THE NORTHERN WRAPS OF THE SAGITTARIUS STREAM AS TRACED BY RED CLUMP STARS: DISTANCES, INTRINSIC WIDTHS, AND STELLAR DENSITIES

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ABSTRACT

We trace the tidal Stream of the Sagittarius dwarf spheroidal galaxy (Sgr dSph) using Red Clump (RC) stars from the catalog of the Sloan Digital Sky Survey—Data Release 6, in the range 150° ≤ R.A. ≤ 220°, corresponding to the range of orbital azimuth 220° ≤ Λ ≤ 290°. Substructures along the line of sight (los) are identified as significant peaks in the differential star count profiles (SCPs) of candidate RC stars. A proper modeling of the SCPs allows us to obtain (1) ≤ 10% accurate, purely differential distances with respect to the main body of Sgr, (2) estimates of the FWHM along the los, and (3) estimates of the local density, for each detected substructure. In the range 255° ≤ Λ ≤ 290° we cleanly and continuously trace various coherent structures that can be ascribed to the Stream, in particular: the well-known northern portion of the leading arm, running from d ≃ 43 kpc at Λ ≃ 290° to d ≃ 30 kpc at Λ ≃ 255°, and a more nearby coherent series of detections lying at a constant distance d ≃ 25 kpc, that can be identified with a wrap of the trailing arm. The latter structure, predicted by several models of the disruption of Sgr dSph, was never traced before; comparison with existing models indicates that the difference in distance between these portions of the leading and trailing arms may provide a powerful tool to discriminate between theoretical models assuming different shapes of the Galactic potential. A further, more distant wrap in the same portion of the sky is detected only along a couple of los. For Λ ≲ 255° the detected structures are more complex and less easily interpreted. We are confident of being able to trace the continuation of the leading arm down to Λ ≃ 220° and d ≃ 20 kpc; the trailing arm is seen up to Λ ≃ 240° where it is replaced by more distant structures. Possible detections of more nearby wraps and of the Virgo Stellar Stream are also discussed. These measured properties provide a coherent set of observational constraints for the next generation of theoretical models of the disruption of Sgr.

Key words: galaxies: dwarf – Galaxy: formation – Galaxy: structure – Local Group – stars: distances

Online-only material: color figures

1. INTRODUCTION

Stellar tidal streams as well as other substructures in the Milky Way (MW) halo are generally interpreted as the relics of the process of hierarchical formation of the MW, as envisaged by the currently accepted cosmological model (Λ-Cold Dark Matter, hereafter; see Bullock et al. 2001, Madau et al. 2008, and references therein). With the advent of large modern surveys, such as the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) and the Sloan Digital Sky Survey (SDSS; Adelman-McCarthy et al. 2008, and references therein), our ability to detect stellar systems and/or structures in the halo and in the disk of the MW has increased dramatically and several large-scale likely relics of the build-up of the Galactic halo have been identified (Ibata et al. 2001a; Newberg et al. 2002; Yanny et al. 2003; Majewski et al. 2003; Martin et al. 2004; Belokurov et al. 2006; Jurić et al. 2008). Also smaller tidal streams have been found around disrupting globular clusters (see, for example, Rockosi et al. 2002, Grillmair & Johnson 2006) or lacking an evident progenitor (Grillmair & Dionatos 2006; Belokurov et al. 2006, hereafter Bel06). The most spectacular example of the process of tidal disruption and accretion of a dwarf satellite into our Galaxy is the Sagittarius dwarf spheroidal galaxy (Sgr dSph), originally discovered by Ibata et al. (1994). The main body of the Sgr galaxy is located at ∼26 kpc (Monaco et al. 2004) from the Sun, beyond the Galactic bulge (Galactic coordinates l, b = +5.6, −14.0). The stellar content of the Sgr dSph is dominated by an intermediate-age relatively metal-rich population, with distributions peaking at age ~6–8 Gyr and [Fe/H] ∼ −0.5 (see Bellazzini et al. 2006a, hereafter B06a, and references therein) but there is also clear evidence for the presence of an older (~10 Gyr) and more metal-poor population as well, including blue horizontal branch (BHB; Ibata et al. 1997; Bellazzini et al. 1999a; Monaco et al. 2003) and RR Lyrae stars (Mateo et al. 1995a; Alcock et al. 1997; Cseresnjes 2001). All the available spectroscopic analyses indicate that the metallicity distribution of Sgr stars is characterized by a broad peak in the range −1.0 ≤ [Fe/H] ≤ 0.0, with a weak tail likely extending beyond [Fe/H] ≤ −2.0 (see B06a; Cseresnjes 2001; Monaco et al. 2005a; Mc William & Smecker-Hane 2006; Bonifacio et al. 2006; Sbordone et al. 2007; Bellazzini et al. 2008; Lagadec et al. 2009).

The body of Sgr dSph appears tidally disturbed (Ibata et al. 1995), and, soon after its discovery, it was realized that there was some tidal debris surrounding the galaxy (Mateo et al. 1996; Fahlman et al. 1996; Alard 1996; Ibata et al. 1997; Majewski et al. 1999). Indeed, it has been subsequently established that there are two huge tidal tails emanating from the edges of the galaxy and approximately tracing its orbital path, as expected from N-body simulations (Johnston et al. 1995; Ibata & Lewis 1998). These tails form a coherent and dynamically cold filamentary structure (hereafter Sgr Stream) that extends for tens of kiloparsecs from the parent galaxy and has been probed with many different tracers. Yanny et al. (2000) used SDSS first-year
different models can be found also in de Jong et al. (2009), Prior et al. (2009b), and Keller et al. (2009).

Bellazzini et al. (2006c, hereafter B06c) demonstrated that yet another kind of tracer can efficiently be used to study the Sgr Stream, i.e., core-He-burning stars lying in the well-populated Red Clump (RC) of the CMD of Sgr dSph. In particular, we showed that it is possible to detect the RC associated with a given sub-structure as a peak in the differential star count profiles (SCPs) of sub-samples of stars selected in a relatively narrow color range including the RC. The spatially localized RC population can be disentangled from the fore-/background contaminating population of the MW by subtracting the underlying SCP, that is, in general, quite smooth and smoothly varying with position in the sky. In B06c, we used this technique to compare the horizontal branch (HB) morphology in the Stream and in the main body of Sgr, finding an age/metallicity gradient along the Sgr remnant (see also Monaco et al. 2007; Chou et al. 2007), while in Correnti et al. (2009), we obtained an independent detection of the recently discovered stellar system Boötes III (Grillmair 2009; Carlin et al. 2009), providing new insight on its nature, structure, and stellar populations. Carrell & Wilhelm (2010) recently presented the results of a spectroscopic survey targeting RC stars in the Sgr Stream, selected as in B06c.

The most natural and direct application of this technique is the determination of accurate distance estimates from the magnitude of detected RC peaks, as the RC is well known and widely used as a standard candle since long time (see Paczynski & Stanek 1998; Stanek & Garnavich 1998; Girardi & Salaris 2001; Babusiaux & Gilmore 2005; Bellazzini et al. 2006b, and references therein). For intermediate/old-age populations, the luminosity of the RC peak shows relatively modest variations as a function of age and metallicity, in particular when measured in the reddest optical passband (as Cousins’ I; see Girardi & Salaris 2001). When used differentially, i.e., looking at the same (or very similar) stellar population in different places, the variations in the intrinsic luminosity of the RC due to age/metallicity effects should vanish. Given also the intrinsic narrowness of the feature in Sgr (see below), the RC seems the ideal tool to accurately trace the run of the distance along the orbital azimuth of the Sgr Stream, from the main body of the galaxy all over the portion of the Stream sampled by the SDSS. The other large survey covering all the extent of the Stream, 2MASS, cannot be used in this way as the associated photometry is not sufficiently deep to reach the RC level.

In this paper, we will use the RC SCP method outlined above to take accurate purely differential measures of the distance of the Northern arms of the Sgr Stream with respect to the main body of the galaxy. This will provide strong constraints for the models of the disruption of Sgr within the Galactic (dark) halo, and, in turn on the physical properties of the dark halo itself (Ibata et al. 2001b; Helmi 2004; Johnston et al. 2005).

The basic idea is the following: (1) we measure the position of the RC peaks in V and I, with independent color selections using $B-V$ and $V-I$ colors, in the main body of Sgr (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3) we transform (from B06a photometry), (2) we select SDSS fields projected onto the Sgr Stream as traced by Bel06, (3)
differences in distance modulus, that is, differences in distance. The whole set of differential distances can be translated into a set of absolute distances by adopting the preferred value of the distance modulus for the main body (see, for example, Alard 1996; Layden & Sarajedini 2000; Monaco et al. 2004; Kunder et al. 2009). The detection of the same peaks in both V and I SCPs provides a useful sanity check on the interpretation of the SCPs and on the derived differential distances. As an additional observational constraint to models of the disruption of Sgr, we also provide an estimate of the characteristic width of the Stream section crossed by our fields (see Section 3.5).

The plan of the paper is as follows. In Section 2, we present the field of the main body that we used as a template and the fields of the Stream used for/in the analysis. In Section 3, we describe the method used to analyze the SCPs and derive the information from the peaks. In Section 4, we present all the SCPs obtained from each field and we discuss some special cases. In Section 5, we compare our results with previous works in the literature, with particular emphasis on the different degree of uncertainty related to the distance estimates. In Section 6, we compare our distance estimates with models that reproduce the three-dimensional shape of the Stream. Finally, we summarize and discuss our results in Section 7.

Some preliminary reports on earlier phases of this project were presented in Correnti et al. (2007, 2008).

2. DATA AND OBSERVABLES

As a reference sample for the stellar population in the core of Sgr we take the photometry of a 1° × 1° wide field located ~2° eastward of the galaxy center at (l, b) ≃ (6°.5, −16°.5), presented in B06a and named Sgr34. This should be considered as fairly representative of the average population of the Sgr galaxy (see Bellazzini et al. 1999a, 1999b; Giulio set al. 2010), avoiding the youngest and most metal-rich populations that appear to reside in the central nucleus (Siegel et al. 2007; Bellazzini et al. 2008). The strong similarity between the population of the Sgr main body and the Stream has been shown by Newberg et al. (2002) and Bel06, by direct comparison of CMDs. To sample the Galactic population at similar angular distance from the Galactic Center as for Sgr34 we used the same control field (CF) also presented in B06a: a 0.5° × 0.5° field, named Gal_Field, at (l, b) ≃ (−6°/0, −14°.5), that was used in B06a to perform the statistical decontamination of the Sgr34 CMD from the foreground/background Galactic stars. Following B06a, we adopted the average reddening values ⟨E(B − V)⟩ = 0.116 for Sgr34 and ⟨E(B − V)⟩ = 0.096 for Gal_Field, as derived from the reddening maps of Schlegel et al. (1998, hereafter SFD98).

