1. INTRODUCTION

The spatial distribution of matter in the universe can be fully described by the two-point correlation function (2PCF) or its Fourier-space counterpart, the power spectrum, if the matter density field were completely Gaussian. However, the nonlinear gravitational evolution and structure formation naturally generates non-Gaussianity (see e.g., Bernardes et al. 2002), which produces a non-zero three-point correlation function (3PCF) even for a primordial Gaussian density field. As a biased tracer to the matter density field, galaxies also typically have non-zero 3PCF. The galaxy 3PCF describes the probability of finding galaxy triplets in the universe. It is usually used in measuring the linear and first-order nonlinear galaxy bias factors, which helps constrain cosmology by breaking the degeneracy between the linear galaxy bias and the amplitude of the matter density fluctuations (usually denoted as $\sigma_8$), the rms fluctuation of the matter density within spheres of radius $8\ h^{-1}\ Mpc$; Gaztanaga & Frieman 1994; Jing & Börner 2004; Zheng 2004; Gaztaña & Scoccimarro 2005; Pan & Szapudi 2005; Sefusatti & Scoccimarro 2005; Guo & Jing 2009; McBride et al. 2011b; Marín et al. 2013; Guo et al. 2014a; Moresco et al. 2014). Efforts have also been made to measure the baryon acoustic oscillation features in the 3PCF (Gaztaña et al. 2009; Slepian & Eisenstein 2015).

The galaxy 3PCF aids in learning about the galaxy–halo connection within the halo occupation distribution (HOD) framework (e.g., Jing et al. 1998; Peacock & Smith 2000; Scoccimarro et al. 2001; Berlind & Weinberg 2002; Zheng et al. 2005, 2009; Guo et al. 2014b). The amplitude of the 3PCF tightens the galaxy occupation number as a function of halo mass (e.g., Kulkarni et al. 2007; Smith et al. 2008; Guo et al. 2015a). The shape of the 3PCF potentially teaches us about the distribution of galaxies inside dark matter halos. The purpose of this paper is to use the measured 3PCFs of galaxies to test halo-based models.

By accounting for the galaxy peculiar velocity distribution (velocity bias) inside halos, Guo et al. (2015a) found that the redshift-space galaxy 3PCF is successfully explained within the HOD framework. One other popular model for inferring the galaxy–halo connection uses the subhalo abundance matching (SHAM; Kravtsov et al. 2004; Conroy et al. 2006; Vale & Ostriker 2006; Wang et al. 2007; Behroozi et al. 2010; Pan & Szapudi 2005; Sefusatti & Scoccimarro 2005; Guo & Jing 2009; McBride et al. 2011b; Marín et al. 2013; Guo et al. 2014a; Moresco et al. 2014). Efforts have also been made to measure the baryon acoustic oscillation features in the 3PCF (Gaztaña et al. 2009; Slepian & Eisenstein 2015).
Table 1

| Sample | \(z_{\text{max}}\) | \(N_{\text{gal}}\) | \(n_{g}(h^{-3}\text{Mpc}^{3})\) | Volume \((h^{-3}\text{Mpc}^{3})\) |
|--------|----------------|-----------------|-----------------|-----------------|
| \(M_{r} < -19\) | \(0.064\) | \(72484\) | \(15.66 \times 10^{-3}\) | \(4.87 \times 10^{-6}\) |
| \(M_{r} < -20\) | \(0.106\) | \(131623\) | \(6.37 \times 10^{-3}\) | \(22.00 \times 10^{-6}\) |
| \(M_{r} < -21\) | \(0.159\) | \(76802\) | \(1.16 \times 10^{-3}\) | \(71.74 \times 10^{-6}\) |

Note. The minimum redshift of all the luminosity threshold samples is \(z_{\text{min}} = 0.02\). The maximum redshift \(z_{\text{max}}\), the total number of galaxies \(N_{\text{gal}}\), the mean number density \(n_{g}\), and the volume of each sample are also displayed.

