Stellar overdensities in the halo: the extent of the Virgo overdensity

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ABSTRACT
We map the three-dimensional extent of the Virgo overdensity by combining distance information from RR Lyrae variables and projected spatial information from the Southern Edgeworth–Kuiper Belt Object Survey and Sloan Digital Sky Survey Data Release 6 photometry. The Virgo overdensity is seen to comprise two filaments 14.5° × 3° and 10° × 3°, and a circular structure 3° in diameter. Together, the three features span 38° of right ascension and declinations of 2° to −15°. RR Lyrae variables place the two filamentary features at heliocentric distances of 20 and 17 kpc, respectively, with projected dimensions of 5 × 1 and 3 × 1 kpc.

Key words: Galaxy: halo – Galaxy: structure.

1 INTRODUCTION
One of the most important processes yet to be understood by modern astrophysics is that of galaxy formation. The halo of the Galaxy offers arguably the best opportunity to study galaxy formation due to its relative quiescence and our ability to obtain accurate kinematics and detailed chemical abundances for a large number of stars. The seminal work of Eggen, Lynden-Bell & Sandage (1962) proposed galaxy formation occurred in the wake of a monolithic collapse of a proto-galactic cloud. Later, Searle & Zinn (1978) challenged this notion by proposing that the halo formed via the accretion of numerous small entities over an extended period.

Today, galaxy formation is discussed within the context of a cold dark matter (ΛCDM) cosmology. This predicts hierarchical structure formation in a way that qualitatively parallels the Searle & Zinn scenario. Observational evidence of the duality in the Galactic halo (Freeman & Bland-Hawthorn 2002; Bell et al. 2007; Carollo et al. 2007) suggests at least two formation mechanisms. The kinematics and star formation history of the inner halo (R < 20 kpc) suggest formation from rapid collapse at an early epoch. The outer halo, on the other hand, possesses kinematics (Carollo et al. 2007) and a level of substructure (Bell et al. 2007) consistent with assembly from disrupted dwarf galaxies.

1.1 The Sagittarius dwarf and the Virgo overdensity
The most prominent ongoing accretion event in the Milky Way halo is the dissolution of the Sagittarius dwarf (Sgr; Ibata, Gilmore & Irwin 1994). The leading and trailing arms of Sgr tidal debris are seen to wrap around the sky (Newberg et al. 2002, 2007; Majewski et al. 2003; Belokurov et al. 2006; Keller et al. 2008). The debriss of Sgr is the largest contribution to substructure in the outer halo yet to be found.

Arguably the next most significant outer halo substructure is the Virgo overdensity (VOD). The VOD was discovered in the Sloan Digital Sky Survey (SDSS; York et al. 2000) as a diffuse overdensity of F-type main-sequence stars spanning some 1000 deg2 (Newberg et al. 2002, 2007) and distances of 6–20 kpc (Jurić et al. 2008). The region has a coincident series of overdensities in RR Lyrae (RRL) variable stars (Vivas & Zinn 2006; Keller et al. 2008) at distances of 16–19 kpc. The studies of Duffau et al. (2006) and Prior et al. (2008) found subsets of RRL show a common radial velocity with very low velocity dispersion (consistent with measurement uncertainties). This is as expected from kinematically cold tidal debris. The moving group was termed the Virgo Stellar Stream to distinguish it from the general stellar overdensity.