To study the Stream, we used the SDSS-DR6 photometry of objects classified as stars (extracted from the SDSS CasJobs query system; Adelman-Mccarthy et al. 2008) for a series of selected fields along the branches A and B, listed in Table 1 and plotted in Figure 1. We chose to follow the two branches separately with non-overlapping fields. These on-Stream fields

| Field | α | δ | l° | b° | ⟨E(B − V)⟩ | σ | αc | δc | l°c | b°c | ⟨E(B − V)c⟩ | σc |
|-------|---|---|----|----|-------------|---|-----|----|-----|----|-------------|---|
| 1A    | 215| 1 | 346| 56 | 0.038       | 0.007 | 226 | 15 | 14  | 56 | 0.034       | 0.009 |
| 2A    | 210| 2 | 339| 60 | 0.033       | 0.006 | 223 | 17 | 21  | 60 | 0.030       | 0.008 |
| 3A    | 205| 3 | 331| 63 | 0.026       | 0.003 | 222 | 29 | 29  | 63 | 0.034       | 0.008 |
| 4A    | 200| 4 | 320| 66 | 0.029       | 0.004 | 220 | 40 | 40  | 66 | 0.024       | 0.010 |
| 5A    | 195| 7 | 309| 70 | 0.031       | 0.005 | 215 | 31.5| 51  | 70 | 0.015       | 0.004 |
| 6A    | 190| 9.5| 296| 72 | 0.024       | 0.006 | 211.5| 35 | 64  | 72 | 0.013       | 0.004 |
| 7A    | 185| 11| 277| 72 | 0.027       | 0.007 | 208 | 43 | 83  | 72 | 0.010       | 0.004 |
| 8A    | 180| 13| 260| 71.5| 0.030      | 0.006 | 202.5| 43.5| 100 | 71.5| 0.014       | 0.006 |
| 9A    | 175| 13.75| 248| 68.5| 0.037      | 0.007 | 199 | 48 | 112 | 68.5| 0.014       | 0.005 |
| 10A   | 170| 15| 238| 65.5| 0.024      | 0.006 | 193.5| 51.5| 122 | 65.5| 0.014       | 0.003 |
| 11A   | 165| 16| 230.5| 62| 0.022      | 0.005 | 187.5| 55 | 129.5| 62 | 0.015       | 0.004 |
| 12A   | 160| 17| 224.5| 58| 0.030      | 0.006 | 180.5| 58 | 135.5| 58 | 0.017       | 0.007 |
| 13A   | 155| 17.75| 220| 54| 0.031      | 0.007 | 172.5| 60 | 140 | 54 | 0.014       | 0.007 |
| 14A   | 150| 18.5| 216| 50| 0.030      | 0.004 | 163.5| 62 | 144 | 50 | 0.011       | 0.006 |
| 15A   | 145| 19| 213| 45.5| 0.030      | 0.006 | 153 | 63 | 147 | 45.5| 0.017       | 0.016 |

Note. a ⟨E(B − V)⟩ is the mean reddening of the field as extracted from Schlegel et al. (1998) maps and averaged over all the stars in the field and σ is the corresponding standard deviation. The subscript c refers to CFs.
We excluded from the adopted sample all the stars within different fields of the same branch. For each on-Stream field (located, for example, at \((l, b) = (l_0, b_0)\)) we also selected a corresponding CF located at the same latitude and at the same angular distance from the Galactic Center on the other side of the Galaxy (i.e., having \((l, b) = (360^\circ - l_0, b_0)\)). Assuming that the MW is symmetric about its center and its disk mid-plane \((l, b) = (0, b)\), to avoid overlap between different fields of the same branch. For each on-Stream field (located, for example, at \((l, b) = (l_0, b_0)\)) we also selected a corresponding CF located at the same latitude and at the same angular distance from the Galactic Center on the other side of the Galaxy (i.e., having \((l, b) = (360^\circ - l_0, b_0)\)).7 Assuming that the MW is symmetric about its center and its disk mid-plane (that should be a reasonable first-order approximation, at least at the Galactic latitudes considered here, \(b \geq 45.5^\circ\); but see Bell et al. 2008), each CF should be fairly representative of the typical Galactic population contaminating our on-Stream fields. Following Bel06, to average out the effects of shot noise, the CFs are larger than the on-Stream fields \((10^\circ \times 10^\circ)\). As shown in Figure 1, the globular clusters NGC5466 and M3, and the dwarf galaxy remnant Boötes III, are enclosed within some of our CFs (Correnti et al. 2009). To avoid any undesired contamination we excluded the stars associated with these stellar systems from the corresponding samples by excising areas of radius \(1^\circ\) (for the globulars) and \(2^\circ\) (for the dwarf galaxy) around their centers. The only known stellar system that is (partially) enclosed in the field F2B.

For our analysis, we adopted the reddening-corrected \(g, r, i, z\) magnitudes as provided by CasJobs. These magnitudes were also corrected using the SFD98 maps; hence, the source of the reddening corrections is homogeneous for all the data sets considered in the present analysis. The mean \(E(B - V)\) and its standard deviation for each field, averaged over all the stars included in the field, are reported in Table 1. It is important to note that the average reddening of our fields is remarkably low \((0.010 \leq E(B - V) \leq 0.038)\) and constant within each field \((0.002 \leq \sigma_{E(B-V)} \leq 0.010)\); hence, any error in the adopted reddening correction would have only a minor impact on our final differential distance estimates. For brevity, in the following all the reported magnitudes and colors are reddening-corrected (i.e., for example, \(V = V_0 = \) extinction-corrected \(V\) magnitude).

The \(g, r, i, z\) magnitudes in the SDSS system have been transformed to the Johnson–Kron–Cousins \(B, V, I\) system (as defined by the standard stars by Landolt 1992) using robust empirical transformations that have been checked to be particularly accurate in the color range typical of RC stars (provided by R. Lupton in 2005,8 derived from large samples of stars in common between SDSS and the extended-database of Landolt’s standards by Stetson 2000). In particular, we obtain \(B\) and \(V\) from \(g\) and \(r\), while \(I\) is obtained from \(i\) and \(z\), adopting the following equations:

\[
B = g + 0.3130(g - r) + 0.2271, \quad \sigma = 0.0107, \quad (1)
\]

\[
V = g - 0.5784(g - r) - 0.0038, \quad \sigma = 0.0054, \quad (2)
\]

\[
I = i - 0.3780(i - z) - 0.3974, \quad \sigma = 0.0063. \quad (3)
\]

Note that the transformed \(V\) and \(I\) are fully independent as they are obtained by independent couples of SDSS magnitudes. Consequently, measures of the position of any significant peak detected in \(V\) and \(I\) SCPs will also be independent, thus providing a powerful cross-check of any detection and distance estimate.

2.1. Selections on the Color–Magnitude Diagram

In Figure 2, we present reddening-corrected \(V, B - V\) and \(I, V - I\) CMDs (focused on the RC features up to the upper region of the MS) of the main-body field Sgr34 and of the corresponding CF \(Gal\_Field\). The comparison between the CMDs of the two fields permits the identification of the main features associated with Sgr and the fore-/background Galactic populations. The RC of the Sgr dSph is a prominent

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7 Except in the case of field F1B, for which the CF is the same as adopted for the field F2B.

8 http://www.sdss.org/dr7/algorithms/SDSSUBVRITransform.html
feature in the CMDs of the Sgr34 field (upper panels), around 
(I, V − I) ≈ (16.9, 0.9) and (V, B − V) ≈ (17.8, 0.8). The wide and inclined RGB can be discerned over the background,
going from (I, V − I) ≈ (16.9, 0.9) to (I, V − I) ≈ (14.0, 1.5)
([V, B − V] ≈ (19.5, 0.8) to (V, B − V) ≈ (16.0, 1.4)], and
continuing beyond the limits of the box. The RGB bump is
apparent at V ∼ 18.2 and I ∼ 17.2, along the RGB (see
Monaco et al. 2002). For V − I ≲ 0.3 (B − V ≲ 0.2) at I ∼ 19.0
(V ∼ 17.9) a portion of the BHB is also visible (Monaco et al.
2003); at V − I ≲ 0.5 (B − V ≲ 0.4) and I ≳ 19.5 (V ≳ 18.5)
the Blue Plume (Mateo et al. 1995b; Bellazzini et al. 1999a;
B06a) population is visible. The sub-giant branch (SGB; for
V − I ≳ 0.8 or B − V ≳ 0.7) and the upper MS (to the blue of
the above limits) appear for I ≳ 19.0 (V ≳ 20.0). For a more
detailed description of the CMD of Sgr see B06a. The strong
vertical band around V − I ∼ 0.7 (B − V ∼ 0.6) running over
the largest part of the CMD, and bending to the red at I ∼ 19,
V ∼ 20, is constituted by MS stars of the MW (mostly from
the thick disk, in this direction, according to the Galactic model
by Robin et al. 2003); the wide band running parallel to the
red of the vertical portion of this feature is mainly populated
by Galactic giants, either in their RGB or RC/HB phase. The
majority of the stars redder than V − I = B − V ∼ 1.0 belongs
to the vertical plume of local Galactic M dwarfs.

The vertical lines in each panel of Figure 2 enclose the
color stripes that we adopted to select the RC population in
the two colors, corresponding to 0.70 ≲ B − V ≲ 0.95
and 0.85 ≲ V − I ≲ 1.05. The choice of the color limits
was made in order to include the bulk of the RC population
even if small color shifts were present due to errors in the
adopted reddening corrections and/or population gradients,
while keeping the contamination from other sources as low as
possible. The distribution in color within the selection windows
(around the magnitude of the observed RC of Sgr) shown in
Figure 3 suggests that color shifts of order ±0.05 mag would
lead just to minor losses of the signal (of the order of 10% with
respect to the number of stars obtained with our choice in the
selection window).

Figure 2 clearly shows that, in addition to Sgr RC stars,
several different contaminants are expected to enter the selection
window. For I ≲ 18.5 (V ≲ 19.5), Galactic giants (mainly RC
stars) should be the primary source of contamination, while the
sequence of Galactic MS stars crosses the selection stripes at
I ≳ 19 and V ≳ 20, boosting the star counts at faint magnitudes.
The RGB of the Sgr population, and in particular the RGB bump,
are also selected by the adopted windows. We will show below
that this source of contamination has a negligible effect on our
SCPs. At I ≳ 19.0 (V ≳ 20.0), the SGB stars of Sgr enter the
selection window; as they are much more numerous than
RGB and RC stars they may provide a serious contribution to
the “background” in our SCPs, at faint magnitudes. Finally, the
MS of Sgr crosses the windows at I ≳ 21 (V ≳ 22). The
actual structure of the contamination entering the windows will
obviously depend on (1) the Galactic population encountered
along the considered line of sight (hereafter los,) and (2) the
distance of the wrap(s) of the Sgr Stream that is(are) crossed
by the considered los. However, the los considered in this study
is all at much higher Galactic latitudes than Sgr34; hence, the
degree of contamination per unit area of the sky should be
lower, and the average distance of the encountered stars should
be higher; hence, most of the contamination by Galactic dwarfs
should occur at fainter magnitudes than discussed above for
Sgr34. Furthermore, all the detections of the Stream presented
here are at distances similar or larger than the main body
of the galaxy sampled by Sgr34; hence, in most cases the contamination by the SGB of the Stream population will occur at fainter magnitudes than in Sgr34. In any case, to limit the contribution by dwarf stars, independently of their origin, we limit our analysis to the magnitude ranges 15.0 ≤ I ≤ 19.5 and 16.0 ≤ V ≤ 20.5. These limits approximately correspond to an accessible range of heliocentric distances 12 kpc ≤ D ≤ 70 kpc (see Figure 5).

While the surface brightness of Sgr at Sgr34 is ~25 mag arcsec^{-2}; typical values for the Stream are ≥30 mag arcsec^{-2} (Mateo et al. 1998; Bellazzini et al. 2003b; Majewski et al. 2003; and references therein). It may be quite hard to identify the feeble signal from such sparse populations even in the presence of low background. In fact, even in the most favorable cases, the RC is barely visible in the CMDs of on-Stream fields (see, e.g., Newberg et al. 2002). The construction and modeling of SCPs described below is very effective in extracting the distance information in these cases (B06c; Correnti et al. 2009).

Finally, there are several indications that there is a sizable metallicity (and presumably age) gradient along the Stream, in the sense that the average metallicity is lower in distant portion of the Stream with respect to the main body of Sgr (B06c; Monaco et al. 2007; Chou et al. 2007). This is generally interpreted as due to a pre-existing population gradient within the original body of the Sgr galaxy, as the tidal tails were preferentially populated by stars that resided in the old and metal-poor outskirts of Sgr (Chou et al. 2007). It must be stressed that the detected gradient means that the relative proportion of intermediate-age and metal-rich stars and old-age metal-poor stars changes along the Stream (and with respect to the main body). This, in turn, changes the HB morphology, i.e., the relative abundance of RC and Blue HB stars (as observed in B06c), but it is not expected to change the intrinsic luminosity of the RC. Indeed, Carrell & Wilhelm (2010) find that the mean metallicity of RC stars along the Stream is very similar to that found in the main body of Sgr. Hence, while the population gradient may bias estimates of the stellar density along the Stream obtained from RC stars, our distance estimates should be unaffected and our characteristic size estimates can be only marginally affected (see Section 3.5 and Figure 18 for further details and discussion).

### 2.2. Detecting RC Peaks in Star Count Profiles

All the SCPs of color-selected RC samples presented in this paper are computed as running histograms (see Bellazzini et al. 2005 and references therein), as these couple the property of collecting the signal from a wide bin with the ability of constraining with great accuracy the location of density maxima, almost independently of the bin width. A bin width of ±0.2 mag and step of 0.02 mag have been adopted here. After different trials, they have been found to provide a good compromise between the exigence of co-adding all the signal from a given RC population (that requires larger bins) and the ability of distinguishing (resolving) nearby peaks (that is favored by smaller bins). The use of generalized histograms (Laird et al. 1988) would have provided a higher degree of smoothing, possibly making some of our SCPs easier to interpret. However, we preferred running histograms as they provide the reader a clearer idea of the local noise on the SCP as well as a scale in real units (stars/ mag bin × FoV). The density scales of the various fields have all been reported to unit standard area (1° × 1°) by applying the corrections due to spherical geometry that is inherent to equatorial coordinates.

