

(NASA)

(Serving Suggestion)

D.P. Stark, A. Loeb, and R.S. Ellis 2007. An empirically calibrated model for interpreting the evolution of galaxies during the reionization era. *ApJ* **668**, 627-642.

Motivations

There are now observations of star-forming galaxies at $z \sim 6$ (still in the Universe's first ~ 0.5 Gyr).

What was their distribution, and what effect did they have on/how were they affected by reionization?

What about galaxies back to $z \sim 7-10$? How abundant might they be, and how might they be best detected (preferably sooner than when JWST becomes available)?

Background

Reionization era: radiation from earliest generations of stars reionized most of the H in the Universe by $z \sim 6$

Lyman-break galaxies (LGBs): named for the high redshifting of the hydrogen gas within them and its absorption band migration into the visible; more a sort of definition by means of detection than by anything particularly “exotic” about them

Lyman- α emitters (LAEs): named for strong emission of Ly α into the IGM, presumably from high star formation rates

Model Assumptions

- Star formation in galaxies at $z \geq 6$ due to dark matter halo coalescence
- Mean age of stars is independent of halo mass
- One galaxy per halo
- Model parameters for best fit to observations at $z \sim 5-6$ are still mostly valid for $z \sim 7-10$ (they're really trying to keep it simple!)

Star formation rate in high-z galaxies

$$\dot{M}_\star(M_{\text{halo}}) = \frac{f_\star (\Omega_b / \Omega_m) M_{\text{halo}}}{t_{\text{LT}}}$$

\dot{M}_\star : star formation rate

M_{halo} : halo mass

f_\star : star formation efficiency

Ω_b / Ω_m : (universal value) ratio of baryons to total halo mass

t_{LT} : star formation timescale, related to the...

ϵ_{DC} : star formation duty cycle; leads to the timescale

(*example given: ϵ_{DC} of 20% at $z \sim 6 \rightarrow$ to a star formation lifetime ~ 200 Myr)*)

Need to balance star formation efficiency and duty cycle!

Luminosities of high-z galaxies

$$L_{\text{Ly}\alpha} = \frac{2}{3} h\nu_{\text{Ly}\alpha} N_{\gamma} T_{\text{Ly}\alpha} (1 - f_{\text{ip}}) \dot{M}_{\star}$$

Ly α luminosity is related to halo mass and star formation rate.

N_{γ} : number of ionizing photons

$T_{\text{Ly}\alpha}$: fraction of Ly α photons that reach the intergalactic medium (IGM)

$(1 - f_{\text{ip}})$: fraction of ionizing photons that do not reach the IGM

Supernova feedback

$$\eta(M_{\text{halo}}) = \begin{cases} f_{\star} \left(\frac{M_{\text{halo}}}{M_{\text{halo,crit}}} \right)^{2/3}, & M_{\text{halo}} < M_{\text{halo,crit}} \\ f_{\star}, & M_{\text{halo}} > M_{\text{halo,crit}} \end{cases}$$

A more complex model factors in “supernova feedback.”

η : star formation efficiency

$M_{\text{halo,crit}}$: “critical” mass at which η can begin to decrease, due to supernovae. Supernovae can decrease star forming efficiency, especially in already lower mass galaxies.

(This causes nothing but trouble later on, but cannot be disregarded)

Star-forming regions in halos

$$r_{\text{vir}} = \left[\frac{GM_{\text{vir}}}{100H^2(z)} \right]^{1/3}$$

r_{vir} : halo virial radius (stellar region)

M_{vir} : halo virial mass

Hubble constant at redshift z :

$$H(z) = H_0 [\Omega_{\Lambda,0} + (1 - \Omega_{\Lambda,0} - \Omega_0)(1 + z)^2 + \Omega_0(1 + z)^3]^{1/2}$$

Cosmic variance

= *<http://cosmicvariance.com>*

Cosmic variance

[How /] Does reionization affect the evolution of galaxies at $z \sim 7-10$?

Cosmic variance: determining the uncertainty in source counts at a target z and in the sample volume. Some process affecting counts in that volume may or may not be confined to that volume. Naturally, more samples/surveys in multiple directions can narrow the uncertainties.

