Architecture of the Andromeda galaxy: a quantitative analysis of clustering in the inner stellar halo

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ABSTRACT
We present a quantitative measurement of the amount of clustering present in the inner ~30 kpc of the stellar halo of the Andromeda galaxy (M31). For this we analyse the angular positions and radial velocities of the carefully selected planetary nebulae in the M31 stellar halo. We study the cumulative distribution of pairwise distances in angular position and line-of-sight velocity space, and find that the M31 stellar halo contains substantially more stars in the form of close pairs as compared to that of a featureless smooth halo. In comparison to a smoothed/scrambled distribution, we estimate that the clustering excess in the M31 inner halo is roughly 40 per cent at maximum and on average ~20 per cent. Importantly, comparing against the 11 stellar halo models of Bullock & Johnston, which were simulated within the context of the ΛCDM (Λ cold dark matter) cosmological paradigm, we find that the amount of substructures in the M31 stellar halo closely resembles that of a typical ΛCDM halo.

Key words: methods: statistical – stars: individual: planetary nebulae – galaxies: individual: M31.

1 INTRODUCTION
Stellar haloes of galaxies are laboratories to test the process of galaxy formation and evolution. Under the current paradigm of hierarchical assembly in a cold dark matter (CDM) cosmology, it is believed that a galaxy, specifically its halo, grows continuously through the infall of smaller galaxies (Searle & Zinn 1978; White & Rees 1978; Helmi & White 1999). Observational evidence for the existence of a range of substructures in galaxy haloes is seen in tidal streams (e.g. Gregg & West 1998; Shang et al. 1998; Cárdeno-Roldán et al. 2000, etc.), stellar shells (e.g. Malin & Carter 1980; Seitzer & Schweizer 1990, etc.) and fans (Weil, Bland-Hawthorn & Malin 1997). In the local universe, the serendipitous discovery of tidal streams and substructures in the halo of the Andromeda (M31) and Milky Way (MW) galaxies (e.g. Majewski 1993; Ibata, Gilmore & Irwin 1995, etc.) provide additional evidence of ongoing accretion. The most prominent and spectacular among the contemporary findings are the Field of Streams (Belokurov et al. 2006) in the MW and the Giant stream (Ibata et al. 2001) in M31.

The amount of substructure in a given halo and the distribution of its properties, such as size, shape and location, are related to the accretion history of the halo. In addition to accretion, the stellar halo is expected to be partly formed by in situ stars. Recent hydrodynamical simulations of galaxy formation (Abadi, NAVarro & Steinmetz 2006; Zolotov et al. 2009; Font et al. 2011; McCarthy et al. 2012) suggest that in the inner regions, the stellar halo might be dominated by in situ stars whose kinematic properties are distinct from accreted stars. In the light of these findings, it is crucial to determine the relative contribution of the accreted component over that of an in situ component, for which a necessary first step would be to quantify the presence of observed substructures. By studying clustering of stars in the stellar halo, one can put constraints on the accretion history of that halo (Johnston et al. 2008; Sharma et al. 2011a).

The two spiral galaxies in the Local Group, whose substructures can be studied in great detail through individual resolved stars, are the MW and the neighbouring M31. For the MW, there has previously been extensive effort to quantify the amount of clustering in the stellar halo, e.g. Lynden-Bell & Lynden-Bell (1995), Clewley & Kinman (2006), Bell et al. (2008), Starkenburg et al. (2009), Cooper et al. (2011), Sharma et al. (2011a), Xue et al. (2011), Janesh et al. (2016), etc. For M31, the relatively recent discovery of various substructures, such as G1 Clump (Ferguson et al. 2002), NE Clump (Zucker et al. 2004), NE/W Shelves (Ferguson et al. 2002), etc., and tidal streams (Ibata et al. 2007; McConnachie et al. 2009; Richardson et al. 2009; Carlberg et al. 2011) also establish a qualitative assurance of clustering. However, to date there has only been a few attempts to quantify the level of substructure in the M31 stellar halo (Gilbert et al. 2009a, 2012; Ibata et al. 2014). Here, we

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1 For recent up-to-date menu of substructures in M31, refer to the Ferguson & Mackey (2016) in its stellar halo.
present a new approach of estimating the amount of clustering in the M31 halo, as well as provide a comparative study with contemporary models.

