

## THE VIRGO STELLAR OVERDENSITY: MAPPING THE INFALL OF THE SAGITTARIUS TIDAL STREAM ONTO THE MILKY WAY DISK

DAVID MARTÍNEZ-DELGADO,<sup>1,2</sup> JORGE PEÑARRUBIA,<sup>3,4</sup> MARIO JURIC,<sup>5,6</sup> EMILIO J. ALFARO,<sup>2</sup> AND ZELJKO IVEZIĆ<sup>5</sup>

*Received 2006 September 5; accepted 2007 January 16*

### ABSTRACT

The recently discovered Virgo stellar overdensity, which extends over  $\sim 1000 \text{ deg}^2$  perpendicular to the Galactic disk plane ( $7 \text{ kpc} < Z < 15 \text{ kpc}$ ,  $R \sim 7 \text{ kpc}$ ), is the largest clump of tidal debris ever detected in the outer halo and is likely related to the accretion of a nearby dwarf galaxy by the Milky Way. We carry out  $N$ -body simulations of the Sagittarius stream to show that this giant stellar overdensity is a confirmation of theoretical model predictions in which the leading arm of the Sagittarius stream crosses the Milky Way plane in the solar neighborhood. Radial velocity measurements are needed to confirm this association and to further constrain the shape of the Milky Way dark matter halo through a new generation of theoretical models. If the identification of the Virgo overdensity and the Sagittarius leading arm is correct, we predict highly negative radial velocities for the stars of the Virgo overdensity. The detection of this new portion of the Sagittarius tidal stream would represent an excellent target for ongoing and future kinematic surveys and for dark matter direct detection experiments in the proximity of the Sun.

*Subject headings:* galaxies: individual (Sagittarius) — galaxies: interactions — Galaxy: halo — Galaxy: structure

*Online material:* color figure, mpeg animations

### 1. INTRODUCTION

In the last decade, various large-scale CCD surveys (the Sloan Digital Sky Survey [SDSS]; the Two Micron All Sky Survey [2MASS]; the QUEST survey) have for the first time found strong evidence for the presence of a significant amount of substructure in the halo of the Milky Way in the form of long tidal streams or stellar clumps (Newberg et al. 2002; Majewski et al. 2003). These have been interpreted as the remnants of the latest mergers occurring as a part of the hierarchical buildup of our Galaxy. In addition,  $N$ -body simulations of these merger events (Helmi 2004; Martínez-Delgado et al. 2004b; Law et al. 2005; Peñarrubia et al. 2006) have been extensively used to (1) associate the tidal debris with their progenitor galaxies, (2) determine the dynamical history of the progenitor satellites, and (3) constrain the distribution of dark matter in the Milky Way. The ultimate goal of these studies is to infer the formation process of the Milky Way from the properties of the present fossil records.

Much of the observational and theoretical effort has focused especially on the two largest tidal streams discovered so far: the tidal stream of the Sagittarius dwarf galaxy, which wraps around the Galaxy in a highly inclined orbit with respect to the Milky Way disk (Ibata et al. 2001; Martínez-Delgado et al. 2001; Majewski et al. 2003), and the Monoceros tidal stream (Yanny et al. 2003; Ibata et al. 2003), a low-latitude tidal stream whose progenitor, possibly the controversial Canis Major dwarf galaxy (Martin et al. 2004; Bellazzini et al. 2004; Martínez-Delgado et al. 2005), moves on a prograde, nearly circular orbit (Peñarrubia et al. 2005), according to the recent proper motions measured by Dinescu et al. (2005). In addition, Rocha-Pinto et al. (2004) reported the discovery of a new possible tidal stream in the Triangulum/Andromeda

constellations, although subsequent theoretical simulations identified this tidal debris as a part of a more distant, metal-poor wrap of the Monoceros tidal stream progenitor (Peñarrubia et al. 2005; D. Martínez-Delgado et al. 2007, in preparation).

In addition to these two large tidal streams, the analysis of large samples of stellar tracers of halo substructure (e.g., RR Lyrae stars, F-type turnoff stars) have revealed the presence of numerous stellar overdensities possibly associated with unknown merger events in the outer halo. In the Virgo constellation, several groups have reported numerous detections of stellar overdensities using different tracers.

1. The most conspicuous one is a diffuse concentration of metal-poor, old stars situated at  $\sim 20 \text{ kpc}$  from the Sun in the direction of the Virgo constellation, first detected by means of the identification of its associated main-sequence turnoff (MSTO) in a color-magnitude diagram (CMD) of a SDSS slice (named S297+63–20.0; Newberg et al. 2002). In addition, Vivas & Zinn (2003) reported a clump of 21 RR Lyrae stars located at  $\sim 20 \text{ kpc}$  from the Sun in the same region of the sky (see also Ivezić et al. 2004 and Vivas & Zinn 2006). This overdensity (named the “12.4<sup>h</sup> clump”) extends over an area of the sky of  $15^\circ \times 1^\circ$  (corresponding to a spatial size of  $5.3 \text{ kpc} \times 0.3 \text{ kpc}$  at  $D \simeq 20 \text{ kpc}$ ) and displays a line-of-sight depth of only  $\simeq 1.5 \text{ kpc}$  (Vivas 2002), which is considerably smaller than that of a similar RR Lyrae overdensity detected at the apocenter of the Sagittarius stream ( $\sim 4 \text{ kpc}$ ; Vivas 2002). Due to its possible tidal origin, they denoted it as the Virgo stellar stream (VSS). Martínez-Delgado et al. (2004b) suggested that the VSS might be related to the complex debris structure of the Sagittarius stream predicted by theoretical models for this region of the sky. However, spectroscopic follow-up of a sample of these RR Lyrae stars by Duffau et al. (2006) showed a fairly narrow velocity distribution that pointed to a progenitor galaxy less massive than the Sagittarius dwarf and, therefore, to a hitherto unknown tidally disrupted dwarf galaxy. Using SDSS photometric data, these authors estimated that the VSS covers roughly an area of  $106 \text{ deg}^2$  in the sky.

2. More recently, Juric et al. (2005) detected a remarkable excess of main-sequence stars toward the direction of the Virgo

<sup>1</sup> Instituto de Astrofísica de Canarias, La Laguna, Tenerife, Spain.

<sup>2</sup> Instituto de Astrofísica de Andalucía (CSIC), Granada, Spain.

<sup>3</sup> Max-Planck-Institut für Astronomie, Heidelberg, Germany.

<sup>4</sup> Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 1A1, Canada.

<sup>5</sup> Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544.

<sup>6</sup> School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540.