Galaxy clustering in dense regions can cause fluctuations in counts (cosmic variance) – one needs to estimate/model the dark matter halo distribution, and the galaxies' effects on the IGM and reionization's effects on the galaxies.

Cosmic variance

$$\tilde{W}(k_x, k_y, k_z) = \frac{\sin(k_x a_x/2)}{(k_x a_x/2)} \frac{\sin(k_y a_y/2)}{(k_y a_y/2)} \frac{\sin(k_z a_z/2)}{(k_z a_z/2)}$$

$$\sigma^2(r) = \int P(k) \tilde{W}^2(k) d^3k$$

\tilde{W} : “window function” for figuring the variance for narrowband surveys (for Ly α emitters), in k -space

$\sigma^2(r)$: variance (of dark matter)

$P(k)$: “power spectrum of density fluctuations extrapolated to $z = 0$ as a function of wavenumber k ”

Effects of variance on surveys

For the Subaru Deep Field (SDF) survey, variance still leaves a $\geq 90\%$ certainty in the counts (number of galaxies).

For LBGs (Hubble UDF, HST/CXO GOODS), the variance leaves greater uncertainty in galaxy counts in the UDF due to the smaller volume sampled.

TABLE 1
VARIANCE IN HIGH- z GALAXY SURVEYS

Field	Type	Field of View (arcmin ²)	z	$L_{\text{Ly}\alpha c}$ (ergs s ⁻¹)	L_{1500} (ergs s ⁻¹ Hz ⁻¹)	$\sigma_{\text{F2F}}^2(L_c)$
GOODS.....	Dropout	160	6	N/A	$10^{28.0}$	0.002
UDF.....	Dropout	11	6	N/A	$10^{28.2}$	0.03
SDF.....	Narrowband	1295	5.7	$10^{41.7}$	N/A	0.001
Cluster.....	Spectroscopic lensing	0.13	8.5–10.4	N/A	N/A	N/A

NOTES.—The field of view for the spectroscopic lensing survey is in the source plane, assuming a median magnification of 10. The crossover luminosity is listed as “N/A” for the lensing survey because the clustering fluctuations are greater than the Poisson noise for all luminosities over which our model predicts sources should be detected.

Effects of variance on surveys

Variance in lensed long-slit spectroscopic surveys: difficult to determine; more complicated geometry of the sampled volume than the parallelopipeds used to approximate the previous two cases.

Near-IR surveys may work for detecting galaxies at $z \sim 10$, but the variance is going to cause greatest uncertainties in those