Structures formed by accretion events exist in coherent phase space defined by their positional coordinates and velocity vectors. Due to its large distance, the proper motions of M31 halo stars are not known at a high-enough fidelity to properly resolve all dimensions. This leaves us with an angular position in sky (i.e. a galactic longitude and latitude; $l$, $b$) and a line-of-sight velocity ($v_{\text{los}}$). Although it is generally an arduous campaign, $v_{\text{los}}$ can be obtained from spectroscopic observations, and is accurate enough to resolve the halo substructures. Fortunately the bright emission lines of the planetary nebulae (PNe), a population of dying stars, make them easily detectable and their line-of-sight velocities measurable with a minimal telescope time. Therefore, PNe have been proven to be excellent tracers for the dynamics of nearby galaxies leading to them being increasingly exploited to study the kinematic and dynamical properties of the M31 (e.g. Nolthenius & Ford 1987; Evans & Wilkinson 2000; Napolitano et al. 2001; Evans et al. 2003; Hurley-Keller et al. 2004; Kniazev et al. 2014, etc.), as well as some early-type galaxy haloes (e.g. Peng, Ford & Freeman 2004; Coccato, Arnaboldi & Gerhard 2013; Longobardi et al. 2015, etc.). To date, the survey using the Planetary Nebulae Spectrograph by Merritt et al. (2006) and Halliday et al. (2006) provides the largest stellar sample in M31 with radial velocity information. Unfortunately, many of these reside in the inner disc and bulge of the galaxy. In general, how representative PNe are of the whole halo population is still an open question. None the less, a few hundreds of PNe in Merritt et al. (2006) catalogue reside in the disc–halo interface or the inner halo of M31, which we use in this study.

In this paper, we provide a quantitative assessment of the amount of clustering present in the inner stellar halo of M31. For this, we utilize the angular coordinates and the radial velocity from archival data of PNe in M31 stellar halo. The layout of this paper is as follows: in Section 2, we describe the main properties of M31 and our sample of PNe. Details of the method we undertake to quantify the substructures in M31 halo are presented in Section 3. In Section 4, we present results of our findings and comparisons with the theoretical models, and further discuss them in Section 5. In Section 6, we provide our concluding remarks.

## 2 DATA

### 2.1 Central properties: M31

A list of the main properties of the M31 galaxy assumed in this work is as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA</td>
<td>00h42m44s33</td>
</tr>
<tr>
<td>Dec</td>
<td>41d16'07'5</td>
</tr>
<tr>
<td>Positionangle ($\theta$)</td>
<td>37:7</td>
</tr>
<tr>
<td>Inclination ($i$)</td>
<td>77.5</td>
</tr>
<tr>
<td>Distance from MW</td>
<td>7800 km</td>
</tr>
<tr>
<td>Heliocentric radial velocity</td>
<td>$-301 \text{ km s}^{-1}$,</td>
</tr>
</tbody>
</table>

where $^{a}$de Vaucouleurs (1958), $^{b}$Hodge (1992), $^{c}$Holland (1998); Stanek & Garnavich (1998); Conn et al. (2012) and $^{d}$de Vaucouleurs et al. (1991); van der Marel & Guhathakurta (2008).

Observed heliocentric velocities are converted to Galacticentric ones by assuming a solar peculiar motion ($U_\odot$, $V_\odot$, $W_\odot$) = (+11.1, +12.24, +7.25) km s$^{-1}$ (Schönrich, Binney & Dehnen 2010) and a circular speed of $220 \text{ km s}^{-1}$ at the position of the Sun.$^2$ To convert an M31 rest-frame centred coordinate system to the heliocentric frame and vice versa, we apply the formulary provided in the appendix B of Metz, Kroupa & Jerjen (2007), mainly used for the coordinate conversion of the synthetic data discussed latter.