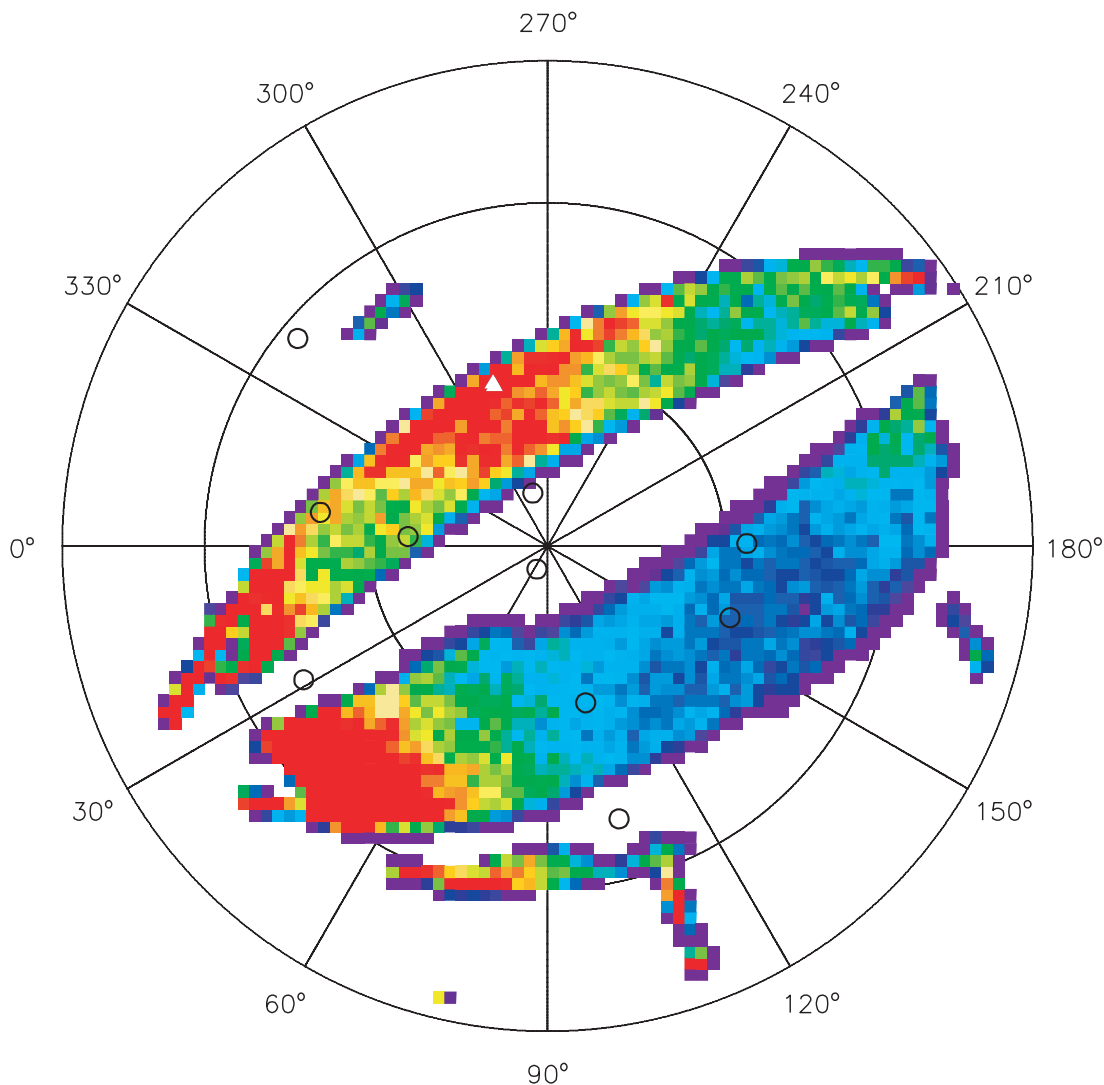


FIG. 1.—Density maps from SDSS of the north Galactic hemisphere. The positions of our positive (*triangles*) and negative (*circles*) detections of the Virgo stellar overdensity, as given in Table 1, are overplotted on a Lambert projection of the density map of Virgo that was given in Jurić et al. (2005). This map was generated by selecting MS stars with  $b < 0^\circ$ ,  $0.2 < g - r < 0.3$ , and  $20 < r < 21$ . Colors represent the number density of stars in the sky, in units of  $\text{deg}^{-2}$ , with purple corresponding to  $1 \text{ star deg}^{-2}$  and red to  $\geq 450 \text{ stars deg}^{-2}$ . Concentric circles correspond to constant Galactic latitude (the north Galactic pole is in the center, and the outermost circle corresponds to  $b = 0^\circ$ ). The high-density patch at  $l = 45^\circ$ ,  $b > 30^\circ$  represents the Milky Way disk protruding into the survey region.

constellation, named the Virgo overdensity (VOD). These authors construct a three-dimensional density distribution of Milky Way stars on the basis of the positions of  $\sim 48$  million stars obtained by the SDSS in order to identify stellar overdensities. The VOD density map reveals a giant, diffuse clump of stars without any evidence of a distinct core that extends over more than  $\sim 1000 \text{ deg}^2$  (see Fig. 1) toward the direction  $(l, b) = (300^\circ, 65^\circ)$ . This stellar overdensity shows a remarkably extended vertical structure perpendicular to the Galactic plane ( $\Delta Z \simeq 8 \text{ kpc}$ , with heliocentric distances between 5 and 17 kpc) that possibly crosses the Galactic plane, extending into the southern Galactic hemisphere (see also Fuchs et al. 2006). The density of the VOD main-sequence stars peaks at  $\sim 16 \text{ kpc}$  from the Sun (or at an RR Lyrae magnitude of  $\sim 16.7$ ), in good agreement with the RR Lyrae distance determination. These authors suggest that the giant stellar overdensity might be related to a hitherto unknown merger event involving a nearby, low-metallicity dwarf galaxy. Alternatively, Xu et al. (2006) suggest that this stellar clump could be related to a nonaxisymmetric Galactic stellar spheroid (see § 3.1).

Although the VOD and the VSS are coincident in position and display a huge sky-projected size, the different vertical structure suggests that they are independent systems. In the absence of radial velocity measurements for the VOD, it is not possible to address whether they share a common origin or are completely unrelated. For this reason, we refer to them with different names in this paper, following the nomenclature given to each overdensity in the original papers.

The main aim of this paper is to investigate the nature of the VOD and to analyze whether this stellar clump could be related to the Sagittarius stream through a comparison between up-to-date theoretical models and the available observational data. The structure, kinematics, and possible origin of the VSS will be analyzed in a companion paper.

In § 2 the theoretical models of the Sagittarius tidal stream are described. In § 3 we discuss the possible origins of the VOD. In particular, we explore the presence of tidal debris from the Sagittarius tidal stream in Virgo by means of updated theoretical models and compare its expected structural parameter with those derived for Virgo. Finally, conclusions are given in § 4.

## 2. THEORETICAL MODELS

The giant stellar overdensity detected in the Virgo constellation is located in a region of the Milky Way where several theoretical models predict the presence of Sagittarius galaxy debris. In order to explore a possible association of the VSS and the VOD with the Sagittarius tidal stream, we compare their derived spatial and kinematic properties with those obtained from up-to-date theoretical models.

Our Galaxy model consists of a Miyamoto-Nagai disk (Miyamoto & Nagai 1975), a Hernquist (1990) bulge, and a Navarro et al. (1996) dark matter halo (hereafter NFW halo). The gravitational potential of each of those components in cylindrical coordinates is

$$\Phi_d(\mathbf{r}) = -\frac{GM_d}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}}, \quad (1)$$

$$\Phi_b(\mathbf{r}) = -\frac{GM_b}{r+c}, \quad (2)$$

$$\Phi_h(\mathbf{r}) = \frac{GM_h}{\ln(1 + r_{\text{vir}}/r_s) - r_{\text{vir}}/(r_s + r_{\text{vir}})} \frac{q_h}{2r_s} \times \left[ \int_0^\infty \frac{m(u)}{1+m(u)} \frac{du}{(1+u)\sqrt{q_h^2 + u}} - 2 \right]. \quad (3)$$

Here  $r_{\text{vir}}$  and  $r_s$  are the virial and scale radii, respectively,  $M_h = M_h(r_{\text{vir}})$ , and  $r^2 = R^2 + z^2$ . The potential of an axisymmetric NFW halo was calculated from Chandrasekhar (1960) using elliptic coordinates:

$$m^2(u) = \frac{R^2}{r_s^2(1+u)} + \frac{z^2}{r_s^2(q_h^2 + u)}, \quad (4)$$

where  $q_h$  is the axis ratio of isodensity surfaces. In this contribution, we denote *oblate* and *prolate* halos as those with  $q_h < 1$  and  $q_h > 1$ , respectively. For spherical halos, equation (3) reduces to

$$\Phi_h = -\frac{GM_h}{\ln(1 + r_{\text{vir}}/r_s) - r_{\text{vir}}/(r_s + r_{\text{vir}})} \frac{\ln(1 + r/r_s)}{r} \equiv -V_c^2 \frac{\ln(1 + r/r_s)}{r/r_s}. \quad (5)$$

Following Johnston et al. (1999), we fix the disk and bulge parameters as  $M_d = 1.0 \times 10^{11} M_\odot$ ,  $M_b = 3.4 \times 10^{10} M_\odot$ ,  $a = 6.5$  kpc,  $b = 0.26$  kpc, and  $c = 0.7$  kpc. The Milky Way halo parameters at  $z = 0$  were taken from Klypin et al. (2002), being  $M_h = 1.0 \times 10^{12} M_\odot$ ,  $r_{\text{vir}} = 258$  kpc, and  $r_s = 21.5$  kpc, which leads to a concentration at the present epoch of  $c = r_{\text{vir}}/r_s = 12$ . According to the results of Peñarrubia et al. (2006), the evolution of the host Galaxy potential is not reflected in the present properties of tidal streams, so we use a static Milky Way potential for simplicity.

