Measuring the evolution of the star formation rate efficiency of neutral atomic hydrogen gas from $z \sim 1–4$

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Galactic Scale Star Formation
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UV UDF team
Damped Lyman Alpha Systems (DLAs)

- Definition of Damped Lyα System (DLA): $N(\text{HI}) \geq 2 \times 10^{20} \text{ cm}^{-2}$
- Distinguishing characteristics of DLAs:
  1. **Gas is Neutral**
  2. Metallicity is low: $[\text{M/H}] = -1.3$ (more on this later)
  3. Molecular fraction is low: $f_{\text{H}_2} \sim 10^{-5}$
- DLAs dominate the neutral-gas content of the Universe out to $z \sim 4.5$
- DLAs cover $1/3$ of the sky at $z = [2.5, 3.5]$

Wolfe et al. 2005
Kennicutt-Schmidt (KS) Relation

\[ \Sigma_{\text{SFR}} = A \Sigma_{\text{gas}} \]

The Star Formation Rate (SFR) surface density goes as the total gas surface density to a power law.

Can rewrite it with column density \( N \):

\[ \Sigma_{\text{SFR}} = K \times (N/N_c)^\beta \]

\( N_c = 1.25 \times 10^{20} \text{ cm}^{-2} \quad \beta = 1.4 \pm 0.15 \)

\( K = 2.5 \times 10^{-4} \text{ M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \)

Kennicutt, 1998
Tightly Correlated HI and FUV emission in M83

Blue: FUV map (GALEX)

Red: HI contours (THINGS)

Bigiel et al. 2010a
Can we see DLAs in emission at $z\sim 3$?

- Gas Density $\leftrightarrow$ SFR (KS)

- SFR $\leftrightarrow$ FUV $L_\nu$

(Madau Kennicutt Calibration)

At $z=3$ 1500 Å $\rightarrow$ 6000 Å
- This puts it in the visible!

- $L_\nu$/area $\leftrightarrow$ Surface Brightness

- Most DLAs:
  $N \sim 2 \times 10^{20} \rightarrow 3 \times 10^{21}$ cm$^{-2}$
  $N_{\text{avg}} \sim 1 \times 10^{21}$ cm$^{-2}$

Only high resolution image sensitive enough
is the Hubble Ultra Deep Field (UDF)
Cumulative comoving SFR density for DLAs

\[ \Sigma_{\text{SFR}}(N) = K \left( \frac{N}{N_c} \right)^\beta \]

\[ \rho_\star(>N) = \int_N^{N_{\text{max}}} \Sigma_{\text{SFR}}(N') \frac{H_0}{c} f(N', X) dN' \]

Wolfe & Chen 2006

Surface Brightness \([\text{mag arcsec}^{-2}]\)
(A proxy for \(N_{\text{HI}}\) via the KS relation)

10% \(K\)
1% \(K\)

K=K_{\text{kenn}}
K=0.1 \times K_{\text{kenn}}
K=0.01 \times K_{\text{kenn}}
Wolfe & Chen 2006 result:

• SFR efficiency of DLAs is a factor of $\geq 10$ below KS relation

Caveat:

• Wolfe & Chen 2006 search excluded objects with high surface-brightness cores ($\mu_V < 26.6$ mag/arcsec$^2$) (i.e. LBGS)

Another possibility:

• Lyman Break galaxy cores may be embedded in DLAs, and may themselves exhibit in situ star formation
LBGs embedded in DLA Neutral Gas Reservoirs
In situ star formation in DLAs associated with LBGs

In-situ star formation

DLA

LBG

Dust
Solution: Ultra Deep u’-band image of UDF with Keck

Keck Telescopes

$1\sigma$ depth = 30.7 mag/arcsec$^2$
Detection limit = 27.6 mag/arcsec$^2$
FWHM = 1.3 arcsec

Use the u-band image to select 407 $z\sim3$ LBGS via their flux decrement from the Lyman break

Rafelski et al. 2009
### 48 compact, symmetric, and isolated z~3 LBGs in V-band

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Rafelski et al. 2011
Stack 48 isolated, compact, symmetric $z \sim 3$ LBGs in the V-band (rest-frame FUV)
Radial surface brightness profile of stacked image

Rafelski et al. 2011
Goal: compare comoving SFR density in outskirts of LBGs to DLAs to obtain a SFR efficiency

Column density of gas varies with radius, we need a differential version of the comoving SFR density (\( \dot{\rho}_* \))

Previously:

\[
\rho_*(>N) = \int_{N}^{N_{\text{max}}} \Sigma_{\text{SFR}}(N') \frac{H_0}{c} f(N', X) dN'
\]

Differential:

\[
\frac{\Delta \dot{\rho}_*}{\Delta N} = \langle \Sigma_{\text{SFR}}(N) \rangle \frac{H_0}{c} f(N, X) \quad \Rightarrow \quad \frac{\Delta \dot{\rho}_*}{\Delta I}
\]
Model differential comoving SFR density for DLAs

Surface Brightness [mag arcsec$^{-2}$]

Differential comoving SFR density per intensity interval

Rafelski et al. 2011
Determine efficiency for each point

Comparison of model to data to determine efficiency

\[
\log \left( \frac{\dot{M}}{I} \right) \left[ \frac{M_{\odot} \cdot yr}{Mpc^3 \cdot ergs \cdot cm^{-2} \cdot sec^{-1} \cdot Hz^{-1}} \right] 
\]

Surface Brightness [mag arcsec^{-2}]

Differential comoving SFR density per intensity interval

Rafelski et al. 2011
The KS relation for atomic dominated gas at $z \sim 3$

\[ \Sigma_{\text{SFR}} \left[ M_{\odot} \text{yr}^{-1} \text{kpc}^{-2} \right] \]

\[ \Sigma_{\text{gas}} \left[ M_{\odot} \text{pc}^{-2} \right] \]

Rafelski et al. 2011
The covering fraction of the outskirts of LBGs is consistent with the DLA covering fraction.

