8$, $g - r \sim 0.4$ to $g \sim 19$, $g - r \sim 0.7$. The turnoff is at $g \sim 22$ or fainter. The right panel shows stars within 7 arcminutes of (RA,Dec) = (187.33°, 6.72°), for comparison.

ple of spheroid stars that can be trusted to answer the question of whether the spheroid is axially symmetric, let alone determine the axial ratio(s). In this paper, I will argue that photometric surveys are critical to detecting the effects of merger streams in the Galaxy; and until all three components of the stellar velocities can be determined for a large number of Galactic stars, they are the best way to discover Galactic substructure.

2. Disk Structure

The SDSS (Gunn et al. 1998; York et al. 2000) and 2MASS have been used to measure the scale heights and lengths of the Galactic thin and thick disks, by modeling the stellar density of stars selected to trace these nearby populations. Using 2MASS K giants, Cabrera-Lavers et al. (2005) found a thin disk scale height of 269 ± 13 pc, and a thick disk scale height of 1062 ± 52 pc. Chen et al. (2001) used primarily main sequence stars in SDSS data to measure a thin disk scale height of 330 ± 3 pc and a thick disk scale height of 580 – 750 pc. Juric et al. (2005) estimate, also from fitting SDSS main sequence stars, that the thin disk scale height is $\approx$ 280 pc and the thick disk scale height is $\approx$ 1200 pc. It is interesting that even with data from a large area on the sky, the measured scale heights do not agree within the quoted errors. One might argue that the distances to the tracers is very poorly known, which might be the source of the discrepancy. But that is not a simple argument because the thin disk scale height measured by Chen et al. (2001) is larger than that of the other two papers, but the thick disk scale height is considerably smaller. I wonder whether the disk model is not as complex as the data — a situation that as I show below has already been encountered in the Galactic spheroid.

3. Dwarf Galaxies

Of the 20 known or suspected dwarf galaxy satellites of the Milky Way, two are naked-eye objects (the Large and Small Magellanic Clouds), 17 have been discovered from their photometry, and only the Sagittarius dwarf galaxy from kinematics (Ibata et al. 1994). The most recent nine discoveries came from two recent photometric sky surveys: 2MASS and SDSS. The controversial Canis Major (or possibly Argo) dwarf galaxy (Martin et al. 2004; Rocha-Pinto et al. 2006), which is hidden in the Galactic plane, was discovered in 2MASS. Eight additional dwarfs have been discovered within the past year in SDSS data (Willman et al. 2005b; Zucker et al. 2006a; Belokurov et al. 2006b; Zucker et al. 2006b; Belokurov et al. 2006a). The SDSS dwarfs are all low surface brightness, and there are dozens of candidates waiting to be followed up. Milky Way satellites, which could be dwarf galaxies or star clusters (Willman et al. 2005a; Belokurov et al. 2006a), are detected in photometric surveys as a statistically significant excess of star counts at a two-dimensional location in the sky. Locality in distance is determined from a color-magnitude diagram such as Fig. 1, which shows the newest SDSS Milky Way satellite candidate. It is not known whether this latest