The actual disruption of satellites is modeled by “live” (i.e., self-consistent, self-gravitating)  $N$ -body realizations of a King (1966) model, with a dimensionless central potential  $W_0 = 4$ , or a concentration parameter  $c \equiv \log(r_t/r_K) \simeq 0.84$ , where  $r_K$  and  $r_t$  are the King and tidal radii, respectively. Our satellite models have  $N = 10^5$  particles. The initial and final (i.e., present) masses are  $M_s(t_0) = 10^9 M_\odot$  and  $M_s(t_f) = 5 \times 10^8 M_\odot$ , respectively. The initial King and tidal radii are  $r_K(t_0) = 0.58$  kpc and  $r_t(t_0) = 4.01$  kpc.

The equation of motion for each satellite particle is

$$\frac{d^2 \mathbf{r}_i}{dt^2} = -\nabla(\Phi_s + \Phi_d + \Phi_b + \Phi_h)_i, \quad (6)$$

where  $\Phi_s$  is the self-gravitational potential of the satellite galaxy and  $i = 1, \dots, N$ . We use SUPERBOX (Fellhauer et al. 2000) to calculate  $\Phi_s$  at each time step and solve equation (6) through a leapfrog scheme with a constant time step of  $\Delta t = 0.65$  Myr, which is about 1/100th of the satellite’s dynamical time.

Note that the Galactic potential is static and, therefore, equation (6) does not implement the response of the Milky Way to the presence of Sagittarius. We also neglect the effects of dynamical friction on the orbit of the Sagittarius galaxy (as suggested by Law et al. 2005).

We have reproduced the  $N$ -body models presented in Law et al. (2005). These models reproduce the following observational constraints:<sup>7</sup>

1. The heliocentric position and radial velocity of the Sagittarius dwarf are  $(D, l, b) = (24 \text{ kpc}, 5.6^\circ, -14.2^\circ)$  and  $v_r = 171 \text{ km s}^{-1}$ , respectively.
2. The orbital plane of Sagittarius has an inclination with respect to the Milky Way disk of  $i \simeq 76^\circ$ .
3. The averaged heliocentric distance for Sagittarius leading arm debris is  $D \sim 50$  kpc.

Items 1 and 2 above show that we have observational measurements for five of the six coordinates that determine the Sagittarius orbit. Law et al. (2005) surveyed the unknown coordinate (namely, the tangential velocity component,  $v_{\text{tan}}$ ) so that the resulting  $N$ -body models reproduced all the observational constraints listed.

Among other free parameters, Law et al. (2005) also explored which halo axis ratio ( $q_h$ ) would produce the best-fitting model to the available observational data. They found that, whereas the geometry and kinematics of the trailing arm are scarcely sensitive to the adopted  $q_h$ , radial velocity measurements of the leading arm were best matched by prolate ( $q_h > 1$ ) halo models, in agreement with Helmi (2004). However, Johnston et al. (2005) showed that Sagittarius models in prolate halos cannot reproduce the observed precession rate in the youngest pieces of the Sagittarius stream. Furthermore, they were able to constrain the halo axis ratio to be  $q_h = 0.83\text{--}0.92$ , excluding models with  $q_h > 1$  at a  $3\sigma$  level. In view of these results, we have performed  $N$ -body simulations where the halo axis ratio was fixed either to  $q_h = 0.8$  or to  $q_h = 1.4$ , excluding for the sake of brevity spherical halos, which reproduce neither the radial velocity variation along the stream nor its precession rate.

In a coordinate system where the Sun is located at  $(X, Y, Z) = (8, 0, 0)$  kpc, with a velocity of  $(U, V, W) = (-10, -220, 7)$  km s<sup>-1</sup> (Binney & Merrifield 1998), the Sagittarius velocities that best fit the kinematic and spatial distributions of stream debris are  $(237, -35, 220)$  km s<sup>-1</sup> for  $q_h = 0.8$  (oblate halo) and  $(244, -39, 249)$  km s<sup>-1</sup> for  $q_h = 1.4$  (prolate halo). With those inputs, we have evolved the  $N$ -body satellite model from 4 Gyr in the past to the present.

## 3. THE ORIGIN OF THE VIRGO OVERDENSITY

In this section we analyze the likelihood of various scenarios that may shed light on the nature of the VOD.

<sup>7</sup> It is also important to remark that we have not included any observational data of the VOD in the fitting of these simulations, which are only based in the fitting of an independent set of data of the Sagittarius tidal stream.

TABLE 1  
POSITIVE AND NEGATIVE DETECTIONS OF VIRGO  
FROM COLOR-MAGNITUDE DIAGRAMS

R.A. (J2000.0)	Decl. (J2000.0)	$l$ (deg)	$b$ (deg)	Detection
12 24 00.00.....	−01 00 00.0	288.62	61.11	Positive
	−00 30 00.0	288.39	61.59	Positive
10 20 00.00.....	40 00 00.0	180.71	56.24	Negative
13 48 16.00.....	52 08 32.0	103.69	62.81	Negative
15 37 49.00.....	69 17 31.0	104.68	41.44	Negative
12 40 00.00.....	18 20 00.0	285.67	80.82	Negative
13 56 21.00.....	−27 10 04.0	320.28	33.51	Negative
13 07 53.00.....	29 21 00.0	65.42	85.75	Negative
10 49 22.00.....	51 03 04.0	158.57	56.78	Negative
14 07 37.00.....	11 50 28.0	356.10	66.48	Negative
16 11 05.00.....	14 57 29.0	28.76	42.18	Negative
14 44 27.00.....	−01 00 00.0	351.54	50.88	Negative

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

### 3.1. The Signature of a Triaxial Galactic Stellar Halo

An alternative explanation for the presence of the unexpected main-sequence (MS) feature in the CMD reported in several studies (the so-called VOD; Newberg et al. 2002; Duffau et al. 2006; Jurić et al. 2005; see § 1) is to postulate the existence of a nonaxisymmetric Galactic model component, such as a triaxial halo (Newberg & Yanny 2005; Xu et al. 2006). We have explored this possibility by inspecting a sample of deep CMDs (with limiting magnitude  $R_{\text{lim}} \sim 24.5$ ) of Galactic fields taken with the Wide Field Camera (WFC) at the prime focus of the Isaac Newton 2.5 m telescope (La Palma, Spain) during different observing runs devoted to the search of tidal debris associated with known Galactic satellites or globular clusters (Martínez-Delgado et al. 2004a). Table 1 lists the position of our fields with positive and negative detections of the MS feature in the CMD. These negative detections can be interpreted as a lack of tidal debris, or that its surface brightness is extremely low to be detected in the small field of view of the WFC ( $35' \times 35'$ ).<sup>8</sup>

Figure 1 shows the position of these negative detections (circles) overlotted on the density map of the VOD derived by Jurić et al. (2005) from SDSS observations. The most interesting result is a negative detection  $\sim 20^\circ$  north of the center of our target field (see Table 1) that clearly shows a decrease of stream star counts in a small area of the sky. Although our sparse pencil-beam survey cannot constrain the spatial extent of this stellar population in the sky, the distribution of negative detections strongly indicates that this MS population is not likely to be a manifestation of a nonaxisymmetric Galactic model component, but is probably associated with the remnants of a dwarf galaxy under tidal disruption, in agreement with previous studies. Jurić et al. (2005) have reached the same conclusion by analyzing the vertical ( $Z$ ) distribution of VOD debris from their sample of SDSS G stars ( $0.10 < r - i < 0.15$ ).