Guo et al. 2010; Moster et al. 2010; Nuza et al. 2013; Rodríguez-Puebla et al. 2013; Sawala et al. 2015, by populating central and satellite galaxies into distinct halos and subhalos identified in high-resolution \(N\)-body simulations. Guo et al. (2016) (hereafter G16) presented an extension to the SHAM model, dubbed as SCAM (subhalo clustering and abundance matching), which allows central and satellite galaxies to have different galaxy–halo relations and matches (fitting) both galaxy abundance and clustering. By comparing the modeling results for galaxy-projected and redshift-space 2PCFs with the HOD, SHAM, and SCAM models, G16 concluded that the HOD and SCAM models generally produce better fits to the observed galaxy 2PCFs than the SHAM model, with the HOD model having slightly lower \(\chi^2\) values. The main difference between the HOD and SCAM models lies in the spatial distribution of satellite galaxies inside halos. The HOD model used in G16 assigns satellites to randomly selected matter particles and the SCAM model put satellites at the centers of subhalos. The radial distribution of subhalos in the host halo is found to be significantly shallower than that of the dark matter (see e.g., Gao et al. 2004; Pujol et al. 2014). In reality, the spatial distribution of satellites may deviate from that of subhalos (e.g., caused by baryonic processes), and there is evidence that satellites follow more closely to the dark matter distribution inside halos (e.g., Wang et al. 2014).

In this paper, we intend to take advantage of the added information in the galaxy 3PCF to see whether we can further distinguish the different halo models. We directly use the bestfit HOD and SCAM models from G16 that jointly fits both the projected and redshift-space 2PCFs to calculate the redshift-space 3PCF and compare with the observation. In Section 2, we briefly describe the galaxy sample, the 3PCF measurements, and the modeling of the 3PCF. We present the modeling results in Section 3 and conclude in Section 4.

2. MEASUREMENTS AND MODELS

We use the same volume-limited luminosity threshold galaxy samples as in Guo et al. (2015b), selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000) Data Release 7 (DR7; Abazajian et al. 2009) Main galaxy sample in the redshift range of 0.02 < \(z\) < 0.2. For the analysis in this paper, we only focus on the three luminosity threshold samples that cover both faint and luminous galaxies, with \(r\)-band absolute magnitude as \(M_{r} < -19\), \(M_{r} < -20\), and \(M_{r} < -21\). We display the sample information in Table 1 and refer the reader to Figure 1 of Guo et al. (2015b) for more details.

Following Guo et al. (2015a), we measure the redshift-space galaxy 3PCF, \(\zeta(r_{1}, r_{2}, \theta)\), on small and intermediate scales using the estimator of Szapudi & Szalay (1998), where triangles from galaxy triplets are parametrized as \((r_{1}, r_{2}, \theta)\), with \(r_{1}\) and \(r_{2}\) \((r_{2} \geq r_{1})\) the lengths of two sides and \(\theta\) the angle between them. We use logarithmic binning schemes for \(r_{1}\) and \(r_{2}\) and linear bins for \(\theta\), with \(\Delta \log r_{1} = \Delta \log r_{2} = 0.2\), and \(\Delta \theta = 0.1 \pi\).

For the model 3PCFs, we use the measurements from the mock galaxy catalogs generated based on the best-fit HOD and SCAM models of G16 and halos/subhalos identified in high-resolution \(N\)-body simulations. The method adopted for the HOD and SCAM modeling of 2PCFs in G16 follows Zheng & Guo (2016), which is based on \(N\)-body simulations and hence is much more accurate than analytic models. It is equivalent to populating halos or subhalos in the simulation given a set of HOD/SCAM parameters and using the measured 2PCFs from the mock catalog as the model prediction. Since the method tabulates all halo distribution functions and clustering properties relevant for galaxy 2PCFs, it is also fast in calculating the model 2PCFs and enables an efficient exploration of the parameter space. To be fully consistent, here we use the same simulations as in the 2PCF modeling of G16.

For the two luminous galaxy samples of \(M_{r} < -20\) and \(M_{r} < -21\), we use the MultiDark simulation of Planck cosmology (MDPL) (Klypin et al. 2016), with the cosmological parameters of \(\Omega_{m} = 0.307\), \(\Omega_{b} = 0.048\), \(h = 0.678\), \(n_{s} = 0.96\), and \(\sigma_{8} = 0.823\). The simulation has a volume of \(1 h^{-3} \text{Mpc}^{3}\) (comoving) and a mass resolution of \(1.51 \times 10^{5} h^{-1} M_{\odot}\). For the sample of \(M_{r} < -19\), in order to resolve the host halos and subhalos, we use a higher-resolution simulation with the same cosmology as the MDPL but with a volume of \(0.43 h^{-3} \text{Mpc}^{3}\) and a mass resolution of \(9.6 \times 10^{6} h^{-1} M_{\odot}\) (referred to as the SMDPL in Klypin et al. 2016). The host halos and subhalos in the simulations are identified with the Rockstar phase-space halo finder (Behroozi et al. 2013), which identifies the spherical halos from the density peaks in the phase space.

