A DIRECT MEASUREMENT OF HIERARCHICAL GROWTH IN GALAXY GROUPS SINCE $z \sim 1$*

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Abstract

We present the first measurement of the evolution of the galaxy group stellar mass function (GrSMF) to redshift $z \gtrsim 1$ and low masses ($M_* > 10^{12} M_\odot$). Our results are based on early data from the Carnegie–Spitzer–IMACS Survey, utilizing low-resolution spectra and broadband optical/near-IR photometry to measure redshifts for a 3.6 μm selected sample of 37,000 galaxies over a 5.3 deg$^2$ area to $z \sim 1.2$. Employing a standard friends-of-friends algorithm for all galaxies more massive than $\log M_* / M_\odot = 10.5$, we find a total of $\sim 4000$ groups. Correcting for spectroscopic incompleteness (including slit collisions), we build cumulative stellar mass functions for these groups in redshift bins at $z > 0.35$, comparing to the $z = 0$ and $z > 0$ mass functions from various group and cluster samples. Our derived mass functions match up well with $z > 0.35$ X-ray-selected clusters, and strong evolution is evident at all masses over the past 8 Gyr. Given the already low level of star formation activity in galaxies at these masses, we therefore attribute most of the observed growth in the GrSMF to group–group and group–galaxy mergers, in accordance with qualitative notions of hierarchical structure formation. Given the factor of 3–10 increase in the number density of groups and clusters with $M_* > 10^{12} M_\odot$ since $z = 1$ and the strong anticorrelation between star formation activity and environmental density during this epoch, this late-time growth in group-sized halos may therefore be an important contributor to the structural and star formation evolution of massive galaxies over the past 8 Gyr.

Key words: cosmology: observations – galaxies: evolution – galaxies: groups: general – galaxies: high-redshift

Online-only material: color figures

1. INTRODUCTION

Just as the relative roles of genetics and environment in shaping human populations are hotly debated, so are the analogous processes argued among those who study the evolution of galaxies. The “nature” of a galaxy in principle is largely determined by the mass of its dark matter halo, since in isolation the collapse of a given amount of matter should give rise to descendents with a consistent set of properties (Berlind & Weinberg 2002). However, like humans, galaxies do not often mature in isolation: their “nurturing” can include gas inflows from the extended cosmic web, mergers with other galaxies, and other external processes.

While it is well established that galaxies’ morphologies (Dressler 1980; Wilman et al. 2009), colors (Cooper et al. 2007; Patel et al. 2009), and star formation properties (Kauffmann et al. 2004; Patel et al. 2011; Quadri et al. 2012) differ in overdense and underdense environments, the reasons behind these correlations are still uncertain. On the extremes, void galaxies tend to exhibit stable, gas-rich, star-forming configurations (Grogin & Geller 2000), while those in rich clusters are overwhelmingly quiescent with morphologies that suggest frequent high-speed interactions (e.g., Farouki & Shapiro 1981). Although such environments provide invaluable laboratories for the study of ex- and in situ galaxy evolution, they represent unusual neighborhoods: much of the galaxy population instead resides in the “suburbs,” i.e., lower-mass groups (Eke et al. 2004). Groups’ influence on their residents may be dramatic, like quenching star formation by keeping cold gas from reaching galaxies (e.g., van den Bosch et al. 2008) and/or facilitating bursts of star formation through mergers (Larson & Tinsley 1978). Consequently, the assembly of groups since $z = 1$ could be a major factor in the decline of cosmic star formation over the same time period (Lilly et al. 1996; Madau et al. 1996).

Despite the ubiquity of groups, homogeneous samples are notoriously difficult to assemble at $z \gtrsim 0.4$. With just a few galaxies spread over ~1 Mpc or more, standard cluster selection techniques (e.g., overdensities exhibiting a well-defined red sequence) cannot be applied. Comprehensive spectroscopic surveys over wide areas are the only reliable way to weed out groups from interlopers; however, such surveys are often biased toward UV-bright, star-forming galaxies at the expense of the massive red galaxies which dominate dense environments. An infrared-selected survey, effectively producing a mass-limited sample at $z \sim 1$, is therefore necessary for an unbiased census of massive galaxies at these redshifts (van Dokkum et al. 2006; Kelson et al. 2012).