### 3.2. Tidal Debris of the Sagittarius Dwarf?

#### 3.2.1. Sky-projected Density Maps

It is well understood from both observations and theoretical modeling that the Sagittarius leading arm turns around and falls

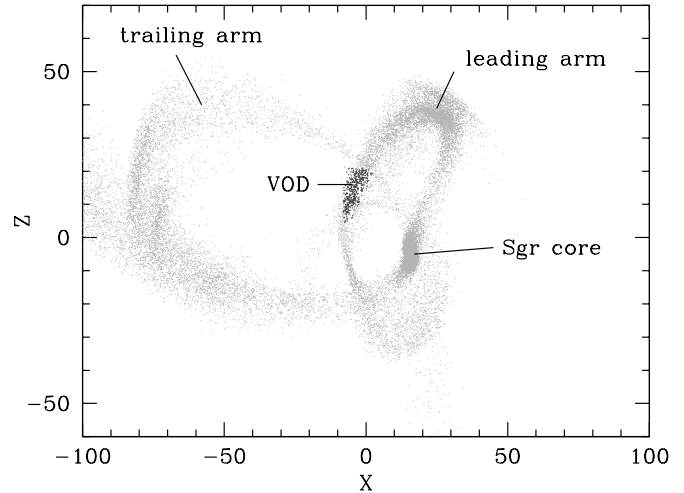


FIG. 2.—Galactic  $X$ - $Z$  projection of our  $N$ -body simulation of the Sagittarius tidal stream in a Milky Way dark matter halo with  $q_h = 0.8$ . For simplicity, only particles unbound less than 2.5 Gyr ago have been plotted. It displays the Sagittarius leading arm falling onto the Galactic disk, crossing the proximity of the Sun (large light gray circle). The particles with a position consistent with that of the VOD are shown in dark gray. [See the electronic edition of the *Journal* for a color version of this figure.]

toward the Galactic plane in the proximity of the solar neighborhood, yielding a vertical debris structure that might cross the Galactic plane and possibly extend into the southern Galactic hemisphere (Majewski et al. 2003; Martínez-Delgado et al. 2004b; Law et al. 2005). This downward flow of the Sagittarius stars onto the Galactic disk may share similar characteristics with those derived for the VOD in the stripe covered by the SDSS. As a guide for the reader, we illustrate this putative scenario in Figure 2, together with identifications of the different parts of the Sagittarius tidal stream obtained from our theoretical models (see § 3.2.2 for a three-dimensional comparison).

To examine whether the VOD is a part of the Sagittarius tidal structure, we compare the predictions from the theoretical models outlined in § 2 to the SDSS data presented in Jurić et al. (2005). When comparing the theoretical stream models against the SDSS, it is important to keep in mind that the observational data may be biased by systematic over- or underestimates of the distance scale. The stellar distances in the SDSS data were derived using an assumed photometric parallax relation whose shape is well constrained, but the zero point may be offset by as much as 0.4 mag (Jurić et al. 2005). This would translate into a 20% error in distance determination, thus potentially moving the observed center of the VOD to anywhere from 8 to 12 kpc. However, even the worst-case scenario would be compatible with the conclusions that we present.

Secondly, the vertical shape and density profile of the VOD (see Fig. 4, *bottom left*) depend strongly on the details of the (still preliminary) Galactic stellar halo model. The density gradients along this vertical structure should therefore be interpreted with caution, especially at low values of  $Z$  (closer to the disk). There the number density of Galactic stars dominates over the stars in the VOD, and even a few percent mismatch in the Galactic model may lead to an artificial increase (or decrease) of the residual stellar density ascribed to the VOD.

In Figure 3 we plot two equal-area projections of stream particles from the models with oblate ( $q_h = 0.8$ ) and prolate ( $q_h = 1.4$ ) halos (*top and bottom, respectively*). In these plots, the north Galactic pole is at the center, concentric circles show lines of constant Galactic latitude  $b$ , and the radial lines denote locations

<sup>8</sup> Martínez-Delgado et al. (2004b) estimated that the limiting surface brightness detection of our CMD technique is  $\Sigma \sim 32 \text{ mag arcsec}^{-2}$ .

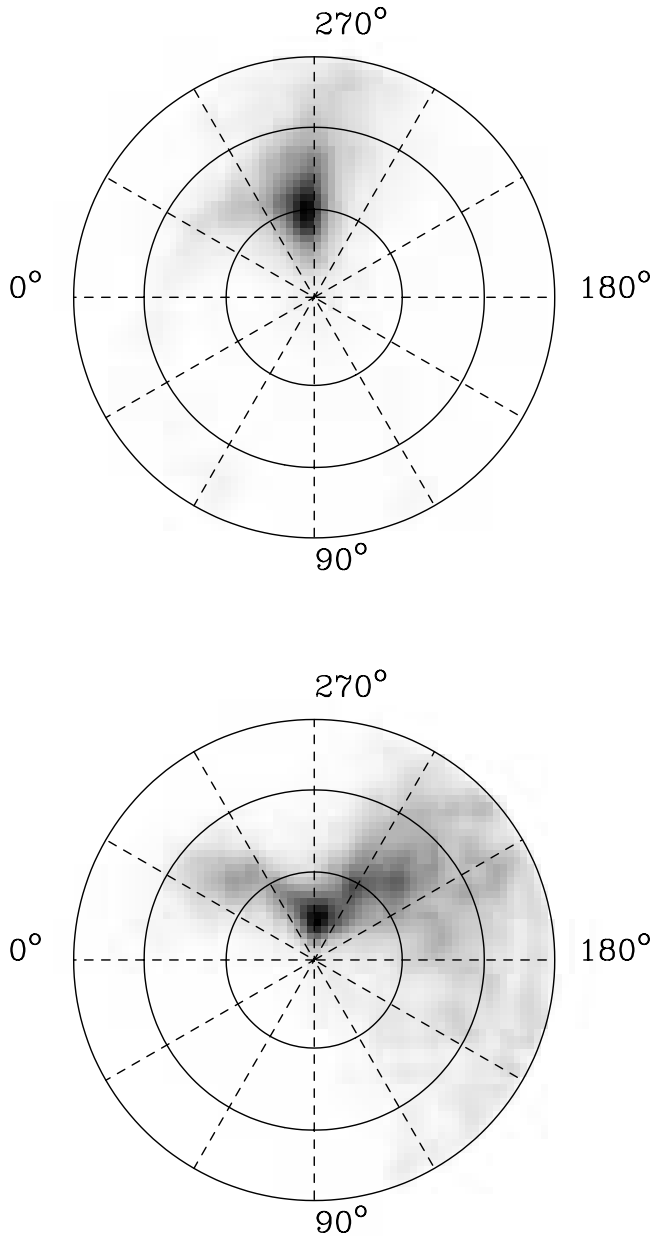


FIG. 3.—Density maps of the Sagittarius leading arm stars with heliocentric distance  $d < 15$  kpc from our  $N$ -body simulation of the Sagittarius tidal stream in a Milky Way dark matter halo with  $q_h = 0.8$  (top) and  $q_h = 1.4$  (bottom).

of constant Galactic longitude  $l$ . The Galactic center is to the left. We restrict the theoretical sample to the distance range of the Jurić et al. (2005) data by including only particles at  $b > 0^\circ$  and  $5 \text{ kpc} < d < 15 \text{ kpc}$ . To estimate the two-dimensional projected density distribution, we convolve the particles with a two-dimensional Gaussian  $\sigma = 2.9^\circ$  kernel. The resulting density is shown as varying shades of gray (black and white regions denote the highest and lowest densities, respectively) and can be directly compared with the observed morphology of the VOD displayed in Figure 1 (which was made with the same scale).

