Densely Sampling the High Redshift Universe

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Galaxy Formation in Cosmological Context

- CMB, supernovae, and a host of other astrophysical techniques have presented strong evidence for a spatially flat, low-density universe dominated by cold dark matter (CDM) with:
  - $\Omega_m \sim 0.27$ (of which $\sim 15\%$ is baryonic)
  - $\Omega_\Lambda \sim 0.73$ (“Dark Energy”)
  - $H_0 \sim 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (current expansion rate)
  - normalization/shape of initial matter fluctuation power spectrum
  - Age $\sim 13.7 \text{ Gyr}$

- Since galaxies have grown by gravitational instability, and dark matter apparently has very simple properties, galaxy formation should be entirely predictable.
Hubble Deep Field, 1996
The "Cosmic Web"

Quasar

Quasar Spectrum

Observer

Hydrogen Gas

Carbon
Why Bother With High Redshift?

>50% of the stars in the present-day universe formed in the interval 3.5 > z > 1.5

Can watch all of the effects that shaped the present-day universe while they were happening

Reddy et al 2007
Star Formation/Black Hole Accretion History of the Universe

Reddy et al 2007

Schmidt et al 1995

Blue points: UV Determinations
Red points: IR Determinations

Galaxies

Bright Quasars
The Star Formation History of the Universe

The Dark Ages

You are here

The enlightenment?

Billion Years Ago 11 14
Tools Needed:

• large ground-based telescope with good spectrographs (especially in the UV/blue and near-IR)
  • Keck: HIRES, LRIS-B, ESI, NIRSPEC all play a significant role
  • Also: P200, Spitzer, HST, Chandra
• Objects just “behind” the volumes/epochs you’d like to study, with plenty of UV flux (QSOs OR galaxies)
• Galaxies within a controlled volume that are easily observed spectroscopically. Precise spectroscopic redshifts are essential.
• The redshift range ~1.8-3.5 is particularly fortuitous:
  • IGM has available dynamic range (important!)
  • arguably the most “exciting” time for star formation, formation of supermassive black holes
Using optical (rest-UV) and near-IR (rest optical) to quantify physical properties of z~2-3 galaxies

Optical spectra:
- IMF
- stellar photospheric abundances
- ISM metallicity
- ISM kinematics

Near-IR spectra:
- Kinematics/dynamical masses
- Ionized gas metallicity
- SFR estimate
- (cold) gas mass estimates
- precise redshifts!
Starburst-driven “Super-Winds”

- Each (core-collapse) SN produces $\sim10^{51}$ ergs of kinetic energy
- Combined effect of many SNe in small volume drives a galaxy-scale “wind”
- Cooler material entrained in hot shocked material travels outward at several hundred km/s
- Mass flux of outflowing material often exceeds the amount of gas being converted into stars
Far-UV Spectra: Gas Flows

Composite spectra of $z \sim 2-2.6$ UV-selected galaxies

Velocity profiles in selected transitions relative to $z_{\text{sys}}$
GALACTIC SCALE OUTFLOW

$M_{\text{out}} \geq 80 M_\odot \text{yr}^{-1} \geq M_{\text{in}} \approx 40 M_\odot \text{yr}^{-1}$

2.5 x $10^5$ stars

$v_- = 250 \text{ km s}^{-1}$

$v_+ = 300 \text{ km s}^{-1}$

IS abs. lines

Lyα Em. line

Lyman Cont. photons?

Graphs showing relative velocity distributions.
Chemistry and ISM Kinematics @ High Redshift

Pettini et al 2002
Stellar Mass/Metallicity Relation at $z \sim 2.2$

Based on H-alpha (K-band) Spectroscopy of $\sim 90$ $z \sim 2-2.6$ galaxies with Keck/NIRSPEC

Erb et al 2006
Mass Comparisons, \( z \sim 2 \) star forming galaxies
(masses on physical scales of \( r \sim 5 \) kpc)

Dynamical vs. \( M^* \)

Dynamical vs. \( (M_{\text{gas}} + M^*) \)

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**Erb et al 2006b**
MOSFIRE
Multi-Object Spectrometer For Infra-Red Exploration

• Near-IR (0.95-2.45μm) imager and multi-object spectrometer

• Spectra of up to 46 objects at a time

• Unique “Cryogenic Slit Unit”

Funded by “public-private partnership”:
• ~50% NSF/TSIP
• ~50% Gordon and Betty Moore

First light: 1st quarter 2010
Caltech+UCLA+WMKO
(Steidel, McLean co-PIs)
MOSFIRE Cryo-Slit Unit
(under test at CSEM, Switzerland)
MOSFIRE as of a few months ago, with front dewar cap removed, temporary electronics rack

