UPDATE ON THE NATURE OF VIRGO OVERDENSITY

ANA BONACA1,2, MARIO JURIĆ3,6, ŽELJKO IVEZİC4, DMITRY BIZYAEV5, HOWARD BREWINGTON3, ELENA MALANUSHENKO3, VIKTOR MALANUSHENKO3, DANIEL ORAVETZ3, KAIFE PAN5, ALAINA SHELDEN5, AUDREY SIMMONS3, AND STEPHANIE SNEDDEN5

1 Department of Astronomy, Yale University, New Haven, CT 06511, USA; ana.bonaca@yale.edu
2 Department of Physics, Faculty of Science, University of Zagreb, Croatia
3 Institute for Theory and Computation, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA; mjuric@cfa.harvard.edu
4 Department of Astronomy, University of Washington, Seattle, WA 98195, USA
5 Apache Point Observatory, P.O. Box 59, Sunspot, NM 88349, USA

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ABSTRACT

We use the Eighth Data Release of Sloan Digital Sky Survey catalog with its additional sky coverage of the southern Galactic hemisphere to measure the extent and to study the nature of the Virgo Overdensity (VOD). The data show that the VOD extends over no less than 2000 deg2, with its true extent likely closer to 3000 deg2. We test whether the VOD can be attributed to a tilt in the stellar halo ellipsoid with respect to the plane of the Galactic disk and find that the observed symmetry of the north–south Galactic hemisphere star counts excludes this possibility. We argue that the Virgo Overdensity, in spite of its wide area and cloud-like appearance, is still best explained by a minor merger. Its appearance and position are qualitatively similar to a near perigalacticon merger event and, assuming that the VOD and the Virgo Stellar Stream (VSS) share the same progenitor, consistent with the VSS orbit determined by Casetti-Dinescu et al.

Key words: Galaxy: formation – Galaxy: halo – Galaxy: structure

1. INTRODUCTION

A growing number of observational campaigns over the last decade showed the richness of substructure in the Milky Way halo. The most vivid discoveries of ongoing accretion onto the Galaxy include the Sagittarius dwarf and its tidal streams (Ivezić et al. 2000; Yanny et al. 2000; Vivas et al. 2001; Majewski et al. 2003, among others), the Monoceros stellar stream (Newberg et al. 2002; Rocha-Pinto et al. 2003), as well as numerous smaller streams and dwarf galaxies abundant in the so-called field of streams (Belokurov et al. 2006). Evidence of ongoing mergers has also been detected in the halo of M31 (Ibata et al. 2001; Kalirai et al. 2006; Fardal et al. 2007), providing further support for the importance of hierarchical merging in galaxy formation.

Even if one is ultimately interested in the processes of galaxy formation in general, the study and understanding of these processes in the Milky Way remains advantageous in many aspects. For example, the proximity of stars and substructures in the Galaxy allows data collection at high resolution, which can be directly tested against predictions from simulations.

In this work, we concentrate on the Virgo Overdensity (VOD; Juric et al. 2008), a cloud-like overdensity of stars spanning distances between 10 and 20 kpc. Parts of the VOD were initially identified as an overdensity of RR Lyrae stars confined to a small region in the Quasar Equatorial Survey Team survey (Vivas et al. 2001), followed by an identification as an overdensity of main-sequence turnoff stars in the same direction (Newberg et al. 2002). However, it was not until the advent of wide-area surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) that the size of the VOD feature was fully recognized (Juric et al. 2008). In particular, using a large photometric sample of main-sequence stars, Juric et al. (2008) have shown that the VOD extends over at least 1000 deg2, spans heliocentric distances between 6 kpc < D < 20 kpc, and also shows an overdensity of M giants in the Two Micron All Sky Survey (Skrutskie et al. 2006). Based on their u−g band color, they further argued for low metallicity of its constituent stars. This is consistent with the spectroscopic determination by Duffau et al. (2006) ([Fe/H] = −1.9), who identified a velocity peak of RR Lyrae stars in the same direction, naming it the “Virgo Stellar Stream” (VSS). Subsequent kinematic studies showed that there may be individual filaments within the VOD/VSS region (Vivas et al. 2008), likely to belong to more than one stream. The current knowledge of VOD/VSS properties is summarized in Table 1.