These maps show a conspicuous, diffuse clump of Sagittarius stream stars that extends over a few hundred square degrees, whose shape and extent resembles those of the stellar overdensity displayed in Figure 1. The position of the overdensity center (defined as the location of maximum density) in the sky depends on the shape of the halo and is consistent with simulations by Law et al. (2005; see their Fig. 13). The oblate model ( $q_h = 0.8$ ) produces a

better agreement with the SDSS data, with the overdensity being centered at  $(l, b) = (277^\circ, 63^\circ)$ . This corresponds to a small offset,  $\sim 11^\circ$ , with respect to the observed position of the VOD [ $(l, b) = (300^\circ, 65^\circ)$ ] as reported by Jurić et al. (2005). When we take into account the uncertainties in the Sagittarius stream modeling (see § 2) and in the SDSS data as noted above, the agreement in position is remarkable. This result also provides a natural explanation for the huge apparent extension of this tidal remnant, since we are observing through a stellar tidal stream that approaches the Sun in an almost radial direction in a localized area of the sky.<sup>9</sup>

The prolate ( $q_h = 1.4$ ) halo model (Fig. 3, bottom) produces a slightly worse estimate of the location of the center of the VOD and its general shape. It does predict a substantial amount of faint, diffuse debris in the  $180^\circ < l < 240^\circ$  region. This is to a degree observed in SDSS data; e.g., the density in the  $180^\circ < l < 210^\circ$  region (see Fig. 1) is apparently greater than that in its symmetric counterpart with respect to the  $l = 0^\circ, l = 180^\circ$  direction.

Interestingly, Gondolo et al. (2005) estimated a local stellar density of the Sagittarius leading arm of between 270 and 740 stars  $\text{kpc}^{-3}$ , corresponding to a range of  $2.1\text{--}7.4 \times 10^{-7}$  stars  $\text{pc}^{-3}$  or  $-15.4 < \ln \delta < -14.1$ . This is within the measured limits of stellar density in the VOD (see Fig. 23 in Jurić et al. 2005).

We note that the interpretation of the faint density excess is muddled by the existence of a different narrow stream in that region (Jurić et al. 2005) that is apparently unrelated to the Sagittarius stream. An alternative scenario is that the narrow stream might be the true origin of the density excess seen in SDSS data, instead of the Sagittarius debris. However, as will become evident in the next subsection, the three-dimensional structure of the VOD strongly disfavors this hypothesis.

### 3.2.2. Three-dimensional Spatial Structure

We compare now the three-dimensional structure of the VOD to the structure obtained from theoretical models of the Sagittarius stream in that region of the sky. We examine various cross sections (horizontal and perpendicular to the Galactic plane) of the VOD and the equivalent cross sections of the Sagittarius stream model.

In Figure 4 we plot the measured stellar density (left) and that obtained from the Sagittarius stream models for two different values of halo flattening,  $q_h = 0.8$  (middle) and  $q_h = 1.4$  (right). The density shown in the top left panel is that shown in Figure 8 (middle left) of Jurić et al. (2005). Before discussing its implications, we very briefly describe the method used here (for a more detailed discussion, we refer the reader to Jurić et al. 2005). The SDSS has observed  $\sim 4.2$  million G stars ( $0.1 < r - i < 0.15$ ) within the survey area. To convert the SDSS star counts to spatial number density, we estimated the distances to individual stars using the photometric parallax relation of Jurić et al. (2005; see their eq. [1]). From the estimated absolute and measured apparent magnitudes and from astrometry, we calculate the three-dimensional  $(X, Y, Z)$  positions of all stars in the SDSS stellar sample. We then bin them to  $dx = 500 \text{ pc}$  pixels in the coordinate system as defined above to obtain a three-dimensional star count map. Finally, by dividing the map by the volume that was observed within each voxel, we obtain a three-dimensional map of the number density within the Milky Way.

The density shown in the top left panel of Figure 4 is a planar cross section of the three-dimensional map along a plane parallel with the Galactic plane and at  $Z = 10 \text{ kpc}$  above it. The colors

<sup>9</sup> An analogy can be made to when a meteoroid stream crosses the Earth; see Nakamura et al. (2000).

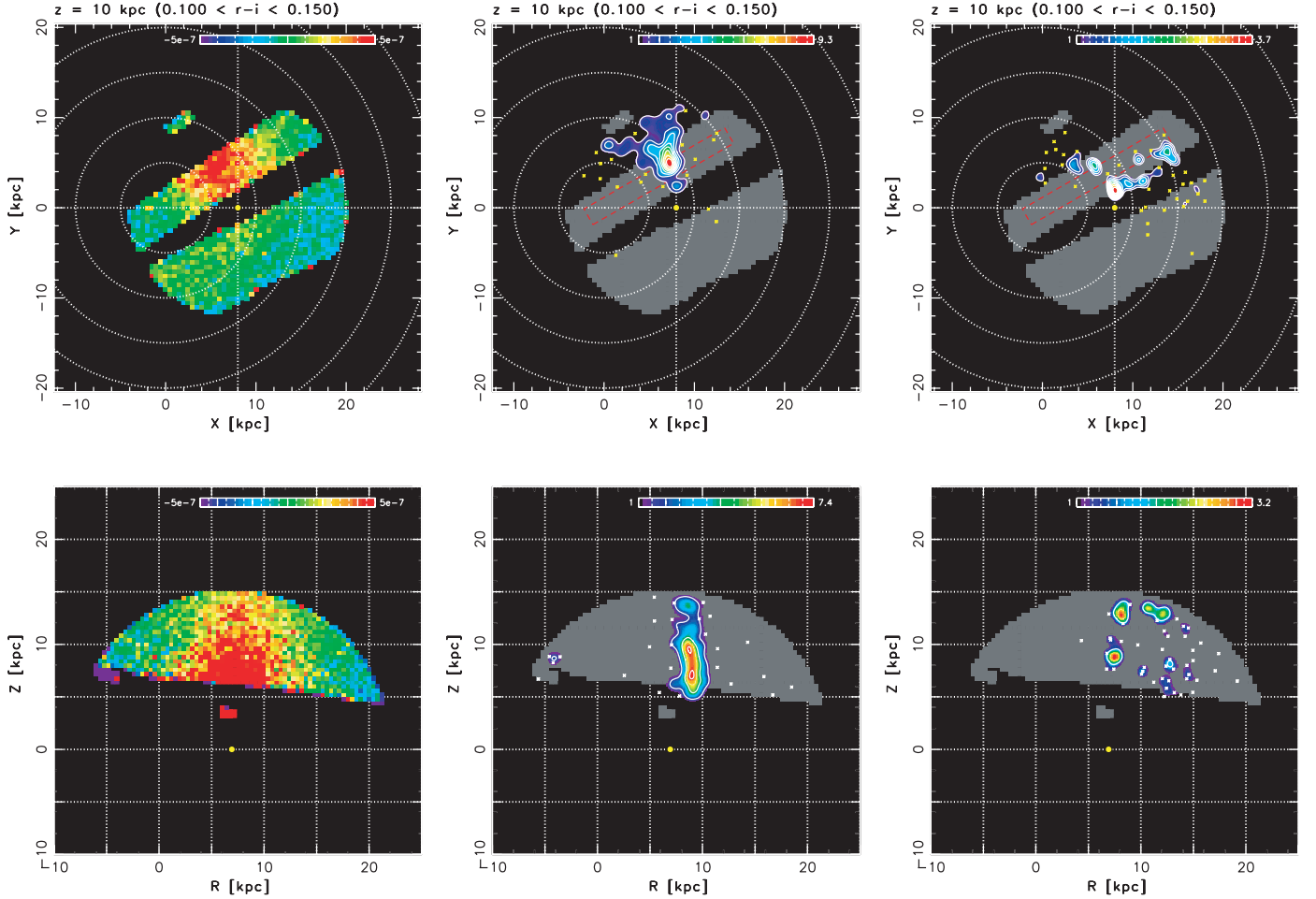


FIG. 4.— *Top*: Comparison of Galactic  $X$ - $Y$  projections of the Virgo overdensity obtained from SDSS data (*left*) with two Sagittarius stream models,  $q_h = 0.8$  (*middle*) and  $q_h = 1.4$  (*right*). In the left panel, we plot the residual stellar density after subtraction of the Galactic stellar density model in a thin  $\Delta Z = 0.5$  kpc slice at  $Z = 10$  kpc above the Galactic plane. The color coding represents the stellar overdensity of  $0.1 < r - i < 0.15$  stars in units of stars  $\text{pc}^{-3}$ . The colored contours in the middle and right panels are the Gaussian-smoothed ( $\sigma = 0.5$  kpc) particles from the Sagittarius simulation (in arbitrary density units). To account for observational errors, the simulation particles were additionally scattered in the radial direction, in accordance with the measured SDSS photometric scatter and the intrinsic scatter of the photometric parallax relation (see Fig. 4 of Jurić et al. 2005). *Bottom*: Comparison of stellar number density in the SDSS slice of the Virgo overdensity with the Sagittarius simulation. The  $Z$ -axis denotes the distance from the Galactic plane. The  $R$  coordinate is the distance from the Galactic center in the  $\phi = 30^\circ$  direction counterclockwise along the axis of Galactic rotation. The color coding and the symbols are the same as above.

