The Evolution of Galaxies and Clusters of Galaxies from $z \sim 7$ to 1: ACS Team Highlights

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When did the first galaxies form?

A related question – when and how was the Universe...

Does large scale structure grow as predicted by the standard WMAP cosmology?
The Evolution of Galaxies from $z \sim 7$ to 4

Bouwens et al. 2007

Cosmic Star Formation Rate

Extinction Corrected

Observed

> 0.3 $L_{z=3}^*$

> 0.04 $L_{z=3}^*$

4671 B-dropouts
1416 V-dropouts
627 i-dropouts

UV Luminosity Function

log$_{10}$ Number / mag / Mpc$^3$
The Evolution of Galaxies from $z \sim 7$ to 4
Bouwens et al. 2007

- “The faint-end slope is very steep and shows little evolution with cosmic time.”
- “$M^*_{1600,\text{AB}}$ brightens considerably (by 0.7 mag) in the 0.7 Gyr from $z \sim 6$ ($M^*_{1600,\text{AB}} = -2.32 \pm 0.19$) to $z \sim 4$ ($M^*_{1600,\text{AB}} = -2.16 \pm 0.10$).”
- “The evolution of $\varphi^*$ is not significant, but is consistent with a mild decline with time ($\varphi^* = 0.0014 \pm 0.6 \text{ Mpc}^{-3}$ at $z = 6$ to $\varphi^* = 0.0011 \pm 0.0002 \text{ Mpc}^{-3}$ at $z = 4$).”
- “The extremely steep faint-end slopes found here suggest that lower luminosity galaxies play a significant role in re-ionizing the universe.”
The Epoch of Reionization: $z > 6$ Quasars

Charts Courtesy Richard L. White (STScI)

Bob Becker (UCD/LLNL)
Xiaohui Fan (Arizona)
Michael Strauss (Princeton)

and the SDSS Collaboration

STScI Workshop, 2006 March 13
Evidence That the Universe is Re-ionized by $z \sim 7$:
19 quasars with $z > 5.7$, $T(z) \leq 1$ Gyr

Fan et al., astro-ph/0512082

- 5 new $z > 6$ quasars found at Keck since January 2006
- Strongest limits on reionization:
  - Absorption in Ly $\beta$ and Ly $\gamma$ GP troughs
  - H II region sizes in proximity zone measured from Ly $\alpha$ line profiles
- $z = 6$ probably marked the end of reionization
  - Neutral fraction still fairly low, $f_{\text{HI}} \sim 0.03$ at $z = 6.4$
  - $f_{\text{HI}}$ is rising rapidly for $z > 6$

Also see Kazuaki Ota’s impressive work on $z \sim 7$ LAEs, this conference.

White et al., 2003, AJ, 126, 1
Proto-clusters and Large Scale Structure in the Early Universe

TNJ 1338, a radio source @ $z=4.1$
Age = 1.97 Gyr

18 orbits; $g$, $r$, $i$, and $z$
Miley & Overzier et al. 2003, Nature
VLT & ACS Observations of TN 1338, a cD Galaxy Forming at z = 4.1 (?)

The SFR is ~ 80 $M_\odot$/yr

(Zirm et al., 2005)
Miley’s VLT L\(\alpha\) Imaging and Spectroscopy of the TN1338 Field

21 L\(\alpha\) Emitters

\(\Delta v_{\text{restframe}} \sim 350 \text{ km/s}\)
ACS Observations of TN1338: A 4σ Excess of g-band Dropouts (LBGs) Relative to Goods Fields

18 orbits; g, r, i, and z

The distribution of LBGs is filamentary.

The median SRF is $\sim 6 \, M_\odot$/yr and the half light radii vary from $< 1$ to 5 Kpc.

The L% galaxies have a median SFR of $\sim 4 \, M_\odot$/yr and sizes from $< 1$ to 3.5 Kpc.

The L% galaxies may be undergoing their first starburst.

Overzier et al. 2006
Conclusions

- There are 2.5 times more g-band dropouts in the TN1338 field than an average GOODS field, a 4 \( \sigma \) excess.
- More than half of the g-band dropouts are located in an area with a 1 arc-minute radius (\( r \sim 1 \) Mpc), a 5\( \times \) increase over GOODS, and a 5\( \sigma \) excess.
- The over density of g-band dropouts and L\( \alpha \) emitters near TN1338 may well be ancestral to present day rich clusters.
LSS and Possible Proto-Clusters at $z = 5.7$


20 hrs Subaru Suprime-Cam, F8150/120
$z = 5.7 \pm 0.05$

Are Miley’s Proto-clusters Embedded in Filaments?
MRC 1138–262: A Massive Cluster Forming at $z = 2.2$


9 ACS WFC orbits, F475W ($\lambda_{\text{rest}} \sim 148.4$ nm)
10 ACS WFC orbits, F814W ($\lambda_{\text{rest}} \sim 254.4$ nm)
MRC 1138–262, $z = 2.2$

- “The statistics are consistent with every dominant cluster galaxy having gone through a luminous radio phase during its evolution (Venemans et al. 2002).”
- “The $K$-band luminosity corresponds to a stellar mass of $\sim 10^{12} M$ (Pentericci et al. 1998), implying that MRC 1138–262, is one of the most massive galaxies known at $z > 2$.”