### 2.2 Stellar halo tracers: PNe

The intrinsic faintness and the vast spatial extension of substructures in M31’s halo (e.g. McConnachie et al. 2009; Richardson et al. 2011; Gilbert et al. 2012; Huxor et al. 2014; Ibata et al. 2014, etc.) mean it is difficult to do a comprehensive survey of the stars therein. However, due to the development of wide-field multi-object spectrographs (Douglas et al. 2002), it is now easy to detect one of the brightest and ubiquitous halo tracers i.e. the PNe. As discussed previously, PNe census has surged lately and currently constitutes the largest stellar sample of M31 halo tracers with radial velocity information. Hence, we use PNe data in this work, which are obtained from the catalogues constructed by Merritt et al. (2006) and Halliday et al. (2006).

The data were observed using the Planetary Nebula Spectrograph on the William Herschel Telescope in La Palma and were subsequently made publicly available online.$^3$ In total, the published catalogue provides 3300 emission-line objects of which only 2730 are identified as possible PNe. Out of the likely PNe sample, roughly 6 per cent of objects are associated with M32, NGC 205, Andromeda IV or even external galaxies. After removing above contaminants, we are left with an initial subsample of 2637 PNe belonging to M31. Distances to these PNe are unfortunately unknown and typical uncertainty in their radial velocities is $20 \text{ km s}^{-1}$.

Our study only focuses on the tracers of the M31 stellar halo. Therefore, to select only objects dwelling in the halo, we restrict the above sample of 2637 PNe to those with a projected distance of $|Y| \geq 5 \text{ kpc}$, the limit adopted from Lee et al. (2008), which provides us the final sample of 228 halo PNe. Lee et al. (2008) find that the velocity dispersion of globular-cluster system doubles beyond the projected distance of 5 kpc compared to the inner 1 kpc region, meaning pressure support dominates over the rotational support in the outer regions. This provides an empirical proof that this cut delineates the halo–disc interface. This can be seen clearly in Fig. 1. The contours show an isodensity region for our entire PNe sample associated with the M31 and similar to one in, e.g., Ferguson et al. (2002), McConnachie et al. (2009) and Ibata et al. (2014), who use red giant branch stars(RGBs). The angles $\xi$ and $\eta$ are the conventional on-sky angles, which are obtained from the gnomonic projection of the object’s RA and Dec. position. The halo subsample obtained after the $|Y| \geq 5 \text{ kpc}$ are shown with red dots. The blue solid ellipse demarcates the approximate limit of the visible disc of inclination 77.5 and radius 2$'$ (27.2 kpc). Our halo PNe subsample falls outside the ellipse, which means the $|Y| \geq 5 \text{ kpc}$ cut is successful in selecting the halo candidates. The observational extent of our final PNe data only extends to $\sim 30 \text{ kpc}$ from the centre of the galaxy. This represents only 1/4 of the total stellar halo, which extends to at least 150 kpc (McConnachie et al. 2009; 2011).

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$^2$ Note that we adopt the IAU recommended value but our main results are unchanged if we use higher value of $\sim 240 \text{ km s}^{-1}$ (e.g. Reid et al. 2009; K allele et al. 2014; Bland-Hawthorn & Gerhard 2016, etc.).

$^3$ http://www.strw.leidenuniv.nl/pns/PNS_public_web/PNS_data.html
Figure 1. M31 PNe data: contours show an isodensity region of PNe in M31 ($N = 2637$) whereas the red points denote its subsample ($N = 228$) residing in the stellar halo. The halo PNe observation extends to a radius of $\sim 30$ kpc. The ellipse shown with blue solid line represents a disc of inclination $77.5^\circ$ and radius $21^\circ$ (27.2 kpc), the approximate limit of the M31 visible disc.

