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Galactic Halo substructure in the Sloan Digital Sky Survey: the ancient tidal stream from the Sagittarius dwarf galaxy

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ABSTRACT

Two studies have recently reported the discovery of pronounced Halo substructure in the Sloan Digital Sky Survey (SDSS) commissioning data. Here we show that this Halo substructure is almost in its entirety due to the expected tidal stream torn off the Sagittarius dwarf galaxy during the course of its many close encounters with the Milky Way. This interpretation makes strong predictions on the kinematics and distances of these stream stars. Comparison of the structure in old horizontal branch stars, detected by the SDSS team, with the carbon star structure discovered in our own survey, indicates that this halo stream is of comparable age to the Milky Way. It would appear that the Milky Way and the Sagittarius dwarf galaxy have been a strongly interacting system for most of their existence. Once complete, the SDSS will provide a unique dataset with which to constrain the dynamical evolution of the Sagittarius dwarf galaxy, it will also strongly constrain the mass distribution of the outer Milky Way.

Subject headings: halo — Galaxy: structure — Galaxy: halo — Galaxy: Local Group — galaxies: kinematics and dynamics — galaxies: individual (Sagittarius dwarf galaxy) — galaxies

1. Introduction

In the standard hierarchical picture of galaxy formation, galaxies like the Milky Way grew by repeated mergers with other galaxies, and in particular with many smaller galaxy "fragments". In the outer regions of galactic halos, disruption timescales can be long, and we can hope to observe galaxy remnants as well as to catch galaxies in the process of being accreted. That this accretion is still an on-going process is clear, as evidenced by the many studies of tidal features in the dwarf satellite galaxies and globular clusters.

However, what is of prime interest is to compare the observed structures to the results of galaxy formation theories. These now make strong predictions about the structure and substructure of galaxy halos. Indeed the standard cold dark matter models appear to be inconsistent with observational constraints, as they over-predict halo clumpiness (see, e.g., Moore et. al 1999).

In an attempt to constrain such theories, several groups have undertaken large scale surveys to uncover substructure in the halo. These include, among others, the "spaghetti" survey (Morrison et al. 2000), the APM carbon star survey (Totten & Irwin 1998; Totten, Irwin & Whitelock 2000; Ibata et al. 2000), and the SDSS survey (Yanny et al. 2000; Ivezić et al. 2000).

The APM carbon star survey, an almost all high-latitude sky survey, revealed the existence of a gigantic band of these intermediate age ($\sim$ 6 Gyr) stars around the sky (Ibata et al. 2000; hereafter paper 1). [4] Approximately half of the

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[4] Extant optical and NIR photometry and detailed optical spectroscopy of the APM colour-selected cool Halo carbon stars show that these stars are identical in nature to those found in AGB populations in other Local Group galaxies, particularly the Magellanic Clouds and many of the dwarf spheroidal Galactic satellites (Totten & Irwin 1998; Totten, Irwin & Whitelock 2000). Furthermore the central part of Sgr has a known AGB carbon star population (Whitelock, Irwin & Catchpole 1996) that also has NIR and opti-

"Halo" carbon stars detected in this survey are located in this ten degree wide band, which is centered on the expected orbit of the Sagittarius dwarf galaxy in a spherical Halo potential (paper 1). Sagittarius, the closest dwarf satellite galaxy to the Milky Way (Ibata, Gilmore & Irwin 1994), is clearly in the process of being tidally torn apart. As shown in paper 1, those carbon stars trace a gigantic tidal stream of debris disrupted off the Sagittarius dwarf galaxy which has now wrapped itself around the Halo. Interestingly, this stream is observed to follow a great circle on the sky, which means that it is probably a coplanar rosette-shaped structure that we observe from within (since it should trace relatively closely the orbit of the center of mass of the dwarf galaxy). Most importantly, however, the fact that the stream is confined to a plane, implies that it does not suffer significant precession, which is only possible if the Galactic halo potential is not significantly oblate.

