Rapid Growth of Massive Galaxies: A Paradox for Hierarchical Formation Models

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Abstract. On behalf of the survey teams I summarize the designs and results of the Las Campanas Infrared Survey and Gemini Deep Deep Survey, both of which were initiated to understand the nature of red galaxies and to study the history of stellar mass assembly. Our results from luminosity function analysis, ISM absorption line measurements, and spectral synthesis modeling show that near-infrared selected galaxies at $1 < z < 2$ are not only massive and abundant but also old and metal enriched, indicating rapid formation of massive systems at higher redshifts.

1 Background

Various galaxy surveys in the optical, near-infrared, and sub-mm have uncovered different galaxy populations at redshift $z > 2$ (see Steidel, Cimatti, and Chapman in these proceedings for discussions), but whether these galaxies are representative of the galaxy population at high redshifts or how they are related to the present-day population is not clear. For example, rest-frame UV-selected samples are presumably sensitive to active star-forming galaxies and biased against evolved, quiescent systems that are faint at ultraviolet wavelengths, while sub-mm samples select mostly dusty star-forming galaxies. In contrast, near-infrared based surveys are sensitive to early-type galaxies at $z = 0 - 3$ that have red optical and near-infrared colors and are known to dominate the total stellar mass at $z = 0$. A complete sample of massive systems at different epoch allows us to study the history of stellar mass assembly and offers important clues for discriminating between different galaxy formation scenarios (e.g. [1]).

But past studies based on near-infrared surveys have yielded inconsistent space density measurements of red galaxies at $z \geq 1$ (see [2] for a list of references). Early-type galaxies are strongly clustered and have no prominent narrowband spectral features at UV wavelengths. If these red galaxies are progenitors of early-type galaxies we see in the local universe (rather than dusty star-forming galaxies), then a wide-field infrared survey is required to minimize the effect of surface density variation between fields due to strong clustering (e.g.[3,4]). Furthermore, deep galaxy spectroscopy is required to obtain a complete sample of these massive systems for spectral diagnostics of their ISM and stellar content.

The Las Campanas Infrared Survey (LCIRS) and Gemini Deep Deep Survey (GDDS) are complementary studies designed to probe the nature of red galaxies and to determine mass assembly history using near-infrared selected galaxies. In the following section I summarize the goals and results of the surveys.
Fig. 1. Uncertainty of surface density measurements of red $I - K \geq 4$ galaxies with $16 < K < 20$ in different survey areas $\Omega$. The surface densities were determined empirically within separate sub-areas randomly selected from the LCIRS fields. The left panel shows the cumulative probability of different surface density measurements for $\Omega = 4.5 - 72$ arcmin$^2$. The vertical dotted line indicates the mean surface density of 0.83 arcmin$^{-2}$ determined over the entire LCIRS K-band selected red galaxies. Based on these curves, we show in the right panel the probability of obtaining a measurement within a factor of two accuracy of the nominal value versus $\Omega$.

2 The Las Campanas Infrared Survey

The LCIRS is a deep, wide-field near-infrared and optical imaging survey, designed to identify a large number of red galaxies at $1 < z < 2$, while securing a uniform sample of galaxies of all types to $z \sim 2$ using photometric redshift techniques ([2,4,5]). The primary objectives are: (1) to examine the nature of the red galaxy population and identify evolved galaxies at redshifts $z > 1$; (2) to study the space density and luminosity evolution of early-type galaxies at redshifts $z \leq 2$; and (3) to measure spatial clustering of massive galaxies, thereby inferring merger rates of these galaxies for constraining theoretical models.