Gilbert et al. 2012). Thus, we are actually only probing the inner stellar halo of M31, or more strictly the disc–inner halo interface.

3 DISTANCE METRIC AND INTERPRETATION

The main aim of our work is to quantify the level of clustering in M31 halo and subsequently compare this with predictions from theoretical models. A particularly useful way to quantify clustering in any data, consisting of points in some arbitrary space, is the two-point correlation function. In astronomy this has been used extensively, mainly to characterize the spatial distribution of galaxies obtained from galaxy-redshift surveys (e.g. Peebles 1980; Landy & Szalay 1993; Mo, van den Bosch & White 2010, etc., and references therein). Similarly, a correlation-function-based approach has also been used to study clustering in the context of the MW galaxy (Starkenburg et al. 2009; Cooper et al. 2011; Xue et al. 2011). We follow a similar approach, described below.

Ideally, one would like a full-phase-space information to perform this kind of study. However, in reality we only possess angular positions, e.g. galactic coordinates $l$ and $b$, and radial velocity $v_{\text{los}}$ of tracers (our PNe). The basic concept of this approach is to compute pairwise distance of all tracers and then study the distribution of these distances. However, to compute the distances a proper choice of metric is required. Following Starkenburg et al. (2009) and Xue et al. (2011), we compute the separation between two PNe $i$ and $j$ using the following metric:

\[ s_{ij} = w_\theta \theta_{ij}^2 + w_{v_{\text{los}}} (v_{\text{los},i} - v_{\text{los},j})^2, \]

where angular separation

\[ \theta_{ij} = \cos^{-1} \{ \cos b_i \cos b_j \cos (l_i - l_j) + \sin b_i \sin b_j \}. \]

The $w_\theta$ and $w_{v_{\text{los}}}$ are weights used to create a consistent metric for the two dimensions: position and velocity. They are derived from the reciprocal of an ensemble average of the separation in the respective dimensions given as

\[ w_\theta = \frac{1}{\langle \theta_{ij}^2 \rangle} \quad \text{and} \quad w_{v_{\text{los}}} = \frac{1}{\langle (v_{\text{los},i} - v_{\text{los},j})^2 \rangle}. \]

A simple interpretation of equation (1) is that stars with small value for $s_{ij}$, or separation, are close pairs and are likely to be a part of the same object or substructure. Furthermore, an excess of close pairs, i.e. large number of stars with small $s_{ij}$, would mean more clustering. On the contrary, a substructureless smooth halo, or a fully phase-mixed halo, should have fewer number of such close pairs.

The performance of the above method has been well tested against various types of simulated data, e.g. on the sets of Monte Carlo samples drawn from simulations of disrupted satellites (Starkenburg et al. 2009), on the data from semi-analytic model of galaxy formation (Cooper et al. 2011) and on the controlled simulation of MW/M31-type galaxies (Xue et al. 2011).

The level of clustering can be further quantified using the information-theory-based concept of Kullback–Leibler divergence (KLD; Kullback & Leibler 1951). The KLD measures the departure...
of the truth distribution $p$ from a candidate model $q$. For discrete probability distributions like the ones we get from equation (1), the KLD of $q$ from $p$ on the set of points $i$ is defined as

$$D_{KL}(p||q) = \sum_i p_i \log \left( \frac{p_i}{q_i} \right).$$

From the above formula, we see that the KLD is an expectation value of the logarithmic difference between two probability distributions, computed with weights of $p_i$. Also, $D_{KL}(p||q)$ is asymmetric in $p$ and $q$, and non-negative. The greater the difference between the two distributions $p$ and $q$, the higher the value of $D_{KL}(p||q)$, and as $p \to q$, $D_{KL}(p||q) \to 0$. Here, both the distributions $p$ and $q$ are discrete and obtained from the histograms of a true close pair distribution and for the averaged distribution of the 200 random versions of the scrambled data. Scrambled data mean the data with the intrinsic pairing between angles $(l, b)$ and velocity $(v_{los})$ are decorrelated. Scrambled data are assumed to represent featureless smooth data against which we can quantify the extent of clustering of the original sample. A $D_{KL}(p||q) \geq 0$ value means distribution of a true close pair is quantitatively different from the distribution of its randomized counterpart.