To construct the redshift-space mock galaxy catalogs, we populate host halos and subhalos in the simulations with galaxies according to the HOD and SCAM models in G16 that best describe the projected and redshift-space 2PCFs. In the models, galaxy velocity bias (the difference between galaxy and dark matter velocity distribution inside halos) is found to be required to fit the redshift-space clustering of the SDSS Main sample galaxies. The central galaxy velocity bias \(\alpha_{c}\) (satellite velocity bias \(\alpha_{s}\)) is parameterized as the ratio of the dispersion of the central (satellite) galaxy motion to that of the dark matter particles in the frame defined by the halo bulk velocity (see Equations (6) and (7) in Guo et al. 2015b).

In the HOD model, a central galaxy is put at its host halo center (defined as the position of the potential minimum), with a velocity offset with respect to the halo bulk velocity characterized by the best-fit central galaxy velocity bias \(\alpha_{c}\). The satellite galaxies are populated by adopting the positions of the randomly selected dark matter particles. The velocity of a satellite galaxy is assigned through scaling the velocity of the dark matter particle relative to the halo bulk velocity by a factor of the satellite galaxy velocity bias \(\alpha_{s}\). In the SCAM model, the central galaxies are populated in the same way as in the HOD model. The satellite galaxies have the positions of the subhalo centers, and the velocities of subhalos relative to halo bulk velocity are scaled according to the satellite velocity bias \(\alpha_{s}\).

For the SCAM models, to connect the central galaxies to the host halos and the satellite galaxies to the subhalos, we consider two models with maximum circular velocities as the properties for the host halos and subhalos, i.e., the \(V_{\text{acc}}\) and \(V_{\text{peak}}\).
models in G16. Both were shown to provide reasonable fits to the projected and redshift-space 2PCFs. In the \( V_{\text{acc}} \) model, the maximum circular velocity is used for the host halos, and the maximum circular velocity at the time of accreting to host halos is adopted for the subhalos. In the \( V_{\text{peak}} \) model, the peak circular velocity over the entire merger history is used for both the host halos and subhalos.

3. RESULTS

The 3PCF measurements are shown as the data points in Figure 1, with triangle configuration of \( r_2 = 2r_1 \) for the three luminosity-threshold samples (blue for \( M_r < -19 \), green for \( M_r < -20 \), and red for \( M_r < -21 \)), from scales of \( r_1 = 0.4 \ h^{-1} \) Mpc to \( r_1 = 6.3 \ h^{-1} \) Mpc. For a given triangle configuration, the amplitude of the 3PCFs is higher for more luminous galaxies. For a given sample, the amplitude of the 3PCFs increases toward smaller scales. For all the samples and for all the scales, the 3PCFs show clear dependence on the shape of galaxy triplets, with the amplitude increasing toward degenerate triangles (\( \theta \sim 0 \) or \( \theta \sim \pi \)). The overall trends of the scale and shape dependences in the 3PCFs agree with previous work (Nichol et al. 2006; Kulkarni et al. 2007; Marin 2011; McBride et al. 2011a; Guo et al. 2014a; Moresco et al. 2016), but we are probing smaller scales than in the previous literature, which can provide tighter constraints to the models, as will be discussed in the following. We measure the 3PCFs from the HOD/SCAM mock catalogs and compare them to the measurements from the SDSS data. The model predictions are shown as curves in Figure 1, with solid lines for the HOD model, dotted lines for the \( V_{\text{acc}} \) model, and dashed lines for the \( V_{\text{peak}} \) model.

