Uncertainties in

The Galaxy Luminosity Function at $z \gtrsim 6$

Hsiao-Wen Chen
Astronomy & Astrophysics / KICP
The University of Chicago

Alexander (Sasha) Kaurov
(UChicago -> IAS)

Fakhri Zahedy
(UChicago)
Significance of $z \geq 6$ galaxies

- Assembly of the first galaxies (and first SMBH)
- Ionization of the intergalactic medium
- Chemical enrichment in early times

The galaxy luminosity function $\rightarrow$
a census of the early galaxy population
Observations of high-redshift galaxies

Spectroscopy is hard...

Keck/MOSFIRE 3-4 hr total integration

Oesch et al. (2015); Stark et al. (2016)
Observations of high-redshift galaxies

A deep image is worth a thousand spectra

Observations of high-redshift galaxies

Star-forming galaxies at very high redshifts

Kenneth M. Lanzetta*, Amos Yahil* & Alberto Fernández-Soto† ‡

* Astronomy Program, Department of Earth and Space Sciences, State University of New York at Stony Brook, Stony Brook, New York 11794-2100, USA
† Instituto de Física de Cantabria, Consejo Superior de Investigaciones Científicas, ‡ Departamento de Física Moderna, Universidad de Cantabria, Facultad de Ciencias, 39005 Santander, Spain

Analysis of the deepest available images of the sky, obtained by the Hubble Space Telescope, reveals a large number of candidate high-redshift galaxies. A catalogue of 1,683 objects is presented, with estimated redshifts ranging from $z = 0$ to $z > 6$. The high-redshift objects are interpreted as regions of star formation associated with the progenitors of present-day normal galaxies, at epochs that may reach back 95% of the time in the Big Bang.

The long-standing effort to identify normal galaxies at high redshifts has undergone dramatic progress in recent months. New observations by Steidel et al.† to magnitude $AB(6030) < 25$ (where $AB(\lambda)$ is the monochromatic magnitude at wavelength $\lambda$) have revealed a population of galaxies at redshift $z \approx 3$ and have demonstrated that the Lyman-limit spectral discontinuity and Lyz-forest spectral decrement, which arise owing to photoelectric absorption by neutral hydrogen along the line of sight, together constitute the most prominent spectral signature of very distant galaxies. This result has two important implications. First, it provides a means of identifying high-redshift galaxies. The spectra of high-redshift galaxies are characterized by (1) a complete absence of flux below the Lyman limit and (2) strongly absorbed flux in the Lyz forest. This spectral signature is observable by means of broad-band photometry and must apply irrespective of the underlying spectral properties of the galaxies because it is imprinted by intervening rather than intrinsic material. Second, it allows high-redshift interpretations of low-redshift galaxies to be...
Selections of high-redshift galaxies (I)

photometric redshifts based on broad-band SEDs

Finkelstein et al. (2015)
Selections of high-redshift galaxies (II)
two-color selections based on expected Lyα discontinuities

Bouwens et al. (2015)
The galaxy luminosity function at $z \gtrsim 6$

$\sim 1500$ galaxies from $\sim$ five deep fields

Finkelstein et al. (2015)
The galaxy luminosity function at $z \approx 6$

In conclusion, we find that a double-power law remains the best-fitting functional form to the data at $z=7.5$. Here the degeneracy between the faint-end slope and the characteristic magnitude results in a similarly satisfactory fit to the majority of the other data points. While there exists some relatively shallow steepening of the faint-end slope at the bright end, this is at the expense of a brighter characteristic magnitude by a factor of 2.5 compared to our data at the bright end, this is at the expense of this being due to contamination by low-redshift galaxies or brown dwarfs in the CANDELS 'wide' fields utilized (also see the recent determinations of the rest-frame UV LF at $z=7$ by Bouwens et al. (2015) and McLure et al. (2015)).

For LBG candidates at the bright-end of the faint-end slope and the characteristic magnitude found by previous studies (e.g. McLure et al. (2013), McLure et al. (2015) updated using the results of this work from McLure et al. (2015) and Finkelstein et al. (2015)), finding that the recent determinations of the rest-frame UV LF at $z=7$ by Bouwens et al. (2015) and McLure et al. (2015) are more, our results favour a smooth evolution in the characteristic magnitude by a factor of 2.5 compared to our data at the bright end, this is at the expense of this being due to contamination by low-redshift galaxies or brown dwarfs in the CANDELS 'wide' fields utilized.

The recent determinations of the rest-frame UV LF at $z=7$ by Bouwens et al. (2015) and McLure et al. (2015) are more, our results favour a smooth evolution in the characteristic magnitude by a factor of 2.5 compared to our data at the bright end, this is at the expense of this being due to contamination by low-redshift galaxies or brown dwarfs in the CANDELS 'wide' fields utilized.