Two SDSS teams have recently presented results from their first year's commissioning data (Yanny et al. 2000; Ivezić et al. 2000). Due to initial technical constraints, the drift-scanning camera took data only on the celestial equator during the commissioning period. Their data consists of two wedges: a NGC sample 87° long and a SGC sample 60° long, with each covering a declination range of only $-1.25° \lesssim \delta \lesssim 1.25°$. Despite the fact that their data provide essentially a two dimensional slice through the Galaxy, they find astonishing sub-structure in the distribution of A-stars. Sharply-defined concentric rings of stars are detected. The number of RR-lyrae variables also cuts off sharply at 50 kpc. The nature of these structures is important, as they are the dominant structure seen in old Halo stars, comprising approximately half of the total number of Halo stars seen in the survey. In this contribution, we show that these A-star Halo sub-structures are morphologically very similar to the expected structure of the tidal debris of the Sagittarius dwarf galaxy, are at similar distances and are highly likely to be part of the Sagittarius stream.

At first sight it may seem surprising that such a limited survey can detect Halo sub-structure. However, since most long-lived Galactic satellite systems appear to be on close to polar orbits the chances of a stellar debris stream intersecting the current SDSS zero-declination survey strips is ≈50%. The Sagittarius stellar stream is currently the only known large relatively intact debris system and is within 13° of a polar orbit.

2. The expected debris of the Sagittarius dwarf galaxy

In paper 1, we undertook a large suite of numerical simulations of the interaction between the Sagittarius dwarf galaxy and the Milky Way, in order to determine how the APM carbon star sample constrains the shape of the Galactic halo. Figure 1 shows a typical high resolution simulation with 10^5 particles, at the end of the integration, at $T = 12\,\mathrm{Gyr}$ (details of these simulations are given in paper 1). For this particular simulation, the initial structure of the dwarf galaxy is a fluffy King model with mass $10^8\,\mathrm{M}_\odot$, half-mass radius of $r_{1/2} = 0.5\,\mathrm{kpc}$ and initial concentration $c = 0.5$. The Milky Way model (termed model H1 in paper 1) has a bulge, a thin disk, a thick disk and an interstellar medium, with parameters identical to the Dehnen & Binney (1998) model 2; the Galactic halo has a flat rotation curve, with a constant density core of radius $r_0 = 3\,\mathrm{kpc}$, and an oblate spheroidal density structure, with density flattening of $q_m = 0.9$. The total mass of the Galaxy model is such that the circular velocity at 50 kpc is $v_c = 220\,\mathrm{km\,s^{-1}}$.

After accounting for a $\sim 50\%$ "background" from other accretion events, such simulations can give a reasonable representation of the observed carbon star distribution, both in spatial position and in kinematics (*cf.* paper 1). The Aitoff projection of this simulation onto the sky (Figure 1), shows that the majority of the particles in this model are clustered close to a very obvious great circle stream. However, the potential is not quite spherical, so orbits suffer some precession. The material first stripped from the dwarf galaxy has had longest to drift away from its progenitor, and so also experiences the largest dif-

cal properties indistinguishable from the APM Halo sample. Normal AGB carbon stars are carbon-enriched during dredge-ups driven by helium burning thermal pulses during the post main sequence phase of 1-2 solar mass stars. As such they are thought to be $> 1-2$ Gyrs old but less than 10 Gyrs old (see e.g. the reviews by Da Costa 1997 and also Azzopardi & Lequeux 1992).

ference in precession. The particles not on the great stream are those that were stripped from the dwarf galaxy at earlier times; indeed, the precession away from the great circle stream effectively provides a chronometer of the time since particles were disrupted from their parent galaxy.

To compare the simulation of Figure 1 to the SDSS commissioning run data, we take a 2.5° equatorial cut though the simulation. As discussed by Yanny et al. (2000) and Ivezić et al. (2000), there may be some mixture of blue star populations in their dataset, however, for simplicity, we assume that they are all blue horizontal branch stars with absolute magnitude $M_{g^\star} = 1.0$. The resulting distribution of these equatorial stars as a function of right ascension and apparent $g^\star$ magnitude is displayed in Figure 2. The resemblance of this distribution with that found by Yanny et al. (2000) (their Figures 3 and 11) is striking. This simulation (which preceded the SDSS result) predicts the azimuthal rings seen by the Sloan Survey. Figure 3 is identical to Figure 2, but the simulation it is derived from was undertaken in a more flattened halo, with $q_m = 0.5$. The sharp ring features seen in Figure 2 and in the SDSS dataset are smeared-out in Figure 3. A spherical Halo ($q_m = 1.0$) gives rise to a slower precession rate (there is still some precession due to the modelled disk component), so a smaller fraction of particles wander off the great circle stream. Unfortunately, we cannot be quantitative in our comparisons to the models without a published list of SDSS A-stars.