We have completed the phase-I $H$-band survey to $H = 20.5$ over 1.1 deg$^2$ and are completing the phase-II $K$-band survey to $K = 20.6$ over 0.75 deg$^2$. The size of our survey area was determined in order to obtain a representative measure of the surface density of red galaxies and a significant signal in clustering analysis [4]. Five random fields have been chosen and each field covers $\approx 26 \times 26$ arcmin$^2$, corresponding to a projected co-moving distance $20\ h^{-1}$ Mpc. This is twice the correlation length observed for early-type galaxies at $z = 0$ (see [4] for references). The large survey area of the LCIRS allows us to estimate empirically the uncertainties in the surface density measurements of red galaxies identified in smaller-area surveys, assuming that the LCIRS galaxy sample are representative of these systems at $z \geq 1$. Figure 1 shows the results based on red galaxies with $I - K \geq 4$ found in non-overlapping, random sub-areas within the LCIRS fields.
Fig. 2. Rest-frame $J$ (left) and $K$ (right) galaxy luminosity function of $>4000$ galaxies identified at $1 \leq z \leq 1.5$ in the LCIRS using photometric redshift techniques. The points were evaluated using a modified stepwise maximum likelihood analysis, explicitly incorporating redshift uncertainties from photometric redshift analysis [6]. Error bars were estimated using a bootstrap technique that takes into account photometric uncertainties, redshift errors, and sampling biases. The thick solid curve in each panel shows our best-fit Schechter luminosity function. For comparison, we present measurements for $K$-selected galaxies at $0.75 < z < 1.3$ from the K20 survey team [7] (dashed curves). We also plot local measurements from the 2MASS survey [8,9] (thin curves).

in comparison to 0.83 arcmin$^{-2}$ as the nominal surface density of $I - K \geq 4$ galaxies determined based on the entire LCIRS red sample. We find based on the curves that a survey area of at least 70 arcmin$^2$ is necessary to identify a statistically representative sample of red galaxies. Our initial clustering analysis based on an $H$-band selected sample over 0.62 deg$^2$ of sky shows that red galaxies with $I - H \geq 3$ have a co-moving correlation length of $9 - 10$ $h^{-1}$ Mpc at $z \simeq 1$, comparable to that of present-day early-type galaxies [4].

Photometric redshifts have been determined for the entire LCIRS galaxy sample based on a combination of available optical $BVRIZ'$ and near-infrared $JHK$ photometry [6], making the LCIRS a complete redshift survey of faint galaxies at $z \geq 1$. But because of relatively large redshift uncertainties, accounting for these errors in all analyses that make use of photometric redshift measurements is necessary to minimize systematic errors. Adopting an $H$-band selected sample and using a technique that explicitly accounts for the non-gaussian characteristics of photometric redshift uncertainties, we have shown that the evolution of the rest-frame $R$-band co-moving luminosity density $\ell_R$ is characterized by $\Delta \log \ell / \Delta \log (1 + z) = 0.6 \pm 0.1$ and that luminous early-type galaxies exhibit only moderate evolution over $z = 0.3 - 1.5$ [6].

Rest-frame $J$- and $K$-band luminosity functions have also been calculated using $>4000$ $K$-band selected galaxies at $1 \leq z \leq 1.5$. Figure 2 shows the best-
fit luminosity functions in $J$ (left panel) and $K$ (right panel) using modified stepwise maximum likelihood method and STY approach as described in Chen et al. [6]. The best-fit Schechter parameters are $M_{J^*} - 5 \log h = -22.6, \alpha_J = -0.3, \phi_J = 0.0144 h^3 \text{Mpc}^{-3}$, and $M_{K^*} - 5 \log h = -23.4, \alpha_K = -0.2, \phi_K = 0.0142 h^3 \text{Mpc}^{-3}$. Figure 2 also shows that our results are consistent at the bright end with the estimates presented by the K20 team for 170 galaxies found at $0.75 < z < 1.3$ over a total sky area of 52 arcmin$^2$ [7] (dashed curves), but exhibit a hint of a turn-over at the faint-end. Comparisons with existing measurements for local galaxies using 2MASS data [2,9] indicate that there is approximately $0.4 - 0.6$ mag fading in luminous ($> L_*$) near-infrared selected galaxies from $z = 1.2$ to $z = 0$, the amount of which may be explained by stellar evolution over the same period of time. These results together suggest little/no evolution in the space density of massive early-type galaxies since $z = 1.5$ and support the hypothesis that these systems were formed at redshift much beyond $z = 1.5$.

3 The Gemini Deep Deep Survey

The GDDS is an ultra-deep spectroscopic survey of near-infrared selected galaxies at $0.7 < z < 1.8$ [10,11]. The primary objectives are: (1) to obtain spectral diagnostics of the ISM and stellar content of massive galaxies at high redshift; (2) to construct the stellar mass function over the target redshift range; and (3) to determine ages and star-formation histories of evolved systems at $z > 1$.