encode the stellar number density (in units of stars  $\text{pc}^{-3}$ ) after the subtraction of Galactic background, on a linear scale, ranging from  $-5 \times 10^{-7}$  (blue) to  $5 \times 10^{-7}$  (red). The black regions are places where SDSS has not observed. The yellow dot marks the position of the Sun in the  $X$ - $Y$  plane ( $X = 8$  kpc,  $Y = 0$  kpc). The circles visualize the presumed axial symmetry of the Galaxy. If the Galactic number density distribution was axially symmetric, the color contours in the observed regions would trace such circles around the Galactic center, and the density distribution would be symmetric with respect to reflection along the  $X$ -axis [ $\rho(X, Y, Z) = \rho(-X, Y, Z)$ ]. As seen in the left panel, the density distribution is neither circular nor symmetric, and it exhibits a strong density enhancement centered approximately at  $X = 6$ ,  $Y = 4$  kpc, which is the VOD (Jurić et al. 2005).

We test under which conditions the VOD might be plausibly identified with the leading arm of the Sagittarius tidal stream by overplotting the equivalent  $X$ - $Y$  slices at  $Z = 10$  kpc of the simulated Sagittarius debris over the contours of the SDSS observed area (the gray area in the middle and right panels of Fig. 4). The stellar density maps in the middle and right panels are constructed in a manner similar to the method used for the SDSS data that was

outlined above. However, we note that the particle counts have been averaged in the  $9 \text{ kpc} < Z < 11 \text{ kpc}$  slice. The difference in thickness, compared to the  $dx = 500$  pc thickness used for the SDSS density estimation, is intended to account for the effect of radial smearing introduced by the intrinsic  $\sigma_{M_r} \sim 0.3$  mag dispersion of the photometric parallax relation. This effect increases the effective radial SDSS voxel scale (for a more detailed discussion, see Jurić et al. 2005). We estimate the density of the Sagittarius debris by convolving the simulation particles in the observed volume with a  $\sigma = 0.5$  kpc Gaussian kernel, thus obtaining the final distribution shown in the figure. The color scheme is that used in the right panel, with equal-density contours added. We also plot, as small crosses, the individual simulation particles that fall off the lowest equal-density contour.

As was the case in Figure 3, the oblate ( $q_h = 0.8$ ) model agrees well with the data within the observational and theoretical uncertainties. It successfully reproduces the diffuse shape of the overdensity and the location of the overdensity maximum. The location of the maximum for the  $q_h = 0.8$  model is within 1.5–2 kpc of the observed  $R \sim 6.5$ –7 kpc maximum of the VOD, and the diffuse morphology of the  $q_h = 0.8$  model appears to show a



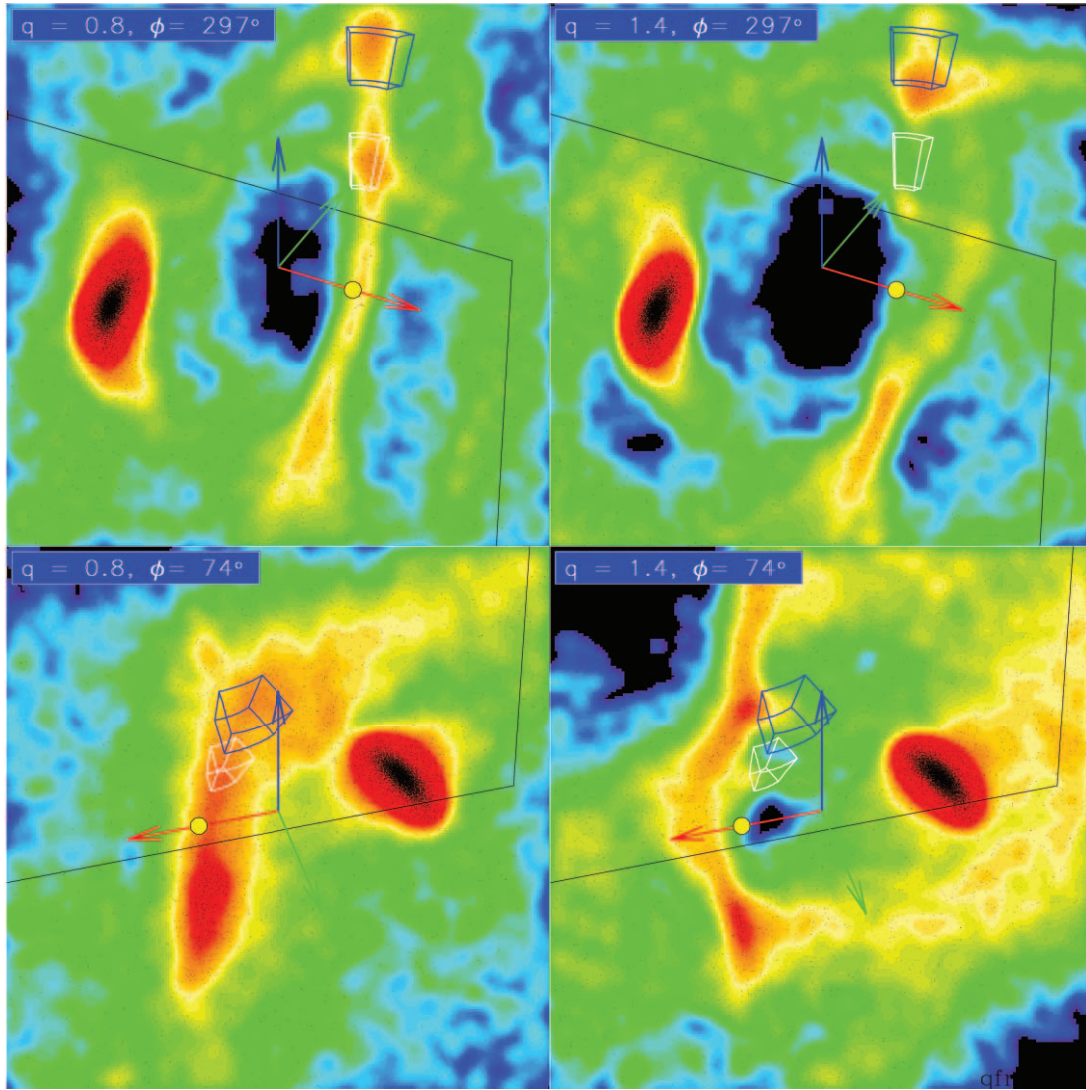


FIG. 5.—Two different three-dimensional projections (*top and bottom*) of the Sagittarius tidal stream models computed for an oblate halo, with  $q_h = 0.8$  (*left*), and a prolate halo, with  $q_h = 1.4$  (*right*). The column density of the simulation particles is represented by the rainbow color map, with red showing the areas of highest density and blue showing the areas of lowest density. Overplotted on the column density map as black dots are the simulation particles themselves. The core of the Sagittarius dwarf is clearly visible as a dense, dark region, due to the high density of the simulation particles that are still gravitationally bound to the dwarf's core. The origin of the coordinate system axes is the Galactic center, with the red axis ( $X$ ) pointing toward the Sun (yellow circle) and the blue axis ( $Z$ ) pointing toward the north Galactic pole. The region in which Jurić et al. (2005) detect the Virgo overdensity is marked by the white wire-frame box. The blue wire-frame box marks the location of the Virgo stellar stream as reported by Duffau et al. (2006). [The left and right panels of this figure are available as *mpeg* animations showing the oblate and prolate halos, respectively, in the electronic edition of the *Journal*.]

considerably better match to the observed morphology than that of the  $q_h = 1.4$  model. Some debris from the  $q_h = 1.4$  model (Fig. 4, *right*) can be also found at the location of the VOD. However, this model predicts the existence of other overdensities where none have been detected, and the morphology at the VOD location is irreconcilable with that inferred from the SDSS data.