The color-coding of Figures 2 and 3 indicates the time elapsed since the particles left the tidal radius of their progenitor. In Figure 2, the tight clumps seen near 2 hours and 14 hours are due to recently disrupted material, which can be composed of young as well as old stars. This is consistent with the detection of a clump of carbon stars in these regions (paper 1). The particles that were disrupted long ago, displayed here in yellow and red, have had many Gyrs to precess away from the great circle stream. The only remaining visible tracers of this material will be old stars, such as RRLyrae variables. This model suggests that the ancient disruption and star-formation history of the Sagittarius dwarf may be traced and analysed with the population of RRLyrae variables first detected by SDSS. In the main body of the Sagittarius dwarf galaxy, blue horizontal branch stars make up a much higher fraction of the total stellar population in its globular clusters than in its field stars (Layden & Sarajedini 2000). The fact that the older parts of its tidal stream display apparently high concentrations of RRLyrae stars suggests a common origin with the Sagittarius dwarf's globular clusters (though this may just reflect continual star-formation in the dwarf galaxy).

Our simulations make strong predictions. First, the radial velocity of the A-stars should vary smoothly as a function of right ascension, as displayed on the top panel of Figure 1. The radial velocity dispersion of these stars in a small range in right ascension should be small also, $\sim 20\,\mathrm{km\,s^{-1}}$, except in regions where multiple streams cross each other, at $\alpha \sim 2$ hours and $\alpha \sim 14$ hours. Furthermore, the majority of the A-stars should have similar radial velocities to those of the carbon stars in the 2 hour and 14 hour regions of paper 1. On the equatorial plane of the sky (where the extant SDSS data lie) at $\alpha \sim 2$ hours, the velocity distribution should be bimodal, with two clumps at Heliocentric radial velocity of $v \sim +200\,\mathrm{km\,s^{-1}}$ and $v \sim -150\,\mathrm{km\,s^{-1}}$. Further along the equatorial plane at $\alpha \sim 14$ hours the mean Heliocentric velocity of the stream stars should be $\sim 50\,\mathrm{km\,s^{-1}}$, with significant dispersion of $\sigma \sim 60\,\mathrm{km\,s^{-1}}$. Secondly, the distances of the A-stars, and RR-lyraes, should also closely follow the range of distances found from the C-star studies. In particular, an upper cutoff of $\approx$50 kpc in the RR-lyrae distances is exactly what is seen in the C-star distribution.

3. Conclusions

We have shown that numerical simulations of the dynamical evolution of the Sagittarius dwarf galaxy, previously reported in paper 1, predict the presence of sharp shell-like features in the Galactic halo. This shell-like structure is due to the effect of orbital precession acting on stars which were disrupted from the Sagittarius dwarf galaxy many billion years ago. Making a cut through our simulated dataset along the equatorial plane of the sky, we find a distribution very similar to that found in A-stars in the SDSS data (Yanny et al. 2000; Ivezić et al. 2000).

The A-stars furthest away from the dominant stream detected in paper 1, belong to those popu-

lations that were first disrupted from the dwarf galaxy. By comparing the relative densities of young to old stars in these tidal structures, it may be possible to reconstruct the dynamical evolution of the Sagittarius dwarf galaxy stream in great detail (Johnston et al. 1999).

The SDSS data that will soon become available along other scan-lines on the sky offer the very useful opportunity to distinguish between the different dynamical models of the Sagittarius dwarf galaxy. Such data will also allow us to distinguish competing models for the mass distribution of the dark halo. For instance, a comparison of the particle distributions of Figures 2 and 3, shows that the enhanced stream precession in the flattened halo of Figure 3 gives rise to a substantial density between $270^\circ < \alpha < 0^\circ$, which is not seen in Figure 2. Data in that right ascension range will provide a means to further constrain the shape of the Galactic halo.