For LBG candidates at the bright-end of the faint-end slope and the characteristic magnitude found by previous studies (e.g. McLure et al. (2013), McLure et al. (2015) updated using the results of this work from McLure et al. (2015) and Finkelstein et al. (2015)), finding that the recent determinations of the rest-frame UV LF at $z=7$ by Bouwens et al. (2015) and McLure et al. (2015) are more, our results favour a smooth evolution in the characteristic magnitude by a factor of 2.5 compared to our data at the bright end, this is at the expense of this being due to contamination by low-redshift galaxies or brown dwarfs in the CANDELS 'wide' fields utilized.

For LBG candidates at the bright-end of the faint-end slope and the characteristic magnitude found by previous studies (e.g. McLure et al. (2013), McLure et al. (2015) updated using the results of this work from McLure et al. (2015) and Finkelstein et al. (2015)), finding that the recent determinations of the rest-frame UV LF at $z=7$ by Bouwens et al. (2015) and McLure et al. (2015) are more, our results favour a smooth evolution in the characteristic magnitude by a factor of 2.5 compared to our data at the bright end, this is at the expense of this being due to contamination by low-redshift galaxies or brown dwarfs in the CANDELS 'wide' fields utilized.

For LBG candidates at the bright-end of the faint-end slope and the characteristic magnitude found by previous studies (e.g. McLure et al. (2013), McLure et al. (2015) updated using the results of this work from McLure et al. (2015) and Finkelstein et al. (2015)), finding that the recent determinations of the rest-frame UV LF at $z=7$ by Bouwens et al. (2015) and McLure et al. (2015) are more, our results favour a smooth evolution in the characteristic magnitude by a factor of 2.5 compared to our data at the bright end, this is at the expense of this being due to contamination by low-redshift galaxies or brown dwarfs in the CANDELS 'wide' fields utilized.

For LBG candidates at the bright-end of the faint-end slope and the characteristic magnitude found by previous studies (e.g. McLure et al. (2013), McLure et al. (2015) updated using the results of this work from McLure et al. (2015) and Finkelstein et al. (2015)), finding that the recent determinations of the rest-frame UV LF at $z=7$ by Bouwens et al. (2015) and McLure et al. (2015) are more, our results favour a smooth evolution in the characteristic magnitude by a factor of 2.5 compared to our data at the bright end, this is at the expense of this being due to contamination by low-redshift galaxies or brown dwarfs in the CANDELS 'wide' fields utilized.

For LBG candidates at the bright-end of the faint-end slope and the characteristic magnitude found by previous studies (e.g. McLure et al. (2013), McLure et al. (2015) updated using the results of this work from McLure et al. (2015) and Finkelstein et al. (2015)), finding that the recent determinations of the rest-frame UV LF at $z=7"
Uncertainties in the luminosity function

• photometry (matching apertures, deblending, etc.)

• contaminations (stars, low-redshift interlopers, etc.)

• cosmic variance

• sample selection (completeness, photometric redshift errors / errors in color selection)
Uncertainties in the luminosity function

- photometry (matching apertures, deblending, etc.)
- contaminations (stars, low-redshift interlopers, etc.)
- cosmic variance
- sample selection (completeness, photometric redshift errors / errors in color selection)
Uncertainties in photometric redshifts (I)

LETTER

A massive protocluster of galaxies at a redshift of \( z \approx 5.3 \)

- photo-z analysis restricted to \( z<6 \)
- uneven sampling in spectroscopic surveys

Capak et al. (2011)
Skelton et al. (2014)

3D-HST

Five deep fields with ~20 - 44 broad/narrow-band images in UV, optical, to IR
Uncertainties in photometric redshifts (I)

F160W detected objects in 3D-HST with
(1) updated $z_{\text{phot}}$ using latest EASY code w/o $z_{\text{max}}$
(2) $z_{\text{spec}}$ from our own literature searches

~3700 F160W-detected objects
Uncertainties in photometric redshifts (I)
Uncertainties in photometric redshifts (I)

- 3700 F160W-detected objects

Fraction of spectroscopic redshifts

- A highly incomplete and inhomogeneous spectroscopic sample!
Uncertainties in photometric redshifts (II)

Chen et al. (2003)
see also Drory et al. (2009)

systematic bias due to imprecise redshift

\[
P_i(m_i, z_i | M_*, \alpha) \propto \int_0^{z_f} 10^{0.4 [M_* - M_i(m_i, z')] (1+\alpha)} \times \exp(-10^{0.4 [M_* - M_i(m_i, z')]}) \times p_i(z_i - z'; z_i) \, dz'
\]
Uncertainties in photometric redshifts (II)

combined redshift error function using

$\sim 50$ F160W-detected objects at $5 < z_{\text{spec}} < 7$

The redshift error function is similar to the mean redshift likelihood function but with an underestimated missed fraction.
Summary

• High-z galaxy samples selected based on fixed color/photo-z cuts may have missed a significant fraction of the high-z population.

• Uncertainties in photometric redshifts are expected to result in flattening in the luminous end of the galaxy luminosity.

• A uniform spectroscopic survey of galaxies at $z > 6$ is needed and critical for calibrating and characterizing photometric redshift errors.