The nature of the VOD remains uncertain. Does it represent a separate accretion event, or is it related to the spatially overlapping Sgr debris? Martínez-Delgado et al. (2007) proposed that the VOD results from the confluence of the leading and trailing arms of Sgr as seen in the N-body models of Law, Johnston & Majewski (2005). The Law et al. models predict highly negative radial velocities for the Sgr material in this region. This is contrary to the observations of Duffau et al. (2006) and Newberg et al. (2007), who find most stars lie at a radial velocity of 100–130 km s−1. Newberg et al. (2007) also note that the models fail to predict the high stellar density seen in the VOD, and that the VOD should be spatially offset from the Sgr leading arm as we observe. This leads Newberg et al. (2007) to conclude that the VOD is a halo substructure of separate origin to Sgr. Vivas et al. (2008) examine the radial velocities of a sample of RRLs in the direction of the VOD at distances of less than 13 kpc. Vivas et al. find that the Virgo Stellar Stream extends to ~12 kpc, but none of the additional RRLs can be ascribed to the leading arm of Sgr. Nevertheless, the study of Prior et al. (2008) finds RRLs at negative radial velocities, which they speculate could be Sgr debris (Prior, Da Costa & Keller, in preparation).
It is evident from Newberg et al. (2002), Belokurov et al. (2006), Duffau et al. (2006), Newberg et al. (2007) and Jurić et al. (2008) that the centre of the VOD lies somewhere to the south of the region surveyed by SDSS. The VOD was traced southwards by Keller et al. (2008). They identified two RRL overdensities in the VOD region: one at a heliocentric distance of 16 kpc, 8° south-east of the centre of the VOD defined by Duffau et al. (2006), and another at 19 kpc and 24° south-east of this centre. Prior et al. (2008) explore the extent of the VOD by looking at a sample of Southern Edgeworth–Kuiper Belt Object (SEKBO) fields that sparsely sample the vicinity of the VOD. This study reveals that the VOD is a large diffuse feature, covering at least 760 deg² of sky.

In the present study, we draw together the SEKBO and SDSS data sets to constrain the 3D extent of the VOD with the aim of clarifying its nature. We use the distance information available from the SEKBO RRL candidates and the spatial extent determined from the combined SEKBO and SDSS Data Release 6 (DR6) data sets. In Section 4, we conclude with some remarks regarding the nature of the VOD.

1.2 Luminosity function excess

We utilize the SDSS DR6 (Adelman-McCarthy et al. 2008) and SEKBO (Keller et al. 2008) photometric data bases to construct luminosity functions over the combined survey area. We have transformed the Johnson V, R of the SEKBO survey (Keller et al. 2002) to SDSS g, r for consistency using the transformations of Lupton (2005). In order to uniformly combine luminosity functions from the two data sets, we needed to consider magnitudes that do not suffer from substantial observational incompleteness. As can be seen from the example colour–magnitude diagrams in Fig. 1, observational incompleteness becomes appreciable in the SEKBO data set at \( g_0 \sim 20 \) (there is some variation in depth amongst the SEKBO fields.). This is almost 2 mag brighter than the limit of SDSS photometry.

To construct the luminosity functions seen in Fig. 1, we utilize the colour range \( 0.1 < (g - r)_0 < 1.0 \) and magnitude range \( 14 < g_0 < 19.75 \). Reddening is as estimated from the Schlegel, Finkbeiner & Davis (1998) reddening maps. This colour range excludes the nearby red disc dwarf star sequence that is of interest to the present study. The size of individual SEKBO fields ranged from 0.81 to 0.60 deg². The areal coverage of each field was dependant on the dither pattern and operational status of CCDs. The SDSS data are compared over a 1 deg² field. To correct for the variation in sample size, we normalized the luminosity functions over the magnitude range \( 14.5 < g_0 < 15.5 \). As can be seen from an example overlap region in Fig. 1, the SDSS and the corresponding SEKBO luminosity functions agree within uncertainties.

We then compared the observational data with synthetic luminosity functions derived from the Besançon galaxy model (Robin et al. 2003). The simulations were constructed for 1 deg² fields with a distance range of 0–120 kpc with magnitude and colour cuts applied as per observations. The Besançon model is a dynamically self-consistent, parametric description of the Galaxy. As Jurić et al. (2008) note, a parametric model is susceptible to the choice of input observations since these are typically based upon small areal coverage and many include unrecognized stellar substructure. The solution of Belokurov et al. (2006) and Jurić et al. (2008) is to directly map the stellar number density using distances derived for main-sequence stars from photometric parallax. The technique requires highly accurate colours in order to precisely derive an absolute magnitude. Jurić et al. (2008) show that magnitudes determined to a precision of 0.01–0.02 mag result in an uncertainty in distance of ±10 per cent. This is a result of the extremely steep absolute magnitude–colour relation inherent in the photometric parallax method. In addition, considerable systematics enter with the choice of a photometric parallax relation (up to ±70 per cent in distance for the bluest halo stars).