## 4 RESULTS

Here we present and discuss the main results of the paper, inferred from studying the distributions of pairwise distance for a set of toy data, the observed PNe data, as well as the synthetic data from simulations of the MW-type galaxies.

### 4.1 Test data and a proof of concept

First, we demonstrate a proof of concept of our method for which we generate a set of test data. The stellar volume density of M31 stellar halo is found to be a continuous single power-law i.e. $\rho \propto r^{-\alpha}$ with $\alpha \in [2.5, 4]$ (e.g. Irwin et al. 2005; Gilbert et al. 2007; Ibata et al. 2007, 2014; Courteau et al. 2011; Deason et al. 2013, etc.). We generate particles following this power-law density distribution with $\alpha = 3.5$. To each of these particles, we assign velocities which are sampled from either an isotropic ($\beta = 0$) or a radial ($\beta = 0.25$) or a tangential ($\beta = -0.34$) distribution. $\beta$ is the Binney anisotropy parameter and describes an orbital structure of the system. The values of $\beta$ can range from $-\infty$ (for purely circular trajectories) to 1 (for purely radial orbits). From the above values of $\beta$, we obtain a set of three different test data sets, which we then project into an observational space 'on sky'. Henceforth, we treat them in the exact same way as we would the observed data.

In Fig. 2, we show the cumulative distributions of logarithm of the pairwise distance obtained from equation (1) and the test data described above. The red, blue and purple dotted lines show the distributions for the radial, tangential and isotropic data, respectively, whereas the dashed lines show the corresponding scrambled data. Precisely speaking, we scramble randomly the order of velocities but the order of angular positions is left unchanged. We then calculate the pairwise distance between two data points in these scrambled data. To get more robust estimates, we use 200 random versions of the scrambled data and only show their average distribution in the figure.

For all of the three data sets, we measure $D_{KL}(p||q) \simeq 0$, meaning the log $F$ of the actual data and their scrambled counterpart are identical. This result can also be attested visually from Fig. 2 by comparing the red/blue/purple dotted lines, which overlap the dashed lines (scrambled counterpart of the synthetic data) of the corresponding colour. This is expected, given that the synthetic data were featureless, or devoid of any substructure by nature. Similarly, we also find that changing the number-density slopes ($\alpha$) to either a slightly higher value of 4 or a lower value of 2.5 still results $D_{KL}(p||q) \simeq 0$.

Note that the black dashed line shows the level of clustering in the scrambled observed PNe data in M31 inner stellar halo. It overlaps with all the three featureless synthetic data. This confirms that scrambling the real data satisfactorily produces a smooth distribution, which we treat as a background and use to compare to any excess in clustering in the following section. For a reference the black dotted line shows the level of clustering in observed PNe data in M31 inner stellar halo, which we further discuss and use in the following section.

### 4.2 Observed data: PNe

We now turn to quantifying the level of clustering in the M31 inner halo at $\lesssim 30$ kpc as traced by PNe. Fig. 3 shows the excess in clustering i.e. the logarithmic difference between the cumulative distributions of pairwise distance, for the data and its scrambled counterpart, as a function of pairwise distance in logarithmic scales. In other words, it is the logarithmic difference between the black dotted and dashed lines shown in Fig. 2. The result is shown with black solid line. The smaller the log $s$ value the closer the pairs are in spatio-kinematic space. For these data, we measure $D_{KL}(p||q) = 0.2$ ($\geq 0$) meaning the cumulative distributions of the data and their scrambled counterpart are quantitatively different from each other i.e. there is an excess of clustering in the PNe data over a smooth distribution. Monte Carlo propagation of uncertainties in the radial velocities of the PNe is found to introduce less than a per cent error in log $F$ and $D_{KL}(p||q)$. We estimate that the clustering excess of M31 inner halo compared to a smoothed distribution, i.e. with the zero excess, is roughly 40 per cent at maximum at the pairwise distance log $s = -3.0$ and on average $\sim$20 per cent over log $s \in [-3.0, 1.5]$.

