HUNTING THE FIRST GALAXIES

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WHY STUDY THE DISTANT UNIVERSE?

- Why do we want to study galaxies in the distant universe?
  - When and how did the Hubble sequence assemble?
    - The Hubble sequence is in place by $z = 1-2$, but when we look further back, galaxies appear very different.
  - When did the first galaxies form?
    - We keep looking further back, and we keep finding galaxies.
  - How does the chemical evolution of the universe proceed?
    - Will we ever find Population III stars?

- These are just some of the most fundamental questions in astrophysics today.
I’ll start with a review of high redshift galaxies, including our current knowledge.

Focus on one goal for the type of high-z science I’d like to do with GMT:

- Confirm the redshifts of $z > 6$ galaxies (and constrain reionization).

- This goal requires a large field-of-view, multi-object, moderate resolution spectrograph in the near-infrared (i.e., NIRMOS).
• Lyman break galaxies: Selected on the basis of a spectral break at 912/1216 Å due to IGM absorption.

• Tens of thousands discovered over $3 < z < 6$; are heavily star forming, but somewhat evolved:
  • SFR $\sim$ 10’s of $M_\odot$/yr; $M \sim 10^{10} M_\odot$ (at $L^*$), $t \sim 100$’s of Myr, $A_V \sim 0.2$ - 1.0 mag.

• Lyman alpha emitters (LAEs): Selected on the basis of a bright Ly$\alpha$ emission line, typically via narrowband imaging.

• 100’s/1000’s discovered - originally thought to be a hallmark of the first galaxies in formation.

• Narrowband selected LAEs are less evolved; SFR $\sim$ 1-10 $M_\odot$/yr; $M \sim 10^{8-9} M_\odot$, $t \sim 1$-100 Myr, $A_V \sim 0$ - 0.2 mag.

• The presence of dust in many LAEs implies they are not the first galaxies.
Galaxies at $z < 6$ do not appear to represent the first galaxies.

Will pushing to higher redshifts find them?

At $z \geq 7$, the Lyman break shifts past 1 $\mu$m, where sky emission causes difficulties.

Ground-based near-infrared broadband studies have had difficulty discovering large samples of LBGs (e.g., Ouchi+09, Castellano+10).

LAEs could be easier to find by placing ultra-narrowband filters between sky lines: gaps corresponding to $z = 7.7$ & 8.8.

Many ongoing or planned projects: DaZle, ELVIS, Dark Ages Survey.

All only one-band detections.
We’ve gotten to the point where ground-based selection is difficult.

Thanks to the IR channel of WFC3, we can push to $z > 7$.

- HUDF09: 192 orbits in the HUDF plus two parallel fields (PI Illingworth).
- ERS: 10x2 WFC3 pointings in GOODS-S (WFC3 SOC).
- CANDELS: ~800 WFC3 orbits over GOODS-S/N, COSMOS, EGS and UDS (PI Faber & Ferguson).

Currently, the HUDF09 and ERS data has led to the first discovery of large samples of $z \sim 7$ ($z'$-drop) and $z \sim 8$ ($Y$-drop) candidate galaxies (e.g., Bouwens et al. 2010abc; Oesch et al. 2010; Finkelstein et al. 2010; McLure et al. 2010, 2011).
• We followed this up with our own study in the HUDF (Finkelstein et al. 2010).

• Goal: to study galaxy stellar population properties.

• Sample selected via photometric redshifts.
Examined the rest-frame UV colors.

- The average color of all $z \sim 7$ galaxies is significantly ($> 4\sigma$) bluer than typical local starbursts.
  - Likely dominated by reduced extinction, but could also be lower metallicities.
- The average color of the faintest galaxies is $\beta = -3!!$
  - However, the uncertainties are large and the sample is small, thus these galaxies are consistent with very blue local galaxies (i.e., NGC1705).

- We studied the stellar masses of these galaxies via SED fitting, and found that they continue the decline in typical mass first seen at lower redshifts.
  - Galaxies at $z > 7$ are more similar to LAEs than LBGs at $z < 6$. 