Our approach to discerning halo substructure is unlike that utilized by Belokurov et al. (2006) and Jurić et al. (2008) that have focused on the density of F-type main-sequence stars. The SEKBO data lack the global photometric accuracy required for such a technique. Due to the propagation of uncertainties in standardization and colour transformation from the non-standard MACHO B and R passbands, the global accuracy of SEKBO photometry is ±0.03 mag in V and R bands (Keller et al. 2008) for \( g < 16 \). This rises to ±0.15 mag at \( g \sim 19.75 \) (with some variation from field to field due to variable survey depth).

For this reason, we have chosen to construct our search for halo substructure via the luminosity function of the observed data. This approach has also been applied in the study of Duffau et al. (2006). Duffau et al. have examined the region of sky between 176° ≤ RA ≤ 210° and –4° ≤ Dec. ≤ 4° in \( 1° \times 1° \) fields. The outline of significant overdensity as described by Duffau et al. (2006) is

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Left-hand panel: a comparison of SEKBO and SDSS colour–magnitude diagrams for a \( 1° \times 1° \) region centred on (RA, Dec.) 192°, –4°. Right-hand panel: a comparison of the luminosity functions derived from the SEKBO (solid line) and SDSS (dashed line) fields with Poisson uncertainties shown. Note the agreement between the luminosity functions derived from the two data sets is within uncertainties until the completeness limit of the SEKBO data at \( g_0 \sim 19.75 \).
shown in Fig. 4. Our approach has also been applied by Newberg et al. (2007) to two fields, one centred on RA = 186° and Dec. = 0° and the other further south at RA = 191°, Dec. = −7:8. Both fields reveal significant luminosity function excess relative to fields at the same galactic latitude but 180° displaced in longitude. None the less, the disadvantage of our technique has the drawback of removing distance information from the view of substructure. However, in Section 2 we merge distance determinations from the distribution of RRLs to constrain the distance to the substructures.

Localized excess over the Besancon model shows regions that depart from an axially symmetric model. While features covering several thousand square degrees (quadruple moments, for instance) may suffer from uncertainty due to the validity or otherwise of the model, we can consider features on scales of several hundred square degrees as representing departures from the local smooth background density.

The bottom panel of Fig. 2 shows a field well separated from substructure in the southern Galactic cap. Here, we see the agreement of the observed luminosity function (LF) with the Besancon model LF to within the Poisson uncertainties. As we proceed through to the area of the VOD, there is a marked excess of stars rising towards the faintest bin considered (at $g_0 = 19.5$ in Fig. 2, top panel; see also Prior et al. 2008).

The cumulative difference between the observed and predicted luminosity functions is then expressed in terms of significance relative to the Poisson uncertainties inherent in the observed sample. That is,

$$S = \left( \sum \frac{(N_{\text{obs}} - N_{\text{model}})^2}{\sqrt{(N_{\text{obs}}^2 + N_{\text{model}}^2)}} \right)^{1/2},$$

where $S$ is the significance of a field, $N_{\text{obs}}$ is the observed number of objects to magnitude bin $i$ and $N_{\text{model}}$ is the predicted number of objects to bin $i$ from the Besancon galaxy model normalized to that observed in the magnitude range $14.5 < g_0 < 15.5$. The resulting map of significance of departure from the luminosity function predicted by the Besancon model is seen in Fig. 3. The SDSS data cover the region of the ‘Field of Streams’ of Belokurov et al. (2006), namely $120° < RA < 220°$, and from the southern SDSS limit (varies from Dec. = −1° to −4°) to Dec. = 34°. In the region of overlap between SDSS and SEKBO, we utilize the SDSS data set in light of the superior photometric precision of the SDSS data.

Fig. 4 expands the northern region of overlap between SDSS and SEKBO. A series of ‘point’ sources are seen – these mark globular clusters in the field (distances <100 kpc, after this the horizontal branch falls out of the magnitude range considered for the luminosity function). The main source of the overdensity in the north is the leading arm of Sgr (see e.g. Belokurov et al. 2006; Fellhauer et al. 2006). Enmeshed with the linear feature of the Sgr leading arm is a large, diffuse region of excess between RA = 170° − 195° and Dec. < 7°. This diffuse region is also coincident with the broad VOD detection of Jurić et al. (2008) that is seen to cover ∼1000 deg$^2$ (centred at 192°, 2°).