We now examine the vertical distribution of matter in the VOD and compare it with the models of the Sagittarius stream. The bottom panels of Figure 4 give a comparison to the observed vertical stellar number density distribution in the Galaxy, cut along a narrow  $\phi = 30^\circ$  plane that passes through the center of the Galaxy and the center of the VOD (see the red dashed box in the top middle and top right panels of Fig. 4). The horizontal coordinate is the distance from the Galactic center,  $R$ , along the  $\phi = 30^\circ$  direction, while the vertical coordinate is the height above the Galactic plane. As in the case of the top left panel, the bottom left panel shows the overdensity as measured from SDSS data

(and is equivalent to the bottom left panel of Fig. 22 in Jurić et al. 2005), while the middle and right panels show the simulated density of the Sagittarius tidal stream as obtained from our simulations (§ 2), using an oblate ( $q_h = 0.8$ ) and a prolate ( $q_h = 1.4$ ) halo, respectively. The color scheme is the same as for the top panels, except that in the case of the bottom left panel we show the fractional residuals with respect to the best-fit Galactic halo model of Jurić et al. (2005).

In the case of the  $q_h = 0.8$  halo, the Sagittarius leading arm is nearly perpendicular to the Galactic plane, with a slight downward density gradient, in agreement with the findings of Jurić et al. (2005). Its location agrees to within  $\Delta R \sim 1$  kpc with the observed position of the Virgo overdensity. In contrast, although the prolate models ( $q_h = 1.4$ ) correctly reproduce the Galactocentric distance of the overdensity ( $R \sim 6\text{--}7$  kpc), they fail to reproduce the observed morphology. These models show a strong density maximum at  $(R, Z) \simeq (7, 8)$  kpc (incompatible with the density map)

and pieces of debris scattered out to  $R \sim 12.5$  kpc (not detected by SDSS). In this working scenario, the VOD morphology strongly disfavors prolate halo models.

The conclusions obtained from these cross sections can be summarized in the different spatial perspectives displayed in Figure 5,<sup>10</sup> which clearly shows the coincidence in position of the VOD and the location of the Sagittarius leading arm. Note that this part of the stream is distributed nearly perpendicularly to the Galactic disk in this direction of the sky. The panels of Figure 5 show two different three-dimensional projections (*top and bottom*) of our Sagittarius model, computed for oblate ( $q_h = 0.8$ ; *left*) and prolate ( $q_h = 1.4$ ; *right*) halos. They visualize the simulated Sagittarius dwarf and its tidally stripped tails in a rainbow color map, with the color encoding the column density of the simulation particles (red being the highest, blue being the lowest), which are overplotted in the panels as black dots. Note that the core of the Sagittarius dwarf corresponds to the darkest region, due to the high density of  $N$ -body particles that are still gravitationally bound to the dwarf's remnants. The coordinate system origin is located at the Galactic center, with the red axis ( $X$ ) pointing toward the Sun (*yellow circle*) and the blue axis ( $Z$ ) pointing toward the north Galactic pole. The region in which Jurić et al. (2005) detect the VOD is marked by the white wire-frame box, whereas the location of the VSS as reported by Duffau et al. (2006; see § 1) is shown by the blue wire-frame box. This coincidence points to a plausible identification of the VOD with the leading arm of the Sagittarius tidal stream or, at the very least, to likely significant pollution of the VOD as seen in the SDSS density maps by the Sagittarius tidal debris.

Taken together, analysis of Figures 1, 3, 4, and 5 clearly suggests that the Virgo overdensity may correspond to the detection of the Sagittarius stream's leading arm falling onto the Milky Way plane. Furthermore, the observed morphology is best described by models assuming an *oblate* Milky Way halo. With these results at hand, it appears fairly unlikely that the VOD is a tidal stream unrelated to the Sagittarius dwarf, and yet it has the predicted location and morphology of the Sagittarius leading arm.

### 3.2.3. Radial Velocity of the Virgo Overdensity

At present there is no kinematic information available for the stars of the Virgo overdensity. Radial velocities are necessary in order to establish unambiguously whether the Virgo overdensity is associated with the Sagittarius stream. Theoretical models predict that, independent of the halo shape, the leading arm of the Sagittarius stream is present in this area of the sky and moves on average with negative radial velocities as it falls onto the Milky Way disk. However, the exact magnitude of the mean radial velocity is a vital discriminator for the halo shape, as prolate and oblate halos lead to fairly distinct trends of  $v_r$  along the leading arm (Martínez-Delgado et al. 2004b; Helmi 2004; Law et al. 2005). We must remark that at present there is no information on the kinematics of the Sagittarius leading arm in this area of the sky, since this part of the stream was not covered by the spectroscopic survey of M giants carried out by Majewski et al. (2004).

There have been radial velocity measurements of RR Lyrae stars in the Virgo constellation that have shown the presence of a spatial overdensity (the 12.4<sup>h</sup> clump; see § 1) located at  $D \simeq 20$  kpc. Duffau et al. (2006) find a mean radial velocity in the Galactic rest frame of  $(v_r)_{\text{gsr}} \simeq 99.8 \text{ km s}^{-1}$  (see Table 1) with a fairly low velocity dispersion ( $\sigma = 17.3 \text{ km s}^{-1}$ ), unexpected for

the smooth population of RR Lyrae stars in the Milky Way, that suggests a possible tidal stream detection. According to theoretical models of the Sagittarius stream, the positive value of  $(v_r)_{\text{gsr}}$  excludes a membership of these stars in the leading arm. However, it is unclear whether the 12.4<sup>h</sup> clump is associated with the Sagittarius stream at all, since the oblate halo models ( $q_h = 0.8$  in this work) also predict the presence of the trailing arm stars in that volume of the Milky Way (see Fig. 5, where the blue wire-frame box represents the 12.4<sup>h</sup> clump position) with an averaged radial velocity of  $(v_r)_{\text{gsr}} = 90 \text{ km s}^{-1}$ , fairly similar to that reported by Duffau et al. (2006) [ $(v_r)_{\text{gsr}} = 83$  or  $100 \text{ km s}^{-1}$ , depending on their sample selection]. Therefore, if the 12.4<sup>h</sup> clump proves to belong to the Sagittarius trailing arm, it would favor the models with  $q_h < 1$ .

## 4. DISCUSSION

Theoretical models of the Sagittarius stream are not able to reproduce all the observational constraints. All models agree that the geometry of the tidal stream (i.e., its three-dimensional spatial distribution) clearly rules out halo models with a prolate shape (Martínez-Delgado et al. 2004b; Johnston et al. 2005; Law et al. 2005) and that Milky Way halos with  $q_h < 1$  are preferred at a  $3\sigma$  level. Paradoxically, the models that best explain the stream structure fail to reproduce the radial velocity trend along the leading arm unless prolate halo models ( $q_h > 1$ ) are invoked (Helmi 2004). Apparently, the present status of the Sagittarius stream modeling is that of a fish biting its tail.

It is not clear how to reconcile observations and theory. Possible explanations for this mismatch are (1) that the Milky Way models are overly simplistic (although similar models successfully reproduce other tidal streams such as Monoceros [Peñarrubia et al. 2005] and the Magellanic stream [Růžicka et al. 2006], both streams being best reproduced by models with oblate halos) or (2) the presence of possible systematic errors in the data of the Sagittarius tidal stream used in the computation of these simulations (as suggested by Chou et al. 2006).

In this contribution, we have investigated the origin of the Virgo overdensity discovered from the analysis of the SDSS data. The VOD is the largest clump of tidal debris ever detected in the outer halo of the Milky Way. We find that the position, apparent angular size, stellar density, and three-dimensional geometry match the theoretical predictions from the present Sagittarius stream models. According to these models, the Virgo overdensity corresponds to the Sagittarius leading arm falling onto the Milky Way disk. In agreement with other portions of the Sagittarius stream, the spatial distribution of the VOD is best reproduced by models with oblate halos ( $q_h < 1$ ). However, we must remark that a unambiguous association between the VOD and the Sagittarius stream cannot be established in the absence of stellar kinematics.