The emission unlikely to be from molecular-dominated gas.

**atomic-dominated gas**

**molecular-dominated gas**

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Rafelski et al. 2011
Comparisons to predictions from simulations (Gnedin & Kravtsov 2010)

**LBG Metallicity**

- KS relation
- KS relation, $K=0.1 \times K_{\text{Kenn}}$
- LBG R/H range
- LBG Uncertainty (1σ)
- LBG outskirts
- All Metals
- DLAs
- G&K 2010 total gas
- G&K 2010 atomic gas
- G&K 2010 molecular gas

**DLA Metallicity**

- KS relation
- KS relation, $K=0.1 \times K_{\text{Kenn}}$
- LBG R/H range
- LBG Uncertainty (1σ)
- LBG outskirts
- DLAs
- G&K 2010 total gas $Z<0.1Z_{\odot}$
- G&K 2010 atomic gas $Z<0.1Z_{\odot}$
- G&K 2010 molecular gas $Z<0.1Z_{\odot}$

Rafelski et al. 2011
What is responsible for the reduced SFR efficiency?

Metallicity of gas?

Background radiation field?

Role of molecular vs. atomic hydrogen gas?

Other possibilities?

To better answer this question, would like to measure SFR efficiency for a range of redshifts.
Metal Abundances versus redshift

\[
\langle Z \rangle = -(0.22 \pm 0.03) z - (0.65 \pm 0.09)
\]

Typical uncertainty

Rafelski et al. 2012 in press
Evolution of Background Radiation Field

Haardt & Madau 2012
Comparison of $z \sim 3$ outskirts with $z=0$ outskirts

\[ \Sigma_{\text{SFR}} \left[ \frac{M_\odot}{\text{yr} \cdot \text{kpc}^{-2}} \right] \]

\[ \Sigma_{\text{gas}} \left[ \frac{M_\odot}{\text{pc}^{-2}} \right] \]

Rafelski et al. 2011
The Ultraviolet Hubble Ultra Deep Field

Measure SFR efficiency at $z \sim 1$ and $z \sim 2$
Improve $z \sim 3$ measurement with larger sample of LBGs
Use existing $i'$ band UDF data for measurement at $z \sim 4$
NUV Coverage of UDF with WFC3

Epoch 1:
March 2 - March 11
6 Orbits / 12 exposures per filter

Epoch 2:
May 28 - June 4
10 Orbits / 20 exposures per filter

Epoch 3:
August 4 - September 19
14 Orbits / 28 exposures per filter
+ 2 failed orbits from above

Total:
30 Orbits / 60 exposures per filter
90 Orbits in total by mid September

29th mag 10 sigma point source limit
UV dropout galaxies at $z \sim 1-3$
Radial surface brightness profile of stacked LBGs at z~4

Inner core

Outskirts

Surface Brightness ($\mu_V$) [mag arcsec$^{-2}$]

Radius [arcsec]

Radius [kpc]

Median LBGs

PSF

1 image sky limit

73 image stack sky limit

PRELIMINARY

Log $\Sigma_{SFR}$ [M$_\odot$ yr$^{-1}$ kpc$^{-2}$]

Radius [arcsec]

0.0 0.2 0.4 0.6 0.8 1.0 1.2

0 2 4 6 8

0.0 0.2 0.4 0.6 0.8 1.0 1.2

0 2 4 6 8

0.0 0.2 0.4 0.6 0.8 1.0 1.2
How do things change at $z\sim 4$?

$\Sigma_{\text{SFR}} \left[ M_{\odot} \text{yr}^{-1} \text{kpc}^{-2} \right]$ vs. $\Sigma_{\text{gas}} \left[ M_{\odot} \text{pc}^{-2} \right]$

- KS relation
- KS relation, $K=0.1 \times K_{\text{kenn}}$
- LBG R/H range
- LBG Uncertainty ($1\sigma$)
- LBG outskirts
- DLAs
- LBG outskirts $z\sim 4$

PRELIMINARY

Heidelberg 2012: Marc Rafelski
Summary

• Measured extended rest-frame FUV emission in outskirts of z~3 LBGs

• Star formation rate efficiency of atomic-dominated gas at z~3 is a factor of ~10 lower than predicted by Kennicutt-Schmidt relation for local galaxies at z=0

• Covering fraction of DLA gas consistent with LBG outskirts, while molecular gas insufficient to cover the LBG outskirts.

• Consistent with predictions from Gnedin and Kravtsov 2010 suggesting the metallicity could be the driver for the lower SFR efficiency

• Measured the metallicity evolution of neutral hydrogen gas out to z~5

• Obtaining NUV data with HST to measure the SFR efficiency at z~1 & 2

• Preliminary measurement of the SFR efficiency at z~4