To see how the three 2PCF-determined models work in predicting the 3PCFs, we compute and compare the \( \chi^2/\text{dof} \) values based on the predicted and measured 3PCFs, which are listed in Table 2, together with those for the 2PCFs in G16. In detail, the \( \chi^2 \) for the 3PCF is determined from

\[
\chi^2 = (\zeta - \zeta^*)^T C^{-1}(\zeta - \zeta^*),
\]

where \( C \) is the full error covariance matrix of the 3PCF data vector \( \zeta(r_1, 2r_1, \theta) \). The quantity with (without) a superscript "*" is the one from the measurement (model). The covariance matrix is estimated using the jackknife resampling method with 400 subsamples as in G16.

For the 2PCF measurements of each sample in G16, we have 12 bins for each of the four 2PCF statistics (the projected 2PCFs and three redshift-space 2PCF multipoles) and one number density, and each of the three models has six free parameters. The dof for the 2PCFs of each sample in G16 is then 43 (dof = 4 \times 12 + 1 - 6).

For the 3PCF measurements, the 400 jackknife subsamples are not enough to accurately estimate the covariance matrices.
We apply the singular value decomposition (SVD) to reduce the effect of noise in the covariance matrix, and only retain the dominant eigenmodes that have eigenvalues of \( \lambda^2 > \sqrt{2}/N_{\text{N}} \) (Gaztañaga & Scoccimarro 2005), where \( N_{\text{N}} \) is the number of the jackknife subsamples. The number of removed eigenmodes, \( N_{\text{N}} \), is subtracted from the dof. As shown in Figure 1, we measure the 3PCF in six different \( r_1 \) bins and each bin has 10 data points at different values of \( \theta \). In total, we have \( N_{\text{N}} = 60 \) data points of the 3PCFs for each sample. As we do not perform model fitting to the 3PCFs, we compute the 3PCF dof as \( \text{dof} = N_{\text{N}} - N_{\text{N}} \).

Generally, the HOD and SCAM models show different predictions of the 3PCFs on both small and intermediate scales. For the most luminous galaxy sample of \( M_r < -21 \), all three models provide reasonable fits to the data, with \( \chi^2/\text{dof} \) varying from 0.80 to 1.09. As seen from Figure 1, except for the smallest scale (top-left panel), the three model predictions for this sample are comparable to each other. For the fainter galaxy samples, the HOD model has much smaller \( \chi^2 \) values than the two SCAM models. The overall trend is similar to the 2PCF case—for luminous samples (with luminosity threshold above \( L^* \)) all three models are reasonable, while for faint samples (with luminosity threshold below \( L^* \)) HOD model shows better performances. We note that the 2\( \sigma \) ranges of the expected \( \chi^2 \) distribution for the 3PCFs of the \( M_r < -19 \), \( -20 \) and \( -21 \) samples are approximately \( 14 \pm 10.6, 21 \pm 13.0, \) and \( 44 \pm 18.8 \), respectively. For faint samples, the differences in the \( \chi^2 \) values of the three models are much more significant with the 3PCFs than those with the 2PCFs, implying that 3PCFs can help further discriminate different models.

Figure 1 suggests that the discrimination power has a large contribution from small scale 3PCFs. This is further supported by the structure in the covariance matrix. Figure 2 shows the normalized covariance matrix of the 3PCF measurements for the \( M_r < -20 \) sample. On large scales (\( r_1 \geq 1 \text{ h}^{-1} \text{ Mpc} \)), there is strong correlation between the different \( \theta \) bins at each \( r_1 \) bin. On small scales, the correlation is approximately between \( \theta \) and \( \pi - \theta \) bins. This is in the Fingers-of-God regime, and such a correlation is expected from one-halo galaxy triplets (see below). On scales of \( r_1 > 0.63 \text{ h}^{-1} \text{ Mpc} \), the measurements in different \( r_1 \) bins are also strongly correlated with each other (much stronger than those seen for the luminous sample in Guo et al. 2015b). The differences among the different model predictions on large scales (being mainly an amplitude shift; see Figure 1) therefore do not contribute significantly to the differences in the \( \chi^2 \) values.

To further investigate the constraining power of the 3PCFs from different scales, we perform a test with the \( M_r < -20 \) sample by removing the 3PCF measurements in one \( r_1 \) bin at a time and compare the resulting \( \chi^2/\text{dof} \). We find that for all three models, the resulting \( \chi^2/\text{dof} \) is largest when the 3PCF measurements from the smallest \( r_1 \) bin (0.4–0.63 \text{ h}^{-1} \text{ Mpc}) are dropped. The small-scale 3PCFs of this sample provides the most discrimination power, consistent with the finding of Guo et al. (2015a). The HOD sample clearly shows a better fit to the small-scale data, which leads to the corresponding smallest \( \chi^2 \) value (15.1). Even though the \( V_{\text{peak}} \) model prediction agrees better (by eye) with the data points on large scales, it does not fit the smallest scale data (\( r_1 < 0.63 \text{ h}^{-1} \text{ Mpc} \)) data and the overall \( \chi^2 \) (48.5) is much larger.