Three significant new features are also seen in the extension to the south-east afforded by the SEKBO data. A linear feature $A$ (198°, −10°) forms a band approximately 3° wide and 14:5 long. A second linear feature $B$ (192°, −2°) is 3° wide and 10° long. The third significant feature $C$, seen at (178°, 0°), is approximately 3° in diameter. The three features are broadly consistent with the area of overdensity discussed in Prior et al. (2008).

2 DISTANCES TO SUBSTRUCTURES FROM RR LYTEAE VARIABLES

The above detections of halo substructure are based upon the excess or deficit of main-sequence and red giant branch populations over the Besancon galaxy model. The range in luminosity exhibited by both stellar populations does not afford any distance information at the low surface densities seen here.

The Keller et al. (2008) study of the RRL overdensity from SEKBO presents the radial distribution of RRL candidates (76 ± 7 per cent of which are RRLs; Prior et al. 2008) across the VOD region. Using the Keller et al. (2008) data set, we can construct a plot of the number density of RRL candidates as a function of distance for the range in right ascension 170°−210°.

The calculation of the RRL number density follows the technique developed by Wetterer & McGraw (1996) and implemented in Keller et al. (2008) (to which we refer the reader for details). The following equation describes the local space density as a function of galactocentric distance:

$$\rho(R) = \frac{1}{4\pi R^2 f(R)} \frac{dN}{dR},$$

where $f(R)$ is the fraction of the total halo volume at $R$ that is sampled by the survey [$f(R)$ is analogous to a solid angle] and $N$ is the number of RRL as a function of distance. Whereas the solid angle is constant as one looks through the halo, $f(R)$ varies as a function of Galactocentric radius and hence must be calculated numerically for each field. To account for the effects of completeness, we multiply each $f(R)$ by the Monte Carlo derived RRLab completeness profile for the field as a function of galactocentric radius. This gives the effective volume of the halo that is sampled by each field. We use equation (2) to calculate the local space density for each candidate. A transformation to heliocentric distance is then made.
Figure 3. The significance of cumulated excess of the observed luminosity function compared to that predicted by the Besancon galaxy model (Robin et al. 2003) to a limiting magnitude of $g_0 = 19.75$ in $1^\circ \times 1^\circ$ fields. Darker shading represents more significant excess over the model, as described by the grey-scale colour bar to the right-hand side. The significance is expressed as the number of sigma over the model (see text for details).

Figure 4. Left-hand panel: a close-up of Fig. 3 to show the central ‘Field of Streams’ region. Numerous point-like features are associated with known globular clusters as shown. The leading arm of Sagittarius debris is seen as the broad feature from 120$^\circ$, 20$^\circ$ to 190$^\circ$, 8$^\circ$. Three new features A, B and C are indicated. The dashed ellipses mark the regions of excess RRL density from Keller et al. (2008). Right-hand panel: a further enlargement of the region around the VOD (Feature B) to show previous detections by Duffau et al. (2006) (solid outline), Vivas & Zinn (2006) (triangle), Ivezić et al. (2005) (star) and Newberg et al. (2007) (circles).

Figure 5. A plot of the number density of RRL candidates in the RA range 170$^\circ$–210$^\circ$ as a function of heliocentric distance. RRL candidates are from Keller, Da Costa & Bessell (2001). The solid line shows the average power-law relation of halo density. From Monte Carlo simulations, we are able to derive $1\sigma$ and $2\sigma$ intervals (dashed lines) above this average relation based on random samples of appropriate sample size. The grey-shaded regions indicate the locations of three significant overdense regions.

The result is seen in Fig. 5. From Monte Carlo simulations of appropriate sample size using the halo density profile defined in Keller et al. (2008) (the solid line in Fig. 5 for $R <$ 45 kpc), we have determined the $1\sigma$ and $2\sigma$ significance contours. These are shown in Fig. 5 as the dashed lines. Fig. 5 shows three peaks of greater than $2\sigma$ significance; at 17, 20 and 34 kpc (heliocentric).