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Monday, March 14, 2011
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Are these the first galaxies?

Likely not, but they look to be less evolved than even galaxies at $z \sim 6$, thus we appear to be getting closer.
By adding up the rest-UV fluxes of our objects, we examine how they would contribute to the ionizing budget necessary for reionization.

- Circles are observed galaxies, triangles are corrected for galaxies below our survey limit.
- If one assumes low clumping factors (Pawlik+09; Finlator+09), then the observed galaxy populations can sustain reionization for large escape fractions (~ 50%).
  - Might be reasonable given escape fraction trends from z=1 - 3 (Siana+10).
THE NEXT STEPS...

- Currently published $z > 7$ samples range from $\sim 5 - 100$ galaxies.

- CANDELS will discover $> 500$ $z > 7$ galaxies, greatly adding to our knowledge of the $z > 7$ universe.

- However, these galaxies all remain candidates until spectroscopically confirmed.

- Currently, we only have estimates of the contamination fraction and redshift distribution of these galaxy samples.

- Both contribute to the uncertainties on the luminosity functions, and thus our ability to use them to constrain reionization.
WE REQUIRE SPECTROSCOPY!

- The most promising method to spectroscopically confirm these galaxies resides with detecting Lyα emission.
  - The observed star-forming properties of galaxy candidates at \( z > 7 \) in the HUDF implies that most have intrinsic Lyα fluxes \( \approx 2 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \).
  - Nearly impossible with current telescopes and instrumentation.
    - All but a few NIR spectrographs are limited to single-objects observations (MMIRS & MOIRCS; soon MOSFIRE, FMOS and KMOS).
  - However, if the IGM becomes more neutral from \( z=6-7 \), then the Lyα EW distribution will change, and Lyα could be even harder to see.
    - Spectroscopic observations will thus place strong constraints on the neutral fraction of the IGM.
CURRENT SPECTROSCOPIC RESULTS

- Of course, the galaxies in the HUDF are from a small volume, and so are mostly too faint for current observatories.
  - Groups have tried to confirm brighter $z > 7$ galaxies from ground-based and HST surveys.
  - We currently know of 3 galaxies with $z_{\text{spec}} > 7$:
    - $z=7.01, 7.11$ (Vanzella+11).
      - $\text{EW}_{\text{rest}} = 64, 50$ Å
    - $z=8.56$ (Lehnert+10).
      - $\text{EW}_{\text{rest}} = 200$ Å!!
  - Fontana et al. (2010) observed 7 $z \sim 7$ galaxies, and only detected one (at $z=6.97$), leading them to the conclusion that the neutral fraction has significantly evolved.
WHAT CAN GMT DO?

- The Near-Infrared Multi-Object Spectrograph (NIRMOS) will be a key instrument to unlock the high redshift universe.

- Current telescopes, even with upcoming multi-object NIR spectrographs, will be unable to spectroscopically confirm the bulk of the $z > 7$ galaxy population.

- Take the Lehnert et al. galaxy as an example.
  - $f_{\text{Ly}\alpha} = 6 \times 10^{-18}$ in 15 hours with SINFONI on the VLT!
  - In the same exposure time, NIRMOS can obtain a $\sim 100\sigma$ detection.
  - Can reach this line flux at $5\sigma$ in just a few minutes.
WHAT CAN GMT DO?

- What about fainter galaxies?
  - Let’s examine an observing scenario for the year 2019...
  - CANDELS has been completed, and has discovered numerous $z \sim 7 - 8$ galaxy candidates, as promised.

I’d like to follow-up CANDELS $z > 7$ galaxy candidates with the GMT!
Only the brightest few $z > 7$ galaxies will be confirmed with 8-10m class telescopes, thus conclusions on reionization, etc., will be tenuous.

- CANDELS should find ~ 240 galaxies at $z_{\text{phot}} > 6.5$ in GOODS-S.
WHAT CAN GMT DO?