![Figure 2](https://academic.oup.com/mnras/article-abstract/464/4/4858/2417454/Architecture-of-the-Andromeda-galaxy-a/4861)

**Figure 2.** Cumulative distributions of the pairwise distances for PNe and synthetic data: the black line shows the distribution for the observed M31 PNe data whereas the colourful lines show the distributions for the featureless synthetic data with power-law density distribution ($\rho$) and a set of velocity anisotropies ($\beta$). Dotted and dashed lines show the distributions before and after the angle and velocity pair were disassociated or scrambled.
Figure 3. Clustering excess in the data compared to its scrambled case: a black line shows excess in clustering for the observed PNe data whereas the remaining colours, as labelled in the figure, show excess in the 17 different Bullock & Johnston (2005) and Johnston et al. (2008) simulated stellar haloes projected on to M31 observational space and convolved with observational errors.

4.3 Comparison with simulated stellar haloes

To make theoretical predictions of substructures in the stellar halo, we use 17 stellar halo models of Bullock & Johnston (2005) and Johnston et al. (2008) and generate stars from the models using GALAXIA\(^5\) (Sharma et al. 2011b). Out of these simulated haloes, 11 (LCDM02–LCDM20)\(^6\) have accretion histories derived from the ΛCDM paradigm. The remaining six haloes have controlled/artificial accretion histories, with accretion events which are predominantly (1) on radial orbits (ratio of the angular momentum of the orbit to the angular momentum of a circular orbit having same energy $\epsilon < 0.2$), (2) on circular orbits ($\epsilon > 0.7$), (3) old/ancient (time since accretion of greater than 11 Gyr), (4) young/recent (time since accretion of less than 8 Gyr), (5) high in luminosity (luminosity greater than $10^7 L_\odot$) and (6) low in luminosity (luminosity less than $10^7 L_\odot$); for further details see Johnston et al. (2008).

To keep our simulated haloes consistent with the observed data, we set the GALAXIA parameters such that it produces a catalogue of approximately the same sample size\(^7\) as the observed PNe. Note that GALAXIA samples an N-body system and if more than one star particle is spawned from an N-body particle, then this can introduce artificial smoothing on small scales. Generating fewer star particles avoids this problem. We must choose a tracer population for our simulated stars and unfortunately, GALAXIA does not generate PNe. Hence, instead we generated RGBs; for the discussion about this choice refer to Section 5. To select RGBs from full halo population generated by GALAXIA, we use colour $B − V > 0.8$ and absolute magnitude $M_v ≤ 4$. To reduce the contamination of main-sequence stars, we have chosen a smaller value for $M_v$ compared to Holmberg & Flynn (2000). The stellar halo generated using GALAXIA is then moved to the observational space of M31 following the transformation mentioned in Section 2, i.e. the stars from the model are projected on the sky as the actual data. Furthermore, we jitter their

\(^5\) The weblink to the GALAXIA software is http://galaxia.sourceforge.net/ and the original Bullock & Johnston (2005) haloes were obtained from the weblink http://user.astro.columbia.edu/~kv/halos/. For the full documentation of the GALAXIA refer to http://galaxia.sourceforge.net/Galaxia3pub.html.

\(^6\) For an easy reference, the halo numberings are kept same as in the original catalogue.