From Keller et al. (2008, fig. 20), we see that the VOD Clump 1 spatially extends over the linear feature B, and Clump 2 is seen to coincide with the southern portion of feature A, as shown in Fig. 4. The more distant and less numerous Clump 3 does not present a well-defined spatial centroid. Feature C does not exhibit a corresponding excess in RRLs. At their determined distances, feature A (20 kpc) has projected dimensions of 5 $\times$ 1 kpc and feature B (17 kpc) dimensions of 3 $\times$ 1 kpc.

3 DISCUSSION OF SUBSTRUCTURES

An extensive literature has been developed that examines the stellar overdensities in this region. Our study is the first to resolve the VOD region into a series of distinct substructures. The filling factor of the three features is significantly less than the 760 deg$^2$ determined by Prior et al. (2008) or $\sim$1000 deg$^2$ by Jurić et al. (2008). We believe this can be understood by the spatial sampling of Prior et al. and their extrapolation to an elliptical morphology. The three features span some 38$^\circ$ of sky similar to the major axis size of 45$^\circ$ determined by Prior et al. It is by increasing our spatial resolution that we are now able to see the details of substructure in this region.

In the following section, we discuss our finds in the light of the existing literature for the region.

3.1 Feature A

Newberg et al. (2007) examine a 1:5 radius field centred at RA = 191$^\circ$, Dec. = $-7^\circ$. This corresponds to the peak overdensity seen in the southerly ‘outrigger’ scan of Sloan Extension for Galactic Understanding and Exploration (SEGUE). This field overlaps with the north-west corner of feature A. SDSS spectroscopy
reveals a marginally significant excess at radial velocities between \( V_{\text{GSS}} = 100 \) and 130 km s\(^{-1}\). Such an excess is also seen by Newberg et al. (2007) towards the VOD (feature \( B \); see below). This suggests that feature \( A \) and the VOD share a common spatial velocity and potentially a common origin.

3.2 Feature \( B \) – the VOD

Feature \( B \) is identified as the VOD. The VOD corresponds to the ‘12.4-h’ clump described by Vivas & Zinn (2006) and first detected as an overdensity in RRLs by Vivas et al. (2001). It was independently seen as an overdensity of F-type main-sequence stars by Newberg et al. (2002) at \( R.A. = 190^\circ \), Dec. = 0 and heliocentric distance of 18 kpc. Using a 2:3-wide band centred on declination \( -1:10:48 \), Vivas & Zinn (2006) find a peak density located at \( R.A. = 186^\circ \) and a heliocentric distance of 17 kpc.

Feature \( B \) is also recovered in the study of RRL candidates from SDSS by Ivezić et al. (2005). The study of Ivezić et al. (2005) finds the VOD centred at \( R.A. = 190^\circ \) in a 2:5-wide band centred on Dec. = 0\(^\circ\). Ivezić et al. (2005) derive a mean heliocentric distance of 18 kpc from the luminosity of the clump candidate RRLs.

Duffau et al. (2006) present spectroscopic follow-up of the ‘12.4-h’ clump and find nine of 18 RRLs studied share a common radial velocity of 100 km s\(^{-1}\) with velocity dispersion less than measurement uncertainties. This moving group was termed the Virgo Stellar Stream to differentiate the population from the region of overdensity. In an examination of SDSS photometry for the adjoining region of sky, Duffau et al. (2006) saw evidence for an excess in the luminosity function (the same technique as applied in the present study) over an area of at least 106 deg\(^2\) of sky centred on \( R.A. = 186^\circ \) and Dec. = \(-1^\circ\).

Since the overdensity is located at the southern edge of the SDSS field, the spatial extent remains unbound. In Newberg et al. (2007), one of the three SEGUE ‘outtrigger’ scans apparently shows that the VOD extends beyond the Dec. = \(-4^\circ\) limit of SDSS to Dec. < \(-15^\circ\). In addition, Newberg et al. (2007) examine the radial velocities of stars in a 1:5 radius centred in \( R.A. = 186^\circ \), Dec. = 0\(^\circ\). At magnitudes corresponding to main-sequence members of the VOD with a distance of 18 kpc, there is a suggestion of a population of stars with radial velocities between 100 and 130 km s\(^{-1}\) as seen in the study of Duffau et al. (2006). Vivas et al. (2008) present evidence that the VSS population extends towards us to around 12 kpc.

