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THE LINK BETWEEN GALAXIES AND DARK MATTER

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Given that dark matter is gravitationally dominant in the universe, and that galaxy formation is closely related to dark matter halos, a key first step in understanding galaxy formation and evolution in the CDM paradigm is to quantify the galaxy-halo connection for galaxies of different properties. Here I will present results about the halo/galaxy connection obtained from two different methods. One is based on the conditional luminosity function, which describes the occupation of galaxies in halos of different masses, and the other is based on galaxy systems properly selected to represent dark halos.

Keywords: Cosmology; galaxies; dark matter.

1. Introduction

Over the last 20 years the Cold Dark Matter (CDM) cosmogony has become the standard paradigm for structure formation. This paradigm assumes the cosmic mass to be dominated by an as yet unidentified, weakly interacting massive particle, and that all structure originated as quantum fluctuations during an early inflationary period. CDM models are specified by a small set of parameters that are heavily constrained by observations such as the Cosmic Microwave Background (CMB) anisotropy, light-element abundances, the distance-luminosity relation of type Ia supernovae, the number density of clusters, cosmic shear due to gravitational weak lensing, large-scale structure, and the properties of the Lyα forest. This set of model parameters also determine the initial and boundary conditions for the formation of galaxies. However, many important problems regarding galaxy formation remain unsolved. First, a degeneracy still exists in cosmological parameters, and so there is still the question whether the current CDM cosmogony can account for all the observed properties of galaxies, or if significant changes in, e.g. the power spectrum and/or the properties of dark matter, have to be made. Second, galaxy formation involves, in addition to cosmological conditions, many complex physical processes, such as gas dynamics, star formation and feedback. Thus, to understand galaxy formation we need to understand which aspects of the theory determine the properties of individual galaxies, and which aspects determine the large-scale distribution of galaxies in the Universe.

It is well established that galaxies reside in extended dark matter halos, which are virialized clumps of dark matter formed through nonlinear gravitational collapse. Numerical simulations and analytical models can now give us a fairly detailed picture of the abundance and clustering of CDM haloes (e.g. Ref. 3). However, in order to build a coherent picture of galaxy formation, we need to be able to link these properties of the halo population to those of the galaxy population. In other words, we need to know how dark matter haloes are populated by galaxies. Here I will summarize results obtained from the conditional luminosity function (CLF) model developed by Yang, Mo and van den Bosch[10] and from using galaxy systems to represent dark halos.

2. The Conditional Luminosity Function Model

The Halo Occupation Distribution, $P(N|M)$, is defined to be the probability that a halo of mass M contains N galaxies (of given properties). Taking into account possible dependence on galaxy luminosity, we can use the Conditional Luminosity Function (CLF) to link the distributions of galaxies and CDM halos. The CLF, denoted by $\Phi(L|M)\mathrm{d}L$, is defined as the average number of galaxies with luminosities in the range L, $L + \mathrm{d}L$ that "live" in halos of mass M (see Ref. 10). It is straightforward to show that the CLF is related to the galaxy luminosity function as

$$\Phi(L) = \int_0^\infty \Phi(L|M)n(M)\mathrm{d}M,$$

where $n(M)$ is the halo mass function, describing the comoving number density of dark matter halos as a function of halo mass M (e.g. Ref. 4). Similarly, we can write the average luminosity in a halo of mass M as

$$\langle L\rangle(M) = \int_0^\infty \Phi(L|M)L\mathrm{d}L,$$

and the average number of galaxies with luminosity $L > L_1$ in a halo of mass M as

$$N_M(L > L_1) = \int_{L_1}^\infty \Phi(L|M)\mathrm{d}L.$$

The two point correlation function of galaxies as function of luminosity can be written as

$$\xi_{\mathrm{gg}}(r|L) = b^2(L)\xi_{\mathrm{dm}}(r),$$

where $\xi_{\mathrm{dm}}(r)$ is the correlation function of dark matter, and

$$\bar{b}(L) = \frac{1}{\Phi(L)}\int_0^\infty \Phi(L|M)b(M)n(M)\mathrm{d}M,$$

with $b(M)$ the linear bias factor of dark matter halos of mass M, describing the enhancement of halo-halo correlation relative to that of dark matter (see Ref. 2). It is important to note that $n(M)$, $b(M)$, and $\xi_{\rm dm}(r)$ are properties of dark halos and of dark matter density field, which are well understood through numerical N-body simulations and analytical models. Thus, for a given cosmological model, the CLF provides a statistical tool to link the distributions of dark matter and galaxies.