The survey makes use of nod & shuffle observing mode [12] for accurate sky subtraction and fringe removal at wavelength beyond 7500 Å. It is aimed at identifying near-infrared selected faint galaxies at $z > 0.8$ to a high completeness level. We have observed 301 spectra in four fields using GMOS on Gemini North. Each of the four fields covers 30 arcmin$^2$ field of view and is located in a separate LCIRS field. The pointing and target selection of the GDDS sample is guided by known information in the wider-field LCIRS sample to maximize the efficiency of identifying a representative sample of faint galaxies at $z > 0.8$. For example, each GDDS pointing is selected from within an LCIRS field to have the number of red galaxies comparable to the global mean, which is important for reliable volume density analyses of early-type galaxies. In addition, we exclude foreground contaminating sources at $z < 0.8$ using photometric redshifts available for all LCIRS sources. Figure 3(a) shows a comparison of the observed $V - I$ color versus $z$ for CFRS [13], GDDS [10], and UV-selected galaxies [14]. It demonstrates that the GDDS is probing a representative galaxy population concentrated at $0.8 \leq z < 2$ with a broad-range of star formation history, from quiescent through active star-forming systems. Conversely, the GDDS results offer necessary tests and verification of the accuracy of LCIRS photometric redshifts. Figure 3(b) shows that the rms scatter between $z_{\text{phot}}$ and $z_{\text{spec}}$ is $\sigma_{\Delta z/(1+z)} \approx 0.1$, consistent with previous results based on a smaller number of galaxies at $0 \leq z < 1$ [6].

The GDDS data have revealed a wealth of information regarding the ISM and stellar content of massive galaxies at $z > 1$. Sample spectra are presented in Figure 4, where we show various GDDS composite spectra as well as individ-
The observed $V - I$ color versus redshift for the GDDS sample (squares), in
correlation to the CFRS sample [13] (crosses), UV-selected galaxies [14] (stars), and
model predictions for a non-evolving elliptical galaxy (solid curve), to an exponentially
decaying star formation rate (SFR) with e-folding time of $\tau = 1$ (dashed curve) and 2
Gyr (long dash-dotted curve), and a constant SFR (short dash-dotted curve). (b) Comparison of photometric and spectroscopic redshifts for $\sim 200$ galaxies identified in the
LCIRS. Spectroscopic redshifts for galaxies in the HDFS and CDFS were collected in
part from the literature and in part from our own observations. Spectroscopic redshifts
for galaxies in the NOAO, 1511, and NTT fields were obtained from the GDDS.

usal sample spectra to demonstrate the data quality. The full sample of GDDS
spectra is presented in Abraham et al. [10]. Specifically, we show in panel (a) the
composite spectrum of early-type (absorption-line dominated) galaxies, panel
(b) intermediate-type galaxies, and in panel (c) late-type (emission-line dominated)
galaxies. For comparison, we include in panel (a) the SDSS composite
for luminous red galaxies (LRG) at $\langle z \rangle = 0.3$ [15] (red curve). Our composite
spectrum for early-type galaxies at $z = 1 - 2$ is strikingly similar to the LRG
composite spectrum at $\langle z \rangle = 0.3$, showing little evolution in the stellar content
of massive and quiescent systems over the redshift interval spanned by the two
samples. We also show the spectrum of a galaxy at $z = 1.34$ in panel (d) together
with the spectrum of the host galaxy of 53W091 at $z = 1.55$ [16] (red curve)
and a starburst galaxy at $z = 1.67$ in panel (e). These spectra demonstrate that
we have good signal-to-noise ratios to obtain accurate and precise redshifts of
individual galaxies using both rest-frame ultraviolet metal absorption features
and weak continuum bumps originating in evolved stellar populations.