Despite these extensive studies, there is still no definitive answer on the origin of the VOD/VSS nor of its extent. Since the stars are metal poor, but cover a wide range of metallicities, both Duffau et al. (2006) and Juric et al. (2008) have argued it to be the debris of a tidally disrupted dwarf spheroidal galaxy. Supporting this hypothesis, Casetti-Dinescu et al. (2009) showed that orbit of an RR Lyrae star associated with the VSS, derived from proper motion and radial velocity observations, is consistent with a merging scenario in its early phase. An alternative, which would explain the unusually large angular size of the VOD, is that the overdensity may not be due to a merger but a misinterpretation of a more complex large-scale structure of the Galactic stellar halo. However, given the limited extent of wide-field data available at the time, this hypothesis could not be tested conclusively.

Recently, the Eighth Data Release (DR8) of the Sloan Digital Sky Survey has become public (Aihara et al. 2011). Compared to previous releases, DR8 adds a significant new area (∼2000 deg2) in the southern Galactic hemisphere, as well as filling in a few “holes” in the northern footprint. Importantly, the added area allows us to conduct symmetry studies, model-free comparisons of stellar number densities along directions where we expect them to be the same if the halo conforms to a given shape (spherical, ellipsoidal, etc.).

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6 Hubble Fellow.

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7 In this paper, we use the term “Virgo Overdensity” to denote both the excess stellar number density, as well as the kinematic peaks observed in the general direction of Virgo at distances ∼5–25 kpc as it is unclear at present whether the two are truly distinct.
In this paper, we use this newly available data set to remeasure the size of VOD, better understand its large-scale structure, and attempt to discern between the two proposed options for its origin. We begin this analysis in Section 2 with an overview of the used stellar sample, details on the photometric parallax, and construction of stellar number density maps. Section 3 brings analysis of density maps, with special attention given to the implications of presented results on the nature of Virgo.

2. DATA AND METHODOLOGY

In this section, we describe characteristics of the SDSS imaging survey and the subset of its stellar sample used in this work. We discuss how the distance to each star was calculated using the photometric parallax method, paying special attention to metallicity effects. In conclusion, we show how the stellar density maps were created.

2.1. SDSS DR8 Imaging Survey

The Sloan Digital Sky Survey III provides an unabridged view of the night sky. Its total imaging footprint covers 14,555 deg², a third of the celestial sphere, including ~5200 deg² of imaging on the southern Galactic hemisphere available in Data Release 8 (Aihara et al. 2011). All of the planned imaging is now complete, but spectra will continue to be taken until the project ends in 2014. These will further enlarge the existing library which already contains spectra of 520,000 stars, 860,000 galaxies, and 120,000 quasars. For a detailed overview of ongoing spectroscopic projects see Eisenstein et al. (2011).

The SDSS photometric component collects data in five optical bands: \( u, g, r, i, \) and \( z \) measured in \( AB \) magnitude system (Gunn et al. 1998, 2006; Fukugita et al. 1996), with 95% completeness levels at magnitudes 22.1, 22.4, 22.1, 21.2, and 20.3, respectively. The latest data release has very accurate purely internal photometric calibration (Padmanabhan et al. 2008, so-called \( \text{"ubercalibration} \)), with the same standard-star-derived zero points used to absolutely calibrate the previous releases. Furthermore, all the imaging data were reprocessed with the new photometric pipelines, featuring enhanced sky-subtraction algorithm. Unfortunately, due to a mistake in data processing, the absolute astrometry of DR8 is less accurate than the previous releases (M. Blanton 2011, private communication), but this is of no consequence to the work presented in this paper.