Currently undergoing its second “cool-down” (to -240° F), inside 25’ high “clean-room” at Caltech
MOSFIRE: A Multi-Object Near-IR (0.95-2.45 μm) Spectrometer for the Keck Telescopes

- 6.1’ x 6.1’ field for imaging and spectroscopy
- Up to 46 objects at a time using a cryogenic slitmask unit (remotely configured)
- R=3300 w/0.7” slit and full coverage of a spectral band (Y, J, H, or K)
- First light in 2010 Q1; collaboration between Caltech and UCLA
- Integration @Caltech underway
Mauna Kea and Laser Guide Stars
Adaptive Optics: How it Works
NGC 1569
SSC B

Hubble NIC2
F160W

(Field of view: 6” x 6”)

15 pc
NGC 1569  
SSC B  

Keck AO  
IHK’  

(Field of view: 6” x 6”)

15 pc
So What are They?
(ACS images of spectroscopically confirmed $z \sim 2$ galaxies; 3” boxes)

Law et al 2007
Hα Maps of z~2.3
Galaxies vs. ACS
(Law et al 2009)

Keck II/OSIRIS+LGSAO

$v_{\text{rot}}/\sigma < 1$

$\sigma \sim 70$-$100$ km/s

$\sim 0.08''$ Resolution

Law, CS, Erb et al 2009
Keck OSIRIS+LGSAO: Spatially Resolved Emission Line Maps of z~2-3 Galaxies

\[ \Delta v_{\text{abs}} \approx 1000 \text{ km s}^{-1} \]

Law et al 2007
The Intergalactic Medium: Generally a Boring Place...

- Normal matter
- Detectable neutral Hydrogen gas
- UV radiation field
- Dark matter potential
• Can use background QSOs, AGN, and galaxies to study gas kinematics, metallicity, etc. in outer parts of foreground galaxies

• Use the interface with the IGM as a barometer for “feedback” processes

⇒ true IGM “tomography” is possible now.
Densely Sampling the Universe @z~1.8-3.2
LBG Color Selection: Controlling the Survey Volume

Relative surface density vs. redshift
~7'x5', ~140 objects, z~1.8-3.2
Using Background Galaxies for Foreground Galaxy Superwinds

- Higher z galaxy probes outflow of lower-z gal at ~15 kpc galactocentric distance
- Absorption @z=1.60 in spectrum of background galaxy is at rest (but with velocity width of 650 km/sec wrt foreground galaxy)
Galaxy Pair Composite Spectra

- 50 pairs 1-5” ($\langle d \rangle = 31$ kpc)
- 190 pairs 5-10” ($\langle d \rangle = 63$ kpc)
- 305 pairs 10-15” ($\langle d \rangle = 103$ kpc)
Densely Sampling the Universe \( @z \sim 1.8-3.2 \)
Galaxy BX210:

$\Delta v \sim 660 \text{ km/sec}$

$v_{\text{max}} \sim -600 \text{ km/sec}$

QSO sightline, 85 kpc away
“Galaxy-centric” Measures

“Pixel-centric” measure
At transverse distances of $\sim 1\, h^{-1}\, \text{Mpc}$ (300-400 kpc physical), CIV and especially OVI, have excess peculiar velocities of many hundred km/s
Lyman Continuum Emission from Galaxies
(the elusive “escape fraction”)

125 $z \sim 3$ galaxies
8-10 hour exposures
(Bogosavljevic, CS, et al 2009)

Shapley, CS, Pettini, Erb 2006
(14 $z \sim 3$ galaxies)
• Observe galaxies both “in front of” and “behind” quasars and use the whole system to explore the intergalactic medium and the energetics of explosive processes in the early universe.
A Quasar “Smokes” the Surrounding ~1 million Lyr
Lyα (z=2.84) Line Image (NB-V)
• 286 Ly α emitters in 5’ x 7’ field (64 have spectra, no interlopers)
• Several giant Ly α “blobs” in same field (example above)
• Maps structure of high-density HI, independent of star formation
• How many are due to fluorescence??
Summary

• We are working on understanding the following during the peak epoch of galaxy formation (z~1.5-3.5):
  – Galaxy-scale star formation
  – Metal enrichment of galaxies and the IGM
  – The circulation of gas, metals between galaxies and the IGM
  – The effects of radiative and hydrodynamical “feedback” on the galaxy formation process
  – The nature of the connection between supermassive black growth and galaxy formation
  – The nature of the ionizing radiation, its spatial variations, sources
• Significant involvement in developing the state-of-the-art tools needed for these and related studies of the high redshift universe:
  – MOSFIRE (2010 commissioning)
  – TMT (Thirty Meter Telescope Project)- instrument and science development