The present study places the VOD in a clearer spatial context by providing broader sky coverage. Our derived mean distance of 17 kpc is in good agreement with previous studies. As can be seen in Fig. 4, there is also agreement between previous positions of VOD presented in the literature and our map of overdensity in this region.

The discovery by Walsh, Willman & Jerjen (2008) of VirZ, a dwarf galaxy candidate at the north-western tip of feature \( B \), is intriguing. Walsh et al. find an optimal distance of \( \sim 40 \) kpc but considerable uncertainty is accommodated by the small number of stars populating the giant branch. The possibility of a connection between VirZ and feature \( B \) is one that must await verification from deeper photometric and kinematic studies.

4 A FIELD OF COMPLEXITY – THE NATURE OF THE VIRGO OVERDENSITY

There are a number of possible interpretations for the morphology we see in Fig. 4. Structures \( A \), \( B \) and \( C \) could represent individual accretion events, or they may be ‘hotspots’ of increased density along a single stream. If describing a coherent structure, the distances to features \( A \) and \( B \) do not indicate a significant line-of-sight inclination for the stream.

The proximity of the features to Sgr and their alignment parallel to the Sgr leading arm stream could point to an origin from Sgr. In this scenario, \( A \), \( B \) and \( C \) may trace the trailing arm of Sgr some \( \sim 270^\circ \) downstream from Sgr. All N-body models in the literature (Helmi & White 2001; Law et al. 2005; Fellhauer et al. 2006), while they differ on the distance to which the trailing arm extends, place the returning trailing arm at a distance of \( \sim 20 \) kpc over the RA range of features \( A \) and \( B \). However, these models do not predict the substantial stellar density seen in the two features. There is also no evidence for a return of the trailing arm from the distribution of M-giants. However, this material is expected to be derived from disruption four orbital periods, or \( 3–3.5 \) Gyr ago (Law et al. 2005), and given that the bulk of M-giants are \( \sim 2–3 \) Gyr or younger (Keller 1999; Layden & Sarajedini 2000) we would expect a marked reduction in the contrast of M-giant tracers along this section of stream.

The possibility of a common origin for features \( A \), \( B \) and \( C \) in Sgr is one that requires clarification as this is critical for studies of the orbit of Sgr and, flowing from this, our ability to constrain the shape of the dark matter halo. Once we have clarified what material is associated with Sgr, we can then realize the potential of Sgr as a test particle of the Galaxy’s dark matter halo shape, \( q = a/c \), \( q \) is fundamental to Galactic dynamics. Recently, the RAVE consortium (Siebert et al. 2008) was unable to estimate \( q \) due to uncertainties in halo+disc mass and disc scalelength. Considering the distance and extension of the Sgr debris, they represent the best opportunity to constrain \( q \). Tracing Sgr debris through the VOD region will provide substantial new kinematic information that will allow much tighter constraints on the models. In turn, this may resolve the discrepancy in determination of \( q \) (current literature ranges from oblate \( q = 0.8 \) to prolate \( q = 5/3 \)).

Should subsequent observations and modelling reveal that the substructure revealed by the present study originates from Sgr, this will represent an important constraint on the number and mass of accretion events in the outer halo over the last \( 3–4 \) Gyr. The accretion history may then be compared to expectations from cosmological simulations. The small scaleheight of the disc suggests an anomalously low late-time merger rate (see e.g. Parry, Eke & Frenk 2008) – our observations will form additional evidence for, or against, this departure from the expectations of \( \Lambda \)CDM.

In light of the apparent complexity of the VOD region, additional radial velocities are critically needed. They will enable us to clarify if features \( A \), \( B \) and \( C \) form a coherent common stream. With revised N-body modelling, it will then be possible to test if these features can be accommodated by an origin in the Sgr debris stream. We aim to obtain further data with the AAT’s AAOmega spectrograph. In the near future, it will be possible to apply the techniques of the present study to the hemispheric coverage of SkyMapper (Keller et al. 2007).

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