The IRAC galaxy correlation functions from SWIRE

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Abstract. We present an analysis of large-scale structure from the Spitzer Wide-area Infrared Extragalactic legacy survey, SWIRE. The two-point angular correlation functions were computed for galaxies detected in the 3.6-micron IRAC band, on angular scales up to a degree. Significant evolution in the clustering amplitude was detected, as the median redshift of the samples increases from \( z = 0.2 \) to 0.6. The galaxy clustering in the GALICS semi-analytic models was compared with the observed correlation functions and found to disagree with the data at faint flux limits.

1. Introduction

The large-scale structure of the universe is a result of the gravitational growth of dark matter density perturbations. The detailed structure is dependent on both the cosmological parameters, which can be constrained by measurements of the cosmic microwave background for example, and the evolution of the dark matter distribution, as modelled with N-body simulations and semi-analytic techniques. It is known that the distribution of galaxies is biased with respect to the dark matter, but the details of the bias is poorly constrained. Observations of the large-scale structure of galaxies, and its evolution, can be used to understand this relationship between galaxy formation and the mass field.

The Spitzer Wide-area Infrared Extragalactic survey (SWIRE; Lonsdale et al. 2003, 2004) is the largest of the Spitzer Space Telescope’s six legacy programmes. When completed, we will have observed a total area of 49 square degrees, split between six fields, in all seven of Spitzer’s imaging bands (3.6–160 \( \mu \mathrm{m} \)). SWIRE is being used to study the history of star formation and the assembly of stellar mass in galaxies, the nature and impact of accretion in active galactic nuclei, and the influence of environment on these processes.

The area and depth of SWIRE combine to produce a survey of significant cosmological volume. Out to the estimated median redshift of \( z = 1 \), the survey proper volume is 0.04 Gpc\(^3\) – larger than the Sloan Digital Sky Survey (DR3 spectroscopic sample, median \( z = 0.1 \); Abazajian et al. 2005). SWIRE is sensitive to both star-forming and passively-evolving galaxies in the same volume, extending out to redshifts of 2–3 and across comoving spatial scales up to 100 Mpc. In Oliver et al. (2004) we presented the first detection of galaxy clustering with Spitzer, measuring a two-point angular correlation function at 3.6 \( \mu \mathrm{m} \) from our validation data. Similarly, Fang et al. (2004) presented their IRAC angular correlation functions from the Spitzer First Look Survey. Here we begin to extend our work to the larger SWIRE survey.
2. The two-point angular correlation functions

The restframe emission of galaxies in the $H$- and $K$-bands is dominated by older stellar populations and traces the stellar mass of galaxies. At the median redshift of the SWIRE survey, this corresponds to the observed 3.6 $\mu$m band, thus a sample of galaxies selected at 3.6 $\mu$m is essentially selected on the basis of the total mass in stars.

The ELAIS (European Large-Area ISO [Infrared Space Observatory] Survey) N1 field has an area of $\sim$9 sq. deg. and has been observed in all seven Spitzer bands. The Version 1.0 source catalogue [Surace et al. 2004] has been used to select three flux-limited samples at 3.6 $\mu$m. A faint sample was selected such that the flux limit of $S_{3.6} \geq 32$ $\mu$Jy was well-above the survey detection limit, ensuring a high source reliability (signal-to-noise $> 40$) and a uniform selection function; this sample covers an area of 1 sq. deg. A medium sample with $S_{3.6} \geq 80$ $\mu$Jy covers 2 sq. deg. and a bright sample has $S_{3.6} \geq 200$ $\mu$Jy over 8 sq. deg. Note that the faint and medium samples are contained within the bright sample and are not independent. Following [Oliver et al. 2004], sources were removed from the initial catalogue if they were identified as point sources in the Two-Micron All Sky Survey (2MASS) or had the 3.6/4.5-$\mu$m colours of stars. The remaining stellar contamination was estimated to be $<3\%$.

The two-point angular correlation function, $w(\theta)$, was calculated for each of the three samples following the same techniques as [Oliver et al. 2004], using the Landay–Szalay estimator. The correlation functions are plotted in figure 1a. A power-law model, $w(\theta) = A \theta^{1-\gamma} - C$, was fitted to the data over $\theta > 0.003$ deg (11$''$) – the 6$''$ photometry aperture limits the reliability of the data on smaller scales. With a fixed slope of $\gamma = 1.8$, the best-fitting correlation amplitudes, $A$, were $(1.8\pm0.2) \times 10^{-3}$ at 32 $\mu$Jy, $(5.8\pm0.4) \times 10^{-3}$ at 80 $\mu$Jy and $(13.9\pm1.0) \times 10^{-3}$ at 200 $\mu$Jy.
3. Comparison with GALICS mock catalogues