In the model considered in Refs. 5 and 10, the CLF is assumed to have the Schechter form:

$$\Phi(L|M)\mathrm{d}L = \frac{\tilde{\Phi}^*}{\tilde{L}^*}\left(\frac{L}{\tilde{L}^*}\right)^{\tilde{\alpha}} \exp(-L/\tilde{L}^*)\mathrm{d}L,$$

where $\tilde{\Phi}^*$, $\tilde{L}^*$ and $\tilde{\alpha}$ all depend on halo mass M. These mass dependencies are parameterized according to physical considerations, with the use of a total of 8 free parameters. For a given set of observational constraints and a given cosmology, a Monte-Carlo Markov Chain is constructed to sample the posterior distribution of the free parameters.

With the observed abundance and clustering of galaxies from optical redshift surveys as observational constraints, a number of interesting results have been obtained, which are summarized in the following. Using only the luminosity function and the correlation lengths as function of luminosity one obtains constraints on Ω_m and σ_8 that are in good agreement with COBE. Models with low Ω_m and high σ_8 as well as those with high Ω_m and low σ_8 are ruled out because they over (under) predict the amount of clustering, respectively. In Refs. 5 and 6, it is found that the predicted cluster mass-to-light ratio, $\langle M_{\rm vir}/L\rangle_{\rm cl}$, to be strongly correlated with σ_8. Using the additional constraints $\langle M_{\rm vir}/L\rangle_{\rm cl} = (350 \pm 70)h\mathrm{M}_\odot$ and $\beta = 0.49 \pm 0.09$ as Gaussian priors significantly tightens the constraints and allows one to break the degeneracy between Ω_m and σ_8. For flat ΛCDM cosmologies with scale-invariant power spectra one obtains that $\Omega_m = 0.27^{+0.14}_{-0.10}$ and $\sigma_8 = 0.77^{+0.10}_{-0.14}$ (both 95% confidence level). Adding constraints from current CMB data, and extending the analysis to a larger cosmological parameter space, one obtains that $\Omega_m = 0.25^{+0.10}_{-0.07}$ and $\sigma_8 = 0.78 \pm 0.12$. There is therefore indication that both the matter density Ω_m and the mass variance σ_8 are significantly lower than their "standard" concordance values of 0.3 and 0.9. The results are in good agreement with the recent results from WMAP7.

The derived CLF can be used to predict several statistics about the distribution of galaxy light in the local Universe (e.g. Ref. 10). Roughly 50 percent of all light is contained in haloes less massive than $\sim 10^{12}\mathrm{M}_\odot$. The halo mass-to-light ratio, $M/L(M)$ reaches a minimum at around $M \sim 10^{12}\mathrm{M}_\odot$, implying that such halos are the most productive in 'producing' light. This is consistent with generic models of galaxy formation, which predict that haloes more massive than $10^{12}\mathrm{M}_\odot$ are inefficient in cooling their baryonic gas, while less massive haloes are inefficient in producing stars because of heating from supernova feedback or other energy sources.