Importantly, the morphological star–galaxy separation algorithm is well understood and has not changed since DR2. It classifies objects as “GALAXY” if

\[
\text{psfMag} − \text{cmagMag} > 0.145.
\]  

This admittedly simple criterion has been shown to work well for selecting clean samples of stars to \( r \sim 21.5 \) (Jurić et al. 2008).

2.2. The Photometric Parallax Relation and Iterative Determination of Distances

More than 95% of stars detected by the SDSS are on the main sequence and of similar age, therefore residing on a fairly constrained, one-dimensional, stellar locus. Provided we have a calibrated color–luminosity (or photometric parallax) relation, this fact allows us to estimate both their absolute magnitudes and distances from multi-band photometry.

Once the absolute magnitude of a star is known, its distance is easily calculated using

\[
D(\text{pc}) = 10^{0.3(M_v-M_p)} / 5 + 1,
\]  

Table 1

Overview of Virgo Overdensity/Stellar Stream Properties

| Quantity                      | Value      | Reference                        |
|-------------------------------|------------|----------------------------------|
| Angular size (deg²)           | >106⁶      | Duffau et al. (2006)             |
|                               | >1000      | Jurić et al. (2008)              |
|                               | ~760⁶      | Prior et al. (2009)              |
|                               | >2000      | This work                        |
| Surface brightness (mag arcsec⁻²) | 32.5       | Jurić et al. (2008)              |
| Distance (kpc)                | 20         | Newberg et al. (2002)            |
|                               | 19         | Vivas & Zinn (2003)              |
|                               | 6 to 20    | Jurić et al. (2008)              |
|                               | 19⁹        | Prior et al. (2009)              |
|                               | 15 to 30   | Brink et al. (2010)              |
| Metallicity [Fe/H]            | -1.86 ± 0.40⁹ | Duffau et al. (2006)         |
|                               | -1.5⁹      | Jurić et al. (2008)              |
|                               | -2.0 ± 0.1 (internal) ± 0.5 (systematic)⁹ | An et al. (2009) |
| Radial velocity (km s⁻¹)      | 99.8 ± 17.3⁶ | Duffau et al. (2006)            |
|                               | 130 ± 10   | Newberg et al. (2007)            |
|                               | 127 ± 10⁶  | Prior et al. (2009)              |
|                               | 134.4 ± 14.0⁶ | Casetti-Dinescu et al. (2009) |
| Proper motion (mas yr⁻¹)      | \( \mu_\alpha \cos \delta = -3.50 ± 0.85, \mu_\delta = 2.33 ± 0.85 \) | Casetti-Dinescu et al. (2009) |
| Origin                        | Sagittarius dSph | Martinez-Delgado et al. (2007) |
|                               | Dwarf galaxy | Jurić et al. (2008); Casetti-Dinescu et al. (2009); This work |

Notes.

* Quantity related to the VSS.
* Spectroscopically derived quantity.
* Photometrically derived quantity.
which then leads to its position in Galactocentric Cartesian coordinates:

\[
\begin{align*}
X &= R_\odot - D \cos l \cos b \\
Y &= -D \sin l \cos b \\
Z &= D \sin(b),
\end{align*}
\]

where \(R_\odot\) is the distance from Sun to the Galactic center and \(l\) and \(b\) are the Galactic longitude and latitude, respectively.

There have been numerous efforts through studies of stellar systems with known distances (e.g., nearby stars, globular clusters) yielding a number of proposed photometric parallax relations (e.g., Hawley et al. 2002; Williams et al. 2002; West et al. 2005; Bilir et al. 2006). In this paper, we use the relation derived by Ivezić et al. (2008):

\[
M_r,(g - i, [\text{Fe/H}]) = M_r^0(g - i) + \Delta M_r,([\text{Fe/H}]),
\]

where the terms \(M_r^0(g - i)\) and \(\Delta M_r,([\text{Fe/H}])\) have been determined to be

\[
\begin{align*}
M_r^0(g - i) &= -0.56 + 14.32(g - i) - 12.97(g - i)^2 \\
&+ 6.127(g - i)^3 - 1.267(g - i)^4 + 0.0967(g - i)^5 \\
\Delta M_r,([\text{Fe/H}]) &= -1.11([\text{Fe/H}]) - 0.18([\text{Fe/H}])^2.
\end{align*}
\]