For the \( M_r < -19 \) sample, the HOD model also has the smallest \( \chi^2 \) value. The covariance matrix for the \( M_r < -19 \) sample is similar to that of the \( M_r < -20 \) sample with strong correlations shown on all scales. The small volume of the \( M_r < -19 \) sample leads to a noisy covariance matrix using the jackknife method, with 46 eigenmodes dropped from the SVD analysis, which reduces the constraining power of its 3PCF.

The three models determined from fitting the projected and redshift-space 2PCFs show differences in the redshift-space 3PCF predictions, suggesting that 3PCFs can help further constrain models. To quantify the improvements in model constraints by adding the 3PCFs, one needs to perform a joint fit to both 2PCFs and 3PCFs. In general, the best-fit model from the joint modeling will shift with respect to the 2PCF-determined model, and the relative contributions from the 2PCFs and 3PCFs will be different from what we have in this paper. While there are accurate and efficient methods to obtain model predictions for the 2PCFs (e.g., Zheng & Guo 2016), an accurate and efficient method for predicting the model 3PCFs is demanding. We therefore focus on models that reproduce the 2PCFs and investigate their performances for the 3PCFs to gain some general insights. Efforts have been made to perform joint

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### Table 2

| \( \chi^2/\text{dof} \) (3PCF) | HOD | \( V_{\text{acc}} \) | \( V_{\text{peak}} \) |
|-----------------|-----|---------------|---------------|
| \( M_r < -19 \) | 26.75/14 | 32.43/14 | 42.58/14 |
| \( M_r < -20 \) | 15.12/21 | 33.64/21 | 48.52/21 |
| \( M_r < -21 \) | 47.88/44 | 35.24/44 | 37.89/44 |

| \( \chi^2/\text{dof} \) (2PCF) | HOD | \( V_{\text{acc}} \) | \( V_{\text{peak}} \) |
|-----------------|-----|---------------|---------------|
| \( M_r < -19 \) | 41.30/43 | 56.71/43 | 59.54/43 |
| \( M_r < -20 \) | 51.30/43 | 64.51/43 | 76.65/43 |
| \( M_r < -21 \) | 52.58/43 | 46.43/43 | 44.82/43 |

**Note.** The dof corresponding to the \( \chi^2 \) of 3PCFs is calculated as \( \text{dof} = N_{\text{N}} - N_{\text{N}} \), where \( N_{\text{N}} \) is the number of data points of \( \zeta \) and \( N_{\text{N}} \) is the number of removed eigenmodes from the SVD analysis (see the text). The \( \chi^2/\text{dof} \) for the best-fit models of 2PCFs in G16 are also shown in the bottom table for comparison.
modeling with 3PCFs calculated based on mock catalogs. For example, Guo et al. (2015a) jointly model the 2PCFs and 3PCFs of $z \sim 0.5$ luminous red galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey (Dawson et al. 2013). Indeed, they found that the inclusion of the 3PCF tightens the constraints on the HOD parameters, especially with the small-scale measurements. The implications from the study with the 2PCF-determined models here qualitatively agree with their results based on the joint 2PCF and 3PCF modeling.

The mock catalogs created in this work not only allow us to measure the model predictions but also enable us to decompose the model 3PCFs into various components. In what follows, we compare the decompositions of the three models on small scales of a few tenths of $h^{-1}$ Mpc, as they are well constrained by the sample number density and the large-scale feature.