The Carnegie–Spitzer–IMACS (CSI) Survey has been specifically designed to characterize massive galaxies and their environments up to $z \sim 1.4$. Here we present a measurement of the evolution of the group stellar mass function (GrSMF), to lower group masses and higher redshifts than have been previously achieved, using early CSI data. Cosmological parameters $h = 0.7$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ are assumed throughout.

2. OBSERVATIONS AND SPECTRAL FITTING

In a companion paper (Kelson et al. 2012), we describe the CSI observing setup and strategy, data reduction, and spectral energy distribution (SED) fitting; a brief summary follows. We employ a simple 3.6 μm flux limit of $m_{AB} < 21$ to select

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galaxies from three of the Spitzer Wide-Area Extragalactic Survey (SWIRE) fields: ELAIS-S1, Chandra Deep Field South, and XMM-Large Scale Structure (XMM-LSS), excluding stars with simple optical/IR color cuts. The 3.6 μm band lies in the rest-frame near-IR for galaxies at $z = 0.5–1.5$, resulting in an approximately mass-selected sample unbiased by dust and star formation. The first two years of observations focused primarily on the XMM-LSS field, giving it the best spectroscopic and photometric coverage at present; here we focus only on data from this 5.3 deg$^2$ field in our analysis.

Targets were observed in multi-slit, nod-and-shuffle mode (Glazebrook & Bland-Hawthorn 2001) with a multiplexing efficiency of $\sim 1800$ objects per 28′′ diameter mask, using the low-dispersion prism (LDP) on the Inamori-Magellan Areal Camera and Spectrograph (IMACS; Dressler et al. 2011) in 2009. In 2010, a second pass was mostly completed with the new uniform-dispersion prism (UDP) which provides superior resolution beyond $\lambda > 7500$ Å. Some overlap between the LDP- and UDP-observed samples was included for cross-calibration and testing; overall, two passes have provided $\sim 40\%$ completeness. The IMACS spectra are supplemented with moderate-depth $J$ and $K$ imaging from the NOAO Extremely Wide-Field InfraRed Mosaic (NEWFIRM) and optical photometry from the Canada–France–Hawaii Telescope Legacy Survey.

The spectra were optimally extracted and combined, and prism and broadband IR data were jointly fit using a generalized set of starburst models described by Kelson et al. (2012). With a series of benchmarks—spectroscopic redshifts in this field (VVDS; Le Fevre et al. 2005), galaxies observed with both the LDP and UDP, and comparing prism redshifts of galaxy pairs (cf. Quadri & Williams 2010)—we infer typical redshift uncertainties of $\Delta z/(1 + z) \sim 0.005–0.015$ at $z < 1$. Notably, unlike photometric redshifts, these errors are comparable for red and blue galaxies since the prism spectrum pinpoints both the 4000 Å break and emission lines. After excluding objects with poor SED fits (typically due to strong active galactic nucleus components, bad photometry, and/or incorrect slit placement) the final catalog contains about 37,000 galaxy redshifts over 5.3 deg$^2$, with an effective stellar mass limit of about $M_*>3 \times 10^{10} M_\odot$ at $z \sim 1$. Largely as a result of CSI’s near-IR selection, this mass limit is a factor $\sim 2$ below that of optically selected surveys for red galaxies at similar redshifts (e.g., DEEP2; Cooper et al. 2010; Kelson et al. 2012).

3. GALAXY GROUPS AT $0.5 < z < 1.2$

3.1. Finding Groups with Friends-of-friends

Groups typically appear as associations of two to a few tens of galaxies over an area of a few hundred projected kpc; accurate redshifts and large areas are therefore critical to building robust group samples. We employ a simple friends-of-friends (FoF; Huchra & Geller 1982) algorithm to find groups in the CSI catalog, limiting the sample to galaxies with $M_*>3 \times 10^{10} M_\odot$, the CSI mass limit for red galaxies at $z \sim 1.2$. Even at the low end our redshift uncertainty ($\sim 0.5\%$) is larger than the expected velocity dispersion of most virialized groups and clusters. Redshift uncertainties were estimated (using the techniques mentioned in Section 2) as a function of $r$-band magnitude and the quadrature sum of each galaxy pair’s $1\sigma$ uncertainties was adopted as the redshift linking length. We used a transverse linking length of $1.0/(1 + z)$ Mpc (matching the Yang et al. 2007 length of 1 Mpc for Sloan Digital Sky Survey (SDSS) groups). The mean group redshift was also adjusted as new members were added, and previous group members falling outside $1\sigma$ from the new mean were removed from the group. In cases where the members of two groups overlapped, the two were merged into a single group, the linking length recalculated, and the membership adjusted accordingly.