This relation was calibrated from SDSS observations of 11 star clusters in metallicity range from +0.12 to −2.50. It builds on the previous work of Jurić et al. (2008) and is in good agreement with other proposed relations in the literature. It is expected to be accurate to ~10%–15% (Ivezić et al. 2008), and the fact that it was directly calibrated on SDSS photometry makes it especially appropriate for use here.

While more accurate, the Ivezić et al. (2008) relation is at a disadvantage compared to, for example, the Jurić et al. (2008) due its need for the \(u\)-band photometry to determine metallicity. Given the shallower depth of the SDSS \(u\)-band observations, this would effectively limit our explorations to ~8 kpc, heliocentric. We therefore chose not to determine metallicity from the photometry, but instead use the metallicity prior given by Ivezić et al. (2008) models to compute the \(\Delta M_r,([\text{Fe/H}])\) needed in Equation (5). Since Ivezić et al. (2008) give the metallicity as a function of position in the Galaxy (that, in turn, depends on the absolute magnitude), this makes our problem an implicit one.

We iteratively solve for \(D\) and \(M_r\) starting with an initial guess for metallicity of \([\text{Fe/H}] = −0.5\). We then compute \(D\) and \(M_r\) from the observed \(g, i\). Next, the expected metallicity at that position in the Galaxy is drawn from distributions given by Ivezić et al. (2008, Equations (18)–(20)), and the process is repeated until convergence is obtained. Note that since Ivezić et al. (2008) give their metallicity distributions separately for the disk and the halo, we randomly assign a star to the disk or halo component, with the weight given by their local contributions. In practice, this detail is of small importance for stars at approximate distance of the VOD, as nearly all belong to the halo.

We have compared the stellar number density dependence on the position in the Galaxy as obtained with the iterative approach to results of Ivezić et al. (2008) as well as the result obtained using Jurić et al. (2008) photometric parallax relation. We found them to be in agreement to within ~10% in the thin and thick disk regions, and discrepant with respect to the normalization of the halo component. In particular, while the overall halo density profile given by Jurić et al. (2008) is correct, we have found their local halo-to-disk normalization to be overestimated by approximately a factor of three.

For Galactic models used in subsequent sections, we have lowered the halo-to-thin disk normalization factor \(f_{H}\) from the Jurić et al. (2008) value to \(f_{H} = 1.6 \times 10^{-3}\). The difference is not surprising in light of a relatively large error bar (50%) that Jurić et al. (2008) have attached to their measurement of \(f_{H}\). We also note that the value used here is more consistent with those traditionally used. A formal fit for the \(f_{H}\) is beyond the scope of this work and will be discussed in a subsequent paper (M. Jurić et al., in preparation). Here, we will refer to it as the galfast model.

2.3. Sample Selection and Maps of Stellar Number Density

To be included in our sample of main-sequence stars, we require the objects to be morphologically classified as “STAR” by the SDSS pipeline, be within ~0.32 mag of the stellar locus as defined by Equation 4 of Jurić et al. (2008), and have colors \(g - r > 0\). The last cut removes extremely blue point sources, such as blue horizontal branch (BHB) stars or blue stragglers. We further require the objects to have \(r, i < 21.5\) to restrict ourselves to the range where SDSS’ morphological star–galaxy separation works well (Jurić et al. 2008). The apparent magnitudes of the resulting sample, containing ~86 million objects, are then corrected for interstellar extinction using the Schlegel–Finkbeiner–Davis (SFD) maps (Schlegel et al. 1998). Finally, we apply the iterative distance/absolute magnitude determination procedure to all objects (stars) of this sample.