\(^7\) Determined by fSample parameter in the GALAXIA.
we check that changing the on-sky area of the sample by ±1 deg² has no discernible impact on our results. We also mask the inner 2 deg² region as done for the observed data (Section 2.2) earlier. Also, the halo stars from the models are unbound from satellites of origin.

In Fig. 3, we show the clustering results of the above simulated haloes. We plot clustering excess, which is the logarithmic difference between the cumulative distributions of pairwise distance for the synthetic data and its scrambled counterpart. Here again we only use \((l, b)\) and \(v_{\text{los}}\) to calculate the pairwise distance in exact same method as for the PNe. As labelled in the figure, different simulated haloes are shown with different colours. The solid and dashed lines of the same colour means haloes of opposite properties, e.g. old and young, radial and circular and high luminosity and low luminosity. The grey and green lines with different line styles and shading show 11 ΛCDM haloes (LCDM02–LCDM20) whereas the black solid line shows result with the PNe data.

Reassuringly Fig. 3 shows a number of expected trends for the simulated haloes. For example, the old halo shown with an orange solid line shows less substructures than its counterpart young halo. This is expected as substructures in an older halo get more time to phase mix. Similarly, the radial halo shows less substructure compared to the circular halo. This is due to the fact that satellites on radial orbit pass close to the Galactic Centre and are more likely to get disrupted due to strong tidal effects. The low- and high-luminosity haloes show similar clustering for \(\log s > -1\), but at smaller \(\log s\) low-luminosity halo shows a systematic rise in clustering. The accretion time and the type of orbits are similar for both low- and high-luminosity haloes; the main difference between them is the luminosity or mass of accretion events. The low-luminosity halo of the M31 have many accretion events but with small mass, and this generates small substructures which will only show up on smaller scales. This explains the sharp rise in clustering at small \(s\). On average the accretion history of a typical ΛCDM halo is not as extreme as those of the six haloes discussed above. As expected the clustering excess for the ΛCDM haloes, except for the LCDM14, lies between the two extreme accretion events. Overall, the above results confirm that our method successfully distinguishes the disparity in haloes.

Interestingly, the excess of substructures in the M31 PNe data is noticeably larger than the extreme smooth models such as the radial and old haloes. In overall clustering in the M31, halo seems to be similar to that of typical ΛCDM haloes. A similar result has also been observed in the MW front by Bell et al. (2008) who found the observations and simulations to be in rough agreement. They also make use of the 11 simulated stellar haloes of Bullock & Johnston (2005). However, they compared the radial dependence of the fractional root-mean-square deviation of the stellar density from a smooth triaxial model in the Galactic main-sequence turn-off stars instead.

5 DISCUSSION

We note that the results presented here could be sensitive to some unquantified systematic biases. Primarily, the PNe data we adopt from Merrett et al. (2006) and Halliday et al. (2006) do not map the M31 stellar halo homogeneously. The survey area mainly covers the disc of the galaxy (which we have masked out in this work) and a few fields beyond the optical radius of M31 (along the minor and major axes targeting in particular known substructures such as the Northern Spur and Southern Stream regions). However, since no velocity limits have been imposed to obtain the PNe sample, we naively expect that the data we analysed have a reasonable completeness in a kinematic space.

As noted previously, GALAXIA does not generate PNe data. Hence, we compare our results for the observed PNe data against RRGBs generated from the GALAXIA model. Our preference for RGBs is governed by two main motivations. First, RGBs are much fairer tracer of the stellar halo as they span a vast range in age and metallicity. Therefore, they provide a good representation of the overall properties of the system in comparison to say blue horizontal branch stars, which represent very old stellar population. Secondly, RGBs are typically the primary target in M31 studies (refer to Ferguson et al. 2002; Gilbert et al. 2009a; Conn et al. 2012; Martin et al. 2013; Ibata et al. 2014, and references therein) mainly due to their intrinsic brightness, and also due to their ability to estimate their distances reliably. Furthermore, we can see in fig. 29(30) of Merrett et al. (2006) that the PNe number counts along the major(minor) axis of M31 show excellent agreement with the \(r\)-band photometry, which is expected to be dominated by low-mass red giants. As such, both RGBs and PNe trace similar intrinsic population and, hence, their kinematic properties are expected to be similar. However, we cannot discount the fact that considering different tracers could introduce systematic differences in the inferred properties of the accreted halo (Sharma et al. 2011a). Hence, a slight fluctuation in the excess for the models shown in Fig. 3 should be expected depending on the choice of tracer population.