In addition, we have constructed a composite spectrum for $13 K$-band
selected galaxies at $1.3 < z < 2$ from the GDDS sample that are also luminous in the UV with $M_{2000} < -19.5$ [11]. A normalized version is shown in
panel (f) of Figure 4, together with a normalized composite spectrum of local
starburst galaxies from Tremonti et al. [17]. The composite spectrum shows
prominent absorption features from Mg II, Fe II together with Mg I and Mn II,
Fig. 4. (a)-(c) GDDS composite spectra for respectively early-type, intermediate, and late-type galaxies at $z = 1 - 2$. (d) The spectrum of a galaxy at $z = 1.34$ from the GDDS, together with the spectrum of the host galaxy of 53W091 at $z = 1.55$ [16] in red, and the model spectrum of a single burst system formed at $z_f = 6$ in blue. (e) The spectrum of a starburst galaxy at $z = 1.67$, showing strong metal absorption features. (f) A normalized composite spectrum of 13 massive star-forming galaxies identified at $\langle z \rangle = 1.6$ from the GDDS, together with a normalized composite spectrum of local starburst galaxies [17].
all of which are stronger than those observed in local starburst systems. It indicates that the ISM of these massive star-forming galaxies has been heavily enriched with metals by \( \langle z \rangle = 1.6 \). Based on a curve-of-growth analysis of all available transitions, Savaglio et al. ([11]) find a mean Fe II column density of \( \log N_{\text{Fe II}}/(\text{cm}^2) = 15.54^{+0.23}_{-0.13} \) that is among the highest observed in either known damped Ly\( \alpha \) absorption systems or in the ISM of host galaxies of gamma-ray bursts (Figure 5a). While the metallicity is uncertain due to the unknown neutral hydrogen content, it is clear that the ISM of these galaxies contains abundant heavy elements. Because of the unknown nature of the galaxies that give rise to damped Ly\( \alpha \) systems, direct column density measurements of the ISM of luminous galaxies at high redshift offer a promising alternative for understanding cosmic chemical enrichment history.

We also determine the formation epoch of the stars seen in quiescent systems that show no signs of recent star formation (lack of emission features in the rest-frame UV). Using a likelihood analysis, we derive a minimum age for each system by comparing predicted spectral energy distributions (SEDs) from different stellar synthesis models with the observed ones established from the GDDS spectra and available LCIRS optical and near-infrared photometry. An example is shown in panel (d) of Figure 4 for a red galaxy at \( z = 1.34 \). The model (blue curve) was obtained for a single burst occurring at \( z_f = 6 \) and passively evolving to lower redshift. The agreement between the observed spectrum and models suggests that this galaxy is at least 3.5 Gyr old, pushing the formation epoch of this galaxy to beyond \( z_f = 6 \) (McCarthy et al. 2004).
Finally, we estimate the total stellar mass of every galaxy in the GDDS sample using a $K$-band mass-to-light ratio determined from comparing the observed multi-color data with a grid of model SEDs with varying dust extinction, metallicity, and star formation history. Figure 5(b) shows rest-frame UV flux (expressed in $M_{2000}$) versus the inferred stellar masses of individual galaxies in three redshift bins spanned by the GDDS sample. We see that a large fraction of the GDDS galaxies have masses $> 10^{10} M_\odot$, and these systems exhibit on average increasing rest-frame UV fluxes (and therefore increasing star formation rate) with increasing redshift. In addition, while few systems with stellar masses $< 10^{10} M_\odot$ are seen at $z > 1.3$ in the GDDS sample due to the $K$ limit of the survey, a tendency for the most massive galaxies to be UV quiescent is found in the low-redshift sample (crosses)—a trend which is similar to what is seen at $z = 0$. This result supports the view that most star formation takes place in lower mass systems even at $z > 1$ (Glazebrook et al. 2004).

In summary, the wide-field multi-color imaging data from the LCIRS and the high-quality nearly complete spectral sample from the GDDS together allow us to conduct a comprehensive study of massive early-type galaxies at $z = 1 - 2$. Our luminosity function analysis indicates that most and perhaps all of the present-day infrared luminous galaxies were in place by $z \approx 1.2$. The rest-frame UV spectra of massive star-forming systems show abundant metals that arise in the ISM of these galaxies, indicating an early heavy element enrichment by $z \approx 1.6$. Finally, spectral synthesis modelling showed that near-infrared selected galaxies at $z > 1$ are massive and that the quiescent ones with no evidence of recent star formation are genuinely old and likely to form at $z > 4$. Together these results suggest a rapid and early formation process of massive galaxies, presenting difficulties for conventional hierarchical formation scenarios.

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