We proceed to divide up the sample in six absolute magnitude bins (spanning \(3.5 < M_r < 9.5\)) and nine shells of heliocentric distance (spanning \(2 < D/\text{kpc} < 20\)). The bin sizes in absolute magnitude and distance are 1 mag and 2 kpc, respectively. Results shown here contain only stars from the brightest absolute magnitude bin (\(3.5 < M_r < 4.5\)), which probe deepest into the stellar halo.

These data are then binned spatially, in Lambert equal area projection, and plotted in hemisphere plots. The projection poles were set to the north and south Galactic pole for examination of northern and southern SDSS data, respectively. The Lambert projection was chosen as it allows for straightforward comparison of sizes of observed structures on different parts of the sky. The map pixel scale of \(dx = 1.5\) was chosen to keep most of the pixels well populated, thus reducing Poisson noise. At a central-distance bin of 9 kpc ~70% of pixels contain at least ~30 stars, while at the largest distance of 19 kpc this fraction is ~50%.

Not all pixels on the map have been fully covered by SDSS observations. This is particularly true for pixels close to the edge of the footprint, and needs to be accounted for. For consistent comparison of data and model predictions, we compute the pixel fraction covered by the SDSS by subdividing each pixel with a \(100 \times 100\) grid, and counting the number of so defined subpixels that contain at least one star. The fraction of pixel area covered by the SDSS is then approximated by the ratio of counted subpixels to the total number of subpixels. Model predictions (discussed below) have been multiplied by this fraction.

Examples of stellar density maps thus obtained are given in Figure 1 (north Galactic hemisphere) and Figure 2 (south Galactic hemisphere). The panels in the left column show SDSS DR8 stellar counts, while galfast model predictions for the same population of stars are given in the center. Model predictions give the expected number of stars in the volume determined by pixel and distance bin size. Finally, a quantitative comparison
Figure 1. Density distribution of F stars in 2 kpc wide shells centered on 5 and 11 kpc, mapped in Lambert equal area projection with circles representing constant Galactic latitude and lines of constant Galactic longitude. Disk area is excluded by plotting only latitudes higher than 30°. Left panels show SDSS DR8 imaging data, with blank areas corresponding to pixels with no data, best-fitting models updated from Jurić et al. (2008) for the same area, corrected for SDSS sky coverage, are on the middle panels, while the data–model residuals (normalized to the model) are on the right panels. At the 5 kpc distance shell, data and model are in very good agreement (apart from the disk region, which was not modeled as carefully), but the 11 kpc shell clearly shows Virgo Overdensity extending over 2000 deg² in general direction of \( l \sim 300°, b \sim 75° \). The Monoceros stream is visible at both distance shells as overdensity on low Galactic latitudes for \( 150° < l < 230° \).

3. RESULTS

In this section, we discuss the density maps constructed as described above, with emphasis on the structure of Virgo Overdensity. Previous studies found the VOD to peak at \( \sim 10 \) kpc. Here, we present and discuss density distribution maps at two distances: \( 5 \pm 1 \) kpc where we do not see signature of the VOD and \( 11 \pm 1 \) kpc where it is very prominent.

3.1. Analysis of Star Counts Maps

As seen in Figure 1, the 5 kpc density map is well matched by the model prediction, resulting in mostly uniform residual map centered around zero. The density map itself reveals the bulk structure of Milky Way and our position inside it. The greatest density is observed at low Galactic latitudes \( (b \lesssim 30°) \) where our distance shell dips into the Galactic disk. In order to reduce the clutter and obtain a better view of the halo stars, the plots show only the region \( b > 30° \). In comparison to the model predictions, we note two features on the map of residuals. First, the slight underdensity in the region heavily populated by disk stars \( (0° < l < 30°, b < 45°) \) due to model parameters tuned to best reproduce the halo, and second, the Monoceros stream viewed as an overdensity on the opposite side of the map \( (90° < l < 230°, b \lesssim 40°) \).