With the almost all high-latitude sky coverage of the APM carbon star survey, only two Halo streams were found (the other probably being due to the Large Magellanic Cloud). Given that SDSS has also intersected the tidal stream from the Sagittarius dwarf galaxy, this stream appears to be by far the dominant contributor to Halo substructure at Galactocentric distances less than ~ 50 kpc. It seems unlikely, therefore, that any more accreted systems of such magnitude will be found by SDSS or other surveys. However, there is hope to discover the much smaller accreted galaxy fragments, if they exist.

The simulation result of Figure 1, has a cautionary tale to tell about using starcounts to determine the shape of the "Halo". That a substantial fraction of the outer Galactic halo stars appear to be clumped on an inclined band on the sky clearly does not mean that the Halo is a thin inclined flattened band! Such structures just tell a complicated story about the process of stellar accretion into the Halo. Since stars only contribute a miniscule amount to the total halo mass, the only way to reveal the dark matter distribution is through dynamical analyses. For this purpose, the dynamically cold streams discussed in this paper are ideal.

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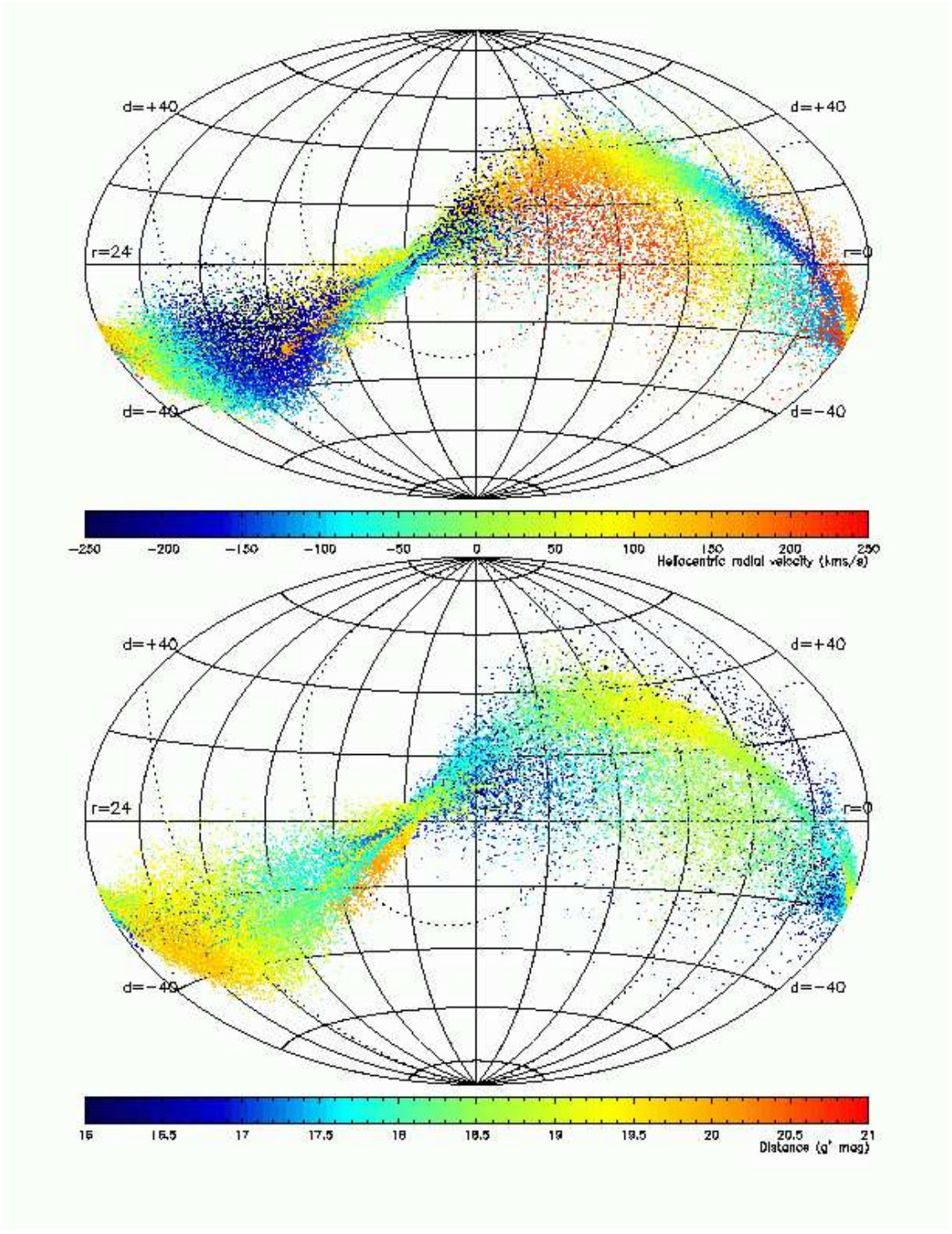
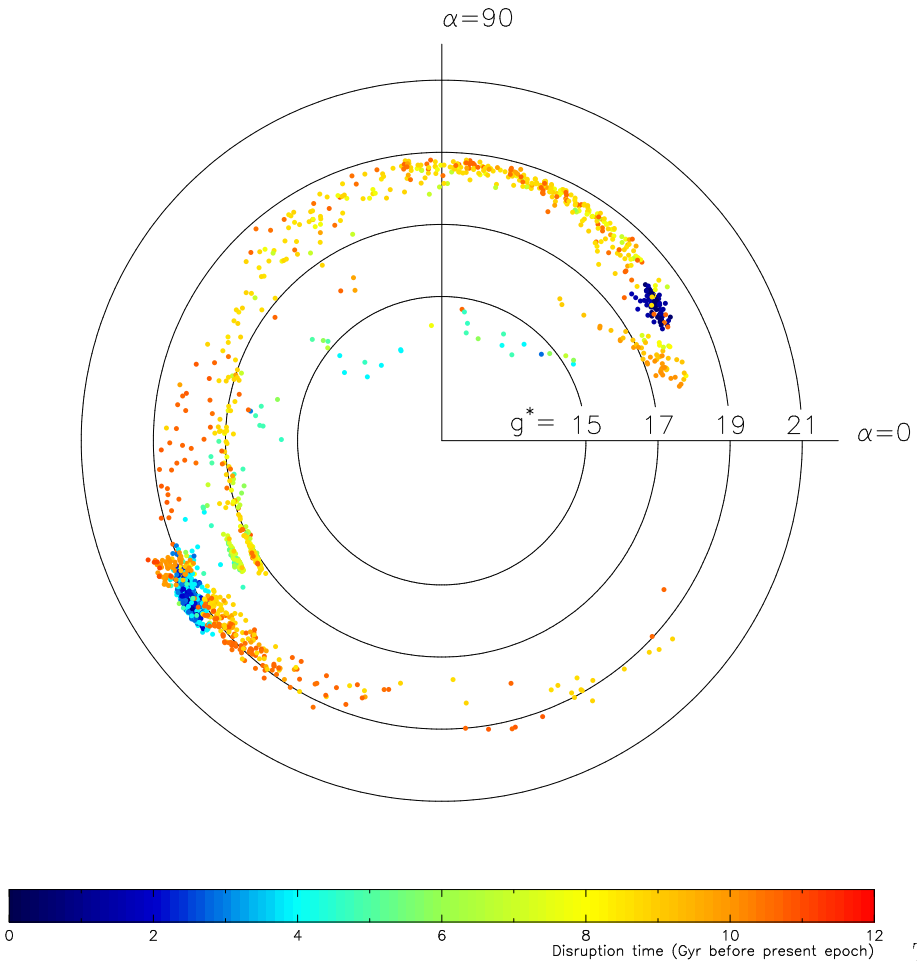
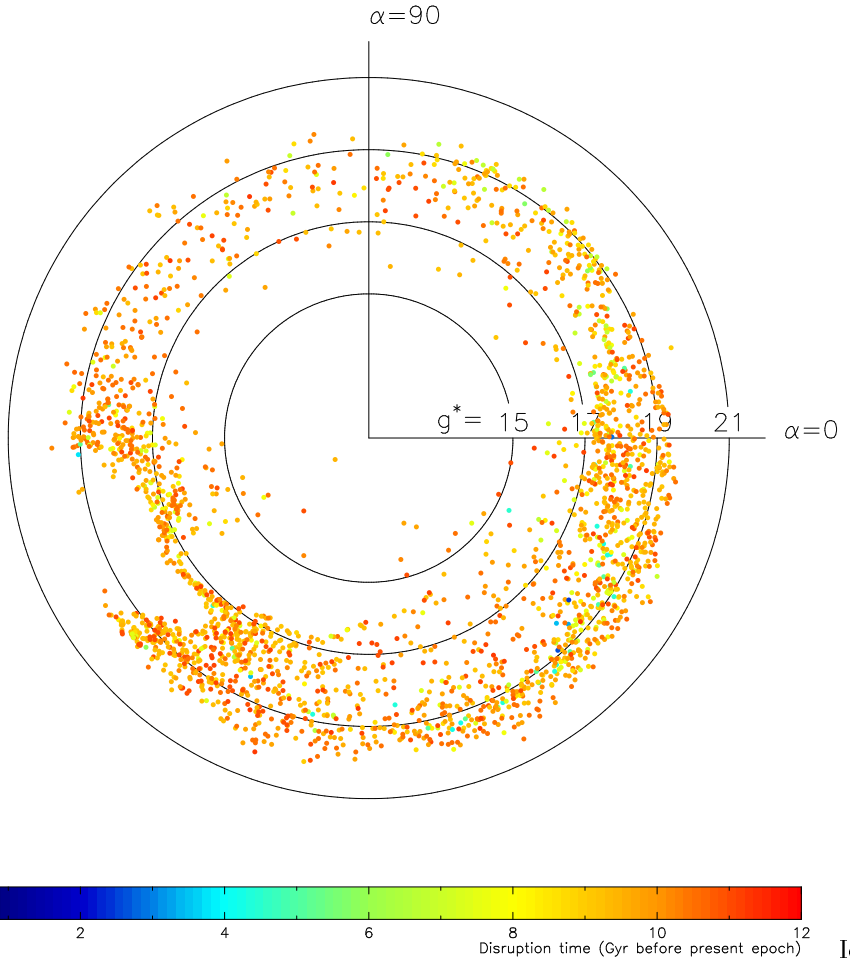


