Fast Outflows identified in Early Star-Forming Galaxies at z=5–6


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Figure 1. Art of viewing the CGM. The galaxy’s central bulge and blue gas outside are fed by filamentary accretion from the IGM (blue). Outflows emerge from the disk in pink and orange, while gas that was previously ejected is recycling. The "use gas" halo in varying tones of purple includes gas that is likely contributed by all these sources and mixed together over time.

More generally, sub-$L^*$ galaxies have extended bursty star formation histories, as opposed to the more continuous star formation found in more massive galaxies, suggesting differences in how and when these galaxies acquire their star forming fuel. As this fuel is from the CGM, we must explain how sub-$L^*$ and $L^*$ galaxies fuel star formation for longer than their $\tau_{\text{dep}}$.

2.1.2. What quenches galaxies and what keeps them that way?

How galaxies become and remain passive is one of the largest unsolved problems in galaxy evolution (Figure 2b). Proposed solutions to this problem involve controlling the gas supply, either by shutting off IGM accretion or keeping the CGM hot enough that it cannot cool and enter the ISM.
Redshift Evolution of Outflow Velocity

Outflow velocities increase at $z > 2$?
How large velocities are at $z > 4$?
Goals of Our Work

This work study outflows in star-forming galaxies:

1. To measure outflow velocities in distant galaxies we can observe (at $z \sim 5–6$).

2. To investigate the redshift evolution of the outflow velocities.

3. To discuss the fundamental galaxy property to determine the outflow velocities.
Challenges at High Redshift

- Deep rest-UV spectra needed for absorption-line analysis
- No nebular emission lines to determine systemic redshift

**Solution:** deep UV spectrum & ALMA [CII]158μm

Steidel et al. (2016)

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[^1]: [Steidel et al. 2016](#)
[^2]: [Rix et al. 2004](#)
[^3]: [Brott et al. 2011](#)
[^4]: [Eldridge & Stanway 2012](#)
[^5]: [Eldridge & Stanway 2016](#)
Sample

Archival seven LBG spectra (PI: P. Capak)

- DEIMOS rest-UV spectra ($T_{exp} \sim 3.5h$)
- ALMA [CII] emission line ($z_{err} \sim 10$ km/s)
- $z = 5–6$ | $\log M^* = 9.6–10.5$

Modified from Barisic et al. (2017)
Modified from Capak et al. (2015)
Analysis — Rest-UV Spectra Stacking

The figure shows the normalized flux distribution across different wavelengths in ångstroms (Å). Key features include:

- **Lyα**
- **Si II**
- **Si II+OH**
- **C II**
- **Si IV**

The wavelength ranges are indicated as follows:

- **Si II**
  - 1250 Å to 1260 Å
- **C II**
  - 1330 Å to 1340 Å
- **Si IV**
  - 1390 Å to 1410 Å

The data is presented in stacked plots, with each spectral line labeled accordingly.
Analysis — Fitting

Fitting results for various transitions in the spectrum, including Ly$\alpha$, Si II, Si II+O I, C II, Si IV, and Si IV. The figure illustrates the normalized flux as a function of wavelength, with peak velocities ($V_{\text{max}}$) and 90% coverage regions highlighted for Si II, C II, and Si IV transitions.
Result 1: Vmax vs. SFR

Red: SiII+CII

Orange: SiII,CII,SiIV → consistent

\[ V_{\text{max}} = 700^{+180}_{-110} \text{ km s}^{-1} \]

Outflow velocity at \( z \sim 6 \) is comparable to one at \( z \sim 2 \)

\( z \sim 0, 1, 2 \) (Sugahara+17)
Result 2: $V_{\text{max}}$ vs. $V_{\text{cir}}$

- Halo circular velocity
  - $M_* \rightarrow M_h$ Behroozi+13
  - $M_h \rightarrow V_{\text{cir}}$ Mo&White 02

- Data points over $z \sim 0-6$
  - agree with predictions
    - FIRE simulations: Muratov+15
    - IllustrisTNG: Nelson+19

V$_{\text{cir}}$ strongly correlates with $V_{\text{max}}$
Result 3: Redshift Evolution of $V_{\text{max}}$

If $V_{\text{max}}$ linearly correlates with $V_{\text{cir}}$ at fixed halo mass:

$$V_{\text{cir}} = \sqrt{\frac{GM_h}{R}} \propto (1 + z)^{\frac{1}{2}}$$

Evolution at $M^* \sim 10^{10.1} M_\odot$

Comparing to:

Jones+13 ($\times$), Du+18 ($\triangle$)
Vmax correlation with gal. properties

Vcir & SFR

Similar Relations

at $z \sim 0$ & at $z=0–6$ (dash)

Fundamental

Vcir or SFR

Different slope of the relations

$\Sigma_{SFR}$ & SFR/M*

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Fast Outflows in Early SFGs at $z=5–6$

**Sample & Analysis**
- LBGs observed with DEIMOS & ALMA (PI. P. Capak)
- $V_{\text{max}}$ by fitting to abs. lines of composite spectrum

**Results**
- $V_{\text{max}} = 700^{+180}_{-110}$ km s$^{-1}$
- Outflow velocity increases at $z \sim 0 \rightarrow 6$ at a fixed $M^*$
- $V_{\text{cir}}$ or SFR would be fundamental to determine $V_{\text{max}}$