Modeling The Redshift-Space Three-Point Correlation Function in SDSS-III

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ABSTRACT
We present the measurements of the redshift-space three-point correlation function (3PCF) for \( z \sim 0.5 \) luminous red galaxies of the CMASS sample in the Sloan Digital Sky Survey-III Baryon Oscillation Spectroscopic Survey Data Release 11. The 3PCF measurements are interpreted within the halo occupation distribution (HOD) framework using high-resolution N-body simulations, and the model successfully reproduces the 3PCF on scales larger than \( 1 \ h^{-1} \text{Mpc} \). As with the case for the redshift-space two-point correlation functions, we find that the redshift-space 3PCF measurements also require the inclusion of galaxy velocity bias in the model. In particular, the central galaxy in a halo on average is in motion with respect to the core of the halo. We discuss the potential of the small-scale 3PCF to tighten the constraints on the relation between galaxies and dark matter haloes and on the phase-space distribution of galaxies.

Key words: galaxies: distances and redshifts—galaxies: haloes—galaxies: statistics—cosmology: observations—cosmology: theory—large-scale structure of universe

1 INTRODUCTION
Contemporary galaxy redshift surveys enable the large-scale distribution of galaxies to be accurately mapped in redshift space. Compared to the real-space distribution, that in redshift space is distorted as a result of galaxy peculiar velocities, which is generally referred to as redshift space distortions (RSD). The RSD effects encode information about the kinematics of galaxies inside dark matter haloes and the growth rate of cosmic structure.

The clustering of galaxies in redshift space has been extensively studied using the two-point correlation functions (2PCFs) (see e.g. Zehavi et al. 2002, 2005, 2011; Li et al. 2006; Coil et al. 2006; Wang et al. 2007; Skibba & Sheth 2009; Li et al. 2012; Guo et al. 2013). The widely-used halo occupation distribution (HOD) modeling of the galaxy 2PCFs provides an opportunity to understand the connection between galaxies and their host dark matter haloes (see e.g. Jing et al. 1998; Peacock & Smith 2000; Scoccimarro et al. 2001; Berlind & Weinberg 2002; Zheng et al. 2005, 2009; Miyatake et al. 2013; Guo et al. 2014b). The observationally constrained relation between galaxies and dark matter haloes provides insight also about galaxy formation and cosmology. Recently, Guo et al. (2014a) (hereafter G14) used the luminous red galaxies (LRGs) in the Sloan Digital Sky Survey-III (SDSS-III; Eisenstein et al. 2011) Baryon Oscillation
Spectroscopic Survey (BOSS; Dawson et al. 2013) to model the redshift-space 2PCFs and found the distribution of galaxy velocities different from that of the dark matter in the haloes, an effect denoted as galaxy velocity bias (see also Reid et al. 2014).

Higher-order statistics, e.g. the three-point correlation function (3PCF), aid in tightening the constraints on HOD parameters and in breaking the degeneracy among parameters (Kulkarni et al. 2007; Smith et al. 2008). The 3PCF, \( \zeta(r_1, r_2, r_3) \), describes the probability of finding galaxy triplets with the separations in between as \( r_1, r_2 \) and \( r_3 \) (see e.g. Bernard et al. 2002 for a review). A non-zero 3PCF naturally arises because of the non-Gaussianity generated during the nonlinear evolution of the density fluctuations, even if primordial fluctuations were perfectly Gaussian. The 3PCF is commonly used to break the degeneracy between the galaxy bias and the amplitude of the matter density fluctuation, and therefore constrains cosmological parameters (Gaztañaga & Frieman 1994; Jing & Börner 2004; Gaztañaga et al. 2005; Zheng 2004; Pan & Szapudi 2005; Guo & Jing 2009; McBride et al. 2011; Marín et al. 2013; Guo et al. 2014c).

In this paper, we measure the redshift-space 3PCF for the same sample of LRGs at redshift \( z \sim 0.5 \) as in G14 and interpret the 3PCF measurements within the HOD framework. In particular, we perform HOD modeling of both the 2PCFs and 3PCF and investigate the additional constraining power from the 3PCF on the HOD parameters, including the galaxy velocity bias.

The paper is structured as follows. In Section 2, we briefly describe the galaxy sample, the 3PCF measurements, and the modeling method. We present our modeling results in Section 3 and conclude in Section 4. Throughout this paper we adopt a spatially flat ΛCDM cosmology with a matter density parameter \( \Omega_m = 0.27 \), \( \sigma_8 = 0.82 \) and a Hubble constant \( H_0 = 100 h \text{ km s}^{-1} \text{Mpc}^{-1} \) with \( h = 0.7 \).