Finally, we like to recap the studies by Gilbert et al. (2009a, 2012) and Ibata et al. (2014) which also quantify the amount of substructures in M31’s halo by detecting kinematically cold components and overdensities over a smooth halo distribution, respectively. Most notably, Ibata et al. (2014) find that 42 per cent of the most metal-poor populations in the M31 halo reside in the stream-like structures whereas 86 per cent of metal-rich population resides in streams. Currently it is difficult to make a robust quantitative comparison of these works with our results, mainly due to differences in the approaches (i.e. statistical analyses). However, all these works qualitatively agree that a significant fraction of the stellar populations in the haloes of M31 are present in substructures. Similarly, we can directly compare our results (black solid line in Fig. 3) for M31’s halo with the equivalent studies of the MW halo; in particular, fig. 5. of Xue et al. (2011). Comparing this with our result for M31, we can say that the clustering excess of halo tracers in these two neighbouring galaxies are of a similar level. For example, the excess of clustering for both the haloes at a pairwise distance of \(\log s = -2\) is roughly 0.15. However, note we only probe the inner halo of M31 whereas Xue et al. (2011) probe the MW stellar halo out to a radius of 60 kpc. Moreover, Xue et al. (2011) use a different halo tracer (blue horizontal branch stars) and, also, a three-dimensional spatial and velocity to measure the pairwise distances. Currently, due to different sample size, spatial coverage, type and extent of stellar halo tracers, it is difficult to make a fair and robust comparison between the haloes of the MW and M31.

The ability of our method to distinguish the level of clustering in haloes with different accretion history, as shown in Section 4.3, is encouraging. In future, it will be useful to repeat the analysis with tracers which extend to much larger distances and far away from the disc, such as using the SPLASH (Gilbert et al. 2009b) and PAndAS (McConnachie et al. 2009) surveys. Such studies will
allow statistically more robust quantification of clustering in the M31 halo and, additionally, it will also open an avenue to produce a direct like-for-like comparison with existing measurements of clustering in the MW stellar halo.

6 CONCLUSIONS

We analyse archival data of PNe (Halliday et al. 2006; Merrett et al. 2006) to quantify the amount of kinematic clustering present in the inner $\lesssim 30$ kpc of the M31 stellar halo. Additionally, we also compare our results with predictions from $N$-body simulations using the 17 synthetic stellar haloes of Bullock & Johnston (2005) and Johnston et al. (2008).

In the three-dimensional space formed by angular coordinates and line-of-sight velocity, we find that the M31 stellar halo shows a significant amount of clustering, when measured in the form of excess of close pairs as compared to its scrambled counterpart. We estimate that the clustering excess of M31 inner halo compared to a smoothed distribution is roughly 40 per cent at maximum (for the closest pairs) and $\sim 20$ per cent on average.

Furthermore, the study of stellar haloes of different accretion histories taken from Bullock & Johnston (2005) and Johnston et al. (2008) models and generated using the GALAXIA software allows a quantitative calibration of our result with PNe. We find that the excess of clustering in M31 is larger than the extreme smooth halo models such as the radial halo (one formed with accretion events which are predominantly on radial orbits) or the old halo (time since accretion of $\gtrsim 11$Gyr). Importantly, we find that the clustering excess in the M31 inner stellar halo is similar to that of a typical $\Lambda CDM$ halo in Bullock & Johnston (2005) models.

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