The situation is radically different at 11 kpc. Even though the general features seen in the 5 kpc plots are also present at 11 kpc, the residuals are dominated by a large overdensity at \( l \sim 300°, b \sim 75° \)—the Virgo Overdensity. Probability of a random fluctuation expanding over such an area is statistically insignificant.

We also present the stellar density maps of the southern Galactic hemisphere derived from SDSS DR8 data, in the same distance shells as for the northern hemisphere (Figure 2). The SDSS footprint of southern sky, limited by geographical location of the telescope, is smaller than in the north, but still large enough to resolve structures on scales as large as several hundreds deg². Apart from the known Hercules–Aquilae cloud \( (l \sim 60°, b \sim -35°) \) and trailing arm of the Sagittarius dwarf galaxy \( (90° < l < 230°, b > -40°) \), there appear to be no strong overdensities in the halo region. However, we do observe a curious density enhancement in the south at low latitudes in the anticenter direction. This overdensity, that could be associated with the Monoceros stream, or be a feature of the thick disk, will be analyzed in a subsequent publication. Other than the mentioned overdensities, the residual maps exhibit a very good fit to the model.

3.2. Extent of the Virgo Overdensity

The fact that the VOD is not only visible on the residual plot, but also as an enhancement on the density plot itself, motivates us for another, model-free look at the data. This approach also
Figure 2. Same as Figure 1 on southern Galactic hemisphere. Apart from the enhancement at low latitudes in the anticenter region that may be related to the Monoceros stream, the Sagittarius stream (90° < l < 230°, b > −40°), and the Hercules–Aquila cloud (l ∼ 60°, b ∼ −35°), no new strong excesses were detected.

reduces the dependence of our results and conclusions on the details of the analytic Galactic model.

Most overdense pixels on the VOD residual plot (lower right panel in Figure 1) are above the l = 0° line. If the halo were symmetric, the halves of the plot divided by this line should also be symmetric. In Figure 3, we compare the stellar density in these halves by plotting the value of

\[ f_{W-E}(l, b) = \frac{\text{data}(l, b)}{\text{data}(360° - l, b)} - 1. \]

For a given pixel at Galactic coordinates (l, b), the value of \( f_{W-E} \) is simply the normalized difference between the star counts in the pixel itself (\( \text{data}(l, b) \)) and its counterpart (\( \text{data}(360° - l, b) \)). The quantity \( f_{W-E} \) is defined only for the pixels with axisymmetrical counterparts, which results in the “bug-like” shape of the plots.

The stellar number density was found to be symmetric on the order of \( \lesssim 10\% \) at distances closer than 5 kpc. However, at 11 kpc the median of \( f_{W-E} \) distribution on the upper half is at \( \sim 20\% \). If we adopt the definition of overdensity as density contrast (here defined with respect to the axisymmetric region) of \( \geq 15\% \), then the total area of Virgo Overdensity as measured in SDSS DR8 is \( \approx 2000 \text{ deg}^2 \), double the size previously measured (Jurić et al. 2008).

Furthermore, we see that the overdensity extends along the l = 300° and 270° SEGUE stripes. This indicates that 2000 deg² is still only a lower limit of its actual size. We attempt to roughly estimate the area of the VOD outside the SDSS footprint by placing an ellipse encompassing most of the pixels with 40% overdensity in the SEGUE stripes as well as the overdensity in the main area of the survey. We find this area to be \( \sim 3000 \text{ deg}^2 \), implying that approximately one-third of the VOD may extend over the area where no data are currently available.

3.3. Luminosity of the Virgo Overdensity

To further characterize the progenitor, we estimate a lower limit on the number of stars associated with VOD. The Virgo area was conservatively limited to region subtended by (200° < l < 210°, b > 40°), (210° < l < 270°, b > 50°), and (270° < l < 340°, b > 60°). To estimate the excess in stellar number counts, we simply subtract the pixel values in symmetric, Virgo-free area from the VOD pixels, and sum over all the pixels and distance range (7–19 kpc). This gives the number of VOD stars with absolute magnitude \( M_r = 4.0 \pm 0.5 \). Following Jurić et al. (2008), and assuming the luminosity function of VOD stars is similar to that of the halo (M. Jurić et al., in preparation), we obtain an order-of-magnitude estimate of \( \sim 10^6 \) for the total number of stars present in VOD. This is consistent with numbers found for large globular clusters and dwarf galaxies.