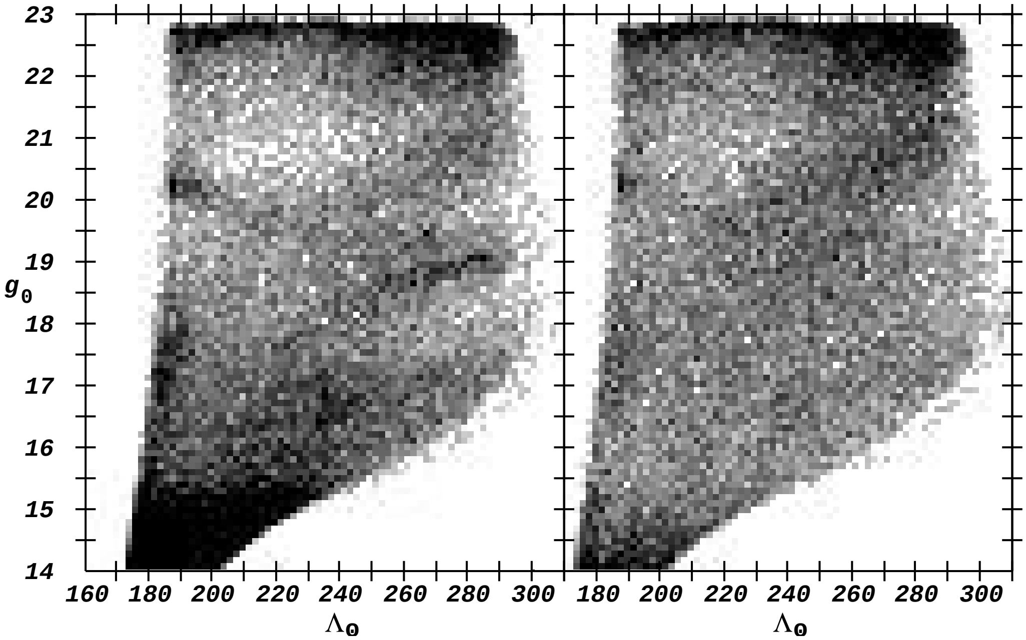

Fig. 2. g_0 magnitude vs. $\Lambda_\odot$ for BHB (left) and BS (right) stars within 15 kpc of the Sgr dwarf orbital plane. $\Lambda_\odot$ is the angle from the Sgr dwarf galaxy, measured from the Sun around the plane of its orbit, as defined in Majewski et al. (2003). The A stars were separated into blue horizontal branch (BHB) and blue straggler (BS) stars using the color separation defined by Fig. 10 of Yanny et al. (2000). This separation is not perfect, and in particular seems to break down at higher reddening near $\Lambda_\odot \sim 180°$. This area of the diagram has Galactic latitude $b < 30°$. The leading tidal tail is evident in BHB stars from $(g_0, \Lambda_\odot) = (19., 290°)$ and sloping down towards the center of the diagram. It is also evident in BS stars two magnitudes fainter. The trailing tidal tail is evident from $(g_0, \Lambda_\odot) = (20.3, 185^\odot)$ and sloping down towards the center of the diagram. There is a very large falloff in the trailing tail BHB number counts at $\Lambda = 195°$. Blue stragglers from the tidal stream in the plane of the Milky Way (Yanny et al. 2003) are seen in both panels at $(g_0, \Lambda_\odot) = (17.5, 185°)$. The confusion is probably due to the higher reddening in this direction. Stars brighter than about 15.5 magnitudes are saturated in the SDSS survey, and therefore have less accurate magnitudes. It is unclear whether the bright stars are BHB stars out to 10 kpc, or BS stars closer than 4 kpc. The latter seems more likely. The Virgo Stellar Stream covers a substantial section of towards the bottom of the BHB diagram, centered at $(g_0, \Lambda_\odot) = (16.5, 240°)$.

find is a star cluster or dwarf galaxy. As we probe objects with fainter surface brightnesses, it may be difficult to distinguish one from the other.

4. Tidal Debris

Although a decade ago it was known that there were stellar moving groups in the Milky Way spheroid (Majewski et al. 1994), no one knew whether tidal debris could be discovered spatially. Currently, at least 6 tidal debris streams that extend tens of degrees or more across the sky have been identified. Three are known or thought to be associated with dwarf galaxies (Ibata et al. 2001; Yanny et al. 2003; Grillmair 2006) and three are known or thought to be associated with globular clusters (Odenkirchen et al. 2003; Grillmair & Johnson 2006; Grillmair & Dionatos 2006). Five of these were discovered in the SDSS data by convolving a template color-magnitude density profile with the data. The Sgr dwarf tidal stream was also detected spatially with A star tracers from the SDSS (Yanny et al. 2000), but