Ultimately this iterative FoF process found 1551 groups in the CSI catalog containing a total of 4140 confirmed galaxies above the mass limit, or an estimated 13,000 galaxies after correcting for incompleteness (as described in the next section). This correction is somewhat larger than that implied by the mean completeness of $\sim 30\%–40\%$ (Kelson et al. 2012), because groups and clusters are relatively dense environments that are difficult to sample with multi-slit spectroscopy. Figure 1 shows a $VJ$ color image of one representative group at $z = 0.935$ along with SEDs of its four confirmed members. These galaxies are circled in white in the image, and with this particular color scale appear to have consistent colors. Three of the member galaxy SEDs look fairly similar, with primarily evolved stellar populations, while the fourth is blue and star forming. This illustrates the high fraction of massive evolved galaxies even in relatively poor groups at high redshifts.

3.2. Incompleteness and Projection Effects

Even with the redshift accuracy of CSI, two effects will introduce serious biases if not taken into account: spurious groups introduced by projected alignments of galaxies, and group members not included in the sample due to the minimum slit spacing of IMACS and yet-incomplete coverage. We correct for the latter effect by creating mock galaxy catalogs based on the target source density and flux distribution (i.e., that of all objects above the Infrared Array Camera flux limit), and estimating the fraction of sources on which slits could be placed $f(\rho)$ as a function of projected density. For a given region of the image, the underlying source number density is then approximated by $n_{true} = n_{abs}/f(\rho)$.

To estimate the contribution of spurious groups due to chance projections, we assigned random redshifts to the galaxies in the sample (keeping the same distribution of source densities) and re-ran the group-finding algorithm. Not surprisingly, the likelihood of chance projections decreases with increasing group mass since a higher concentration of galaxies in a given region is more likely to be a “true” group or cluster; this contamination fraction varies from 60% at the low end (log $M_*/M_\odot \sim 11.5$) to 10% for groups an order of magnitude more massive; over the full group sample the mean contaminant fraction is about 40%. We therefore only consider group stellar masses above log($M_*/M_\odot$) $> 11.7$, where the contribution from spurious groups is below 50%. Note that the number of “real” and “projected” groups both depend similarly on group-finding parameters like the linking lengths, and so the net (statistically corrected) number of groups in any mass bin is relatively insensitive to these parameters.

3.3. Calculating the Cumulative Group Stellar Mass Functions

The CSI group catalog was conservatively selected from a galaxy sample which is complete to log($M_*/M_\odot$) $> 10.5$ at $z < 1.2$ for both red and blue galaxies. Calculation of the GrSMFs is therefore straightforward, simply a matter of summing the number of groups detected in mass and redshift bins and dividing by the effective survey volume (taking into account area not covered due to gaps between masks, bright stars, etc.). Above the adopted mass limit of groups above...
log\( (M_\star /M_\odot) = 11.7 \), there are 686 groups. We subdivided the sample into redshift bins \( z = 0.35–0.55, 0.55–0.9 \), and 0.9–1.2. Our cumulative GrSMFs are binned such that the first (highest-mass) bin contains three groups, and the number of groups in each successively lower-mass bin is incremented by either one or a multiplicative factor of 1.1, whichever is greater; this provides a roughly constant binning in \( \log N \) at low masses. Finally, to correct for projection effects the GrSMF of the previously described “randomized” (i.e., spurious) groups was calculated the same way and subtracted.