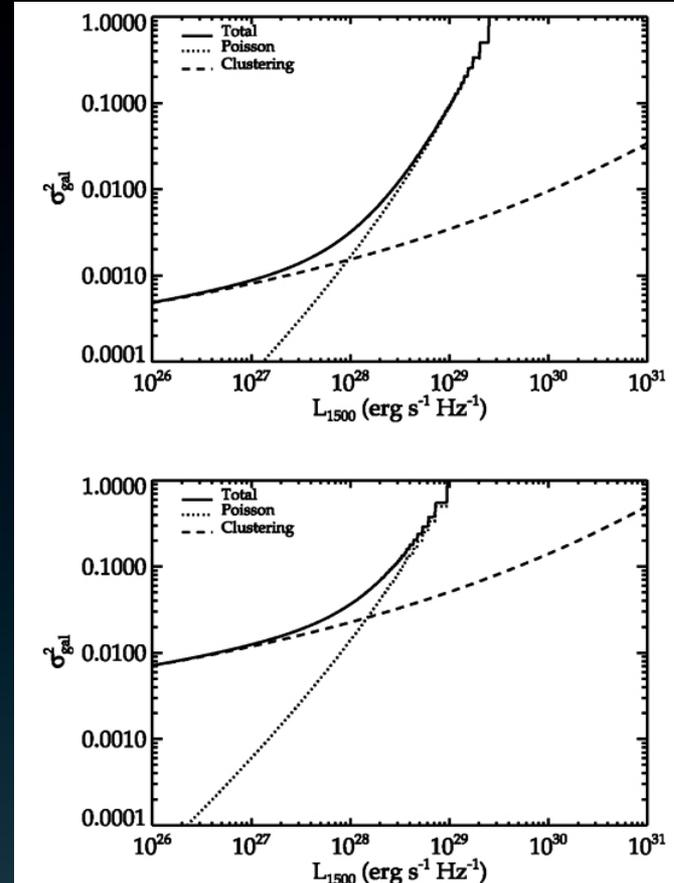


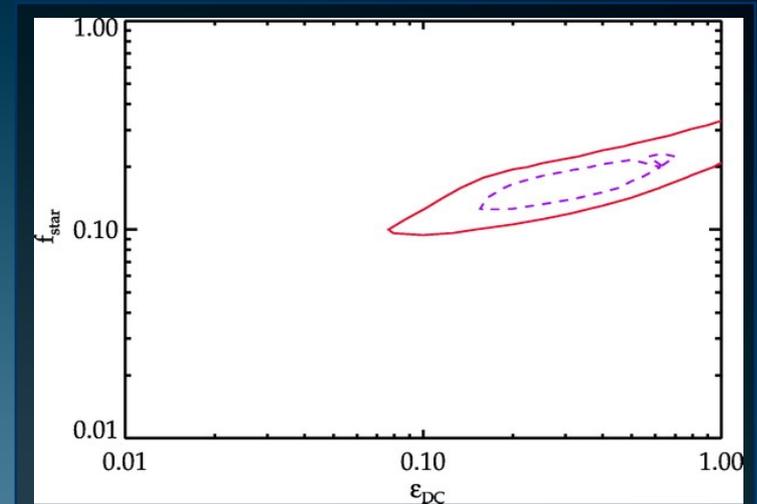
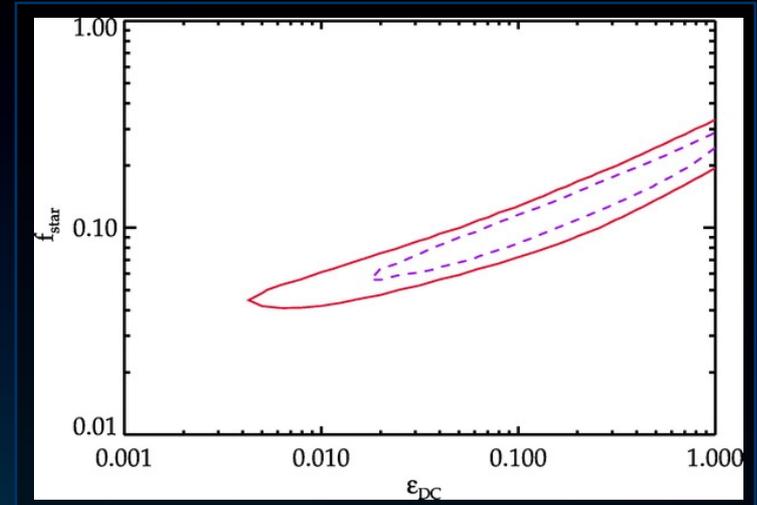
FIG. 2.—Variance in dropout LBG survey. The total variance (solid line) is the sum of the variance from Poisson noise (dotted line) and clustering fluctuations (dashed line). In the case of a survey such as the *HST* GOODS observations of the CDF-S and HDF-N (limiting luminosity of 5×10^{28} ergs s⁻¹ Hz⁻¹), the clustering fluctuations of $z \sim 6$ LBGs are greater than 6% (top). In the UDF (limiting luminosity of 8×10^{27} ergs s⁻¹ Hz⁻¹), clustering fluctuations result in a slightly higher uncertainty of $\geq 15\%$ – 20% (bottom).

Model calibration

Created a grid of LBG luminosity functions by varying star formation efficiency and duty cycle; found the closest match to observations for $z \sim 5-6$ ($\epsilon \approx 0.2$, $f \approx 13\%$)

Can we assume that's still applicable to $z \sim 7-10$?