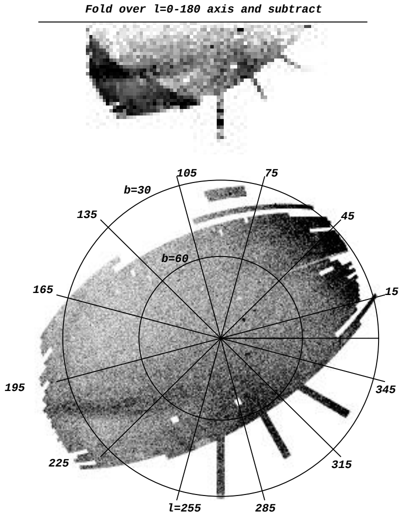

Fig. 3. F Star Polar Plot of North Galactic Cap. The bottom panel shows stars with $0.2 < (g - r)_0 < 0.3$ and $(u - g)_0 > 0.4$ in the magnitude range $20.0 < g_0 < 21.0$. Darker areas of the diagram contain more F stars. All of the magnitudes were corrected using the reddening map of Schlegel et al. (1998) before selection. At the center of the panel is the North Galactic Pole. Circles of constant Galactic latitude are marked, and the distance between concentric circles of constant Galactic latitude was stretched to preserve solid angle per pixel. The dark areas at low latitude and towards the Galactic center probably represent the smooth portion of the Galactic spheroid. The dark line from $(l, b) = (205°, 25°)$ to $(l, b) = (255°, 70°)$ is the leading tail of the Sgr tidal stream. The dark area centered at $(l, b) = (300°, 60°)$ is the Virgo Stellar Stream. The top panel shows a subtraction of the pixels on the top half of the polar diagram, which does not contain any obvious tidal debris, from the lower half, with the assumption that the star counts are symmetric about $l = 0°, 180°$. One sees in the subtracted diagram that the Virgo Stellar Stream peaks in this magnitude range at $(l, b) = (300°, 64°)$, and does not extend to lower Galactic latitudes.

the association of the overdensity with the Sgr dwarf galaxy was first done with carbon star tracers (Ibata et al. 2001). Later, the stream was traced all the way around the sky using stellar tracers from the SDSS and 2MASS (Newberg et al. 2003; Majewski et al. 2003).

Fig. 2 shows without a doubt that Galactic substructure can and has been discovered and traced with color-selected A stars. The dataset used to create the figure includes all of SDSS DR5, and a small additional sample from SDSS II that fills in the North Galactic Cap. Evident are the largest tidal streams known in the Galaxy. The figure also illustrates the difficulty of identifying the well-mixed component of the stellar spheroid. No photometric survey of a small portion of the sky could reliably measure spheroid shape or parameters. Even with full sky data, it is difficult to identify and avoid lumps that are many kiloparsecs across.

5. Spheroid Shape and the overdensity in Virgo

Recently, Newberg & Yanny (2005) showed, from plots of the stellar density of spheroid stars at constant Galactic latitude, that the spheroid is not axially symmetric. Newberg & Yanny (2006) fit a triaxial Hernquist profile to the spheroid stars. The reason that little more than conference proceedings describing this work have so far been published is that it has proven very difficult to show that the χ^2 fits are fitting only the smooth component, and are not being affected by unidentified lumps in the Galactic spheroid.

Fig. 2 shows in A-type stars an overdensity in the Virgo constellation. The overdensity in the Virgo constellation has been identified by previous authors (Vivas et al. 2001; Newberg et al. 2002; Duffau et al. 2006; Juric et al. 2005). It turns out that it also makes a large contribution to the asymmetry of the spheroid noticed by Newberg & Yanny (2005). Because it is difficult to avoid the Virgo overdensity and the Sagittarius overdensity, it is difficult to show conclusively that the spheroid is triaxial, even though all data subsets that we have tried converge to a similar spheroid shape and attempts have been made to avoid the overdensity in Virgo when fitting the smooth component of the spheroid.