To illustrate at best the case of the detection of the RC of a spatially confined stellar system in a color-selected SCP, we show in Figure 4 the V and I SCPs for the Sgr34 field (continuous lines), compared with those obtained for the CF Gal Field, normalized by the ratio of background densities between the two fields.

The shapes of the Sgr34 and Gal Field SCPs are remarkably similar: the only exception is the very strong and well-defined peak corresponding to the RC of the Sgr galaxy seen in Figure 2. It is interesting to note that while also other features related to Sgr are visible in the CMDs and (at least partially) included in the selection windows, as for example the RGB bump, in the SCPs the RC is the only signal emerging from the Sgr population. Independently of the origin of the stellar mix actually selected, the SCP of the CF, and, by analogy, the SCP of the contaminating

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9 However, it should be noted that the MS of wraps of the Streams that are too nearby to have their RC detected with the present technique may contribute to the contamination of our color-selected samples of candidate RC stars. Moreover, other unknown substructures may contribute to the contamination (see, Correnti et al. 2009, for example).

10 Except in the case of Sgr34 where the limits are 15.0 ≤ I ≤ 18.5 and 16.0 ≤ V ≤ 19.5.

11 Running histograms are histograms in which the step is smaller than the bin width. The adoption of steps much smaller than the bin width removes the dependence from the starting position of the binning that affects classic histograms. Clearly, the values of adjacent bins are not statistically independent.

12 With rare exceptions in which bins of ±0.25 mag have been adopted to enhance the signal of a weak feature. All these cases are clearly indicated in the following.

13 This ratio is dominated by the ratio of the areas of the fields, Sgr34 being ≃ 4 times larger than Gal Field. However, Gal Field samples a direction ∼ 2° closer to the Galactic Plane and ∼ 0.5° closer to the Galactic Center than Sgr34; hence, the (column) stellar density is intrinsically larger in the former field. The actual density ratio, computed in selected CMD boxes where the contribution from Sgr dSph stars is negligible, is ∼ 3, see Bellazzini et al. (1999b) and B06a.
population that is superposed on the RC in the Sgr34 SCP, are quite smooth and have a very simple behavior; in B06c, Correnti et al. (2009), and in Section 3.1, we show that this is the general behavior of the SCP of the back/foreground population in the vast majority of the considered los, thus justifying the choice of a very simple model for them, as described in Section 3.

2.3. Sensitivity of the Technique

Before proceeding with the description of the method adopted to obtain the actual differential distance estimates, it may be useful to study the sensitivity of our SCPs to the various properties of any encountered substructure (distance, density, etc.). To do that we used the dedicated Web tool\(^{14}\) of the BASTI repository of stellar models (Pietrinferni et al. 2004; Cordier et al. 2007) to produce a synthetic population of \(\sim 45000\) stars having age and metallicity similar to the bulk of the Sgr population (age = 6 Gyr, \([\text{Fe}/\text{H}] = -0.5\)). The CMD and the color-selected RC SCP of the population are shown in the left panels of Figure 5. The synthetic stars have been distributed along the los according to Gaussian distributions having various mean distances \(D = 15, 25, 40,\) and \(65 \text{ kpc}\) and FWHM of 3.3 kpc or 6.6 kpc, to simulate the crossing of a wrap of the Stream at various distances and with different characteristic sizes along the los. A FWHM \(\sim 3.3 \text{ kpc}\) is quite typical of sections of Stream wraps crossed perpendicularly by a given los, as measured on the models of the disruption of the Sgr galaxy by Law et al. (2005). The FWHM \(\sim 6.6 \text{ kpc}\) has been considered to account for cases of sparser portions of the Stream and/or non-perpendicular intersections with the los. The SCPs of the resulting color-selected RC population have been derived (properly including realistic photometric errors\(^{15}\)) and added to the SCP of the background of Figure 4, as modeled in Figure 6 to simulate the detection of the same structure with the method prescribed in Section 3.

\(^{14}\) http://albione.oa-teramo.inaf.it

\(^{15}\) For each passband, we fitted the error curve derived from SDSS photometric errors with exponential functions. Then we used the fitted functions to assign the proper average error to each synthetic star (according to its magnitude) and we added to each synthetic magnitude an error component extracted from a Gaussian distribution having \(\sigma\) equal to the average error.

(A color version of this figure is available in the online journal.)
applied here. The results of this simulation are shown in the right panels of Figure 5.

The most obvious effect shown in Figure 5 is the increase of sensitivity with the distance of the structure. This is due to two factors: (1) the inherent “compressive” property of the magnitude scale, by which, for instance, a difference in distance of 3.3 kpc corresponds to a difference in magnitudes of the magnitude scale, by which, for instance, a difference in distance.

This effect is illustrated in the right panels of Figure 5. applied here. The results of this simulation are shown in the right panels of Figure 5.

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This effect is illustrated in the right panels of Figure 5. }
is always within a factor from 0.5 to 2 times the statistically correct 1σ error, thus providing a realistic estimate of the uncertainty of our measures.

3. Lower panels: the global model, obtained by summing \( f(x) \) and \( G(x) \), is compared to the observed SCPs. This final form of the overall fit is what we will show for all the considered fields in Section 4. In Section 3.1, we will show that the adopted model of the foreground component of the considered SCPs \( (f(x)) \) provides an adequate representation of what is observed in actual CFs and predicted by current Galactic models.

The application to the Sgr34 field just described provides also the zero points of our differential distance scale, i.e., the magnitude of the RC in the main body of Sgr, \( V = 17.82 \pm 0.02 \) and \( I = 16.87 \pm 0.02 \). As a sanity check, we verify if these numbers are compatible with theoretical stellar model predictions.\(^{16}\) Adopting the distance modulus \( (m - M)_0 = 17.10 \pm 0.15 \) for Sgr (Monaco et al. 2004) we obtain \( M_I = -0.23 \pm 0.15 \) and \( M_V = +0.72 \pm 0.15 \). These correspond to ages in the range 5–7 Gyr for [Fe/H] = −0.4 and 9–11 Gyr for [Fe/H] = −0.7 in the models by Girardi & Salaris (2001), in good agreement with all recent estimates of the typical age of the bulk of the Sgr stars (see, Layden & Sarajedini 2000; Monaco et al. 2002; Böhm et al. 2006).

### 3.1. The SCPs of Control Fields

To verify empirically that the peaks we interpret as due to intersections of the considered los with Stream wraps are not due to Galactic structures, we have inspected all the color-selected SCPs of the CFs described in Section 2. The overall conclusion is that there is nothing similar to the peaks we observe in the SCP of our on-Stream fields in generic Galactic fields at similar distances from the plane and the center of the Galaxy.

In Figure 10, we show various examples: the SCPs of six on-Stream fields (continuous lines) are compared to the SCPs of their corresponding CFs (dotted lines, see Figure 1). The best-fit models for the on-Stream SCPs, together with the background and the 3σ levels, are also reported, using the same symbols as in Sections 3 and 4. The two SCPs are normalized by the ratio of the sampled areas, but any other reasonable normalization (for example, by the ratio between the number of stars that fall inside our color selection) does not significantly change the results.

The shapes of the SCPs are very similar in the range not affected by the peaks associated with the Stream, as already observed when we have done the same comparison in the main body (Figure 6). It is quite clear that the strong and well-defined peaks observed in on-Stream fields are lacking in the SCPs of CFs (however, there is no guarantee that genuine and yet unrecognized structures are present also along these los). It is also reassuring to note that the models for the SCP of the contaminating back/foreground population we have adopted for the on-Stream fields provide a good description also of the CF SCPs, at least out to \( V \approx 18.5 \). Beyond this limit it is quite clear that in the on-Stream fields there is an additional source of contamination, that has to be ascribed to RGB, SGB, and MS stars from the Stream population itself, as discussed in Section 2.1. This provides further support to the idea that the adopted approach of fitting the back/foreground component directly on on-Stream SCPs is the most effective way to get rid of this kind of self-contamination from other species of Stream stars, that would not have been possible if we merely subtracted the CF SCPs to the on-Stream ones.

In the lower right panel, we present the case of F15A that will be discussed in Section 4.1. It is interesting to note the close similarity between the two considered SCPs for this field, where we do not detect any signal from the Stream, and they are therefore expected to be (both) dominated by the generic halo/thick disk Galactic population.

### 3.2. Examples of On-Stream Fits

In Figures 7 and 8, we show two examples of application to on-Stream fields, the fields F7A and F5A, respectively. In the first case, a broad peak with significance above 4σ is detected in both the \( V \) and \( I \) SCPs. The derived differential distances with respect to the main body are in good agreement, within the uncertainties. The \( f(x) + G(x) \) model provides an excellent description of the observed SCPs.

Two significant peaks are detected in the SCPs of the field F5A (Figure 8); thus, in this case, we need a model with two Gaussian components. Both peaks are significantly narrower than that found in the field F7A. Nevertheless the model \( f(x) + G_1(x) + G_2(x) \) provides an excellent representation of the observed SCPs. The differential distances obtained from the \( V \) and \( I \) SCPs are in good agreement: there is no doubt that we are detecting the same structures in both SCPs.

To place the results shown in Figures 7 and 8 into the proper context, we plot the positions of the detected peaks into

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\(^{16}\) That, however, are quite uncertain and model dependent, in an absolute sense, for stars in this evolutionary phase. For instance, the absolute \( I \) magnitude of the peak for an age = 6 Gyr, [Fe/H] = −0.5 model from the BASTI data set (shown in Figure 5), is matched by a model of age = 1.7 Gyr and [Fe/H] = −0.4 from the set by Girardi & Salaris (2001).
Figure 8. Same as Figure 7, but for a different field (field F5A). The method is the same although this field shows more than one peak.

(A color version of this figure is available in the online journal.)

Figure 9. Upper panels: de-reddened running histogram SCPs, zoomed in the region of the peak(s), of color-selected RC candidates for the Stream field F5A (left panel) and F7A (right panel). The meaning of the lines is the same as Figure 7, the red line represents the global model, \( f(x) + G(x) \), with the best-fit value of \( G(x) \) mean (value for which \( \chi^2 = \chi^2_{\text{min}} \)). Middle and lower panels: as upper ones, with the exception that the values of the \( G(x) \) means are those that have \( \chi^2 = +\chi^2_{\text{min}} \) (middle panels and \( \chi^2 = +2\chi^2_{\text{min}} \) lower panels, respectively). It is clearly visible that in these last two cases the fit is totally unsatisfactory.

(A color version of this figure is available in the online journal.)

Figure 10. Comparison between a sample of the on-Stream SCPs studied in this paper (continuous histogram; best-fit model in red) and the SCP of the corresponding CFs.

(A color version of this figure is available in the online journal.)

Stream is expected to be confined within a few kpc about it. We compare our detections with one of the N-body models of the tidal disruption of Sgr by Law et al. (2005). In particular, we plot in Figure 11 the results of the evolution of the N-body model of Sgr within a Galactic DM halo of prolate shape (flatness \( q = 1.25 \), see Law et al. 2005; Johnston et al. 2005, for further details on the models). To compare observations and model in a consistent way we transformed our relative distances into absolute values by adopting the same distance modulus for Sgr as Law et al. (2005), i.e., \( (m - M)_0 = 16.9 \) (Mateo et al. 1995a). The points of the model that are encountered by the considered FoVs along the los (F7A and F5A, from left to right, respectively) are plotted as heavier dots.

Taking the considered model as a realistic representation of the actual Sgr relic (a very reasonable assumption, in first approximation; Law et al. 2005), it is clear that any los around the considered plane would cross one or more different wraps of the Stream, at different distances (see Figure 11). The peak from F7A and the most distant peak from F5A seem to match a distant portion of the leading arm. The nearest peak from F5A matches very well with a wrap of the trailing arm that appears narrow and well defined and that is crossed nearly perpendicular by the considered los. According to the considered model, both los should also cross a nearby wrap at a distance not enclosed in our range of sensitivity, that is delimited by the two dashed circles in Figure 11. No wrap is expected to lie outside \( D = 60 \) kpc in the region sampled by our fields.