(The bottom plot includes the estimated SN feedback effect)



Model calibration and LBGs, LAEs

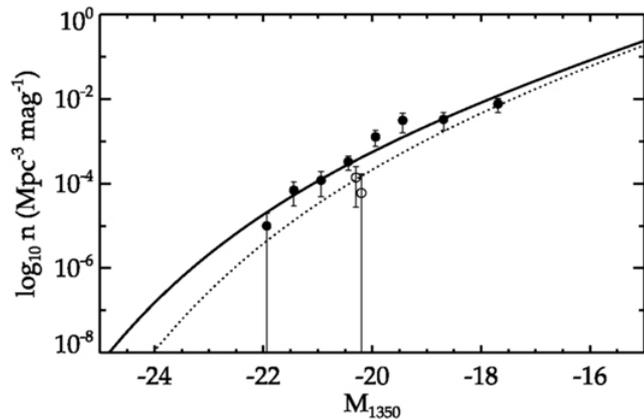


FIG. 5.—LBG luminosity function at $z = 6$ (solid line) and $z = 7.6$ (dotted line) obtained using the model parameters that maximize the likelihood at $z = 6$. The filled and open circles correspond to observed LBG abundances at $z = 6$ (Bouwens et al. 2006) and $z = 7.6$ (Bouwens & Illingworth 2006), respectively. The two data points at $z = 7.6$ (offset horizontally for clarity) correspond to more and less conservative selections of z -dropouts in Bouwens & Illingworth (2006). While there is not yet much data at $z = 7.6$, the existing data at these two redshifts can be fitted without any evolution in the fit parameters f and ϵ_{DC} .

Best fit curves to observations of
 LBGs at $z = 6, 7.6$ (left)
 LAEs at $z = 5.7, 6.5$ (right)

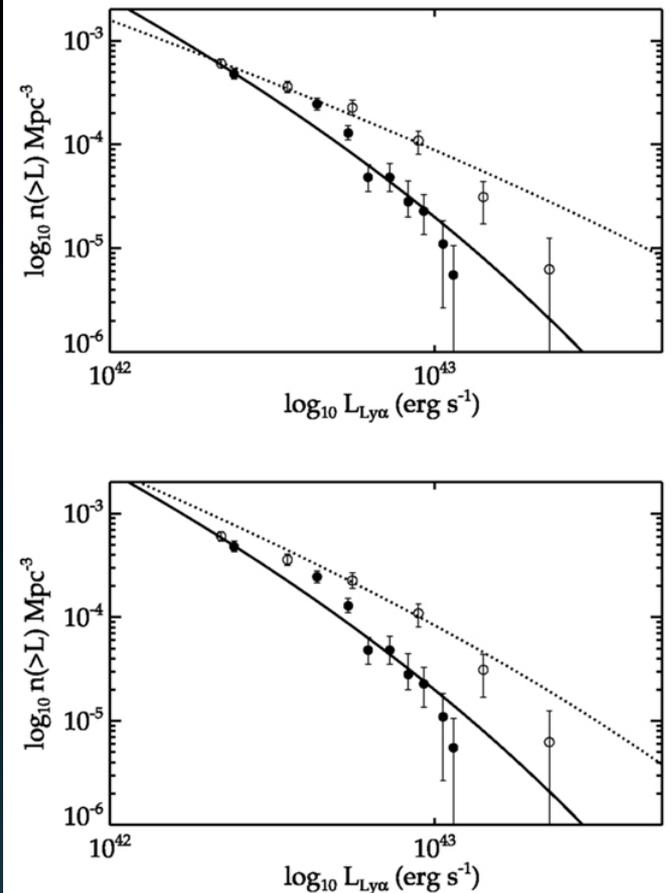


FIG. 7.—Top: $\text{Ly}\alpha$ luminosity function at $z = 5.7$ (dotted line) and $z = 6.5$ (solid line) obtained using the model parameters that maximize the likelihood. Open and filled circles are observed abundances at $z = 5.7$ from Shimasaku et al. (2006) and at $z = 6.5$ from Kashikawa et al. (2006), respectively. Bottom: Same as the top panel, but for best-fitting parameters to model that now include a simple prescription for supernova feedback.