In Figure 3, we show the decomposition in the HOD model for the total 3PCF of the $M_s < -20$ sample, as a function of scale and angle. The total 3PCF is decomposed into the contributions of one-halo, two-halo, and three-halo components (denoted as “1h,” “2h,” and “3h,” respectively). The different halo components are further divided into contributions of galaxy triplets formed by different combinations of central and satellite galaxies, as labeled. On small scales (a few tenths of $h^{-1}$ Mpc), the one-halo term has a large contribution, as expected. In particular, it dominates the signal for degenerate triangle configurations ($\theta \sim 0$ or $\theta \sim \pi$), which results from the triplets elongated along the line of sight caused by the nonlinear redshift-space distortion (the Fingers-of-God effect). On large scales (a few $h^{-1}$ Mpc), the three-halo term (especially from central-central-central triplets) dominates, with two-halo components involving central galaxies contributing substantially.

The decompositions of the two SCAM models ($V_{\text{acc}}$ and $V_{\text{peak}}$) models have similar trends as for the HOD model.

However, the three models are different in detail. In Figure 4, we compare the decompositions of the three models on small ($r_1 \sim 0.5 h^{-1}$ Mpc) and large ($r_1 \sim 5 h^{-1}$ Mpc) scales. On scales of $r_1 < 1 h^{-1}$ Mpc, the HOD model better agrees with the data (Figure 1). From Figure 4, it is clear that the differences in the models are mainly caused by the one-halo term. The HOD model has significantly larger contributions from the one-halo satellite–satellite–satellite triplets (“1h s-s-s”), while such triplet contributions in the two SCAM models are less substantial (lower than the HOD model by a factor of about two). As shown in Figures 14 and 15 of G16, in the SCAM models, satellite galaxies tend to populate slightly less massive halos and move faster (higher satellite velocity bias) than in the HOD model. Even though the SCAM models have a higher satellite fraction, the fast motion of satellites dilutes the amount of small-scale galaxy triplets, reducing the one-halo “c-c-s” and “s-s-s” triplets. We note that even at such small scales, the two-halo and three-halo terms still have significant contributions. This is a consequence of the redshift-space distortion effects that change the line-of-sight distribution of galaxies in redshift-space (see Figure 2 of Zheng & Guo 2016 for the case of the 2PCF, where the two-halo terms still have significant contributions to the small-scale Fingers-of-God feature).

On large scales, the HOD model seems to agree with the $V_{\text{acc}}$ model quite well. Figure 4 shows that the dominant contributions, the “3h c-c-c” and “3h c-s-c” triplets, have similar 3PCF amplitudes for the two models. There are differences in other components, e.g., in the HOD model higher contributions from the “1h c-s-s,” “1h s-s-s,” “2h c-s-s,” and “2h s-s-s” components and smaller contributions from the “3h c-s-c” and “3h s-s-s” terms. The central galaxy occupation functions for these two models are quite similar (G16), as they are well constrained by the sample number density and the large-scale
galaxy bias (Zheng et al. 2007; Zehavi et al. 2011; Guo et al. 2014b). The above subtle differences mainly originate from the different satellite galaxy occupation functions and satellite velocity bias. These differences are trivial, as their contribution to the total 3PCFs is insignificant.

Comparing the different components of the $V_{\text{acc}}$ and $V_{\text{peak}}$ models, the $V_{\text{peak}}$ model usually has higher amplitudes on scales of $r > 1\, h^{-1}\, \text{Mpc}$. For smaller scales, the $V_{\text{peak}}$ model is only slightly lower for the two one-halo components of “1h c-s-s” and “1h s-s-s,” and much larger for other components. This is consistent with what we find in Figure 1 and Table 2, where the $V_{\text{peak}}$ model generally has a higher 3PCF amplitude than the $V_{\text{acc}}$ model.

The decomposition also demonstrates that the shape dependence (i.e., dependence on $\theta$) of the 3PCF varies in the different components. The one-halo terms show the strongest dependence. The nonlinear redshift-space distortion (Fingers-of-God effect) makes the distribution of galaxies inside halos appear to be elongated along the line of sight, favoring triplets close to degenerate triangles ($\theta \sim 0$ or $\theta \sim \pi$). The strong shape dependence of the one-halo terms dominates on small scales, but plays almost no role on large-scale 3PCFs, as their contribution to the total 3PCF diminishes. The large-scale shape dependence comes from the three-halo terms, reflecting the filamentary structure on linear or weakly nonlinear scales from gravitational evolution (Scoccimarro et al. 2001; Nichol et al. 2006).