## 2 DATA AND MEASUREMENTS

In this paper, we use the same volume-limited LRG sample as in G14 (i-band absolute magnitude \( M_i < -21.6 \) and \( 0.48 < z < 0.55 \)), selected from SDSS-III BOSS CMASS galaxies (Eisenstein et al. 2011; Bolton et al. 2012). Following Guo et al. (2014c), the 3PCF is calculated using the estimator of Szapudi & Szalay (1998). The triangles are represented in the parameterization of \( (r_1, r_2, \theta) \), with \( r_2 \geq r_1 \) and \( \theta \) being the angle between \( r_1 \) and \( r_2 \). We use linear binning schemes for \( r_1, r_2 \) and \( \theta \), with \( \Delta r_1 = \Delta r_2 = 2 h^{-1} \text{Mpc} \), and \( \Delta \theta = 0.1 \pi \).

To correct for the fibre collision effect in the redshift-space 3PCF, \( \zeta(r_1, r_2, \theta) \), we assign the redshift of each fibre-collided galaxy from its nearest neighbor (Guo et al. 2012, 2014c). To further reduce any residual effect on scales slightly larger than the projected fibre collision scale in SDSS-III (~0.5 \( h^{-1} \text{Mpc} \)) (Gunn et al. 2006; Dawson et al. 2013; Smee et al. 2013), we only consider the triangle configurations of \( r_2 = 2 r_1 \) and \( r_1 \geq 1 h^{-1} \text{Mpc} \), which will ensure that all sides of the triangle are larger than \( 1 h^{-1} \text{Mpc} \). We measure the redshift-space 3PCF for six \( r_1 \) bins, centered at \( 2 h^{-1} \text{Mpc}, 4 h^{-1} \text{Mpc}, ..., 12 h^{-1} \text{Mpc} \), with each bin having 10 triangle configurations of different values of \( \theta \).

For HOD modeling, we also adopt the 2PCF measurements from G14 and perform a joint fit with the 3PCF, which allows a study of the information content related to the HOD constraints from the 3PCF. The 2PCF measurements include the projected 2PCF (\( w_p \)), the monopole (\( \xi_0 \)), quadrupole (\( \xi_2 \)) and hexadecapole moments (\( \xi_4 \)) of the redshift-space 2PCF from 0.13 to 51.5 \( h^{-1} \text{Mpc} \) (see details in G14). The full covariance matrix (including the cross-correlation between the 2PCF and 3PCF measurements) is estimated from \( N_{jk} = 403 \) jackknife subsamples (G14). To reduce the effect of noise in the covariance matrix, we apply the method of Gaztañaga & Scoccimarro (2005) and only retain the modes that have eigenvalues \( \lambda^2 \geq \sqrt{2/N_{jk}} \). Figure 1 displays the covariance matrix of the 3PCF. In each \( r_1 \) bin, the measurements of different \( \theta \) bins are strongly correlated with each other. The correlation between different \( r_1 \) bins is stronger for larger \( r_1 \), implying better constraints to the model from the measurements at smaller scales.

Following G14, we adopt the five-parameter HOD model of Zheng, Coil & Zehavi (2007) and include two additional velocity bias parameters, \( \alpha_v \) and \( \alpha_s \), for central and satellite galaxies, respectively. To model the redshift-space 2PCF, we use the simulation-based model of Zheng & Guo (2014) (see also G14), which is equivalent to populating haloes in the simulations with galaxies for a given HOD prescription. For the dark matter halo catalogs, we use the MultiDark simulation output at \( z = 0.53 \) (see details in Prada et al. 2012). The haloes are defined using the spherical overdensity (SO) algorithm, with a mean density ~237 times that of the background universe at \( z = 0.53 \). The halo centre is defined as the position of the dark matter particle with the minimal potential. We choose the bulk velocity of the inner 25 percent halo particles around the potential minimum as the halo (core) velocity, and the velocity bias is parameterized in this frame, as in G14.

We place the central galaxies at the halo centres, with their velocities the same as the halo velocities. For satellite galaxies, we assign the positions and velocities of randomly-selected dark matter particles. We then add the velocity bias effect. The central galaxy velocity bias is parameterized as an additional Gaussian component with zero mean and a standard deviation of \( \alpha_v \sigma_v \), where \( \sigma_v \) is the line-of-sight (LOS) velocity dispersion of the dark matter particles in each halo. For the satellite velocity bias, the relative LOS velocity of a satellite galaxy to the halo core is scaled by \( \alpha_s \) (as detailed in G14), therefore the 1D satellite galaxy velocity dispersion \( \sigma_s \) is a factor of \( \alpha_s \) times that of the dark matter particles, \( \sigma_s = \alpha_s \sigma_v \).
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3 RESULTS

We explore the constraining power of the 3PCFs on the HOD parameters (including velocity bias parameters) by fitting different combinations of 2PCFs and 3PCFs.