To check the concordance of these GrSMFs with those found in other studies at lower redshifts and higher masses, we adopted two complementary samples from the literature: the SDSS group catalog by Yang et al. (2007), and massive X-ray-selected clusters at \( z \sim 0 \).5.35 from the ROSAT All-Sky and 400 Degree (400d) surveys (Burenin et al. 2007; Vikhlinin et al. 2009). 400d includes 36 clusters at \( z > 0.35 \) and 49 at \( z \lesssim 0.2 \) detected in 400 deg\(^2\) of ROSAT PSPC observations and followed up with Chandra to obtain total virial masses. To create a \( z \sim 0 \) sample comparable to CSI, we chose a highly restricted subset of groups from the Yang et al. (2007) “Sample II” catalog with at least two galaxies of \( \log(M_\star /M_\odot) > 10.5 \) between 0.025 < \( z < 0.075 \) (the upper bound being the redshift where SDSS is complete at these masses), and calculated the cumulative group mass function. In contrast, the 400d survey provides an X-ray-selected cluster sample given in virial, not stellar, masses. We therefore recomputed their mass functions in terms of \( M_{500} \) using the volumes in Figure 11 of Vikhlinin et al. (2009) and transformed their virial masses to stellar masses with the Giodini et al. (2009) relations.

If the group masses have substantial uncertainties, the observed mass function will be biased toward larger masses (due to the steepness of the GrSMF). This effect is small for SDSS and 400d, but significant for CSI, which has relatively large-mass errors. To correct for this, we convolved the SDSS mass function with CSI’s expected stellar mass error distribution, and thereby estimated the shift in the CSI GrSMF as a function of group stellar mass. All CSI GrSMFs were corrected accordingly, with a mass shift of \( \sim 0.5 \) dex.

Figure 2 shows the CSI, SDSS, and Vikhlinin et al. (2009) mass functions overplotted, all in terms of \( \log M_\star /M_\odot \). As an
additional check, we include the HIFLUGCS X-ray-selected cluster mass function from Reiprich & B"ohringer (2002), transforming their $M_{200}$ values to $M_*$ with relations given by Lagan"{a} et al. (2011; which were specifically computed from HIFLUGCS). Poisson errors are shown on the CSI data points; cosmic variance is not included, but using the Trenti & Stiavelli (2008) Cosmic Variance Calculator we estimate it will add an additional 10%–20% (greatest in the $0.35 < z < 0.55$ bin and at the highest masses) to the number density uncertainty; however, for the most part the Poisson uncertainties dominate. Despite the major selection differences, the SMFs of the $z \sim 0$ optical and X-ray samples are in good agreement, suggesting that the adopted transformations from virial to stellar masses are reasonably robust.

4. DISCUSSION

4.1. Concordance with Massive X-ray-selected Clusters

The effective upper mass limit of our GrSMFs where we “run out” of volume are, in the realm of galaxy clusters, not particularly massive: at $M_* \sim 10^{12.5} M_\odot$ (above which we only have 12 groups in our sample), in the literature they would typically be called “rich groups” or “poor clusters.” The lack of rich CSI clusters is simply a result of the limited area covered by CSI: while 5.3 deg$^2$ (and the ultimate goal of 15 deg$^2$) is very large for a $z \sim 1$ galaxy survey, the richest, most massive clusters are rare enough that much larger areas are needed to find significant numbers of them at low to intermediate redshifts. As noted in the previous section, such samples are provided by large X-ray surveys covering hundreds of square degrees; here we have adopted the 400d survey (Vikhlinin et al. 2009) as a principal comparison sample.

Figure 2 shows that the cluster mass functions of Vikhlinin et al. (2009; transformed to stellar masses by the Giodini et al. 2009 conversion factors, though see Leauthaud et al. 2012) not only pick up more or less where CSI leaves off, but also represent a smooth continuation of the CSI GrSMFs to a factor $\sim 2$ higher mass. This is the first demonstration of the connection between group and cluster SMFs at these high redshifts. While not a particularly surprising result, it provides further evidence that our observing strategy and group selection methods are robust, and that the groups found by CSI bridge a key gap between individual galaxies and massive clusters in the distribution of dark matter halos. Although deep X-ray and IR observations provide compelling evidence of massive clusters at $z > 1$ (McCarthy et al. 2007; Papovich et al. 2010; Rosati et al. 2009), no homogeneously selected sample currently exists at these redshifts; indeed, the rapid decline in cluster abundances at high stellar masses seen in Figure 2 (if it is similarly steep at $z = 0.9–1.2$) suggests that such objects are extremely rare. The most common progenitors of low-$z$ clusters must therefore lie at group masses at $z > 1$.