Both the more distant F5A detection and the single F7A detection occur in regions where the model predicts the confluence and crossing of different wraps. At a first glance to Figure 11, it may appear that the constraining power of a single “mean position” of a Stream wrap, as derived with our method, is not sufficient to describe the complex structure of the Sgr remnant along a given los. In Figure 12, we compare the observed RC peaks of F5A and F7A (and their best-fit Gaussian models) with the peaks derived from the N-body model shown in Figure 11.
and from the oblate-halo model from the same set (Law et al. 2005) by (1) selecting the model particles encountered by the FoV cone, (2) assigning to each of them the absolute magnitude of the RC ($M^\text{RC} = +0.72$ and $M^\text{RC} = -0.23$, according to Section 3) and deriving their apparent magnitude according to their distance, (3) adding Gaussian photometric errors as a function of the apparent magnitude similar to the observed ones, and (4) producing the running histogram of the derived magnitudes with the same settings adopted for the observed SCPs. To make easier the comparisons shown in Figure 12, the synthetic SCPs have been multiplied by an arbitrary normalization factor. The qualitative resemblance of the observed and predicted structures for the prolate-halo model is striking. On the other hand, the oblate-halo model is clearly unable to reproduce the observations, even in terms of number of Stream wraps encountered by the considered los.

A more thorough comparison of our observations with theoretical models of the disruption of Sgr will be presented in Section 6. Here, we are just interested to demonstrate that our method allows a detailed comparison between models and observations not only in terms of mean distances, but also in terms of the actual shape of the structures along the los (Figure 12, left panels, in particular). In other words, a fully successful model of the Sgr Stream must reproduce the correct position and shape of the observed peaks: this provides the opportunity for a fruitful detailed comparison between models and observations also in regions where different Stream wraps cross each other. In this study, we provide the position and the FWHM of the peaks (as the most basic shape parameter, see Section 3.5) but anyone interested in more detailed comparisons can easily reproduce our results and obtain plots such as Figure 12.

In Section 4, the SCPs of all the considered on-Stream fields, with the associated detections, will be presented and briefly discussed. In agreement with the qualitative predictions of the model shown in Figure 11, in most cases we will detect two peaks at different distances.

3.3. Classification of the Detections

We divided the detections into three categories, assigning a flag to each of them, according to the following criteria.

1. $\Delta < 1$: peaks that are above the $3\sigma$ threshold both in the $V$ and $I$ SCPs, and having the same $\Delta$ in both passbands, within the errors. These are called primary peaks.
2. $\Delta < 2$: peaks having the same $\Delta$ in both passbands, within the errors, but reaching the $3\sigma$ threshold only in one of the two SCPs. In all the $\Delta = 2$ cases described in the following, the weaker peak is always just below $3\sigma$. These are called secondary peaks.
3. $\Delta > 2$: clearly visible peaks having the same $\Delta$ in both passbands, within the errors, but not reaching the $3\sigma$ threshold in both the SCPs. These correspond to uncertain detections that we report just for completeness. In some case, a weak peak in the SCP in one band is tentatively identified as it corresponds to a stronger peak in the other SCP. These peaks are called tertiary peaks.

The observed SCPs and the detected peaks will be briefly described and discussed in Section 4.

3.4. Number of RC Stars Associated with Each Peak

Our modeling of the observed SCP automatically also provides an estimate of the total number of stars associated with any given peak. This gives a useful additional constraint for theoretical models; we will illustrate this possibility with an example in Section 6.2. In Table 2, we provide the number of stars...
associated with a given peak normalized to an area of 25 deg$^{-2}$ (quite similar to the actual area of our fields). This number is the weighted mean of the estimates obtained from the $V$ and $I$ SCPs, where the assumed error on the estimate from each SCP is just the square root of the observed number (hence, it should be considered as a lower limit to the real error).
Adopting the Sgr 34 field as a baseline (having $N_{\text{Sgr34}}^{\text{RC}} \simeq 1500$ stars deg$^{-2}$, and $m_{\text{II}} = 25.5$ mag arcsec$^{-2}$; Monaco et al. 2005b), and translating our on-Stream estimates into stars deg$^{-2}$ units ($N_i^{\text{RC}}$, for the field $i$) we can transform our numbers into surface brightness, according to the same formula used in Bellazzini et al. (2006b):

$$\mu_{V,i} = \mu_{V,\text{Sgr34}} - 2.5 \log \left( \frac{N_i^{\text{RC}}}{N_{\text{Sgr34}}^{\text{RC}}} \right) + \Delta(m - M)_0 \quad (4)$$

derived from Renzini (1998), where $\Delta(m - M)_0 = (m - M)_0^\text{Sgr} - (m - M)_0^\text{Sgr34} = \Delta V = \Delta I$. Using Equation (4), we find that the $V$ surface brightness of the portions of the Sgr Stream studied in this paper range between 30.6 mag arcsec$^{-2}$ and 33.6 mag arcsec$^{-2}$, quite typical of tidal tails and in good agreement with previous results (see, for example, Bellazzini et al. 2003b and references therein).

It is important to recall that the measured densities refer only to RC stars; in the presence of a population gradient (as is likely the case in the Stream; Bellazzini et al. 2006c; Chou et al. 2007) they would trace different fractions of the total stellar content at different positions along the Stream. Analogously, the derived surface brightness estimates have been rescaled assuming the stellar mix of Sgr34 for all the considered portions of the Stream. For this reason, these estimates should be considered with caution: given the sense of the gradient it is expected that they provide lower (faint) limits when converted into luminosity or surface brightness. In this context, it is interesting to note that if we convert our surface brightness into the same density units ($L_{\odot}$ kpc$^{-1}$) adopted by Niederste-Ostholt et al. (2010), we find that our results are fully compatible with the trend of density as a function of R.A. derived by these authors (see their Figure 7), for both branches. On the other hand, our densities are lower than theirs by a factor of $\sim 4$–5. It is reasonable to assume that part of the difference may be accounted for by the effect of the population gradient described above.

### 3.5. Depth Along the los of the Stream Wraps

Figure 12 shows that the observed RC peaks also contain valuable information on the characteristic size of the section of the Stream branches crossed by our los, as peaks at similar distances display different widths. To obtain a quantitative estimate of the linear width along the los of the structures identified here, we recurred to the synthetic population described in Section 2.3. In particular, we tried to reproduce the models of the observed peaks with smoothed histograms of the synthetic RC population, properly including the effects of photometric errors. As done in Section 2.3, we assign a distance along the los to each star of the synthetic RC population according to a Gaussian distribution having the same mean and normalization as the observed peak, and we search for the value of $\sigma_\mu$ giving the best match between the two models. In Table 2, we report the FWHM (in kpc) of the adopted distributions, FWHM = 2.35$\sigma_\mu$. The best match is found by minimizing $\chi^2$ and typical uncertainties are $\sim 20\%$. The adopted procedure gets rid of the effects of the distance on the width of the SCP peaks discussed in Section 2.3.

Since the synthetic population that we adopt is strictly single-age and single-metallicity, the intrinsic luminosity width of its RC should be smaller than the actual width of the RC of Sgr, as the latter hosts stars spanning a range of ages and metallicities (B606a; Girardi & Salaris 2001; Siegel et al. 2007; Bellazzini et al. 2008). For this reason, the FWHM values we obtain in this way must be considered as strong upper limits to the real values. Moreover, it has to be recalled that we report FWHM along a given los, that may have various incidence angles with respect to the encountered Stream wraps. Applying the method to the Sgr34 field we obtain FWHM $\leq 3$ kpc, not too far from the minor-axis FWHM in the plane of the sky as obtained from the best-fit King (1962) model by Majewski et al. (2003), i.e., FWHM $\approx 1.1$ kpc, in particular, if we take into account that the los toward the core of Sgr is (likely) not exactly perpendicular to the major axis of the dwarf galaxy (see Figure 11). Based on this test, it is reasonable to assume that our FWHM overestimates the true values by a factor of $\geq 2$.

In any case, the ratio between the FWHM of two different los/locations in the Stream, or, equivalently, the differential trend of the FWHM as a function of orbital azimuth along a given Stream wrap can directly be compared to the predictions of theoretical models of the disruption of Sgr.

### 4. ON-STREAM DETECTIONS

In this section, we present all the SCPs obtained from each analyzed field of branches A and B; we plot the SCPs in the $V$ and $I$ bands in Figure 15 for branch A, and Figure 16 for branch B. Together with the observed SCPs, we also plot the background model ($f(x)$, dashed lines), the threshold limits for the detections (dotted lines, respectively $3\sigma$, $4\sigma$, $5\sigma$), which as mentioned previously, include both the Poisson noise and the uncertainty in the fit, and the global model that fits the observed SCPs ($f(x) + G(x)$, red lines). Each field is labeled according to the names assigned in Table 1 and with its Galactic coordinates ($l, b$).

In summary, we detect 26 primary (flag = 1) peaks, 10 secondary (flag = 2), and 14 tertiary (flag = 3) peaks. Most of the considered SCPs show two significant peaks, corresponding to subsequent crossings of different wraps of the Stream along the los. The trend of the peak distance as a function of Sgr longitude ($\Lambda_{\text{Sgr}}$) shown in Figure 13 can be useful to better understand the morphology of the various SCPs presented below. Most primary peaks appear to trace a wrap of the leading arm whose distance from the Sun steadily decreases from $D \simeq 45$ kpc at $\Lambda_{\text{Sgr}} \simeq 290^\circ$ to $D \simeq 20$ kpc at $\Lambda_{\text{Sgr}} \simeq 230^\circ$. Both primary and secondary peaks trace a more nearby filamentary structure at a constant distance $D \simeq 25$ kpc, from $\Lambda_{\text{Sgr}} \simeq 290^\circ$ to $\Lambda_{\text{Sgr}} \simeq 260^\circ$, that then bends toward larger distances, reaching $D \simeq 40$ kpc at $\Lambda_{\text{Sgr}} \simeq 230^\circ$. This feature is tentatively identified as a wrap of the trailing arm (see Section 6). The two wraps cross at $\Lambda_{\text{Sgr}} \simeq 245^\circ$ (see Section 6). Some secondary and tertiary peaks seem to trace more feeble distant or nearby wraps (see Section 6 for a deeper discussion). The comparison with the considered model suggests that most of the detected peaks can be associated with the Sgr Stream. The tertiary peak at $\Lambda_{\text{Sgr}} \sim 263^\circ$ and $D \simeq 18$ kpc, and the primary peak at $\Lambda_{\text{Sgr}} \sim 280^\circ$ and $D \simeq 19.5$ kpc, are possibly associated with other overdensities in the Virgo constellation (see Juric et al. 2008; Duffau et al. 2006; Newberg et al. 2007, and references therein), as discussed in some detail in Section 6.

Before proceeding in the description of the various detections, we anticipate that the differential distance moduli ($\Delta V = \Delta I = \Delta R$)
Figure 13. Distribution of the primary (red filled circles: branch A and blue filled squares: branch B), secondary (red open circles: branch A and blue open squares: branch B), and tertiary detections (red starred symbols: branch A and blue stars: branch B) in the $\Lambda_{\text{Sgr}}$ vs. the heliocentric distance plane (a true distance modulus of 16.90 has been adopted here). The horizontal dashed lines enclose the range of sensitivity of our method. The prolate-halo $N$-body model by Law et al. (2005) is also reported (small dots) as an aid for the interpretation of the plot. The heavier dots are those enclosed in the cones of the considered FoVs. (A color version of this figure is available in the online journal.)

V Field $\text{RC} - V_{\text{RC}34}$; the analogous definition being valid also for $\Delta I$, reported in Table 2, obtained from primary and secondary peaks detected in the $V$ and $I$ SCPS are in excellent agreement, as shown in Figure 14. This confirms the reliability of our detections and distance estimates. For this reason, from Section 5 and in Figure 13 we adopt the mean of $\Delta V$ and $\Delta I$ as our final differential distance moduli estimates.

4.1. Branch A Detections

In branch A, we analyzed 15 fields, the corresponding observed SCPS, and the adopted best-fit models are shown in Figure 15. We obtained a total of 24 peak detections, with the following classification: ten primary peaks, five secondary peaks, and nine tertiary peaks. The SCPS of the first five fields (from F1A to F5A, upper left panel and first two rows of the upper right panel of Figure 15) display a common general behavior: they present two main peaks, the one at fainter magnitudes always being the strongest (a primary peak in all cases), while the brighter ones are wider and span all the classes from flag $= 1$ to flag $= 3$, depending on the specific field. It is quite clear that this series of peaks traces two coherent structures placed at different distances along the los. The $I$-band SCP of F4A may suggest a splitting of the brighter/weaker peak into two separate components: we consider this interpretation as unlikely, nevertheless the result obtained with a three peaks model is briefly discussed in Section 4.3. The only exception is a primary peak detected at $V \sim 16.5$ in F1A: this likely corresponds to the nearest wrap of the Stream that emerges from the $d \lesssim 12$ kpc circle (where our method is blind), which is the most eastern of all the considered los (see Section 6).