GALICS (Galaxies In Cosmological Simulations) is a hybrid model of galaxy evolution which combines high-resolution N-body simulations of the dark matter content of the universe with semi-analytic prescriptions to describe the fate of the baryons within the dark matter halos (Hatton et al. 2003). The simulations have $256^3$ particles in a $140 \, h_{70}^{-1} \, \text{Mpc}$ box, with a minimum halo mass of $2 \times 10^{11} \, M_\odot$. Within each halo, some fraction of the gas mass is cooled and turned into stars which then evolve. The spectral energy distributions of these model galaxies are computed by summing the contribution of all the stars they contain, tracking their age and metallicity. A mock catalogue is generated by projecting a cone through the simulation at a series of timesteps (redshifts), and calculating the properties of the galaxies ‘observed’ in the cone. The GALICS project have made available several of these cones, from which we have constructed mock catalogues of the SWIRE survey, in 1-sq.-deg. patches.

We have calculated the two-point angular correlation functions for the GALICS catalogues, using three flux-limited samples corresponding to the SWIRE data described in the previous section. In figure 2 we compare the GALICS correlation functions (shaded regions) with the SWIRE results (points; figure 1a). At the brighter flux limits ($S_{3.6} \geq 80 \, \mu\text{Jy}$ & $200 \, \mu\text{Jy}$) the clustering in the simulations is consistent with the data. For a fixed $\gamma = 1.8$, the amplitudes of the best-fitting power-laws differ by $< 2$-$\sigma$ between the data and the simulations in each sample. The larger uncertainties in the model correlation functions are due to the small size (1 sq. deg.) of the simulations compared with the data (8 sq. deg. at $200 \, \mu\text{Jy}$) – there are significantly fewer sources contributing to the estimation of $w(\theta)$. In the faintest sample, $S_{3.6} \geq 32 \, \mu\text{Jy}$, the model predicts stronger clustering than we observe on scales $> 1 \, \text{arcmin}$. The amplitude of the GALICS correlation function, $A = (2.7 \pm 0.2) \times 10^{-3}$, differs by $> 3$-$\sigma$ from that of the SWIRE data.

Figure 2. The SWIRE 3.6-μm angular correlation functions compared with the GALICS simulations for the three flux-limited samples. The shaded regions are the 1-$\sigma$ error bounds on $w(\theta)$ from the mock catalogues; the data points and best-fitting curves correspond to figure 1a.
4. Clustering evolution

The angular correlation function is the projection along the line of sight of the spatial correlation function, \( \xi \), and is dependent on both the redshift distribution and luminosity function of galaxies in the survey and on the evolution of the spatial clustering. At fainter flux limits the survey probes to higher redshifts and larger volumes, and this reduces the strength of the projected clustering. This is shown in figure 1b where we plot the amplitude, \( A \), of the angular correlation function against the limiting magnitude for a range of \( K \)-band surveys (Roche et al. 2003). We used the GALICS simulations to estimate the equivalent \( K \)-band limit for our 3.6-\( \mu \)m-selected samples, and plot these SWIRE clustering amplitudes on the same figure. Our new data have much smaller errors in \( A \) and are in agreement with the \( K \)-band surveys.

Also plotted in figure 1b (light lines) are three models of clustering evolution, \( \xi(r, z) = (r/r_0)^{-\gamma}(1+z)^{-(3+\epsilon)} \) with \( \epsilon = 0, -0.4 \) & \(-1.2 \), from Roche et al. (2003). We note that these models appear to be offset from the data for \( K \leq 18 \), and we have renormalized the \( \epsilon = 0 \) model to agree with the SWIRE amplitudes (heavy line). This renormalized model is consistent with most of the existing \( K < 18 \) data and, significantly, a linear interpolation of the model passes through the 2MASS data points at \( K < 14 \) (dotted line).

We make several conclusions based on these results. First, the correlation length \( r_0 \) (or the amplitude \( A \)) of stellar mass selected samples (at \( K \)-band & 3.6 \( \mu \)m) appears to be smaller than that of the \( I \)-band selected sample used in the models (Roche et al. 2003). Second, the scatter in the ground-based \( K \)-band data limits their ability to discriminate between the models (figure 1b). The SWIRE flux limit, \( S_{3.6} = 3.7 \) \( \mu \)Jy, corresponds to an equivalent \( K \approx 20.5 \) and we will soon measure the correlation function to this depth, with smaller errors than the existing data. Third, the observed amplitude of the correlation function at faint flux limits is inconsistent with the GALICS catalogues (figure 2) and appears to be more complex than the power-law models of Roche et al. (2003) in figure 1b. Detailed modelling of the redshift distribution, luminosity function and clustering evolution is being developed, which will enable us to gain further understanding of the observed galaxy clustering.

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