From Fig. 3 and Fig. 4 we argue that the number density of the Virgo feature decreases towards the Galactic plane. The lower panel of Fig. 3 shows F stars from about 14 to 23 kpc from the Sun. Note the roughly circularly sym-

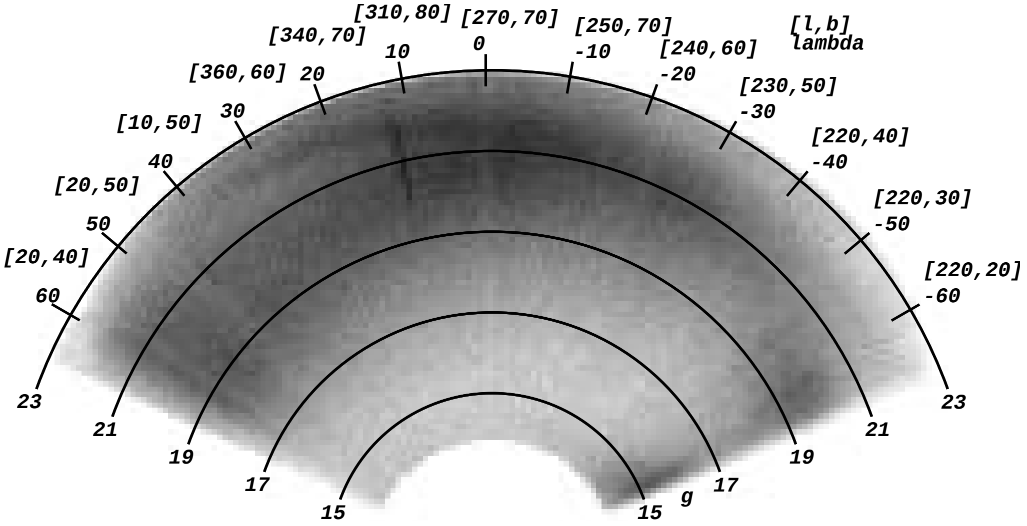

Fig. 4. Wedge plot of F turnoff stars from SDSS stripes 9-21 inclusive. Notice that the stars in the Virgo overdensity (top center, just below and crossed by the Sagittarius dwarf leading tidal tail, does not extend towards the Sun. The F stars in this plot come from the region of the sky between the Galactic pole and the end of the data at the bottom of Fig. 3. Data from the three ”outrigger” stripes of data extending along constant Galactic latitude at the bottom of the plot were not included. The g magnitudes of the F turnoff stars are plotted radially. The angle on the sky is given in SDSS survey λ, which is angle along the survey stripes, and is not related to Majewski's $\Lambda_\odot$, which is used in Fig. 2. The Galactic coordinates are only approximate, since the thickness of this data wedge is 30°.

metric Virgo overdensity near the bottom of the plot, and somewhat separated from the narrower Sagittarius dwarf tidal stream coming in from the left.

The top panel of Fig. 3 shows the residual after the top of the polar plot is subtracted from the bottom — the obvious way to trace the Virgo overdensity under the assumption that the spheroid is axially symmetric. Clearly, the density decreases towards lower Galactic latitudes, with a center at $(l, b) = (300°, 64°)$. Even if one does not assume the Galaxy is axially symmetric, number counts show the density decreasing towards lower Galactic latitudes along $l = 300°$.

Fig. 4 shows a wedge plot of F stars 31.3° thick that shows the Virgo overdensity localized in distance about 18 kpc from the Sun, assuming an average F star absolute magnitude of $M_g = 4.2$. Within the errors, this is roughly consistent with the knot of A-type stars in Fig. 2 at 14.5 kpc from the Sun, assuming an average A star absolute magnitude of $M_g = 0.7$. This is also consistent with the positions of the Virgo RR Lyrae stars studied by Duffau et al. (2006) using a combination of photometry and spectroscopy.