Fig. 1.— The end-state of the simulation (at $T = 12\,\mathrm{Gyr}$) of the dwarf galaxy model D1 (originally containing 10^5 particles) in the Galactic potential model H1 with $v_c = 220\,\mathrm{km\,s^{-1}}$, and $q_m = 0.9$ is shown. The upper panel displays color-coded Heliocentric radial velocities, while the bottom panel shows the stellar distances, color-coded as a function of $g^\star$ apparent magnitude. Though the distribution of the majority of the debris follows approximately a Great Circle on the sky, a significant amount of material is also precessed away from the Great Circle stream. The SDSS commissioning run dataset is confined to $\pm 1.25°$ of the equatorial plane in two stripes at $23.5^h < RA < 3.5^h$ and $9.7^h < RA < 15.5^h$. The model predicts a high density of stream stars in the SDSS dataset at two regions at right ascension of ~ 2 hours and ~ 14 hours. This is where the A-colored star clumps are found in the SDSS dataset.



The diagram shows a 2.5 degree wide slice through the (celestial) equatorial plane of the simulation displayed in Figure 1, which was evolved in a Galactic potential with an almost spherical halo (mass flattening $q_m = 0.9$). The color of the particles marks the time since they were ejected beyond the tidal limit of the dwarf galaxy progenitor. The similarity of this distribution to the data of Yanny et al. (2000) (their Figures 3 and 11) is striking. In this model, the azimuthal ring-like features are produced by material that was disrupted off the Sagittarius dwarf galaxy at early times, and which has had a long time to precess in the Galactic potential.



Identical to Figure 2, except that the data is derived from a simulation in a $q_m = 0.5$ flattened halo. Note the marked difference to Figure 2, especially in the right ascension range $270° < \alpha < 0°$. Further SDSS data in that region will greatly help the discrimination of competing models of the dynamical evolution of the Sagittarius dwarf galaxy, and of the structure of the outer Halo. The hole in the particle distribution near 210° is due to the structure of the tube orbits populated by the particles (see Figure 10 of paper 1).