The CLF obtained can be used to populate dark matter haloes in high-resolution N-body simulations to construct mock galaxy redshift surveys.[11] These mock surveys can be used to investigate various clustering statistics under exactly the same selection effects as observational samples. The predicted two-dimensional correlation function $\xi(r_p, \pi)$ reveals clear signatures of redshift space distortions caused by velocity dispersions in individual dark halos. The projected correlation functions for galaxies with different luminosities and types, derived from $\xi(r_p, \pi)$, match the observations well on scales larger than $\sim 3h^{-1}$Mpc. On smaller scales, however, the model overpredicts the clustering power by about a factor two if $\sigma_8 = 0.9$ is adopted. Modeling the "finger-of-God" effect on small scales reveals that the ΛCDM model with $\sigma_8 \simeq 0.9$ predicts pairwise velocity dispersions (PVD) that are $\sim 400\,\mathrm{km\,s^{-1}}$ too high at projected pair separations of $\sim 1\,h^{-1}$Mpc. A strong velocity bias in massive haloes, with $b_{\rm vel} \equiv \sigma_{\rm gal}/\sigma_{\rm dm} \sim 0.6$ (where $\sigma_{\rm gal}$ and $\sigma_{\rm dm}$ are the velocity dispersions of galaxies and dark matter particles, respectively) can reduce the predicted PVD to the observed level, but does not help to resolve the over-prediction of clustering power on small scales. Consistent results can be obtained within the ΛCDM model with $\sigma_8 \simeq 0.75$, indicating again that the value of σ_8 must be as low as that obtained from the CLF model.

3. Galaxy Groups: A Link Between Galaxies and Dark Halos

A more direct way of studying the galaxy-halo connection is by using galaxy groups, provided that these are defined as sets of galaxies that reside in the same dark matter halo. Note that we refer to a system of galaxies as a group regardless of its richness, including isolated galaxies (i.e. groups with a single member) and rich clusters of galaxies. With a well-defined galaxy group catalogue, one cannot only study the properties of galaxies as function of their group properties (e.g. Refs. 8, 9, 12 and 17), but one can also probe how dark matter haloes trace the large-scale structure of the universe (e.g. Ref. 13). Yang *et al.*[14] have developed a halo-based group finder that is optimized for grouping galaxies that reside in the same dark matter halo. Using an iterative approach, the group finder uses the average mass-to-light ratios of groups, obtained from the previous iteration, to assign a tentative mass to each group. This mass is then used to estimate the size and velocity dispersion of the underlying halo that hosts the group, which in turn is used to determine group membership in redshift space. Finally, each individual group is assigned a halo mass based on its characteristic stellar mass. Using mock galaxy redshift surveys constructed from the CLF model (see Ref. 11), it is found that this group finder is very successful in associating galaxies according to their common dark matter haloes. In particular, the group finder performs also reliably for poor systems, including isolated galaxies in small mass haloes. This makes this halo-based group finder ideally suited to study the relation between galaxies and dark matter haloes over a wide dynamic range in halo masses. Thus far, the halo-based group finder has been applied to both the 2dFGRS[14] and to the SDSS.[16]

3.1. *The correlation function of groups*

Yang *et al.*[13] (see also Ref. 7) analyzed the 2-point correlation function (2PCF) of galaxy groups ranging from isolated central galaxies to rich clusters of galaxies. The real-space correlation length (r_0) obtained for these systems ranges from ~ 4 to $\sim 15\,h^{-1}$Mpc. Redshift distortion is clearly detected in the redshift-space correlation function, and the degree of distortion is consistent with the assumption of gravitational clustering and halo bias in the cosmic density field. The observed correlation amplitude (and the corresponding bias factor) as a function of group abundance can well be reproduced by associating galaxy groups with dark matter halos in the standard ΛCDM model, suggesting that galaxy groups can be used to study the halo population in a statistical way.

3.2. *Group-galaxy cross-correlation function*

In order to probe the spatial distribution of galaxies in and around dark matter haloes, Yang *et al.*[15] measured the cross-correlation function between galaxies and groups (haloes) (hereafter GHCCF). The resulting GHCCFs show a clear transition from the "1-halo" to the "2-halo" terms at around the halo virial radius. The "1-halo" term measures the correlation between the group center and the galaxies that are part of that group (i.e. it measures the radial distribution of galaxies within their parent haloes), while the "2-halo" term measures the large scale correlation between galaxies that reside in different parent haloes. One can study the GHCCF as a function of group mass and various properties of the galaxies (luminosity, stellar mass, color, spectral type, and specific star formation rate). Overall, more massive groups reveal a stronger GHCCF than low mass groups. On large scales, the GHCCF is stronger for galaxies that are more luminous, more massive, red, early-type and/or with a low SSFR. All these trends can be understood in terms of the mean bias of their host haloes (i.e. more massive haloes are more strongly biased). Comparing the GHCCFs obtained from observation with those obtained from detailed mock galaxy redshift surveys suggests that the overall behavior of the GHCCFs obtained from the mock catalog is similar to that obtained from the observation, except that the GHCCFs of the mock samples have steeper small scale ("1-halo" term) profiles than observed. By carefully comparing the observational results with a set of MGRSs, one can determine the concentration parameters for the distribution of galaxies (of different types) in haloes of different masses. The distribution of galaxies in dark matter haloes seems to be significantly less concentrated than that of the dark matter particles as predicted by the standard ΛCDM model.