We also explore in Newberg et al. (2007), the possibility that the Virgo overdensity extends towards the Galactic center (to the left in Fig.4). However, the color of the turnoff is significantly redder for stars towards the Galactic center than it is towards the Virgo overdensity. The shift in turnoff color and the smooth, contiguous distribution of stars near the Galactic center suggest that Virgo Stellar Stream is at least not the dominant source of stars at any magnitude for survey $\lambda > 20°$.

Although we do not rule out lower density tails or an extended volume for the Virgo overdensity, there is a peak of the star distribution 14-20 kpc from the Sun in the direction $(l, b) = (300°, 64°)$. The overdensity does not appear to increase towards the Galactic plane down to 5 kpc from the Galactic plane as Juric et al. (2005) suggested it might.

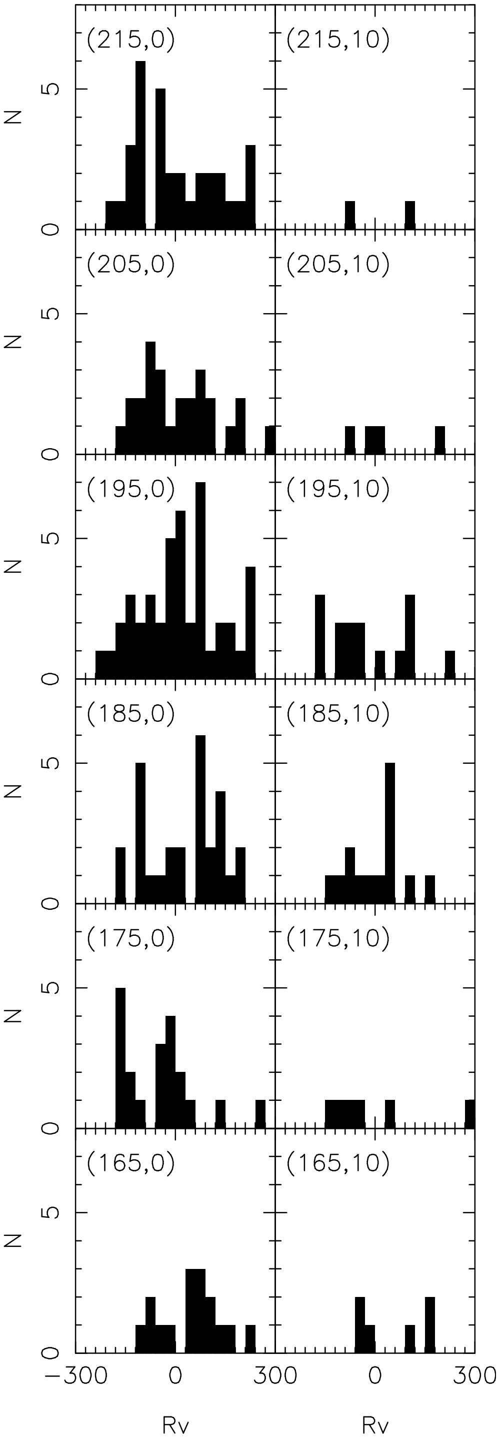

Fig. 5. GSR radial velocities of BHBs in 10° × 10° areas centered at labeled (RA,Dec).

From Fig. 2, the leading Sgr tidal debris, the trailing Sgr tidal debris, and the Virgo overdensity all conspire to be approximately in the same place. This point has been articulated in Majewski et al. (2003) and subsequent articles. But I think there exists in the Virgo overdensity a significant population of stars that is not associated with either tidal tail. The Duffau et al. (2006) velocities indicate a receding structure not likely to be part of the infalling leading tidal debris. In Newberg et al. (2007), we will show that the colors of the stars in the Virgo overdensity are redder than those in the Sagittarius leading tidal tail. The wide separation from the rest of the trailing debris makes it seem unlikely to be part of that structure. Besides, it looks like it has a center, unlike tidal tails.

