Probing Early Galaxies with the Hubble, Subaru, and ALMA Legacy Data

Masami Ouchi
University of Tokyo
Outline
• Recent observational progresses for early galaxies and reionization at a redshift up to $z \sim 10$.
  
  – Hubble+Subaru+Planck2016 const. on $Q_{\text{HII}}(z)$, $f_{\text{esc}}$ & $M_{\text{truc}}$
  – Hubble and ALMA measurements of morphology & ISM
  – On-going Subaru surveys

Robertson et al. (2010)
EARLY GALAXIES AND REIONIZATION
Hubble Frontier Fields (HFF)

- 6 clusters by deep Hubble ACS and WFC3-IR imaging (Lotz+16)
- Lensing magnifications for faint galaxies behind the clusters.

- 3 year program spending 840 orbits. Started from fall 2013.
  (Atek+14,15, Ishigaki+15, Oesch+15,McLeod+15,+16, Livermore+16...)
- On-going. 4/6 completed. The obs. continue until this summer.
Mass Models

100-200 multiple images for modeling w parametric lensing package (glafic; Oguri+10)
• 127 galaxies at z=6-10 identified by dropout technique, 18 out of which have $\mu>10$ (Kawamata +16)
UV Luminosity Functions

No flattening or break at the faint-end LF. No sig. of feedback effect down to \(-14\) mag at \(z \sim 7\).
Evolution of UV Luminosity Density

Ionizing photon emission rate

\[ \dot{n}_{\text{ion}} = \int_{-\infty}^{M_{\text{trunc}}} f_{\text{esc}}(M_{\text{UV}}) \xi_{\text{ion}}(M_{\text{UV}}) \Phi(M_{\text{UV}}) L(M_{\text{UV}}) dM_{\text{UV}} \]

\[ \rho_{\text{UV}} \]
Background: Ionizing Photon Shortage Not Serious?

- \( \rho_{\text{UV}} \) is decreasing to \( z \sim 10 \), while large WMAP/Planck2013 \( \tau_e \) suggests more ion. photons??
  - Problem of the ionizing photon shortage
- CMB estimate \( \tau_e \) decreases from \( \sim 0.09 \) to \( \sim 0.07 \) (Planck2015), to \( \tau_e = 0.058 \pm 0.012 \) (Planck2016)
  - \( \Delta \tau_e = 0.04 \) at \( z = 0-6 \) in ionized univ. \( \rightarrow \) Only the remaining \( \Delta \tau_e \sim 0.01-0.02 \) at \( z > 6 \) (Ishigaki15)
  - Ionizing photon shortage is no more serious problems. Worrying too many ionizing photons.
  - Strong physical constraints with Planck2016 and the HST res. Including an upper limit of \( f_{\text{esc}} \).
Evolution of UV Luminosity Density

Ionizing photon emission rate

\[ \dot{n}_{\text{ion}} = \int_{-\infty}^{M_{\text{trunc}}} f_{\text{esc}}(M_{\text{UV}}) \xi_{\text{ion}}(M_{\text{UV}}) \Phi(M_{\text{UV}}) L(M_{\text{UV}}) dM_{\text{UV}} \]

3 free parameters

\[ \rho_{\text{UV}} \]
Constraints on $f_{\text{esc}}$ and $M_{\text{trunc}}$

- $<f_{\text{esc}} \xi_{\text{ion}} > \sim 0.15 - 0.3$ (for log $<\xi_{\text{ion}} > = 25.2$). Note the upper limit of $f_{\text{esc}} < 0.3$
- $M_{\text{trunc}} \sim -13$

If the other ionizing sources (except Galaxies) give negligible contributions to ion phot. prod.
- Lya emitter (LAE) sensitive to neutral IGM: Subaru deep (106 hour integ.) large area survey
- At $z=7.3$, a comparable Lya lum. depth as previous lower-$z$ ($z=3-6$) survey (Konno+14).
- However, only 7 sources... $\sim 1/10$ of the expected number if no evolution from $z=6.6$. 