3.3. *Galaxy-galaxy lensing*

Li *et al.*[1] used galaxy groups from the SDSS together with mass models for individual groups to study the galaxy-galaxy lensing signals expected from galaxies of different luminosities and morphological types. The model predictions were compared with the observational results obtained from the SDSS for the same samples of galaxies. The observational results were found to be ell reproduced in a ΛCDM model based on the WMAP 3-year data, but a ΛCDM model with higher σ_8, such as the one based on the WMAP 1-year data, significantly over-predicts the galaxy-galaxy lensing signal. These results suggest that, once a correct model of structure formation is adopted, the halo masses assigned to galaxy groups based on ranking their stellar masses with the halo mass function, are statistically reliable. The results obtained imply that galaxy-galaxy lensing is a powerful tool to constrain both the mass distribution associated with galaxies and cosmological models.

3.4. *Halo occupation statistics*

With a well-defined group catalog, one can also investigate the properties of galaxy occupation in dark matter halos. Yang *et al.*[17] measured the CLF separately for all, red and blue galaxies, as well as in terms of central and satellite galaxies. The CLFs for central and satellite galaxies can be well modelled with a log-normal distribution and a modified Schechter form, respectively. About 85% of the central galaxies and about 80% of the satellite galaxies in halos with masses $M_h > 10^{14}h^{-1}\mathrm{M}_\odot$ are red galaxies. These numbers decrease to 50% and 40% in halos with mass $M_h \sim 10^{12}h^{-1}\mathrm{M}_\odot$. For halos of a given mass, the distribution of the luminosities of central galaxies, L_c, has a dispersion of about 0.15 dex. The mean luminosity (stellar mass) of the central galaxies scales with halo mass as $L_c \propto M_h^{0.17}$ ($M_{*,c} \propto M_h^{0.22}$) for halos with masses $M \gg 10^{12.5}h^{-1}\mathrm{M}_\odot$, and as a steeper relation for smaller halos. Measuring the luminosity and stellar mass gaps between the first and second brightest (most massive) member galaxies, $\log L_1 - \log L_2$ and $\log M_{*,1} - \log M_{*,2}$, one finds that the central galaxies follow a distribution different from that of satellite galaxies in halos smaller than $10^{14.5}h^{-1}\mathrm{M}_\odot$. The fraction of fossil groups, defined as $\log L_1 - \log L_2 \geq 0.8$, ranges from 2.0–2.5% for groups with $M_h \sim 10^{14}h^{-1}\mathrm{M}_\odot$ to 12–60% for groups with $M_h \sim 10^{13}h^{-1}\mathrm{M}_\odot$. The number distribution of satellite galaxies in groups of a given mass follows a Poisson distribution, in agreement with the occupation statistics of dark matter sub-halos. This provides strong support for the standard lore that satellite galaxies reside in sub-halos. Finally, the halo mass distribution for galaxies of a given luminosity or stellar mass can also be measured. The most luminous and massive galaxies are predominately central galaxies in massive halos, while less luminous and less massive galaxies can either be the central galaxies in small halos or satellite galaxies in massive halos. The fraction of satellites changes from $\sim 5.0\%$ for galaxies with $M_r \sim -22.0$ to $\sim 40\%$ for galaxies with $M_r \sim -17.0$.

For a more detailed discussion about the halo occupation results, see Xiaohu Yang's contribution to this volume.

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