First, we follow the traditional way of constraining the five-parameter HOD model by fitting the projected 2PCF, $w_p$. The model implicitly assumes no velocity bias and does not account for redshift errors. As discussed in G14, the best-fit model for $w_p$ cannot reproduce the clustering measurements in the redshift space for $\xi_0$, $\xi_2$, and $\xi_4$ because it neglects the galaxy velocity bias. The predicted redshift-space 3PCFs from the $w_p$-only best-fitting model are shown as dotted curves in Figure 2. Clearly, the model does not provide a good fit to the measured 3PCFs (circles with error bars) on all scales. The 3PCF $\zeta$ is over-predicted, especially on small scales. For the 60 3PCF data points, the model corresponds to a value of $\chi^2$ of 84.6.

Next we investigate the best-fitting model from the simultaneous fit to $w_p$ and the multipole moments ($\xi_{0,2,4}$), which includes the two galaxy velocity bias parameters and the redshift errors (G14). The predicted redshift-space 3PCFs are shown as the dashed blue curves in Figure 2. Compared to the $w_p$-only model, the $w_p + \xi_{0,2,4}$ model better reproduces the measured 3PCFs, producing $\chi^2 = 72.6$ for the 60 3PCF data points. Even though the model still shows an over-prediction of $\zeta$ on small scales, it lies largely within the one-sigma range from jointly fitting 2PCFs and 3PCFs (shaded region; see below).

The above study demonstrates that galaxy velocity bias is needed to interpret the measured redshift-space 3PCFs. Conversely, it implies that the redshift-space 3PCFs can provide constraints on the velocity bias parameters, which is a point we discuss later. We now investigate constraints from jointly fitting $w_p$ and the 3PCFs, including the two velocity bias parameters. The best-fitting model is shown as the dashed red curves in Figure 2, which reproduces the measurements successfully, with an overall $\chi^2$/dof of 46.4/68.

Finally, we perform a joint fit to $w_p$, $\xi_{0,2,4}$, and $\zeta$. The best-fitting models are shown as the solid black curves in Figure 2, which represents the 3PCF measurements remarkably well on all scales. The overall best-fitting $\chi^2$/dof value, to all measurements, is 97.4/110, and the $\chi^2$ from the 60 3PCF data points is 42.4. There is a slight over-prediction for triangle configurations of $\theta \sim 0.4\pi$ on scales of $r_1 > 7 h^{-1}$Mpc. According to the covariance matrix in Figure 1, the measurements for these triangle configurations are strongly correlated among the neighboring $\theta$ bins, which implies that the fit cannot be simply judged by $\chi^2$-by-eye. The shaded re-
gions are the 1σ uncertainties around this best-fit model. On large scales ($r_1 > 7 \, h^{-1}\text{Mpc}$), all four models are consistent within the 1σ uncertainties, with the $w_p$-only model showing the largest deviation. The four models are more readily separate on smaller scales, where the contribution of the one-halo term (i.e. the contribution from intra-halo galaxy triplets) becomes important. This result indicates that the small-scale 3PCF measurements are important in discriminating the models and in constraining the galaxy distribution within halos.

Figure 3 shows the constraints on the HOD from the four models in Figure 2. The left panel presents the best-fitting mean occupation functions. The mean occupation functions of central galaxies can already be well constrained by $w_p$, and the four models show only small variations. The well-constrained mean occupation function of central galaxies explains why the 3PCFs on large scales are similar for the four models. The best-fitting mean occupation functions from $w_p$-only or from including $\xi_{0,2,4}$ or $\zeta$ are similar. Including all the 2PCFs and 3PCFs lead to a shallower high-mass slope. However, the uncertainty in the high-mass slope is large, as indicated by the shaded region (1σ) for the $w_p + \xi_{0,2,4} + \zeta$ fit, and the satellite mean occupation functions from the four models are in good agreement. In fact, the uncertainty in the high-mass slope is even larger if we do not include the 3PCFs. The 3PCFs thus tighten the constraints on the high-mass slope, as expected from the larger weight towards higher halo mass from the intra-halo galaxy triplets. However, we do not find substantial tightening for the high-mass slope, which results from the lack of 3PCF measurements on scales below $1 \, h^{-1}\text{Mpc}$.

The agreement between the mean occupation functions constrained from the $w_p$-only fit and the joint fit, together with the difference in the corresponding model 3PCFs, suggests that galaxy velocity bias plays an important role in explaining the data. The right panel of Figure 3 shows the velocity bias constraints (contours of 95% confidence level) for the three relevant models.