If the Virgo overdensity proves to belong to the Sagittarius stream, it might represent the key piece to solve the paradox described above, as we have for the first time the opportunity to measure the radial velocity of *millions* of stream stars just in the region where observations and theoretical models do not match. In addition, the detection of a new portion of the stream's leading arm provides strong constraints on future theoretical models and will help to address whether the Sagittarius stream passes through the solar neighborhood as it crosses the Milky Way plane (as predicted by Kundu et al. 2002; Majewski et al. 2003; Martínez-Delgado et al. 2004b). In that case, the Sagittarius stream would represent an important target for the ongoing Radial Velocity Experiment (RAVE) survey (Steinmetz et al. 2006), whose goal is to measure the radial velocity of  $\sim 10^6$  stars in both hemispheres. Thanks to the large sample of radial velocities, if the Milky Way

<sup>10</sup> This figure shows snapshots of a set of movies that are included as supplementary material in the electronic version of this paper and are also available at <http://www.astro.princeton.edu/~mjuric/sgr-virgo/>.



crossing occurs at a heliocentric distance of  $D < 3$  kpc, its presence will be detected in form of an excess of stars with  $v_r < 0$  in the northern hemisphere ( $b \geq 0^\circ$ ) and with  $v_r > 0$  for  $b < 0^\circ$  with respect to the background population of Milky Way stars (J. Peñarrubia et al. 2007, in preparation). The presence of a tidal stream in the solar neighborhood also represents an excellent target for weakly interacting massive particle (WIMP) direct detection experiments, since a substructure of dark matter in the proximity of the Sun would yield a “cold” flow of WIMPs through the detector of either of these dark matter experiments (see Savage et al. 2006 and Gondolo et al. 2005 for details). This would make the solar vicinity an excellent laboratory for probing the physical properties and nature of dark matter.

We thank Brian Yanny and Kathy Vivas for making available to us some results on the Virgo tidal stream during the preparation of this paper. We also thank the anonymous referee for useful comments that helped to improve this manuscript. D. M.-D. acknowledges funding by the Spanish Ministry of Education and Science (Ramon y Cajal contract and research project AYA 2001-3939-C03-01). J. P. thanks Julio Navarro for financial support.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is <http://www.sdss.org/>.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, the University of Basel, Cambridge University, Case Western Reserve University, the University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max Planck Institute for Astronomy (MPIA), the Max Planck Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, the University of Pittsburgh, the University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

#### REFERENCES

- Bellazzini, M., Ibata, R., Monaco, L., Martin, N., Irwin, M. J., & Lewis, G. F. 2004, *MNRAS*, 354, 1263
- Binney, J., & Merrifield, M. 1998, *Galactic Astronomy* (Princeton: Princeton Univ. Press)
- Chandrasekhar, S. 1960, *Principles of Stellar Dynamics* (New York: Dover)
- Chou, M.-Y., et al. 2006, *ApJL*, submitted (astro-ph/0605101)
- Dinescu, D. I., Martínez-Delgado, D., Girard, T. M., Peñarrubia, J., Rix, H.-W., Butler, D., & van Altena, W. F. 2005, *ApJ*, 631, L49
- Duffau, S., Zinn, R., Vivas, A. K., Carraro, G., Méndez, R. A., Winnick, R., & Gallart, C. 2006, *ApJ*, 636, L97
- Fellhauer, M., Kroupa, P., Baumgardt, H., Bien, R., Boily, C. M., Spurzem, R., & Wassmer, N. 2000, *NewA*, 5, 305
- Fuchs, B., Phleps, S., & Meisenheimer, K. 2006, *A&A*, 457, 541
- Gondolo, P., Freese, K., Newberg, H. J., & Lewis, M. 2005, *NewA Rev.*, 49, 193
- Helmi, A. 2004, *ApJ*, 610, L97
- Hernquist, L. 1990, *ApJ*, 356, 359
- Ibata, R. A., Irwin, M. J., Lewis, G. F., Ferguson, A., & Tanvir, N. 2003, *MNRAS*, 340, L21
- Ibata, R. A., Irwin, M. J., Lewis, G. F., & Stolte, A. 2001, *ApJ*, 547, L133
- Ivezić, Z., et al. 2004, in *ASP Conf. Proc. 327, Satellites and Tidal Streams*, ed. F. Prada, D. Martínez-Delgado, & T. J. Mahoney (San Francisco: ASP), 104
- Johnston, K. V., Law, D. R., & Majewski, S. R. 2005, *ApJ*, 619, 800
- Johnston, K. V., Majewski, S. R., Siegel, M. H., Reid, I. N., & Kunkel, W. E. 1999, *AJ*, 118, 1719
- Jurić, M., et al. 2005, *ApJ*, submitted (astro-ph/0510520)
- King, I. R. 1966, *AJ*, 71, 64
- Klypin, A., Zhao, H., & Somerville, R. 2002, *ApJ*, 573, 597
- Kundu, A., et al. 2002, *ApJ*, 576, L125
- Law, D. R., Johnston, K. V., & Majewski, S. R. 2005, *ApJ*, 619, 807
- Majewski, S. R., Skrutskie, M., Weinberg, M., & Ostheimer, J. 2003, *ApJ*, 599, 1082
- Majewski, S. R., et al. 2004, *AJ*, 128, 245
- Martin, N., Ibata, R. A., Bellazzini, M., Irwin, M. J., Lewis, G. F., & Dehnen, W. 2004, *MNRAS*, 348, 12
- Martínez-Delgado, D., Aparicio, A., Gómez-Flechoso, M. Á., & Carrera, R. 2001, *ApJ*, 549, L199
- Martínez-Delgado, D., Butler, D. J., Rix, H.-W., Franco, V. I., Peñarrubia, J., Alfaro, E. J., & Dinescu, D. I. 2005, *ApJ*, 633, 205
- Martínez-Delgado, D., Dinescu, D. I., Zinn, R., Tutsoff, A., Coté, P., & Boyarchuck, A. 2004a, in *ASP Conf. Ser. 327, Satellites and Tidal Streams*, ed. F. Prada, D. Martínez-Delgado, & T. J. Mahoney (San Francisco: ASP), 255
- Martínez-Delgado, D., Gómez-Flechoso, M. Á., Aparicio, A., & Carrera, R. 2004b, *ApJ*, 601, 242
- Miyamoto, M., & Nagai, R. 1975, *PASJ*, 27, 533
- Nakamura, R., Fujii, Y., Ishiguro, M., Morishige, K., Yokogawa, S., Jenniskens, P., & Mukai, T. 2000, *ApJ*, 540, 1172
- Navarro, J., Frenk, C. S., & White, S. D. M. 1996, *ApJ*, 462, 563
- Newberg, H. J., & Yanny, B. 2006, *J. Phys. Conf. Ser.*, 47, 195
- Newberg, H. J., et al. 2002, *ApJ*, 569, 245
- Peñarrubia, J., Benson, A. J., Martínez-Delgado, D., & Rix, H. W. 2006, *ApJ*, 645, 240
- Peñarrubia, J., et al. 2005, *ApJ*, 626, 128
- Rocha-Pinto, H. J., Majewski, S. R., Skrutskie, M. F., Crane, J. D., & Patterson, R. J. 2004, *ApJ*, 615, 732
- Růžička, A., Palouš, J., & Theis, C. 2007, *A&A*, 461, 155
- Savage, C., Freese, K., & Gondolo, P. 2006, *Phys. Rev. D*, 74, 043531
- Steinmetz, M., et al. 2006, *AJ*, 132, 1645
- Vivas, A. K. 2002, Ph.D. thesis, Yale Univ.
- Vivas, A. K., & Zinn, R. 2003, *Mem. Soc. Astron. Italiana*, 74, 928
- . 2006, *AJ*, 132, 714
- Xu, Y., Deng, L. C., & Hu, J. Y. 2006, *MNRAS*, 368, 1811
- Yanny, B., et al. 2003, *ApJ*, 588, 824