THE ANISOTROPIC SPATIAL DISTRIBUTION OF CDM SUBHALOS

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Abstract. I review recent results on the relative spatial distribution of substructure in CDM halos. I show that the spatial distribution of subhalos is anisotropic and generally prolate with a long axis that is closely aligned with the long axis of the mass distribution of the host halo. I show that the correlation between the subhalo distribution and the long axis of the host halo is strong both in dissipationless and dissipational gasdynamical simulations. More massive subhalos tend to be more strongly clustered along the major axis of the host halo reflecting filamentary accretion. The anisotropy of subhalos has potential implications for the interpretation of several observations both in the Local Group and beyond. For example, I show that while the mean projected mass fraction in substructure in the central regions of CDM halos is \( f_{\text{sub}} \approx 0.4\% \), \( f_{\text{sub}} \) is a strong function of projection angle and is \( \sim 6 \) times higher for projections nearly collinear with the major axis of the host.

1 The Planarity of Milky Way Satellites

Holmberg (1969) reported that satellite galaxies of spiral primaries with projected separations \( r_p \lesssim 50 \text{ kpc} \) are tend to lie near the short axes of the light distributions of their primaries. Zaritsky et al. (1997) revisited this issue and found evidence for alignment in the same sense as Holmberg for satellites within \( r_p \sim 200 - 500 \text{ kpc} \). The angular distribution of galaxies has been of recent interest with increased data from large surveys and the possibility of these data to relate the orientations of galaxies to their halos in a statistical way (e.g., Sales & Lambas 2004; Brainerd 2004; Azzaro et al. 2005, A05), as well as studies of satellites in the Local Group.

Kroupa et al. (2005, K05) recently argued that the nearly planar distribution of Milky Way (MW) satellites is a serious challenge to the standard cold dark
Fig. 1. Left: The cumulative fraction of satellites with an angular position $<|\cos(\theta)|$ from the major axis of the host halo mass distribution as a function of $|\cos(\theta)|$. The thin, solid line represents an isotropic distribution. The dashed, dotted, and dot-dashed lines are the distributions of subhalos of 3 simulated MW host halos, with $V_{\text{sat}}^{\text{max}} \geq 0.075V_{\text{host}}^{\text{max}}$. The thick, solid line represents the 11 MW satellites. The MW satellites are placed on the plot by assuming that the rotation axis of the MW is aligned with the major axis of the halo. Right: The differential fraction of subhalos as a function of angular displacement from the major axis of the primary, cluster halo. An isotropic distribution is uniform in $|\cos(\theta)|$. The triangles show the results from 8 dissipationless cluster simulations employing adiabatic gas physics. The squares show results from simulations of the same 8 clusters including radiative gas cooling and star formation.

Zentner et al. (2005, Z05) addressed this issue from a theoretical standpoint, and similar results were reported in contemporaneous papers Libeskind et al. (2005, L05) and Kang et al. (2005). They showed that the conclusions of K05 were incorrect for two reasons: first, the statistical analysis of K05 was not valid for small samples, such as the 11 observed MW satellites, and for such samples the statistic they used is non-discriminatory; second, K05 incorrectly assumed that the null hypothesis for CDM should be an isotropic satellite distribution.

Z05 showed that the distribution of CDM subhalos is anisotropic. Subhalos or subsets thereof, the likely sites of galaxy formation, are preferentially aligned near the long axes of the triaxial mass distributions of their primary halos. This is shown explicitly in the left panel of Figure 1 for a sample of 3 simulated approximately MW-sized, CDM halos (see Z05 for details). The angle between the major axis of the primary halo and the position of the subhalo is $\theta$ and an isotropic distribution is uniform in the variable $\cos(\theta)$. The principal axes of the host halo were computed using only particles within 30% of the halo virial radius, to focus on the region where the central galaxy resides. The satellites were selected to have maximum circular velocities $V_{\text{sat}}^{\text{max}} \geq 0.075V_{\text{host}}^{\text{max}}$, where $V_{\text{host}}^{\text{max}}$ is that of the host halo. These satellites are roughly the size required to host the observed MW dwarf satellites.
Anisotropy of CDM Subhalo Distributions

(e.g., Kravtsov et al. 2004). The Kolmogorov-Smirnov probability of selecting the simulated subhalo sample from an isotropic distribution is \( P_{KS} \sim 10^{-4} \).

In addition, Z05 demonstrated that planar distributions of subhalos, similar to that of the MW satellites, are not unlikely due largely to accretion along preferred directions. Such planes are typically aligned with the major axis of the primary halo. Thus, the MW satellites are consistent with CDM predictions, provided that the pole of the MW is aligned with the major axis of the surrounding halo. The metal-poor globular clusters surrounding the MW and the satellites of M31 show evidence of a similar alignment and new techniques may yield constraints on the orientation of the MW halo (e.g., Gnedin et al. 2005). However, such alignments present a challenge for simple scenarios of disk galaxy formation because the angular momenta of DM halos tend to be perpendicular to halo major axes.

The results of Z05, Kang et al. (2005) and L05 are all based on dissipationless \( N \)-body simulations; however, one of the effects of baryonic dissipation is to make DM halos more spherical than their counterparts in dissipationless simulations (e.g., Kazantzidis et al. 2004). One may inquire whether the alignment of satellites along the principal axes of host halos is as prevalent in dissipational simulations. One might expect differences between dissipational and dissipationless simulations to be small in this regard because both the major axis and the positions of satellites reflect the directions of recent accretion along filaments and because subhalos are biased toward large halo-centric distances compared to DM (\( r > 0.3 R_{\text{vir}} \)).