The velocity bias constraints from $w_p + \xi_{0,2,4}$ are the same as in G14. When replacing $\xi_{0,2,4}$ with the redshift-space 3PCF $\zeta$, the velocity bias constraints originate from $\zeta$. Indeed, the red contour in the right panel of Figure 3 shows that the 3PCF data requires the existence of central galaxy velocity bias $\alpha_c$. The value of $\alpha_c$ is consistent with that from the 2PCF constraints. The effect of the central velocity bias can be inferred from the comparison between the $w_p$-only prediction with no central velocity bias and the $w_p + \zeta$ fit with central velocity bias for the 3PCFs on large scales in Figure 2. The model with no velocity bias shows a clear over-prediction of $\zeta$ for nearly degenerate triangle configurations (i.e., $\theta \sim 0$ and $\theta \sim \pi$). Consider the situation in an overdense region, which appears squashed in redshift space along the line of sight because of large-scale infall. The effect of the central velocity bias is to smear out the redshift-space distribution of galaxies, making the distribution less squashed. A less squashed distribution reduces the possibility of finding degenerate triangle configurations, and thus lowers the amplitude of $\zeta$ for $\theta \sim 0$ and $\theta \sim \pi$, leading to a better fit to the data.

In terms of the satellite velocity bias, the 3PCFs prefer to have satellite galaxies moving faster than dark matter ($\alpha_s > 1$). Such a constraint comes mainly from the small-scale $\zeta$, where the Fingers-of-God (FoG) effect in the redshift-space distribution of galaxies contributes. The $\alpha_s > 1$ satellite velocity bias, in combination with the central velocity bias, enhances the FoG. This situation causes the galaxy distribution more extended, and such a dilution reduces the possibility of finding small-scale galaxy triplets, lowering the small-scale 3PCF $\zeta$. This effect clearly explains the difference seen in the small-scale $\zeta$ in Figure 2 between the $w_p$-only prediction and the $w_p + \zeta$ fit. The satellite velocity bias constraint (red contour) from the 3PCFs shows a tentative tension with that (blue contour) from the 2PCFs, even though it is at a level of $< 2\sigma$. If the tension is confirmed with more accurate measurements, the model would need to be improved, e.g. by introducing freedom in the spatial distribution profiles of satellites inside haloes (see the tests in G14). The current data are not able to show whether such elements are needed, since the joint modeling with $w_p + \xi_{0,2,4} + \zeta$ leads to a good fit (black contour), with best-fitting $\chi^2/dof = 97.4/110$. With the current data, we conclude that combining the measurements of the 2PCFs and the 3PCF significantly strengthens the constraints on the galaxy velocity bias, as demonstrated by the smaller black contour in the right panel of Figure 3.

4 CONCLUSION

In this paper, we measure the redshift-space 3PCFs for a volume-limited sample of LRGs ($0.48 < z < 0.55$) in the SDSS-III BOSS CMASS DR11 data, and perform HOD modeling of the 3PCFs and
2PCFs. Similar to the case with the 2PCFs (G14), explaining the 3PCF measurements requires the existence of galaxy velocity bias, with which we are able to reproduce the observed galaxy 3PCFs remarkably well on all scales larger than $1 \, h^{-1}\text{Mpc}$.

By combining with the 2PCFs, the galaxy 3PCFs tighten the constraints on the HOD parameters, because the three-point distribution is more sensitive to the galaxy occupations in more massive haloes (Kulkarni et al. 2007). Both the redshift-space 2PCFs or 3PCFs can be used to constrain galaxy velocity bias. Either of them leads to a consistent central galaxy velocity bias of around 0.25, i.e., on average the central galaxy is in motion with respect to the core of its host halo (with mass around $2 \times 10^{13} \, h^{-1}M_{\odot}$; see G14). As discussed in G14, such a motion is consistent with those inferred from other observations, including the extrapolation from the measurements in galaxy clusters (Lauer et al. 2014). The satellite velocity distribution is consistent with that of the dark matter from either constraint and from the joint one.

As seen from the covariance matrix and the fitting results, the 3PCFs on small scales ($r < 7 \, h^{-1}\text{Mpc}$) have stronger constraining power on the HOD parameters (including the velocity bias parameters). Since we limit our measurements of the 3PCF to scales larger than $1 \, h^{-1}\text{Mpc}$ to reduce the fibre collision effects, we have only small improvements on constraining the satellite occupation function (compared to those from the 2PCFs) and the constraints to the phase-space distribution of satellite galaxies within haloes are loose. The satellite velocity bias is degenerate with the spatial distribution of satellites within dark matter haloes (see Figure 11 of G14). The 3PCF is more sensitive to the satellite distribution profile, since it probes the shape with triangles of different shapes. The tentative tension of the satellite velocity bias constraints between using $\xi_{0,2,4}$ and $\zeta$ (right panel of Figure 3) may indicate the departure of the spatial distribution of satellites from that of the dark matter. Therefore, the small-scale 3PCF measurements may serve as a powerful way of understanding the satellite galaxy distribution within haloes. We plan to explore such a possibility in our future work by using survey samples free of fibre collision effects and by considering small bins in triplet separation.

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