3.4. Test of the “Tilted Halo” Model

Given the large extent of the VOD, an attractive hypothesis is that it may not be an overdensity in the stellar halo but a signature of a more complex stellar halo density distribution. For example, proposals have been put forward that the Hercules–Aquila cloud is a signature of dynamical interaction of the disk with the stellar bar, and not a merger event (Humphreys et al. 2011).
An oblate halo model, with axes aligned with those of the Galactic disk, does not produce an overdensity signature in maps constructed in Section 2.3. However, if its axes were not aligned with the Galactic disk (e.g., if it is “tilted”), such an overdensity signature will occur (Figure 4). With the SDSS data in the southern hemisphere available for a significant portion of the sky, it is possible to test this tilted halo model by directly comparing the stellar number density above and below the Galactic plane.

We proceed similarly to steps taken in previous section and plot the values of \( f_{\text{N-S}} \) defined by

\[
   f_{\text{N-S}}(l, b) = \frac{\text{data}(l, b)}{\text{data}(l, -b)} - 1
\]

in Figure 5. \( \text{data}(l, b) \) once again denotes stellar number count in pixel centered at \((l, b)\) and distance of 11 kpc, analogous to the bottom rows of Figures 1 and 2. Note how the value of \( f_{\text{N-S}} \) is only defined for those pixels which have data available both above \((b > 0)\) and below \((b < 0)\) the Galactic plane. Although the distribution of \( f_{\text{N-S}} \) values is noisy, there is no clear over- or underdensity as would be predicted by Figure 4.

This is further confirmed by the distribution of densities in pixels not affected by overdensities (excluded regions include Sagittarius dwarf galaxy at \( |b| < 60^\circ \) and \( 120^\circ < l < 150^\circ \), \( 45^\circ < |b| < 60^\circ \) and Hercules–Aquilae at circle of radius \( 7^\circ \) around \( l = 55^\circ, b = -30^\circ \)). The distribution is slightly asymmetric, but the median is at \(-0.01\), while the width of the distribution (with semi-interquartile range of 0.22) is consistent with the noise visible on the map of \( f_{\text{N-S}} \) values. Given the distribution centered around zero excess of north versus south, we can conclude that on the scales of \( \sim 20 \) kpc, halo is symmetric with respect to the Galactic plane.

This remains true when the exercise is repeated for distance shells in \( 7–19 \) kpc range. Figure 6 shows how the median of \( f_{\text{N-S}} \) distributions similar to that in Figure 5 changes with distance. The error bars denote the distributions’ interquartile range (IQR). The plot shows remarkable consistency in difference of star counts between northern and southern Galactic hemisphere, the largest deviation being \( \sim 10\% \) at \( 7 \pm 1 \) kpc, and considerably smaller in most other distance bins.

We therefore conclude that a tilted halo cannot account for the existence and observed extent of the Virgo Overdensity.

4. DISCUSSION

Previous studies determined the distance range, radial velocities, and metallicity of stars making up the VOD (see Table 1). Several authors have also reported evidence of substructure (e.g., Duffau et al. 2006). In this paper, we have used the SDSS DR8 data to reassess the extent of the VOD and find it likely to extend over \( \sim 3000 \) deg\(^2\) of the sky, three times more than the original Jurić et al. (2008) estimate.

Stellar overdensities are usually attributed to merger remnants, but VOD’s size and morphology make it unlike a typical tidal stream thus calling for a more cautious interpretation. An alternative to the merger remnant hypothesis is that the VOD is a signature of a more complex global halo density distribution (for a discussion why other proposed hypotheses are less likely, see Section 5.5 in Jurić et al. 2008). In this paper, we have tested whether a “tilted” halo can explain the observed signature.