Model calibration and LBGs, LAEs

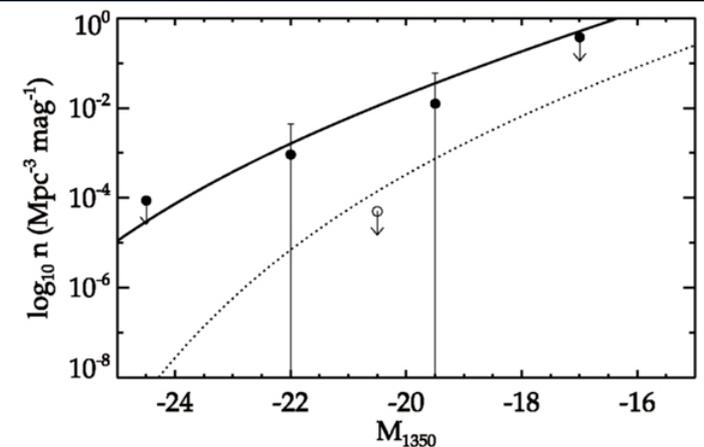
- Suggests that star formation efficiency and lifetime increased from $z = 6.5$ to $z = 5.7$.
- The masses in stars of the brightest LAEs may be 10^7 - $10^8 M_{\text{Sun}}$; brighter ones are less massive?
- By comparison they suggest LBGs have stellar masses 10^8 - 10^{10} . This may be due to their younger age (not enough time to form as many stars) or the lack of formed dust to absorb Ly α and lower the outside transmission.
- As it ages, a LAE may increase the galaxy's dust content sufficiently to absorb more Ly α , or clear out dust (by way of SNe, AGNs); but this also decreases star formation – the object eventually ceases being a “LAE.”

Model predictions for high redshift ($z \sim 7-10$)

Extended model from fitting observations at $z \sim 5-6$ to predicting what may be found at $z \sim 7-10$ (with a little support from possible observations of sources at $z \geq 7$)

Keep the simplification that the same model parameters apply to dark matter halos evolving between $z = 5-10$; the evolution of luminous LBGs between $z \sim 6-10$ may not be due to significant changes in star formation efficiency or duty cycle, but to general halo growth.

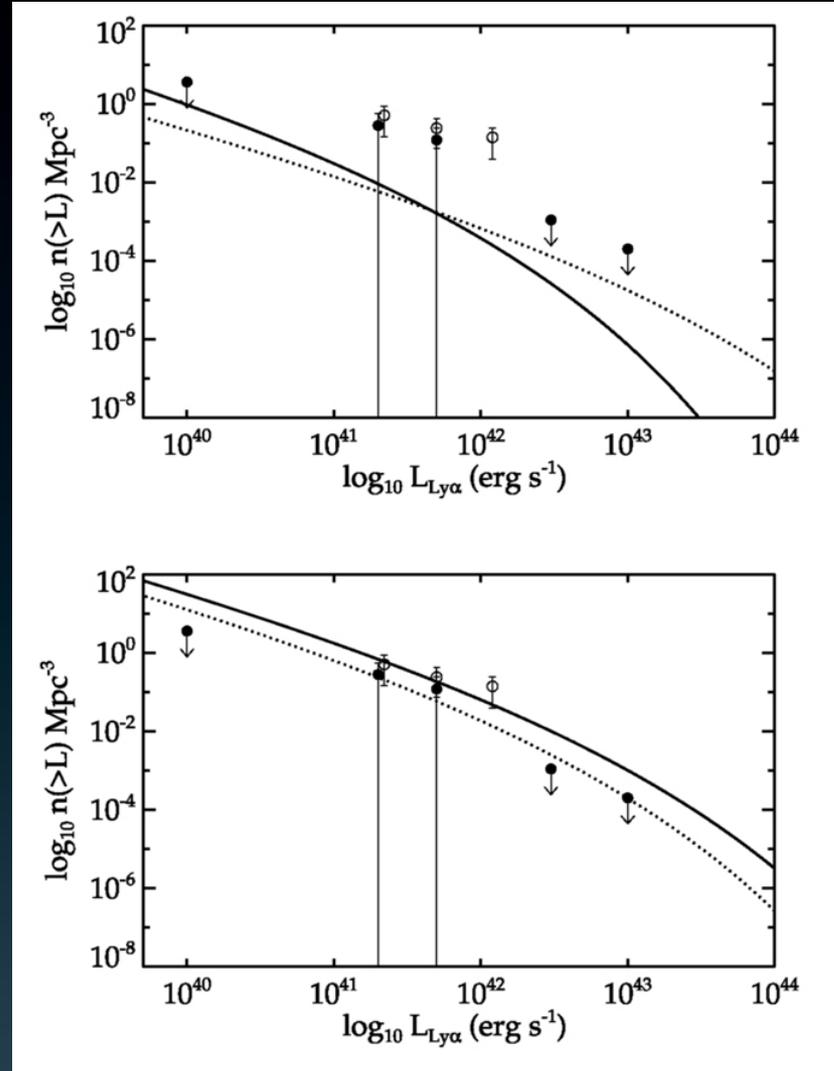
Predicted number of luminous LBGs at $z = 9$, based on fit to several candidate high- z LBGs