Figure 14. Comparison between the differential distance moduli obtained from peaks in the $V$ and $I$ SCPS for primary (upper panel) and secondary (lower panel) peaks. (A color version of this figure is available in the online journal.)

The SCPS of F6A (second upper right panel of Figure 15) present an overall structure similar to those described above. However, we identified additional (fainter) peaks, and finally we adopted a three peak solution, whose validity is confirmed by the inspection of SCPS obtained with reduced bin width (i.e., higher resolution, see Section 4.3 for an alternative). The newly resolved third peak, at magnitude $V \sim 19$ ($I \sim 18$), corresponds to a distance $D \approx 42$ kpc at $\Lambda_{\text{Sgr}} \approx 265^\circ$; this detection seems related to a very distant wrap of the leading arm (see, for example, Figure 22). F6A is the only branch A field in which we detect a peak related to this distant wrap of the leading arm, that was observed also by Bel06 (see Section 5); the same structure is detected in branch B along the same los, as well as along an additional one (F8B).

F7A is one of the two fields in branch A that presents only one detection: SCPS (third upper right panels of Figure 15) show a single, very prominent primary peak. As discussed above, this los intercepts a region where two or three wraps of the Stream cross each other. Figure 12 shows that the presence of a single peak is nevertheless consistent with model predictions. In both the SCPS of the adjacent field F8A, a remarkably weak peak appears at a similar position as in F7A; hence, we obtain only a tentative flag $= 3$ detection. We have no convincing explanation for the weakness of the peak detected in this field: it may be related to the complex structure of the various Stream wraps or to a local dip in the density along the Stream. In the SCPS of the F9A field, we identify again two peaks, the faintest one being very prominent and wide; also this los intercepts a region of crossing wraps;

18 We note that this is the only case in which a change in the bin width produced a change in the interpretation of the SCPS.
Figure 15. Fits of the observed SCPs (in $V$ and $I$) for fields on Branch A of the Sgr Stream. The numbers in parentheses are the Galactic longitude and latitude of the center of the field in degrees. The meaning of the symbols is the same as in Figures 7 and 8, above. No global fit has been attempted for SCPs that did not show significant RC peaks (F13A, F14A, F15A).

(A color version of this figure is available in the online journal.)

thus, superposed structures may contribute to the production of a strong and remarkably wide primary peak. The weaker/brighter peak is more interesting: it is clearly identified in both SCPs, even if below the 3σ threshold, at $V \sim 17.20$ ($I \sim 16.30$): as discussed later in Section 6 this feature may trace a near wrap of the Stream that was never detected before.

SCPs of fields from F10A to F12A show two peaks at similar positions, with a remarkable variety of absolute and relative strengths. This may reflect the highly structured morphology that is suggested by models in this region (see Section 6). F11A is crossed by the Orphan Stream (Bel06; Belokurov et al.2007).

While the distance of this structure ($\sim 30$ kpc toward this los) does not match with the detected peaks, we cannot rule out some contamination from Orphan Stream stars in this field.

We did not find any convincing signal in F13A, F14A, and F15A; the overall shape of the SCPs appears quite different from the other cases and, in the case of F15A, the polynomial model did not provide a satisfactory fit to the background population. In particular, the SCPs present a strong excess at bright magnitudes ($V \lesssim 18$, $I \lesssim 17$) with respect to those in the previously discussed fields, such that they appear flat or even decreasing with increasing magnitude. These are the fields at the lowest galactic latitude; hence, we attribute these features to contamination by (relatively) nearby stars from the
Galactic thick disk (and, possibly, the Monoceros structure, see Figure 1 of Bel06) that overwhelms the signal from the Sgr Stream RC. This seems confirmed by the comparison with the corresponding CFs (the case of F15A is shown in Figure 10, in Section 3.1), that display SCPs essentially indistinguishable from those of the on-Stream fields. This implies that the adopted technique can be used successfully only at large distances from the Galactic plane. Given the above reasons we preferred not to consider for further analysis the possible peaks at $V(I) \sim 16(15)$ and $V(I) \sim 17.5(16.5)$ in F14A.

4.2. Branch B Detections

In branch B, we analyzed 13 fields, obtaining a total number of 26 detections, with the following classification: 16 primary, 5 secondary, and 5 tertiary peaks. The main structures found in branch A are mirrored also in branch B, as clearly shown in Figure 13. In all the fields (except F7B), we detect at least two peaks; in two cases (F8B and F12B), we also detect a third peak; in F8B, this is likely tracing the more distant Stream wrap running nearly parallel to the main wrap of the leading arm (see above and Figure 13); in another case (F5B), in addition to three peaks analogous to those in F8B, we found an additional nearby peak (see Section 6 for a discussion). An alternative interpretation for the SCPs of F12B is presented in Section 4.3. Quite surprisingly, the SCPs of F6B appear completely smooth and featureless. In this case, we were not able to find an explanation for this behavior (but see above for the discussion of the similar case of F8A).

In analogy with F7A (and F8A), F7B is the only case of branch B SCPs fitted with a single peak model. The morphology
of the $I$-band SCP and the comparison with the adjacent F8B field suggest that two, or possibly three peaks may be merged together in this SCP. However, we were unable to resolve the peak into separate components even in SCPs with smaller bin width (as for the case of F6A). We caution the reader that this primary detection is likely concealing significant—but as yet undetected—substructure.

### 4.3. A Few Special Cases

There are a few cases in which the observed SCPs do not provide unequivocal indications for the model to be adopted, in particular concerning the number of $G_1(x)$ functions to be included in the model, i.e., the number of detected peaks. F7B, briefly discussed above, is the only case in which we feel that the observed peak is due to the merging of two (or, more likely, three) adjacent peaks that we cannot resolve. In Figure 17, we present acceptable alternative models (with respect to the solutions shown in Figures 15 and 16, and listed in Table 2) for the three cases in which our preference for the adopted models (Table 2) is only marginal, and is also supported by the continuity within a large-scale structure (a Stream wrap). In Table 3, we report the corresponding alternative solutions, that can be replaced with those of Table 2 by those readers who may use our values to constrain models of Sgr, if they judge them more appropriate for some reason.

### 4.4. Intra-branch Fields

In this analysis, we do not consider the structure of the Stream in the declination direction. We fully adopted the view of Belokurov et al. (2006), where the leading arm of the Stream as seen from TO stars in the SDSS bifurcates into branches A and B around R.A. = 220° and the separation between the branches increases with decreasing R.A. We proceeded to a basic verification of this scenario by looking at the SCPs of a few intra-branch (I) fields (not shown here, for brevity), located at intermediate declination with respect to the A and B fields F5, F7, F10, and F12. In agreement with the results of Belokurov et al. (2006), we find that the SCPs of F5I and F7I mimic the structure of the SCPs of the corresponding A and B fields, showing peaks at the same position with similar shape, but weaker than in the on-Stream fields (i.e., tracing a lower stellar density). In the SCPs of F10I, the peaks seen in the A and B SCPs are just barely visible and they completely disappear in F12I. Hence, these limited set of tests confirm the reality and the morphology of the Stream bifurcation as observed by Belokurov et al. (2006).

### 4.5. The Color of the RC Peaks

The color of the RC peak is known to be very sensitive to metallicity and weakly sensitive to age, in the range of ages relevant for this study (4–12 Gyr; Girardi & Salaris 2001). As our procedure of independent peak detections in $V$- and $I$-band SCPs automatically provides the colors of the RC peaks, it is worth checking if there is any hint of a color (metallicity) gradient along the Stream. In Figure 18, the colors of the observed peaks are compared to the theoretical models by Girardi & Salaris (2001). All of the peak detections shown in Figure 18 are compatible with having the same color within the uncertainties (that are quite large for some non-primary peaks). It is interesting to note that the large majority of points cluster around the $[M/H] = -0.7$ model, in good agreement with the results by Bellazzini et al. (2006a) and Carrell & Wilhelm (2010; see also Section 2.1). No significant trend of color (metallicity) of the RC population with orbital azimuth is apparent and the few points showing the larger color difference from the mean locus are always among those having the most uncertain color estimates.

## 5. COMPARISON WITH PREVIOUS ANALYSES

Before discussing in detail the comparison between our distance estimates and the findings from previous works, it is worth considering the difference between the performances of the various adopted tracers. The intrinsic stability (and
ubiquity along the Stream) of our standard candle (RC stars), the adopted analysis, best suited for the detection and location of RC peaks, and the purely differential nature (Stream versus main body) of our measures, make our distance estimates the most comprehensive, accurate and homogeneous set publicly available (even if limited to the region of sensitivity described above). The uncertainties associated with our estimates are lower than any previous work, with a typical values of above). The uncertainties associated with our estimates are lower than any previous work, with a typical values of 5% raising to ≤10% in the worst cases. For example, Majewski et al. (2003) report that the characteristic uncertainty of their photometric parallaxes based on M giant is ∼20%; Martin et al. (2004) showed that uncertainties in the age/metallicity of the considered populations may lead to systematics of order ∼30% in the distance scale based on M giants. F stars (assumed to be TO stars of Sgr) proved to be an excellent mean to trace even very feeble substructures (Belokurov et al. 2006; Newberg et al. 2007). However, the assumption of a common absolute magnitude for all color-selected F stars implies large uncertainties, as these stars span a range of luminosities much larger than RC stars. For example, if we consider the distribution in V magnitude of (1) the RC selected with our color window and (2) the MSTO stars selected in color as done by Bel06 (and limited to V > 20.0) in the photometry of the Sgr34 field, we found two obvious single-peaked distributions, but while the FWHM of the RC peak is ∼0.3 mag, the MSTO star peak has FWHM ∼2 mag. Indeed, Cole et al. (2008), in their pilot project on stripe 82, showed that the assumption of a fixed magnitude for these stars may lead to very large errors. BHB stars are easier to select against the Galactic foreground, but are rarer than RC stars. Moreover, even if selected in a color range where the HB is nearly perfectly horizontal, the distribution in magnitude of these stars is not expected to be as clearly peaked as the RC (see B06c). In this sense, the SGB, used by Bel06 and Keller (2009), is more promising, as it is a very narrow feature in CMDs of metal-rich populations. However, it should be much more sensitive to metallicity and age variations than the RC (see, for example, B06a, and references and discussion therein), and being much (intrinsically) fainter, its use is limited to a lower distance range, for any given data set. Finally, RR Lyrae stars (Ivezic et al. 2000a; Vivas & Zinn 2006; Prior et al. 2009a; Keller et al. 2008) can provide distances with very superior accuracy with respect to our method; well-sampled light curves can also give indications on physical properties of individual stars (metallicity, for example) that cannot be obtained from RC stars. However, RR Lyrae are (likely) less frequent than RC stars over most of the Stream extension and, above all, they need time series information to be safely identified and to obtain a reliable apparent magnitude averaged over the pulsation period: for this reason, the available data cover a much smaller region of the sky with respect to generic “single epoch” standard candles.

### 5.1. Comparison with Specific Detections

Yanny et al. (2000) were the first to interpret a stellar overdensity in the halo as possibly due to the Sgr Stream. In the first available (equatorial) stripe of the SDSS, they identified an excess of A-type stars around Λ_0 ∼ 295°, adjacent to our field F1A. The heliocentric distance inferred is of 48 kpc, in good agreement with our estimate for the main wrap of the leading arm in this direction (D ∼ 45 kpc at Λ_Sgr ∼ 290°). This result was later confirmed by the more thorough study by Newberg et al. (2002), that used F stars as main tracers. Although they do not comment on it, the Yanny et al. (2000) data also showed an excess of A-type stars less than 20 kpc away along the same los (see their Figures 18 and 19). This may be more easily identified with the constant-distance coherent structure we see at d ∼ 25 kpc than to the nearest wrap that we (possibly) detect at Λ ∼ 287° and d ∼ 13 kpc.

A similar detection of two density enhancements toward the Northern Loop was reported by Ivezić et al. (2000a), from the study of RR Lyrae in the same SDSS stripe studied by Yanny et al. (2000), and by Vivas & Zinn (2006), also using RR Lyrae from the QUEST RR survey, which explored nearly the same region of the sky as Sgr Stream (D ∼ 45 kpc at Λ_Sgr ∼ 270°–290°). Both studies comment primarily on an excess of RR Lyrae stars at 45–50 kpc (corresponding to the main wrap of the leading arm); however, a structure around ∼20 kpc is also noted.