H. Ford & ACS Team, NZ Mar 07
MRC 1138–262, $z = 2.2$

- The radio galaxy is associated with a 3 Mpc–sized structure of galaxies, with a mass $\sim 2 \times 10^{14} \, M_\odot$, the presumed, antecedent of a local cluster."
  
- The star formation rate inferred from the extended continuum emission is $\sim 100 \, M_\odot \, yr^{-1}$ (45\% of the total luminosity). We likely are witnessing the production of the massive, iron-enriched ICM that is already present in clusters at $z \sim 1$. 

The high-z clusters that I will describe are elongated (filamentary) and have two or more sub-clusters.

These massive clusters are still forming, and are high-mass analogs of the low-z super-cluster and super-group that were so beautifully described by Meghan Gray and Kim-Vy Tran.
ACS Observations of Clusters of Galaxies, $z = 0.8$ and $1.3$

CL1226, $z = 1.237$, $T_z = 5.7$ Gyr

ACS i,z & VLT K

ACS i, z & VLT K
38 Spectroscopically Confirmed Members in CL1226

Demarco et al. 2007 (in press)
Evidence That CL1226 Is Still Forming

- The cluster galaxies, X-ray emitting ICM (Rosati et al. 2004), and dark matter (Lombardi et al. 2005) are elongated in the east-west direction.
- The X-ray emitting gas has a “cold front” indicating a merger of two sub-clusters.
- The velocity distribution suggests two sub-clusters, each with $\sigma_0 \sim 475$ km s$^{-1}$. 
The intrinsic scatter in the colors of the confirmed Es (\(\sigma_{\text{int}} = 0.023 \pm 0.0007\)) gives mean luminosity-weighted ages of \(2.6 - 3.3\) Gyr, corresponding to “formation” at \(z = 2.7\) to \(3.6\). The isochrones in the color-color diagram give an age of \(~3\) Gyrs.
CL1054 $z = 0.831$, V, i, z, $T_z = 6.5$ Gyr (48%)
CL0152, $z = 0.837$
CL0152 & MS1054 @ z = 0.83

CL0152 (z=0.837)  MS1054 (z=0.831)
Morphology/Star-formation Segregation in CL0152

Star-forming Galaxies in CL0152

- Most star-forming galaxies have $r_{625} - i_{775}$ colors bluer than 1.0, but six are in the red cluster sequence (though not in the cluster core).
- There are five compact early-type star-forming galaxies that may be the progenitors of dwarf elliptical galaxies.

The Distribution of Dark (and Baryonic) Mass in CL0152

Jee et al. 2006

\[ M_p(r \leq 1 \text{ Mpc}) = 4.92 \pm 0.44 \times 10^{14} \text{ M}_\odot \]

\[ M/L = 95 \pm 8 \text{ M}_\odot / L_B \]
Spatial Comparison of Total Mass, Light, and Hot Gas

Overlay of the mass contours (white solid) on the i<sub>775</sub> luminosity distribution (color-coded).

Overlay of the mass contours (white solid) on the smoothed x-ray background (color-coded).

- The mass estimates from the lensing analysis are consistent with those from X-ray, SZ, and velocity dispersion analyses.
- The total projected mass and the mass-to-light ratio within 1 Mpc are estimated to be \((4.92 \pm 0.44) \times 10^{14} M_\odot\) and \(95 \pm 8 M_\odot/L_{B,\odot}\).
- The two peaks of intracluster medium traced by X-ray emission are lagging behind the corresponding dark matter clumps, indicative of an on-going merger.
$z = 0.83$ Precursors of Low-Mass E/S0s at $z = 0$

Holden et al. 2007

MS 1054.4-0321 and CL 0152.7-1357
**z = 0.83 Precursors of Low-Mass E/S0s at z = 0**

- Previous work finds that the early-type galaxy fraction in rich clusters increases from $\sim$60% at $z = 0.8$ to $\sim$80% at $z = 0$ when using luminosity-selected samples.
- The fraction of early-type galaxies is $79 \pm 6\%$ at $z = 0.83$ and $87 \pm 6\%$ in Coma for galaxies with $M > 10^{11.1} M_\odot$ ($M_*$ for clusters), *consistent with no evolution*.
- The galaxies which will become the bulk of the $L_*$ early-type population at $z = 0$, may be late-type galaxies at $z = 0.8$ with masses of $4 - 8 \times 10^{10} M_\odot$, ($\sim M_*$ for the field population).
Summary of (Some of) What We Have Learned

- Galaxies grow larger, brighter, and dustier from $z \sim 7$ to $z \sim 4$.
- The faint of the LF is very steep at $z \sim 6$; the low luminosity galaxies provide sufficient UV to re-ionize the universe.
- Large scale structure is already recognizable at $z \sim 5$, and may already have identifiable proto-clusters.
- Radio galaxies at $z = 2$ to 5 are in over dense regions, and likely are the progenitors of BCGs.
- Rich clusters at $z \sim 1$:
  - often are very elongated with two or more concentrations that are merging.
  - contain a hot ICM with [Fe/H] similar to low z clusters.
  - usually do not yet have a dominate BCG.
  - show morphological segregation between “old” early type galaxies and star forming galaxies.
  - have a fraction of E/S0 galaxies in a mass selected sample that is the same as in low z clusters.