Observational Studies of Galaxy Formation: Reaching back to ~500 Myr after the Big Bang

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Much of the discussion at this workshop has been on galaxy formation / evolution at late times...

SFRs in galaxies are decreasing with cosmic time...

Quenching / AGN feedback seems to become important
Galaxy Formation / Evolution is very different at $z \geq 3$

- SFRs in galaxies are increasing rapidly with time
- Galaxies appear to be growing exponentially...
- Feedback processes seem to be less important...
Galaxy Formation / Evolution is very different at $z \geq 3$

Halos of $L^*$ / sub-$L^*$ galaxies form from $z \sim 15$ to $z \sim 3$...
1) How quickly do galaxies grow with cosmic time?

-- measure in a number of different ways....

UV Light -- or UV Luminosity functions
    (discussed in my presentation)

Stellar Mass -- or Mass Functions
    (discussed in Valentino’s presentation)
Fundamental Questions for Galaxies at $z \geq 3$

2) How does the Visible Matter in growing Galaxies Relate to Dark Matter?

How does this work at high redshift?

SNe?

Halo Mass Function

Luminosity Function

Inefficient Gas Cooling

Yang et al. 2003

UCSC 8/19/10 RJB
3) How rapidly does the SFR density of the universe increase with cosmic time? (can derive by integrating the UV LFs)

** Important for the build-up of metals, dust in universe...

4) What role does the growth of galaxies have in the reionization of the universe?
Glimpse of Galaxy Growth
at $z<6...$
Galaxies at $z \sim 4, 5, 6$ ($B, V, i$-dropouts)

UV Luminosity Functions

1. LFs have a Schechter-like shape... with cut-off at bright end

2. Galaxies become more luminous as a function of cosmic time
Brightening and Fading of LF with time

Bright

Faint

$M^*_{\text{UV}}$

$M^*_{1500}$

Downsizing

Hierarchical Buildup

AGN Feedback?

Redshift
Glimpse of Galaxy Growth at $z \geq 7...$
Shuttle Servicing Mission SM4
Current WFC3/IR Samples

Wide-Area Observations + Two Ultra-Deep HUDF09 Fields

Total z>=7 WFC3/IR sample
~66 z~7 z-dropouts
~47 z~8 Y-dropouts

~113 z~7-8 galaxies now known

Took us ~1-2 months to devise technique for selecting robust samples
Special Thanks to My Collaborators

With a Special Thanks to:

The HUDF09 WFC3 IR team: Garth Illingworth, Rychard Bouwens, Marijn Franx, Pieter van Dokkum, Massimo Stiavelli, Ivo Labbe, Michele Trenti, Marcella Carollo, Pascal Oesch, Dan Magee
Galaxy Growth at High Redshift...

How do z>6 LFs look? What is the shape?

Bouwens et al. 2010a,b; Ouchi et al. 2009; see also Castellano et al. 2010
How do z>6 LFs look? What is the shape?

Galaxy Growth at High Redshift...

z~7 UV LF also has a Schechter-like shape

Bouwens et al. 2010a,b; Ouchi et al. 2009; see also Castellano et al. 2010
How do z>6 LFs look? What is the shape?

Not clear yet that the z~8 LF is Schechter....

Bouwens et al. 2010; Castellano et al. 2010
What do we learn from the shape of the UV LFs at $z>=7$?

Why does the UV LF cut-off at bright magnitudes?

STANDARD EXPLANATIONS AT $z\sim0$:
1. Inefficient cooling of gas.... (hot flows)
2. AGN feedback...

Halo masses are so low that neither explanation may be very effective...

Bouwens et al. 2010a,b; Ouchi et al. 2009; see also Castellano et al. 2010
Summary

1. One distinct feature in the observed LF is an abrupt cut-off at the bright end of the LF.
2. At $z \sim 0$, this feature is thought to result from inefficient cooling at large halo masses, AGN feedback, or dust extinction.
3. The above mechanisms are only effective at large masses, i.e., $> 10^{11.5} M_\odot$.
4. Since most dark matter halos at $z > 5-6$ have much smaller masses than $10^{11.5} M_\odot$, we would not expect these mechanisms to impart a sharp cut-off in the UV LF.
5. But the UV LFs at $z \sim 5-6$ do seem to have a sharp cut-off at the bright end. Why?
6. What will we find for LFs at $z \sim 7-9$? Soon to be available HST WFC3 data will allow us to explore this issue.
What is the faint-end slope?
(How numerous are very low luminosity galaxies?)