Majewski et al. (2003) provided a clear panoramic view of the Sgr Stream using M giants as standard candles; they were able to trace very neatly the trailing tail all over the Southern Galactic hemisphere, as well as part of the leading arm closer to the main body of the galaxy, up to R.A. ∼ 190°. They report two cases of M giants excess along the los in common with the present analysis. The most evident at a distance D ∼ 45 kpc, compatible with our estimates, and the other one, less pronounced, at a distance D ∼ 20–25 kpc, for which the interpretation is not so clear as in the case of A stars and RR Lyrae detections.

All the detections mentioned above, as well as others toward specific directions, also not included in the range considered here (Martinez-Delgado et al. 2001, 2004; Bellazzini et al. 2003b; Vivas & Zinn 2006), are collected and reported in Figure 17 of M03. This figure, as well as Figure 19 in Law & Majewski (2010), clearly illustrates how it may be difficult and misleading to put results from different sources (and on different distance scales) all together. In this sense, it is more fruitful to compare our results with other data sets providing homogeneous distance estimates for significant portions of some wrap in common with those detected here.

For instance, Bel06, who used A–F dwarf stars from the SDSS to trace the Stream, detected a distant gradient along the main wrap of the leading arm that is in good agreement with our

### Table 3

| Field | l° | b° | ΔV | εV | ΔI | εI | d | εd | sign. (V) | sign. (I) | FWHM | #RC | εN | Flag |
|-------|----|----|----|----|----|----|----|----|----------|----------|------|-----|-----|------|
| 4A    | 320| 66 | 0.94| 0.04| 0.97| 0.05| 40.8| 4.2| >5σ     | 5σ       | 7.5  | 158 | 8  | 1    |
|       | −0.16| 0.09| −0.17| 0.09| 24.4| 2.8 | <3σ | <3σ | 1.9      | 1.9      | 107  | 6   | 3   | 1    |
| 2B    | 346.5| 65 | 1.08| 0.09| 1.08| 0.06| 43.3| 4.8| >5σ     | >5σ      | 9.3  | 187 | 10 | 1    |
|       | 0.13 | 0.15| 0.08| 0.12| 27.6| 3.7 | 5σ  | 5σ  | 14.0     | 14.0     | 499  | 14  | 1   | 1    |
| 12B   | 208.5| 60.5| 0.88| 0.15| 0.94| 0.15| 40.0| 5.6| <3σ     | 3σ       | 8.1  | 92  | 6  | 2    |
|       | −0.21| 0.15| −0.17| 0.15| 24.1| 3.3 | 3σ  | 3σ  | 12.0     | 12.0     | 155  | 9   | 1   | 1    |
results (for both branches). More interestingly, Bel06 found a double detection in a few branch A los (from F5A to F7A); in addition to the main wrap of the leading arm, they found also a more distant structure, ∼15 kpc behind. This finding is also in excellent agreement with our results (see Section 4.1). The only difference is that we detect this structure, at similar distance, also in the corresponding branch B fields.

Newberg et al. (2007) investigated the relationship between several previously identified substructures in the direction of Virgo and the Sgr Stream using imaging and spectroscopic observations of F stars and BHB stars from SDSS and SEGUE. In their Table 1, they reported the detections associated with the Sgr Stream, providing also estimates of the distance of these structures. This allowed us to perform the direct comparison on a nearly polar orbit, it seems the ideal tracer to study the overall shape and the degree of clumping of the Galactic halo as a whole. For this reason, the most recent N-body modeling efforts have focused on constraining the shape of the DM halo of the MW (Ibata et al. 2001b; Martínez-Delgado et al. 2004; Helmi 2004; Law et al. 2005, 2009; Johnston et al. 2005; Fellhauer et al. 2006; Law & Majewski 2010). However, it turned out that the conclusions of these studies depended on the specific set of observational constraints considered, and it is now generally accepted that none of the static-potential axisymmetric halo models considered are able to reproduce simultaneously all the available positional and kinematic data (see Yanny et al. 2009a and Law et al. 2009 for references and discussion). In a recent contribution, Law et al. (2009) anticipated that the adoption of triaxial halo models can help to solve this problem: in Section 6.3, we briefly consider the N-body model they produced as a follow-up of that analysis (Law & Majewski 2010). In any case, it is quite clear that currently available models are far from perfect and more detailed simulations are needed to extract all the possible information on the Galactic DM halo from the Sgr Stream, as more (and more accurate) observational constraints become available. For example, Fellhauer et al. (2006) interpreted the bifurcation of the trailing arm giving rise to the A and B branches considered here as produced by the precession between two subsequent orbits. As the implied amount of precession is relatively small, this, in turn, requires that the potential felt by Sgr should be nearly

Niederste-Ostholt et al. (2010) that concentrated their analysis on the detection of the leading arm and on an accurate distance estimate for this wrap of the Stream.

In conclusion, the overall agreement with previous detections of the leading arm is very good. The situation for the other coherent structures detected here is more difficult to judge; in our view, the only firm conclusion that can be drawn is that several independent studies found evidence for some structures located in front of the main wrap of the leading arm, in the considered range of A. It is unclear if some of these detections can be associated with the constant distant (putative) wrap of the trailing arm detected here or to even more nearby wraps. In this sense, it is interesting to note that a similar coherent structure, at a similar distance, is detected also by Keller (2009), using SGB stars (see his Figure 7).

6. COMPARISON WITH MODELS

As soon as it was realized that Sgr was likely undergoing tidal disruption, several authors attempted to model the process by means of N-body simulations, to establish the plausibility of proposed models and to infer the properties (mass, orbit) of the original system (Velazquez & White 1995; Johnston et al. 1995; Ibata et al. 1997; Edelsohn & Elmegreen 1997; Ibata & Lewis 1998; Gómez-Flechoso et al. 1999; Johnston et al. 1999; Jiang & Binney 2000; Helmi & White 2001). It is interesting to note that Velazquez & White (1995) were able to provide estimates of perigalactic and apogalactic distances and orbital period remarkably similar to those obtained in the most recent studies, just one year after the discovery of Sgr (Rperi ∼ 10 kpc, Rapo ∼ 52 kpc, and Prot ∼ 0.76 Gyr, to compare, for instance, with Rperi ∼ 15 kpc, Rapo ∼ 60 kpc, and Prot ∼ 0.85 Gyr, from Law et al. 2005). The possible role of Sgr in the formation of the Galactic Disk warp was studied by Ibata & Razoumov (1998) and Bailin (2003).

However, since the Sgr Stream appears as a remarkably coherent structure crossing a large part of the Galactic halo on a nearly polar orbit, it seems the ideal tracer to study the overall shape and the degree of clumping of the Galactic halo as a whole. For this reason, the most recent N-body modeling efforts have focused on constraining the shape of the DM halo of the MW (Ibata et al. 2001b; Martínez-Delgado et al. 2004; Helmi 2004; Law et al. 2005, 2009; Johnston et al. 2005; Fellhauer et al. 2006; Law & Majewski 2010). However, it turned out that the conclusions of these studies depended on the specific set of observational constraints considered, and it is now generally accepted that none of the static-potential axisymmetric halo models considered are able to reproduce simultaneously all the available positional and kinematic data (see Yanny et al. 2009a and Law et al. 2009 for references and discussion). In a recent contribution, Law et al. (2009) anticipated that the adoption of triaxial halo models can help to solve this problem: in Section 6.3, we briefly consider the N-body model they produced as a follow-up of that analysis (Law & Majewski 2010). In any case, it is quite clear that currently available models are far from perfect and more detailed simulations are needed to extract all the possible information on the Galactic DM halo from the Sgr Stream, as more (and more accurate) observational constraints become available. For example, Fellhauer et al. (2006) interpreted the bifurcation of the trailing arm giving rise to the A and B branches considered here as produced by the precession between two subsequent orbits. As the implied amount of precession is relatively small, this, in turn, requires that the potential felt by Sgr should be nearly
spherical. However, the similarity between the two branches (in terms of distance, kinematics, and stellar content) led Yanny et al. (2009a) to suggest that in fact the two branches are composed by stars lost at the same epoch, i.e., they are in the same orbital phase. In this case, the separation between the two branches would not be related to orbital precession and would have nothing to say about the shape of the potential. In their recent analysis, Niederste-Ostholt et al. (2010) adopt the same orbital phase. In this case, the separation between the two branches would not be related to orbital precession and would have nothing to say about the shape of the potential. In their recent analysis, Niederste-Ostholt et al. (2010) adopt the same view as Yanny et al. (2009a).¹⁹

In the present contribution, we provide very accurate distance estimates along the northern branches of the Sgr Stream as powerful constraints for future generations of Sgr disruption models that will include effects such as halo triaxiality, dynamical friction, time-evolving Galactic potential, etc. In this section, we discuss our findings in comparison with the predictions of the three models by Law et al. (2005, L05 hereafter), just to show how powerful accurate distance constraints can be in distinguishing between different models (some examples of such comparisons have already been presented in Section 3.2 and Figure 13). One of the main aims of the studies by L05 and Johnston et al. (2005) was to use the existing observations on the Sgr Stream to constrain the shape of the Galactic halo. For this reason, the three models they provide describe the final state of the evolution of a realistic progenitor of Sgr after a few orbits within a Galactic potential having a prolate, spherical, or oblate DM halo. For sake of simplicity, in the following we will refer to these models as to the oblate (O), spherical (S), and prolate (P) models, respectively. In all the models, each particle is flagged according to the perigalactic passage in which it becomes unbound from the main body of the galaxy. Here, we refer to stars still bound or lost during the current perigalactic passage as having \( p = 0 \); \( p = -1, -2, -3, -4 \) refers to particles lost one, two, three, and four perigalactic passages ago, respectively. \( p = 0 \) stars are out of the range accessible with the fields considered here, according to the L05 models. When we speak of "young" and "old" wraps of the Stream we refer to portions of the Stream whose population is dominated by particles lost in the most recent or less recent perigalactic passages, respectively, on an age-scale encompassing the last \( \sim 5 \) orbits, i.e., \( \sim 3–4 \) Gyr.

In Figures 20, 21, and 22, the three models are compared with the positions of the observed RC peaks in the \( X_{\odot, \text{Sgr}} \) vs. \( Y_{\odot, \text{Sgr}} \) plane,²¹ as in Figure 11. It is immediately apparent from Figure 20 that the trend traced by our primary peaks rules out the O model that fails to reproduce the most prominent branch of the Stream seen in SDSS data, i.e., the portion of the leading arm descending from the NGP (while there is some agreement for the—putative—nearby portion of the trailing arm). The case of the spherical model is similar, even if the disagreement between observations and model prediction is less severe (Figure 21).

The comparison with the prolate model is the most interesting and we take it also as the occasion to describe the trends found in our data in a deeper detail. For a more fruitful discussion we provide Figure 22 in a larger format with respect to its analogs for the oblate and spherical models (see also Figure 13). It should be stressed that, in the following, we interpret the coherent structures we have detected using this specific model as a guideline. For an example of a different interpretation see Section 6.3. There are several features worth noticing in Figure 22.

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¹⁹ See also the discussion in Law & Majewski (2010).

²⁰ Publicly available at http://www.astro.virginia.edu/~sm4in/Sgr.

²¹ For brevity, in the following, we will drop the "\( \odot \)". Sgr index any time we found this convenient; \( X_{\odot, \text{Sgr}}, Y_{\odot, \text{Sgr}} \) and \( X, Y \) are interchangeable. For the same reason, the values of \( X, Y \) must be always intended as expressed in kpc, even if not explicitly stated.
1. For $X_{\odot\text{Sgr}} \gtrsim -7$ kpc, the agreement between the positions of our primary branch A peaks and the portion of the leading arm going from $(X, Y) \simeq (16, -40)$ to $(X, Y) \simeq (-7, -28)$ is excellent. Also primary branch B peaks follow the same trend thus confirming that the two structures lie at the same distance (see also Figure 13 and Belokurov et al. 2006; Fellhauer et al. 2006; Yanny et al. 2009a). According to the considered model, this part of the leading arm is dominated by $p = -1$ particles up to $X_{\odot\text{Sgr}} \simeq 0$, and by a mix of $p = -2$ and $p = -3$ particles for $X_{\odot\text{Sgr}} \lesssim 0$.

2. Several detections seem to extend the path of the arm down to $(X, Y) = (-15, -15)$, possibly suggesting a slightly less elongated shape of the arm with respect to the model predictions. The coherence of the structure is less clear in this region: the models predict that various wraps cross here and this may be source of some confusion.