Model predictions for high redshift ($z \sim 7-10$)

Model fit based on as-yet uncertain detection of LAEs at $z = 9$.

- The better fit on the bottom suggests the sources detected are likely at a lower z .
- For them to be at $z = 9$ might require either an unrealistically high star formation efficiency (100%!) or a model revision to allow for a top-heavy IMF.



Implications for future surveys

This simplified model cannot predict with great confidence the actual number of luminous sources detectable at higher z (7-10).

The authors hope their model is useful in designing instruments and/or deciding the scope of future surveys (depth, volume, integration time, *etc.*).

Implications for future surveys

VISTA (Visible and IR Survey Telescope for Astronomy): possibly online later this year

WFC3 (Wide Field Camera; near-IR): on HST; coming in 2008

- Authors predict WFC3 would require several hundred hours of collection to get even one LBG (at J or H-band magnitudes of ≤ 31.3 and ≤ 29.5 , *resp.*) at $z \sim 10$ (plenty more at lower z).

Implications for future surveys

DAZLE (Dark Ages z Ly- α Explorer): narrow band VLT imager for surveys at z 6.5-12

- Model prediction based on estimated survey volume needed to detect one LAE (with luminosity 1.5×10^{42} erg/s) at z = 7.7 (it could detect more at lower z, like 6.5)
- Large uncertainty due to high expected variance.
- If the candidate high-z sources just shown are genuinely high-z, you'd get more (possibly ≥ 100). Will still likely require integration times of ~70-80 hrs.
- SN feedback could lower this substantially.

Implications for future surveys

MOSFIRE (Multi-Object Spectrograph for IR Exploration): to be installed on Keck 1 (10m); for a lensing survey

- Could detect 9 LAEs with $L > 10^{40.5}$ ergs/s at $z = 7.5$ and 4 at $z \approx 10$ — but, again, SN feedback could lower this substantially (to one or two at 7.5, and none at 10)
- Using HST's WFC3 for a lensing survey instead, assuming integration time of 350 hrs, they predict 82 LBGs at $z = 7.5$ and 6 at $z = 10$ (working with ~ the same magnitudes as the previous calculation)

GSS (Gemini Genesis Survey): with adaptive optics, may yield up to 30 LAEs at $z \sim 8-10$ if, again, the previous LAEs are genuinely high- z (otherwise, it may still be 3-7 sources detected, or fewer with SN feedback factored in)

Conclusions

Just hang in there for JWST – it'll solve everything!

Conclusions

- Model parameters are good at least for $z \sim 5-6$. Seeing whether they hold for $z \sim 7-10$ will require more observations (and/or confirmation of tentative observations). It may still inform proposed surveys for high- z objects.
- Model parameters may need to be adjusted to account for significant evolution between $z \sim 10$ and $z=6$.
- Clustering variance is a greater concern for lensing surveys than for more direct surveys for LAEs or LBGs.
- Supernova feedback may render present or soon-online instruments unable to detect high- z sources, and we'll just have to wait for the next generation of instruments.

Conclusions

The empirically calibrated model for interpreting the evolution of galaxies during the reionization era is not for everyone; ask your doctor if the empirically calibrated model for interpreting the evolution of galaxies during the reionization era is right for *you*.

Conclusions

Women who are pregnant, nursing, or may become pregnant should not use the empirically calibrated model for interpreting the evolution of galaxies during the reionization era.

Conclusions

Do not taunt the happy fun empirically calibrated model for interpreting the evolution of galaxies during the reionization era.

Questions?