Lower luminosity galaxies provide the dominant contribution to SFR / luminosity densities

(see also Ouchi et al. 2009; Oesch et al. 2010; Yoshida et al. 2006)
Galaxy Growth at High Redshift...

How rapidly does the UV LF evolve from z~10+ to z~3? (Are there many UV bright galaxies at z~10?)

Bouwens et al. 2010
Galaxy Growth at High Redshift...

How rapidly does the UV LF evolve from $z \sim 10+$ to $z \sim 3$? (Are there many UV bright galaxies at $z \sim 10$?)

Very uniform evolution of UV LFs with redshift

Bouwens et al. 2010

68% and 95% confidence intervals
Integrate the UV LFs at z~7 and z~8, one derives the SFR density

Bouwens et al. (2010); Gonzalez et al. (2010)

Star Formation Rate density

Suggests IMF at high-redshift similar to that at lower redshift... and SFR / stellar mass estimates reasonable

Bouwens et al. (2010); Gonzalez et al. (2010)
Shuttle Servicing Mission SM4
Previous State of Art: LFs at $z_{\sim}4-6$, $z_{\sim}2-3$

Bouwens et al. 2007; Reddy et al. 2009

(see also Giavalisco 2005; Ouchi et al. 2004; Yoshida et al. 2006; Beckwith et al. 2006)
ERS observations in UV let us search for star-forming galaxies at $z \sim 1 \Rightarrow z \sim 2.5$

WFC3/UVIS results in the ERS field

Oesch et al 2010c; see also Hathi et al. 2010
The Evolution of the UV LF from $z \sim 7-8+$ to $z \sim 1$

What is the faint-end slope in FUV at $z < 3$?

$\alpha = -1.7 \pm 0.2$

$\alpha = -1.9 \pm 0.3$

Oesch et al. 2010; Reddy & Steidel 1999; Bouwens et al. 2010
Results are improving rapidly!

Deeper data already upon us!
More ultra-deep WFC3/IR observations coming!

Integration time over the HUDF is increasing by a factor of 2!
More ultra-deep WFC3/IR observations coming!

111 orbit integration
Reaches 29.5 mag
(within factor of ~4 of the depths planned for JWST deep field)

First Year Data
15 z~7 galaxies
16 z~8 galaxies

Second Year Data
28 z~7 galaxies
25 z~8 galaxies
The Evolution of the UV LF from $z \sim 7-8+$ to $z \sim 1$

Bouwens et al. 2010a,b; Ouchi et al. 2009; see also Castellano et al. 2010
Stay tuned for a variety of exciting results!
Galaxy formation in the z>=4 universe is very different in behavior from later times. WFC3/IR allows us to very efficiently identify galaxies at high redshift. We identify 67 z~7 z-dropouts and ~48 z~8 Y-dropout galaxies in the new observations. The UV LF of galaxies appears to have a Schechter-like shape at z~7 and also plausibly at z~8. The faint-end slope of the UV LF at z~7 and z~8 is ~ −1.9 ± 0.3. The evolution of the UV LF continues very smoothly from z~8 to z~4, with an essentially linear rate of evolution with redshift. Comparing the SFR density with that expected from the published stellar mass density, we find reasonable agreement -- suggesting that the IMF at z>4 may not be that different from what it is at later times. WFC3/UVIS allows us to efficiently select star-forming galaxies at z<3 and measure their FUV flux. We identify >1000 galaxies to ~0.1 L* in the ~50 arcmin² WFC3/UVIS observations. The faint-end slope of the UV LF at z~1-3 is ~ −1.7 ± 0.2. Much exciting data coming!