The right panel of Figure 1 is an explicit demonstration that dissipational processes do not significantly alter the alignment of halo and satellites. The figure shows an analysis of the eight cluster halos of Kazantzidis et al. (2004) simulated once with dissipationless, adiabatic gas physics and a second time including radiative cooling and star formation. Though the inner halos in the cooling simulations are significantly rounder, the alignment of host halo and satellites remains pronounced.

2 Is There an Angular Bias Between Subhalos and Dark Matter?

It is interesting to quantify the relationship between the spatial distributions of the smooth, DM components of host halos and the subhalos that reside within them. Do the subhalos simply follow the triaxial mass distribution? There are several potential ways to address this issue, such as computing angular correlations etc., and I discuss two intriguing quantifications in this section. One way to address the relationship of subhalos and DM is through the ratios of the principal axes of inertia denoted \( a \geq b \geq c \). For subhalos, the inertia tensor can be computed in two ways. In the first, each subhalo is counted equally and in the second method, each subhalo can be counted in proportion to its bound mass. The result is a “number-weighted” inertia tensor and a “mass-weighted” inertia tensor. Figure 2 shows a comparison between the axis ratios of host DM halos using, computed as specified above, and the mass- and number-weighted axis ratios of their subhalo populations. The sample consists of 26 hosts with \( 180 \text{ kms}^{-1} \leq V_{\text{host}} \leq 400 \text{ kms}^{-1} \) and their subhalos simulated with the ART code (Kravtsov et al. 1997). The particle mass
Fig. 2. The shape distribution of DM compared to the distribution of satellite halos. The left panel shows the axis ratio \(b/a\), while the right panel shows the axis ratio \(c/a\). Each panel is a scatter plot of the axis ratios of all DM in each host halo on the horizontal axis against the axis ratios of each of the subhalo populations on the vertical axis. The triangles show number-weighted subhalo axis ratios and the squares represent mass-weighted subhalo axis ratios. All subhalos with \(V_{\text{sat}}/V_{\text{host}} \geq 0.1\) are included.

is \(m_p = 4.9 \times 10^6 h^{-1} M_\odot\), the spatial resolution is \(\sim 150 h^{-1}\) pc, and each host contains \(\geq 2 \times 10^5\) particles within its virial radius.

The number-weighted axis ratios in Fig. 2 show that the full number-weighted satellite populations broadly trace the DM distributions of their host halos. However, notice that the mass-weighted axis ratios are systematically smaller than that of the DM in the host halo. More massive subhalos are more strongly biased toward a flattened distribution than small subhalos, a result consistent with the studies of Z05, L05, and A05. The robustness of this result has been checked by randomly re-assigning the weights (masses in this case) among the subhalo populations. The axis ratios based on these randomized weights are generally similar to the number-weighted axis ratios shown in Figure 2. This angular bias for large subhalos is not entirely surprising. The smallest subhalos have generally been accreted over an extended period of time and interact gravitationally as DM particles, adopting a self-consistent configuration with the host potential. The largest subhalos have typically been accreted more recently so they more faithfully reflect the directions of recent infall, and they tend to be more strongly biased to form in overdense filaments.

As a second comparison between substructure and smooth mass, consider the 2D projected fraction of mass in substructure, \(f_{\text{sub}}\). This quantity is constrained by measurements of flux ratio anomalies in multiply-imaged quasar systems (e.g., Dalal & Kochanek 2002), and can be used as a probe of cosmological parameters that influence the growth of small-scale structure. Zentner & Bullock (2003) and Mao et al. (2004) have made predictions for the mean projected substructure
Fig. 3. Substructure mass fractions as a function of projection angle from the major axis of the host halo. The squares represent the average $f_{\text{sub}}$, measured from all 26 host halos, using two projections for each host. The outer errorbars represent the scatter among projections and the inner errorbars represent the estimated error in the mean of $f_{\text{sub}}$. The shaded band represents the 90% confidence region of $f_{\text{sub}}$ from the measurement of Dalal & Kochanek (2002).

mass fractions, with the former considering a variety of primordial power spectra and dark matter properties. In what follows I show the projected substructure mass fraction as a function of projection angle $\theta$, from the major axis of the host halo. Following Mao et al. (2004), I have computed $f_{\text{sub}}(\theta)$ as a function of projection angle using all mass and substructures within 3 virial radii of the center of each host, in order to include correlated material associated with each halo. I projected in cylinders of radius $r_p = 0.03 R_{\text{vir}}$, comparable to the Einstein radii of strong-lens systems. The result is shown in Figure 3 along with the observed 90% confidence region for $f_{\text{sub}}$ measured in quadruply-imaged systems by Dalal & Kochanek (2002). The mean substructure mass fraction is approximately $f_{\text{sub}} \approx 0.4\%$ with a large scatter, consistent with Mao et al. (2004). Interestingly, $f_{\text{sub}}(|\cos(\theta)|)$ is $\sim 5$ -- $6$ times higher for projections near the long axis of the host. If elliptical galaxies are well aligned with their host halos, this result may have important consequences for determinations of $f_{\text{sub}}$ in multiply-imaged quasar systems and several other observed properties of strong lenses.
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