Konno, MO et al. (2014)
**Accelerated Evolution of Lya Luminosity at z>~7**

- Decreasing Lya LFs (and $\rho_{\text{Lya}}$) from $z=6.6$ even to 7.3. Moreover, the Lya LF (and $\rho_{\text{Lya}}$) is accelerated at $z>\sim 7$.
- No accelerated evol. of UV LFs($\rho_{\text{UV}}$) at $z\sim 7$
  - Likely by IGM scattering of Lya (cosmic reionization),
  $\rightarrow$the evolution of $Q_{\text{HII}}$ is rapid at $z\sim 7$

---

Konno, MO et al. (2014)
Reionization History and CMB $\tau_e$

- $Q_{\text{H II}}$ estimates from the accelerated Lya evolution.
  - Prefer moderately low $Q_{\text{H II}}$ at $z \sim 7$. Late reionization.

Consistent Results of $Q_{\text{H II}}(z)$ and Ionizing Sources, $\tau_e$, $f_{\text{esc}}$, $M_{\text{trunc}}$
MORPHOLOGY AND ISM
• Average Sersic index for ~190,000 SF gals-> n=~1.5 (disk-ish)
  Corrected for SB dimming effects by fitting
  
  \[ r_e \propto (1 + z)^{-1.12 \pm 0.06} \]
z=0

Milky Way

M82

z=9

Galaxy (Average)

Ono et al. 2012

NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

c) Shogakukan
• $f_{\text{clumpy}} \equiv N_{\text{clumpy}} / N_{\text{all}}$: Majority of $\sim L^*$ galaxies at $z \sim 2$ have clumps (see +Guo+14)
• Evolution of $f_{\text{clumpy}}$ follows the trend of the SFRD evolution
• Consistent with violent disk instability (VDI) scenario (Keres+05,+09)?

Shibuya, MO+16

Clumpy Galaxies

L=0.3-1 L*
• $\Sigma_{\text{SFR}}$ increases towards high-z by the size evol.
• Intensive star-formation in a small vol. ISM change?

Shibuya, MO, Harikane+15
Deficit of [CII]158um emission (Ouchi+13,Ota+14,Knudsen+16; cf. Capak+15)

Detection of [OIII]88um, but no [CII]158m (Inoue+16).

→ High ionization state of ISM (consistent w CIII]+CIV det.:Stark+15,+16; Maseda’s talk)

Inoue et al. (2016)
ON GOING SUBARU SURVEYS
Subaru Hyper Suprime-Cam (HSC) Survey

- Subaru optical imager Hyper Suprime-Cam (HSC)
  - Subaru/HSC survey has started since March 24, 2014 under the collaboration of JP/US/TW.
  - ~1/3 of observations are completed.
• SHMR at $10^{11}\text{M}_{\odot}$ decreases from $z=0$ to $z\sim 4$, and increases to $z\sim 7$
• Signature of feedback efficiency change??
HSC Survey z~6-7 LAEs (On-Going)

- Goals: LAEs at z=5.7, and 6.6 in 30 deg$^2$ (and z=7.3 in 3 deg$^2$).
  - Expecting ~20,000 LAEs (hundreds of Lya blobs) down to L(Lyα)~3x10$^{42}$erg/s

- Now:
  - Shallow data only (~20 deg$^2$ data for z=6.6 LAEs and ~5 deg$^2$ data for z=5.7 LAEs)
  - Several rare bright LAEs, like Himiko, CR7, and COLA1 are identified (w spec. conf.).
  - Faint AGN and galaxy contribution?
Summary

• The HST, Subaru, and ALMA study results of Early galaxies and reionization up to z~10.
  – Hubble+Subaru+Planck2016 const. on $f_{\text{esc}}$ $M_{\text{truc}}$ & $Q_{\text{HII}}(z)$
    • $<f_{\text{esc}}>$~0.15-0.3
    • No truncation found in LFs. The statics also infers $M_{\text{trunc}}$ > -13
    • $Q_{\text{HII}}(z)$ of Subaru LAE suggests moderately high HI frac at z~7-8
      → Self-consistent picture of reion history and ionizing photons.
  – Hubble and ALMA constraints on morphology and ISM
    • More compact galaxies towards high-z: $r_e \propto (1+z)^{-1.1}$
    • Clumpy galaxy fraction peaks at z~2, and decreases towards z~8
    • High $\Sigma_{\text{SFR}}$. ALMA [CII]158um deficit and [OIII]88um detections
      Suggestive of high ionization state.

– On-going Subaru surveys
  • $M_*/M_h$ ratio upturn(z>~4) Signature of feedback efficiency change?
  • Large area HSC LAE survey identifying high EW(Lya) objects