The radial distributions of the satellite galaxies in the HOD and SCAM models are different (G16), with the HOD model having a steeper satellite distribution. This difference (as well as the mean occupation function of satellites) contributes to the difference in the small-scale 3PCFs from the three models. The shape of the halo, defined by the satellite galaxies, can be another factor, as the relative mass scale shift among the three models corresponds to halo shape change. However, as already discussed, the shape dependence of the small-scale 3PCF mainly results from redshift-space distortion; the (real-space) shape of halos is not expected to play a major role. To test this, we compare the halo shape in the HOD and SCAM models. Given that halos can be well described by triaxial ellipsoids (Jing & Suto 2002; Despali et al. 2016; Vega et al. 2016), we follow the method laid out in Allgood et al. (2006) to compute the eigenvectors of the reduced inertial tensor for the triaxial ellipsoids traced by satellite galaxies in the three models, and the directions of the eigenvectors define the three principal halo axes. We perform the calculation for all the halos with three or more satellites in the three models.

Figure 5 shows the probability distributions of the two axis ratios of $b/a$ and $c/a$ in the three models, assuming the lengths of the semi-principal axes of $c \leq b \leq a$. The overall distributions of the axis ratios in the three models are quite similar. The average axis ratios in all three models are around $b/a = 0.5$ and $c/a = 0.2$. The probability distributions of the axis ratios roughly stay the same even if we consider the satellite galaxy distributions within different distances to the halo centers. While the overall halo shape distribution marginalized over the full model parameter spaces could be different for the case shown here, the comparison made in Figure 5 is to check the effect of the halo shape on the best-fit models shown in Figure 1. The comparison implies that the differences seen in the model predictions (Figure 1) are the result of the differences in the radial distribution, the mean occupation function, and the velocity bias of satellite galaxies, rather than the shape distribution of satellite galaxies. In addition, given the large role played by the small-scale redshift-space distortion in the shape dependence of the small-scale 3PCFs, it is unlikely that the intrinsic halo shape (defined by the satellite distribution) can be well constrained by the redshift-space 3PCFs.

4. CONCLUSION

In this paper, we present the luminosity-dependent redshift-space galaxy 3PCF measurements for the SDSS DR7 Main galaxy sample. The measurements are then used to test three models, the HOD model and two SCAM models (based on $V_{\text{acc}}$ and $V_{\text{peak}}$). These models are obtained by fitting the projected and redshift-space galaxy 2PCFs (G16), and the 3PCF predictions come from mock catalogs.

For the most luminous galaxy sample ($M_r < -21$), the predictions from all three models agree well with the 3PCF measurements. For the fainter samples ($M_r < -20$ and $M_r < -19$), the prediction from the HOD model generally provides a better match to the measurements. This strengthens the trend seen in modeling galaxy 2PCFs (G16)—all models work reasonably well for samples with luminosity threshold above $L^*$, while the HOD model stands out in better fitting faint samples (with luminosity threshold below $L^*$).

We decompose the total 3PCFs into contributions from different types of galaxy triplets. On small scales, the 3PCFs are dominated by contributions from one-halo galaxy triplets, and the dependence on the triangle shape is driven by the redshift-space distortion (the Fingers-of-God effect). This is consistent with the fact that the 3PCFs in projected space have a much weaker shape dependence than those in redshift space, as found by Guo et al. (2014a). The intrinsic halo shape defined by the distribution of satellites, however, does not contribute much to the shape dependence of the 3PCFs, as the halo shape in redshift space is largely determined by the motion of satellites. On large scales, the 3PCFs are dominated by contributions from three-halo galaxy triplets, and the shape dependence reflects the filamentary structure from gravitational evolution. The small-scale 3PCFs, where the three model predictions more strongly deviate from each other (in both 3PCF amplitude and shape), are related to the radial distribution, the mean occupation function, and the velocity bias of satellite galaxies, so we expect that the small-scale 3PCFs can further constrain the above galaxy–halo connection and distinguish different models.
In conclusion, besides the traditional application of the galaxy 3PCF to measure the nonlinear galaxy bias (e.g., Guo & Jing 2009; McBride et al. 2011b; Marin et al. 2013), the additional information encoded in the 3PCF can be used to distinguish the various halo (and subhalo) models, as well as tighten the constraints on the occupation distribution of galaxies inside halos (e.g., Kulkarni et al. 2007; Guo et al. 2015b). More insights can be yielded by jointly modeling 2PCFs and 3PCFs in future work.

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