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- CANDELS should find ~ 240 galaxies at $z_{\text{phot}} > 6.5$ in GOODS-S.
  
- Using the empirically derived $z \sim 7$ Ly$\alpha$ EW predictions of Stark et al. (2011) along with the “observed” magnitudes and calculated photo-z’s, we can predict what the Ly$\alpha$ line flux distribution should be for this sample.
Distribution peaks at $f_{\text{Ly}a} \sim 5 \times 10^{-18}$.

Current telescopes can only efficiently reach $10^{-17}$ (at $5\sigma$).

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- Miss the bulk of the galaxy population.

In just ~ an hour, NIRMOS will reach $\sim 1 \times 10^{-18}$ (at 5σ).

- Should detect > 90% of the covered CANDELS galaxy sample.

Want to be more conservative?

- Get to $5 \times 10^{-19}$ in ~ 4 hours.
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**WHAT CAN GMT DO?**

One night on GMT with NIRMOS:

Four masks, ~ 1-1.5 hours per mask.

Yield: ~ 150-200 spectroscopically confirmed $z \sim 7-8$ galaxies.
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Or many more w/ MANIFEST (provided fibers don’t cause a significant throughput hit)
CAVEATS...

- This scenario assumes that the IGM is primarily ionized.
  - If it is neutral it could substantially attenuate the Lyα fluxes.
    - Unless the majority of galaxies are able to ionize their surroundings, or the majority of escaping Lyα is redshifted due to outflows.
  - This is where it gets interesting...
    - What if we see less galaxies?
      - Then we’ll have the first hard constraints on the rising neutral fraction in the IGM!
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Distribution of expected number of galaxies using the predicted $z \sim 7$ equivalent width distribution.

$N_{\text{gal}} = 104 \pm 17$
What about as-yet undiscovered galaxies?

- JWST should discover galaxies out to \( z \sim 12 \) and possibly higher (if they exist).
- Assuming factor of 3 fainter intrinsically (\( d_L \)), and another factor of 2 fainter due to an increasingly neutral IGM.
  - \( f_{\text{Ly}a} \sim 2 \times 10^{-19} \)
  - \( 5\sigma \) achievable in \( \sim 20 \) hours.
- Beats both JWST \( R \sim 100 \) and \( R \sim 1000 \) modes.
**CONCLUSIONS**

- Current telescopes and NIR spectrographs only have the ability to spectroscopically confirm the very few brightest galaxies at $z > 7$.
  - And they do it very inefficiently.
- NIRMOS on the GMT will allow the first large scale spectroscopic surveys in the reionization epoch.
  - Crucial to trace the evolution of the neutral fraction in the IGM
    - As well as the contamination and redshift distribution, which are important for just about everything we study (luminosity function, colors, etc.).
- NIRMOS will also allow insight into these most distant of galaxies by studying similar objects at lower redshift via rest-frame optical emission lines.
  - Again, current instrumentation is not sufficient to build a large statistical sample, thus we will have to wait for the GMT, and hopefully NIRMOS.
• Broadly, $z\sim7-8$ galaxies have more in common with $z = 2-6$ LAEs than LBGs.

• Can learn about $z \sim 2-3$ LAEs via rest-frame optical emission lines.

• We have begun doing this with $z \sim 2$ galaxies discovered in the HETDEX pilot survey.

• These LAEs appear very low metallicity.
These observations were very time consuming; one night on Keck with NIRSPEC to study three galaxies (only detecting two).
And, the two we did detect were very bright in Ly$\alpha$ ($3 - 6X L^*_{Ly\alpha}$).
1.5 hr with Keck/NIRSPEC

1.5 hr with GMT/NIRMOS

6 $L^*_{Ly\alpha}$
0.2 $L^*_{\text{Ly} \alpha}$ in 12 hours.
Not only will GMT/NIRMOS allow much fainter flux limits, but the multiplexing capability will allow the construction of large statistical samples of LAEs/LBGs (or whatever you want to study!).