4.2. Hierarchical Growth Over the Past 8 Gyr

The combined CSI and 400d mass functions show strong evolution over the redshift range $z = 0.35–1.2$, with much of the evolution occurring between the $z \sim 1$ and $z \sim 0.6$ redshift bins. Similarly, there is another significant increase in number density between the lowest-redshift bin of CSI and the $z = 0$ groups and clusters. In the two lowest-redshift CSI bins there appears to be only marginal evolution between the mass functions; this may be a result of cosmic variance or residual mass uncertainties. Overall, however, the observed evolution appears to qualitatively reflect hierarchical structure formation: the ranks of massive groups and clusters ($\log M_* / M_\odot \gtrsim 12.2$) grow strongly over this redshift interval, while the number density of lower-mass groups is more constant (presumably because new groups are formed from below our mass limit as others merge into the more massive clusters). Although these hierarchical trends can be seen in the 400d cluster data alone, CSI and SDSS demonstrate that this growth continues to masses $\sim 0.5$ dex lower.

Due to the small number of high-mass clusters, the mass functions in Figure 2 are shown as cumulative number densities. To better illustrate the observed hierarchical growth, another projection of the GrSMF evolution is shown in Figure 3. Here, the number densities of galaxies in three mass bins (two from CSI/SDSS and one from 400d) are shown as a function of redshift. The difference between low- and high-mass groups is striking: at $\log(M_*/M_\odot) = 12–12.4$ the abundance of groups is relatively flat, but at masses $\sim 0.4$ dex higher the number density declines far more rapidly with increasing redshift. More quantitatively, we fit a power-law $n \sim (1 + z)^{\alpha}$ and find $\alpha = -1.6 \pm 0.2$ for groups with $12.0 < \log M_* < 12.4$ and $\alpha = -4.2 \pm 0.7$ at $12.4 < \log M_* < 12.8$; the difference in slopes is therefore significant at the 3.5σ level. X-ray clusters may exhibit marginally faster growth ($\alpha = -5.6 \pm 1.4$), but due to the large uncertainties and potential systematics in their estimated stellar masses we cannot determine whether this steepening trend continues to $\log M_* > 12.8$.

5. SUMMARY AND FUTURE WORK

By employing low-resolution prism spectroscopy to obtain accurate redshifts for a mass-complete galaxy sample over 5.3 deg$^2$, we have assembled the most comprehensive catalog of 686 galaxy groups down to a stellar mass limit of $10^{11.7} M_\odot$. 

![Figure 3. Number density of groups in three stellar mass bins. For the two lower mass bins, data at $z \sim 0$ and $z > 0.25$ are taken from SDSS and CSI, respectively, while the most massive clusters are from the low- and high-$z$ samples of Vikhlinin et al. (2009), converted to stellar masses. Lines are power-law fits of the form $n \sim (1 + z)^{\alpha}$, with $\alpha = -1.6 \pm 0.2$, $-4.2 \pm 0.7$, and $-5.6 \pm 1.4$ in order of increasing mass; due to potential systematic offsets between the optically and X-ray-selected samples, the latter is less reliable and we show it as a dotted line. The hierarchical buildup of groups, where those with higher masses grow more rapidly, is evident in this figure. (A color version of this figure is available in the online journal.)]
and up to redshifts $z \sim 1.2$. The CSI GrSMFs follow a smooth continuation of the X-ray-selected cluster mass functions of Vikhlinin et al. (2009) when these are transformed to stellar masses. Most notably, the number density of high-mass groups and clusters increases more rapidly than low-mass groups; since the galaxies in these objects exhibit low average star formation rates relative to the field (R. J. Williams et al. 2012, in preparation; see also George et al. 2012), hierarchical processes like mergers and accretion likely dominate their growth.