3. The model predicts the presence of a more ancient (mostly populated by $p = -2$ and $p = -3$ particles) and wider wrap running nearly parallel to the portion of the leading arm described above, but behind it. This structure has been detected in branch B, where one flag = 2 point, at $(X, Y) \sim (-5, -44)$, in coincidence with a branch A detection, and a flag = 3 detection at $[(X, Y) \sim (-14, -35)]$. These points appear to trace the outer edge of this wrap as depicted by the considered model. On the other hand, there is no detection (in any branch) for $X \gtrsim 0$, i.e., where the detection of the second wrap should be easier, according to the model, as the separation from the inner wrap increases with $X$ and the feature is denser and narrower in that region. This lack of detection seems confirmed by the independent results of Belokurov et al. (2006), that, however, detect the most distant wrap at $X < 0$ only in the direction of branch A. To have a deeper insight into this problem in Figure 24 we provide a direct comparison between observations and model at the SCP level, as done in Figure 12. Here, we compare the observed SCP of the F1A, F2A, and F3A fields with the SCPs obtained from the model in the considered los for particles lost one, two, three, and four perigalactics ago. From the upper right panel it is clear that the dense $X > 0$ part of the outer wrap, produced by $p = -2$ particles in the model, has no counterpart in the observed SCPs and would easily be detected if actually there. On the other hand, the sum of the relics having $p = -1, -3$, and $p = -4$ provides a satisfactory match to all the observed peaks. This suggests that there is a real mismatch between the L05 P model predictions and our observations in this part of the halo. We note that the spherical model suffers from the same problem, while the oblate model does not predict a strong signal at that position, but it fails to match all the observations at $X < 0$ for this wrap.

4. A coherent series of detections lying at nearly constant $Y \sim 25$ kpc, traced from $X \sim 8$ to $X \sim -14$ in both branches, traces a filamentary structure that is identified here for the first time. Isolated detections with M giants and RR Lyrae were previously reported at $\Lambda \simeq 295^\circ$ (Majewski et al. 2003; Vivas & Zinn 2006; Ivezić et al. 2000a). This feature matches quite well a wrap of the trailing arm that is present in all the L05 models; it can be appreciated from Figures 13 and 22 that the agreement with the P model is very good. For $X < -14$ however the positions of the peaks do not trace the model prediction anymore. This apparent discontinuity along this branch cannot be (only) due to the distance effects discussed in Section 2.3 as the distance is expected to increase and the sensitivity of the method should increase accordingly. Moreover, we are able to detect peaks both more and less distant than the position predicted.
Figure 24. Comparison of the observed SCPs in the fields F1A, F2A, and F3A with the synthetic SCPs obtained by adding the (arbitrarily normalized) los histogram from the prolate $N$-body model (as in Figure 12) to the best-fit background model of the considered field. Each of the four (triple) panels reports the synthetic SCPs including only $N$-body debris stripped from the main body one, two, three, or four orbits ago, going from the upper left, to the upper right, to the lower left, and to the lower right panels, respectively.

(A color version of this figure is available in the online journal.)

by the model along these $los$. This feature has no counterpart in the triaxial halo model discussed in Section 6.3. It is clear that additional information is needed to understand better the nature of this structure, from, for example, the kinematics of member stars.

5. There are primary and tertiary branch B detections, plus one tertiary branch A detections, tracing a feeble (but coherent) spur from an ancient ($p = -3, -4$) wrap, predicted by the model to arch between $(X, Y) \sim (-10, -15)$ and $(X, Y) \sim (-3, -22)$. As far as we know this is the first detection of this nearby portion of the Stream. A couple of primary branch B detections (and a tertiary branch A detection) may trace similar substructures on the near side of the constant-distance portion of the trailing arm (see Section 6.3 for an alternative interpretation).

6. There are a couple of other cases of slight distance mismatches between branch A and branch B detections, occurring, however in the region around $(X, Y) \sim (-10, -25)$
where different wraps of the Stream cross each other. It may be challenging to disentangle the various contributions based on distances alone. A more interesting case is provided by the two pairs of detections around $(X, Y) \sim (-23, -30)$, a region where the model predicts only feeble structures and branch B detections are clearly more nearby than branch A ones. It is intriguing to note that the few particles of the model lying in this region are not uniformly distributed but appear to form two approximately parallel tiny bridges that reasonably reproduce the observed pattern. Also in this case this is the first detection of such structures.

7. Both the P and S models by L05 predict the presence of a fairly dense and narrow wrap composed by $p = -3$ and $p = -4$ particles crossing the accessible range of the $X$, $Y$ plane from $(X, Y) \sim (-7, -7)$ to $(X, Y) \sim (5, -12)$, where it emerges from the $d \lesssim 12$ kpc zone of insensitivity of our method (the triaxial model briefly discussed in Section 6.3 also displays a similar feature). Here we have a primary detection from the SCP of F1A that currently is the first detection of this nearby wrap of the leading arm.23 A detailed exploration of the $d \lesssim 12$ kpc zone would require a different kind of analysis; hence, it is postponed to a future contribution. We note, however, that Monaco et al. (2007) studied the chemical composition and the kinematics of a small sample of M giants that can be attributed to this nearby wrap.

8. Two branch B detections, located at $(X, Y) \sim (-3, -16)$ and $(X, Y) \sim (+3, -18)$, F5B and F2B, respectively, do not seem to match any significant structure of the spherical and prolate L05 models; the primary one (that with positive $X$) is marginally consistent with the part of the leading arm plunging toward the Sun of the oblate model (but see Section 6.3). As anticipated in Section 4.1, their position ((R.A.,decl.) = (195°, +16°), $d \sim 18$ kpc and (R.A., decl.) = (190°, +18:5), $d \sim 19.5$ kpc, respectively) is fully compatible with the outer fringes (i.e., the high Galactic latitude edge) of the nearby overdensity S297+63-20.5, discovered by Newberg et al. (2002) and discussed in detail in Newberg et al. (2007). It is unclear why we do not detect the structure in other adjacent fields, or in the corresponding branch A fields. This may be due to the intrinsic weakness of the RC signal from these nearby features, or it may reflect a high degree of complexity of the sub-structures, as suggested in the analyses by Keller et al. (2009) and Vivas et al. (2008). Newberg et al. (2007) provided positional and kinematic evidence arguing against the association of S297+63-20.5 with the Sgr Stream, that was originally proposed by Martínez-Delgado et al. (2007) and cannot be completely ruled out at the present stage (see also the discussion in Law & Majewski 2010). However, Figure 22 provides further support for the conclusions by Newberg et al. (2007): the peaks detected here do not present any continuity with the main branches of the leading and trailing arms of the Stream as traced in the present analysis (but see also Section 6.3). Our data suggest that the leading arm crosses the Galactic plane at $\sim 10$ kpc from the Sun, toward the Anticenter, in agreement with Newberg et al. (2007) and Seibroke et al. (2008). On the other hand, the identification of S297+63-20.5 with the Virgo Stellar Stream (VSS; Duffau et al. 2006; Vivas et al. 2008) seems likely, while the relationship between VSS and the Virgo Over Density (Juric et al. 2008; Newberg et al. 2007; Keller et al. 2009) is less certain (see Newberg et al. 2007; Keller 2009). We are currently following up these possible detections of S297+63-20.5/VSS in F5B and F6B (also looking for the structure at lower latitudes). If confirmed, they would provide the first detection of RC stars in these structures, in analogy with the cases of Boo III discussed in Correnti et al. (2009). RC stars may provide new insights on the nature of complex series of structures recently identified in the direction of Virgo (Keller et al. 2009; Keller 2009).

All the features and correlations with the P model described above can be seen even more clearly and directly in Figure 13 that provides the most natural way to compare our measures with models. For example, the match between two weak model structures described in point 6 above and our detections can be very clearly appreciated in that plot, at $230° \lesssim A \lesssim 245°$ and $d \simeq 37$ kpc. The linear trend of the increasing distance with decreasing $A$ of the two parallel sets of observed points is very nicely matched by corresponding filaments of particles in the model.

Figure 23 shows that the overall morphology of the three models is remarkably similar in the $X_{\odot,Sgr}$ versus $Z_{\odot,Sgr}$ plane and reproduces the general trends of the data (except for the Oblate model, that predicts a total lack of particles for branch B detections at $X_{\odot,Sgr} > 0$, at odds with observations). A more detailed analysis is beyond the scope of this paper. On the other hand, we must conclude, from the results summarized above, that the prolate model by Law et al. (2005) is the one (among those considered here) providing the best match to the positional data considered here. It should be stressed that with this we do not intend to say that a prolate halo model is favored by our data, as the comparison was limited to just three very specific models that are already known not to be able to fit all the positional and kinematical observational constraints available (Law et al. 2009). In particular, it should be recalled that the available radial velocities of Stream stars seem to favor prolate models (Helmi 2004), while the angular precession of the leading arm with respect to the trailing arm favors spherical or slightly oblate models (L05; Johnston et al. 2005; Newberg et al. 2007; Prior et al. 2009a, and references therein). We simply note that any future model intended to fit all the observed characteristics of the Sgr Stream must have a spatial structure very similar to that of the prolate model by Law et al. (2005), at least in the portion of space sampled by our study, unless an alternative origin is assumed for the $d \sim 25$ kpc structure we tentatively interpreted as the trailing arm.

6.1. Trends of Depth as a Function of Orbital Azimuth

In line with the above discussion, in Figure 25, we compare the (FWHM along the los described in Section 3.5 with those measured from the distribution of particles of the Prolate model of L05, along the same los. The following discussion is mainly intended to illustrate the possible use of the derived FWHM. It should be considered that there are additional sources of uncertainty affecting this comparison, associated with the measure of FWHM in models. For example, the measured width depends on the actual number of particles of the model, the limited number of particle may lead to underestimates of the actual width. This expected effect is clearly confirmed

23 While the distinction between leading and trailing arms is easy and sensible for particles lost in the latest two perigalactic passages, it becomes increasingly blurred for Stream wraps dominated by more ancient relics, as a particle can reach the same position in these parts of the Stream both from the leading and from the trailing sides of the tidal tails.
in Figure 25, where observed FWHM are always equal or larger than their model counterparts. The disentanglement of overlapping structure may also be problematic, as is unavoidably performed in different ways in the observed SCPs and in the N-body models.

To minimize the possible ambiguities associated with the collapse of complex structures along the los into a single FWHM measure (see Section 3), especially in regions where different wraps cross one another, in Figure 25 we limit our comparison to $X > 10$ kpc peaks tracing the two main wraps (leading and trailing arms) that are 30 kpc apart at $A_{Sgr} = 290^\circ$ and cross each other at $A_{Sgr} = 265^\circ$, and we consider only primary and secondary peaks.

The most interesting and sensible comparison is between the trends of the FWHM as a function of orbital azimuth. The upper panels of Figure 25 show that the observed and predicted trends for the leading arm are indeed similar, both in direction and in amplitude, for both branches. The agreement of the absolute values of the FWHM is also satisfying (within a factor of $\sim 2$), with four branch A and one branch B detections closely matching the model predictions. The FWHM of the considered detections from F1A and F3A gives some reason of concern, as they break the continuity of the observed trend: this may suggest that there may be some unresolved structure in these peaks. Alternatively we have to accept variations of a factor of $\sim 2$ as due to the uncertainty inherent to the adopted method of estimating FWHM. The overall agreement is reasonable also for the putative trailing arm.

It is interesting to note that the different trends observed in the two branches of the leading arm are reproduced by the P model that do not present any bifurcation (see also Figure 26, for a similar behavior in the $\Lambda$ versus density trend in the leading arm).

**Figure 25.** Comparison between the trends with $A_{Sgr}$ of the observed FWHM along the los (the same symbols as Figures 20, 21, and 22, and the predictions of the Prolate model by L05 (open triangles). The comparison is limited to the los from F1 to F7 (i.e., those providing the cleanest tracing of the leading and trailing arms). The upper row of panels refers to detections in the leading arm and the lower row to detections in the trailing arm. The left and right columns refer to branches A and B, respectively. The field numbers increase (from F1 to F7) from right to left, as in Figure 13 and Figures 20–22.

(A color version of this figure is available in the online journal.)

**Figure 26.** Same as Figure 25 for the density of RC stars as a function of $A$. An arbitrary normalization factor of 2 is applied to all the density values from the theoretical model.

(A color version of this figure is available in the online journal.)