And what of the velocities? Wouldn't it have been easier to find this structure through kinematics? Fig. 5 shows all of the BHB line-of-sight (GSR) velocities available from SDSS for color-selected BHB stars with $15.9 < g_0 < 17.8$ in the Virgo region, corrected to the local standard of rest. Since SDSS BHB spectra were obtained only when extra fibers were available, not all BHBs in these regions have spectra, and the number of spectra obtained may not be indicative of the number of BHBs in that area of the sky. The apparent magnitudes of the BHB stars were selected so that the stars are in the range from 11 to 26 kpc from the Sun. The coordinates in parentheses give the (RA,Dec) coordinates of the center of the 10° × 10° area of the sky from which the spectra were selected.

I do not know how to relate them to spheroid substructure. Certainly, they are not Gaussian. Probably, they represent stars from more than one Galactic component. Significant positive ($V_{gsr} \sim 60$ km/s) peaks are found near the center of the Virgo overdensity: (RA,Dec)= $(192°, 1°)$, also consistent with Duffau et al. (2006). There also seem to be significant negative velocity peaks in many places. Could some of these be associated with Sgr or other streams? One might ponder what line-of-sight GSR velocity distribution is expected for a tidally disrupted dwarf galaxy that extends over tens of degrees on the sky. Even if all of the stars were traveling in the same spatial direction, one might find wildly different line-of-sight velocities just from projection effects. The radial velocities on the one hand overwhelm us with information and on the other hand leave us in desperate need of more data.

6. Conclusion

Photometric surveys are currently our most effective tool for understanding the big picture in Galactic structure. They are the most successful method for finding dwarf galaxies, the most successful method for identifying tidal debris, and, well okay no method has yet been very successful in understanding the smooth component of the Galactic spheroid.

In this paper, I showed how we can isolate the Virgo overdensity using photometry from the SDSS. This process outlines the important methods we have for identifying Galactic structure through photometry. It is important to isolate similar objects that can be used as tracers: BHBs, RR Lyraes, F turnoff stars that are bluer than the thick disk, K giants and M giants are all populations that have been very successful for studying the stellar spheroid. These are all populations that are bright enough to be seen to great distances in the Milky Way halo and can be photometrically separated from the more numerous disk stars in the solar neighborhood. Studies of disk populations can rely on the fact that they are much more numerous, but might benefit from photometric separation of populations by metallicity.

Using stellar tracers, Galactic components can be separated by density, and to some extent by stellar population. Density contrast identifies the unrelaxed components of the Galaxy (those that have not yet been well mixed), and traces the outline of those populations that are well mixed.

To be most effective for Galactic astronomy, the photometric survey should be in at least three filters with precision color information, cover a large contiguous area of the sky, and probe the entire depth of the Galaxy. The precision color information is required to select stellar tracers. The large volume is required to understand the big picture. Gone are the days when astronomers could blithely assume that the Galactic components are smooth, or axially symmetric, or fit a simple power law or exponential profile. Preferably, main sequence stars, which are more numerous and therefore allow greater spatial resolution than brighter types of stars, could be cataloged to the edge of the Galaxy. Currently, the most urgent need for publicly available, high quality photometric data is in the southern hemisphere and at low Galactic latitude. Since we have detected star streams to the edge of the SDSS, even using our brightest, furthest stellar tracers, it stands to reason that a deeper survey would be useful. Photometry comes first. So we can understand the big picture. And spectroscopy is our future. We need not just a few radial velocities, but millions. We need not just one or two velocity components, but all three. We need spectral information about the stellar populations to better understand the photometry. In the end, the reviewer is right. The best way to detect the effects of merger streams in the data *is* to obtain kinematics of these stars and show that they occupy a relatively narrow part of the energy/angular momentum space.

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