Figure 4 shows schematically how a tilted halo would appear as an overdensity in Figures 3 and 5. Axisymmetric halo on the left panel would be observed as being completely symmetric in both \( f_{\text{W-E}} \) and \( f_{\text{N-S}} \) values defined earlier, but if the halo were tilted as seen in the right panel on Figure 4, a VOD-like enhancement in stellar number counts would be observed in the “western” side of the \( f_{\text{W-E}} \) plot. Halo tilt would also be evident on the \( f_{\text{N-S}} \) plot because the number counts on the “south” would be larger compared to the symmetric area on the “north.” However, as we can see from Figure 5, this is not the case. In fact, given the difference in stellar number counts between north and south areas mapped by the SDSS, we can constrain any north–south halo asymmetry to be less than 10%. As the density contrast of the VOD gets as high as \( \sim 50\% \) (see Figure 3), it is clear that this simple tilted halo model can only amount to a
minor contribution to the overall enhancement in density. This leaves the merger hypothesis as the most likely. While the VOD’s morphology is clearly different from those of other streams (e.g., Sagittarius, GD1, etc.), its cloud-like appearance is not entirely unique. Other such overdensities have been observed, e.g., Hercules–Aquila cloud (Belokurov et al. 2007) or Triangulum-Andromeda (Rocha-Pinto et al. 2004). Similar structures appear in Galactic halo formation simulations as well. For example, the Johnston et al. (2008) simulations modeled to match observed properties of Local Group galaxies predict several cloud-like morphologies with surface brightness \( \approx 32.5 \text{ mag arcsec}^{-2} \) in a Milky Way type galaxy. This is broadly consistent with what we see in Virgo Overdensity; however, we do find traces of VOD as close as 7 kpc from the Galactic center, closer than the simulations would predict. Given the simplicity of the simulations, this may not be a serious issue.

Furthermore, the accretion origin of the VOD is consistent with kinematic measurements of an RR Lyrae star assumed to belong to the VSS (Casetti-Dinescu et al. 2009). Based on the radial velocity and proper motion measurement with a baseline of a century, Casetti-Dinescu et al. (2009) have determined the orbit of a VSS RR Lyrae, having \( r_{\text{peri}} = 11 \pm 1 \text{ kpc} \), \( r_{\text{apo}} = 89^{+52}_{-32} \text{ kpc} \), and a period of \( T = 1.2^{+0.6}_{-0.4} \) Gyr. The measured orbit passes through the VOD, indicating that VOD and VSS may be connected structures with a common origin. Also, the high eccentricity of the orbit is consistent with the observed high eccentricities in simulated merger events that result in cloud-like structures.

Taken together, all these lines of evidence point to the VOD being a signature of a high eccentricity merger event observed

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**Figure 5.** Map of difference in star counts in northern and southern Galactic hemisphere (see bottom left panels in Figures 1 and 2, respectively), normalized to the south. A very good match of the number counts over 20 kpc range provides strong constraints on the halo symmetry with respect to the Galactic plane and disfavors the tilted halo interpretation for the Virgo Overdensity.

**Figure 6.** Symmetry of stellar halo with respect to the Galactic plane as a function of distance from the Sun. \( f_{N-S} \), as defined in Equation (7), is here computed only for the areas not contaminated by Hercules–Aquila cloud and Sagittarius stream. The error bars represent the semi-interquartile ranges of the \( f_{N-S} \) distribution. The biggest deviation from symmetry (denoted by the dashed line at zero) is \( \sim 10\% \) (dotted line), found in the 7 kpc distance bin. Note there are no strong asymmetry signatures in the distance range where the VOD is prominent.

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8 While one can always invoke even more complex halo shapes to explain the observations, at some point these become unreasonably contrived.
at perigalacticon. Future kinematic studies are the best way to further verify this conclusion.

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