### 6.2 Trends of Density as a Function of the Orbital Azimuth

In strict analogy with the analysis described in the previous subsection, in Figure 26, we present the comparison of the observed and predicted trends of the stellar density (see Section 3.4) as a function of $A$. The measured density is compared with the density of particles in the same wrap of the P model. The density scale of the model has been multiplied by the arbitrary factor of 2.5, to achieve a reasonable normalization with the observed values. As in Section 6.1 the comparison presented is just intended as illustrative of the possible use of these numbers and it is limited to the cleanest portions of the leading and trailing arms, at $X > -10$ kpc.

For the leading arm, the match between the overall observations and the models is acceptable, in particular for branch A. The highly discrepant point at $A \sim 263^\circ$ is associated with an especially complex SCP model, with three overlapping peaks (F5B): for this reason, we are inclined to ascribe the discrepancy to an erroneous density estimate.

On the other hand, while the model predicts low or even negative gradients of density with increasing $A$, the observations show a very strong positive gradient, similar in both branches.24 This is an obvious example of the kind of constraints that can be achieved with these data: in principle, any fully successful model of the disruption of Sgr must also reproduce a density gradient similar to the observed one. However, it has to be taken into account that the available models are intended to describe the DM halo in which the baryonic part of the galaxy is embedded. While, for example, stars and DM particles in the Stream should not greatly differ in their kinematical and positional properties, their density would follow the same trends only if mass strictly follows light also in tidal tails, which is very

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24 It has to be recalled that the bifurcation in two branches is an observed property of the main wrap of the leading arm. There is no reason to discuss other wraps as divided into two branches: here, this is merely incidental due to the adopted distribution of the observed fields that were chosen to trace the bifurcation.
remarkable increase of the density of this wrap for similar fashion to the P and S models, the T model predicts a were also found by Bel06. It is interesting to note that, in a same is true for the sparse detections behind the main wrap that regard and we are in good agreement with these authors. The as the model is found to fit the observations by Bel06 in this (A color version of this figure is available in the online journal.) adopted by L05).

When this paper was ready for submission, a preprint was posted (Law & Majewski 2010), following up the preliminary analysis by Law et al. (2009). In that study, a new N-body model of the disruption of Sgr within a triaxial Galactic potential is shown to provide a reasonable match to most of the existing observational constraints. In particular, the new model reproduces the distance versus A trend reported by Bel06 for the main wrap of the leading arm, the precession between the leading and trailing arms, and it matches the existing sets of kinematic measures. As we have stressed before, it is far beyond the scope of this analysis to find out which is the best available model. However, it is worth showing the comparison between our results and this new model, for completeness and (above all) as a very instructive example of how the interpretation of observed features may depend on the considered model (see Section 7 for discussion). From the inspection of Figures 27 and 28, it can be concluded that the triaxial halo model provides a reasonable match to distance gradient of the main wrap of the leading arm, over the whole range of Λ covered by our data. This is not unexpected as the model is found to fit the observations by Bel06 in this regard and we are in good agreement with these authors. The same is true for the sparse detections behind the main wrap that were also found by Bel06. It is interesting to note that, in a similar fashion to the P and S models, the T model predicts a remarkable increase of the density of this wrap for Λ ≥ 275° (X ≥ 0) that is not observed, neither in this work or by Bel06.

unlikely to be the case (see Peñarrubia et al. 2008 and references therein).

6.3. The Triaxial Model by Law & Majewski (2010)

Moreover, the T model does not seem to display the narrow and dense structure of the main wrap of the leading arm that in the P model appears to match so well our coherent set of primary detections in that region. We postpone a detailed comparison between the observed structure along the los and the predictions of the P and T models to a future contribution: here, we limit the discussion to the main features of the models (i.e., trends of distance with orbital azimuth).

The new model makes predictions very similar to those of the P and O models also regarding the nearest wrap of the Stream, running across the whole range of Λ sampled by our data. However, it should be noted that it predicts this wrap to lie below our sensitivity limit at any Λ, in the observed range; thus, it is unable to match the observed points at Λ ≥ 287° and d ≥ 13 kpc, at odds with the P model. The T model presents a very coherent narrow wrap of the trailing arm running at nearly constant d ≃ 20 kpc from Λ ≥ 290° to Λ ≥ 250°, then it begins to bend gently toward d ≥ 25 kpc from Λ ≥ 235° where it crosses with the leading arm. This feature matches very nicely the nearby (d ≤ 25 kpc) detections that we tentatively attributed to S297+63-20.5/VSS and to an ancient spur of the leading arm, in the comparison with the P model described in detail in Section 6.

On the other hand, the coherent structure we detect from Λ ≥ 260° to Λ ≥ 250°, that we interpreted as a wrap of the trailing arm, is not present in the T model. The same is true for the d ≥ 40 kpc structures at Λ ≤ 245°. The orbital path of the simulated Sgr galaxy matches also these structures, so it is not excluded that they may correspond to very ancient wraps. However, it has to be noted that the T model is the remnant of the evolution of a Sgr progenitor for z ≥ 8 orbits (not just ∼4 as for S, O, and P models), thus it should include wraps populated from more ancient stripping events than the S, O, and P models.

In conclusion, while the P model still appears to provide a more thorough match of the observed structures, the T model...
provides a promising alternative that deserves to be investigated in further detail. Not surprisingly, the mere comparison with our own (limited) data set shows that both models need to be refined.

7. SUMMARY AND CONCLUSIONS

We have used RC stars to trace the long tidal tail of the Sgr dSph galaxy in the portion of the Northern sky sampled by the SDSS-DR6. Structures along the los are identified as peaks in the (otherwise smoothly increasing) I- and V-band SCPs of color-selected samples of candidate RC stars, from \( \sim 5^\circ \times 5^\circ \) fields covering the whole extension of the two main branches (A and B) of the Sgr Stream identified by Belokurov et al. (2006) in the same data set. Any other part of the Stream in addition to these branches is expected to lie (approximately) in the same plane, i.e., it should be visible in the considered fields. The analysis was focused on obtaining the most accurate and reliable distances to all the wraps of the Stream that we were able to detect.

Many significant peaks were consistently found in both the SCPs of several fields. The observed SCPs were modeled as a series of Gauss curves (one for each peak) superposed to a polynomial accounting for the smooth fore-/background population. For each significant peak, we derived a purely differential estimate of its distance (with uncertainties \( \lesssim 10\% \)), an estimate of the FWHM along the los, and an estimate of the associated density of RC stars attributable to the considered structure. All the derived quantities are provided in Table 2 as powerful constraints for the new generations of models of the disruption of the progenitor of Sgr dSph within the MW halo.

To illustrate the potential of our measures in that context we compared them with the three models made publicly available by L05. These provide a realistic realization of the present epoch configuration of particles that were originally bound to a progenitor similar to Sgr that was evolved for \( \gtrsim 4 \) orbital periods within a static Galactic potential with different degrees of flattening (a spherical, oblate, and prolate halo, respectively). The models (and in particular the Prolate halo one, that matches well most of our observations) are also used as guidelines for the interpretation of our results. The great complexity of a structure like the Sgr Stream, multiply wrapped around the Galaxy, requires a process of convergence between models and observations: the latter must constrain models but the former are indispensable to re-conduce such a complexity to a single structure (see Section 6.3).

Our technique resulted in higher-accuracy distance estimates with respect to previous studies and demonstrated high sensitivity to feeble structures. However, the sensitivity is easily destroyed by contamination from Galactic sources: for these reasons, we had to limit our survey to \( b > 50^\circ \), while other (more abundant) tracers are able to follow the Stream down to \( b > 30^\circ \). The overall agreement with previous analyses is good (see Section 5). Finally, and most importantly, our method proved especially efficient in the detection of (relatively) nearby structures. In the following, we summarize and briefly discuss the main conclusions of this study, taking Figures 13 and 22, as references.

1. For \( \Lambda \gtrsim 255^\circ \) (\( X \gtrsim -10 \) kpc) the leading arm of the Stream is cleanly and coherently detected in both branches, going from \( d = 43 \) kpc at \( \Lambda \simeq 290^\circ \) to \( d = 30 \) kpc at \( \Lambda \simeq 255^\circ \). This is in full agreement with the results obtained with other tracers (Newberg et al. 2007; Niederste-Ostholt et al. 2010). This portion of the leading arm is the most unambiguous and robustly constrained.

2. In the same range of \( \Lambda \) (and \( X \)) a remarkably coherent structure is also very clearly detected at nearly a constant distance from us, \( d \simeq 25 \) kpc. According to the S and P models by L05 this can be interpreted as a wrap of the trailing arm, while it has no obvious counterpart in the recently presented T model (Law & Majewski 2010). The P model matches the observed structure very well. Previous detections of this wrap were reported only around \( \Lambda \simeq 295^\circ \) (see Majewski et al. 2003, for discussion and references).

3. The comparison with the L05 models strongly suggests that the run of the relative distance as a function of \( \Lambda \) of the two wraps described above has a strong power in discriminating between different models of the Stream. In particular, the S and O models by L05 clearly fail to reproduce the observed trends. On the other hand, the P model reproduces the trend nearly perfectly.

4. Weak detections of a further, more distant wrap (running parallel to the leading arm, in the same range of \( \Lambda \) as above) were also obtained. These support similar results by Belokurov et al. (2006). An enhancement of the density of this wrap at \( \Lambda \gtrsim 275^\circ \), predicted by the S, P, and T models, seems to be excluded by this analysis (in agreement with Bel06).

5. Turning to the \( \Lambda \lesssim 255^\circ \) (\( X \lesssim -10 \) kpc) portion of the survey, this is characterized by a very complex structure, partly due to the crossing of multiple wraps predicted to occur in this region by all the models. Hence, the interpretation of these structures is less straightforward and must be considered as tentative. However, the P model appears to provide a reasonable match to all the detections in this region: for these reasons, we adopt it as a guideline for our best-effort interpretation of the data (see Section 6.3 for an alternative view).

6. The leading arm seems to be traced beyond \( \Lambda \simeq 255^\circ \), continuing its trend of linear decrease of its distance down to \( d \simeq 20 \) kpc at \( \Lambda \simeq 220^\circ \). Extrapolating from the observed trend one would expect the arm to cross the Galactic disk at \( \sim 10 \) kpc from the Sun, in agreement with the conclusions by Newberg et al. (2007), Seabroke et al. (2008), and Law & Majewski (2010). The degree of coherence of the detections in this portion of the leading arm is lower suggesting the possible presence of further (unresolved) substructure or due to higher uncertainties associated with weaker and overlapped structures.

7. In the same region, the continuation of the trailing arm is coherently traced where predicted by the P model up to \( \Lambda \gtrsim 240^\circ \) (\( X \gtrsim -15 \) kpc). For \( \Lambda \lesssim 235^\circ \), in particular, we lack any detection corresponding to the well-defined structure predicted by the model (the same is true for the T model). On the other hand, coherent detections are obtained behind the main wrap of the trailing arm as predicted by the P model for \( \Lambda \lesssim 240^\circ \). These detections may indicate a different shape for that portion of the trailing arm. However, as discussed above, they match two more feeble structures running parallel to the main arm. It is obvious that the P model is not adequate to fit all our observations, in spite of the overall good match.

8. The most nearby detections are the more difficult to interpret robustly. However, the single primary detection at \( d \simeq 13 \) kpc and \( \Lambda \simeq 287^\circ \) (just beyond the \( d \lesssim 25 \) kpc region) provides a promising alternative that deserves to be investigated in further detail. Not surprisingly, the mere comparison with our own (limited) data set shows that both models need to be refined.
12 kpc “zone of avoidance” of our technique) matches the prediction of all the three L05 models, as well as for the model by Law & Majewski (2010). For this reason, we are quite confident to have detected for the first time the nearest wrap of the leading arm. We are currently following up this finding, to check if the predicted d ∼ 10 kpc wrap can be detected also in other l.o.s.

9. The three detections at d ∼ 20 kpc and Λ ∼ 245° are matched by a spur of the P model. The two detections at d ∼ 18 kpc and Λ ∼ 260° have been tentatively ascribed to the S297+63-20.5/VSS overdensity. The T model matches very well all of these detections with a single narrow wrap of the Sgr trailing arm. However, Law & Majewski (2010) confirm that the kinematics predicted by their model toward VSS is markedly different from what observed by Duffau et al. (2006) and Newberg et al. (2007).

10. The overall trends of FWHM along the los as a function of R.A. along the leading arm (branches A and B) are in fair agreement with those by Niederste-Ostholt et al. (2010). Our estimates of the total luminosity per kpc at any given R.A. are lower than theirs by a factor of ∼4–5.

12. Kinematic follow-up of the newly identified structures is clearly urgent. Carrell & Wilhelm (2010) recently demonstrated that this can be carried on using exactly the same tracer stars, i.e., RC stars.

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