This result illustrates the power of large prism surveys like CSI to effectively bridge the gap between galaxy- and cluster-mass halos, allowing studies of an ubiquitous galaxy environment. As noted before, this result is based on an early sample comprising about one-third of the total CSI area and 25% of the expected spectra. While these early data provide a qualitative picture of hierarchical growth in group stellar mass, forthcoming CSI data which attain improved completeness over the full $15 \text{ deg}^2$ area will allow us to robustly track the stellar mass growth of groups and clusters, and for the first time directly test theoretical models in the gap between galaxy and cluster-mass dark matter halos. Additionally, deep X-ray observations (and/or stacks of existing shallower data) in the CSI fields will allow a direct comparison of stellar and virial masses for X-ray detected groups, providing an unprecedented window into the underlying halo growth.

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REFERENCES

Berlind, A., & Weinberg, D. H. 2002, ApJ, 575, 587
Burenin, R. A., Vikhlinin, A., Hornstrup, A., et al. 2007, ApJS, 172, 561
Cooper, M. C., Coil, A. L., Gerke, B. F., et al. 2010, MNRAS, 409, 337
Cooper, M. C., Newman, J. A., Weiner, B. J., et al. 2007, MNRAS, 376, 1445
Dressler, A. 1980, ApJ, 236, 351
Dressler, A., Bigelow, B., Hare, T., et al. 2011, PASP, 123, 288
Eke, V. R., Baugh, C. M., Cole, S., et al. 2004, MNRAS, 348, 866
Farouki, R. T., & Shapiro, S. L. 1981, ApJ, 243, 32
George, M. R., Leauthaud, A., Bundy, K., et al. 2012, ApJ, 742, 125
Giodini, S., Pierini, D., Finoguenov, A., et al. 2009, ApJ, 703, 982
Glazebrook, K., & Bland-Hawthorn, J. 2001, PASP, 113, 197
Grogin, N. A., & Geller, M. J. 2000, AJ, 118, 2561
Huchra, J. P., & Geller, M. J. 1982, ApJ, 257, 423
Kauffmann, G., White, S. D. M., Heckman, T. M., et al. 2004, MNRAS, 353, 713
Kelson, D. D., et al. 2012, ApJ, submitted (arXiv:1207.0783)
Laganá, T., Zhang, Y. -Y., Reiprich, T. H., & Schneider, P. 2011, ApJ, 743, 13
Larson, R. B., & Tinsley, B. M. 1978, ApJ, 219, 46
Leauthaud, A., George, M. R., Behroozi, P. S., et al. 2012, ApJ, 746, 95
Le Fevre, O., Vettolani, G., Garilli, B., et al. 2005, A&A, 439, 845
Lilly, S. J., Le Fèvre, O., Hammer, F., & Crampton, D. 1996, ApJ, 460, L1
Madau, P., Ferguson, H. C., Dickinson, M. E., et al. 1996, MNRAS, 283, 1388
McCarthy, P. J., Yan, H., Abraham, R. G., et al. 2007, ApJ, 664, L17
Papovich, C., Momcheva, I., Willmer, C. N. A., et al. 2010, ApJ, 716, 1503
Patel, S. G., Kelson, D. D., Holden, B. P., Franx, M., & Illingworth, G. D. 2011, ApJ, 735, 53
Patel, S. G., Kelson, D. D., Holden, B. P., et al. 2009, ApJ, 694, 1349
Quadri, R. F., & Williams, R. J. 2010, ApJ, 725, 794
Quadri, R. F., Williams, R. J., Franx, M., & Hildebrandt, H. 2012, ApJ, 744, 88
Reiprich, T., & Böhringer, H. 2002, ApJ, 567, 716
Rosati, P., Tozzi, P., Gobat, R., et al. 2009, A&A, 508, 583
Trenti, M., & Stiavelli, M. 2008, ApJ, 676, 767
van den Bosch, F. C., Aquino, D., Yang, X., et al. 2008, MNRAS, 387, 79
van Dokkum, P. G., Quadri, R., Marchesini, D., et al. 2006, ApJ, 638, L59
Vikhlinin, A., Burenin, R. A., Ebeling, H., et al. 2009, ApJ, 692, 1053
Willman, D. J., Oemler, A., Jr., Mulchaey, J. S., et al. 2009, ApJ, 692, 298
Yang, X., Mo, H. J., van den Bosch, F. C., et al. 2007, ApJ, 671, 153